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The impact of humidity standards on energy efficient cooling in california

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THE IMPACT OF HUMIDITY STANDARDS ON ENERGY EFFICIENT COOLING IN CALIFORNIA

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Executive Summary

EXECUTIVE SUMMARY

The interior environmental conditions specified by standards significantly affect both the amount of energy used in conditioning buildings and also the design approaches used to achieve those conditions. Designers and building operators are required to keep environmental conditions in compliance with applicable standards for liability reasons, if none other. One of the most commonly used comfort standards, ASHRAE Standard 55-1992 [ASHRAE 1992], recently set an upper limit of 60% relative humidity (RH) for its human comfort zone. The 60% RH limit, lower than in previous versions of the Standard, would restrict the use of direct evaporative cooling and ventilative cooling, two energy efficient cooling technologies that are particularly well-suited for California transition climates. Standard 55-1992's humidity limit would increase the energy needed for cooling in California buildings, thereby affecting the productivity and competitiveness of California industries, and negatively impacting the environment.

The scientific basis for the change in upper humidity limit was not clearly expressed in Standard 55-1992. Recognizing the lack of experimental data to support the 60% RH upper limit, the cognizant Standards Project Committee (SPC 55-81R) developed an interim solution based solely on comfort considerations in the form of an addendum [ASHRAE 1995] that changes the upper humidity limit to a constant 20°C (68°F) wet bulb temperature for summer conditions and a constant 18°C (64°F) wet bulb temperature for winter conditions. The Committee also suggested that new research was needed to better define the level and shape of the upper humidity boundary.

The objectives of the current study are to:

1. Perform a review of the literature and results of previous comfort studies to assess the current state of knowledge regarding the effects of high humidities on comfort, thermal acceptability, and other important parameters, such as skin wettedness and skin temperature.

2. Conduct a laboratory study to provide more extensive experimental data to substantiate the relationship of thermal comfort and humidity at effective temperatures (ET*) along the higher temperature boundary of the established comfort zone of ASHRAE Standard 55-1992.

3. Examine the impact of the upper humidity limit in ASHRAE Standard 55-1992 on the use of evaporative cooling in California commercial buildings, and its associated impact on energy consumption.

This final report is presented in two parts as summarized below.

1. **Laboratory Study of Comfort Under Warm-Humid Conditions in an Office Environment.**
   This section contains the results of the literature review and the laboratory study aimed at providing more extensive experimental data to examine the relationship between thermal comfort and humidity under warm-humid conditions, and in particular, the upper humidity limit [ASHRAE 1995] of Addendum 55a to ASHRAE Standard 55-1992, one of the most

widely used comfort standards. To accomplish this, 92 human subjects were tested under steady-state conditions in a controlled environment chamber configured to resemble a modern office space. The subjects were exposed to a range of humidities (RH = 50%, 60%, 70%, and 80%) under the worst-case thermal conditions, namely along the warm upper boundary of the summer comfort zone (ET* = 26°C [79°F]), as specified in ASHRAE Standard 55-1992. During the test, subjects repeated a series of step-exercises to simulate three different activity levels (1.2 met, 1.6 met, and 4-5 met), representative of a range of typical office work. Subjects wore typical informal office attire with an insulation value of 0.6 clo.

Thermal acceptability data for steady-state test conditions at 1.2 met indicate that the upper humidity limit (based on an 80% acceptability criterion) is well above 60% RH and probably closer to 70% RH along the warmest temperature boundary (ET* = 26°C [79°F]) of the comfort zone specified in ASHRAE Standard 55-1992.

2. **Impact of Humidity Standards on Commercial Building Energy Use.**
This section contains the results of two independent analyses to evaluate the impact of humidity standards on evaporative cooling strategies: one using a spreadsheet model to evaluate impacts on the design and system selection process, and the other using DOE-2 simulations to assess both comfort and energy implications. The first analysis shows that the upper humidity limits under consideration in ASHRAE Standard 55-1992 should only be an issue for climates having a design wet bulb temperature above a critical level. Most of California's 16 climate zones do not have such a high design wet bulb temperature. The DOE-2 simulations show that evaporative coolers could save an average of 40% of the cooling and fan energy for a typical mid-size commercial building. If evaporative coolers were used in 25% of all commercial buildings in the state, this would result in annual energy savings of approximately 2,220 GWh of electricity and 2.7 million therms of natural gas.

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SECTION 1

Laboratory Study of Comfort under Warm-Humid Conditions in an Office Environment

LABORATORY STUDY OF COMFORT UNDER WARM-HUMID CONDITIONS IN AN OFFICE ENVIRONMENT

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ABSTRACT

This experiment examines the relationship between thermal comfort and humidity under warm-humid conditions, and in particular, the upper humidity limit in ASHRAE Standard 55-1992 [ASHRAE 1995]. There are significant energy implications to the position of this limit, and there is at present insufficient experimental basis to justify its being used in the design of buildings. To be convincing, the limit should apply to humidity effects known to affect occupants while they are engaged in realistic levels of activity. Such effects have not been measured before.

To address this need, 92 human subjects were tested under steady-state conditions in a controlled environment chamber configured to resemble a modern office space. The subjects were exposed to a range of humidities (RH = 50%, 60%, 70%, and 80%) under the worst-case thermal conditions permitted by the standard, namely along the warm upper boundary of the summer comfort zone (ET* = 26°C [79°F]). During the test, subjects repeated a series of step-exercises to simulate three different activity levels (1.2 met, 1.6 met, and 4-5 met), representative of a range of typical office work. Subjects wore typical informal office attire with an insulation value of 0.6 clo.

Thermal acceptability data for steady-state test conditions at 1.2 met indicate that the upper humidity limit (based on an 80% acceptability criterion) is well above 60% RH and probably closer to 70% RH along the warmest temperature boundary (ET* = 26°C [79°F]) of the comfort zone specified in ASHRAE Standard 55-1992.

INTRODUCTION

Background and The ASHRAE Standard

The interior environmental conditions specified by standards significantly affect both the amount of energy used in conditioning buildings and also the design approaches used to achieve those conditions. Designers and building operators are required to keep environmental conditions in compliance with applicable standards for liability reasons, if none other. ASHRAE Standard 55-1992 [ASHRAE 1992, 1995] recently set the upper humidity limit for its human comfort zone. This new limit is lower under warm conditions than the limit used in previous versions of the Standard. It would restrict the use of direct evaporative cooling and ventilative cooling, two energy efficient cooling technologies that are particularly well-suited for California transition climates. Standard 55-1992's humidity limit would increase the energy needed for cooling in

California buildings, thereby affecting the productivity and competitiveness of California industries, and negatively impacting the environment.

The scientific basis for the change in upper humidity limit was not clearly expressed in Standard 55-1992. There was surprisingly little literature addressing the influence of humidity on comfort. Although it did not specifically attempt to determine this relationship, the largest relevant study [Tanabe et al. 1987] done at the time of the revision to the Standard suggested that comfort may be affected by humidity at approximately 80% RH and above. This is substantially higher than the limits in Standard 55. Recognizing the lack of experimental data to support the 60% RH upper limit, the cognizant Standards Project Committee (SPC 55-81R) developed an interim solution based solely on comfort considerations in the form of an addendum [ASHRAE 1995] that changes the upper humidity limit to a constant 20°C (68°F) wet bulb temperature for summer conditions and a constant 18°C (64°F) wet bulb temperature for winter conditions. The use of constant wet bulb lines as the upper humidity boundaries is based on the strong correlation between skin wettedness and discomfort under warm conditions. The Committee also suggested that new research was needed to better define the level and shape of the upper humidity boundary. The purpose of the current study is to provide more extensive experimental data to substantiate the relationship of thermal comfort and humidity at effective temperatures (ET*) along the higher temperature boundary of the established comfort zone of ASHRAE Standard 55-1992.

Human subject tests [Nevins et al. 1966, Fanger 1970, Tanabe et al. 1987, de Dear et al. 1991] have shown that humidity has only a modest effect on thermal sensation at temperatures within the comfort zone. On the bases of this work, conditions even above 80% relative humidity can be comfortable in terms of thermal sensation. From the perspective of the body's thermal balance, there is no upper limit to humidity, since temperature adjustment is sufficient to achieve thermal neutrality at very high humidity. The physics of the effect of humidity on heat loss and thermal sensation are well developed, and indices such as ET* and the Predicted Mean Vote (PMV) equation include the effects of humidity in scaling temperature and thermal sensation.

Independent of thermal sensation, there is the somewhat different question of *comfort* at high relative humidities. McIntyre (1980) cites several studies showing that for operative temperatures within the comfort zone, differences in RH as disparate as 20% and 70% can be undetectable, let alone a source of discomfort. Tanabe et al. (1987) suggest that at high humidity levels (80% RH), perception of thermal sensation does not act as a reliable predictor of thermal comfort and concludes that the use of thermal sensation to establish limits of thermal comfort is inappropriate at higher levels of humidity.

The mechanism by which humidity affects comfort is not known. One possible hypothesis is that hygroscopic absorption of atmospheric moisture by the skin's stratum corneum, or by salt on the skin's surface, increases skin wettedness. Skin wettedness is known to be closely connected to human perception of comfort/discomfort under warm conditions [Gagge et al. 1971]. Discomfort might be caused by a clinging sensation of clothing on the wet skin, caused by softening of the stratum corneum over which clothing fibers pass, and possibly due to changes in the clothing fibers themselves.

Another hypothesis is that humidity level affects comfort differently during variation in metabolic levels. People at any normal indoor metabolic level (e.g., less than or equal to 1.2 met) may in their daily activities temporarily elevate their met rates by climbing stairs, carrying packages, etc. During the elevated activity, a higher heat loss is required for thermal balance. If the humidity is high, the heat dissipation ability of the body is reduced, and the sweat rate will increase over that of a body in a dry environment. The resulting skin wettedness may persist after the activity rate has subsided and skin cooled off. Discomfort would then be due to either the increased skin temperature during the intermittent exercise, or the residual skin wettedness left over after the exercise.

Finally, there is the possibility that the humidity is perceived in the respiratory system or some other site. McIntyre (1980) refers to a sense of 'oppressiveness' cited in German standards. We have not found experimental evidence for such hypotheses in the literature. However, an experimental investigation should attempt to detect such sensations if they are present.

It should be noted that upper limits on humidity will also be constrained by biotic health influences such as mold growth and dust mites, whose growth is affected by humidity. The extent of biotic growth depends very much on the design of the building envelope, the HVAC system type, and whether the system recirculates air or uses a 'once-through' strategy. In no case is it well correlated to the humidity in the space. This topic is distinct from thermal comfort and is addressed by ASHRAE in a separate standard, Standard 62.

Review of Previous Laboratory Experiments on Humidity and Comfort

Houghten and Yaglou (1923) developed the Effective Temperature scale (ET), based on experiments with twin climate chambers. Subjects moved between the chambers and voted within 15 minutes of switching. The ET scale shows combinations of temperature and humidity that result in equal comfort. Glickman et al. (1950) concluded that the ET scale overemphasized the effect of humidity for long-term exposures. Koch et al. (1960) concluded that between 20°C - 34°C, and 20% - 90% RH, humidity had only a small effect on comfort. Nevins et al. (1966) determined that the temperature can be increased by 0.3°C for each 10% reduction in RH. McNall et al. (1967) tested several metabolic rates in a design similar to Nevins et al. (1966) and found little humidity effect at low metabolic rates and an increased humidity effect at higher metabolic rates. Andersen et al. (1973) found no effect on the perception of humidity of changes between 10% -70% RH.

de Dear et al. (1989) studied the impact of humidity on thermal comfort during step changes between 20% and 80% RH. While most previous experiments examined long-term, steady-state responses, this experiment looked at a subject's instantaneous response to a change in humidity as well as how that response changed over the 90 minutes immediately following. Twin climate chambers were used with the subjects spending an initial acclimation period in the first chamber before moving to the second. The study found that the thermodynamics of moisture absorption and desorption in clothing fibers during humidity transients affected the heat balance and thermal sensation of the subjects. Very similar thermal sensation responses were obtained for both nude subjects and subjects dressed in polyester clothing, indicating that human skin absorption and desorption were responsible for the instantaneous, but short-lasting (less than 30 minutes), effect of the humidity step-changes. The effect was most pronounced for subjects wearing natural wool, in which cases there was an immediate change in thermal sensations that lasted for at least 90 minutes.

The J.B. Pierce Foundation conducted a test chamber study [Berglund 1989] of human subjective and physiological responses to a range of humidity levels under summer air-conditioning conditions. Twenty subjects were each exposed to the twenty-seven combinations of three steady-state air temperatures (21°C, 24°C, 27.2°C), three dew point temperatures (1.7°C, 11.1°C, 20°C), and three metabolic rates (sitting = 0.94 met, intermittent walking and standing = 1.95 met, and continuous walking = 2.84 met). Subjects felt cooler, drier, and more comfortable at the lower humidities and temperatures and also judged the air to be fresher with a more acceptable air quality. The effect of temperature on thermal comfort was found to be about one order of magnitude higher than that of humidity, while humidity played a larger role in the subjects' assessments of air quality. The subjects also indicated that equal changes in humidity were more perceptible at higher humidities than at lower humidities.

In a recent paper, Berglund (1995) further analyzed the results from the above chamber study and concluded that the judgment of whether an environment is thermally acceptable or not depends on both thermal sensation and perceived skin moisture. This result accounts for the fact that at a given temperature, warm discomfort will increase with increasing humidity. By considering only the data set for sedentary subjects wearing 0.56 clo (summer conditions) under humidity conditions above the middle of the comfort zone, Berglund shows that the loci of points representing 80% thermal acceptability correlate fairly well with the newly prescribed upper humidity limit (constant wet bulb temperature of 20°C (68°F) for summer conditions) of Addendum 55a to ASHRAE Standard 55-92 [ASHRAE 1995]. Berglund suggests that agreement would be improved if the comfort zone were shifted to slightly cooler temperatures (≈1.5°C [2.5°F]).

Hayakawa et al. (1989) investigated the physiological and psychological effects of air temperature and humidity on the human body at three different metabolic rates during summer conditions. In a climate chamber, four female subjects wearing 0.03 clo were exposed to the forty-eight combinations of three air temperatures (30°C, 32.5°C, 35°C), four relative humidities (30%, 50%, 70%, 90%), and three metabolic rates (approximately 1 met, 1.5 met, and 2 met). The results indicated that at 30°C, near the upper boundary of the comfort zone for sedentary activity and 0.03 clo, there was no significant difference in thermal sensation vote for humidities up to 70%. Discomfort vote, however, appeared to be more sensitive to changes in humidity between 50% and 70% RH, even under sedentary conditions at 30°C. Both thermal sensation vote and discomfort vote increased noticeably at higher activity levels.

de Dear et al. (1991) conducted a laboratory study of ninety-eight college-age Singaporeans, who were exposed to ten different combinations of humidity (35% and 75% RH) and temperature (five temperatures around the upper temperature limit of the ISO 7730 [ISO 1984] and ASHRAE Standard 55-92 comfort zones). Subjects wore standard 0.6 clo uniforms and were sedentary throughout the three-hour experiments. Humidity was found by probit analysis to play only a relatively minor role in determining the temperature at which 20% thermal dissatisfaction occurred (27.7°C and 26.6°C for the low and high humidity conditions, respectively).

Tanabe and Kimura (1994) describe a series of chamber experiments they had previously performed in Japan examining the effect of humidity on thermal comfort. In one test, sixty-four college-aged subjects were exposed for three hours to air temperatures at and above the upper boundary of the ASHRAE-specified comfort zone. Relative humidities of 50% and 80% were tested as well as several air movement levels. They concluded that PMV overpredicts thermal sensation vote for hot and humid conditions. For low air movement, the difference was on the order of half a category width, but increased with increasing air velocity.

In a recent ASHRAE-sponsored field experiment in the tropics [de Dear and Fountain 1994], a total of 1,234 thermal acceptability responses with accompanying thermal environmental measurements were collected. These data were analyzed to look at the effect of humidity on thermal acceptability within the temperature limits of the summer comfort zone in ASHRAE Standard 55-92. The results from 909 complete questionnaire responses falling between 23°C and 26°C were binned according to relative humidity in equal intervals of 10% from 30% to 70% RH. Within each bin the percentage of subjects expressing thermal dissatisfaction was noted. No clear trend in thermal dissatisfaction was found between 30% and 70% RH for temperatures between 23°C and 26°C, as the dissatisfaction percentage and number of subjects for each of the four relative humidity bins were as follows (with increasing humidity): 21.7% of 60, 18.5% of 271, 19.9% of 347, and 15.2% of 231.

Koseki et al. (1994), Imamura et al. (1994), and Tanabe et al. (1995a and 1995b) describe a recent study in which 72 subjects were exposed to different combinations of air temperature (25°C, 28°C, 30°C) and relative humidity (30%, 50%, 70%) in a test chamber outfitted to look like a realistic office. The metabolic rate was 1.1 met and the subjects wore a standard uniform of 0.5 clo. The results showed that SET* had good correlation with thermal sensation vote. Thermal acceptability was more sensitive to changes in humidity at higher temperatures (30°C). For warmer temperatures (SET* > 28°C), the percentage of subjects voting "warm dissatisfied" from this study was greater than that found in a previous chamber study (see Tanabe et al. 1987). In discussing the differences between these two studies, Imamura (1995) points out that in the more recent study the activity level was 1.1 met, representing a variety of typical office work, while in the earlier study of Tanabe et al. (1987), the subjects were completely sedentary (1.0 met).

In another recently-completed Japanese study directed by Tanabe, sixteen subjects were each exposed to the eight combinations of two temperatures (SET* = 26°C, 28°C) and four relative humidities (RH = 35%, 55%, 65%, 75%) [Imamura 1995]. The experimental procedures in this study were similar to those used in the current study in that subjects wore a 0.6 clo standard uniform and were asked to perform a step exercise every ten minutes to simulate different activity levels (1.2 met and 1.6 met). Thermal sensation and comfort votes were obtained through surveys, and humidity was measured at two locations underneath the clothing allowing the calculation of skin wettedness. Thermal sensation vote was very nearly constant across the entire range of humidities tested (35%-75% RH) at a given temperature. The average thermal sensation was around zero (neutral) at 26°C SET* and 0.8 at 28°C SET*. The comfort vote at 1.2 met was similar for 35%-75% RH after three hours exposure. The feeling of skin moisture was also similar for 35%-75% RH. Thermal acceptability was judged on a continuous scale from 1.0 (completely acceptable) to -1.0 (completely unacceptable). The average thermal acceptability at SET* = 26°C was constant and equal to 0.7 for all humidities tested. At the warmer SET* = 28°C test condition, average thermal acceptability was lower and still nearly constant (0.3-0.4) for 35%-75% RH.

Skin Moisture

Winslow et al. (1937) were the first to recognize that skin moisture is strongly correlated with discomfort under warm conditions. Gagge (1937) quantified skin moisture in terms of the parameter skin wettedness, *w*, defined as the ratio of the rate of evaporative water loss to the maximum possible evaporative loss from the skin to the environment.

Kerslake (1972) showed that a useful expression for skin wettedness (*w*) is:

$$w = (P_m - P_a) / (P_{ssk} - P_a) \qquad (1)$$

where

P_m = vapor pressure at skin surface
P_a = ambient vapor pressure
P_{ssk} = saturated vapor pressure at skin temperature

Gagge et al. (1971) found the normal value of *w* for human skin without sweating to be 0.06. Using the above definition, *w* can theoretically increase to 1.0, when the skin surface is fully wet. Human subject experiments by Gagge et al. (1967) found that the upper limit of the comfort zone for sedentary activity corresponded to a skin wettedness of about 0.20. Other comfort studies with clothed subjects found that comfort was unlikely for skin wettedness levels above 0.25 [Berglund and Cunningham 1986]. In laboratory studies on exercising subjects, Gagge et al. (1969) concluded that the sweating response is a more important determinant for comfort than skin temperature. It was also found that during exercise, subjects were not as sensitive to skin wettedness, and as the metabolic rate increased so did the skin wettedness level corresponding to acceptable conditions. Berglund (1989) also discussed peoples' sensitivity to skin moisture under warm conditions. Under hot-dry conditions, people can be comfortable even at high perspiration rates because their skin can remain dry. Under hot-humid conditions, however, when the skin moisture evaporation potential is significantly reduced, parameters such as increased air motion, humidity control, and clothing design to promote increased ventilation and vapor transport in the air space between skin and clothing become increasingly important as a means of decreasing skin wettedness and discomfort.

Present Investigation

In this laboratory study, 92 human subjects were exposed to thermal conditions representative of the warm upper boundary of the ASHRAE-specified summer comfort zone for light, primarily sedentary activity [ASHRAE 1992, 1995] (see Figure 1). Relative humidities of 50%, 60%, 70%, and 80% were tested along the constant ET* = 26°C (79°F) line, allowing the relationship between thermal sensation, comfort and acceptability to be investigated under warm-humid conditions.

The laboratory study was designed to represent an application of the ASHRAE comfort standard to a realistic space in the following ways.

1. Subjects were tested in a controlled environment chamber configured to resemble a modern office space with typical furniture and partitions.
2. During the test, subjects repeated a series of step-exercises to simulate three different activity levels (1.2 met, 1.6 met, and 4-5 met), representative of a range of typical office work.
3. Test conditions along the upper boundary (ET* = 26°C [79°F]) of the comfort zone were selected based on a 1.2 met activity level and a clothing insulation value of 0.6 clo, representing the highest value of the summer clothing insulation range (0.35 to 0.6 clo) specified in ASHRAE Standard 55. This value is higher than the typical clothing value of 0.5 clo used in the summer comfort zone presented in Figure 2 of Standard 55-1992. An additional amount of overall insulation (up to 0.27 clo based on manikin measurements) was produced by the typically padded office chairs in which the subjects sat during the experiments. Although chair insulation has been neglected in practice, when accounted for in the current study, all test conditions are actually outside of (warmer than) the comfort zone described in Standard 55. The amount may be significant, as the increase in Standard Effective Temperature attributable to this clo-value increase is at least 2°C (refer to Table 2). This means the experimental conditions in this study are conservative for their purpose.

Subjective responses to the test conditions were obtained from all subjects through written surveys that were completed nine times during the 3-hour experiment. As an exploratory investigation of the practicality of a newly developed local skin wettedness sensor, a limited number of subjects (twenty-five) were instrumented to measure local skin temperature and skin wettedness under their clothing. Details of the experimental methods used in this study are given below.

EXPERIMENTAL METHODS

Controlled Environment Chamber

All experiments were performed in a controlled environment chamber (CEC) measuring 18 ft by 18 ft by 8 ft, 4 in. (5.5 m by 5.5 m by 2.5 m) and located in the Building Science Laboratory, University of California, Berkeley. The CEC is designed to resemble a modern office space while still allowing a high degree of control over the test chamber's thermal environment [Bauman and

Arens 1988]. The floor is fully covered with carpet tiles, the finished gypboard walls are heavily insulated and painted white, triple-pane windows in the two exterior walls provide a view to the outside, the suspended ceiling contains patterned acoustical tile, and four 2 ft (0.6 m) square recessed dimmable lighting fixtures are mounted in the ceiling. As shown in Figure 2, a raised access floor system provides a 2 ft (0.6 m) high subfloor plenum, and the suspended ceiling provides a 1.5 ft (0.5 m) ceiling plenum. By providing a sense of realism seldom achieved in a laboratory setting, the CEC design minimizes (at least partially) some of the unknown psychological effects associated with "test cell" experiments using human subjects.

A typical modular office configuration was installed in the test chamber. As shown in Figure 3, medium-height (65-in. [1.65 m]) partitions were set up to produce four small 60-in.-by-75-in. (1.5-m-by-1.9-m) workstations, each containing a desk and a padded swivel office chair. During the experiments, three workstations were occupied by subjects and the fourth was used by the researcher conducting the tests.

The CEC's reconfigurable air distribution system permits ducted or plenum air to be supplied to and returned from the test chamber at any combination of ceiling and floor locations. Figure 2 shows the airflow configuration used during the tests reported here, consisting of a conventional ducted ceiling supply-and-return air distribution system. Figure 3 also shows the locations of the supply diffuser and return register used during the tests in relation to the nine-by-nine grid of 2-ft-by-2-ft (0.6-m-by-0.6-m) suspended ceiling panels (dotted lines in figure). During all tests, supply air was provided through a single perforated lay-in diffuser, positioned near the center of the room. At this position, the internal pattern deflectors were adjusted to produce a four-way airflow pattern. A single perforated return register was located adjacent to one wall during all tests.

The CEC air distribution system also allows a separately controlled airflow to be provided in the annular space between the inner and outer window panes. During all tests, airflow through the annular space maintained the temperature of the interior window pane at approximately the average indoor air temperature. Consequently, the exterior walls and windows were not a source of thermal asymmetry, but contributed to the maintenance of a uniform thermal environment throughout the test chamber.

Temperature and humidity levels in the test chamber were maintained at desired setpoints by a dedicated mechanical system controlled by a commercial direct digital control (DDC) system. Humidification is provided by a steam jacket distribution manifold served by an electronic steam humidifier. Primary heating is provided by hot-water coils served by a 60-gallon electric hot water heater; auxiliary heating is provided by a 1 kW electric duct heater. Cooling and dehumidification are provided by cold-water coils served by a 7.5-ton packaged water chiller attached to a chilled water storage tank filled with a 20% glycol-water mixture.

All experiments were carried out under steady-state conditions. To achieve these conditions, the mechanical system was turned on in the morning, allowing the chamber's thermal mass (e.g., furniture, walls, etc.) to warm up and reach equilibrium with the expected average room temperature for the upcoming experiments. Typically, two 3-hour tests were conducted each day, one beginning at 1 pm and the second at 6 pm.

In ASHRAE Standard 55-1992 [ASHRAE 1992], the warm upper boundary of the summer comfort zone is defined along a constant effective temperature (ET*) line of 26°C (79°F), and the upper humidity boundary is defined along a constant relative humidity line of 60%. To investigate the acceptability of humidity levels around the upper comfort zone boundary, it was decided to focus on a range of humidities (RH = 50% - 80%) under the worst-case thermal conditions, namely along the upper ET* line of the comfort zone. Table 1 lists the four test conditions investigated showing the different combinations of air temperature and relative humidity (RH) setpoints used to maintain a constant ET* of 26°C in all experiments (see also Figure 1). The air temperature was calculated from Gagge et al. (1986) to give the same ET* for each level of relative humidity. These calculations were made with the following assumptions: (1) 1.2 met, (2) 0.6 clo, (3) air temperature = mean radiant temperature, and (4) air velocity ≤ 0.1 m/s. At 50% RH, air temperature is equal to ET* (26°C), but at higher RH values, air temperature is correspondingly reduced.

Table 1. Laboratory Test Conditions

Test Cond.	Set Points RH (%)	Set Points Temp. (°C)	Measured RH (%) Ave.	Measured RH (%) St. Dev.	Measured Temperature (°C) Ave.	Measured Temperature (°C) St. Dev.	Human Subjects Total	Human Subjects Instr.
1	50	26.1	50.1	2.19	26.1	0.38	21	4
2	60	25.7	60.0	1.51	25.8	0.33	22	4
3	70	25.3	70.1	2.06	25.4	0.40	20	2
4	80	24.9	79.9	2.48	24.9	0.36	21	7

In setting up the experimental configuration to be a realistic office setting, it was desirable to have subjects sit in a typical padded swivel office chair. This had the effect of increasing the overall thermal insulating value of the subjects' clothing from the assumed value of 0.6 clo (based on clothing alone) up to a significantly higher maximum value of 0.87 clo (see later discussion in *Clothing Level*). For comparison, Table 2 lists two sets of predicted comfort indices (ET* and SET*) as calculated according to Gagge et al. (1986) for the two different clothing levels, and for an activity level of 1.2 met. Both of these two indices combine temperature and humidity into a

Table 2. Predicted Comfort Indices

Test Condition RH(%)	Test Condition Temp(°C)	Prediction (0.6 clo, 1.2 met) ET* (°C)	Prediction (0.6 clo, 1.2 met) SET* (°C)	Prediction (0.87 clo, 1.2 met) ET* (°C)	Prediction (0.87 clo, 1.2 met) SET* (°C)
50	26.1	26.1	26.3	26.1	28.3
60	25.7	26.1	26.3	26.2	28.4
70	25.3	26.1	26.2	26.4	28.5
80	24.9	26.1	26.2	26.6	28.7

single index. While ET* depends on clothing and activity, SET* (standard effective temperature) allows a more meaningful comparison to be made as it is defined in terms of a standard set of conditions representative of typical indoor applications (e.g., in terms of a subject wearing clothing that is standardized for the activity concerned) [ASHRAE 1993]. Table 2 shows that increasing the assumed clo value from 0.6 to 0.87 produces only a modest increase in ET* (there is no difference at the reference relative humidity of 50%), but generates a more significant increase in SET* of at least 2°C.

As discussed by Brager et al. (1993), the influence of chair insulation on thermal comfort model predictions has often been neglected in practice. Rather than adjust the air temperature setpoint downward to account for the added chair insulation, it was decided to follow common practice, which generally ignores the effects of chair insulation, and use the four original test conditions (listed in Table 1) based only on the subjects' average clothing level of 0.6 clo.

During all tests a constant volume of 270 cfm (130 L/s) of conditioned air was supplied to the chamber through the overhead diffuser. This volume (0.83 cfm/ft^2 [4.3 $L/s\text{-}m^2$]) was sufficient to maintain good air diffusion performance throughout the room, providing close to uniform thermal conditions in all four workstations. Handheld measurements taken in each workstation under conditions of 80% RH and 24.9°C found agreement among all workstations within ±2% RH and ±0.1°C. Additional measurements confirmed that, due to the long warm-up period and steady-state operation of the chamber, mean radiant temperature was very nearly identical to room air temperature. This assumption was therefore applied to all test results and subsequent analysis. All measured velocities were ≤ 0.1 m/s (20 fpm), representing still-air conditions.

The stability of test conditions (temperature and relative humidity) maintained by the CEC's control system is summarized for all experiments in Table 1. The average temperatures are very close to the setpoints with the standard deviations less than 0.4°C (0.7°F). The relative humidities are also well controlled with the standard deviations less than 2.5% for all test conditions. Figure 4 shows an example trend report displaying temperature and relative humidity for one test with setpoints of temperature = 24.9°C, and RH = 80%, indicating the stability of test conditions for a typical test.

Instrumentation

During all tests the mechanical system controlled average room humidity based on measurements of a bulk polymer humidity sensor mounted on one wall of the chamber at a height of 1.5 m (5 ft). The manufacturer's stated accuracy of this sensor is ±2% RH. Calibration accuracy of this RH sensor was checked by side-by-side comparison with a high precision dewpoint temperature sensor (accuracy of ±0.5°C [±0.9°F]) and a sling psychrometer, and was found to agree with factory specifications. Average room air temperature was controlled based on measurements of a shielded thermistor temperature probe, positioned at the 1.1 m (3.6 ft) height in the workstation occupied by the researcher. Calibration of the temperature sensor found agreement to within ±0.1°C (±0.2°F) of a high quality laboratory mercury thermometer. The above two sensors were monitored continuously and recorded at two-minute intervals by the computer-based DDC system, producing a trend report for the average temperature and relative humidity during the test period (see above for discussion of control stability).

Additional portable instrumentation was used by the researcher to verify the accuracy of the chamber control sensors described above. A commercially-available indoor climate analyzer was used for this purpose. The analyzer contains four high precision sensors capable of measuring the four physical parameters necessary for the evaluation of thermal environments: air temperature, dewpoint temperature, air velocity, and radiant temperature asymmetry. The manufacturer's specifications comply with the required measurement accuracy of ASHRAE Standard 55-92 [ASHRAE 1992] and ISO Standard 7726 [ISO 1985]. The researcher recorded air temperature and relative humidity measured by the analyzer at regular intervals during the test period.

Measurement of Skin Wettedness

As described earlier, skin wettedness, *w*, can be calculated (Eqn. 1) by determining three quantities: P_a, P_m, and P_{ssk}. P_a, the ambient vapor pressure, is considered to be constant around the body and is based on the average temperature and humidity of the surrounding air. P_m, the vapor pressure at the skin surface, is based on measurement of the temperature and relative humidity in the space between the skin and clothing. P_{ssk}, the saturated vapor pressure at skin temperature, is calculated from measurement of the skin temperature.

Following an approach introduced by Berglund (1985), we developed a local skin wettedness sensor capable of measuring the necessary quantities described above. Figure 5 shows a schematic cutaway diagram of the skin wettedness sensor. The key component is a commercially-available miniature integrated circuit relative humidity sensor, having dimensions of 8 mm x 4 mm x 0.6 mm (0.32 in. x 0.15 in. x 0.025 in.). The total accuracy is ±2% RH over the range 0-100% RH at 25°C with a time constant of 15 seconds. This factory calibration was verified as described above by side-by-side comparison with a high precision dewpoint temperature sensor and a sling psychrometer. To provide protection for the fragile sensor, it and a small thermistor are housed inside a short length of plastic tubing. When taped to the body, the two sensors are positioned less than 3 mm above the skin surface and exposed through the open end of the tubing, enabling the measurement of the temperature and relative humidity just above the skin surface. In addition, at each measurement location on the body, a separate sensor, consisting of a thermistor mounted with epoxy inside a small nickel-coated copper dish (hollowed-out shell of lithium watch battery), was used to record local skin temperature. Both of the above mentioned thermistors have a ±0.1°C (±0.2°F) accuracy rating which was verified by intercomparison. The skin temperature sensor is described in greater detail by Fountain (1993).

A harness consisting of five sets of the above described sensors was fabricated and connected to two microdataloggers for continuous monitoring. The microloggers were programmed to record measurements every 10 seconds and store 1-minute average data for subsequent analysis. Table 3 lists the five measurement locations (also see Figure 6) that were used according to the studies of Berglund (1985 and 1989). Also shown are the weighting factors used to calculate skin wettedness for the whole body. Since all measurements are made underneath clothing, the calculated whole-body skin wettedness is not representative of bare skin, but only of the value under clothing.

Table 3. Measurement Locations for Local Skin Wettedness and Temperature

Measurement Location	Whole-Body Weighting Factor
Inner side of the left upper arm	0.173
Center of the chest near heart	0.216
Upper part of the back between the shoulder blades	0.216
Inner side of the right thigh	0.235
Back side of the right calf	0.160

Preliminary Tests

Metabolic Rate

In real office spaces, the occupants are usually involved in various levels of activity, including sitting quietly, standing and talking, frequently walking around, and even a short-term exertion (e.g., going up or down several flights of stairs). The increase in activity results in increased physiological effort, metabolic heat, and perspiration, all of which may affect people's sensation of comfort. For the conditions of the current set of experiments (along the warm upper boundary of the summer comfort zone), it was hypothesized that at increasingly higher humidity levels, office workers may be less able to adjust physiologically to even short-term increases in metabolic rate above the sedentary 1.2 met specified in ASHRAE Standard 55-1992. We therefore decided to test the human subjects at three different activity levels, representative of typical office work. The design of the exercise protocol has been described previously by Arens et al. (1993) and involves the subject getting up from his/her seat at regular intervals, and stepping up and down a specific number of times on a nearby 8-inch step. The subject then returns to his/her seat. The three different activity levels that the subjects simulated using this approach are defined as follows: (1) 12 steps / 10 minutes (≈1.2 met); (2) 20 steps / 5 minutes (≈1.6 met); and (3) 40 steps one-time, representing a short-term exertion of approximately 4-5 met.

In order to accurately determine metabolic rate, physiological measurements were made of selected subjects in an exercise physiology laboratory on campus. During these tests, an oxygen consumption measurement apparatus was used to measure (through indirect calorimetry) the metabolic rate for each subject as they repeated the same sequence of activities to be used in the subsequent chamber experiments. The apparatus was connected to the subject through a mouthpiece, allowing the quantity and characteristics of the inhaled and exhaled air to be measured. This information was then analyzed to estimate the metabolic rate.

The rate of metabolic heat produced by the body is most accurately measured by the rate of respiratory oxygen consumption and carbon dioxide production. An empirical equation for metabolic rate is given by Nishi (1981):

$$M = 352\,(0.23\,RQ + 0.77)\,V_{O_2} / A_D, \text{ in W/m}^2 \tag{2}$$

where

RQ = respiratory quotient; the molar ratio of V_{CO_2} exhaled to V_{O_2} inhaled, dimensionless
V_{O_2} = volumetric rate of oxygen consumption at 0°C, 101 kPa, L/min
A_D = DuBois surface area, m^2

The value of the respiratory quotient, RQ, used in the equation depends on a person's activity, diet, and physical condition. In this case, we determined it by direct measurement and inserted it into Equation 2. A total of eleven subjects (six male and five female) were tested in the exercise physiology laboratory. Subjects arrived one hour before the test and spent this time sitting quietly to reach their normal basal metabolic rate. At the beginning of the test period, each subject was monitored while sitting for the first 20 minutes to estimate his/her basal metabolic rate. All subjects then repeated two sets of the 12-step exercise over the next 20 minutes, followed by 20 more minutes of sitting quietly. Finally, seven subjects repeated two sets of the 20-step exercise over the next 10 minutes followed by 20 minutes of sitting quietly. The other four subjects performed one 40-step exercise followed by 30 minutes of sitting quietly.

Figure 7 displays a timeline of the exercise protocol used in the human subject experiments in terms of the average metabolic rate for each activity level that was quantified from the above tests. In Figure 7, these results are repeated for each step-cycle during the course of the experiment to show the approximate metabolic rate versus time. The figure shows that after an initial 20-minute adjustment period (allowing the subject to cool down after arriving at the laboratory), the 12-step exercise was repeated every 10 minutes for the first 90 minutes, producing an average rate of 1.20 met. Beginning at the 91st minute, the subjects repeated the 20-step exercise every 5 minutes for 20 minutes, producing an average rate of 1.63 met. At the 111th minute, the subjects returned to the 12-step exercise every 10 minutes for 20 minutes. At the 131st minute, the subjects did 40 steps one time only, producing a peak rate of 4.3 met, and then sat in their chairs for 30 minutes until the test ended at the 162nd minute.

In the above exercise protocol, the choice of a 90-minute duration for the first activity period at 1.2 met was made to ensure that the subjects would have reached equilibrium with their thermal environment. This was based in part on the results of Berglund (1989) who found that the responses of subjects under similar test conditions typically reached quasi-steady values at or before 60 minutes of exposure. The subsequent activity periods were significantly shorter (20 minutes or less) and were intended to test the response of subjects to realistic short-term variations in their activity levels. Results from these later periods were not intended to represent steady-state responses.

Clothing Level

In this preliminary test, a segmented thermal manikin was used to measure the thermal insulating value of the clothing and office chair that were to be used in the human subject experiments. Thermal manikins, originally developed to measure thermal insulation of clothing, are heated dummies that simulate the heat transfer between humans and their thermal environment. Tanabe et al. (1994) describe the thermal manikin used in the current study, and also review the use of manikins in previous comfort research. Briefly, the outer surface of the manikin is heated by wound nickel wire (0.012 in. [0.3 mm] diameter) that covers the entire surface area at a maximum spacing of 0.08 in. [2 mm]. The manikin is segmented into sixteen individually-controlled body parts, so that under steady-state conditions, the local heat loss can be derived from the electricity consumption of each part. A computer-based data acquisition system records the manikin's skin temperature and heat loss for each body part at one-minute intervals. Each data record represents the mean of 60 individual measurements; an average of five records (300 observations) was used for data analysis.

The measured heat loss by the manikin is used to calculate a manikin-based equivalent temperature (t_{eq}), defined as the temperature of a uniform enclosure in which a thermal manikin with realistic skin surface temperatures would lose heat at the same rate as it would in the actual environment. This equivalent temperature can then be inserted into the ISO (1984) computer program for calculating PMV, based on Fanger's PMV model [Fanger 1970]. In this test, we used the measured skin temperature and steady-state sensible heat loss to the environment to calculate the average insulating value for the clothing and chair [as described by Tanabe et al. 1994].

The female manikin was dressed in the typical office attire to be used in the human subject experiments, consisting of underwear, long-sleeve shirt, pants, and socks (all cotton). To measure clothing insulation only, the manikin was first placed in a sitting position in a metal wide-mesh chair, similar to the string chair used in many past comfort studies. This type of chair provides essentially no additional insulation to the clothed manikin. Under steady-state environmental conditions of 22°C (71.6°F) and 50% RH, the thermal resistance of the clothing ensemble was measured to be 0.6 clo. This represents the upper limit for the range of typical summer clothing insulation values (0.35 clo to 0.6 clo) described by ASHRAE Standard 55 [ASHRAE 1992]. By selecting a 0.6 clo clothing ensemble, the intent of the current study was to investigate worst-case conditions along the upper temperature and humidity boundaries of the ASHRAE comfort zone.

The manikin was then placed in the typical padded swivel office chair, allowed to reach equilibrium with the environment, and retested under the same thermal conditions. In this case, the overall thermal resistance of the clothing and chair together was measured to be 0.87 clo, substantially higher than the value obtained for the clothing alone. This result represented a maximum overall insulation value, as the manikin was positioned to have contact with both the seat and back of the chair. During the subsequent human subject experiments, subjects would sometimes sit in this position, sometimes lean forward (contact only with the chair seat) to read or complete the survey, and periodically stand up and perform the step exercises. The average clothing insulation value for subjects in the current study would therefore fall somewhere between 0.6 clo and 0.87 clo. In a similar study, Imamura (1995) reported that a manikin wearing a 0.6 clo ensemble had its overall clothing/chair insulation value increased to 0.7 clo when seated in a typical office chair with contact on the seat only.

Finally, the range of clothing worn by the subjects was constrained to be considerably smaller than one would expect from a typical population during the summer period between March and

September. This reduction in adaptive recourse by the subjects should reduce their satisfaction with the environments.

Human Subjects

Human subjects were recruited by distributing posters around the local campus area. A total of 92 subjects participated in the experiments. However, after analyzing the test results, eight subjects were eliminated from the database due to unacceptable test conditions (e.g., unstable temperature/humidity control). The remaining 84 subjects consisted of 42 females and 42 males, ranging in age from 18 to 56 years old. Table 4 lists some of the mean physical characteristics of the subjects based on the background survey that each of them completed when they first arrived. Most of the subjects were students and all were paid for their participation in the experiment. Those who agreed to be instrumented to measure skin wettedness and skin temperature (described previously) were paid $25; all others were paid $20. Refer to Table 1 for a breakdown of how many subjects (total and instrumented) were tested for each test condition. As noted earlier, we instrumented only a limited number of subjects to study the practicality of the measurement technique and to provide sample skin wettedness data for the four test conditions. Each subject participated in only one experiment.

Table 4. Statistics of Subjects' Physical Condition

	Male (42)		Female (42)	
	Average	St.D.	Average	St.D.
Age (yr)	25.0	7.3	24.1	6.2
Exercise (hr/wk)	4.7	4.0	4.6	3.1
Smoke (cig/day)	0.24	0.84	0.13	0.49
Weight (kg)	69.3	9.0	59.0	8.3
Height (cm)	176	7	166	7
Caffeinated beverage (cup/day)	1.6	1.8	0.6	0.8

Survey Methods

Two survey methods were used during the human subject experiments. The first was a one-time background survey asking demographic questions and opinions about the subject's favorite work place. The second survey was a repeated "comfort" survey asking questions about thermal sensation, thermal preference, perception and acceptability of humidity and skin wettedness, and other scaled responses to their surrounding environment at that point in time.

Background Survey

A two-page background survey was administered to all subjects when they first arrived for the experiment (see Figure 8). The survey addresses basic demographic characteristics of the subjects, including age, sex, height, weight, ethnicity, hours of exercise each week, and average daily consumption of cigarettes and caffeinated beverages (see Table 4). The subjects were also asked where they lived during the first three years of their lives. The intended use of this information was to test the hypothesis that people's climate exposure at a very early age may influence their subsequent response to warm thermal environments [Osada 1982]. The answers included the U.S., England, Denmark, Canada, Germany, Hong Kong, China, Iran, Malaysia, Taiwan, Korea, Vietnam, France, Sweden, Australia, Scotland, Ireland, India, Japan, and Senegal, indicating quite a diverse set of subjects.

The second page of the background survey asked about the importance of several environmental characteristics of the subject's favorite work place. The characteristics included temperature, humidity, indoor air quality, ventilation and air movement, types and levels of sounds, lighting, etc. The subjects were asked to indicate how they feel by selecting one of four possible responses to each characteristic: not at all important, slightly important, moderately important, and very important. More than 80% of the subjects indicated that ventilation and air movement, temperature, air quality, lighting, sounds, and opening or closing a window to be comfortable are "moderately important" or "very important." In comparison, the humidity of the air was rated as being slightly less important with 75% of the subjects indicating that it is "moderately important" or "very important."

Repeated Survey

The repeated survey was a one-page questionnaire that was completed periodically by each subject a total of nine times during the course of the experiment. A copy of the survey is shown in Figure 9. The survey asks how the subject is feeling in terms of several scales of comfort, sensation, and acceptability at the exact time of the survey. The scales include the 7-point ASHRAE thermal sensation scale (cold, cool, slightly cool, neutral, slightly warm, warm, hot), a 5-point comfort scale (intolerable, very uncomfortable, uncomfortable, slightly uncomfortable, comfortable), and 3-point air motion scale (too little, just right, too much). The subjects were asked to rate the feeling of skin wettedness for the whole body and at five local areas of the body (head, armpit, abdomen, leg, foot) on a 4-point scale (soaking wet, wet, damp, normal). Their perception of the humidity of the air in the room was rated on a 7-point scale (very humid, humid, slightly humid, neutral, slightly dry, dry, very dry). Finally, they were asked how the air felt on two scales (stale to fresh, and not stuffy to stuffy), and how they felt on two scales (very sleepy to very alert, and very energetic to very fatigued). The subjects were also asked if the feeling was acceptable or not for most of the above described scales.

Test Procedure

All subjects were instructed over the telephone to follow certain procedures prior to their arrival at the laboratory (see Figure 10a). Upon arrival they were immediately admitted to the test chamber where they sat in a padded swivel office chair at one of the three workstations indicated in Figure 3. The workstations were separated by partitions so the subjects could not see each other during the test. Each test used three subjects, unless someone failed to show up, in which case the test proceeded with one or two subjects. By prearrangement, one of the three subjects for each test agreed to be instrumented to measure skin temperature and skin wettedness. With the assistance of a researcher (of the same sex) this subject undressed down to his/her underwear, attached the sensors to the selected locations (Figure 6), and redressed with the standard cotton office clothing provided by the researcher (previously tested with the manikin).

During the first 20 minutes of the test period, the subjects were allowed to use an electric fan to provide additional air movement and help them adjust to the warm-humid conditions in the chamber, as well as the effects of the higher metabolic rate they had recently been experiencing as they traveled (via foot or bike) to the laboratory. This was designed to provide a more natural feeling because they had just come in from the outside environment, where there was generally a lower humidity level and greater air motion. During this initial 20-minute adjustment period, each subject completed the background survey (Figure 8), and signed a consent form regarding their voluntary participation in the test (Figure 10b).

During the test, the subjects were allowed to sit at their desk (unless instructed otherwise), reading, writing, or listening to music (with headphones). They were allowed to drink a small amount of water, if necessary, to keep their throat from drying. They could talk with each other if they wanted about anything except the experiment, to avoid biasing each others' responses.

Figure 11 shows the complete experimental record used by the researcher to conduct each test. The record provided a timeline to keep track of when the subjects should do an activity or fill out the repeated survey (Figure 9). As shown, after the 20-minute arrival period, the subjects repeated the 12-step exercise every 10 minutes while filling out the survey every 30 minutes. The survey was always filled out immediately before the next exercise began. Beginning at the 91st minute, the subjects repeated the 20-step exercise every 5 minutes until the fourth survey was filled out at the 110th minute. The subjects then returned to the 12-step exercise every 10 minutes until the 5th survey was filled out at the 130th minute. The subjects then did 40 steps, representing a big exertion, and remained seated while filling out the last four surveys. The first of these was completed immediately after, and the remaining three were done at 5, 15, and 30 minutes after the 40-step exercise.

RESULTS

A complete set of results from the experiments is presented in the appendixes. Appendix A contains the tabulated answers to the repeated surveys for each subject. Subjective data from seven of the nine repeated surveys are shown, beginning with the survey completed at the 90th minute of the test. Appendix B presents individual physiological data from each of the instrumented subjects. Appendix C lists the general comments received from all subjects. The major findings from the study are presented and discussed below.

Thermal Sensation and Thermal Acceptability

Figure 12 shows the average thermal sensation votes from the nine repeated surveys for each of the four test conditions. Each point represents the average of all subjects in a given test condition who completed their surveys at the designated time. For each of the four test conditions (RH = 50%, 60%, 70%, 80%), the maximum number of responses was 21, 22, 20, and 21, respectively (refer to Table 1), although all subjects did not always answer every question on the survey. By plotting the results versus time, the format used in this figure and in several subsequent figures is intended to show a comparison of the responses from the subjects for both the different humidity conditions and the different activity levels of the experiment. As discussed previously, data from the survey taken at the 90th minute show steady-state responses to a 1.2 met activity level. The 110-minute data are based on 20 minutes of 1.6 met activity; the 130-minute data are based on a return to the 1.2 met activity level for 20 minutes; the 132-minute data are based on responses immediately after the short-term exertion of 4-5 met.

The results of Figure 12 indicate that the measured thermal sensation (TS) was similar for all four test conditions (RH = 50%, 60%, 70%, 80%). The steady-state 1.2 met values (90th minute) are very nearly identical and just slightly above the TS vote of "slightly warm" (average TS = 1.1 on the seven point ASHRAE thermal sensation scale with cold = -3, cool = -2, slightly cool = -1, neutral = 0, slightly warm = 1, warm = 2, hot = 3). As expected, thermal sensation did increase at higher activity levels, but the same trends were preserved for all test conditions. At the end of the 20-minute 1.6 met activity, average TS increased to 1.6; after returning to the 1.2 met activity for 20 more minutes, average TS decreased to 1.2, slightly above the steady-state value; immediately after the short-term exertion, average TS increased to 2.2, indicating that the subjects were definitely feeling "warm" for all test conditions.

Figure 13 shows the percentage of subjects indicating that the thermal sensation feeling is acceptable over the 162-minute timeline of the experiments. Despite the very similar thermal sensation votes at the steady-state 1.2 met value, noticeably more subjects exposed to RH = 50% and 60% conditions thought these feelings were acceptable (at least 88%) compared to those exposed to RH = 70% and 80% conditions (no more than 77%). This finding supports the results of Tanabe et al. (1987) suggesting that thermal sensation does not act as a reliable predictor of thermal comfort at high humidity levels. Nevertheless, considering that the thermal test conditions are slightly warmer than specified in the ASHRAE comfort zone (due to the higher overall clo value to account for the effect of the chair), the percent acceptability for all humidity levels is close to the 80% minimum level to which the comfort zone is intended to correspond. Thermal sensation acceptability drops significantly at the end of the 1.6 met activity period and again, immediately after the short-term exertion. The response pattern is the same for the four humidity levels. However, the subjects exposed to the RH = 50% conditions showed far less reduction after the exertion, and they recovered more quickly, rising to 100% acceptability at the end of the experiment, significantly higher than the responses for the other three test conditions.

A cross-frequency matrix of measured thermal sensation (TS) vs. thermal acceptability at the steady-state 1.2 met condition (90th minute) is shown in Table 5 to allow a detailed comparison of these two parameters. TS is binned according to the conventional approach that considers the central three categories of the thermal sensation scale (slightly cool, neutral, slightly warm) to represent comfortable (or thermally acceptable) conditions. Because we used a continuous form of the scale on the repeated survey, this central "acceptable" category corresponds to all votes that satisfy the following condition: $|TS| < 1.5$. TS votes on the warm side of this central category were binned in a "warm-hot" category ($TS \geq 1.5$). There were no TS votes below -1.5. Measured thermal acceptability votes are shown for each of the four humidity test conditions.

The results of Table 5 indicate that for all test conditions combined, 83% (57 out of 69) of all subjects considered their thermal sensation to be acceptable. All except one of the subjects (98%)

Table 5. Thermal Sensation and Acceptability

Thermal Sensation		Thermal Acceptability														
		RH 50%			RH 60%			RH 70%			RH 80%			RH 50-80%		
		Yes	No	Row Total *(Col. %)*	Yes	No	Row Total *(Col. %)*	Yes	No	Row Total *(Col. %)*	Yes	No	Row Total *(Col. %)*	Yes	No	Row Total *(Col. %)*
2,3 warm - hot	#	5	2	7	5	2	7	3	3	6	3	4	7	16	11	27
	Row %	*71*	*29*	*(41)*	*71*	*29*	*(37)*	*50*	*50*	(35)	*43*	*57*	*(44)*	*59*	*41*	(39%)
-1, 0, 1 sl. cool- sl. warm	#	10	0	10	12	0	12	10	1	11	9	0	9	*41*	*1*	*42*
	Row %	*100*	*0*	*(59)*	*100*	*0*	*(63)*	*91*	*9*	*(65)*	*100*	*0*	*(56)*	*98*	*2*	*(61%)*
Column Total	#	15	2	17	17	2	19	13	4	17	12	4	16	57	12	69
	Row %	*88*	*12*	*100*	*89*	*11*	*100*	*76*	*24*	*100*	*75*	*25*	*100*	*83*	*17*	*100*

voting in the central TS category for all humidity levels considered their conditions to be acceptable, suggesting that the boundaries of this category could be expanded while still satisfying 80% of the people. For those subjects voting in the "warm-hot" TS category, a surprising majority (71%) for the RH = 50% and 60% conditions still voted that it was thermally acceptable. At the RH = 70% and 80% levels, subjects in the "warm-hot" category were fairly evenly split between yes and no votes for acceptability, representing the difference observed in Figure 13.

Table 5 also shows that 69 total subjects answered the thermal acceptability question (yes or no) for the 1.2 met condition, indicating that a significant number (15 out of 84) failed to do so. This may be due to the fact that if the degree of acceptability is unclear to the subjects, they will have difficulty choosing a yes or no response (the only options available). In the future, we plan to incorporate a continuous acceptability scale between yes and no with "not sure" at the midpoint.

The thermal acceptability (TAC) results are useful in evaluating the appropriateness of the upper humidity limit of the comfort zone specified in ASHRAE Standard 55. The recommended limits of the comfort zone in Standard 55 are supposed to correspond to a 10% dissatisfaction criterion measured in laboratory experiments, with another 10% of the occupants dissatisfied from local thermal discomfort, such as drafts and radiant asymmetries as encountered in real environments [ASHRAE 1992, 1995]. If the current data are evaluated using the 90% acceptability criterion, the TAC results support an upper humidity limit of at least 60% RH along the warmest temperature boundary (ET* = 26°C [79°F]) of the summer comfort zone.

However, for the following reasons a case can be made that the TAC found in this experiment should be equivalent to those found in actual buildings under the same thermal conditions.

1. Because the controlled environment chamber used in the current study is designed to resemble and operate much like a modern office space, the differences between the chamber and realistic indoor environments are expected to be minimized.
2. It is possible that the local thermal discomfort does not fully explain the 80% maximum acceptability found in field studies. In each of the field studies done with precise instrumentation in recent years [Schiller et al. 1988, de Dear and Fountain 1984], there has been no evidence of local effects; indeed, there has often been dissatisfaction with absence of perceived air movement.
3. It is also possible that varied clothing and activity levels are contributors. Both of these effects have been studied in the current experiment.

It may well be appropriate to use the same 80% thermal acceptability criterion from Standard 55 when evaluating the limits of the comfort zone based on data from the current study.

Assuming an 80% acceptability criterion, the TAC data for 1.2 met shown in Figure 13 (90th minute) and Table 5 indicate that the upper humidity limit is well above 60% RH along the warm temperature boundary (ET* = 26°C) of the summer comfort zone. In fact, considering that all subjects were tested with a combined (clothing plus chair) thermal insulation value approaching 0.87 clo that is greater than the highest clo value for the summer comfort zone (0.6 clo), these results are certain to be conservative. Under these elevated clo test conditions, TAC was 76% for

RH=70% and 75% for RH=80%, just below the 80% acceptability criterion. Although the current results are limited to the warm edge of the comfort zone, they suggest that TAC will be at least as high at lower temperatures along the upper humidity boundary.

As discussed earlier, Berglund (1995) analyzed data from a previous study [Berglund 1989] and developed a curve fit to predict TAC as a function of air temperature and humidity ratio. The resulting set of curves representing loci of equal thermal acceptability for sedentary activity (0.94 met) and typical summer clothing (0.56 clo) compared reasonably well with the new upper humidity limit of Standard 55. However, Berglund's correlations showed a significant decrease in acceptability as conditions approached the warm upper boundary of the comfort zone, which is why he suggested that agreement would be improved if the comfort zone was shifted to slightly cooler temperatures. At the two lower humidity test conditions of the current study (RH = 50%, 60%; ET* = 26°C), Berglund's correlation predicts a TAC of only 64%. In comparison, the current experimental data show dramatically higher values for TAC (88%-89%), despite being based on both a higher activity level (1.2 met) and higher clothing insulation (0.6 clo to 0.87 clo). Berglund's correlations were based on nine relatively widely spaced combinations of temperature and humidity, requiring significant interpolation between test conditions. None of Berglund's test conditions were in the near vicinity of those used in the current study. The current results provide evidence that thermal acceptability is at least 80% at the warm-humid upper corner of the comfort zone in Standard 55.

Comfort Sensation Vote

Figure 14 shows the average comfort sensation vote from the nine repeated surveys for each of the four test conditions. The results indicate a similar trend to the thermal sensation data shown in Figure 13 in which no significant differences are observed between the different humidity levels. The average comfort sensation vote at the 90th minute (steady-state 1.2 met) was 0.9, slightly below "slightly uncomfortable, but acceptable." After 20 minutes of 1.6 met activity, average comfort sensation vote increased to 1.2; after returning to the 1.2 met activity for 20 minutes the average comfort sensation vote dropped to 1.1; immediately after the high activity exertion, the average comfort sensation vote increased to 1.6, indicating that the subjects were feeling on average closer to "uncomfortable" than slightly uncomfortable;" and 30 minutes after the exertion, the average comfort sensation vote had decreased to 0.7, a value even lower than the original steady state 1.2 met value. The rather quick recovery after the high activity exertion is interesting to note; in fact the average comfort sensation vote had decreased to 1.1, the same level as just before the exertion, within five minutes. Subsequently, the comfort sensation vote decreased to an even lower level, in part due to the fact that subjects were now completely sedentary in their chairs (no step exercises), representing an activity level closer to 1.0.

Air Humidity

Figure 15 shows the average perception of air humidity by the subjects in terms of a 7-point scale ranging from very humid to very dry. During the first 90 minutes of the experiment at the 1.2 met activity level, there was an increase in the perception of air humidity corresponding to an increase in the humidity test condition. However, at the 90-minute steady-state value, there was no statistically significant difference between the average air humidity perception for each of the four test conditions (ANOVA P-value = 0.6). The average values ranged from 0.3 at RH = 50% up to 0.8 at RH = 80%, where 0 = "neutral" and 1 = " slightly humid." It may be difficult for subjects to accurately distinguish differences in the air humidity. One subject commented that "I can feel hot and warm humidity on my body, but not in terms of air humidity." During the remainder of the experiment at the different short-term activity levels, there were no identifiable differences between the perception of air humidity at different humidity test conditions. The overall pattern of response did show an increase in the perception of air humidity corresponding to an increase in activity level.

Figure 16 shows the percentage of subjects indicating that their perception of air humidity is acceptable. Although the subjects had difficulty distinguishing between different air humidity conditions (Figure 15), air humidity acceptability is seen to decrease noticeably with increasing humidity level. The ANOVA test found that perceived humidity acceptability is significantly associated with the humidity level (P-value = 0.08). At the steady-state 1.2 met condition, 95% of the subjects thought that 50% RH was acceptable, while only 62% thought that 80% RH was acceptable. The humidity acceptability is consistently high throughout the experiment for the 50% RH condition, only dropping below 80% immediately after the short-term exertion, but then recovering back up to 100% at the end of the test. In general, the acceptability at the 80% RH condition is the lowest throughout the experiment. Surprisingly, although there is a significant difference between the acceptability at 50% and 60% RH conditions, the humidity acceptability at the 60% and 70% RH conditions are seen to be nearly equivalent during most of the experiment. Except for the 50% RH condition, the humidity acceptability decreases with increasing activity level.

Air Movement

Figure 17 shows the average perception of air movement in terms of a three-point scale ("too little," "just right," "too much"). Throughout the experiment, the average perception is that the air movement is somewhat less than "just right" for all test conditions. There is no significant difference between the four humidity conditions for all activity levels, except immediately after the short-term exertion. At this point, air movement perception at the 50% RH condition remains constant, but drops noticeably for higher humidity levels, particularly 60% and 80% RH.

Figure 18 shows the percentage of subjects indicating that their perception of air movement is acceptable. At the steady-state 1.2 met condition, the air movement acceptability ranged from 80% for the 70% RH condition to 57% for the 60% and 80% RH conditions, suggesting no clear relationship between air movement acceptability and humidity level. The air movement acceptability seems to be most sensitive to increased activity levels. Immediately after the short-term exertion, the air movement is considered to be acceptable by 70% of the subjects for the 50% RH condition, but this percentage drops to a low of 19% for the 80% RH condition.

Due to the low "still-air" velocity conditions maintained during these experiments, the insensitivity of the subjects' perception and acceptability of air movement at different humidity levels is not surprising, particularly at 1.2 met. However, when the subjects experience higher metabolic rates, they become more perceptive to increases in humidity, eliciting a corresponding desire for greater air movement to provide thermal relief. In fact, several comments were received from the subjects indicating that under warm conditions, a lack of air motion affected their comfort and ability to work efficiently. Some said that if they experienced these warm-humid conditions in their home, they would immediately open some windows to increase the air movement. By opening windows and providing more air circulation, they felt that there would be more fresh air to improve the air quality, and greater air movement to improve their thermal comfort and alertness levels.

Air Quality

The subjects were asked in the repeated survey to rate how the air feels in terms of two scales: (fresh -- stale) and (stuffy -- not stuffy). Similarly, they were asked to rate how they felt in terms of two scales: (very alert -- very sleepy) and (very fatigued -- very energetic). Figures 19 - 22 present the average results for these four scales. In all four figures, there is no consistent pattern of differences between different humidity levels for all activity levels. The average responses on the fresh--stale scale and stuffy--not stuffy scale were toward the stale side and stuffy side of the midpoint, respectively, for nearly all test conditions. The average response on the alert--sleepy scale was slightly on the sleepy side of the midpoint, except immediately after the short-term exertion. The average response on the fatigued--energetic scale was slightly on the fatigued side of the midpoint.

Figure 23 shows the percentage of subjects indicating that the air quality is acceptable. The air quality acceptability is seen to be generally higher for the 50% RH condition than the other humidity conditions throughout the experiment. There are no observed significant differences between air quality acceptability for the 60% - 80% RH conditions. The acceptability of the air quality tends to decrease with increasing activity level for all humidity conditions.

The subjects' judgments of air quality acceptability are well correlated with the other acceptability votes on the survey: thermal sensation, air humidity, air movement, and skin wettedness. This is shown in Table 6, in which the "acceptable" and "not acceptable" air quality votes are binned against the same two categories for each of the above four parameters.

Skin Moisture

Physiological measurements of skin temperature and wettedness were made on a limited number of subjects to explore the effects of transitory metabolic rates. They allow some comparison with the subjective responses obtained from the repeated surveys. Mean physiological data are based on seventeen instrumented subjects, as indicated in Table 1. Figures 24 and 25 show plots of measured mean skin temperature and mean skin wettedness under the clothing (measured and calculated according to equation [1]), respectively, for each of the four test conditions over the duration of the test period. One-minute average data are reported; the missing data points during the first 10-20 minutes correspond to the initial arrival period during which the measurement harness is attached to the subject.

Table 6a. Air Quality Acceptability vs. Thermal Sensation Acceptability

Relative Humidity (%)	Thermal Sensation = "acceptable"		Thermal Sensation = "not acceptable"	
	Air Quality = "acceptable" (%)	Air Quality = "not acceptable" (%)	Air Quality = "acceptable" (%)	Air Quality = "not acceptable" (%)
50	84	16	26	74
60	81	19	9	91
70	81	19	14	86
80	70	30	21	79
Total votes	*321*	*83*	*28*	*136*

Table 6b. Air Quality Acceptability vs. Air Humidity Acceptability

Relative Humidity (%)	Air Humidity = "acceptable"		Air Humidity = "not acceptable"	
	Air Quality = "acceptable" (%)	Air Quality = "not acceptable" (%)	Air Quality = "acceptable" (%)	Air Quality = "not acceptable" (%)
50	83	17	13	87
60	83	17	6	94
70	81	19	4	96
80	85	15	18	82
Total votes	*380*	*79*	*21*	*181*

Table 6c. Air Quality Acceptability vs. Air Movement Acceptability

Relative Humidity (%)	Air Movement = "acceptable"		Air Movement = "not acceptable"	
	Air Quality = "acceptable" (%)	Air Quality = "not acceptable" (%)	Air Quality = "acceptable" (%)	Air Quality = "not acceptable" (%)
50	88	12	26	74
60	89	11	13	87
70	84	16	11	89
80	85	15	23	77
Total votes	*335*	*52*	*44*	*207*

Table 6d. Air Quality Acceptability vs. Skin Wettedness Acceptability

Relative Humidity (%)	Skin Wettedness = "acceptable"		Skin Wettedness = "not acceptable"	
	Air Quality = "acceptable" (%)	Air Quality = "not acceptable" (%)	Air Quality = "acceptable" (%)	Air Quality = "not acceptable" (%)
50	82	18	45	55
60	77	23	0	100
70	67	33	5	95
80	77	23	21	79
Total votes	*376*	*118*	*27*	*142*

Mean skin temperatures are seen to increase over much of the first 90-minute period for all test conditions, as the subjects reach equilibrium with the environment at 1.2 met. The steady-state 1.2 met mean values range from approximately 34°C to 34.5°C. During the twenty-minute increased activity period at 1.6 met, mean skin temperatures decrease slightly for all test conditions, corresponding to an increase in skin wettedness (see below). Over the entire test period, however, there is no clear skin temperature pattern in relation to increased humidity. Mean skin temperatures are generally lowest for the 50% RH condition, highest for the 60% or 80% RH conditions, with 70% RH in between. Even after the 40-step exertion (between the 131st and 133rd minutes), mean skin temperatures exhibit only small fluctuations for most test conditions. Measurements for the 70% RH condition are based on only two subjects, one of whom produced atypical physiological data, helping to explain some of the unusual results for this test condition.

With the exception of the 70% RH condition, mean skin wettedness values under the clothing are fairly stable during the initial 1.2 met period. The steady-state 1.2 met mean values range from approximately 0.12 to 0.16, all less than the 0.20 upper limit of the comfort zone for sedentary activity, as found by Gagge et al. (1967). For all test conditions, skin wettedness clearly increases with increasing activity level, as this occurs both during the twenty-minute 1.6 met period (mean maximum value = 0.25) and temporarily after the 40-step exertion (mean maximum value = 0.30). Skin wettedness also recovers fairly quickly during lower activity periods, as it decreases for all test conditions after the above-mentioned increases. Small fluctuations are observed to roughly coincide with the step exercises being performed at regular intervals. However, as with skin temperature, there is no clear pattern in relation to changes in humidity test conditions.

An important consideration in the notable variability of both skin temperature and wettedness in response to changes in humidity test conditions is the fact that all instrumented subjects in this study were tested only once. In comparison, the study by Berglund (1989), which covered a broader range of temperature, humidity, and activity level test conditions, used the same five subjects for each of the 27 different combinations of test conditions. Although skin temperature was not very sensitive to changes in test conditions, by reducing the sources of individual variability in this way, Berglund was able to conclude that skin wettedness increases with increasing humidity level.

Figure 26 presents an example set of detailed physiological data from one individual subject in the current study. The figure shows data for the five measurement sites (arm, chest, back, thigh, calf) in the following plots: (1) boundary layer temperature (temperature in the air layer between skin and clothing), (2) boundary layer relative humidity, (3) skin temperature, and (4) skin wettedness. In addition, a plot showing mean skin temperature and wettedness is included. Appendix B presents the detailed physiological data in this same format for all instrumented subjects in the current study. As seen in Figure 26, large differences are found between different body parts for both skin temperature and wettedness. In general, the skin wettedness was higher for the chest and back than for the three measurement sites on the extremities (arm, thigh, calf). This is shown more clearly for the steady-state 1.2 met condition in Figure 27.

Figure 28 shows the average feeling of whole-body skin wettedness based on the nine repeated surveys completed by all subjects (both instrumented and non-instrumented). The skin wettedness is rated on a scale ranging from "normal" to "damp" to "wet" to "soaking wet." The general trend of responses is quite similar to that observed for the measured skin wettedness (compare to Figure 25). In Figure 28, the feeling of skin wettedness increases with increasing activity level, and also tends to increase with increasing humidity, particularly at the 80% RH level. The average steady-state 1.2 met value is close to the midpoint between "normal" and "damp." The maximum skin wettedness feeling occurs immediately after the short-term exertion (132nd minute) with the average response close to "damp" and the feeling for the 80% RH condition well above this level.

Figure 29 shows the percentage of subjects indicating that their feeling of whole-body skin wettedness is acceptable. At the steady-state 1.2 met condition, at least 90% of the subjects exposed to humidity test conditions of 50% to 70% RH found their whole-body skin feeling to be acceptable. This acceptability percentage dropped significantly down to 71% for the 80% RH condition. The large number of subjects who judged their skin feeling to be acceptable for humidities up to and including 70% RH supports the earlier discussion regarding thermal acceptability and the implication that the upper humidity limit of the comfort zone could be as high as 70% RH. In general, the acceptability of whole-body skin feeling decreased with increasing activity level. Subjects exposed to the 80% RH test condition consistently rated their skin feeling as less acceptable than those exposed to the lower humidity test conditions. Differences in skin feeling acceptability between subjects in the 50% to 70% RH range were less distinct. Immediately after the short-term exertion, the minimum acceptability percentages were obtained for all test conditions, including only 20% for those exposed to the 80% RH condition. During the final thirty minutes of the test after the short-term exertion, however, skin feeling acceptability for all test conditions recovered quite rapidly back toward the percentages achieved at the steady-state 1.2 met condition.

Acceptability vs. Humidity

Figure 30 summarizes the relationship between four acceptability parameters and relative humidity under steady state conditions at 1.2 met. The percentage of subjects voting "acceptable" are shown for thermal sensation, feeling of whole-body skin wettedness, air humidity perception, and air quality perception. As discussed previously, thermal acceptability is quite high (nearly 90%) for relative humidities of 50% and 60%, but then drops to around 75% for higher humidities. Skin wettedness feeling acceptability remains above 90% until the RH = 80% level is reached, where it decreases significantly. Air humidity acceptability shows the most consistent pattern in relation to changes in humidity, decreasing with increasing humidity. Air quality acceptability shows no significant association with humidity.

Comments

At the end of the test each subject was given the opportunity to record any comments they had about the experiment. One of the most common comments received expressed a desire for greater air movement, such as being able to open the windows. Similarly, some subjects complained of stuffiness and wanted fresher air. Despite these comments on air movement and air quality, there were almost no complaints about annoying odors. A few subjects complained about the amount of required exercise, and some said they would not tolerate working for 8 hours in an office environment like this one. All relevant comments have been tabulated by test condition and are listed in Appendix C.

CONCLUSIONS

The purpose of the current study was to examine the relationship between thermal comfort and humidity under warm-humid conditions. To accomplish this, 92 human subjects were tested under steady-state conditions in a controlled environment chamber configured to resemble a modern office space. The subjects were exposed to a range of humidities (RH = 50%, 60%, 70%, and 80%) under the worst-case thermal conditions, namely along the warm upper boundary of the summer comfort zone (ET* = 26°C [79°F]), as specified in ASHRAE Standard 55-1992. During the test, subjects repeated a series of step-exercises to simulate three different activity levels (1.2 met, 1.6 met, and 4-5 met), representative of a range of typical office work. Test conditions along the upper boundary of the comfort zone were selected based on a 1.2 met activity level and a clothing insulation value of 0.6 clo which all subjects wore (representing typical summer office clothing), despite the fact that an additional amount of overall insulation (up to 0.27 clo based on manikin measurements) was added due to the padded office chairs in which the subjects sat during the experiments.

The major conclusions from the study are summarized below.

1. Thermal acceptability (TAC) data for the steady-state 1.2 met test conditions indicate that the upper humidity limit (based on an 80% acceptability criterion) is well above 60% RH and probably closer to 70% RH along the warmest temperature boundary (ET* = 26°C [79°F]) of the comfort zone specified in ASHRAE Standard 55-1992. This is in spite of the fact that the experimental conditions were significantly conservative. The combination of the subjects wearing the highest level of summer clothing specified in Standard 55 (0.6 clo), and sitting in realistic padded chairs, added at least 2°C to the SET* of the subjects, above the comfort zone boundary.

2. Whole-body skin feeling acceptability was at least 90% for the steady-state 1.2 met test conditions with humidities ranging from 50% to 70%. To the extent that overall thermal acceptability is affected by the feeling of skin moisture, these results show that 70% RH at ET* = 26°C is an acceptable condition.

3. There was no significant variation in average thermal sensation vote between the four humidity test conditions (RH = 50% to 80%) along the constant ET* = 26°C comfort zone boundary for all activity levels investigated. At the steady-state 1.2 met test condition, the average thermal sensation vote on the seven-point scale was 1.1, just above "slightly warm." The lack of sensitivity of thermal sensation to humidity changes up to 80% RH supports the

results of Tanabe et al. (1987) suggesting that thermal sensation does not act as a reliable predictor of thermal comfort at high humidity levels.

4. Based on the limited physiological data that were collected, there was no clear pattern of variation in relation to changes in humidity for both measured skin temperature and wettedness. For a given humidity condition, average skin temperature did tend to decrease with increasing activity level, but the rate of response was relatively slow. Average skin wettedness clearly increased with increasing activity level (in combination with a decrease in skin temperature) and responded fairly quickly to changes in activity level.

5. The acceptability of perceived air humidity was found to be significantly affected by humidity level. Although subjects had difficulty distinguishing between different air humidity conditions, air humidity acceptability decreased noticeably with increasing humidity level, and tended to decrease with increasing activity level.

6. Similar to the thermal sensation results, no significant variation was found between the four different humidity test conditions for subjective votes of comfort sensation, air humidity perception, air movement perception, air freshness and stuffiness feeling, and alertness and fatigued feeling.

7. Survey results of subjects at different activity levels found observable patterns for many of the parameters in response to changes over the range of realistic short-term activities (1.6 met for 20 minutes, and 1-2 minute exertion at 4-5 met) representing typical office work. Thermal sensation vote, comfort sensation vote, and whole-body skin wettedness feeling all consistently increased with increasing activity level. Thermal sensation acceptability, air humidity acceptability, air movement acceptability, air quality acceptability, and whole-body skin feeling acceptability all consistently decreased with increasing activity level.

8. During the 30-minute rest period (no exercise) just after the short-term exertion, skin wettedness was found to recover surprisingly quickly to its pre-exertion value for all humidity test conditions. This result was contrary to our original hypothesis that after elevated activity, particularly at higher humidities, skin wettedness would persist causing discomfort. For all humidity levels except 50% RH, all of the acceptability parameters reached their minimum values immediately after the short-term exertion, but recovered upward thereafter.

This study generated a great deal of useful experimental data. These are now being complemented and extended through an ASHRAE funded research project on the upper humidity limit. The two data sets will be analyzed together to provide scientific justification for the recommended upper humidity limit of the comfort zone in future revisions to ASHRAE Standard 55a-1995.

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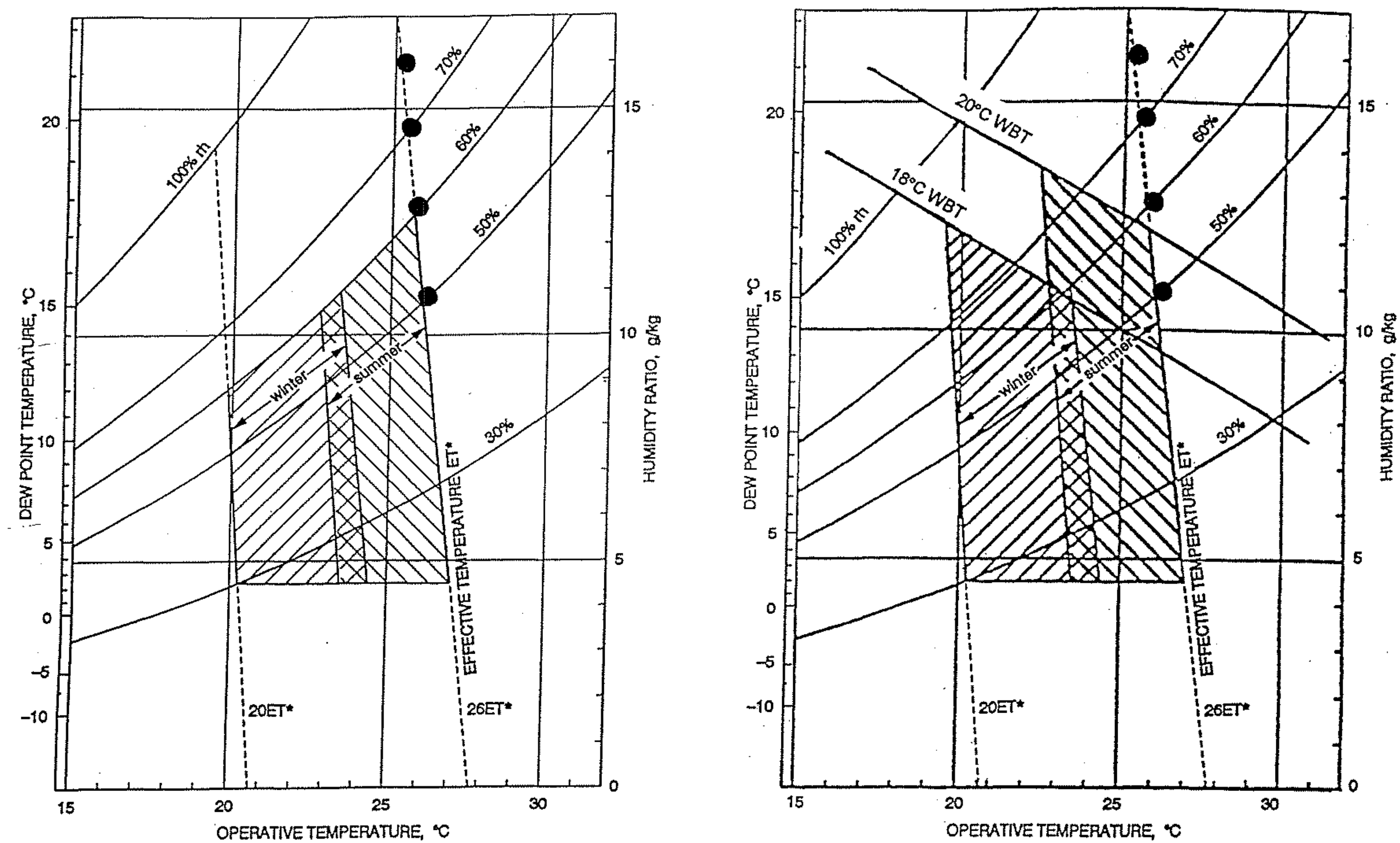
FIGURES

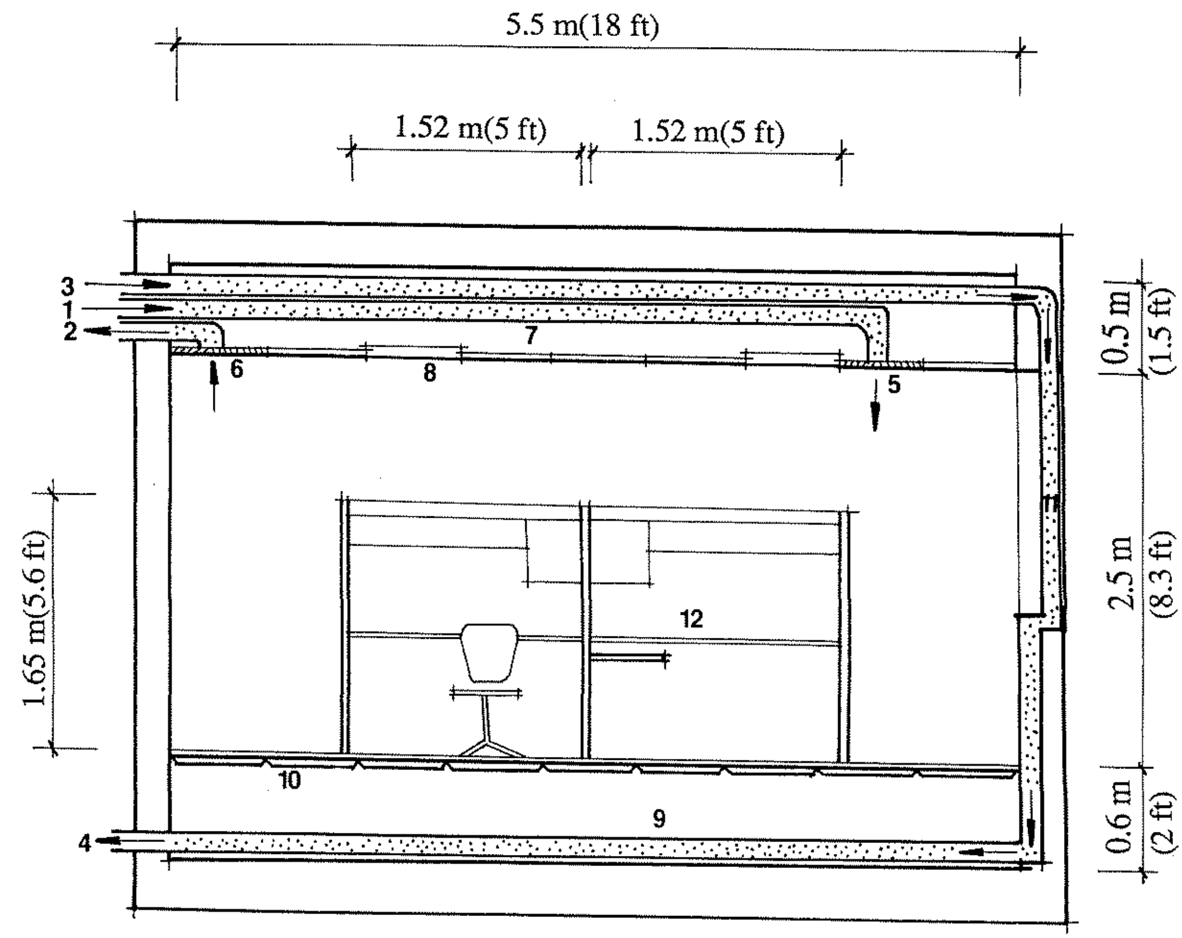
TABLES



(a) Comfort Zone of ASHRAE Standard 55-92

(b) Addendum 55a to ASHRAE Standard 55-92

Figure 1. Test conditions vs. Comfort zone



1 ceiling supply
2 ceiling return
3 annular space supply
4 annular space return
5 ceiling supply diffuser
6 ceiling return register
7 ceiling plenum
8 ceiling luminaire
9 sub-floor plenum
10 access floor system
11 window plenum
12 workstation furniture

Figure 2. Section: Controlled Environment Chamber

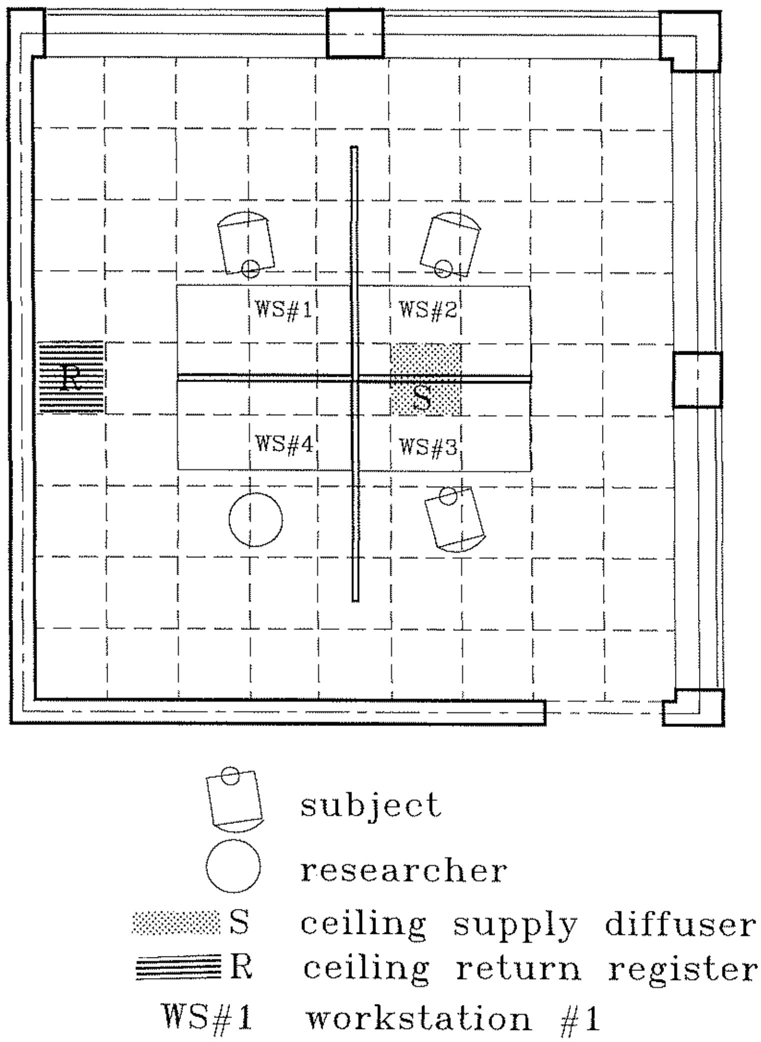
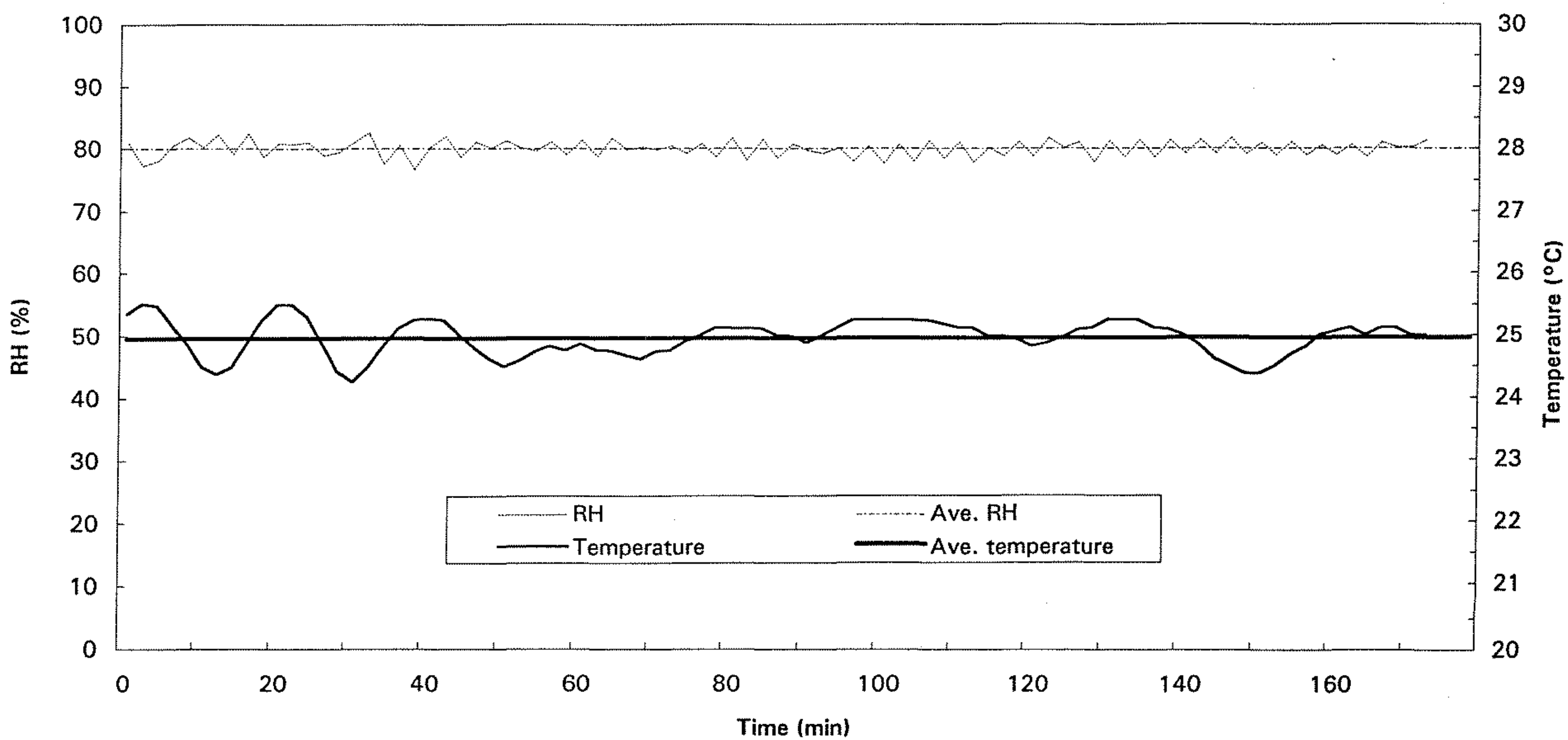


Figure 3. Floor/Ceiling Plan: Controlled Environment Chamber

Figure 4. Example Trend Report of Test Conditions

Test date: 7/5/94
Test time: 1:00pm-4:00pm

Test condition	*RH (%)*	*Temperature (°C)*	*Dew point (°C)*
Set point	*80.0*	*24.9*	*21.2*
Average	80.0	25.0	21.3
Maximum	82.6	25.5	22.0
Minumum	76.6	24.3	20.6
St. Dev	1.30	0.30	0.30



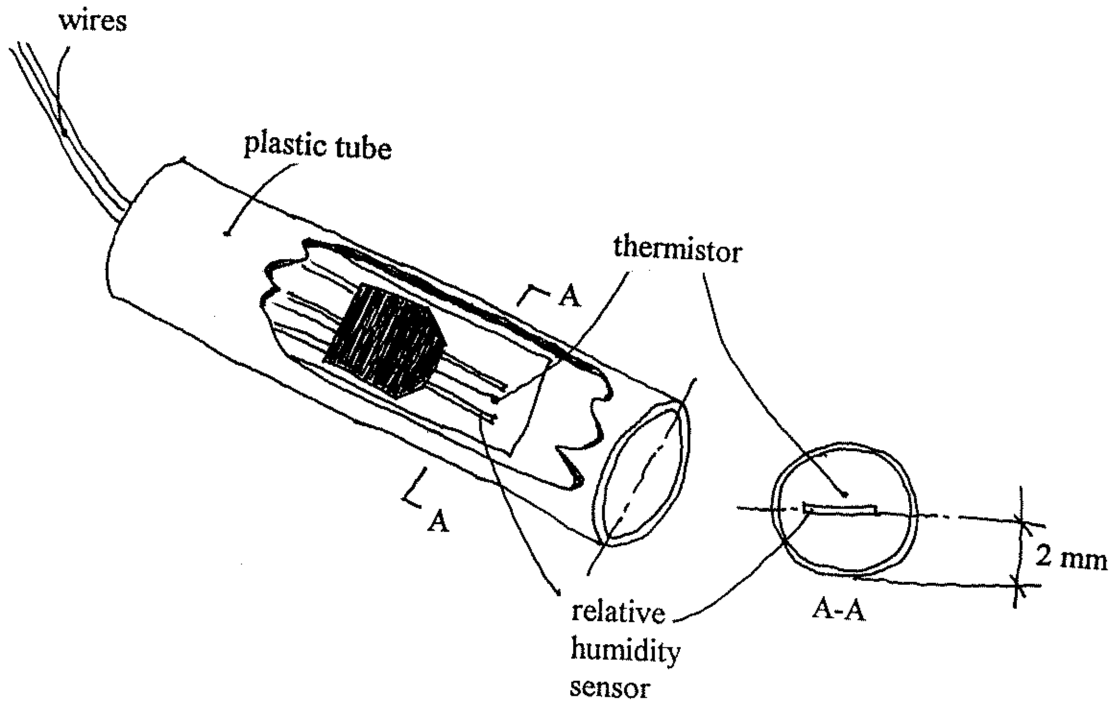


Figure 5. Skin Wettedness Sensor

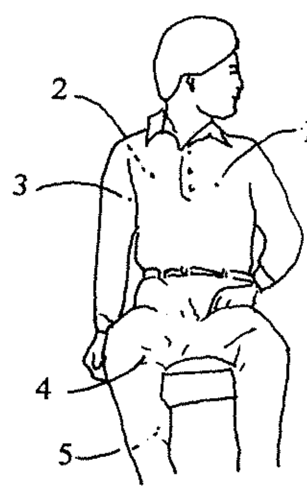


Figure 6. Skin Wettedness Sensor Locations

Figure 7. Metabolic Rate for Exercise Protocol

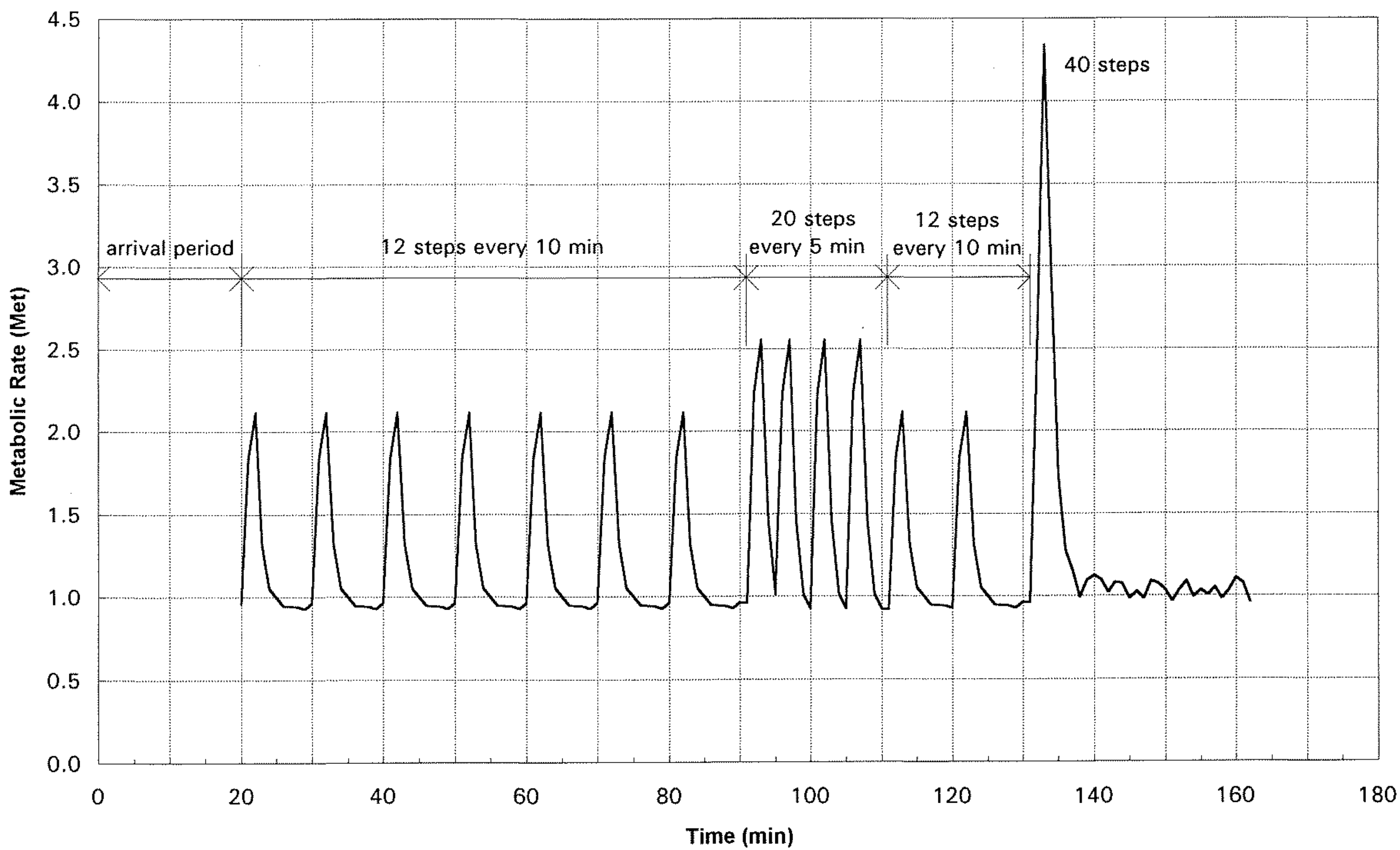


Figure 8. Background Survey

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

1. Name: ____

2. Date:____

3. Phone number: ____

4. Home zip code: ____

5. Where did you live in the first three years of your life?

   Country: ____________ State: ______________

6. What is your approximate height? _____ Feet _____ Inches

7. What is your approximate weight? _____ Pounds

8. What is your age? _____ Years

9. Your sex?
   1 ❑ Male
   2 ❑ Female

10. Your ethnic background?

    1 ❑ Asian American
    2 ❑ Black
    3 ❑ Caucasian
    4 ❑ Hispanic
    5 ❑ Other (please specify:_______________________)

11. Is English your primary language?
    1 ❑ Yes
    2 ❑ No

12. How many cigarettes do you smoke per day? _____ Cigarettes

13. How many cups of caffeinated beverages do you drink per day? _____ Cups

14. How many hours do you exercise per week? _____ Hours

Figure 8 (cont.)

A number of characteristics related to your **favorite work place** (e.g., library, home, or office) are given below. Please indicate how IMPORTANT TO YOU each characteristic is by circling the number that reflects how you feel.

4 very important
3 moderately important
2 slightly important
1 not at all important

How important to you is: (circle one number for each item)

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

PLEASE STOP HERE

You will be periodically asked by the researcher to fill out the following questionnaires. Please follow the way of answering questions on the provided sample questionnaire.

Figure 9. Repeated Survey
Questionnaire Time: ______________

At this moment I feel:

- hot
- warm
- slightly warm
- neutral
- slightly cool
- cool
- cold

- Comfortable
- slightly uncomfortable
- uncomfortable
- very uncomfortable
- intolerable

Air motion is

- too much
- just right
- too little

Is air motion acceptable? ❐ yes ❐ no

Is this feeling acceptable? ❐ yes ❐ no

My skin feels:

	soaking wet	wet	damp	normal	**Is it acceptable?**
whole body					❐ yes ❐ no
head					❐ yes ❐ no
armpit					❐ yes ❐ no
abdomen					❐ yes ❐ no
leg					❐ yes ❐ no
foot					❐ yes ❐ no

I perceive the air as

very humid — humid — slightly humid — neutral — slightly dry — dry — very dry

Is the air humidity acceptable? ❐ yes ❐ no

The air feels:

fresh — stale

stuffy — not stuffy

I feel:

very alert — very sleepy

very fatigued — very energetic

Is the air quality acceptable? ❐ yes ❐ no

Figure 10a. Pretest Instructions

INSTRUCTIONS

- No alcohol for 24 hours prior to the experiment because it will bias your results. No food one hour before and during the test. Water is available upon request during the test. However, subjects are advised to drink sparingly.

- Subjects are required to wear socks, long pants, long sleeve shirt. Uniforms are provided for the person whose skin wettedness and temperature will be measured with the sensor harness. When making the schedule for subjects, ask one of them in the same group whether or not he/she will volunteer to have the harness on.

- Remind the subjects of not physically exerting themselves in the two hours preceding the appointment. Walking around is fine but going for a run or lifting some weights would possibly bias the results so that it may lengthen the test.

- Subjects are advised that if they think they are coming down with a cold or fever, do not come. Instead, call us and reschedule.

Figure 10b.

UNIVERSITY OF CALIFORNIA, BERKELEY

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COLLEGE OF ENVIRONMENTAL DESIGN
CENTER FOR ENVIRONMENTAL DESIGN RESEARCH
390 WURSTER HALL
BERKELEY, CALIFORNIA 94720

TEL: (510) 642-2896

Consent Form - Thermal Comfort Experiment
May 25, 1994

In this experiment, summertime conditions in an office are simulated in this room.

If you agree to take part in this research, you will be asked to spend about 3 hours in the Controlled Environment Chamber in 272 Wurster Hall. Prior to the experiment, you will be asked to fill out a background survey. The background survey asks a few questions about your background and impressions of your thermal comfort in your work place. In the lab, we will ask you to sit in a chair and read or listen to music. We will periodically ask you to stand up and do some light activity, ask questions about how you feel. At the end of the experiment, we will pay you $20.

For normal healthy people, there is no physical risk in being exposed to the climate conditions of this test. This is a comfort experiment, NOT a heat stress experiment. The maximum temperature and relative humidity ranges that you might be exposed to in this experiment are 76°F to 79°F and 50% to 80%, respectively.

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

Your participation in this research is voluntary. You are free to refuse to take part, and you may stop taking part at any time. If you have any questions about this research, you may call Edward Arens @ 642-1158.

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

Print your name here ______________________________

Signature __________________ **Date** ______________

Figure 11

Experimental Record

RH/Temperature: ______/______ (°C): Outdoor Temp.: ______ (°C)

Dateof the Test: ______ Time of the Day: 1:00 pm 7:00 pm

Subject's Name: ______ Researcher's Name: ______

Time	Survey	Physical Measurement	Activity Description	Steps	Metabolic Rate (met)	Note
0 min	arrival		arrival	12	1.2	oral tempeperature
20 min			1st activity	12	1.2	
30 min	1st survey		2nd activity	12	1.2	
40 min			3rd activity	12	1.2	
50 min			4th activity	12	1.2	
60 min	2nd survey		5th activity	12	1.2	
70 min			6th activity	12	1.2	
80 min			7th activity	12	1.2	
90 min	3rd survey	✓			1.2	the end of 1.2 met
91 min			8th activity	20/5min	1.6	
95 min			9th activity	20/5min	1.6	
100 min			10th activity	20/5min	1.6	
105 min			11th activity	20/5min	1.6	
110 min	4th survey	✓			1.6	the end of 1.6 met
111 min			12th activity	12	1.2	
120 min			13th activity	12	1.2	
130 min	5th survey	✓			1.2	the end of 1.2 met
131 min			14th activity	40	high	
132 min	6th survey		No activity			transition
137 min	7th survey		No activity			
147 min	8th survey		No activity			
162 min	9th survey		No activity			

Figure 12. Average Thermal Sensation

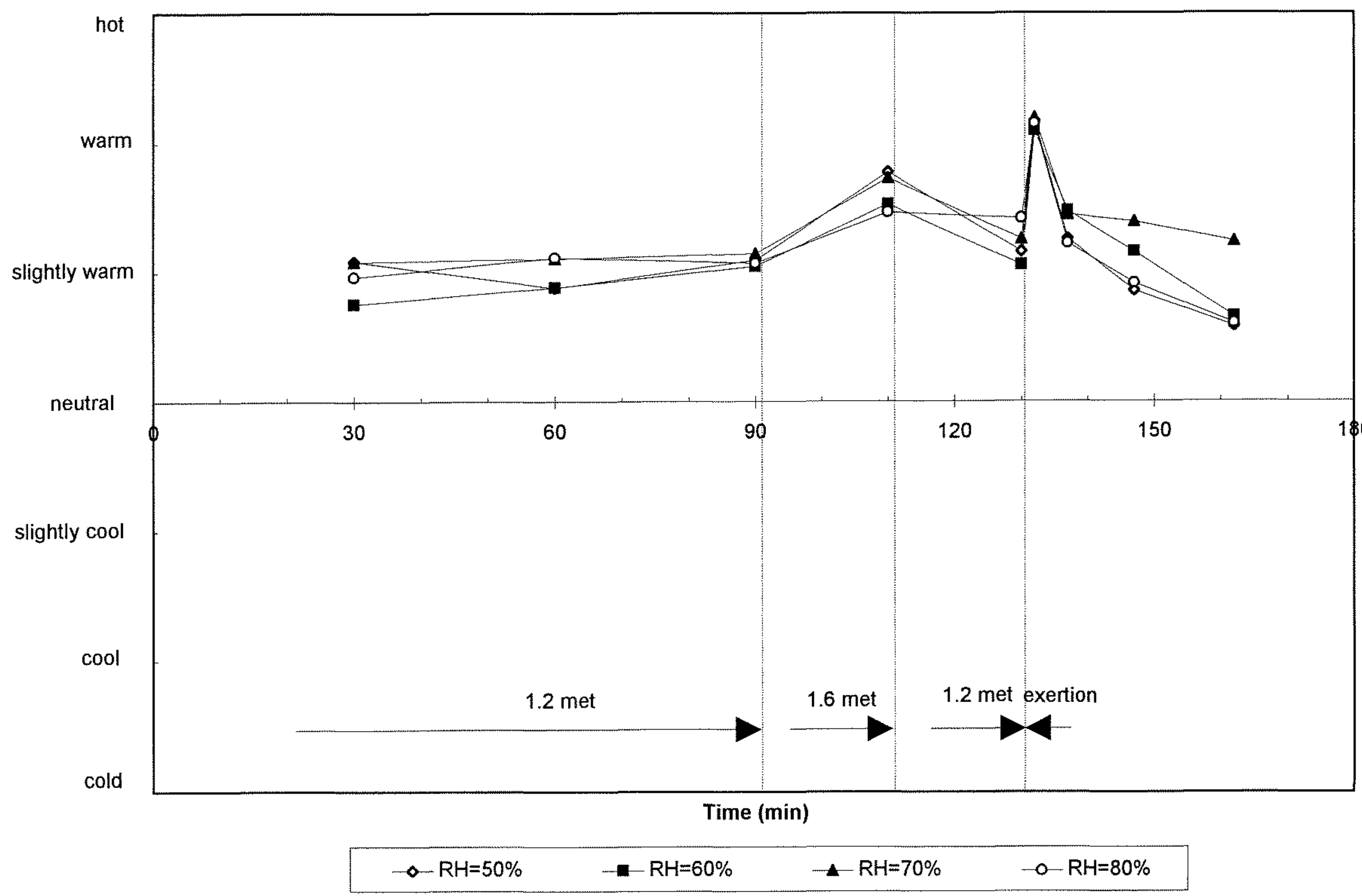


Figure 13. Thermal Sensation Acceptability

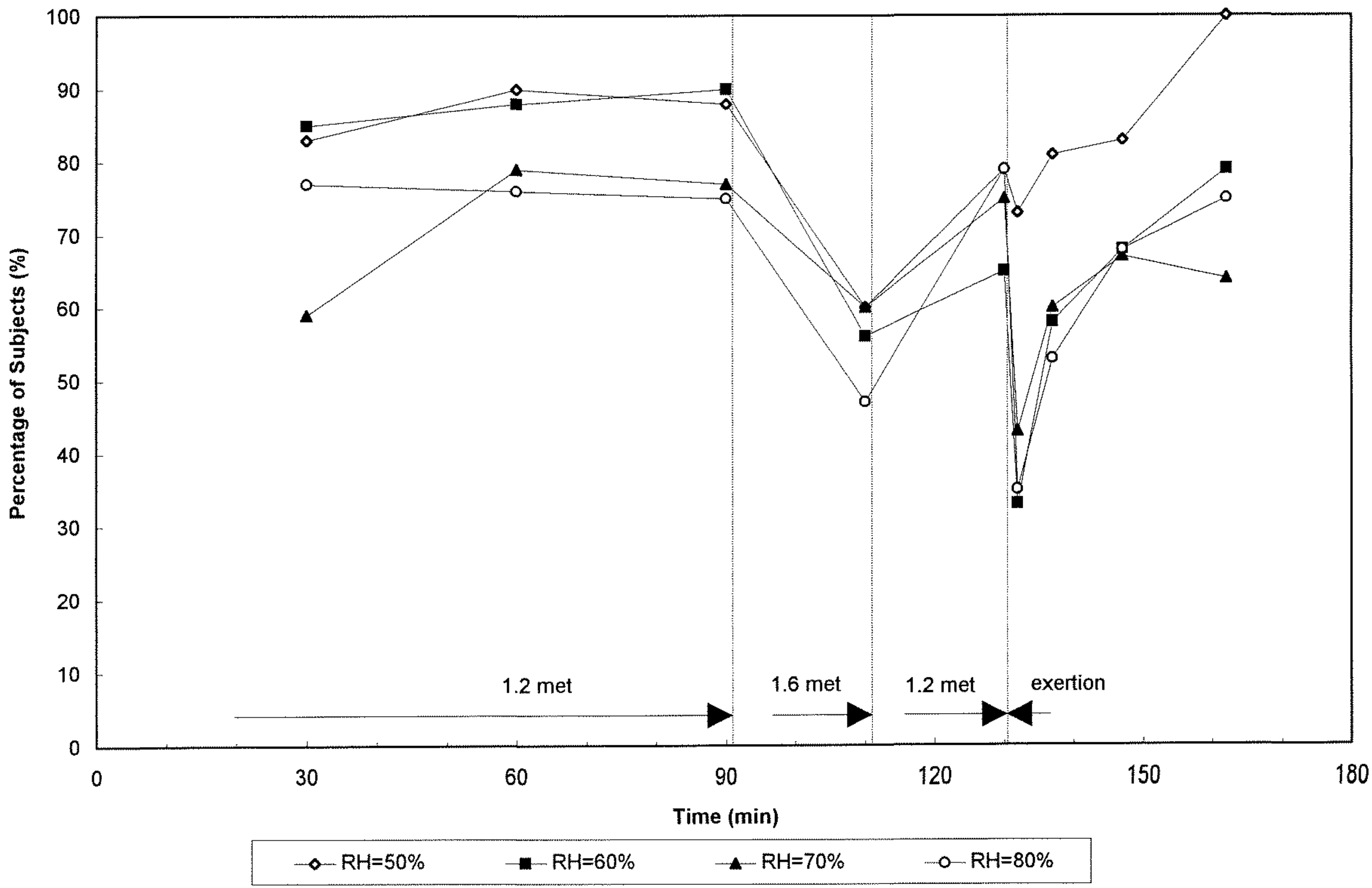


Figure 14. Average Comfort Sensation Vote

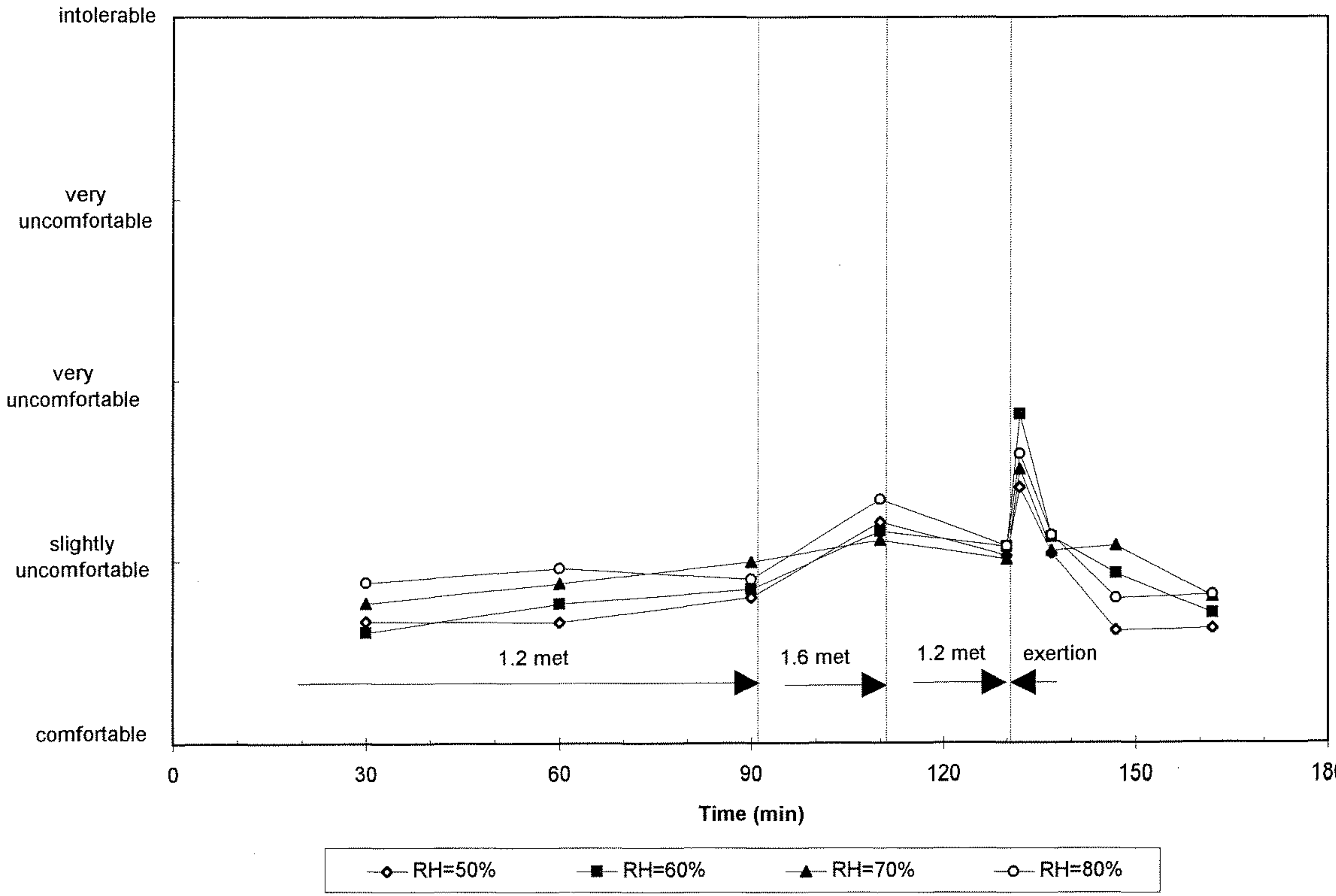


Figure 15. Average Air Humidity Perception

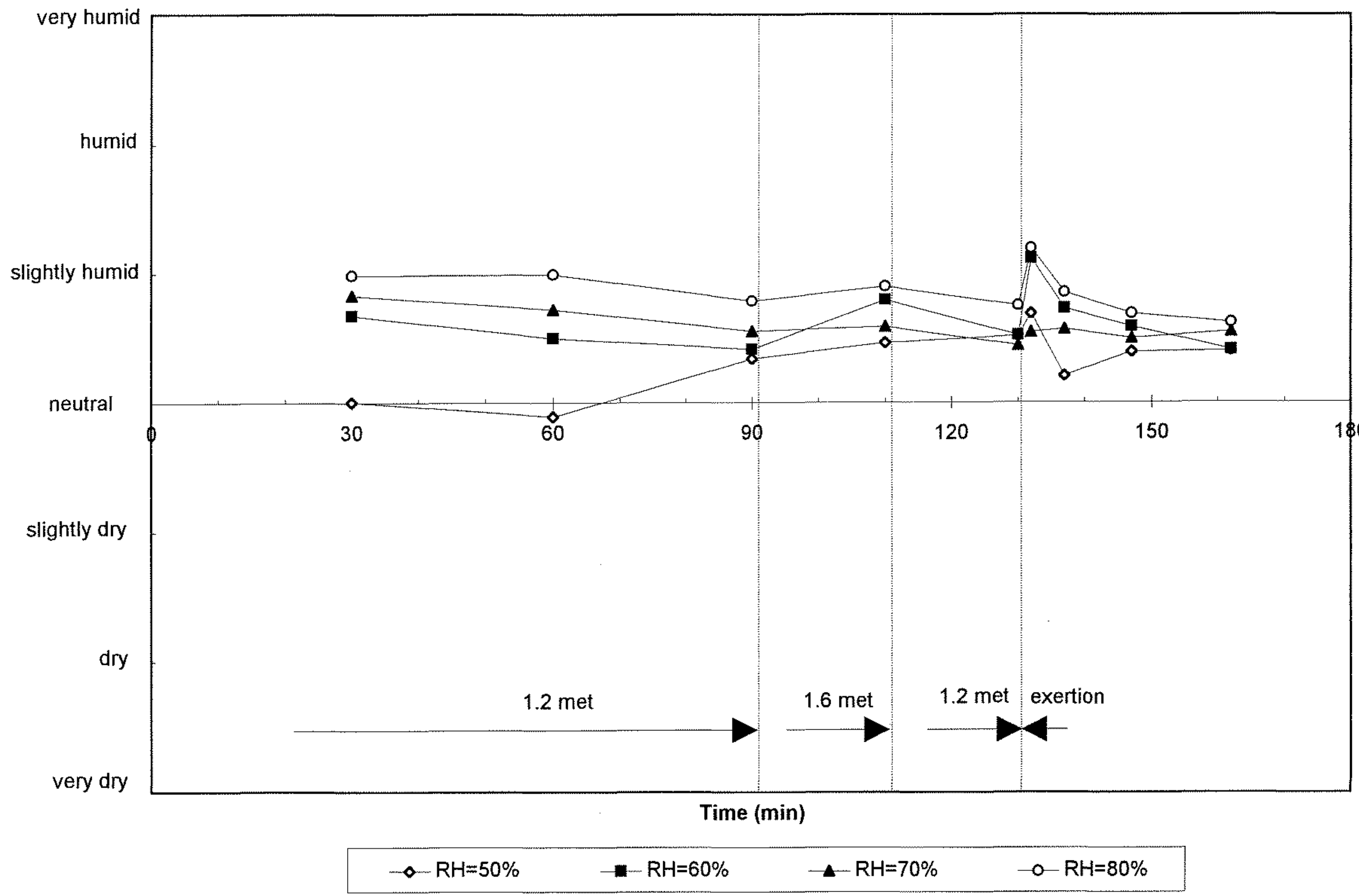


Figure 16. Humidity Acceptability

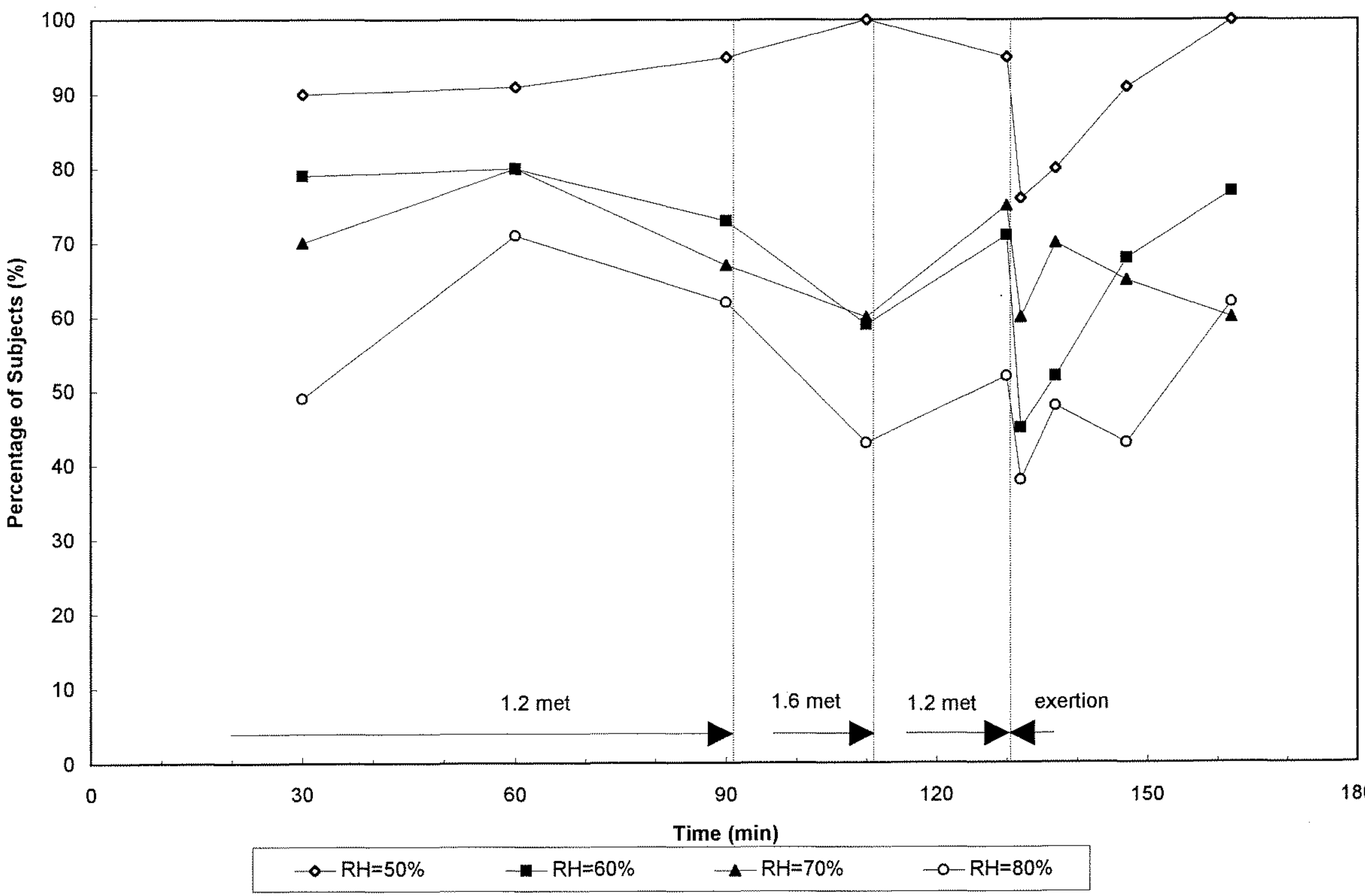


Figure 17. Air Movement Perception

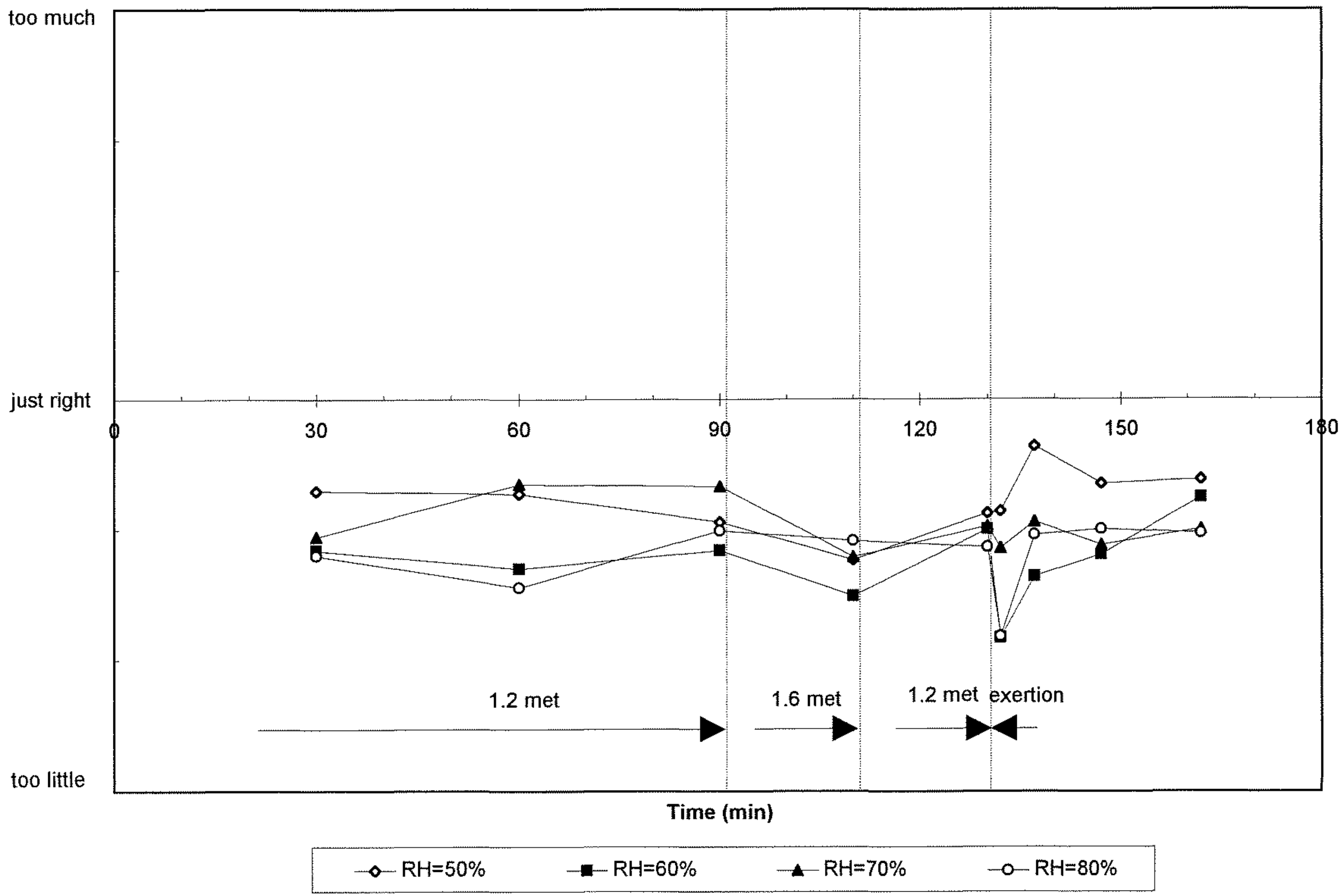


Figure 18. Air Movement Acceptability

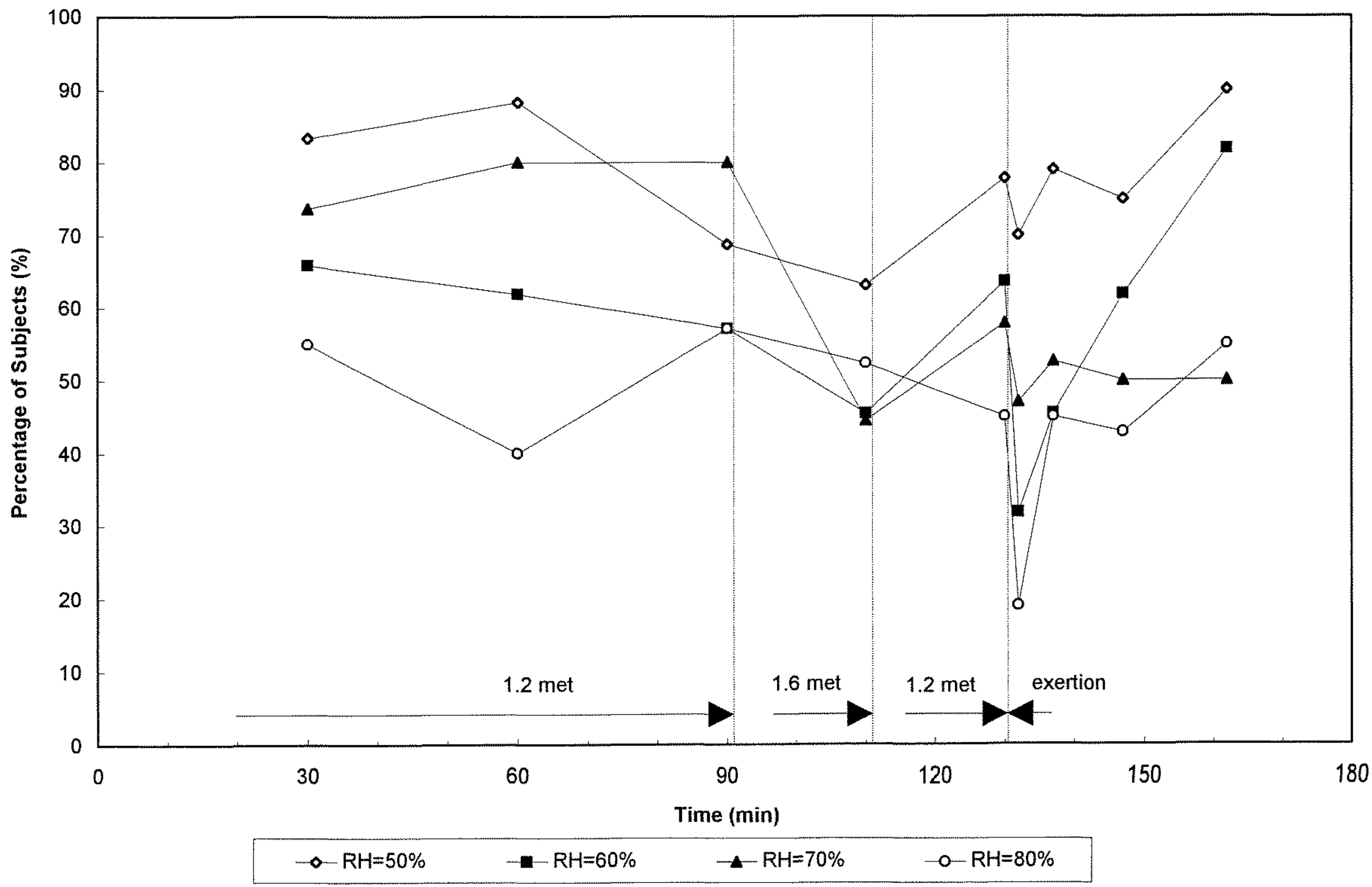


Figure 19. Air Freshness Feeling

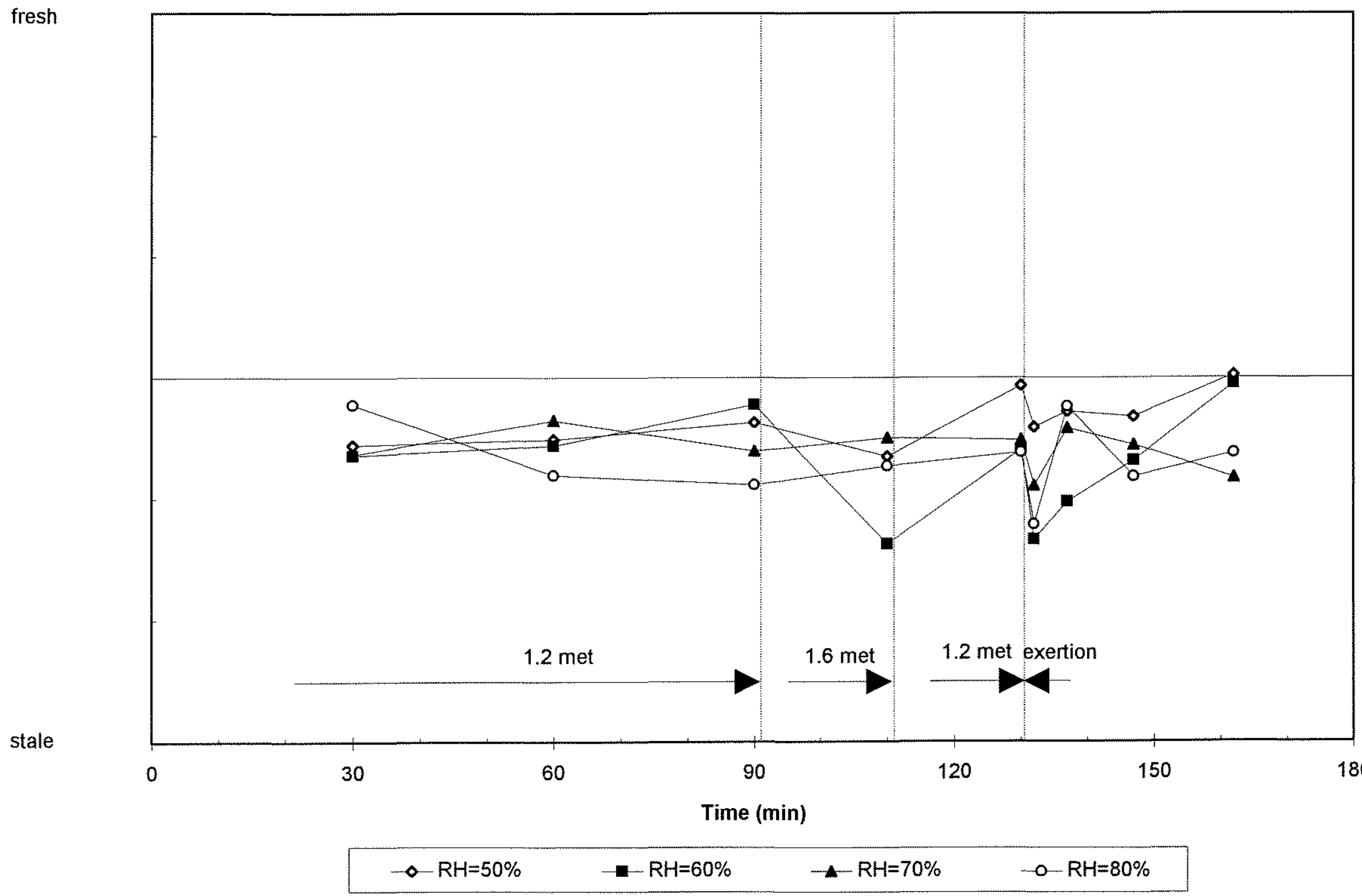


Figure 20. Stuffiness Feeling

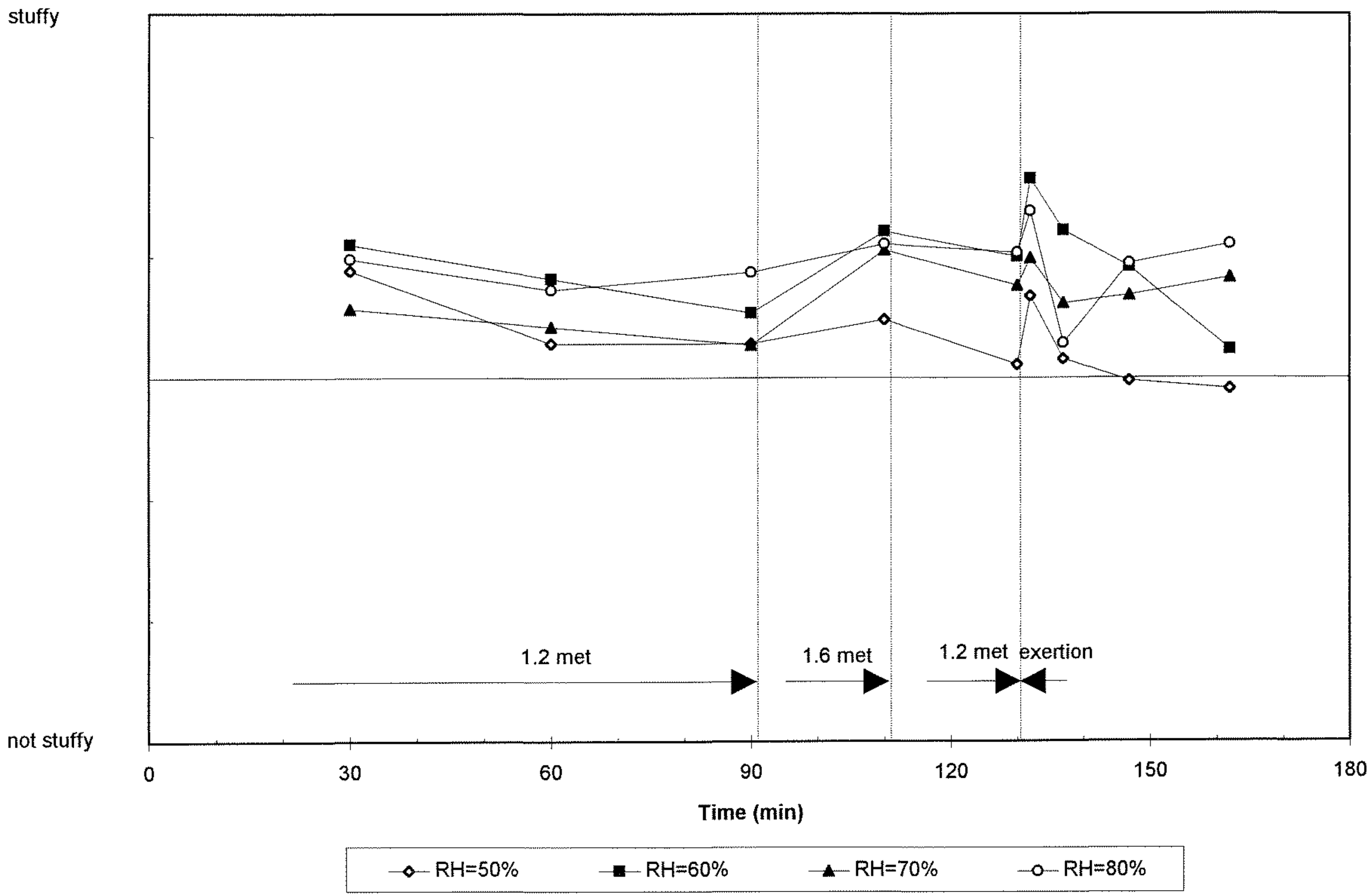


Figure 21. Alertness Feeling

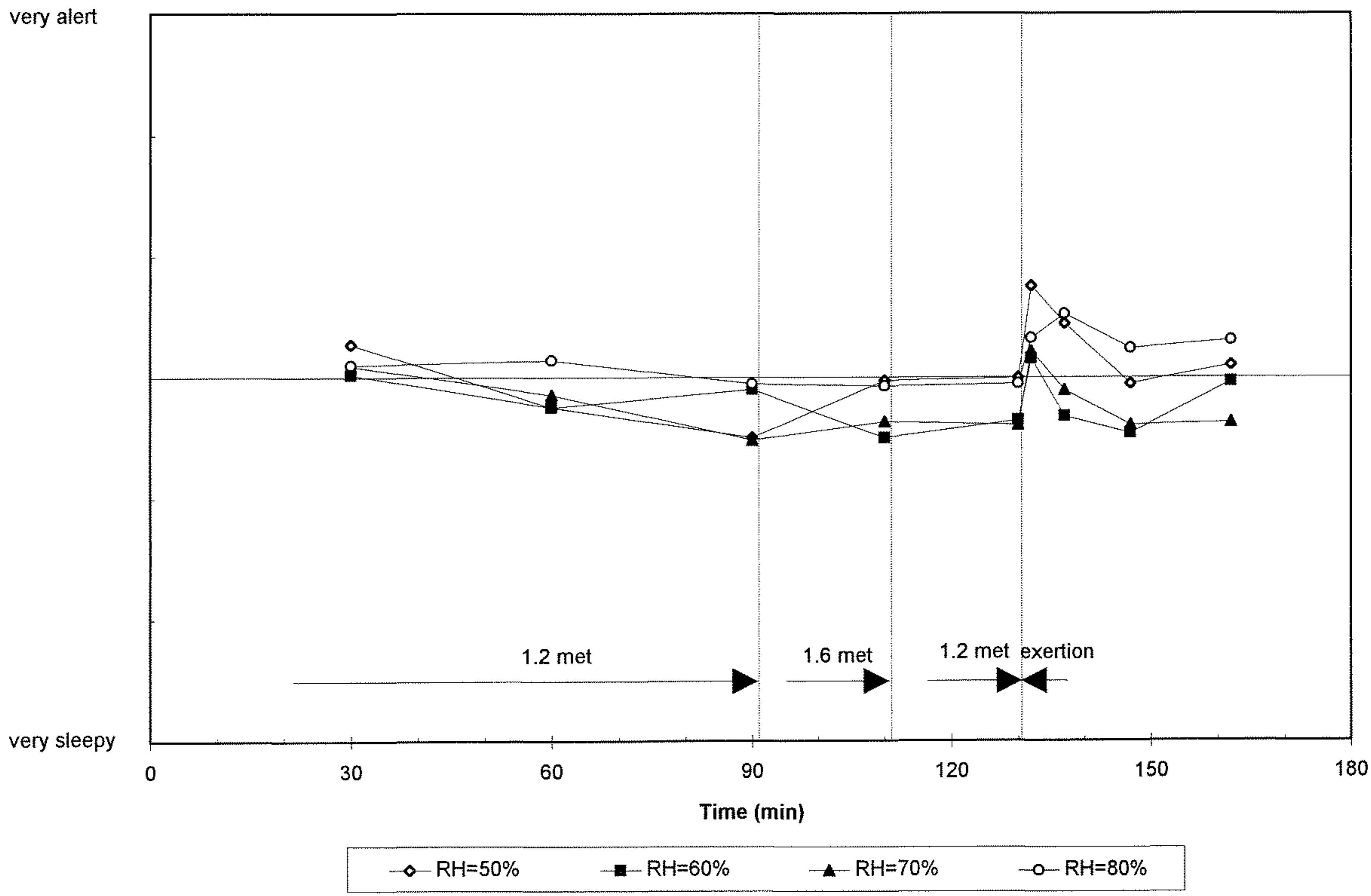


Figure 22. Fatigued Feeling

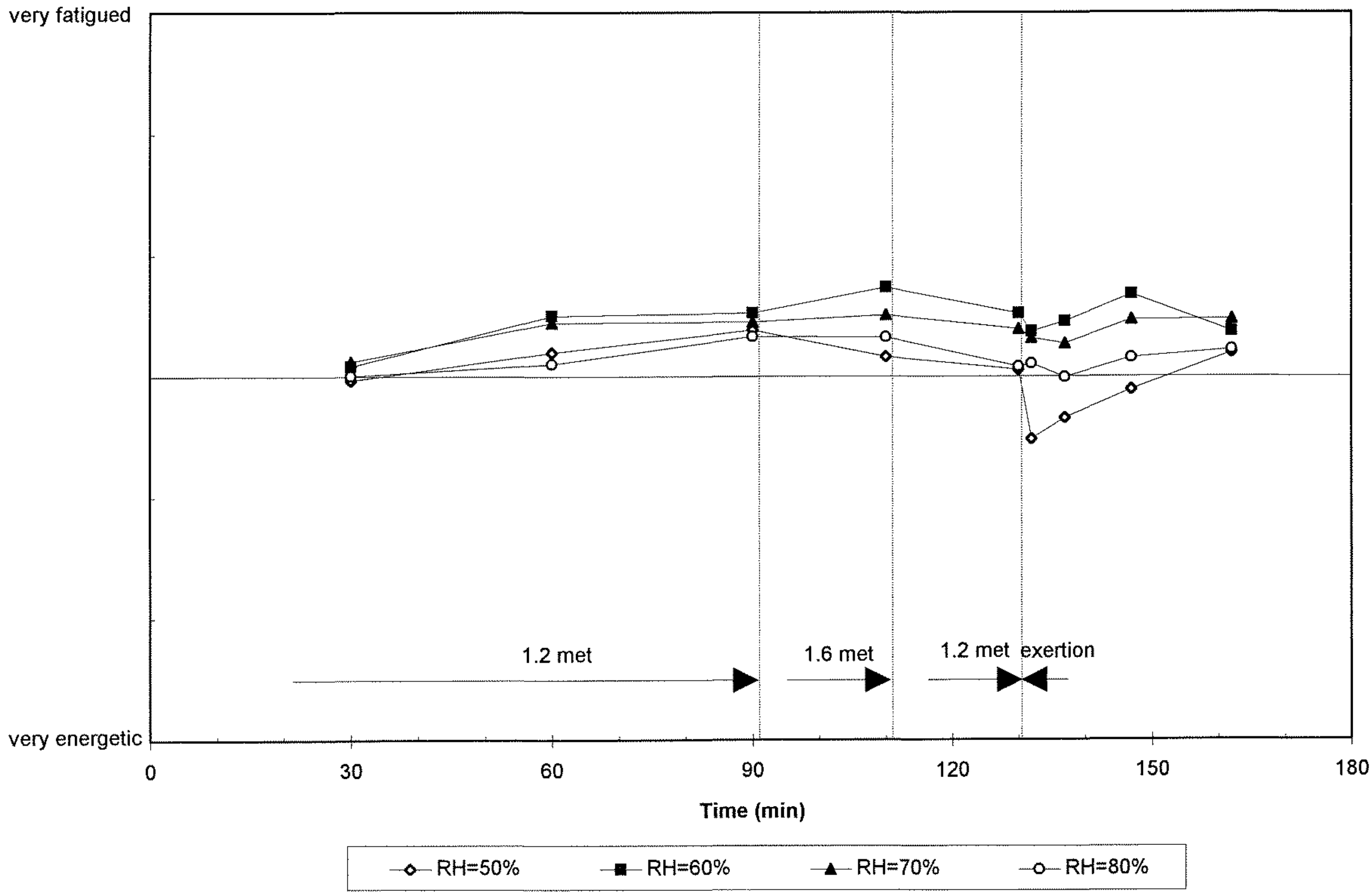


Figure 23. Air Quality Acceptability

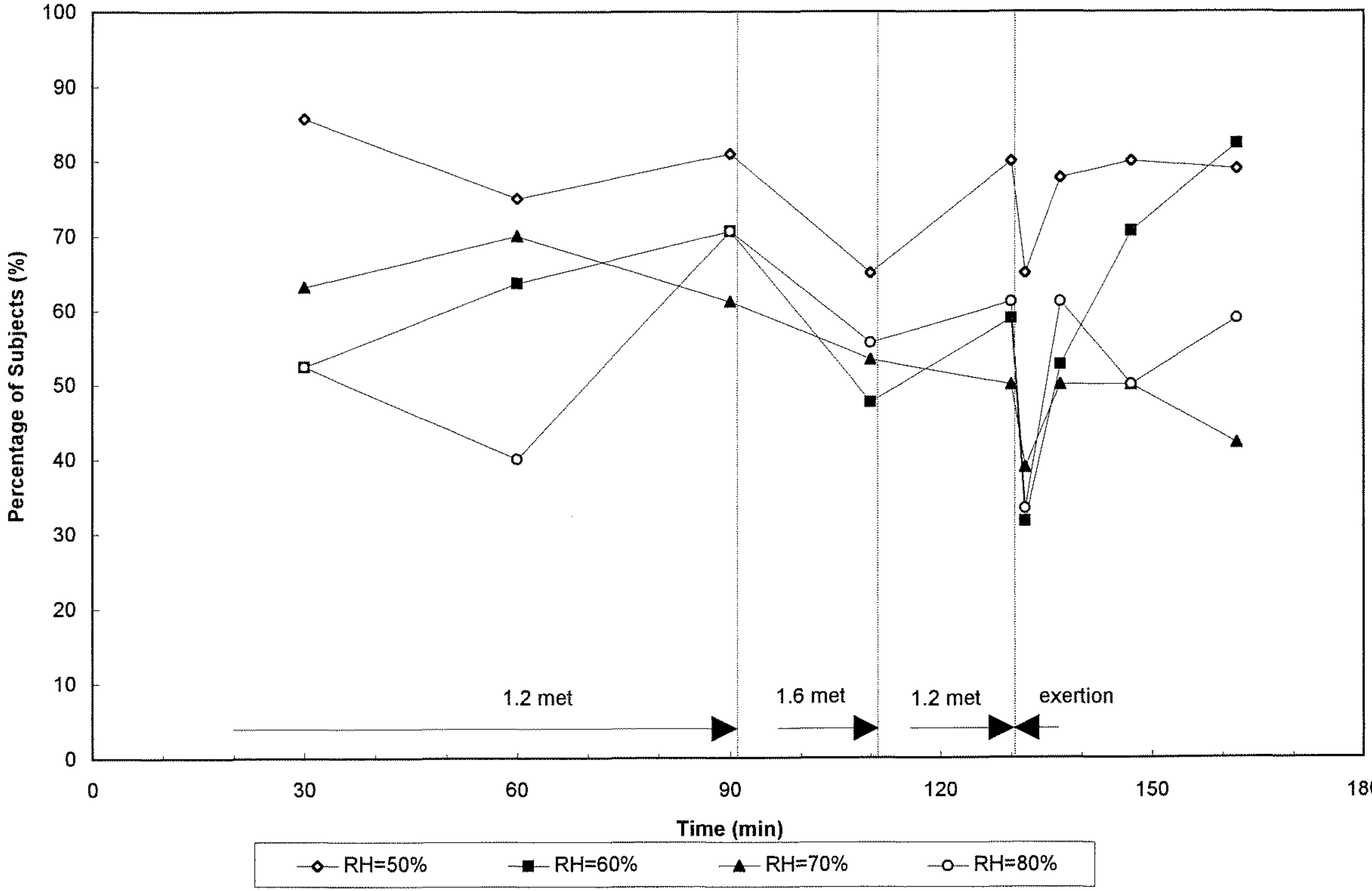


Figure 24: Mean Skin Temperature vs Time

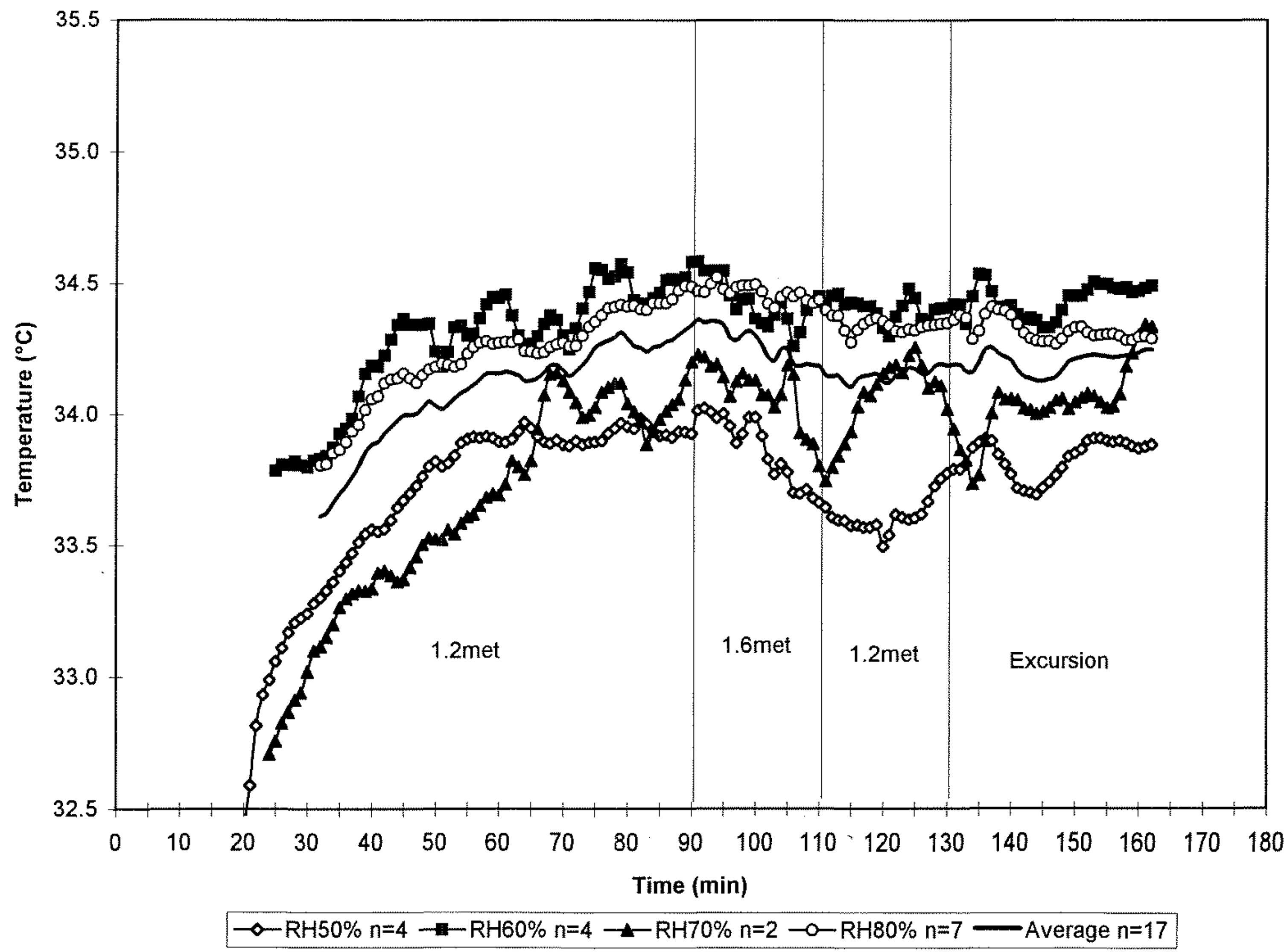


Figure 25: Mean Skin Wettedness vs Time

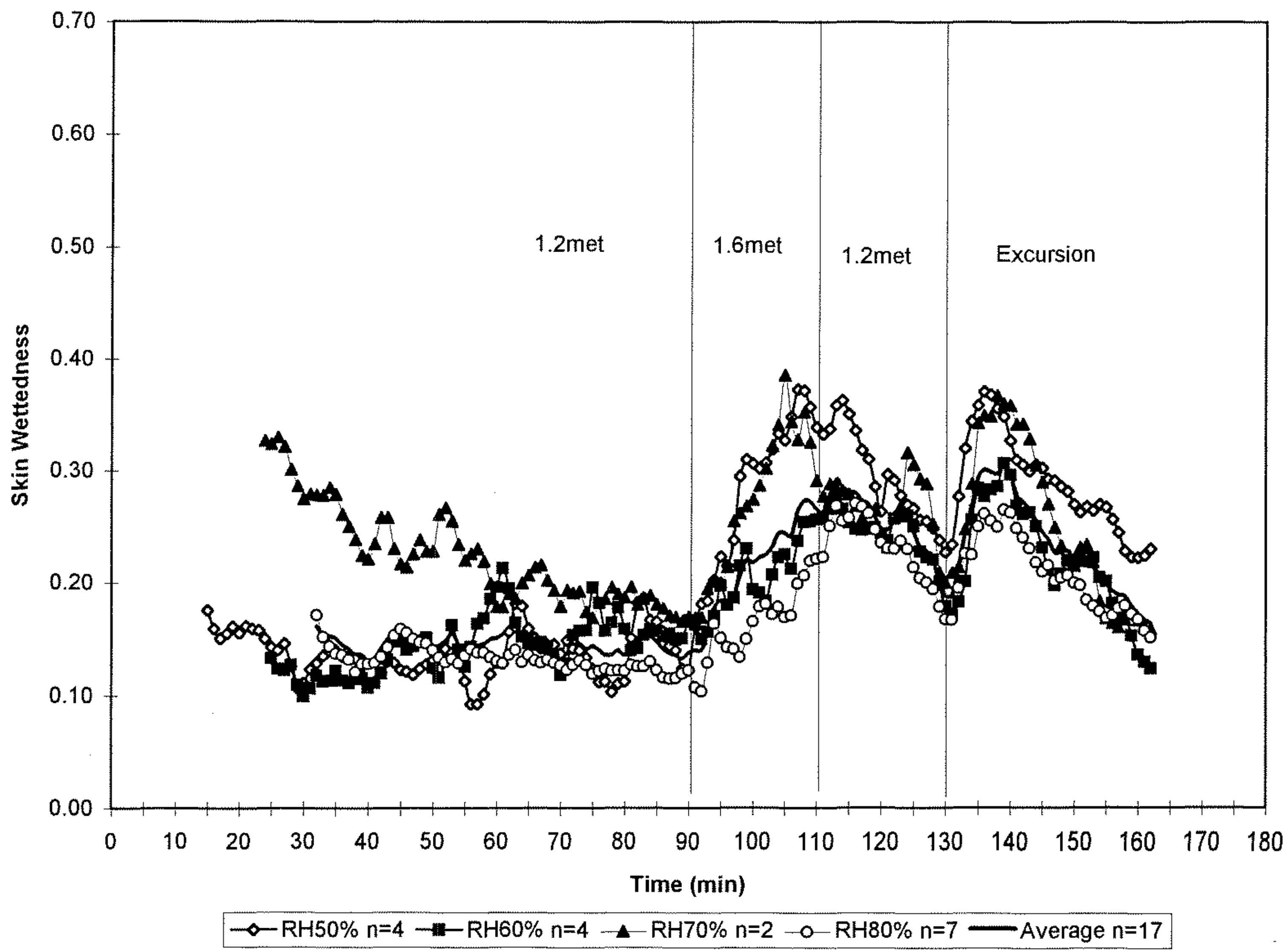
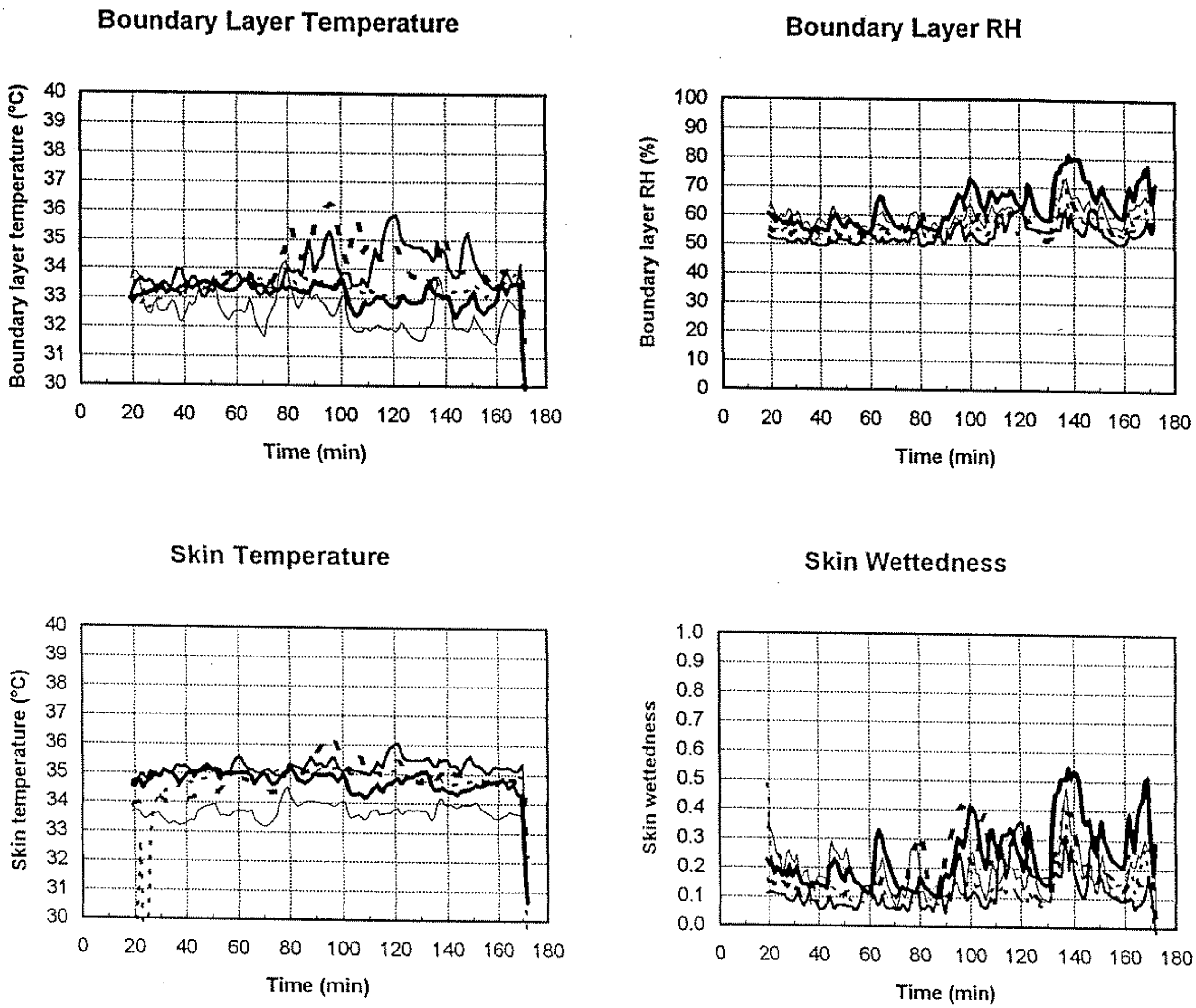
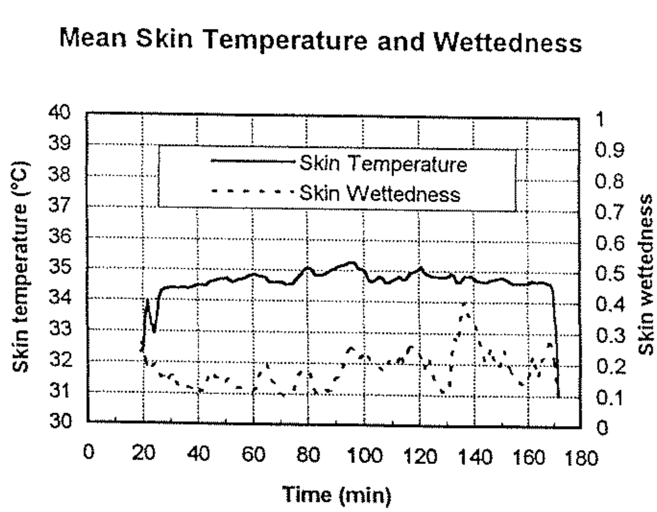
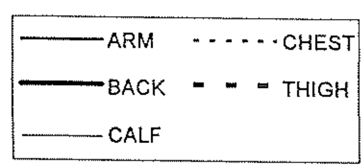


Figure 26. Example Physiological Data







Individual Physiological Data
Subject No.75
Date: 07/06/94
Time: 1:00pm-4:00pm
RH = 80% T = 24.9°C

Figure 27: Skin Wettedness at 1.2 Met

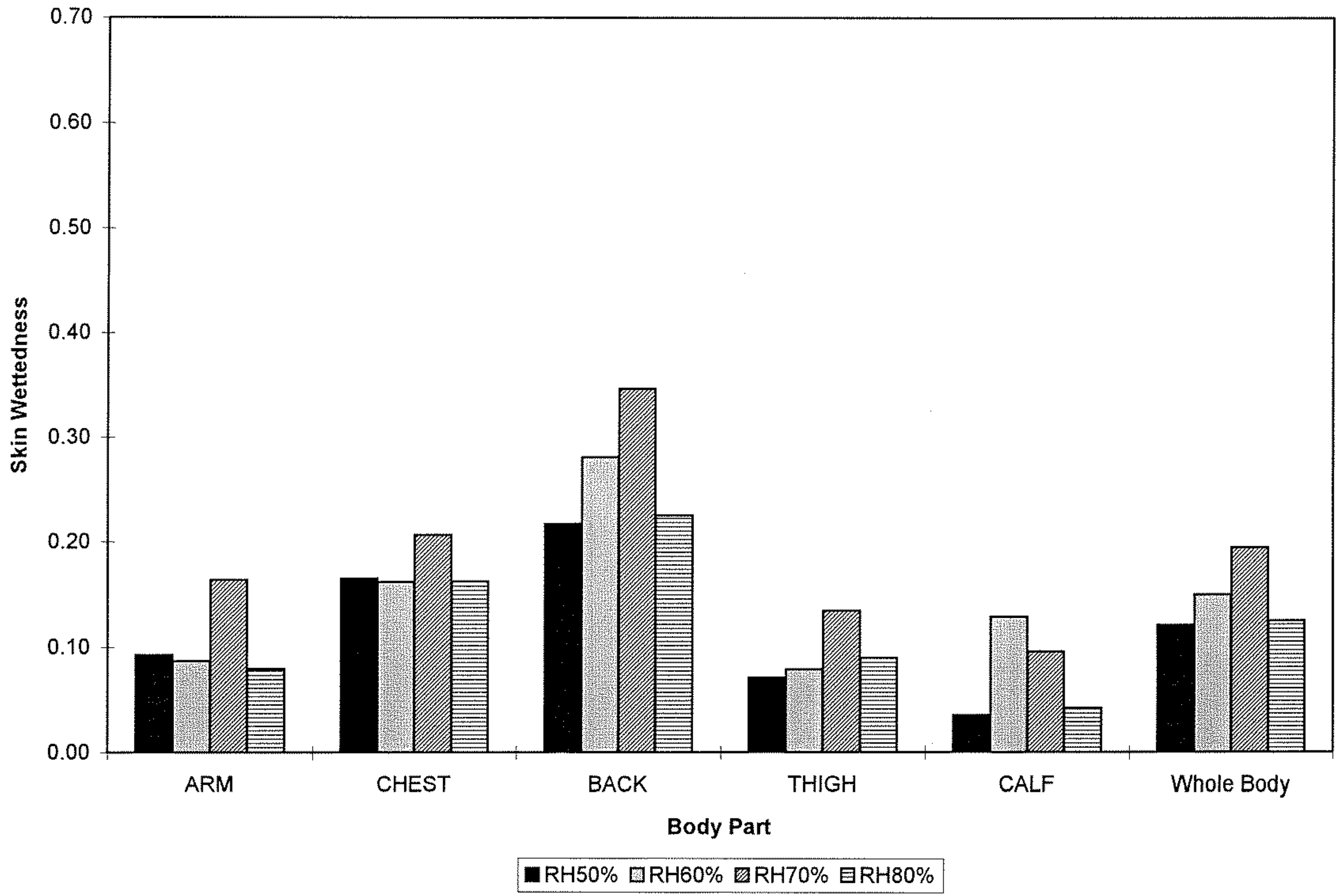


Figure 28. Average Whole-body Skin Wettedness Feeling

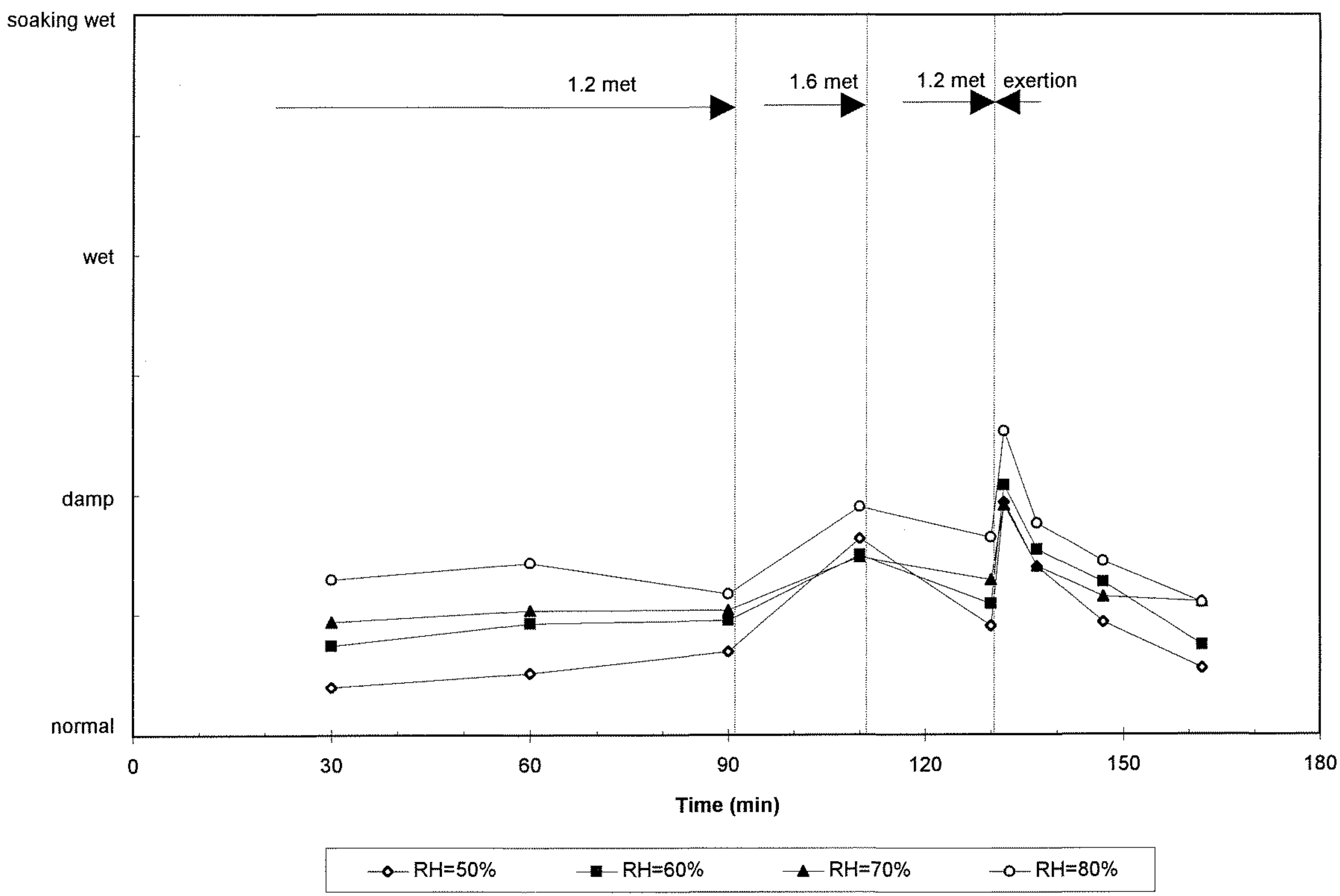


Figure 29. Whole-body Skin Feeling Acceptability

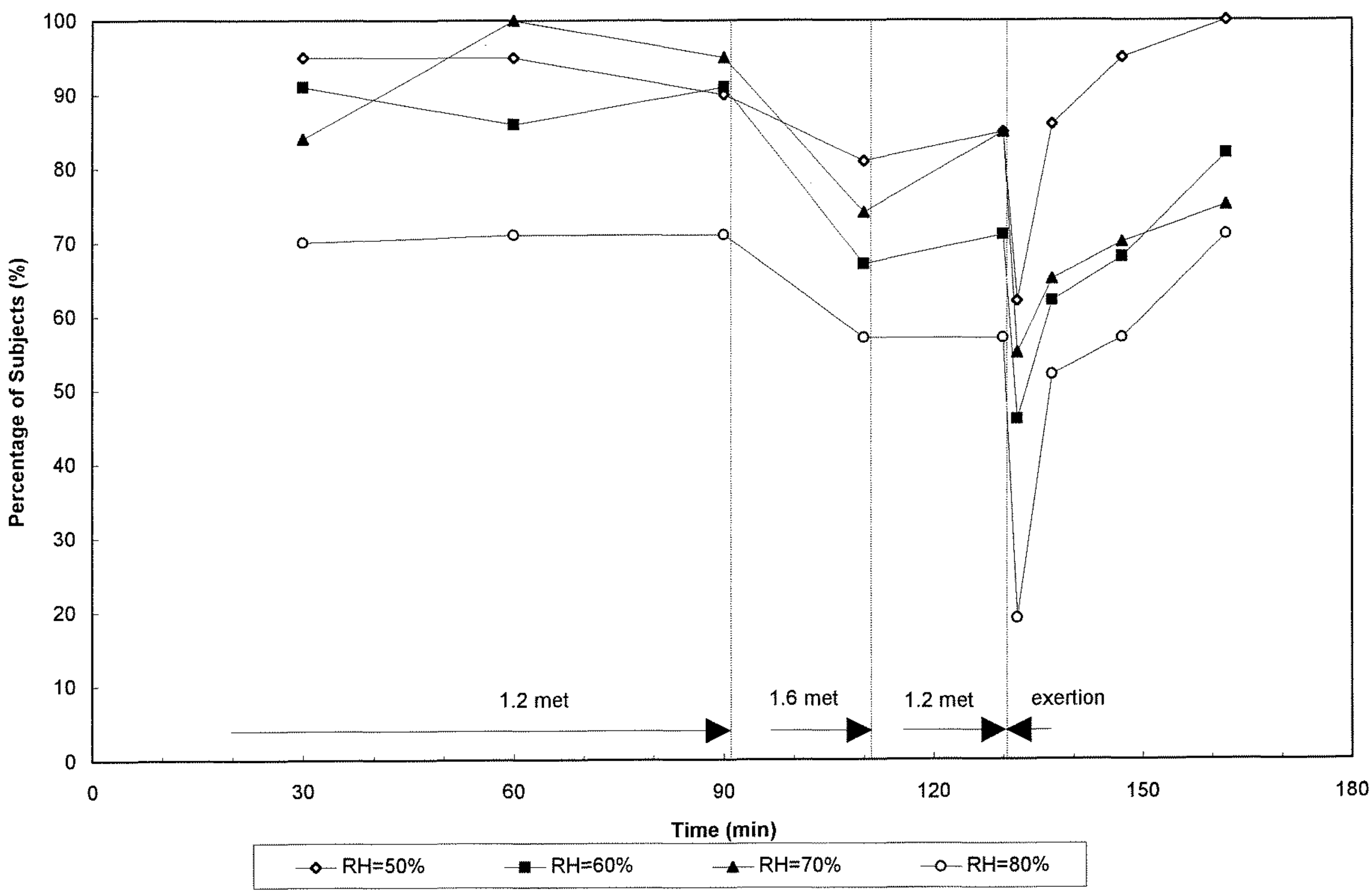
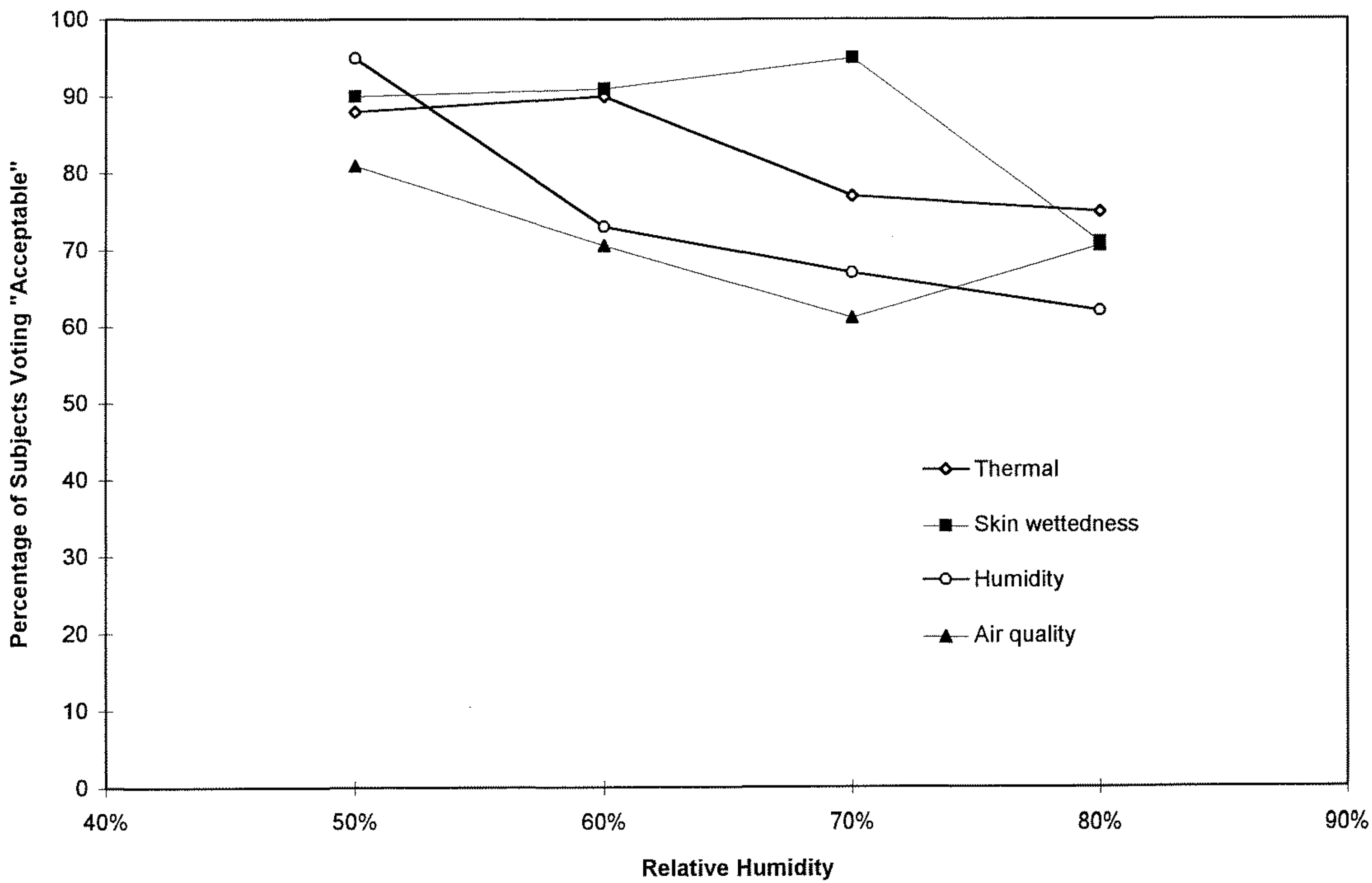


Figure 30. Subjective Acceptability Percentage Under Four RH Levels
(1.2 met)



APPENDIX A

Repeated Survey Results

Subjective votes at 90th minute (1.2 met)

Condition	Thermal sensation cold = -3 hot = +3	Comfort sensation comfortable = 0 intolerable = 4	Air movement perception too little = -3 too much = +3	Skin wettedness feeling: Whole-body normal = 0 soaking wet = 6	Head normal = 0 soaking wet = 6	Armpit normal = 0 soaking wet = 6	Abdomen normal = 0 soaking wet = 6	Leg normal = 0 soaking wet = 6	Foot normal = 0 soaking wet = 6	Humidity perception very humid = -3 very dry = +3
50%RH	0.3	0.6	-1.5	0.4	0.4	0.4	0.4	0.4	0.4	2.2
50%RH	0.0	0.2	-0.5	0.2	0.1	0.1	0.1	0.2	0.1	-0.8
50%RH	1.5	1.0	-1.5	0.3	0.3	0.0	0.4	0.4	2.1	0.6
50%RH	2.0	1.0	-1.0	0.5	0.2	0.6	0.3	0.7	1.0	0.0
50%RH	2.0	1.0	-2.0	0.2	0.0	0.1	0.0	0.2	0.2	-1.0
50%RH	2.0	1.0	-1.8	0.0	0.0	0.0	0.0	0.0	0.0	-2.0
50%RH	2.0	1.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.0
50%RH	1.2	0.3	-0.5	0.2	0.2	0.5	0.1	0.1	0.5	0.3
50%RH	0.2	0.8	-1.5	1.2	1.6	2.3	1.5	1.6	2.3	-1.3
50%RH	2.0	0.8	-1.5	1.0	0.4	1.5	0.7	0.7	0.7	1.4
50%RH	1.0	1.0	1.5	1.0	1.0	2.0	1.0	0.0	1.0	-2.0
50%RH	1.2	0.3	-0.2	0.9	0.3	0.5	1.5	1.6	1.8	0.7
50%RH	2.2	2.0	-2.2	2.5	2.5	2.3	2.2	2.1	2.3	-1.0
50%RH	1.0	1.0	-1.0	2.0	0.0	2.0	2.0	1.0	0.0	-1.0
50%RH	0.0	0.4	-1.0	1.0	1.0	2.0	2.0	1.0	0.0	-0.5
50%RH	0.0	0.0	0.0	0.0	1.0	2.0	1.0	0.0	0.0	-0.5
50%RH	0.4	0.3	-0.8	1.1	1.1	1.1	1.2	1.1	2.1	0.0
50%RH	2.3	2.1	-2.5	1.6	1.7	2.3	1.7	1.6	2.5	-0.3
50%RH	0.4	0.7	0.5	0.0	0.2	0.0	0.8	0.7	0.0	-0.7
50%RH	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50%RH	1.4	1.3	-1.4	0.5	1.6	2.4	2.4	0.5	4.4	-0.2
60%RH	0.5	0.4	-0.2	0.5	0.2	0.4	0.4	0.4	0.5	-0.2
60%RH	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
60%RH	0.8	0.1	-0.2	0.2	0.0	0.0	0.0	0.0	0.0	-0.9
60%RH	1.0	0.8	-1.0	0.9	0.5	0.6	0.6	0.6	1.5	1.5
60%RH	0.0	0.0	-0.5	0.0	1.0	0.2	1.0	0.5	1.0	1.5
60%RH	1.6	0.8	-1.5	0.5	1.1	0.5	0.8	0.0	0.3	-1.3
60%RH	0.2	0.3	0.0	0.0	0.0	0.0	0.1	0.1	2.0	0.1
60%RH	0.4	0.5	-1.0	0.7	1.0	0.3	0.5	0.6	0.7	-0.2
60%RH	2.0	0.8	-2.0	1.0	2.0	2.0	0.0	2.0	5.0	-0.5
60%RH	2.0	3.0	-2.0	3.0	3.0	3.0	3.0	3.0	4.0	-2.0
60%RH	0.8	0.8	-0.8	1.3	1.2	2.5	2.5	1.5	3.3	-0.5
60%RH	0.2	0.5	-0.8	0.2	0.2	0.2	0.2	0.2	0.2	-0.5
60%RH	0.3	0.0	-2.5	0.3	0.0	0.2	0.2	0.0	1.0	-0.2
60%RH	2.0	1.3	-1.3	2.2	1.6	1.0	1.0	1.0	1.2	1.3
60%RH	1.0	2.0	-2.5	1.5	2.1	1.5	1.5	1.5	2.5	-2.2
60%RH	1.5	1.2	-0.6	1.7	2.0	2.2	2.0	2.0	2.5	-0.2
60%RH	1.3	1.0	-1.2	1.5	1.5	1.5	1.5	1.7	2.0	1.0
60%RH	1.8	1.8	-1.2	1.3	0.8	1.4	0.8	0.8	1.4	-2.3
60%RH	2.5	1.0	-1.8	0.8	0.7	0.2	0.3	0.3	0.7	-0.5
60%RH	0.8	0.3	-1.3	1.0	0.3	0.3	0.2	0.2	0.3	-0.7
60%RH	3.0	2.0	-3.0	2.0	3.0	4.0	2.9	3.0	2.0	-2.0
60%RH	-0.5	0.0	-0.2	0.3	0.4	0.3	0.2	0.2	0.2	-0.3
70%RH	1.0	0.8	-0.5	0.8	0.0	0.0	0.2	0.6	1.2	-1.5
70%RH	-0.5	2.5	-1.0	1.0	0.2	1.5	0.2	0.6	0.5	0.8
70%RH	0.9	0.2	0.0	0.2	0.2	0.2	0.2	0.1	0.1	0.0
70%RH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
70%RH	2.0	1.5	-1.0	1.0	0.0	1.0	0.0	0.0	1.0	-2.0
70%RH	1.3	0.8	-1.8	0.2	0.2	0.2	0.2	0.2	0.2	1.4
70%RH	1.0	1.0	-1.0	0.0	0.0	1.8	0.8	0.0	0.0	-2.0
70%RH	2.2	1.4	-2.3	0.0	0.7	1.0	1.8	1.0	2.0	-1.8
70%RH	1.9	1.6	-1.8	2.5	2.8	2.8	3.1	3.2	3.5	-1.7
70%RH	0.9	0.3	0.7	0.7	0.8	0.8	0.7	0.8	0.8	1.2
70%RH	1.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.0
70%RH	2.5	1.5	-1.2	2.0	2.0	2.0	2.0	1.0	2.0	-1.8
70%RH	1.5	1.0	0.8	1.1	1.2	0.8	1.3	0.8	0.7	0.0
70%RH	0.8	1.0	0.0	0.5	1.2	1.8	1.3	1.0	2.0	-0.3
70%RH	-0.2	0.0	-0.5	1.3	1.0	1.6	0.5	1.2	1.4	-1.0
70%RH	2.2	1.2	-1.5	2.8	3.7	2.8	2.8	1.8	3.7	-1.5
70%RH	1.5	1.3	-1.3	1.5	1.5	1.5	1.5	1.6	2.0	2.5
70%RH	2.6	2.5	-2.5	2.0	2.5	3.3	2.5	2.6	4.7	-1.4
70%RH	0.0	0.5	0.0	2.5	2.5	1.3	1.7	1.4	2.7	-0.5
70%RH	0.3	0.8	-0.5	0.7	0.4	1.2	0.5	0.8	2.0	-0.5
80%RH	-0.5	0.3	0.0	.	1.4	2.7	1.2	1.2	3.2	0.5
80%RH	2.0	0.5	-1.0	1.0	0.3	1.3	1.3	1.5	0.3	-1.8
80%RH	0.8	0.5	-1.0	0.5	0.6	0.6	0.6	0.6	0.7	-0.8
80%RH	1.4	0.8	-1.8	1.0	1.2	1.8	0.2	0.2	1.3	-1.0
80%RH	2.0	1.0	-2.5	1.0	1.0	1.0	1.0	1.0	1.0	0.0
80%RH	0.5	1.0	-1.0	1.0	1.0	0.5	0.5	1.3	1.3	-1.0
80%RH	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	-1.0
80%RH	0.0	0.5	-1.5	0.5	0.1	0.3	0.2	0.7	0.9	1.3
80%RH	1.8	1.5	-1.2	1.0	1.5	1.5	0.8	1.8	1.8	0.0
80%RH	0.2	0.3	-1.2	0.5	0.7	0.2	0.2	0.2	0.2	-1.8
80%RH	1.5	1.2	-1.5	1.5	1.0	1.5	1.8	0.4	1.8	-1.3
80%RH	1.8	3.0	-2.0	3.3	3.2	0.3	0.8	1.2	0.2	-3.0
80%RH	1.0	1.0	-1.0	0.8	0.0	0.0	0.0	0.0	0.5	-1.0
80%RH	0.5	0.4	0.0	0.7	1.0	1.8	0.2	0.2	0.0	1.2
80%RH	1.8	0.5	-1.3	1.4	0.2	1.4	0.3	0.4	0.6	-1.2
80%RH	1.1	1.3	-0.7	1.8	0.3	1.8	0.8	0.8	0.2	-0.8
80%RH	1.0	1.2	-1.6	1.3	1.3	1.9	1.2	1.8	2.2	-1.1
80%RH	2.0	1.4	-1.5	2.0	1.0	2.7	1.8	2.3	1.8	-2.5
80%RH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80%RH	1.8	1.5	2.3	1.6	1.3	1.5	1.2	1.3	1.1	0.8
80%RH	1.8	1.0	-2.8	2.5	2.5	3.1	2.5	2.6	2.3	-2.0

Subjective votes at 90th minute (1.2 met, cont.)

Condition	Freshness fresh = 0 stale = 6	Stuffiness stuffy = 0 not stuffy = 6	Alertness very alert = 0 very sleepy = 6	Fatigue very fatig. = 0 very energ. = 6	Thermal acceptability yes = 1 no = 2	Air movement acceptability yes = 1 no = 2	Humidity perception acceptability yes = 1 no = 2	Air quality acceptability yes = 1 no = 2	Skin wettedness acceptability Whole-body yes = 1 no = 2	Head yes = 1 no = 2	Armpit yes = 1 no = 2	Abdomen yes = 1 no = 2	Leg yes = 1 no = 2	Foot yes = 1 no = 2
50%RH	3.6	3.0	5.0	4.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.5	2.3	3.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.5	2.0	3.5	2.3	2	2	1	2	1	1	1	1	1	2
50%RH	4.0	2.0	4.0	3.0	.	.	1	1	1	1	1	1	1	1
50%RH	5.0	1.0	1.0	3.3	1	1	2	2	1	1	1	1	1	1
50%RH	5.0	1.0	4.0	1.0	1	1	.	1	1	1	1	1	1	1
50%RH	1.0	5.0	2.0	3.0	1	2	1	1	1	1	1	1	1	1
50%RH	3.3	5.5	3.5	4.3	1	1	1	1	1	1	1	1	1	1
50%RH	5.5	0.6	4.5	1.2	1	2	1	2	1	1	1	1	1	1
50%RH	4.5	1.5	3.5	1.5	1	1	1	1	1	1	1	1	1	1
50%RH	4.0	1.3	4.0	2.0	1	1	1	1	1	1	1	1	1	1
50%RH	1.3	4.2	4.2	2.3	.	1	1	1	1	1	1	1	1	1
50%RH	4.5	0.6	4.3	1.7	1	2	1	1	1	1	1	1	1	1
50%RH	4.0	1.0	5.0	2.0	1	1	1	1	1	1	1	1	1	1
50%RH	1.0	4.0	4.0	3.0	1	.	1	1	2	1	2	2	1	1
50%RH	0.0	6.0	2.0	5.0	1	.	1	1	1	1	1	1	1	1
50%RH	2.5	3.0	2.0	3.8	1	1	1	1	1	1	1	1	1	1
50%RH	4.5	0.5	5.5	0.5	2	2	1	2	2	2	2	2	1	2
50%RH	4.5	3.5	3.0	2.5	.	.	1	1	1	1	1	1	1	1
50%RH	2.0	4.3	2.0	3.1	1	1	1	1	1	1	1	1	1	1
50%RH	3.6	4.8	3.5	2.5	.	.	1	1	1	1	1	1	1	2
60%RH	3.0	3.0	2.0	4.0	1	1	1	1	1	1	1	1	1	1
60%RH	2.0	4.5	2.5	3.0	1	1	1	1	1	1	1	1	1	1
60%RH	2.0	2.0	4.0	2.0	1	1	1	.	1	1	1	1	1	1
60%RH	1.0	2.0	1.0	3.0	1	2	2	.	1	1	1	1	1	2
60%RH	4.0	3.5	3.0	2.0	1	1	1	1	1	1	1	1	1	1
60%RH	2.2	2.2	.	3.5	1	2	1	1	1	1	1	1	1	1
60%RH	1.2	5.0	1.6	3.5	1	.	1	1	1	1	1	1	1	1
60%RH	4.0	2.0	2.5	3.2	1	1	1	1	1	1	1	1	1	1
60%RH	5.0	0.5	5.6	4.1	.	2	2	2	1	1	1	2	1	2
60%RH	6.0	0.0	5.0	0.0	2	2	2	2	2	2	2	2	2	2
60%RH	3.5	2.5	3.5	1.5	1	1	1	1	1	1	1	1	1	1
60%RH	3.5	2.5	3.0	2.5	1	1	1	1	1	1	1	1	1	1
60%RH	4.0	1.5	4.0	2.1	.	1	1	1	1	1	1	1	1	1
60%RH	3.0	2.0	2.0	4.0	1	2	1	.	1	1	1	1	1	1
60%RH	0.5	4.0	2.1	2.0	.	1	2	2	1	1	1	1	1	1
60%RH	4.0	5.0	4.0	2.5	1	1	1	1	1	1	1	1	1	1
60%RH	4.7	0.8	4.1	2.1	1	2	1	.	1	2	1	1	1	2
60%RH	4.5	1.6	4.8	1.5	1	2	2	2	1	1	1	1	1	1
60%RH	1.6	2.5	1.8	2.8	1	1	1	1	1	1	1	1	1	1
60%RH	4.1	2.2	2.1	2.2	1	2	1	.	1	1	1	1	1	1
60%RH	5.9	0.1	5.0	1.0	2	2	2	2	2	2	2	2	2	2
60%RH	1.2	4.8	1.5	2.0	1	1	1	1	1	1	1	1	1	1
70%RH	3.0	2.0	3.0	3.0	2	1	2	2	1	1	1	1	2	2
70%RH	3.5	3.5	4.5	3.0	.	1	1	.	1	1	1	1	1	1
70%RH	1.2	5.5	1.2	5.5	1	1	1	1	1	1	1	1	1	1
70%RH	3.0	4.2	3.0	2.3	1	1	1	1	1	1	1	1	1	1
70%RH	3.0	1.5	3.5	1.2	1	2	2	2	1	1	1	1	1	2
70%RH	5.0	2.8	4.0	2.0	1	2		2	1	1	1	1	1	1
70%RH	4.7	1.0	4.0	4.2	1	1	2	2	1	1	1	1	1	1
70%RH	4.7	1.5	4.0	3.0	.	2	1	2	1	1	1	1	1	2
70%RH	5.4	4.0	4.0	2.0	1	1	1	.	1	1	1	1	1	1
70%RH	2.3	2.7	2.5	3.2	1	1	1	1	1	1	1	1	1	1
70%RH	2.0	4.0	2.0	4.0	1	1	1	1	1	1	1	1	1	1
70%RH	2.0	4.0	1.9	2.0	2	1	2	1	1	1	1	1	1	1
70%RH	3.5	3.3	2.8	2.9	.	1	1	1	1	1	1	1	1	1
70%RH	3.7	4.6	2.5	4.0	1	1	1	1	1	1	1	1	1	1
70%RH	2.3	2.3	3.0	3.0	1	1	1	1	1	1	1	1	1	1
70%RH	5.5	0.5	4.4	1.4	2	2	2	2	2	2	2	2	2	2
70%RH	5.5	1.5	5.3	0.8	1	1	1	1	1	1	1	1	1	2
70%RH	5.5	0.5	5.6	0.4	2	1	2	2	1	1	1	1	1	2
70%RH	3.0	3.3	5.3	0.6	1	1	1	1	1	2	1	1	1	1
70%RH	3.3	1.9	3.9	2.5	1	1	.	1	1	1	2	1	1	2
80%RH	2.5	3.0	3.3	2.8	.	1	1	1	1	1	1	1	1	2
80%RH	3.8	2.3	2.0	3.0	1	1	2	2	1	1	1	1	1	1
80%RH	3.3	2.5	3.5	3.0	1	1	1	1	1	1	1	1	1	1
80%RH	4.3	2.5	4.0	2.8	1	2	1	1	1	1	2	1	1	2
80%RH	5.0	1.0	3.0	3.0	.	1	1	1	1	1	1	1	1	1
80%RH	4.5	1.8	3.2	2.5	.	1	1	.	1	1	1	1	1	1
80%RH	3.0	3.0	3.0	3.0	1	1	1	.	1	1	1	1	1	1
80%RH	4.2	3.0	2.8	2.0	1	1	1	1	1	1	1	1	1	1
80%RH	3.0	4.0	2.8	2.8	1	1	1	1	2	2	2	1	2	2
80%RH	3.5	1.5	3.5	2.5	1	2	2	1	1	1	1	1	1	1
80%RH	4.0	1.9	3.0	2.9	1	2	2	2	2	1	2	2	1	2
80%RH	5.7	0.0	1.3	5.0	2	2	2	2	2	2	1	1	1	1
80%RH	3.0	4.0	4.0	2.0	.	2	2	2	2	1	1	1	1	1
80%RH	4.2	2.1	1.6	3.5	1	1	1	1	1	1	1	1	1	1
80%RH	5.0	0.8	0.0	4.0	2	2	2	2	2	1	1	1	1	1
80%RH	4.2	2.2	2.6	3.4	1	1	1	1	1	1	1	1	1	1
80%RH	4.4	1.1	4.5	1.8	1	1	1	1	1	1	1	1	1	1
80%RH	4.0	1.2	3.0	2.0	2	2	2	1	1	1	1	1	1	1
80%RH	1.0	5.0	2.0	3.0	1	1	1	.	1	1	1	1	1	1
80%RH	5.0	0.8	5.5	0.6	2	2	2	.	2	2	2	2	2	2
80%RH	4.0	1.0	5.5	0.5	.	2	1	1	1	1	1	1	1	1

Subjective votes at 110th minute (1.6 met)

Condition	Thermal sensation	Comfort sensation	Air movement perception	Skin wettedness feeling: Whole-body	Head	Armpit	Abdomen	Leg	Foot	Humidity perception
	cold = -3	comfortable = 0	too little = -3	normal = 0	normal = 0	normal = 0	normal = 0	normal = 0	normal = 0	very humid = -3
	hot = +3	intolerable = 4	too much = +3	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	very dry = +3
50%RH	0.6	0.8	-2.0	0.4	0.4	0.4	0.4	0.5	0.5	2.3
50%RH	0.0	0.2	-1.0	0.2	0.2	0.1	0.1	0.1	0.1	-0.8
50%RH	0.2	0.6	-1.0	1.5	0.3	0.4	1.0	1.8	2.0	-0.1
50%RH	1.0	1.0	-1.0	0.5	0.5	0.5	0.5	0.5	1.0	-0.7
50%RH	2.0	1.8	-2.0	0.3	0.5	0.5	0.5	0.5	0.5	0.0
50%RH	3.0	1.2	-2.0	1.0	1.0	1.0	1.0	1.0	1.0	-3.0
50%RH	2.0	1.0	0.0	1.0	0.0	1.0	1.0	1.0	1.0	0.0
50%RH	1.3	0.5	-1.5	0.4	0.3	0.6	0.2	0.2	0.6	-0.2
50%RH	2.4	1.5	-1.5	2.4	2.6	3.4	2.8	2.6	3.3	1.5
50%RH	2.0	1.0	-1.3	3.5	1.5	3.5	3.5	3.5	4.3	1.0
50%RH	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0	2.0	-1.5
50%RH	2.6	1.8	-1.8	2.8	2.8	3.7	3.7	0.4	3.7	-0.7
50%RH	2.7	2.0	-2.6	3.2	3.2	3.2	3.2	3.2	3.2	0.2
50%RH	1.0	1.0	-1.0	2.0	0.0	2.0	1.0	0.0	0.0	-1.0
50%RH	2.0	1.0	0.0	2.0	1.0	2.0	2.0	0.5	1.0	-1.0
50%RH	2.8	1.0	1.1	4.0	4.0	4.0	1.9	1.0	0.0	0.0
50%RH	1.0	1.0	-1.5	1.8	1.8	2.1	1.2	1.2	2.8	-1.0
50%RH	2.8	2.8	-3.0	1.8	2.8	2.8	2.5	2.5	3.5	-0.8
50%RH	2.2	1.0	-1.8	2.0	2.8	2.0	1.6	0.2	0.0	-2.0
50%RH	2.2	1.0	-1.5	1.8	0.8	2.0	1.0	1.1	2.0	-1.5
50%RH	2.5	2.3	-1.6	0.7	0.9	3.6	3.8	2.8	4.5	.
60%RH	0.0	0.0	-1.0	0.8	0.1	0.6	0.3	0.5	0.8	0.2
60%RH	0.0	0.2	-0.7	0.0	0.0	0.0	0.0	0.0	0.0	-0.5
60%RH	2.0	1.0	-2.0	0.3	0.2	0.2	0.1	0.0	0.6	0.0
60%RH	2.0	1.0	-1.5	1.4	1.9	2.0	1.4	1.9	2.0	1.8
60%RH	1.0	0.3	-1.0	1.0	1.0	2.0	2.0	2.0	3.0	1.5
60%RH	2.0	1.0	-2.0	1.7	2.1	1.0	2.5	-0.1	0.5	-2.0
60%RH	1.0	1.5	-2.0	0.7	0.5	1.2	0.4	0.5	1.6	-0.8
60%RH	1.0	1.5	-0.5	0.7	1.3	0.7	0.6	0.6	1.0	-1.0
60%RH	2.0	2.3	-2.0	2.4	4.5	3.0	1.8	.	6.0	-1.6
60%RH	2.0	3.0	-3.0	3.0	3.0	3.0	3.0	3.0	4.0	-2.0
60%RH	0.8	0.7	-0.5	1.5	0.5	2.5	2.5	1.5	3.5	-1.3
60%RH	0.3	0.5	-0.5	0.3	0.3	0.6	0.3	0.3	0.3	-0.5
60%RH	1.0	0.5	-1.5	0.0	0.1	0.1	0.2	0.1	0.3	0.0
60%RH	2.2	1.3	-2.0	3.0	1.8	1.3	1.7	2.0	2.3	-2.0
60%RH	2.5	2.2	-2.5	2.8	3.7	2.2	2.3	1.8	3.3	-2.2
60%RH	2.0	1.0	-1.5	2.0	2.2	2.5	2.7	2.2	2.7	1.0
60%RH	1.3	1.0	-1.8	2.0	2.0	1.8	1.5	2.0	2.5	-1.0
60%RH	2.2	2.0	-2.1	2.2	1.9	2.6	2.2	2.2	2.3	-2.3
60%RH	2.7	1.1	-1.8	1.2	0.5	0.5	0.4	0.5	0.6	-1.6
60%RH	0.8	0.6	1.2	1.4	0.8	1.6	1.2	1.2	1.2	-1.0
60%RH	3.0	2.0	-3.0	4.0	3.0	4.0	3.0	4.0	3.0	-3.0
60%RH	1.8	0.9	-1.6	0.5	0.6	0.4	1.2	0.4	0.4	0.8
70%RH	2.0	1.5	-1.5	2.0	1.0	1.3	0.7	1.6	1.8	-1.6
70%RH	1.2	1.0	-1.0	1.5	0.2	1.5	0.2	0.2	1.4	-0.5
70%RH	0.8	1.5	-1.5	0.5	0.7	0.7	1.1	1.0	0.6	-0.9
70%RH	0.0	0.0	0.0	0.2	0.3	0.3	0.2	0.2	0.2	0.7
70%RH	2.5	0.5	0.0	0.0	0.0	0.0	0.0	1.0	2.0	1.0
70%RH	2.0	1.0	-2.0	0.3	0.0	0.2	0.2	1.0	1.0	1.0
70%RH	2.0	1.0	-2.0	1.0	0.8	1.8	1.0	0.0	0.0	-1.8
70%RH	2.0	2.0	-1.9	1.3	0.0	1.2	1.4	1.2	1.5	-1.0
70%RH	2.2	2.0	-2.1	3.2	2.8	3.5	3.1	3.2	3.4	-2.0
70%RH	1.2	0.3	-0.7	0.8	0.8	0.8	0.8	0.8	0.8	1.2
70%RH	2.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
70%RH	2.9	0.4	-2.0	2.0	2.1	2.8	3.0	2.2	2.0	-2.0
70%RH	1.8	1.4	-0.8	1.8	1.0	2.0	1.2	1.3	1.3	-1.0
70%RH	2.5	2.0	-1.8	2.0	1.6	2.3	2.7	1.9	3.2	-1.0
70%RH	1.0	0.5	-0.8	1.3	1.3	1.8	1.3	1.6	1.5	-0.9
70%RH	1.2	0.8	-1.3	3.4	4.3	3.3	2.5	2.5	3.4	-1.7
70%RH	2.5	3.1	-2.5	1.7	1.7	1.7	1.7	1.7	2.3	2.5
70%RH	2.7	2.8	-2.5	3.4	2.8	3.5	1.8	1.5	4.4	-2.5
70%RH	1.5	-0.4	-0.8	1.5	3.2	2.8	2.5	2.7	3.3	-1.0
70%RH	0.6	0.9	-0.1	0.7	.	.	.	0.8	2.3	-0.3
80%RH	1.3	1.6	-1.5	4.2	3.2	3.2	4.2	2.2	4.2	-1.6
80%RH	1.2	0.5	-2.0	0.5	0.6	1.3	0.2	2.1	0.1	-1.8
80%RH	0.8	1.2	-1.2	0.3	0.5	0.5	0.5	0.5	0.5	-0.3
80%RH	2.0	2.0	-2.0	3.0	2.3	2.7	1.0	0.8	2.5	-2.0
80%RH	3.0	3.0	0.0	4.0	2.0	2.0	2.0	3.0	2.0	0.0
80%RH	-1.5	1.0	-0.2	1.0	1.0	1.0	0.5	1.5	1.5	1.0
80%RH	1.0	1.5	0.0	2.0	2.0	2.0	1.0	1.0	2.0	-1.0
80%RH	0.5	0.5	-1.8	1.2	0.3	0.8	0.8	1.0	1.2	-0.5
80%RH	1.8	1.0	-0.5	2.0	1.0	2.3	1.2	1.8	1.8	0.0
80%RH	2.0	1.2	-2.0	1.5	3.5	1.2	0.2	1.2	0.2	-2.5
80%RH	2.3	2.0	-1.5	2.5	1.5	2.5	3.2	2.5	2.9	-1.5
80%RH	2.3	2.9	-0.5	4.2	4.2	0.6	1.4	2.3	0.2	-3.0
80%RH	2.0	0.6	-0.5	0.5	0.2	0.0	0.0	0.0	0.0	-1.0
80%RH	2.5	0.8	-1.2	1.8	3.5	2.8	1.8	1.9	0.5	-1.4
80%RH	1.2	1.5	-3.0	2.2	2.0	1.8	0.6	1.4	1.3	-1.8
80%RH	1.6	0.7	0.2	1.8	1.2	2.6	1.2	1.2	0.7	-0.8
80%RH	1.5	0.7	-1.4	1.2	1.7	1.4	1.2	1.7	1.9	-1.4
80%RH	2.5	2.3	-2.4	2.5	1.6	3.0	3.0	2.5	2.3	-2.4
80%RH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80%RH	0.6	0.6	1.4	0.8	1.1	1.0	1.0	1.0	1.2	0.9
80%RH	2.0	2.5	-2.8	2.7	3.0	3.1	3.2	3.7	2.2	2.2

Subjective votes at 110th minute (1.6 met, cont.)

					Thermal	Air movement	Humidity perception	Air quality	Skin wettedness acceptability					
	Freshness	Stuffiness	Alertness	Fatigue	acceptability	acceptability	acceptability	acceptability	Whole-body	Head	Armpit	Abdomen	Leg	Foot
	fresh = 0	stuffy = 0	very alert = 0	very fatig. = 0	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1
Condition	stale = 6	not stuffy = 6	very sleepy = 6	very energ. = 6	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2
50%RH	4.2	4.5	4.2	5.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.2	2.5	2.0	4.0	.	1	1	1	1	1	1	1	1	1
50%RH	1.0	5.0	1.5	3.0	1	1	1	2	1	1	1	1	2	2
50%RH	4.0	2.1	4.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.5	3.0	0.5	4.2	2	1	1	2	1	1	1	1	1	1
50%RH	5.0	0.0	4.0	2.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.0	3.0	2.0	3.0	1	1	1	.	1	1	2	1	1	2
50%RH	3.5	4.5	3.5	3.5	1	1	1	1	1	1	1	1	1	1
50%RH	4.5	0.0	3.3	1.6	2	2	1	2	2	1	2	2	2	2
50%RH	4.6	1.3	3.2	2.0	1	1	1	1	1	1	1	1	1	2
50%RH	5.0	2.0	4.0	2.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.5	3.3	3.5	1.8	2	2	1	1	2	2	2	2	2	2
50%RH	5.0	1.5	3.5	1.5	2	2	1	2	1	1	1	1	1	1
50%RH	5.0	1.0	5.0	2.0	1	1	1	1	1	1	1	1	1	1
50%RH	2.0	4.0	3.0	3.0	2	.	1	1	2	1	2	2	1	1
50%RH	0.0	6.0	2.0	5.0	1	.	1	1	1	1	1	1	1	1
50%RH	3.8	2.8	3.0	3.0	1	2	1	1	1	1	1	1	1	1
50%RH	4.4	0.8	5.5	0.5	2	2	1	2	2	2	2	2	1	2
50%RH	4.0	3.6	2.5	4.0	1	1	1	1	1	1	1	1	1	1
50%RH	4.2	1.5	2.2	2.5	2	2	1	2	1	1	1	1	1	1
50%RH	3.3	0.5	1.2	3.0	2	2	.	2	1	1	2	1	1	2
60%RH	3.0	2.0	3.0	3.5	1	1	1	1	1	1	1	1	1	1
60%RH	3.0	3.0	2.0	3.5	1	1	1	1	1	1	1	1	1	1
60%RH	5.0	1.5	4.5	1.5	1	2	1	1	1	1	1	1	1	1
60%RH	3.0	1.5	3.5	2.5	2	2	2	2	2	2	2	2	2	2
60%RH	4.0	3.0	3.0	2.0	1	1	1	1	1	1	1	1	1	1
60%RH	4.5	1.2	2.0	3.0	2	1	1	1	1	2	1	2	1	1
60%RH	5.5	0.5	4.0	2.0	2	2	2	2	1	1	2	1	1	1
60%RH	4.0	2.0	6.2	2.5	1	1	1	1	1	1	1	1	1	1
60%RH	6.0	1.0	5.5	3.2	2	2	2	2	2	2	2	1	.	2
60%RH	6.0	0.0	5.0	1.0	2	2	2	2	2	2	2	2	2	2
60%RH	4.0	1.5	3.5	1.5	1	1	1	2	.	.	.	.	.	.
60%RH	3.5	2.5	3.5	2.5	1	1	1	1	1	1	1	1	1	1
60%RH	3.0	3.5	2.2	4.0	.	1	1	1	1	1	1	1	1	1
60%RH	4.3	1.0	1.5	4.2	2	2	2	2	2	1	1	1	3	3
60%RH	5.5	0.5	4.5	1.2	.	2	2	2	2	2	1	2	1	1
60%RH	4.5	1.0	5.0	1.0	1	1	2	2	1	1	1	2	1	2
60%RH	4.4	1.5	4.2	1.5	2	2	1	2	2	2	1	1	1	2
60%RH	5.0	1.0	4.8	1.5	.	2	2	2	1	1	1	1	1	1
60%RH	5.5	1.5	3.5	2.7	1	1	1	1	1	1	1	1	1	1
60%RH	4.6	1.7	1.6	1.8	2	2	1	.	1	1	1	1	1	1
60%RH	5.8	6.0	0.8	1.0	.	2	2	2	2	2	2	2	2	2
60%RH	2.2	2.0	3.3	2.2	1	2	1	1	1	1	1	1	1	1
70%RH	3.5	2.4	2.2	2.2	2	2	2	2	2	2	2	1	2	2
70%RH	3.5	1.5	2.5	3.5	.	1	1	.	1	1	1	1	1	1
70%RH	2.5	1.5	1.5	4.0	2	1	1	2	1	1	1	1	1	1
70%RH	3.2	2.5	4.3	2.3	1	1	1	1	1	1	1	1	1	1
70%RH	2.0	3.0	3.0	3.0	1	1	1	1	1	1	1	1	1	2
70%RH	4.5	2.0	4.0	2.0	2	2	1	.	2	1	2	2	2	2
70%RH	5.0	1.0	4.0	2.0	.	2	2	2	1	1	1	1	1	1
70%RH	4.9	1.0	2.9	2.7	.	2	2	.	1	1	1	1	.	1
70%RH	5.1	1.2	4.1	1.5	.	2	2	2	2	2	2	1	1	1
70%RH	1.6	2.1	2.6	4.0	1	1	1	1	.	.	.	.	.	.
70%RH	2.0	3.0	2.0	5.0	1	1	1	1	1	1	1	1	1	1
70%RH	2.0	3.2	3.1	3.1	2	.	1	.	1	1	1	1	1	1
70%RH	3.1	2.4	3.6	2.4	.	1	1	1	1	1	1	1	1	1
70%RH	1.6	4.8	3.5	2.2	1	1	1	1	1	1	1	1	1	1
70%RH	3.0	3.1	3.0	2.5	1	.	1	.	1	1	1	1	1	1
70%RH	4.7	0.5	2.6	3.5	1	2	2	1	2	2	2	2	2	2
70%RH	5.5	0.5	5.7	0.0	2	2	2	2	1	1	1	1	1	2
70%RH	5.5	0.5	5.5	0.5	2	2	2	2	2	2	2	1	1	2
70%RH	1.5	1.5	4.3	1.5	1	2	1	1	1	2	1	1	1	1
70%RH	5.3	1.2	3.0	2.0	1	2	2	2	1	1	1	1	1	2
80%RH	4.1	1.2	4.6	2.8	2	2	2	2	2	1	1	2	1	2
80%RH	3.8	1.0	1.8	2.8	1	1	2	2	1	1	1	1	1	1
80%RH	3.3	1.5	3.5	2.5	1	1	1	1	1	1	1	1	1	1
80%RH	4.0	3.0	4.5	2.0	2	2	2	1	2	2	2	1	1	2
80%RH	2.0	4.0	2.8	2.9	1	1	1	1	1	1	1	1	1	1
80%RH	3.5	2.3	3.8	2.2	.	1	1	1	1	1	1	1	1	1
80%RH	2.0	3.0	4.0	2.0	2	1	2	1	2	2	2	1	1	2
80%RH	4.4	2.8	3.2	2.0	1	1	1	1	1	1	1	1	1	1
80%RH	3.0	1.8	3.0	3.0	2	1	1	1	2	2	2	1	2	2
80%RH	2.5	0.5	2.5	2.8	1	1	2	.	2	2	1	1	1	1
80%RH	4.5	1.0	3.5	2.5	2	2	2	2	2	1	2	2	2	2
80%RH	5.9	0.0	1.7	4.1	2	2	2	2	2	2	1	2	2	1
80%RH	3.0	3.0	3.0	2.0	.	2	2	2	2	1	1	1	1	1
80%RH	4.6	0.8	2.2	2.1	2	2	2	2	1	1	1	2	2	1
80%RH	5.2	0.1	0.2	4.0	2	2	2	2	2	2	2	1	2	1
80%RH	2.2	4.5	1.6	4.3	1	1	1	1	1	1	1	1	1	1
80%RH	4.4	1.2	3.5	2.5	1	1	1	1	1	1	1	1	1	1
80%RH	4.9	1.1	4.2	2.1	2	2	2	2	1	1	1	2	2	1
80%RH	0.0	5.0	1.0	5.0	1	1	1	.	1	1	1	1	1	1
80%RH	5.6	1.5	4.5	1.6	2	2	2	.	1	1	2	1	2	2
80%RH	5.5	0.5	5.5	1.0	1	2	1	1	1	1	1	1	1	1

Subjective votes at 130th minute (1.2 met)

Condition	Thermal sensation	Comfort sensation	Air movement perception	Skin wettedness feeling: Whole-body	Head	Armpit	Abdomen	Leg	Foot	Humidity perception
	cold = -3	comfortable = 0	too little = -3	normal = 0	normal = 0	normal = 0	normal = 0	normal = 0	normal = 0	very humid = -3
	hot = +3	intolerable = 4	too much = +3	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	very dry = +3
50%RH	1.8	0.7	-2.0	0.5	0.5	0.5	0.5	0.5	0.5	2.3
50%RH	0.0	0.3	-0.7	0.1	0.1	0.2	0.2	0.1	0.2	-1.3
50%RH	-0.5	0.2	-0.3	0.5	0.0	0.5	0.0	0.8	1.4	0.0
50%RH	0.3	0.7	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.7
50%RH	2.5	2.0	-2.8	1.0	0.0	0.0	0.0	0.5	1.0	-1.5
50%RH	3.0	2.2	-2.0	1.2	1.0	1.0	1.0	1.0	1.2	-2.0
50%RH	2.0	1.0	0.0	2.0	1.0	2.0	2.0	2.0	2.0	-1.0
50%RH	0.4	0.5	-0.4	0.2	0.2	0.5	0.2	0.2	0.5	-0.3
50%RH	0.4	0.4	0.3	0.6	0.6	1.3	0.8	0.8	0.8	0.1
50%RH	1.5	1.3	-1.5	1.4	0.5	2.6	1.8	2.3	1.5	1.5
50%RH	1.0	1.0	1.0	2.0	1.0	2.0	1.0	1.0	2.0	-1.5
50%RH	2.2	1.3	-1.5	1.8	1.4	1.4	1.9	1.9	1.3	-1.5
50%RH	0.2	0.6	-0.5	0.2	0.3	0.2	0.2	0.2	0.2	0.0
50%RH	0.5	0.0	0.0	0.0	0.0	0.5	1.0	0.0	0.0	-0.5
50%RH	0.0	0.4	-0.5	0.5	0.5	1.0	1.5	0.0	0.6	0.0
50%RH	2.0	2.0	-1.0	2.0	1.0	2.0	2.0	1.1	0.1	0.0
50%RH	0.8	1.0	-0.4	0.9	0.9	0.9	0.9	0.9	1.6	0.4
50%RH	1.3	2.0	-2.3	.	2.0	2.0	1.5	1.5	2.0	-1.0
50%RH	2.0	1.4	-1.0	2.1	2.0	2.0	2.0	1.4	1.8	-2.0
50%RH	0.5	0.0	-0.8	0.5	0.2	0.5	0.0	0.0	0.7	-0.4
50%RH	2.5	2.6	-1.6	0.6	1.8	4.3	3.6	2.3	4.8	-1.5
60%RH	0.2	0.5	-0.5	0.4	0.0	0.2	0.0	0.1	0.5	0.1
60%RH	-0.1	0.1	0.0	0.2	0.0	0.2	0.0	0.0	0.0	0.0
60%RH	2.3	0.8	2.5	0.2	0.3	0.2	0.2	0.2	0.2	0.8
60%RH	2.0	1.0	1.0	1.6	2.0	2.0	1.2	1.2	2.0	1.0
60%RH	0.5	0.3	-1.0	0.0	0.0	1.5	0.6	0.6	2.0	1.5
60%RH	1.5	0.8	-1.5	0.5	1.1	0.4	1.0	0.0	0.5	-2.0
60%RH	1.0	0.0	-1.5	0.0	0.0	1.8	0.2	0.2	0.2	0.8
60%RH	-0.2	0.3	1.0	0.7	0.7	0.3	0.5	0.6	1.0	0.5
60%RH	2.3	4.0	-2.5	2.7	5.5	4.7	3.0	3.8	6.0	-1.3
60%RH	1.1	1.8	-3.0	2.0	1.0	2.0	2.0	2.0	3.0	-1.0
60%RH	0.2	0.2	-0.5	0.5	1.3	2.3	1.8	0.4	0.4	0.7
60%RH	1.0	0.5	-0.5	0.2	0.2	0.2	0.2	0.2	0.2	-0.2
60%RH	1.5	1.0	-2.8	0.5	0.4	0.3	0.4	0.3	0.8	-1.0
60%RH	0.5	0.6	-1.0	.	.	.	.	.	.	.
60%RH	1.8	2.5	-2.2	2.6	3.3	2.3	1.8	1.8	2.5	-2.8
60%RH	0.3	0.8	-0.5	1.2	1.2	1.4	1.4	1.0	1.4	0.5
60%RH	1.5	1.2	-1.5	2.0	2.0	1.5	1.6	2.0	2.7	-1.0
60%RH	2.1	1.8	-2.1	2.4	3.3	3.2	2.3	1.6	3.5	-2.5
60%RH	0.2	0.2	0.1	0.1	0.1	0.2	0.2	0.2	0.2	-0.3
60%RH	0.8	0.8	-1.9	1.9	1.3	2.1	1.1	1.1	1.2	-1.5
60%RH	3.0	4.0	-3.0	3.0	4.0	4.0	3.0	4.0	3.0	-3.0
60%RH	-0.3	0.5	-0.7	0.2	0.2	0.2	0.2	0.2	0.2	-0.3
70%RH	2.1	1.8	-1.0	2.1	1.6	2.5	1.8	1.3	2.0	-2.0
70%RH	1.0	0.8	-2.0	1.5	0.2	1.5	0.6	0.6	0.6	-0.2
70%RH	0.9	0.8	-1.0	1.0	0.8	0.9	1.0	1.3	0.8	-1.4
70%RH	0.0	0.0	0.0	0.2	0.2	0.2	0.3	0.3	0.3	1.2
70%RH	0.0	0.0	0.0	0.0	0.2	2.0	0.0	0.0	2.0	0.0
70%RH	2.5	2.6	-1.5	0.5	0.4	0.5	1.2	1.2	1.2	0.8
70%RH	2.0	1.0	-2.0	1.0	1.2	2.0	0.8	0.0	1.0	-2.0
70%RH	2.0	1.3	-2.5	0.3	0.8	1.8	1.5	1.4	1.8	-1.0
70%RH	2.2	2.1	-1.9	3.5	3.5	3.6	3.5	3.4	2.8	-1.8
70%RH	1.2	0.7	-0.7	1.2	1.5	1.3	1.3	1.3	1.3	-1.2
70%RH	1.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
70%RH	1.0	0.6	-0.4	1.0	1.0	2.0	4.1	0.8	0.8	-1.5
70%RH	2.2	1.8	0.0	2.0	1.6	1.4	2.1	1.2	1.2	0.0
70%RH	2.5	1.2	0.0	0.8	0.8	2.0	2.0	0.2	2.6	-0.3
70%RH	1.2	0.9	0.0	2.0	1.5	2.0	1.5	1.8	2.0	-0.7
70%RH	0.2	0.8	-2.6	0.7	1.3	1.7	0.6	0.6	0.6	0.7
70%RH	2.1	1.2	-1.2	1.7	1.7	1.7	1.8	1.8	2.3	2.5
70%RH	0.6	1.3	-1.5	1.4	1.5	2.5	1.4	1.4	3.5	-0.8
70%RH	0.5	0.5	-1.5	2.6	3.4	2.5	3.4	2.4	3.7	-1.6
70%RH	0.0	0.8	-0.8	1.3	0.6	1.4	1.3	1.0	1.5	0.4
80%RH	2.2	0.3	-1.6	2.5	2.8	2.3	2.3	2.3	3.3	-0.2
80%RH	0.7	0.4	-1.4	0.3	0.2	0.6	0.2	2.0	0.0	-1.5
80%RH	0.8	0.8	-0.5	0.3	0.4	0.5	0.5	0.5	0.5	-0.2
80%RH	1.2	1.0	-0.6	1.5	0.7	2.8	0.5	1.5	2.0	0.0
80%RH	3.0	1.0	0.0	4.0	4.0	3.0	2.0	2.0	1.9	0.0
80%RH	1.5	2.0	-1.5	2.0	2.0	2.0	1.0	2.0	2.0	-1.5
80%RH	3.0	2.0	-2.0	3.0	3.0	4.0	3.0	3.0	4.0	-2.0
80%RH	1.8	1.5	-2.2	1.3	0.5	0.5	0.8	1.2	1.3	-1.2
80%RH	1.8	1.0	-0.8	1.5	1.0	2.0	1.5	2.0	2.0	0.0
80%RH	1.1	1.1	-2.0	0.5	0.5	0.2	0.2	0.5	0.4	-1.2
80%RH	1.0	1.7	-0.5	1.8	1.0	1.8	1.8	1.2	1.6	-1.0
80%RH	0.9	1.0	-0.5	3.7	4.2	0.3	0.8	1.3	0.5	-2.5
80%RH	1.0	0.7	-0.3	0.5	0.2	0.1	0.1	0.1	0.1	-0.5
80%RH	-0.2	0.2	0.8	1.4	2.2	2.8	1.2	0.5	0.0	0.1
80%RH	1.8	1.5	-3.0	1.6	0.5	0.6	0.5	0.4	0.5	-1.4
80%RH	0.8	0.2	0.5	1.2	0.3	1.2	0.3	1.3	0.2	0.5
80%RH	1.8	1.2	-1.8	1.8	2.2	1.7	1.5	1.9	2.7	-1.6
80%RH	2.3	1.5	-1.3	2.2	1.4	2.5	1.9	2.6	1.8	-2.5
80%RH	0.0	0.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.2	0.5
80%RH	1.8	1.8	-2.3	1.2	1.1	1.4	1.4	1.3	1.2	2.4
80%RH	1.5	1.8	-2.0	2.2	2.1	2.4	2.2	1.8	1.4	-2.0

Subjective votes at 130th minute (1.2 met, cont.)

Condition	Freshness	Stuffiness	Alertness	Fatigue	Thermal acceptability	Air movement acceptability	Humidity perception acceptability	Air quality acceptability	Skin wettedness acceptability Whole-body	Head	Armpit	Abdomen	Leg	Foot
	fresh = 0 stale = 6	stuffy = 0 not stuffy = 6	very alert = 0 very sleepy = 6	very fatig. = 0 very energ. = 6	yes = 1 no = 2	yes = 1 no = 2	yes = 1 no = 2	yes = 1 no = 2	yes = 1 no = 2	yes = 1 no = 2	yes = 1 no = 2	yes = 1 no = 2	yes = 1 no = 2	yes = 1 no = 2
50%RH	4.0	4.0	4.5	4.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.0	3.2	3.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	0.2	5.5	1.0	4.2	1	1	1	1	1	1	1	1	1	2
50%RH	3.5	2.2	3.0	3.0	.	.	1	1	1	1	1	1	1	1
50%RH	5.0	1.0	1.0	4.5	1	2	1	2	1	1	1	1	1	1
50%RH	6.0	1.0	4.0	4.0	1	1	1	1	.	.	.	.	.	.
50%RH	3.0	3.0	3.0	3.0	.	1	1	1	1	1	2	2	2	2
50%RH	2.5	4.5	3.6	3.2	1	1	1	1	1	1	1	1	1	1
50%RH	1.5	4.5	1.5	4.5	1	1	1	1	1	1	1	1	1	1
50%RH	5.0	1.0	3.2	2.0	1	.	1	.	1	1	1	1	1	1
50%RH	4.0	1.0	4.5	1.3	1	1	1	1	1	1	1	1	1	1
50%RH	2.5	3.0	3.0	3.0	2	2	2	2	2	2	2	2	2	2
50%RH	2.0	4.7	1.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.0	3.0	5.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.0	3.0	1.5	3.0	1	.	1	1	1	1	1	2	1	1
50%RH	1.1	5.0	4.0	3.0	1	1	.	1	1	1	1	1	1	1
50%RH	2.0	4.0	2.0	4.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.2	0.6	5.2	0.7	2	2	1	2	2	2	2	2	1	2
50%RH	4.0	2.0	2.0	2.0	2	1	1	1	2	1	1	1	1	1
50%RH	3.3	3.0	3.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	2.6	1.5	4.1	0.5	2	2	1	2	1	1	2	2	1	2
60%RH	2.5	3.0	2.1	3.1	1	1	1	1	1	1	1	1	1	1
60%RH	1.5	4.5	1.5	5.0	1	1	1	1	1	1	1	1	1	1
60%RH	5.5	1.5	5.1	0.8	2	2	1	.	1	1	1	1	1	1
60%RH	3.0	2.0	2.0	3.0	2	1	2	2	2	2	2	2	2	2
60%RH	4.0	3.5	3.0	2.0	1	1	1	1	1	1	1	1	1	1
60%RH	3.0	2.0	2.0	3.0	1	1	1	1	1	1	1	1	1	1
60%RH	3.0	1.2	3.0	3.0	1	1	1	1	1	1	1	1	1	1
60%RH	2.0	3.4	2.2	3.8	1	1	1	1	1	1	1	1	1	1
60%RH	5.5	0.6	4.0	4.2	2	2	2	2	1	2	1	1	2	2
60%RH	6.0	0.0	5.0	0.0	2	2	2	2	2	2	2	2	2	2
60%RH	1.8	3.2	1.3	4.5	1	1	1	.	1	1	1	1	1	1
60%RH	3.5	2.8	3.0	3.0	1	1	1	1	1	1	1	1	1	1
60%RH	4.0	1.0	3.0	0.5	1	1	1	1	1	1	1	1	1	1
60%RH	.	.	.	.	.	1	.	.	.	.	.	.	.	.
60%RH	5.0	1.0	5.0	1.0	2	2	2	2	2	2	1	1	2	2
60%RH	3.7	1.5	3.2	3.0	1	1	1	1	1	1	1	1	1	1
60%RH	4.6	0.8	4.5	1.5	2	2	1	.	2	2	1	1	2	2
60%RH	4.9	0.5	4.8	0.9	2	2	2	2	2	2	2	1	1	1
60%RH	0.6	4.5	4.6	2.3	1	1	1	1	1	1	1	1	1	1
60%RH	5.0	1.0	3.6	2.0	1	2	1	2	1	1	1	1	1	1
60%RH	5.9	0.0	6.0	1.0	.	2	2	2	2	2	2	2	2	2
60%RH	0.5	4.0	1.6	4.5	1	1	1	.	1	1	1	1	1	1
70%RH	3.8	1.0	4.0	1.5	2	2	2	2	2	2	2	2	2	2
70%RH	4.5	3.0	3.5	2.0	.	1	1	.	1	1	1	1	1	1
70%RH	3.5	1.0	3.0	3.8	2	2	2	2	1	1	1	1	1	1
70%RH	2.3	3.3	4.5	1.5	1	1	1	1	1	1	1	1	1	1
70%RH	1.0	3.0	0.5	4.0	1	1	1	1	1	1	2	1	1	2
70%RH	5.0	2.5	4.5	3.0	2	2	1	2	2	2	2	2	2	2
70%RH	5.0	1.0	4.0	2.0	.	2	2	2	1	1	1	1	1	1
70%RH	4.9	0.8	2.9	2.9	.	1	1	.	1	1	1	1	1	2
70%RH	5.6	1.1	4.5	1.1	.	2	2	2	2	2	2	1	1	1
70%RH	3.6	1.8	3.0	3.4	1	1	1	1	1	1	1	1	1	1
70%RH	2.0	3.0	2.0	4.0	1	1	1	1	1	1	1	1	1	1
70%RH	3.4	2.7	3.4	2.5	1	1	1	.	1	1	1	1	1	1
70%RH	2.8	3.8	3.1	3.2	1	1	1	1	1	1	1	1	1	1
70%RH	1.5	4.5	2.3	3.5	.	.	1	.	1	1	1	1	1	1
70%RH	2.1	2.9	2.9	2.2	1	1	1	1	1	1	1	1	1	1
70%RH	2.3	2.5	1.3	4.3	1	2	1	1	1	1	1	1	1	1
70%RH	5.5	0.5	5.5	0.2	1	1	2	2	1	1	1	1	1	2
70%RH	3.5	1.5	4.5	1.5	1	2	1	2	1	1	1	1	1	2
70%RH	4.5	1.5	4.2	3.3	1	1	1	1	1	2	1	1	1	2
70%RH	3.5	3.3	4.3	2.3	1	2	1	2	1	1	1	1	1	1
80%RH	2.4	1.8	4.5	2.5	1	2	2	1	1	1	1	1	1	2
80%RH	4.0	2.0	4.0	3.0	1	1	1	2	1	1	1	1	1	1
80%RH	2.5	1.5	4.5	1.8	1	1	1	.	1	1	1	1	1	1
80%RH	3.0	3.0	2.5	4.0	1	1	1	1	2	1	2	1	1	2
80%RH	3.0	5.0	3.0	3.0	1	1	1	1	1	1	1	1	1	1
80%RH	4.0	2.0	4.0	2.0	.	2	2	2	2	2	2	1	2	2
80%RH	4.0	1.0	3.0	2.0	2	2	2	2	2	2	2	2	2	2
80%RH	4.8	0.8	3.2	2.0	1	1	1	1	1	1	1	1	1	1
80%RH	3.2	1.6	3.2	3.0	1	1	1	1	2	2	2	1	2	2
80%RH	5.2	2.5	2.8	2.5	1	2	2	2	1	1	1	1	1	1
80%RH	3.3	1.6	2.5	3.5	2	2	2	2	2	1	2	2	2	2
80%RH	5.0	0.5	1.5	4.0	1	1	2	2	2	1	1	1	2	1
80%RH	3.0	3.0	3.0	3.0	2	2	2	.	2	1	1	1	1	2
80%RH	1.3	3.6	2.5	4.0	1	1	1	1	1	1	2	1	1	1
80%RH	5.0	0.2	0.3	4.2	2	2	2	2	2	1	1	1	1	1
80%RH	1.5	3.6	0.0	5.0	1	.	1	1	1	1	1	1	1	1
80%RH	4.5	0.8	3.6	1.5	1	2	1	1	1	1	1	1	1	1
80%RH	4.3	1.8	3.0	3.0	1	2	2	1	1	1	1	1	2	1
80%RH	2.0	3.0	3.0	3.0	1	1	1	1	1	1	1	1	1	1
80%RH	5.0	1.2	5.0	1.3	.	2	2	.	2	2	2	2	2	2
80%RH	5.0	1.0	5.0	3.0	1	2	1	1	1	1	1	1	1	1

Subjective votes at 132nd minute (right after exertion)

			Air movement	Skin wettedness feeling						
	Thermal sensation	Comfort sensation	perception	Whole-body	Head	Armpit	Abdomen	Leg	Foot	Humidity perception
	cold = -3	comfortable = 0	too little = -3	normal = 0	normal = 0	normal = 0	normal = 0	normal = 0	normal = 0	very humid = -3
Condition	hot = +3	intolerable = 4	too much = +3	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	very dry = +3
50%RH	2.0	1.0	-2.0	1.0	0.4	0.5	0.3	0.3	0.6	2.4
50%RH	1.4	0.5	-1.2	0.5	0.2	0.5	0.1	0.3	0.3	-1.5
50%RH	1.5	1.0	0.2	1.5	0.2	1.0	1.6	1.5	2.3	-0.1
50%RH	2.0	1.0	-1.0	0.6	1.1	0.6	0.6	0.6	1.4	-0.7
50%RH	2.5	2.5	-2.0	1.4	0.2	0.4	0.5	0.2	1.0	-1.5
50%RH	3.0	2.0	-3.0	1.0	1.0	1.0	1.0	1.0	1.0	-2.0
50%RH	2.1	2.0	0.0	4.0	1.0	4.0	4.0	4.0	4.0	-1.0
50%RH	2.3	1.3	-1.5	0.8	1.5	1.8	0.2	0.2	1.8	-1.2
50%RH	2.5	2.3	-1.3	2.8	3.7	3.7	2.7	3.7	3.7	-1.4
50%RH	2.6	2.0	-1.5	3.3	2.6	4.5	4.5	4.6	4.7	1.5
50%RH	2.0	2.5	1.0	2.0	2.0	2.5	2.0	2.5	3.0	-2.0
50%RH	2.9	1.8	-2.0	3.6	3.6	4.0	4.0	4.1	4.1	1.8
50%RH	2.5	0.7	-0.5	2.0	2.0	2.0	1.5	2.0	1.3	0.0
50%RH	2.0	0.5	0.0	0.0	0.0	0.6	1.6	0.0	0.0	-0.6
50%RH	2.0	0.5	0.0	0.5	0.5	1.7	1.0	1.6	0.9	0.0
50%RH	2.5	1.0	1.0	3.0	4.0	5.0	4.0	2.0	1.0	-0.1
50%RH	1.3	1.5	-0.5	2.4	2.0	2.1	2.1	2.1	3.8	-1.0
50%RH	2.3	2.5	-2.5	3.0	3.2	3.6	3.3	2.6	3.8	-1.2
50%RH	2.3	1.7	-2.0	2.0	2.6	2.8	2.2	1.7	2.9	-2.2
50%RH	1.4	0.6	-1.2	0.6	0.0	0.9	1.0	0.6	1.0	-1.0
50%RH	2.5	0.6	1.8	4.7	2.0	4.3	4.3	4.4	5.3	-2.7
60%RH	0.7	0.5	-0.8	0.7	0.2	0.7	0.8	0.8	1.0	-0.2
60%RH	1.0	0.2	-0.4	0.7	0.0	0.0	0.0	0.0	1.2	-0.8
60%RH	3.0	2.4	-2.8	1.8	1.9	2.7	1.2	0.3	2.6	-0.3
60%RH	2.3	2.6	-2.0	2.2	2.2	2.5	2.6	2.7	3.7	2.2
60%RH	1.0	0.5	-1.7	0.8	0.8	0.8	0.8	0.8	3.2	1.5
60%RH	2.0	1.0	-1.0	1.4	1.1	1.8	3.0	0.5	0.0	-2.0
60%RH	2.9	2.5	-3.0	3.0	4.0	4.0	0.0	1.0	4.0	-1.0
60%RH	1.0	1.2	-1.0	1.0	1.0	0.7	0.8	0.5	1.2	-0.4
60%RH	2.6	4.4	-3.0	3.4	5.3	3.8	3.0	4.1	6.0	-2.0
60%RH	3.0	3.0	-3.0	4.0	3.0	4.0	4.0	3.0	4.0	-3.0
60%RH	1.6	0.8	-2.0	2.8	1.5	2.4	2.4	1.6	3.4	-1.7
60%RH	1.0	1.0	-1.0	0.2	0.2	1.0	0.2	0.2	0.2	-1.0
60%RH	2.0	1.1	-2.8	0.3	0.2	1.0	0.3	0.2	2.5	-1.0
60%RH	2.0	1.3	-1.5	2.0	2.0	1.7	1.7	2.0	2.0	-1.5
60%RH	2.6	4.0	-2.5	3.0	3.8	2.5	2.6	1.7	3.5	-2.5
60%RH	2.5	0.5	1.0	1.6	1.7	1.7	1.5	1.8	1.0	-0.3
60%RH	2.5	2.5	-2.4	3.0	3.9	3.5	3.0	4.0	3.8	-1.5
60%RH	2.5	2.2	-2.0	3.4	3.7	3.8	3.2	2.3	3.2	-2.5
60%RH	2.5	1.5	-1.3	1.7	0.2	1.2	0.6	1.2	1.3	-1.8
60%RH	2.1	1.5	-3.0	2.5	2.0	3.0	2.0	2.5	2.2	-1.5
60%RH	3.0	4.0	-3.0	5.0	5.0	5.0	4.0	5.0	4.0	-3.0
60%RH	2.3	1.1	-1.3	1.2	0.8	1.8	1.8	1.5	1.7	-0.5
70%RH	1.8	1.7	-1.1	2.0	0.8	0.7	0.8	0.7	0.7	-2.0
70%RH	2.0	1.5	-1.5	2.5	0.3	1.7	0.6	0.6	1.8	-0.7
70%RH	1.8	1.8	-2.0	1.4	1.5	1.4	1.7	1.7	1.3	-1.3
70%RH	0.7	0.3	-0.4	0.2	0.2	0.8	0.8	0.2	0.3	0.4
70%RH	2.9	-1.0	1.0	1.0	2.0	3.0	1.0	0.0	1.9	1.0
70%RH	2.4	2.1	-1.2	0.8	0.7	0.8	0.8	0.8	0.7	0.0
70%RH	3.0	2.0	-2.2	2.0	1.0	2.0	2.0	1.9	2.0	-2.1
70%RH	2.3	2.4	-2.8	2.0	2.2	3.0	2.2	2.1	3.0	-2.0
70%RH	2.5	2.8	-2.5	4.9	4.1	4.5	3.8	3.5	3.7	-2.4
70%RH	1.9	0.5	-0.5	1.6	1.6	1.5	1.3	1.5	1.5	-1.8
70%RH	2.0	0.0	1.0	1.0	.	1.0	1.0	1.0	1.0	0.0
70%RH	2.0	1.0	0.3	1.0	1.0	2.5	1.5	2.0	1.5	-1.5
70%RH	2.8	1.9	-1.0	3.0	2.0	2.5	2.8	1.4	1.1	-1.0
70%RH	2.7	2.0	-2.0	1.2	0.4	2.2	1.9	2.3	2.0	0.0
70%RH	2.0	1.4	0.0	1.5	2.1	2.6	2.2	2.7	3.0	0.0
70%RH	2.3	1.7	-1.5	2.3	3.6	3.5	2.8	1.8	3.4	1.4
70%RH	2.5	2.0	-2.6	1.8	1.8	1.8	1.8	1.8	2.5	2.7
70%RH	1.6	1.5	-1.5	2.5	1.7	1.7	1.7	1.7	4.3	-2.5
70%RH	2.5	2.5	-2.3	3.5	2.7	1.8	3.7	1.6	3.6	0.5
70%RH	2.2	2.0	-0.2	2.0	0.8	1.7	1.7	1.5	2.2	0.4
80%RH	2.2	2.4	-1.6	4.2	3.2	3.2	2.7	3.2	4.3	-1.3
80%RH	2.3	0.9	-1.8	1.8	2.1	1.7	0.5	2.9	0.2	-2.2
80%RH	1.3	1.4	-1.4	0.8	0.9	0.8	0.7	0.7	1.3	-0.9
80%RH	2.0	2.0	-1.5	3.2	2.2	2.2	1.0	1.0	3.2	-0.5
80%RH	3.0	0.5	0.0	5.0	4.0	2.0	2.0	2.0	1.9	0.0
80%RH	2.0	3.0	-2.0	2.5	2.0	2.0	1.5	2.5	2.5	-2.0
80%RH	3.0	3.0	-3.0	4.0	3.0	4.0	3.0	3.0	4.0	-2.0
80%RH	2.4	1.5	-2.5	1.3	0.8	0.9	1.3	1.2	1.8	1.2
80%RH	2.0	1.0	-0.5	1.8	1.6	2.0	1.5	1.8	1.8	0.0
80%RH	2.0	2.0	-2.2	2.2	3.8	0.6	0.5	1.5	0.5	-1.8
80%RH	2.3	1.5	-2.0	4.0	1.5	3.8	4.0	2.3	3.0	-1.2
80%RH	2.3	2.6	-1.6	5.3	5.6	1.5	1.8	3.2	0.6	-2.8
80%RH	2.0	0.5	-0.5	1.0	0.3	0.3	0.3	0.3	0.8	-0.6
80%RH	2.1	0.6	-0.8	2.1	4.0	2.1	1.5	0.8	0.2	-2.0
80%RH	2.0	2.0	-3.0	2.2	1.6	0.8	0.6	0.6	0.6	-2.0
80%RH	2.5	0.3	-1.5	1.8	1.2	2.8	1.2	2.5	1.2	-0.3
80%RH	2.3	2.0	-2.6	2.3	2.7	3.2	2.7	3.4	3.7	-2.2
80%RH	2.8	2.5	-3.0	3.0	1.8	3.0	3.6	3.5	2.7	-3.0
80%RH	1.5	1.0	-2.0	1.0	1.0	0.0	0.5	1.0	1.6	-1.0
80%RH	1.4	0.7	-2.3	1.6	1.5	1.5	1.5	1.4	1.5	1.7
80%RH	1.8	1.8	-2.6	2.0	2.4	2.5	2.3	1.7	1.5	-2.2

Subjective votes at 132nd minute (right after exertion, cont.)

					Thermal	Air movement	Humidity perception	Air quality	Skin wettedness acceptability					
	Freshness	Stuffiness	Alertness	Fatigue	acceptability	acceptability	acceptability	acceptability	Whole-body	Head	Armpit	Abdomen	Leg	Foot
	fresh = 0	stuffy = 0	very alert = 0	very fatig. = 0	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1
Condition	stale = 6	not stuffy = 6	very sleepy = 6	very energ. = 6	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2
50%RH	4.6	4.5	4.2	4.8	.	1	1	1	1	1	1	1	1	1
50%RH	4.0	2.0	1.5	4.0	.	1	1	1	1	1	1	1	1	1
50%RH	0.5	5.5	1.0	4.8	1	1	1	1	2	1	1	2	2	2
50%RH	3.5	2.5	2.9	2.9	1	1	1	.	1	1	1	1	1	1
50%RH	5.0	0.5	0.7	3.5	1	1	1	2	1	1	1	1	1	1
50%RH	5.8	0.0	4.0	2.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.0	3.0	3.0	3.0	2	1	1	1	2	1	2	2	2	2
50%RH	-0.5	-0.5	0.5	-0.5	1	1	1	1	1	1	2	1	1	2
50%RH	4.1	1.6	2.1	3.8	2	2	2	2	2	2	2	2	2	2
50%RH	5.0	1.0	2.0	4.0	1	1	1	2	2	1	2	2	2	2
50%RH	4.0	1.0	4.0	2.0	1	1	1	1	1	1	1	1	1	1
50%RH	4.6	1.2	2.5	4.3	.	2	2	2	2	2	2	2	2	2
50%RH	2.1	4.0	1.0	4.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.0	3.0	5.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	1.0	3.0	1.0	4.0	1	.	1	1	1	1	2	1	2	1
50%RH	1.0	6.0	1.0	5.0	1	1	1	1	1	1	1	1	1	1
50%RH	2.0	4.3	2.0	4.0	1	1	1	2	1	2	2	1	1	2
50%RH	5.6	0.5	3.5	0.5	2	2	2	2	2	2	2	2	2	2
50%RH	4.5	2.3	2.0	5.0	1	2	2	1	2	2	1	1	1	1
50%RH	3.1	3.0	3.0	4.1	1	2	1	1	1	1	1	1	1	1
50%RH	5.7	0.4	0.2	5.7	2	2	2	2	2	1	2	2	2	2
60%RH	3.1	2.7	2.3	3.5	1	1	1	1	1	1	1	1	1	1
60%RH	3.5	3.3	2.7	1.9	1	1	1	1	1	1	1	1	1	1
60%RH	5.7	0.1	4.5	3.6	2	2	1	2	2	2	2	1	1	2
60%RH	4.2	1.0	3.9	3.4	2	2	2	2	2	2	2	2	2	2
60%RH	4.0	2.0	2.0	4.0	1	1	1	2	1	1	1	1	1	2
60%RH	4.4	1.0	3.5	2.0	2	2	.	2	1	1	1	2	1	1
60%RH	6.0	0.0	1.5	3.0	2	2	2	2	2	2	2	1	1	2
60%RH	3.5	2.0	2.2	2.2	1	1	1	1	1	1	1	1	1	1
60%RH	5.0	1.0	4.0	3.0	2	2	2	.	2	2	2	1	2	2
60%RH	6.0	0.0	3.0	2.0	.	2	2	2	2	2	2	2	2	2
60%RH	4.5	2.1	2.2	3.5	2	2	2	1	1	1	1	1	1	1
60%RH	2.5	2.3	3.0	3.0	1	1	1	1	1	1	1	1	1	1
60%RH	5.0	1.0	3.0	4.0	.	1	1	1	1	1	1	1	1	1
60%RH	2.5	2.5	2.0	.	.	2	2	.	2	2	2	2	2	2
60%RH	5.5	0.5	5.0	1.0	2	2	2	2	2	2	1	2	2	2
60%RH	4.0	1.0	3.0	3.0	1	1.5	1	2	2	2	2	2	1	2
60%RH	4.4	0.6	3.3	1.1	2	2	2	.	2	2	2	1	2	2
60%RH	5.2	0.6	3.2	3.1	2	2	2	2	2	2	2	1	1	1
60%RH	4.6	0.6	1.5	3.5	2	2	.	2	1	1	1	1	1	1
60%RH	4.2	2.0	1.5	1.3	2	2	2	2	2	1	2	2	2	1
60%RH	6.0	0.0	4.0	2.0	.	2	2	2	2	2	2	2	2	2
60%RH	1.6	3.5	1.3	1.1	2	2	1	2	1	1	1	1	1	1
70%RH	3.8	0.1	4.0	1.0	2	2	2	2	2	2	2	2	2	2
70%RH	3.5	1.5	0.7	3.4	.	1	1	.	1	1	1	1	1	2
70%RH	2.4	2.9	2.0	3.5	2	2	2	2	2	2	2	2	2	1
70%RH	3.9	3.4	3.5	2.4	1	1	1	1	1	1	1	1	1	1
70%RH	1.0	4.0	1.0	5.0	1	1	1	1	1	1	2	1	1	2
70%RH	3.6	2.9	4.3	0.5	2	.	1	2	2	2	2	2	2	2
70%RH	6.0	0.0	3.8	1.1	.	2	2	2	2	2	1	2	1	2
70%RH	5.9	0.0	1.9	3.9	.	2	2	2	2	2	2	1	1	2
70%RH	5.8	0.0	5.0	1.0	.	2	2	2	2	2	2	2	1	1
70%RH	3.2	2.4	2.8	3.1	1	1	1	1	1	1	1	1	1	1
70%RH	2.0	4.0	2.0	4.0	1	.	1	1	1	1	1	1	1	1
70%RH	3.0	3.3	2.0	2.9	1	.	1	1	1	1	1	1	1	1
70%RH	3.9	2.1	1.9	5.0	.	1	1	1	1	1	1	1	1	1
70%RH	2.3	3.5	3.5	2.6	1	1	1	.	1	1	1	1	1	1
70%RH	3.0	3.8	1.2	4.0	2	1	1	1	1	1	1	1	1	1
70%RH	5.5	0.8	2.6	2.8	2	2	2	2	2	2	2	2	2	2
70%RH	5.7	0.5	5.5	0.5	2	2	2	2	1	1	1	1	1	2
70%RH	4.5	1.5	4.5	1.5	1	2	2	2	1	1	1	1	1	2
70%RH	4.5	1.5	1.5	2.5	2	2	1	2	2	2	1	2	1	2
70%RH	4.4	2.0	2.0	3.0	2	1	1	2	2	2	2	2	2	2
80%RH	4.5	1.7	4.3	3.4	2	2	2	2	2	2	2	1	2	2
80%RH	4.7	0.7	0.9	2.9	1	2	2	2	2	1	1	1	2	1
80%RH	3.2	2.2	3.2	2.4	1	1	1	.	1	1	1	1	1	1
80%RH	4.0	2.3	3.5	2.0	2	2	1	2	2	2	2	1	2	2
80%RH	3.8	2.0	3.0	3.0	1	1	1	1	2	1	1	1	1	1
80%RH	5.0	0.8	5.0	1.0	.	2	2	2	2	2	2	1	2	2
80%RH	4.0	1.0	3.0	2.0	2	2	2	2	2	2	2	2	2	2
80%RH	5.2	1.0	1.5	4.0	1	1	1	1	1	1	1	1	1	1
80%RH	1.5	2.5	3.5	4.2	2	1	1	1	2	2	2	2	2	2
80%RH	5.0	2.0	2.5	3.0	2	2	2	2	2	2	2	1	2	1
80%RH	4.0	2.0	3.0	2.5	2	2	2	2	2	1	2	2	2	2
80%RH	4.3	2.2	1.2	4.0	2	2	2	2	2	2	2	2	2	1
80%RH	3.0	3.0	3.0	3.0	2	2	2	2	2	1	1	1	1	2
80%RH	4.5	1.5	1.5	2.0	1	2	2	2	1	1	1	1	1	1
80%RH	5.5	0.1	0.2	4.5	2	2	2	2	2	2	2	1	1	1
80%RH	0.1	5.0	0.5	5.5	2	2	1	1	2	1	2	1	2	2
80%RH	5.2	0.6	2.3	3.2	2	2	2	1	2	2	2	1	2	2
80%RH	6.0	0.5	1.0	1.9	2	2	2	1	2	1	1	2	2	2
80%RH	4.0	2.0	4.0	2.0	1	2	1	2	2	1	1	1	1	2
80%RH	5.5	0.5	4.6	0.8	2	2	2	.	2	2	2	2	2	2
80%RH	5.5	0.5	4.5	3.5	1	2	1	.	1	1	1	1	1	1

Subjective votes 5 minutes after exertion

			Air movement	Skin wettedness feeling						
	Thermal sensation	Comfort sensation	perception	Whole-body	Head	Armpit	Abdomen	Leg	Foot	Humidity perception
	cold = -3	comfortable = 0	too little = -3	normal = 0	normal = 0	normal = 0	normal = 0	normal = 0	normal = 0	very humid = -3
Condition	hot = +3	intolerable = 4	too much = +3	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	very dry = +3
50%RH	1.6	1.0	-2.0	0.6	0.2	0.5	0.2	0.3	0.5	1.8
50%RH	0.8	0.5	0.0	0.2	0.2	0.2	0.2	0.2	0.2	-1.8
50%RH	0.5	0.2	0.0	0.5	0.2	0.5	0.5	1.0	1.3	0.8
50%RH	0.8	0.8	-0.8	0.3	0.6	0.6	0.4	0.4	0.9	-0.5
50%RH	1.5	1.0	5.0	0.5	0.2	0.3	0.3	0.4	0.8	-1.5
50%RH	3.0	2.1	-3.0	1.0	1.0	1.0	1.0	1.0	1.0	-2.0
50%RH	2.0	2.0	-1.0	4.0	1.0	4.0	4.0	4.0	4.0	0.0
50%RH	0.5	0.4	-0.4	0.2	0.2	0.6	0.2	0.2	0.8	0.2
50%RH	-0.6	0.3	0.0	0.7	0.7	1.2	0.7	0.7	0.7	0.2
50%RH	2.0	1.0	-1.5	3.0	2.0	2.7	3.5	3.5	3.6	2.3
50%RH	1.5	1.5	1.0	1.8	1.0	2.0	1.6	1.0	2.0	-2.0
50%RH	2.3	1.4	-1.5	1.8	1.8	1.8	1.8	2.5	5.8	-0.5
50%RH	1.0	1.0	-0.3	0.5	1.0	0.5	0.6	0.7	0.7	0.0
50%RH	1.0	0.0	-0.1	0.0	0.0	0.0	1.0	0.0	0.0	0.0
50%RH	1.0	0.5	-1.0	0.8	0.5	1.5	1.4	0.5	0.5	-0.5
50%RH	-1.0	1.0	1.0	4.0	5.0	5.0	4.0	2.0	1.0	1.2
50%RH	0.2	0.5	-1.0	0.5	1.2	1.1	0.4	0.5	1.8	1.0
50%RH	2.9	3.1	-2.5	3.7	4.2	3.8	3.8	3.8	4.9	-1.2
50%RH	2.3	1.0	-1.5	1.4	1.9	2.1	0.3	1.2	1.8	1.6
50%RH	0.7	0.2	-0.5	0.1	0.4	0.0	0.1	0.1	0.0	-1.0
50%RH	2.4	2.4	2.5	3.7	2.4	4.3		3.6	5.7	-2.4
60%RH	0.0	0.2	-0.6	0.1	0.2	0.3	0.3	0.2	0.9	-0.2
60%RH	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
60%RH	2.0	1.0	-1.4	0.2	0.8	0.8	0.1	0.1	0.9	0.0
60%RH	2.5	2.8	-1.9	4.2	3.9	4.0	4.3	4.1	5.2	2.5
60%RH	1.5	0.6	-1.0	0.7	0.7	1.6	1.5	1.0	3.0	1.5
60%RH	1.3	0.3	-1.8	0.8	0.5	1.0	2.5	0.5	0.2	-1.3
60%RH	2.0	1.0	-1.9	2.0	2.0	2.0	0.7	0.3	0.3	-0.7
60%RH	1.3	1.3	-1.0	1.0	1.3	0.8	1.0	0.7	1.0	-0.4
60%RH	1.3	1.5	-2.8	2.5	5.8	3.5	2.3	3.3	6.0	-0.3
60%RH	1.0	2.0	-3.0	4.0	4.0	4.0	4.0	4.0	5.0	-2.0
60%RH	0.5	0.3	-0.5	0.7	1.5	2.2	1.6	0.5	2.2	-0.2
60%RH	-0.3	0.2	-0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
60%RH	2.5	0.5	-1.0	1.0	0.2	0.3	0.2	0.2	1.2	.
60%RH	1.8	1.2	-1.3	1.7	1.7	1.3	1.3	1.7	1.6	-1.3
60%RH	2.5	4.0	-2.5	3.0	3.7	2.8	2.3	2.5	3.5	-2.5
60%RH	1.8	1.5	-0.5	1.3	1.3	1.3	1.2	1.3	1.1	0.3
60%RH	1.5	0.5	-2.5	2.9	3.4	3.3	2.7	2.6	3.5	-1.5
60%RH	1.7	1.2	-1.0	1.8	2.3	3.2	2.2	1.6	2.5	-2.5
60%RH	2.2	1.0	0.6	0.5	0.5	0.5	0.6	0.8	0.8	-2.1
60%RH	1.2	0.8	-1.1	1.9	1.8	2.7	1.4	1.5	1.3	-0.9
60%RH	2.0	2.0	-3.0	3.1	4.0	4.0	4.0	4.0	3.0	-3.0
60%RH	2.2	1.0	-1.5	0.2	0.2	0.2	0.2	0.2	0.1	-0.8
70%RH	0.8	0.8	-1.0	1.9	1.0	1.8	2.0	1.9	1.5	-2.1
70%RH	-0.8	0.0	0.0	0.3	0.3	1.3	0.4	0.3	0.2	0.0
70%RH	0.8	0.9	-0.5	0.5	0.9	0.7	0.8	0.6	0.6	-1.2
70%RH	-0.1	0.1	-0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.8
70%RH	2.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	1.0
70%RH	1.0	1.0	-1.6	0.2	0.0	0.2	0.7	0.7	0.7	0.9
70%RH	2.9	1.2	-2.1	1.0	1.1	1.8	1.0	0.9	2.0	-2.1
70%RH	2.8	2.5	-2.5	2.0	2.0	2.3	1.9	1.6	2.9	-1.0
70%RH	2.3	2.7	-2.8	4.3	4.3	4.8	4.2	3.9	3.4	-2.3
70%RH	0.8	0.5	-0.5	1.2	1.3	1.3	1.4	1.2	1.2	-1.3
70%RH	2.0	0.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
70%RH	2.5	2.0	-0.9	0.9	0.4	1.0	1.0	1.0	0.3	-2.5
70%RH	1.2	1.2	-0.8	1.2	1.2	0.8	1.2	0.7	0.6	1.1
70%RH	0.2	0.3	-1.0	0.5	0.2	1.2	1.6	1.9	1.5	-0.8
70%RH	2.2	0.9	0.0	1.6	1.2	1.7	1.4	1.5	1.5	-0.3
70%RH	2.3	1.7	-1.5	2.5	3.3	2.3	2.3	1.8	2.5	-1.7
70%RH	2.5	0.8	-1.3	1.8	1.8	1.8	1.8	1.8	2.3	2.7
70%RH	1.5	1.4	-2.3	2.7	2.5	2.5	1.8	1.8	3.6	-2.5
70%RH	1.4	1.5	-1.6	3.3	2.8	3.7	3.8	2.2	3.8	-0.6
70%RH	0.6	0.6	-0.3	0.9	0.8	1.0	0.8	1.0	1.5	0.5
80%RH	0.9	0.8	0.2	3.7	3.2	3.2	2.8	2.8	3.2	-0.5
80%RH	2.0	1.0	-2.0	1.8	2.1	1.6	1.9	3.1	0.5	-2.0
80%RH	0.2	0.8	-0.8	0.5	0.5	0.3	0.5	0.6	0.8	-0.5
80%RH	1.6	1.2	-1.5	2.2	2.0	3.0	1.8	0.6	2.0	-1.5
80%RH	2.0	1.0	0.0	4.0	3.0	2.0	2.0	2.0	2.0	0.0
80%RH	-1.0	1.0	-0.5	1.0	1.0	1.0	1.0	2.0	2.0	-0.5
80%RH	1.0	1.0	-2.0	2.0	2.0	3.0	3.0	1.0	2.0	0.0
80%RH	0.5	0.8	0.8	0.8	0.3	0.8	0.6	1.0	1.2	-0.2
80%RH	1.0	1.0	-0.2	1.0	0.8	1.8	1.8	1.8	1.8	0.0
80%RH	0.2	0.8	0.0	1.5	1.6	0.2	0.5	0.8	0.2	-1.8
80%RH	1.0	1.0	-1.5	1.8	0.7	1.3	1.8	1.2	2.0	-1.3
80%RH	2.2	3.5	-2.5	5.6	5.7	2.4	2.8	3.3	1.5	-3.0
80%RH	1.0	0.5	-0.4	0.5	0.1	0.1	0.1	0.1	0.7	0.0
80%RH	2.1	1.7	-0.8	0.8	1.8	1.1	0.5	0.2	0.0	0.2
80%RH	1.8	1.8	-3.0	1.6	1.9	1.0	0.5	0.6	0.5	-1.6
80%RH	1.2	0.2	0.2	1.3	0.7	1.8	0.3	1.4	0.8	-0.1
80%RH	1.3	1.0	-0.8	1.5	1.6	1.9	1.6	1.8	2.6	-1.4
80%RH	1.8	0.8	-1.0	1.5	1.0	1.5	2.2	1.8	1.8	-2.4
80%RH	1.0	1.0	-2.0	1.0	0.0	0.0	0.5	0.0	0.5	-1.5
80%RH	2.1	1.9	-2.2	1.0	0.9	1.0	1.0	1.1	1.2	2.0
80%RH	1.8	1.2	-2.0	1.8	2.1	2.2	1.8	1.7	1.6	-1.8

Subjective votes 5 minutes after exertion (Cont.)

					Thermal	Air movement	Humidity perception	Air quality	Skin wettedness acceptability					
	Freshness	Stuffiness	Alertness	Fatigue	acceptability	acceptability	acceptability	acceptability	Whole-body	Head	Armpit	Abdomen	Leg	Foot
	fresh = 0	stuffy = 0	very alert = 0	very fatig. = 0	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1
Condition	stale = 6	not stuffy = 6	very sleepy = 6	very energ. = 6	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2
50%RH	4.0	3.9	4.1	4.0	.	1	1	1	1	1	1	1	1	1
50%RH	4.0	1.5	3.6	1.3	.	1	.	.	1	1	1	1	1	1
50%RH	1.0	5.0	1.3	3.2	1	1	1	1	1	1	1	1	1	1
50%RH	3.9	2.2	3.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	4.5	1.0	0.8	4.1	1	1	1	2	1	1	1	1	1	1
50%RH	6.0	0.0	3.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.0	3.0	3.0	3.0	2	1	1	1	2	1	2	2	2	2
50%RH	2.5	4.5	3.5	3.4	1	1	1	1	1	1	1	1	1	1
50%RH	0.6	5.3	0.5	4.5	1	1	1	1	1	1	1	1	1	1
50%RH	5.1	0.5	2.0	3.5	1	1	2	2	1	1	1	1	1	1
50%RH	4.4	1.8	3.5	1.5	.	1	1	1	1	1	1	1	1	1
50%RH	3.2	3.2	2.5	3.6	.	2	2	2	1	1	2	2	2	2
50%RH	2.5	5.0	1.0	5.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.0	3.0	4.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	1.0	4.0	1.0	4.0	.	.	1	1	1	1	2	2	1	1
50%RH	0.0	6.0	1.0	5.0	1	.	1	1	1	2	2	1	1	1
50%RH	3.0	3.1	2.5	3.5	1	1	1	1	1	1	1	1	1	1
50%RH	4.9	0.5	6.0	0.7	2	2	2	2	2	2	2	2	2	2
50%RH	2.7	3.8	2.0	4.5	1	2	1	1	1	1	1	1	1	1
50%RH	4.1	2.0	3.1	2.9	1	1	1	.	1	1	1	1	1	1
50%RH	5.5	0.5	2.3	3.5	2	2	2	.	2	1	2	2	2	2
60%RH	3.1	2.5	2.4	3.5	1	1	1	1	1	1	1	1	1	1
60%RH	2.9	4.0	1.0	3.9	1	1	1	1	1	1	1	1	1	1
60%RH	5.0	2.0	4.0	0.5	2	2	1	1	1	1	1	1	1	1
60%RH	4.5	0.7	3.8	3.5	2	2	2	2	2	2	2	2	2	2
60%RH	4.2	1.0	2.0	3.3	1	1	1	2	1	1	1	1	1	2
60%RH	1.0	1.0	3.3	1.8	1	2	1	1	1	1	1	2	1	1
60%RH	5.0	3.1	3.0	3.0	2	2	2	2	2	2	2	1	1	1
60%RH	3.5	2.5	3.5	3.2	1	1	1	1	1	1	1	1	1	1
60%RH	5.5	1.5	5.3	3.0	2	2	2	2	1	2	2	1	1	2
60%RH	6.0	0.0	3.0	1.0	2	2	2	2	2	2	2	2	2	2
60%RH	3.0	3.5	2.5	2.2	1	1	1	1	.	.	.	.	.	.
60%RH	3.0	3.2	3.0	3.0	1	1	1	1	1	1	1	1	1	1
60%RH	5.0	0.8	3.0	3.1	.	1	.	1	1	1	1	1	1	1
60%RH	3.0	2.4	1.8	4.0	.	1	1	1	1	2	1	1	1	1
60%RH	5.0	1.0	5.0	1.8	2	2	2	.	2	2	2	1	2	2
60%RH	4.0	2.0	4.5	4.0	1	1	1	1	1	1	1	1	1	1
60%RH	5.3	0.5	4.8	1.3	2	2	2	.	2	2	2	2	2	2
60%RH	4.5	2.0	3.9	2.0	1	1	2	2	2	2	2	1	1	1
60%RH	2.2	1.5	3.2	1.8	1	2	2	2	1	1	1	1	1	1
60%RH	3.6	2.2	2.9	2.9	2	2	1	2	2	1	2	1	1	1
60%RH	5.9	0.0	4.0	2.0	.	2	2	2	2	2	2	2	2	2
60%RH	3.4	1.8	3.2	1.2	1	2	2	.	1	1	1	1	1	1
70%RH	4.0	1.5	4.0	1.9	2	2	2	2	2	1	2	2	2	2
70%RH	0.5	4.5	1.2	4.5	1	.	1	1	1	1	1	1	1	1
70%RH	1.7	1.5	1.6	4.0	2	2	2	2	1	1	1	2	1	1
70%RH	3.7	3.5	3.1	3.1	1	1	1	1	1	1	1	1	1	1
70%RH	2.1	5.8	2.0	4.0	1	1	1	1	1	1	1	1	1	2
70%RH	3.1	2.1	3.1	3.0	2	2	1	.	2	1	2	2	2	2
70%RH	5.8	0.9	4.9	0.8	.	2	2	2	2	1	2	1	1	2
70%RH	5.0	0.6	3.2	3.4	.	2	1	2	2	2	2	2	2	2
70%RH	5.6	0.1	5.0	0.8	.	2	2	2	2	2	2	2	1	1
70%RH	3.0	2.1	2.9	3.0	1	1	1	1	1	1	1	1	1	1
70%RH	1.0	5.0	1.0	4.0	1	1	1	1	1	1	1	1	1	1
70%RH	2.0	4.0	3.0	2.9	2	1	1	.	1	1	1	1	1	1
70%RH	3.5	3.6	3.2	3.0	.	1	1	1	1	1	1	1	1	1
70%RH	2.0	5.0	4.5	2.5	1	1	1	1	1	1	1	1	1	1
70%RH	3.2	1.5	1.1	3.3	1	1	1	1	1	1	1	1	1	1
70%RH	4.5	0.5	3.3	2.9	2	2	2	2	2	2	2	2	1	2
70%RH	5.4	0.6	5.8	0.5	1	1	1	2	1	1	1	1	1	2
70%RH	5.5	0.5	4.5	1.3	1	2	2	2	1	1	1	1	1	2
70%RH	4.6	2.3	2.5	3.5	2	2	1	2	2	2	2	2	1	2
70%RH	2.2	2.0	2.3	2.2	1	1	1	1	1	1	1	1	1	1
80%RH	2.6	2.9	2.3	3.4	1	2	2	1	2	2	2	1	1	2
80%RH	4.5	0.7	1.3	1.6	2	2	2	2	2	2	1	1	2	1
80%RH	3.5	2.2	4.2	1.3	.	1	1	1	1	1	1	1	1	1
80%RH	4.0	2.3	3.0	3.0	2	2	2	2	2	2	2	2	1	2
80%RH	1.0	6.0	2.9	3.0	1	1	1	1	1	1	1	1	1	1
80%RH	3.0	2.5	4.0	2.0	.	1	1	1	1	1	1	1	2	2
80%RH	2.0	4.0	2.0	4.0	2	2	1	1	2	2	2	2	2	2
80%RH	2.1	5.3	1.5	3.5	1	1	1	1	1	1	1	1	1	1
80%RH	2.3	4.3	3.2	4.0	1	.	1	1	1	1	2	2	2	2
80%RH	5.0	2.3	3.0	2.5	1	1	2	2	2	2	1	1	1	1
80%RH	4.1	1.8	2.5	2.8	2	2	2	2	2	1	2	2	2	2
80%RH	4.0	0.5	1.5	4.0	2	2	2	2	2	2	2	2	2	2
80%RH	2.3	2.0	2.0	3.0	2	2	2	.	1	1	1	1	1	2
80%RH	0.8	5.6	0.7	3.5	2	1	1	1	1	1	1	1	1	1
80%RH	5.4	0.5	0.4	3.1	2	2	2	2	2	2	2	1	1	1
80%RH	0.2	5.4	0.3	5.4	1	1	1	1	2	1	2	1	2	1
80%RH	3.0	2.2	2.0	4.0	1	1	1	1	1	1	1	1	1	1
80%RH	4.3	1.8	3.4	2.6	1	1	2	1	1	1	1	1	1	2
80%RH	4.0	2.0	4.3	2.0	1	2	2	.	1	1	1	1	1	2
80%RH	5.0	1.2	4.2	1.5	2	2	2	2	2	2	2	2	2	2
80%RH	5.0	1.5	3.3	3.0	1	2	1	.	1	1	1	1	1	1

Subjective votes 15 minutes after exertion

			Air movement	Skin wettedness feeling						
	Thermal sensation	Comfort sensation	perception	Whole-body	Head	Armpit	Abdomen	Leg	Foot	Humidity perception
	cold = -3	comfortable = 0	too little = -3	normal = 0	normal = 0	normal = 0	normal = 0	normal = 0	normal = 0	very humid = -3
Condition	hot = +3	intolerable = 4	too much = +3	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	soaking wet = 6	very dry = +3
50%RH	1.1	0.3	-2.8	0.6	0.2	0.5	0.3	0.2	0.2	1.8
50%RH	0.3	0.3	0.0	0.2	0.2	0.2	0.2	0.2	0.2	-1.3
50%RH	0.8	0.7	-0.3	0.5	0.3	0.5	0.8	0.5	1.1	1.0
50%RH	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.3
50%RH	0.8	1.0	-2.0	0.3	0.3	0.5	0.5	0.5	0.5	-1.8
50%RH	3.0	1.0	-2.1	1.0	1.0	1.0	1.0	1.0	2.0	-2.0
50%RH	2.0	1.0	-1.0	4.0	3.0	4.0	4.0	4.0	4.0	0.0
50%RH	-0.2	0.3	-0.2	0.2	0.2	0.4	0.2	0.2	0.4	-0.1
50%RH	1.2	0.5	1.8	0.7	0.7	1.1	0.7	0.7	0.8	-2.2
50%RH	1.8	1.0	-0.5	1.3	0.7	1.8	1.9	1.8	1.8	2.3
50%RH	1.5	1.0	1.5	1.5	1.3	1.8	1.8	1.5	1.9	-2.2
50%RH	1.5	0.7	-1.2	1.5	1.5	1.8	1.5	1.8	2.0	-0.8
50%RH	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.2	2.0
50%RH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50%RH	0.5	0.1	0.0	0.5	1.0	1.0	1.0	0.2	0.4	0.0
50%RH	-2.0	0.0	0.0	1.0	2.0	2.0	1.0	0.0	0.0	0.0
50%RH	1.1	1.3	-1.6	1.5	2.1	2.1	0.6	1.4	2.5	-1.0
50%RH	1.0	1.8	-2.5	2.2	2.2	2.2	2.2	1.8	2.6	-0.5
50%RH	1.0	0.0	-0.5	0.0	0.8	0.5	0.0	0.0	0.4	-1.0
50%RH	0.2	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.4
50%RH	2.4	1.7	-2.0	2.4	2.3	4.3	4.5	4.7	5.7	-2.4
60%RH	0.0	0.6	-1.1	0.4	0.4	0.3	0.4	0.4	0.8	-0.3
60%RH	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
60%RH	2.0	0.5	-2.1	0.1	0.1	0.1	0.2	0.2	0.1	0.7
60%RH	1.7	0.8	-1.0	1.8	1.7	1.7	1.0	1.4	2.4	1.5
60%RH	0.0	0.5	0.8	0.0	0.0	0.8	0.8	1.3	3.5	0.6
60%RH	1.6	0.4	-1.5	1.6	2.1	0.5	2.1	0.3	0.1	-2.0
60%RH	-0.4	0.0	0.1	0.0	0.0	1.1	0.1	0.1	0.2	-0.3
60%RH	0.7	0.5	-0.5	0.5	0.6	0.3	0.5	0.4	0.7	-0.3
60%RH	2.0	1.8	-2.0	2.3	6.0	2.5	2.5	3.1	6.0	-0.6
60%RH	2.1	2.0	-3.0	3.0	2.0	3.0	3.0	2.0	3.0	-2.0
60%RH	1.3	0.5	-1.5	2.5	2.5	3.4	2.2	2.2	4.2	-1.3
60%RH	0.3	0.3	-0.5	0.1	0.1	0.2	0.2	0.2	0.2	0.5
60%RH	2.1	1.0	-2.0	0.3	0.0	0.0	0.2	0.0	1.7	-1.0
60%RH	1.0	1.0	-1.0	1.5	1.4	1.3	1.3	1.5	1.6	-1.5
60%RH	2.5	4.5	-2.8	3.5	4.0	3.8	3.3	3.5	3.7	-2.5
60%RH	2.0	1.4	0.0	1.1	1.2	1.2	1.0	1.2	1.2	0.1
60%RH	2.0	1.0	-1.8	2.5	3.0	2.4	2.0	2.6	3.3	1.0
60%RH	1.2	0.9	-0.4	1.3	1.6	2.3	1.1	1.1	1.5	-1.9
60%RH	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.6
60%RH	0.2	0.3	-2.0	1.2	1.2	1.2	1.2	1.4	1.3	-0.8
60%RH	3.0	2.0	-3.0	4.0	4.1	4.0	2.0	2.0	2.0	-2.0
60%RH	-0.3	0.3	-1.1	0.2	0.2	0.1	0.1	0.2	0.2	-0.2
70%RH	0.5	0.6	-1.0	2.0	1.5	3.2	2.7	2.1	2.3	-2.7
70%RH	-1.3	0.3	-0.2	0.4	0.3	1.4	0.4	0.3	0.4	-1.3
70%RH	0.8	0.8	-1.6	0.3	0.3	0.3	0.3	0.3	0.3	0.1
70%RH	0.3	0.3	-0.4	0.2	0.3	0.3	0.5	0.3	0.3	-0.3
70%RH	2.9	2.0	-1.4	0.0	0.0	1.0	0.0	0.0	2.0	1.0
70%RH	2.0	2.0	-2.7	1.0	0.5	0.3	1.0	1.0	1.0	1.0
70%RH	1.1	1.2	-1.0	0.1	0.0	1.8	0.9	0.2	1.8	-0.9
70%RH	2.5	1.5	-2.6	1.4	1.6	1.7	1.7	1.4	2.0	-1.0
70%RH	2.0	1.7	-2.0	4.0	3.9	4.4	3.9	3.5	2.9	-1.6
70%RH	1.1	0.6	-0.7	1.4	1.4	1.4	1.5	1.5	1.5	-1.7
70%RH	2.0	0.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
70%RH	1.7	1.4	-0.8	0.9	0.0	2.0	1.0	1.0	0.0	-1.5
70%RH	1.7	0.6	0.0	0.8	0.8	0.8	0.8	0.8	0.8	1.1
70%RH	1.0	0.5	-1.0	0.5	0.2	0.9	2.0	2.0	2.0	-1.0
70%RH	2.2	0.5	-0.8	0.9	0.5	0.9	0.5	0.5	0.9	-0.5
70%RH	2.2	1.8	-2.5	2.8	3.3	3.5	2.6	2.4	3.5	-2.3
70%RH	2.8	2.6	-3.0	1.8	1.8	1.8	1.8	1.8	2.4	2.7
70%RH	0.6	1.6	-1.2	0.6	1.5	0.7	0.7	0.7	2.8	-0.6
70%RH	1.5	1.2	-1.6	2.8	2.7	3.8	3.7	1.6	3.8	-0.5
70%RH	0.2	0.5	0.0	0.0	0.0	0.1	0.2	0.1	0.8	0.0
80%RH	0.3	0.3	-0.3	2.9	3.2	2.8	2.1	1.5	3.1	0.3
80%RH	1.8	0.9	-1.8	2.4	1.5	2.7	1.1	3.3	0.3	-2.3
80%RH	0.5	0.7	-1.4	0.3	0.3	0.5	0.5	0.3	0.4	-0.3
80%RH	1.8	1.6	-1.5	2.3	2.3	4.0	1.0	0.7	1.8	-1.8
80%RH	1.0	0.3	-1.0	2.0	2.0	0.9	1.0	1.0	0.8	0.0
80%RH	2.0	2.0	-2.0	2.0	2.0	2.0	1.0	2.0	2.0	-2.0
80%RH	1.0	1.0	-2.0	2.0	1.0	2.0	1.0	0.0	1.0	-1.0
80%RH	0.8	1.2	-2.3	2.0	0.5	0.8	1.0	1.2	1.5	1.5
80%RH	1.0	0.7	0.0	0.6	0.8	1.4	2.4	1.6	1.6	0.0
80%RH	0.0	0.6	-0.5	0.5	0.5	0.2	0.2	0.2	0.2	-1.3
80%RH	0.9	1.0	-1.3	1.5	0.3	1.8	1.8	0.8	1.6	-1.2
80%RH	0.0	0.8	-0.8	3.7	3.8	0.6	1.2	1.8	0.2	-2.8
80%RH	1.5	0.4	0.2	0.6	0.2	0.2	0.2	0.2	0.6	0.5
80%RH	0.2	0.2	0.8	0.3	0.8	1.2	0.6	0.2	0.0	1.8
80%RH	0.8	0.8	-2.9	1.5	1.4	0.8	0.4	0.4	0.4	-1.3
80%RH	0.2	0.2	0.2	0.8	0.2	1.5	0.2	0.8	0.4	-0.2
80%RH	0.5	0.5	-1.4	1.2	0.8	1.2	0.5	1.7	2.1	-1.0
80%RH	1.7	0.3	-1.0	0.8	0.8	1.2	1.4	1.4	1.4	-1.5
80%RH	1.0	0.5	-2.0	0.4	1.0	0.0	0.0	0.0	1.0	-1.5
80%RH	1.2	1.8	-2.0	1.0	0.8	1.0	1.0	1.0	1.0	1.5
80%RH	1.0	0.9	1.9	1.5	1.7	2.0	1.8	1.3	1.0	-1.9

Subjective votes 15 minutes after exertion (Cont.)

	Freshness	Stuffiness	Alertness	Fatigue	Thermal acceptability	Air movement acceptability	Humidity perception acceptability	Air quality acceptability	Skin wettedness acceptability Whole-body	Head	Armpit	Abdomen	Leg	Foot
	fresh = 0	stuffy = 0	very alert = 0	very fatig. = 0	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1
Condition	stale = 6	not stuffy = 6	very sleepy = 6	very energ. = 6	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2
50%RH	5.0	4.5	4.6	5.8	.	1	1	1	1	1	1	1	1	1
50%RH	3.5	2.2	3.6	2.5	1	1	1	1	1	1	1	1	1	1
50%RH	2.3	4.0	1.0	3.8	1	1	1	1	1	1	1	1	1	1
50%RH	3.0	2.3	3.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	5.0	0.5	0.3	4.3	1	1	1	2	1	1	1	1	1	1
50%RH	4.5	1.0	3.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.0	3.0	3.0	3.0	2	1	1	1	2	1	2	2	2	2
50%RH	3.5	5.5	3.6	3.5	1	1	1	1	1	1	1	1	1	1
50%RH	5.2	0.5	6.0	0.6	1	2	2	2	1	1	1	1	1	1
50%RH	4.5	0.5	3.5	2.2	1	1	1	2	1	1	1	1	1	1
50%RH	4.5	1.5	4.2	1.5	1	1	1	1	1	1	1	1	1	1
50%RH	3.0	3.3	3.0	3.1	.	2	1	1	1	1	1	2	2	2
50%RH	0.2	5.5	0.0	5.5	1	1	1	1	1	1	1	1	1	1
50%RH	3.0	4.0	3.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	1.0	4.5	1.0	4.5	.	.	1	1	1	1	1	1	1	1
50%RH	0.0	6.0	3.0	3.1	1	1	1	1	1	1	1	1	1	1
50%RH	4.0	2.0	2.0	4.0	1	2	1	1	1	1	1	1	1	1
50%RH	4.4	0.4	5.1	0.6	2	2	1	2	.	.	.	.	.	.
50%RH	2.0	5.0	3.0	4.0	1	1	1	1	1	1	1	1	1	1
50%RH	4.0	3.2	3.5	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	4.2	4.1	4.7	1.3	2	2	2	.	1	1	2	2	2	2
60%RH	3.4	2.3	3.0	2.9	1	1	1	1	1	1	1	1	1	1
60%RH	1.8	3.8	2.0	3.7	1	1	1	1	1	1	1	1	1	1
60%RH	5.4	0.9	5.5	0.8	2	2	1	1	1	1	1	1	1	1
60%RH	4.6	1.7	3.5	3.2	2	2	2	2	2	2	2	2	2	2
60%RH	2.2	3.6	2.2	3.6	1	1	1	1	1	1	1	1	1	2
60%RH	4.4	1.0	4.0	2.0	1	2	2	2	2	2	1	2	1	1
60%RH	1.5	4.4	1.1	4.1	1	1	1	1	1	1	1	1	1	1
60%RH	3.8	2.2	4.0	2.0	1	1	1	1	1	1	1	1	1	1
60%RH	5.4	0.8	4.0	2.0	2	2	2	2	2	2	1	1	1	2
60%RH	6.0	0.0	4.0	1.0	2	2	2	2	2	2	2	2	2	2
60%RH	4.5	1.5	3.5	1.8	1	1	1	1	1	1	1	1	1	1
60%RH	3.5	2.5	3.0	3.0	1	1	1	1	1	1	1	1	1	1
60%RH	5.0	1.0	3.0	2.0	.	1	1	1	1	1	1	1	1	1
60%RH	3.0	3.0	2.0	4.0	1	1	1	.	1	1	1	1	1	1
60%RH	5.5	0.5	5.3	1.0	.	2	2	.	2	2	2	2	2	2
60%RH	0.4	1.6	3.2	2.0	1	1	1	1	1	1	1	1	1	1
60%RH	4.6	1.3	4.8	1.5	2	2	2	.	2	2	1	1	2	2
60%RH	3.9	2.1	3.4	2.8	1	1	1	1	1	1	1	1	1	1
60%RH	0.6	4.7	1.5	3.2	.	1	1	1	1	1	1	1	1	1
60%RH	4.6	1.9	4.2	2.0	1	.	1	.	1	1	1	1	1	1
60%RH	6.0	1.0	4.0	2.0	2	2	2	2	2	2	2	2	1	1
60%RH	1.0	4.1	5.0	0.5	1	1	1	.	1	1	1	1	1	1
70%RH	3.5	1.0	4.1	1.0	1	2	2	2	2	2	2	2	2	2
70%RH	4.7	2.8	1.5	3.4	.	1	1	.	1	1	1	1	1	1
70%RH	1.2	2.6	1.7	4.3	2	2	1	1	1	1	1	1	1	1
70%RH	2.6	2.2	4.7	1.2	1	1	1	1	1	1	1	1	1	1
70%RH	4.0	5.0	1.0	4.8	2	2	1	1	1	1	1	1	1	2
70%RH	4.1	2.1	4.7	1.7	2	2	2	2	2	2	2	2	2	2
70%RH	4.9	2.1	3.8	3.0	.	1	2	2	1	1	2	1	1	2
70%RH	5.0	0.0	3.3	3.2	.	2	2	2	2	2	1	1	1	2
70%RH	5.0	1.1	5.0	1.0	.	2	2	2	2	2	2	2	1	1
70%RH	3.3	2.2	3.0	2.8	1	1	1	1	1	1	1	1	1	1
70%RH	2.0	4.0	1.0	4.0	1	1	1	1	1	1	1	1	1	1
70%RH	2.0	3.9	3.2	2.7	1	1	1	.	1	1	1	1	1	1
70%RH	2.1	4.1	2.0	4.0	1	1	1	1	1	1	1	1	1	1
70%RH	3.5	1.5	4.2	1.6	1	1	1	1	1	1	1	1	1	1
70%RH	3.0	3.0	4.0	3.0	1	1	1	1	1	1	1	1	1	1
70%RH	5.6	0.5	4.4	0.5	.	2	2	2	2	2	2	2	2	2
70%RH	5.6	0.2	4.3	1.7	2	2	2	2	1	1	1	1	1	2
70%RH	3.5	1.5	4.5	1.5	1	2	1	2	1	1	1	1	1	1
70%RH	2.5	3.5	4.5	2.5	2	2	1	2	2	2	2	2	1	2
70%RH	3.0	3.0	3.0	2.7	1	1	1	1	1	1	1	1	1	1
80%RH	2.5	3.5	3.4	2.4	1	1	1	1	1	2	1	1	1	2
80%RH	5.1	1.0	1.1	2.5	2	2	2	2	2	1	1	1	2	1
80%RH	3.5	1.3	5.3	1.7	1	1	1	1	1	1	1	1	1	1
80%RH	4.0	2.2	4.0	2.0	2	2	2	2	2	2	2	1	1	1
80%RH	6.0	0.0	3.0	3.0	1	2	1	2	1	1	1	1	1	1
80%RH	6.0	0.0	5.0	2.0	.	2	2	2	2	2	2	2	2	2
80%RH	4.0	1.0	3.0	2.0	2	2	2	.	2	2	2	2	1	2
80%RH	5.0	0.8	4.0	2.0	1	1	1	2	2	1	1	1	1	1
80%RH	1.8	4.5	1.8	4.2	1	1	1	1	1	1	2	2	2	2
80%RH	4.0	2.3	2.2	3.2	1	1	2	1	1	1	1	1	1	1
80%RH	4.0	2.0	2.2	2.6	2	2	2	2	2	1	2	2	1	2
80%RH	4.0	1.6	1.0	4.6	1	2	2	2	1	1	1	2	2	1
80%RH	3.0	3.0	3.0	3.0	.	2	2	.	1	1	1	1	1	2
80%RH	0.5	5.2	0.6	3.8	1	1	1	1	1	1	1	1	1	1
80%RH	4.6	0.9	0.5	3.3	2	2	2	2	2	2	2	1	1	1
80%RH	1.2	4.8	1.0	4.8	1	1	1	1	1	1	1	1	1	1
80%RH	2.8	2.1	3.0	3.0	1	1	1	1	1	1	1	1	1	1
80%RH	3.0	3.0	3.0	2.5	1	1	2	1	1	1	1	1	1	1
80%RH	5.0	2.0	4.0	2.0	1	2	2	.	2	1	1	1	1	2
80%RH	5.2	0.7	4.5	1.6	2	2	2	.	2	2	2	2	2	2
80%RH	5.0	1.2	2.3	3.6	1	2	1	.	1	1	1	1	1	1

Subjective votes 30 minutes after exertion

Condition	Thermal sensation cold=-3 hot=+3	Comfort sensation comfortable=0 intolerable=4	Air movement perception too little=-3 too much=+3	Skin wettedness feeling: Whole-body normal=0 soaking wet=6	Head normal=0 soaking wet=6	Armpit normal=0 soaking wet=6	Abdomen normal=0 soaking wet=6	Leg normal=0 soaking wet=6	Foot normal=0 soaking wet=6	Humidity perception very humid=-3 very dry=+3
50%RH	-0.2	0.3	-2.5	0.2	0.3	0.3	0.1	0.1	0.3	1.3
50%RH	0.3	0.5	-0.2	0.2	0.2	0.2	0.2	0.2	0.2	-1.6
50%RH	-0.2	0.0	-0.1	0.2	0.1	0.1	0.2	0.4	0.8	0.1
50%RH	0.0	0.5	-0.6	0.0	0.3	0.0	0.0	0.0	0.6	-0.4
50%RH	1.0	2.0	-2.0	0.0	0.0	0.1	0.0	0.0	0.5	-1.0
50%RH	3.0	1.0	-2.0	0.0	0.0	0.0	0.0	0.0	1.0	-2.0
50%RH	1.0	1.0	0.0	3.0	1.0	3.0	3.0	3.0	3.0	0.0
50%RH	-0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.1
50%RH	-0.5	0.2	0.1	0.5	0.5	0.8	0.5	0.5	0.5	0.7
50%RH	2.0	1.0	-1.0	0.7	0.2	0.6	0.5	1.0	1.0	0.5
50%RH	1.5	0.8	1.5	1.8	1.2	1.8	1.7	1.4	1.6	-1.5
50%RH	0.8	0.5	-0.5	1.0	0.8	0.8	0.8	0.8	0.8	-0.2
50%RH	0.3	0.0	-0.4	0.0	0.0	0.0	0.0	0.2	0.2	-2.0
50%RH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50%RH	0.0	0.0	0.0	0.3	0.7	0.8	0.6	0.6	0.5	0.0
50%RH	1.0	2.0	-2.0	1.0	1.0	2.0	0.9	0.0	0.0	-2.0
50%RH	-0.4	0.3	-0.4	0.2	0.6	0.5	0.1	0.2	0.9	0.0
50%RH	0.2	0.8	-1.5	0.5	0.1	0.5	0.0	0.1	1.2	0.8
50%RH	0.6	0.7	-1.0	0.6	0.3	2.0	1.3	0.0	0.7	-0.7
50%RH	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50%RH	1.6	1.4	-0.6	1.3	1.8	3.8	4.5	3.6	5.5	-0.5
60%RH	0.0	0.2	-0.5	0.2	0.0	0.1	0.2	0.2	0.5	0.1
60%RH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.2
60%RH	0.7	0.0	-0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
60%RH	1.1	1.0	-0.7	1.3	1.5	1.4	1.2	1.2	1.6	1.5
60%RH	-0.1	0.5	0.0	0.0	0.2	1.0	0.7	0.7	3.6	0.5
60%RH	2.0	0.4	-0.6	1.0	0.4	0.4	3.0	1.0	2.0	-1.7
60%RH	0.0	0.0	-0.7	0.0	0.0	0.0	0.0	0.0	1.0	1.0
60%RH	0.2	0.2	0.0	0.3	0.2	0.2	0.2	0.0	0.2	0.0
60%RH	0.8	1.3	-2.5	2.6	6.0	6.0	2.3	3.5	6.0	-0.8
60%RH	2.0	2.0	-3.0	2.0	1.0	2.0	2.0	2.0	3.0	-2.0
60%RH	0.2	0.3	-0.8	0.2	0.1	0.2	0.2	0.2	1.7	-0.7
60%RH	0.0	0.2	-0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
60%RH	2.1	1.0	-2.0	0.0	0.2	0.2	0.2	0.2	2.0	-1.3
60%RH	0.8	0.8	-1.0	1.5	1.5	1.1	1.2	1.5	1.2	-1.0
60%RH	2.0	4.0	-2.3	2.5	3.5	3.2	2.2	2.2	2.8	-2.2
60%RH	1.2	0.5	1.0	0.5	0.5	0.7	0.7	0.8	1.0	0.0
60%RH	0.8	0.7	-1.5	1.5	2.0	1.3	1.3	1.9	2.5	-0.9
60%RH	1.0	1.0	-1.3	1.1	0.7	0.9	0.7	0.6	1.1	-1.2
60%RH	-1.7	0.2	2.2	0.1	0.1	0.0	0.0	0.0	0.0	0.3
60%RH	-0.3	0.2	-1.0	0.2	0.2	0.4	0.0	0.3	0.8	0.2
60%RH	1.6	1.0	-1.0	1.0	2.0	2.0	1.0	1.0	0.1	-1.0
60%RH	0.0	0.2	-0.2	0.2	0.2	0.2	0.1	0.1	0.1	-0.2
70%RH	0.5	0.6	-1.2	1.7	0.3	2.1	1.5	0.7	0.4	-1.1
70%RH	1.4	0.5	-1.3	0.6	0.6	0.6	0.5	0.5	0.4	0.2
70%RH	0.1	0.3	-0.6	0.2	0.2	0.2	0.2	0.2	0.2	-0.2
70%RH	0.2	0.2	-0.4	0.2	0.2	0.3	0.2	0.2	0.1	0.8
70%RH	2.0	0.5	1.0	1.2	1.0	1.0	0.0	0.0	2.0	-2.0
70%RH	1.0	0.5	-0.2	0.0	0.1	0.1	0.1	0.1	0.1	2.8
70%RH	0.8	0.2	-2.1	0.9	0.0	1.9	0.8	0.0	0.8	-0.8
70%RH	2.4	1.6	-2.8	1.2	0.8	1.3	1.0	1.0	1.6	-1.0
70%RH	1.8	1.7	-2.0	3.3	2.9	3.5	2.6	2.4	2.2	-1.0
70%RH	1.0	0.7	-0.9	1.6	1.5	1.5	1.5	1.5	1.5	-1.8
70%RH	2.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
70%RH	2.5	2.0	-1.0	0.8	0.9	1.9	1.0	0.1	0.5	-2.0
70%RH	1.1	0.3	0.0	0.8	0.5	0.5	0.9	0.5	0.5	-0.8
70%RH	0.5	0.1	-0.1	0.3	0.6	1.8	1.0	1.6	1.4	-0.5
70%RH	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.3
70%RH	1.3	0.7	-1.5	1.3	2.3	1.8	1.6	1.2	1.5	-2.2
70%RH	2.8	3.2	-3.0	1.6	1.6	1.6	1.8	1.8	2.5	2.7
70%RH	0.4	0.5	-0.5	0.7	0.7	0.6	0.6	0.6	2.3	-0.6
70%RH	1.8	1.5	-2.5	3.7	3.7	3.7	3.7	2.8	4.3	-1.8
70%RH	1.2	1.0	-1.5	1.0	0.7	0.9	0.9	0.6	1.1	-1.4
80%RH	-0.2	0.4	-0.4	3.2	2.7	2.7	2.8	2.7	3.2	-0.4
80%RH	0.9	0.2	-1.9	0.8	1.1	0.5	0.6	2.2	0.3	-1.9
80%RH	0.0	0.5	-0.2	0.4	0.3	0.4	0.4	0.5	0.5	-0.3
80%RH	1.0	0.5	-1.0	1.0	0.7	1.3	0.2	0.2	1.3	0.0
80%RH	1.0	0.3	1.0	1.0	1.0	0.0	0.0	0.0	0.0	-1.0
80%RH	2.0	3.0	-3.0	2.0	2.0	2.0	2.0	2.0	2.0	-2.0
80%RH	1.0	1.0	-2.0	1.0	1.0	1.0	0.0	0.0	1.0	1.0
80%RH	0.3	0.8	-2.0	1.2	0.8	1.2	0.8	1.3	1.5	1.8
80%RH	0.3	0.3	0.2	0.4	0.4	1.0	1.0	1.5	1.5	0.0
80%RH	0.0	0.0	-0.5	0.5	0.5	0.2	0.2	0.2	0.3	-1.5
80%RH	1.0	1.2	-1.2	1.2	0.5	1.3	1.3	0.5	1.4	-1.0
80%RH	0.3	1.2	-1.2	3.2	3.3	1.2	1.6	1.8	0.2	-2.8
80%RH	0.0	0.5	-0.3	0.2	0.2	0.2	0.2	0.2	0.2	-0.1
80%RH	-0.2	0.3	0.0	0.0	0.5	0.1	0.0	0.1	0.0	-0.3
80%RH	1.2	2.0	-2.8	2.0	2.0	0.5	0.4	0.4	0.4	-1.3
80%RH	0.2	0.2	0.2	0.3	0.3	0.7	0.2	0.5	0.2	-0.5
80%RH	1.0	0.6	-1.0	1.2	0.8	0.7	0.6	1.5	2.0	-0.9
80%RH	1.0	0.3	-0.3	0.4	0.3	0.5	0.6	0.4	0.3	-1.0
80%RH	0.0	0.2	-2.0	0.5	0.5	0.0	0.0	0.0	0.5	-1.0
80%RH	1.5	3.2	-2.0	1.2	1.2	1.1	1.2	1.2	1.3	1.6
80%RH	0.4	0.4	-1.4	1.3	1.5	1.5	1.7	1.2	0.8	-1.4

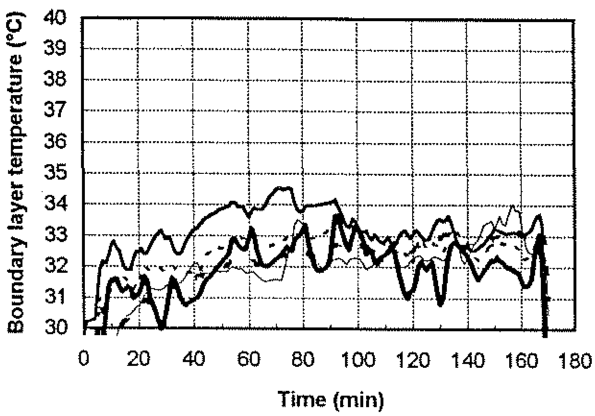
Subjective votes 30 minutes after exertion (Cont.)

					Thermal	Air movement	Humidity perception	Air quality	Skin wettedness acceptability					
	Freshness	Stuffiness	Alertness	Fatigue	acceptability	acceptability	acceptability	acceptability	Whole-body	Head	Armpit	Abdomen	Leg	Foot
	fresh = 0	stuffy = 0	very alert = 0	very fatig. = 0	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1	yes = 1
Condition	stale = 6	not stuffy = 6	very sleepy = 6	very energ. = 6	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2	no = 2
50%RH	3.6	3.5	4.5	3.5	.	1	1	1	1	1	1	1	1	1
50%RH	4.0	2.0	4.0	2.0	1	1	1	1	1	1	1	1	1	1
50%RH	0.5	5.0	1.0	4.1	1	1	1	1	1	1	1	1	1	1
50%RH	3.5	3.0	3.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	4.0	2.2	1.0	4.5	1	1	1	2	1	1	1	1	1	1
50%RH	4.0	1.0	3.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	3.0	3.0	3.0	3.0	.	1	.	1	.	.	.	.	.	.
50%RH	3.5	5.6	2.5	4.5	1	1	1	1	1	1	1	1	1	1
50%RH	0.5	5.3	4.0	1.3	1	1	1	1	1	1	1	1	1	1
50%RH	5.5	1.0	3.5	2.3	1	1	1	2	1	1	1	1	1	1
50%RH	4.5	1.5	4.0	1.5	.	1	1	.	1	1	1	1	1	1
50%RH	2.5	4.0	2.4	2.6	.	1	1	1	1	1	1	1	1	1
50%RH	1.0	1.2	0.5	1.4	1	1	1	1	1	1	1	1	1	1
50%RH	2.0	4.0	2.0	2.0	1	1	1	1	1	1	1	1	1	1
50%RH	1.0	4.5	1.0	5.0	1	.	1	1	1	1	1	1	1	1
50%RH	5.1	2.0	5.0	2.0	1	2	1	2	1	1	1	1	1	1
50%RH	1.5	4.0	1.6	4.0	1	1	1	1	1	1	1	1	1	1
50%RH	4.5	0.6	4.5	1.8	1	2	1	2	1	1	1	1	1	1
50%RH	2.7	2.8	4.0	3.0	.	1	1	.	1	1	1	1	1	1
50%RH	3.0	5.0	3.0	3.0	1	1	1	1	1	1	1	1	1	1
50%RH	2.7	3.7	3.4	1.4	.	1	1	1	1	1	2	2	1	2
60%RH	2.5	3.2	2.4	3.2	1	1	1	1	1	1	1	1	1	1
60%RH	2.5	4.1	2.3	3.6	1	1	1	1	1	1	1	1	1	1
60%RH	4.1	2.6	4.8	0.8	1	1	1	1	1	1	1	1	1	1
60%RH	4.2	2.0	2.9	3.0	2	2	2	2	2	2	2	2	2	2
60%RH	2.5	4.0	3.0	2.0	1	1	1	1	1	1	1	1	1	2
60%RH	1.5	4.5	1.0	4.0	1	1	1	1	1	1	1	2	1	1
60%RH	0.0	6.0	1.0	4.0	1	1	1	1	1	1	1	1	1	1
60%RH	2.0	3.3	2.2	3.0	.	1	1	1	1	1	1	1	1	1
60%RH	5.3	1.0	5.3	1.0	2	2	2	2	2	2	2	1	2	2
60%RH	6.0	0.0	4.0	1.0	2	2	2	2	2	2	2	2	2	2
60%RH	4.5	2.2	4.5	2.2	1	1	1	.	1	1	1	1	1	1
60%RH	3.1	2.8	3.0	3.0	1	1	1	1	1	1	1	1	1	1
60%RH	6.0	0.5	3.2	1.5	.	1	2	1	1	1	1	1	1	1
60%RH	2.5	3.0	1.8	4.1	1	1	1	.	1	1	1	1	1	1
60%RH	5.0	0.8	5.1	0.4	2	2	2	.	2	2	1	1	1	1
60%RH	2.0	3.0	3.8	3.0	1	1	1	1	1	1	1	1	1	1
60%RH	4.3	0.8	4.2	2.2	1	1	1	.	1	2	1	1	2	2
60%RH	3.9	2.5	3.0	3.0	1	1	1	1	1	1	1	1	1	1
60%RH	0.5	5.5	0.8	4.7	1	1	1	1	1	1	1	1	1	1
60%RH	1.5	3.0	2.8	3.0	1	1	1	1	1	1	1	1	1	1
60%RH	3.0	2.0	2.0	3.0	.	1	1	1	1	2	2	1	1	1
60%RH	0.2	4.1	3.7	2.2	1	1	1	.	1	1	1	1	1	1
70%RH	3.6	2.5	3.2	1.9	2	2	2	2	2	1	2	2	1	1
70%RH	4.3	1.5	0.5	5.5	.	1	1	1	1	1	1	1	1	1
70%RH	1.9	3.0	.	.	.	1	1	1	1	1	1	1	1	1
70%RH	3.3	2.7	2.3	1.4	1	1	1	1	1	1	1	1	1	1
70%RH	4.8	1.3	3.0	1.0	1	1	2	2	1	1	1	1	1	2
70%RH	3.4	1.2	3.8	3.0	2	1	2	2	1	1	1	1	1	1
70%RH	4.0	1.9	5.5	2.1	.	2	2	2	2	1	2	1	1	2
70%RH	5.5	0.5	2.6	3.0	.	2	2	2	1	1	1	1	1	2
70%RH	4.0	1.1	4.6	0.9	.	2	1	2	2	1	1	1	1	1
70%RH	3.1	1.9	3.3	3.0	1	1	1	1	1	1	1	1	1	1
70%RH	1.0	5.0	1.0	5.0	1	1	1	1	1	1	1	1	1	1
70%RH	2.2	3.0	3.7	2.5	2	2	1	.	1	1	1	1	1	1
70%RH	3.2	2.2	3.0	3.0	.	1	1	1	1	1	1	1	1	1
70%RH	3.8	2.5	3.7	3.2	1	1	1	1	1	1	1	1	1	1
70%RH	3.6	3.0	4.3	3.0	1	1	1	1	1	1	1	1	1	1
70%RH	5.5	2.5	4.7	1.3	1	2	1	2	1	1	1	1	1	1
70%RH	5.8	0.3	5.5	0.5	2	2	2	2	1	1	1	1	1	2
70%RH	4.5	1.5	4.6	1.3	1	2	1	2	1	1	1	1	1	2
70%RH	4.3	4.5	2.5	3.6	2	2	2	2	2	2	2	2	2	2
70%RH	4.5	1.3	2.3	2.8	1	2	2	2	2	1	2	2	2	2
80%RH	1.6	2.5	2.4	1.9	.	1	1	1	1	1	1	1	1	2
80%RH	4.0	1.7	0.9	2.8	1	2	2	2	1	1	1	1	2	1
80%RH	2.4	2.7	3.3	2.6	1	.	1	.	1	1	1	1	1	1
80%RH	4.0	2.5	2.3	4.0	1	2	1	1	1	1	1	1	1	1
80%RH	4.0	1.0	2.9	3.0	1	1	1	1	1	1	1	1	1	1
80%RH	6.0	0.0	6.0	1.0	.	2	2	2	2	2	2	2	2	2
80%RH	5.0	0.0	4.0	2.0	2	2	1	2	2	2	2	1	1	2
80%RH	4.6	1.2	3.2	2.5	1	1	1	1	1	1	1	1	1	1
80%RH	1.4	3.2	3.2	3.0	1	1	1	1	1	1	1	1	2	2
80%RH	5.0	1.5	3.0	2.5	1	1	2	2	1	1	1	1	1	1
80%RH	3.2	2.2	2.3	3.0	2	2	2	2	2	1	2	2	1	2
80%RH	4.0	0.5	1.3	3.8	2	2	2	2	2	2	1	2	2	2
80%RH	3.0	3.0	3.0	3.0	.	1	2	.	1	1	1	1	1	1
80%RH	4.9	1.8	1.5	2.8	1	1	1	1	1	1	1	1	1	1
80%RH	5.2	0.7	0.0	4.0	2	2	2	2	2	2	2	1	1	1
80%RH	1.8	3.6	2.7	2.6	.	1	1	1	1	1	1	1	1	1
80%RH	2.0	3.0	3.0	3.0	1	1	1	1	1	1	1	1	1	1
80%RH	2.0	3.8	1.4	3.0	1	1	1	1	1	1	1	1	1	1
80%RH	2.0	3.0	3.0	3.0	1	2	1	.	1	1	1	1	1	1
80%RH	5.5	0.5	5.6	0.4	.	2	2	.	2	2	2	2	2	2
80%RH	4.5	1.4	1.5	4.5	1	1	1	1	1	1	1	1	1	1

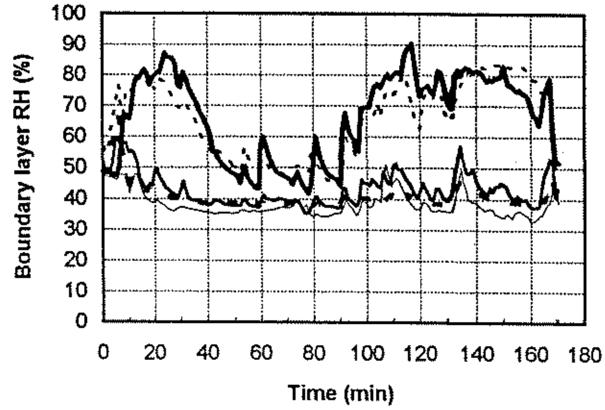
APPENDIX B

Individual Physiological Data

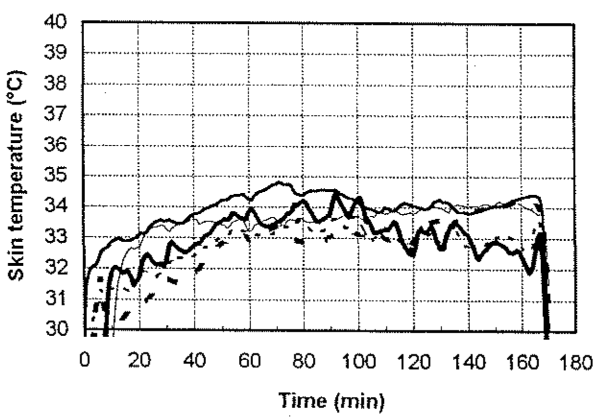
Boundary Layer Temperature



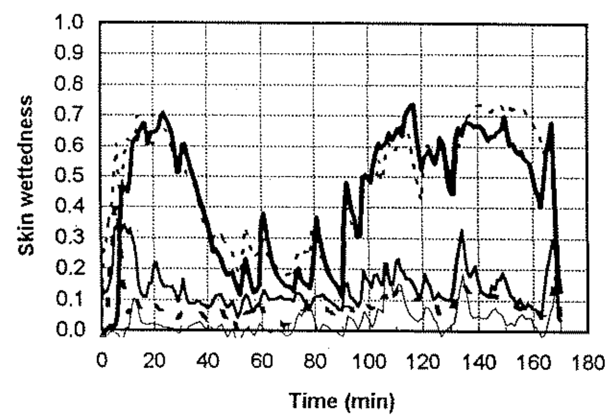
Boundary Layer RH



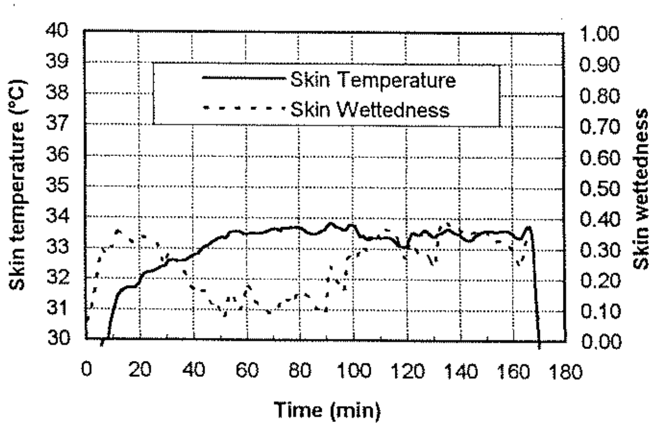
Skin Temperature

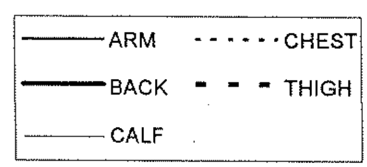


Skin Wettedness



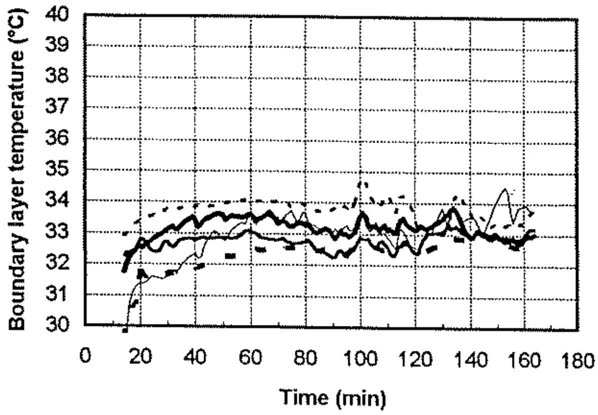
Mean Skin Temperature and Wettedness



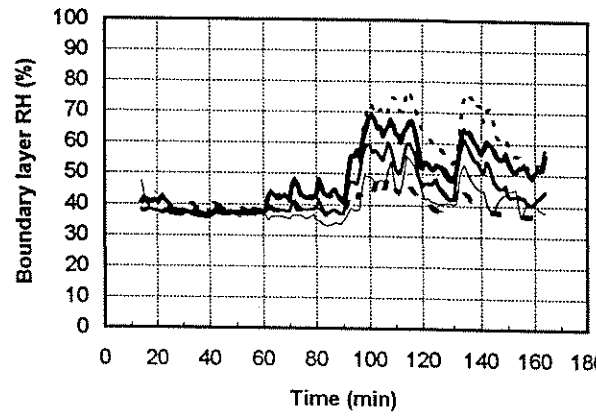


Individual Physiological Data
Subject No.57
Date: 06/16/94
Time: 1:00pm-4:00pm
RH = 50% T = 26.1°C

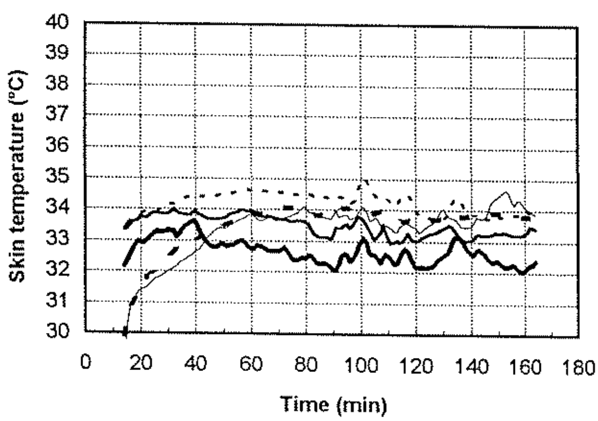
Boundary Layer Temperature



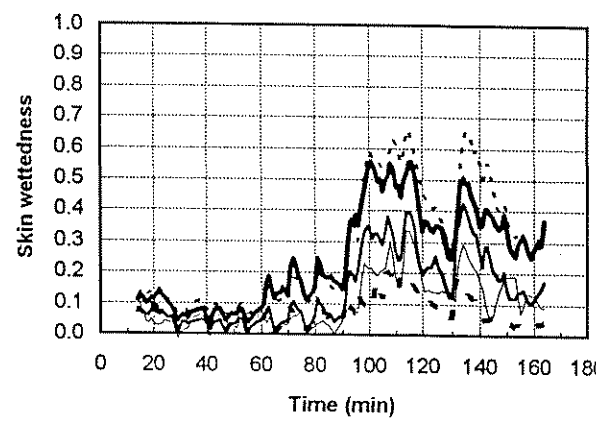
Boundary Layer RH



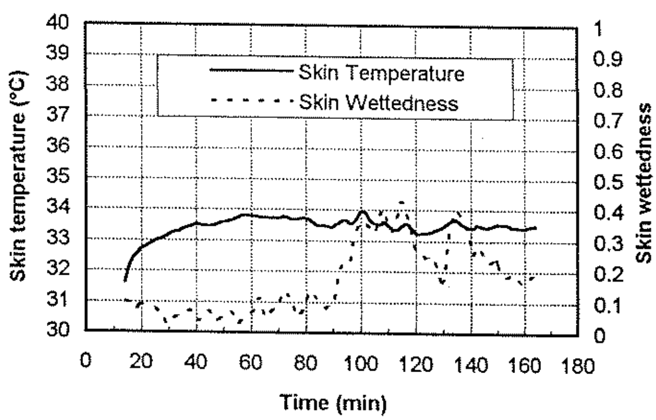
Skin Temperature

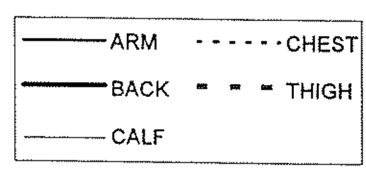


Skin Wettedness



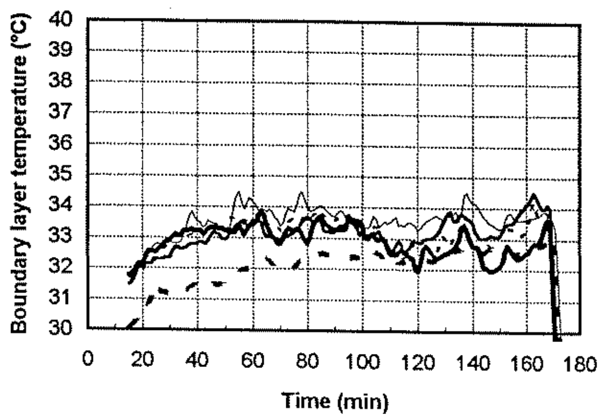
Mean Skin Temperature and Wettedness



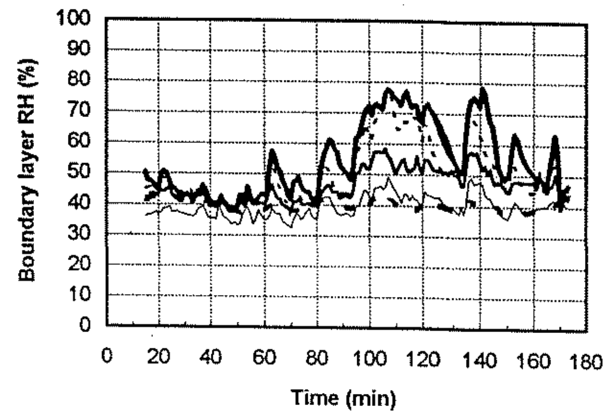


Individual Physiological Data
Subject No.66
Date: 06/21/94
Time: 7:00pm-10:00pm
RH = 50% T = 26.1°C

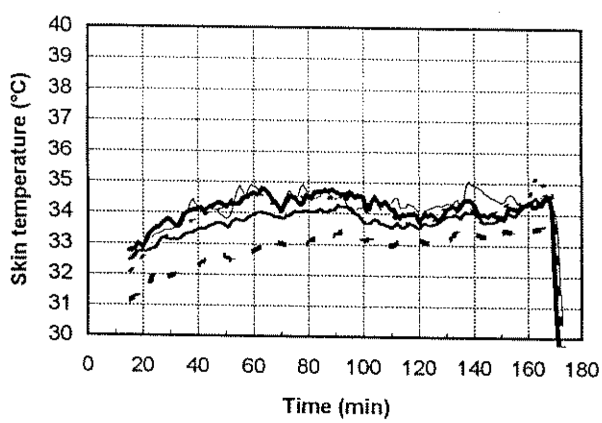
Boundary Layer Temperature



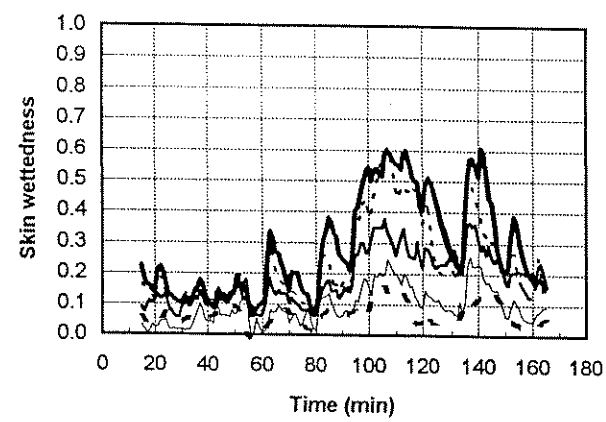
Boundary Layer RH

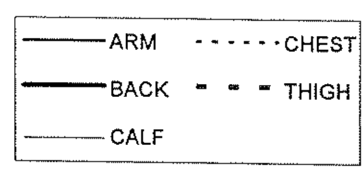


Skin Temperature

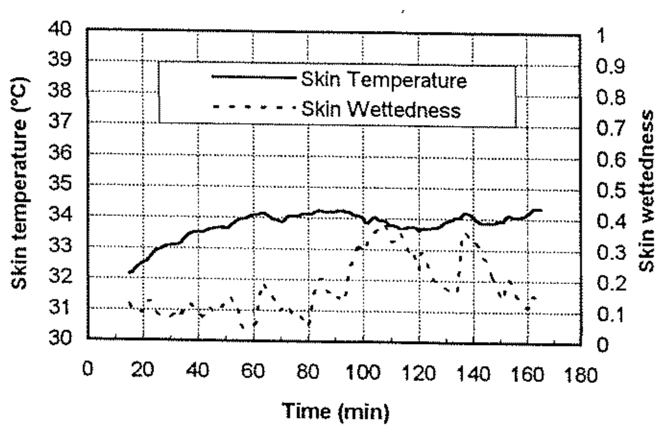


Skin Wettedness



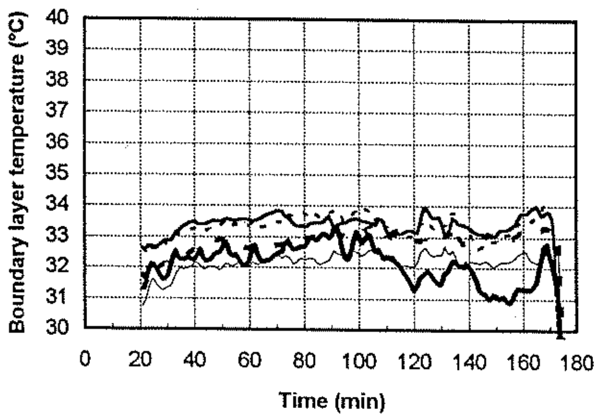


Mean Skin Temperature and Wettedness

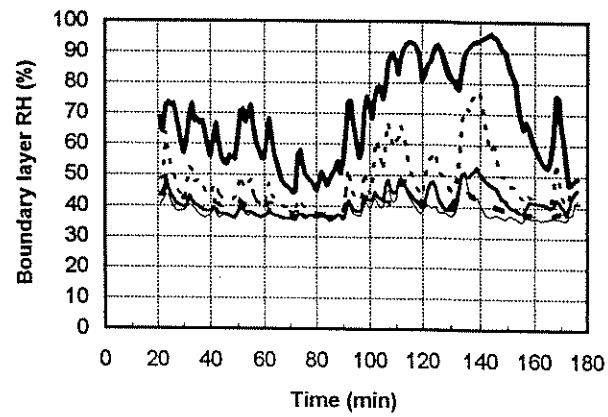


Individual Physiological Data
Subject No.69
Date: 06/22/94
Time: 1:00pm-4:00pm
RH = 50% T = 26.1°C

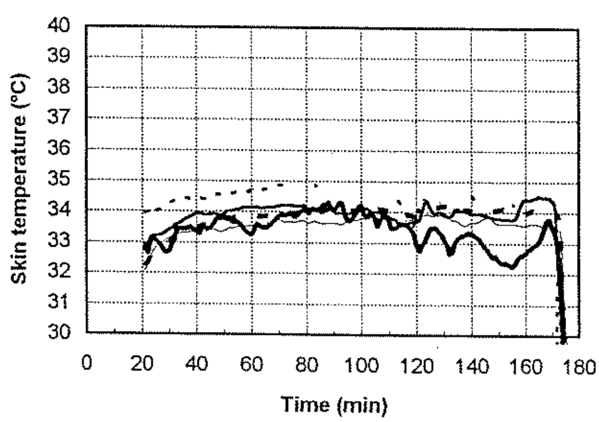
Boundary Layer Temperature



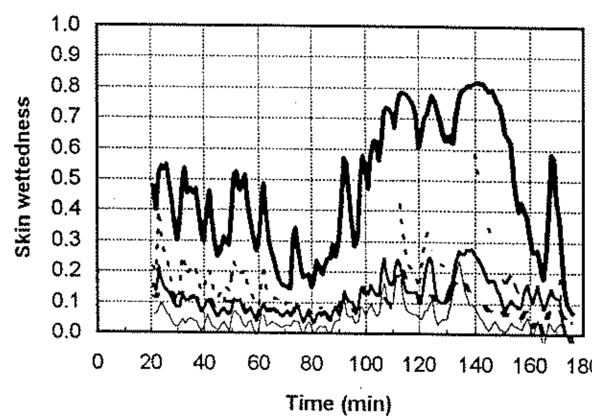
Boundary Layer RH

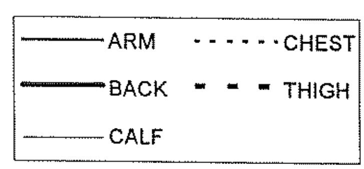


Skin Temperature

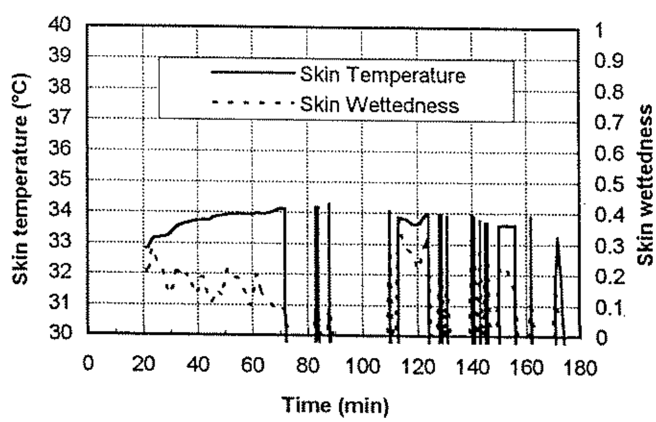


Skin Wettedness



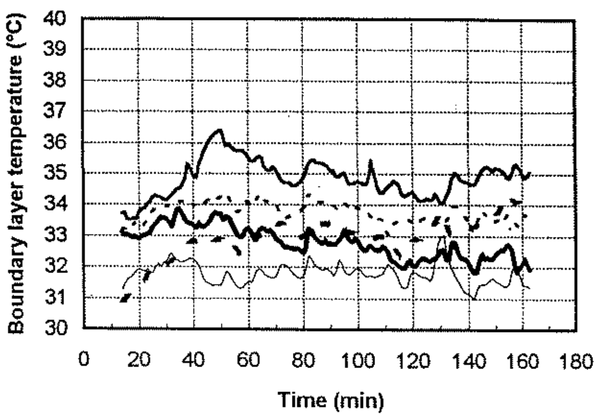


Mean Skin Temperature and Wettedness

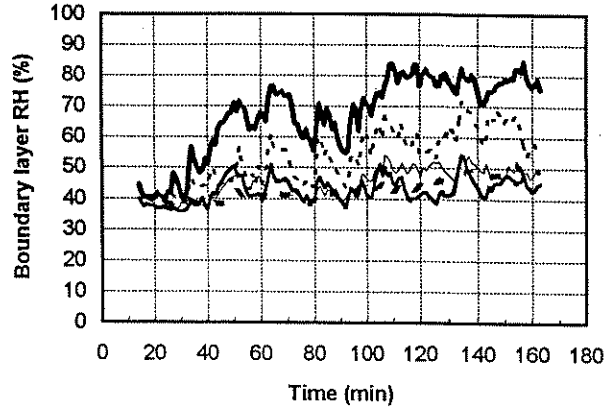


Individual Physiological Data
Subject No.87
Date: 07/08/94
Time: 1:00pm-4:00pm
RH = 50% T = 26.1°C

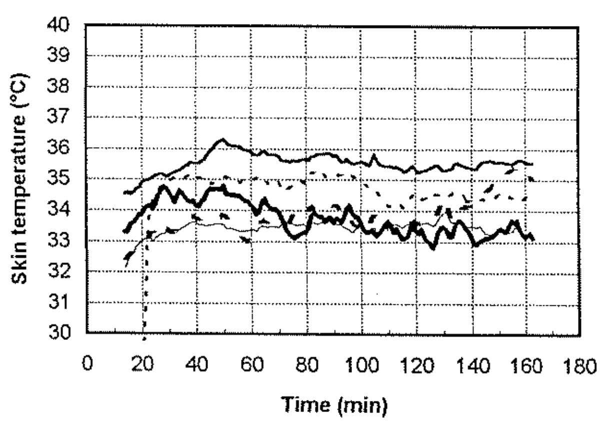
Boundary Layer Temperature



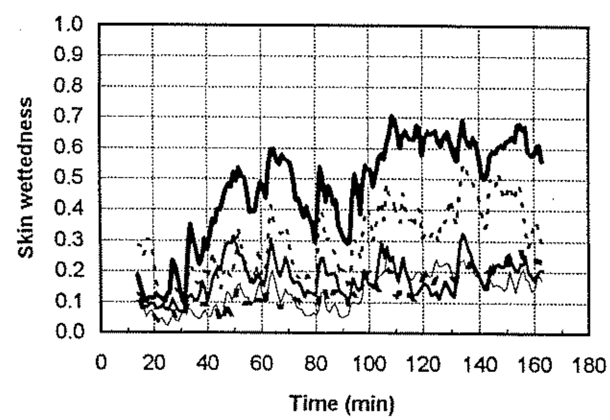
Boundary Layer RH



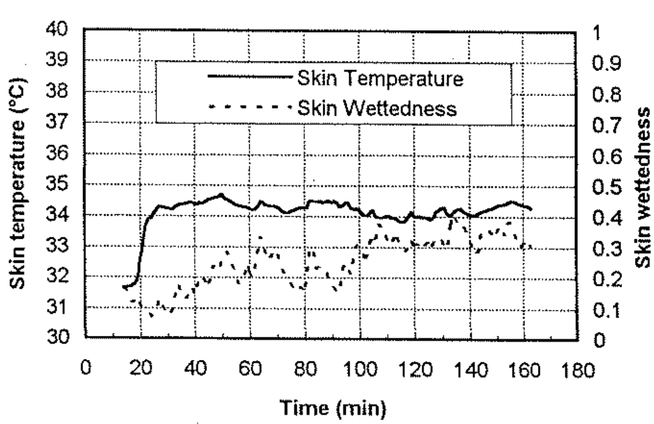
Skin Temperature

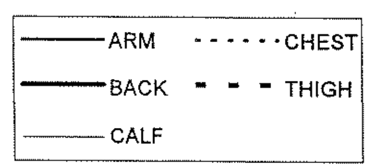


Skin Wettedness



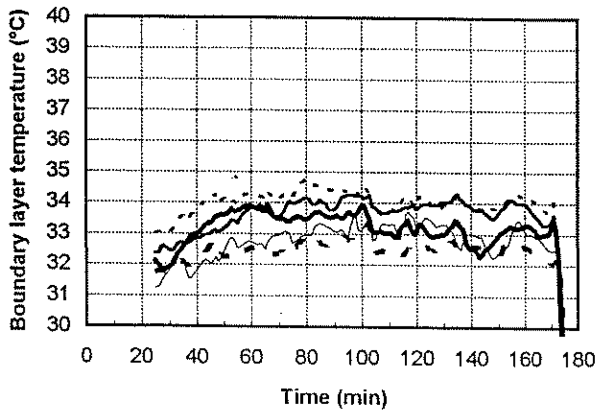
Mean Skin Temperature and Wettedness



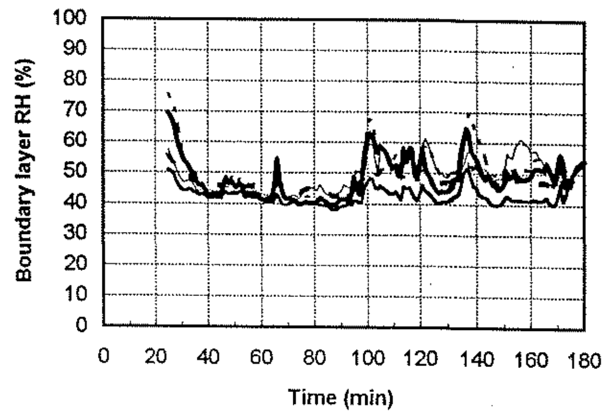


Individual Physiological Data
Subject No.90
Date: 07/08/94
Time: 7:00pm-10:00pm
RH = 50% T = 26.1°C

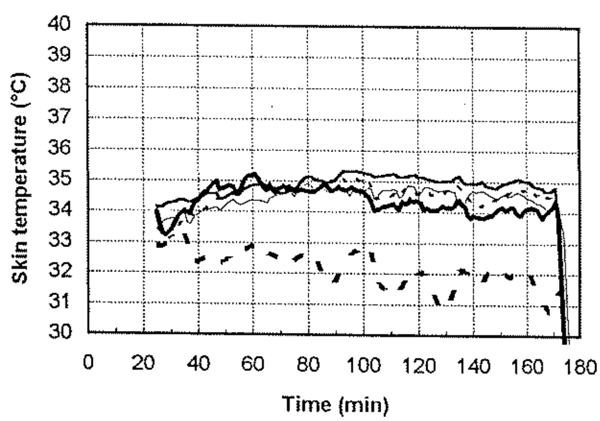
Boundary Layer Temperature



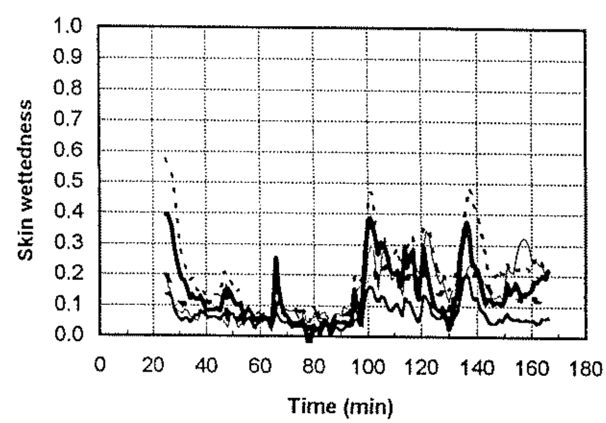
Boundary Layer RH



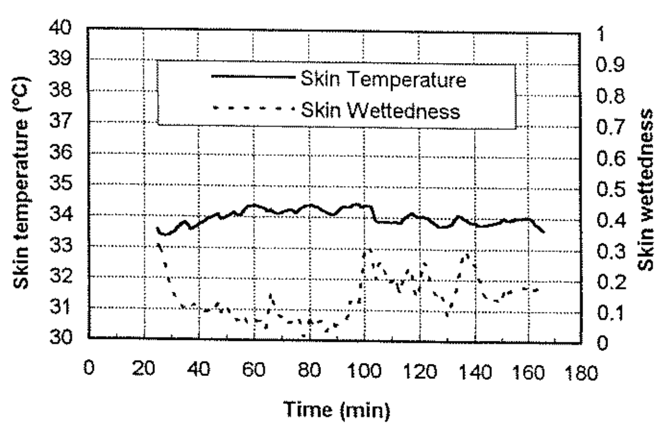
Skin Temperature

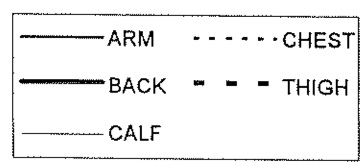


Skin Wettedness



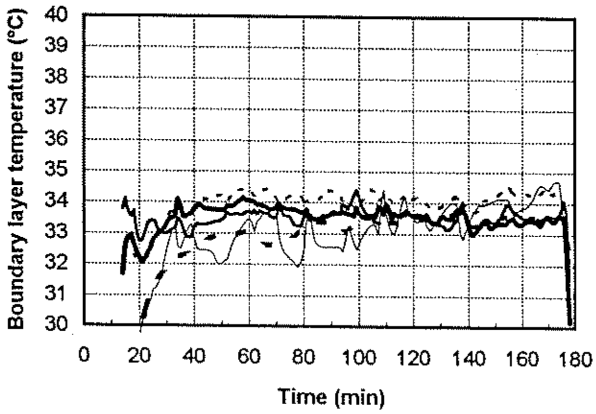
Mean Skin Temperature and Wettedness



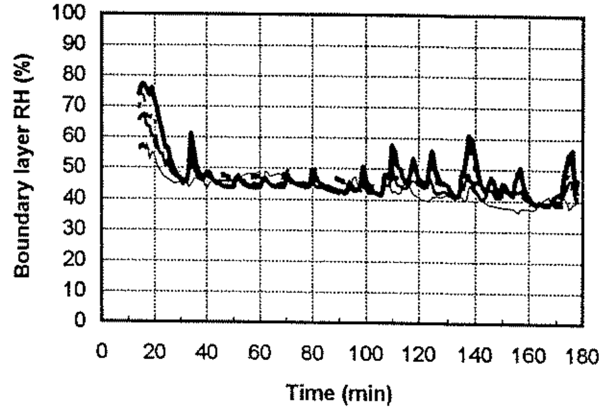


Individual Physiological Data
Subject No.22
Date: 06/02/94
Time: 7:00pm-10:00pm
RH = 60% T = 25.8°C

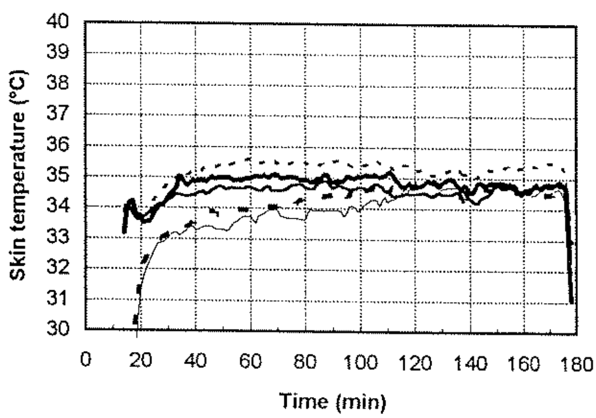
Boundary Layer Temperature



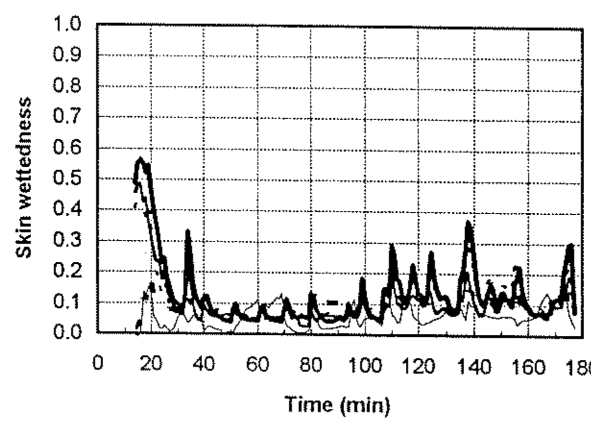
Boundary Layer RH

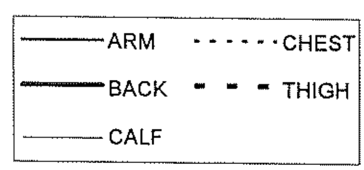


Skin Temperature

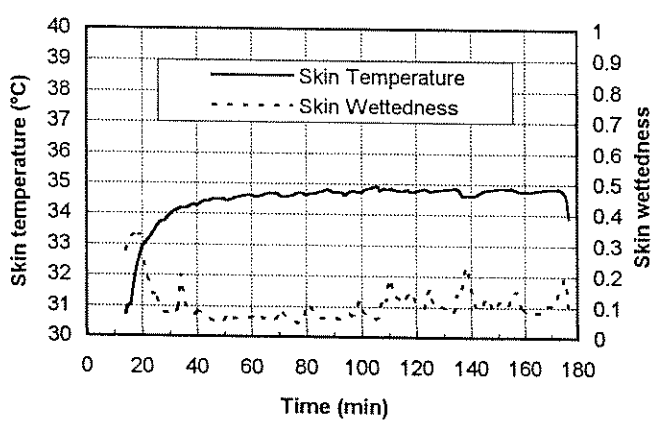


Skin Wettedness



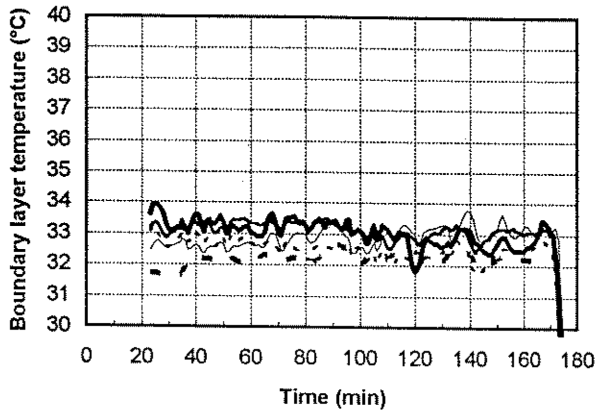


Mean Skin Temperature and Wettedness

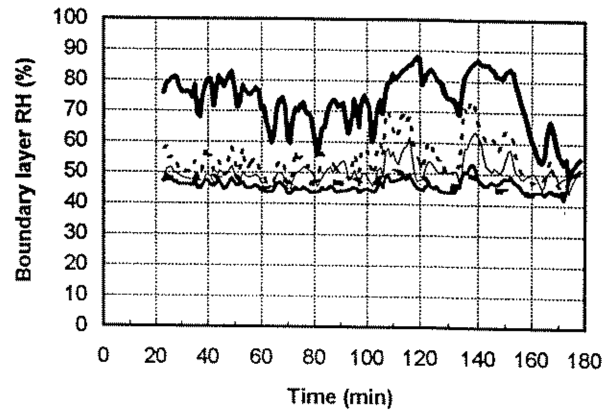


Individual Physiological Data
Subject No.45
Date: 06/13/94
Time: 1:00pm-4:00pm
RH = 60% T = 25.8°C

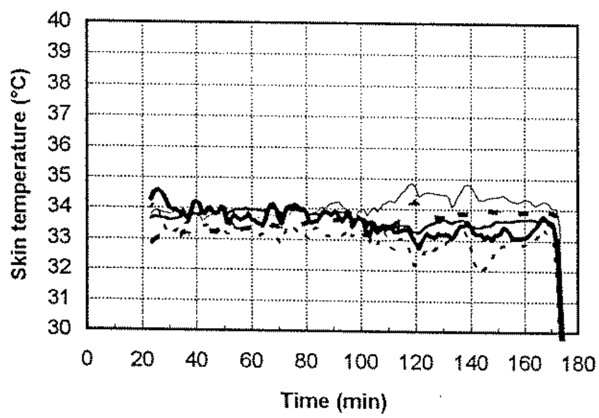
Boundary Layer Temperature



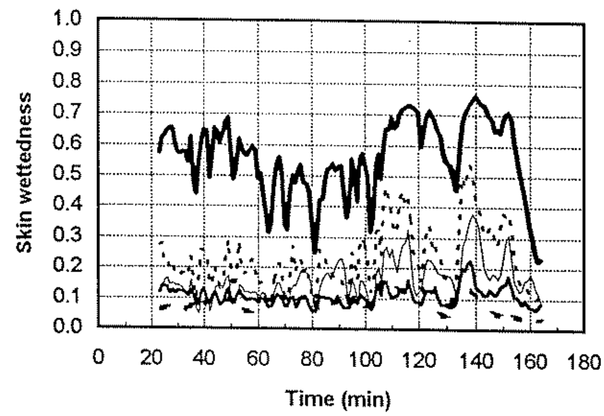
Boundary Layer RH



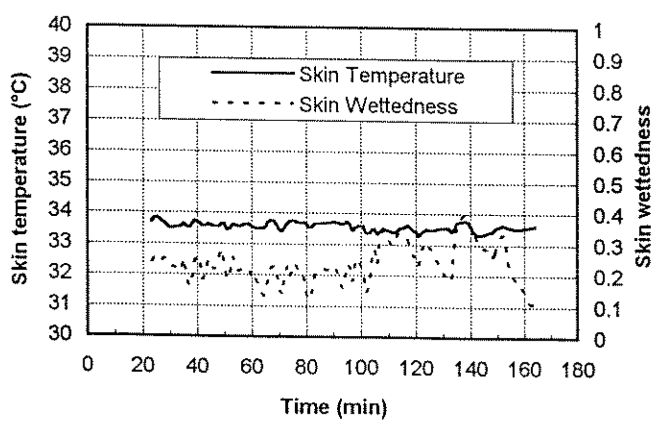
Skin Temperature

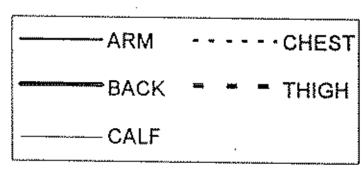


Skin Wettedness



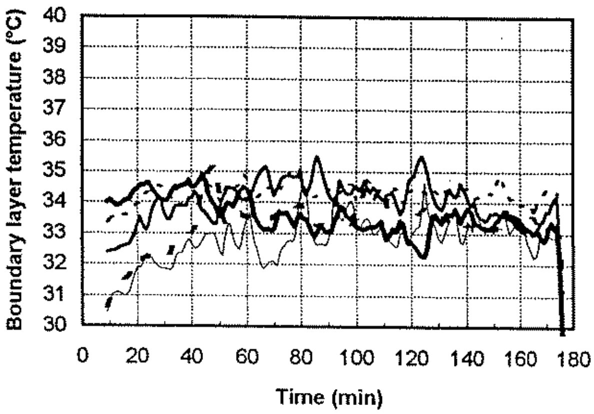
Mean Skin Temperature and Wettedness



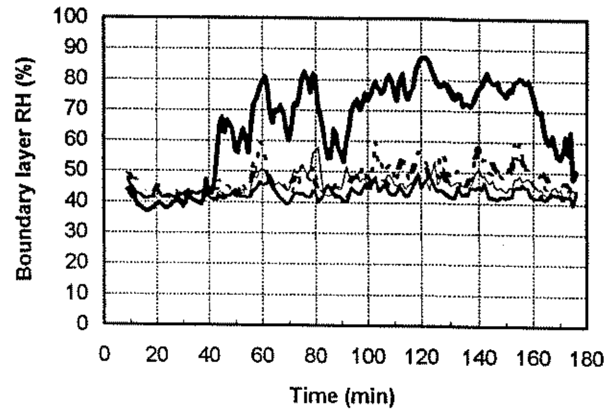


Individual Physiological Data
Subject No.48
Date: 06/13/94
Time: 7:00pm-10:00pm
RH = 60% T = 25.8°C

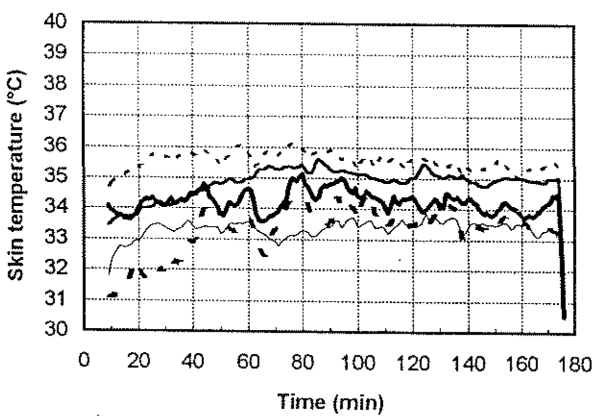
Boundary Layer Temperature



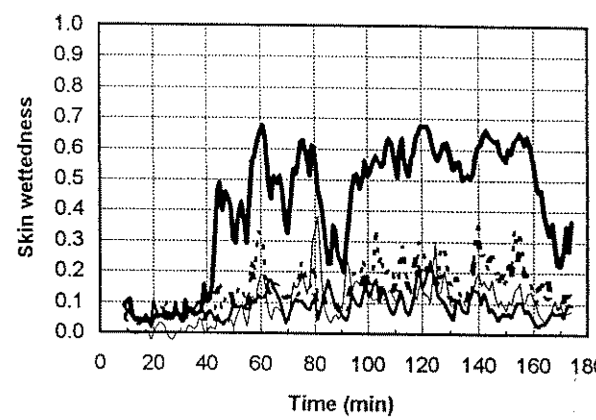
Boundary Layer RH



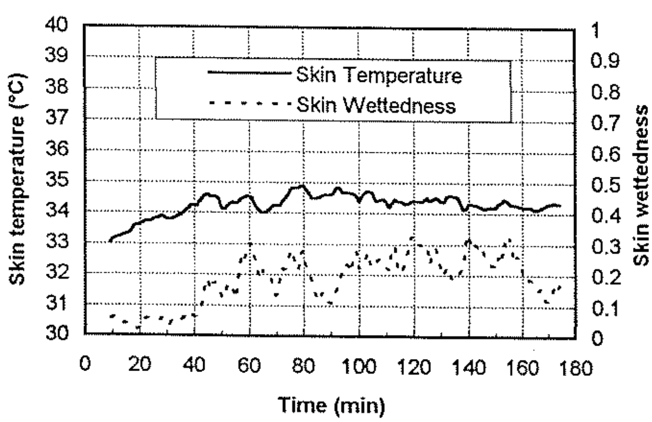
Skin Temperature

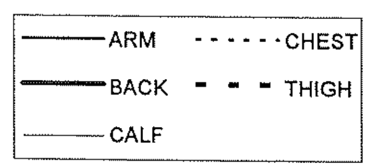


Skin Wettedness



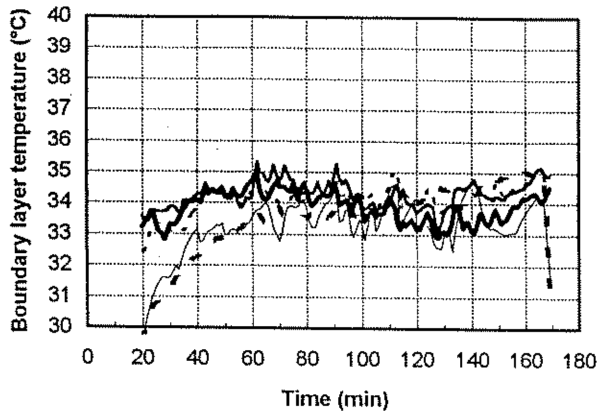
Mean Skin Temperature and Wettedness



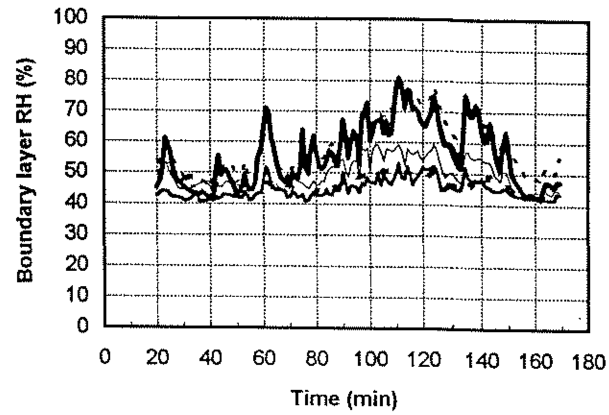


Individual Physiological Data
Subject No.51
Date: 06/14/94
Time: 1:00pm-4:00pm
RH = 60% T = 25.8°C

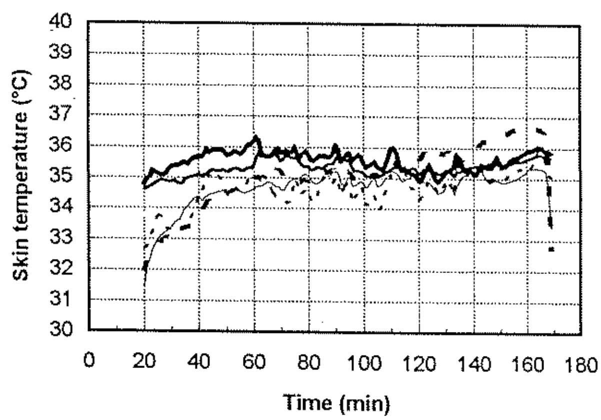
Boundary Layer Temperature



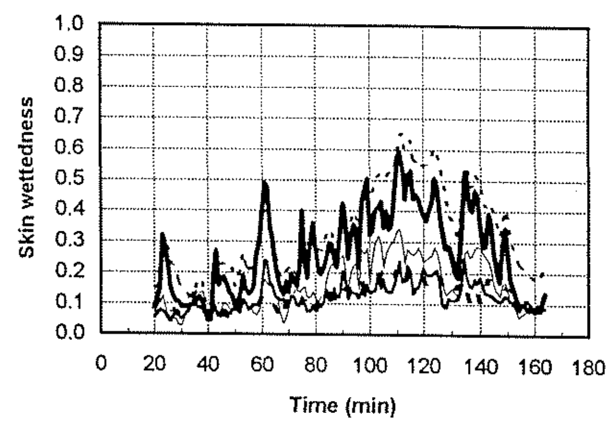
Boundary Layer RH



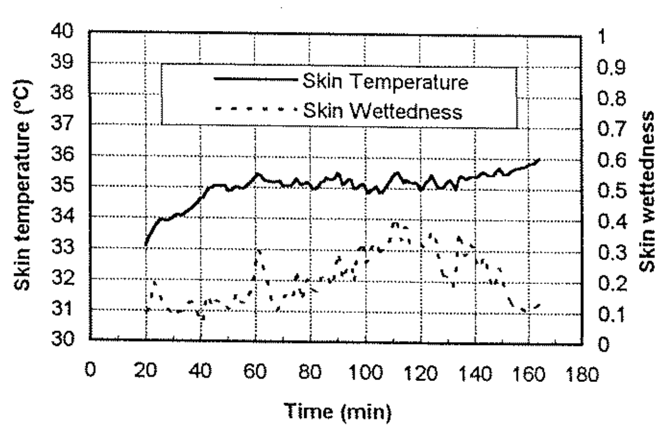
Skin Temperature

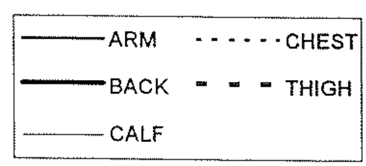


Skin Wettedness



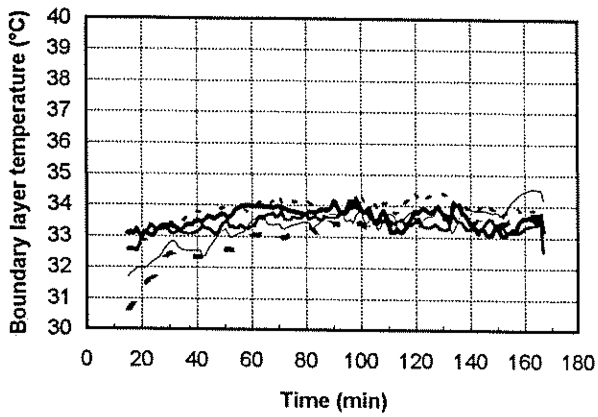
Mean Skin Temperature and Wettedness



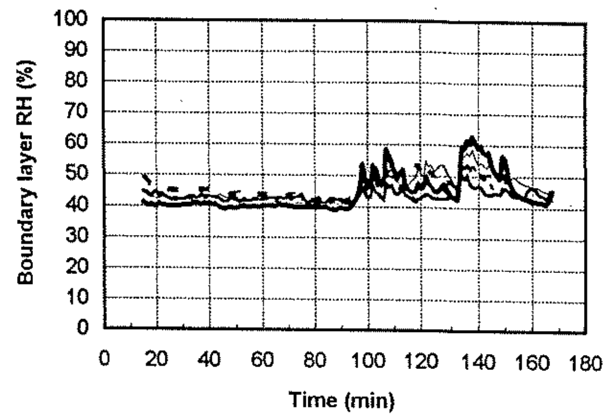


Individual Physiological Data
Subject No.54
Date: 06/14/94
Time: 7:00pm-10:00pm
RH = 60% T = 25.8°C

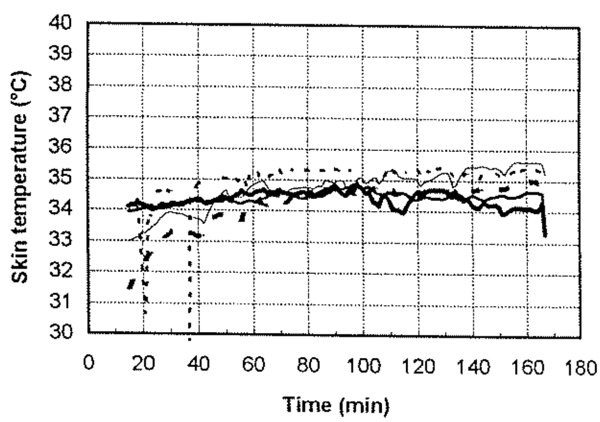
Boundary Layer Temperature



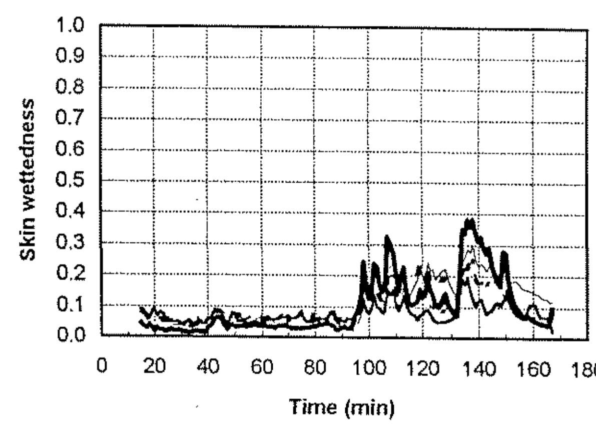
Boundary Layer RH



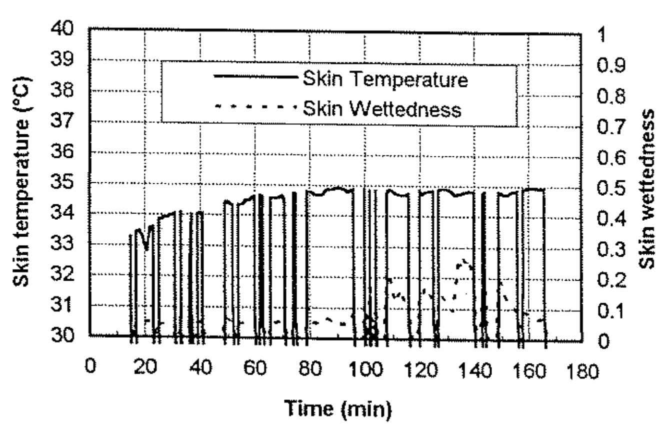
Skin Temperature

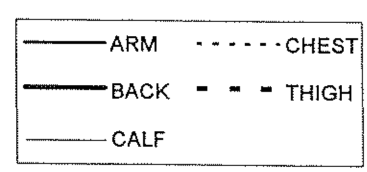


Skin Wettedness



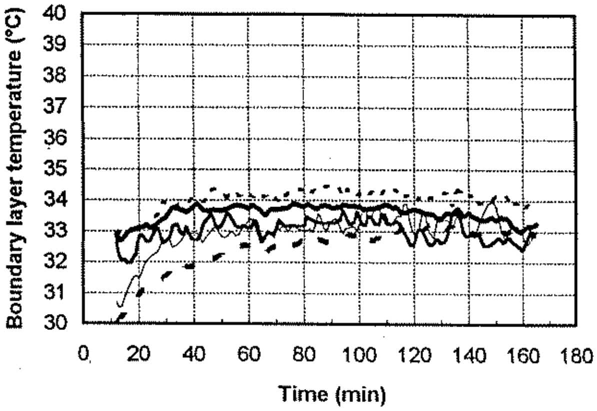
Mean Skin Temperature and Wettedness



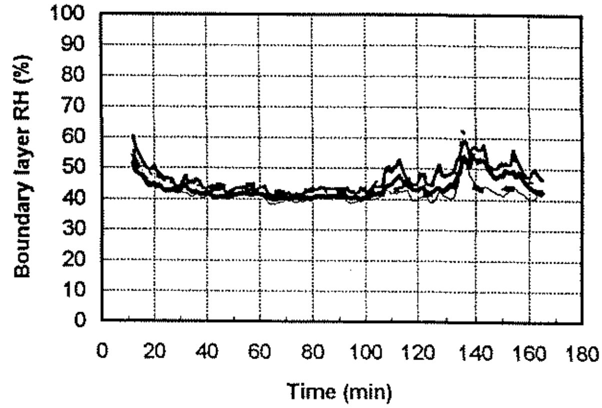


Individual Physiological Data
Subject No.81
Date: 07/07/94
Time: 1:00pm-4:00pm
RH = 60% T = 25.8°C

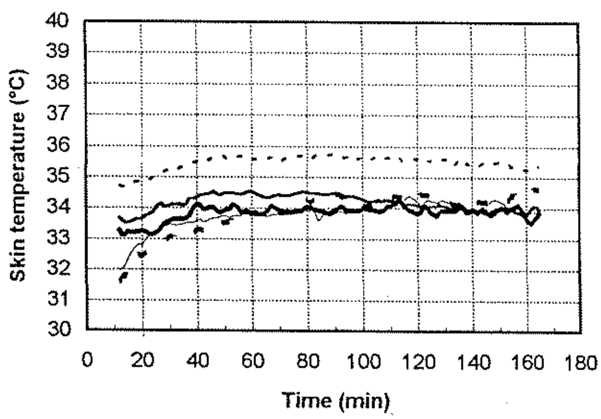
Boundary Layer Temperature



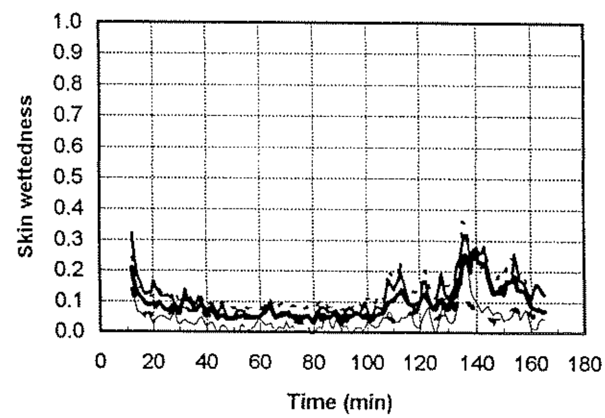
Boundary Layer RH



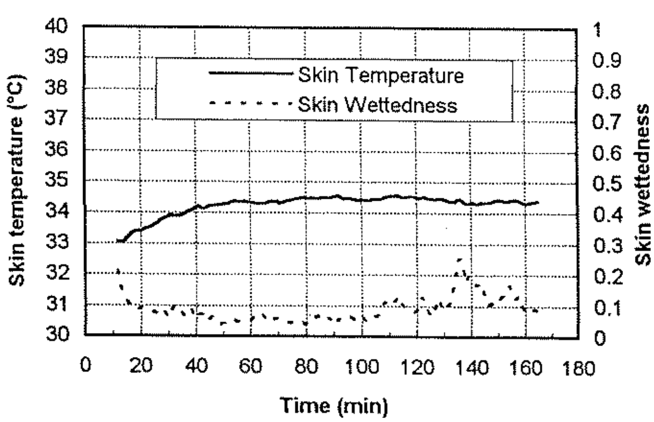
Skin Temperature

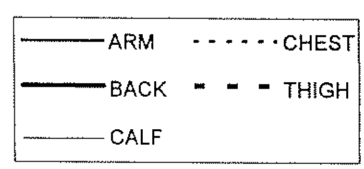


Skin Wettedness



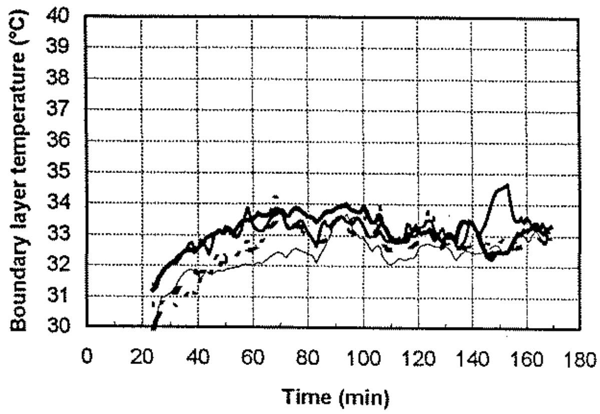
Mean Skin Temperature and Wettedness



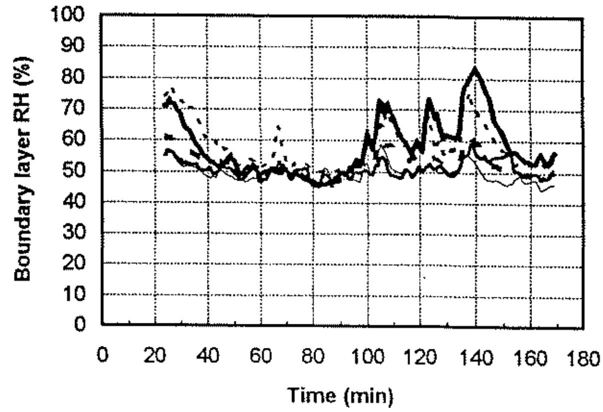


Individual Physiological Data
Subject No.84
Date: 07/07/94
Time: 7:00pm-10:00pm
RH = 60% T = 25.8°C

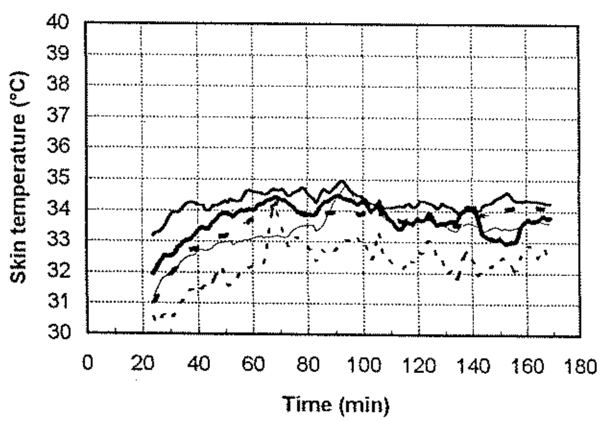
Boundary Layer Temperature



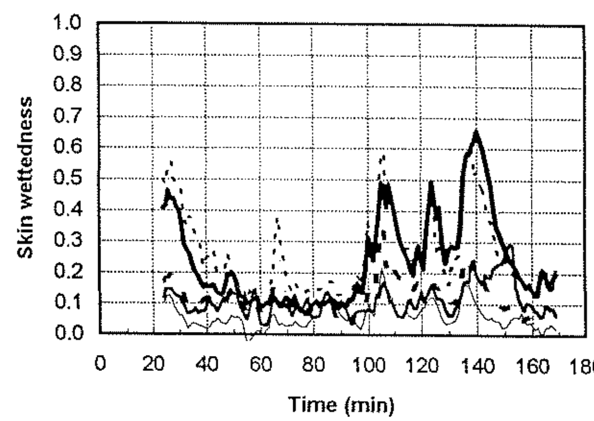
Boundary Layer RH



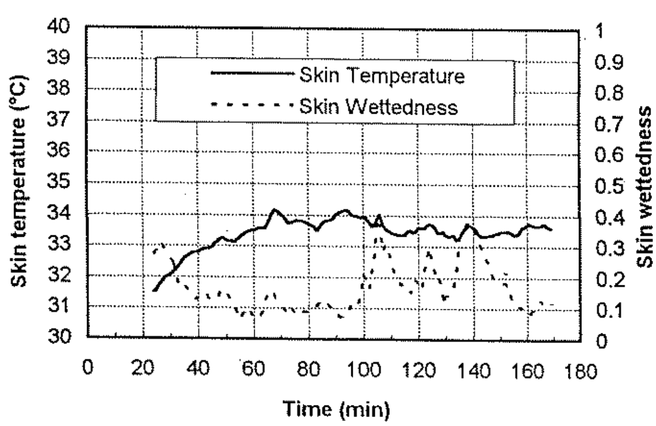
Skin Temperature

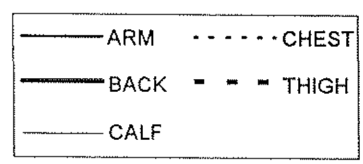


Skin Wettedness



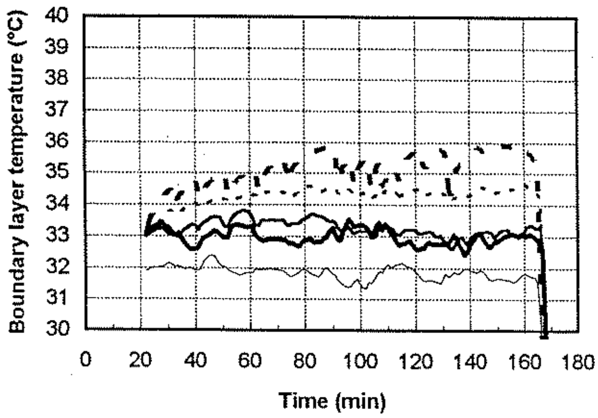
Mean Skin Temperature and Wettedness



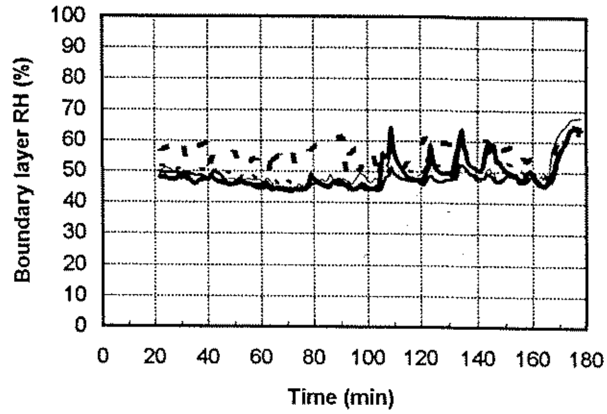


Individual Physiological Data
Subject No.16
Date: 06/01/94
Time: 7:00pm-10:00pm
RH = 70% T = 25.3°C

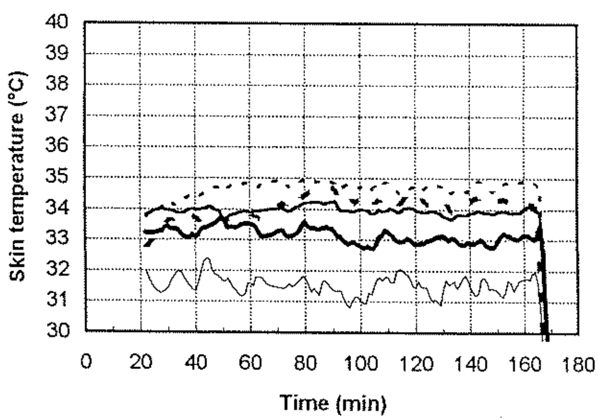
Boundary Layer Temperature



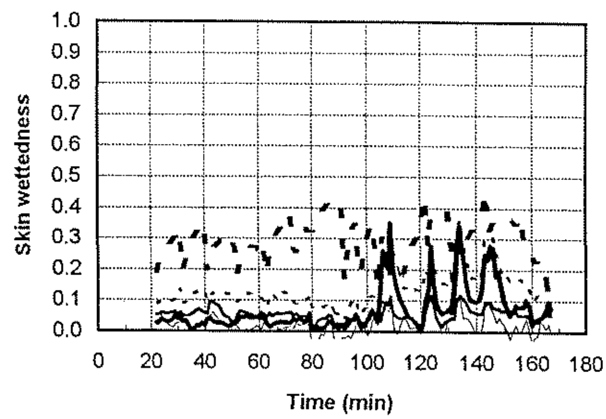
Boundary Layer RH



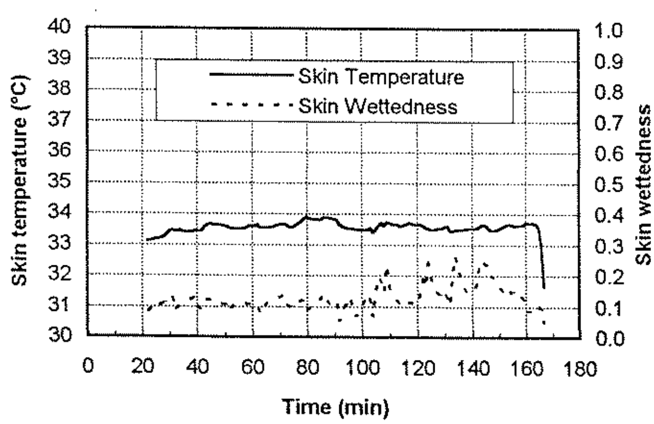
Skin Temperature

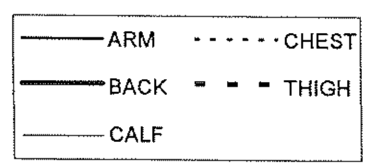


Skin Wettedness



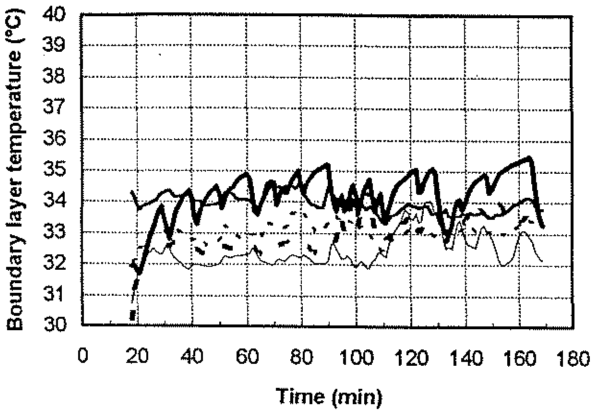
Mean Skin Temperature and Wettedness



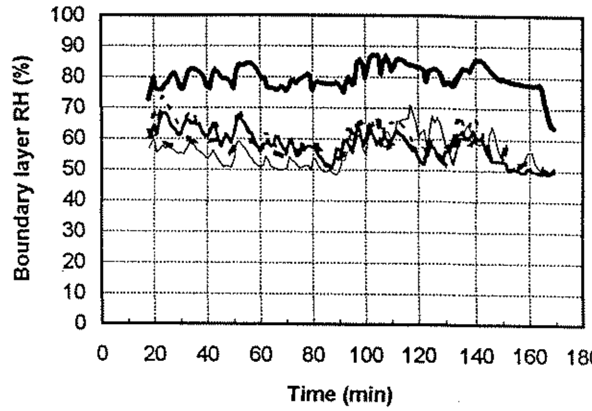


Individual Physiological Data
Subject No.19
Date: 06/02/94
Time: 1:00pm-4:00pm
RH = 70% T = 25.3°C

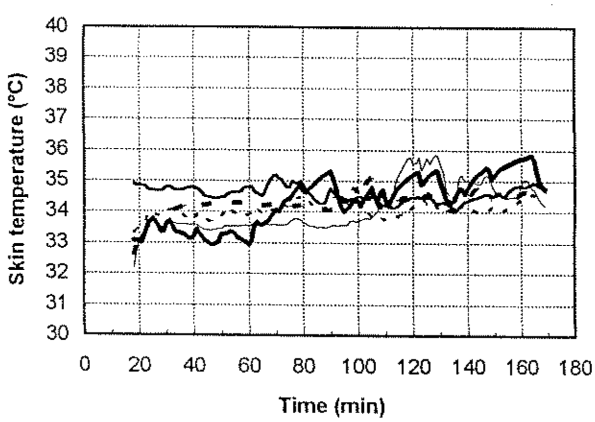
Boundary Layer Temperature



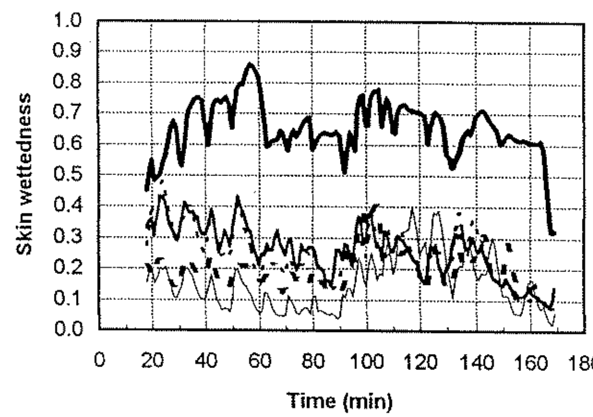
Boundary Layer RH



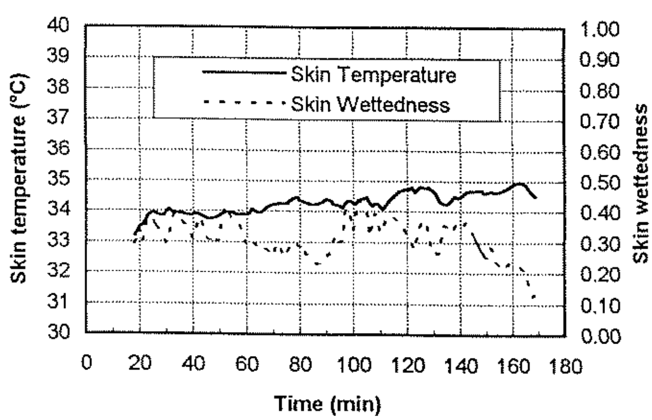
Skin Temperature

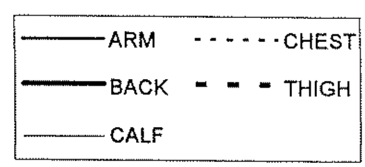


Skin Wettedness



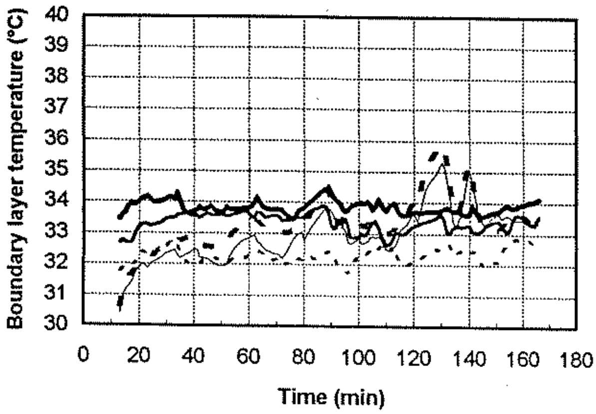
Mean Skin Temperature and Wettedness



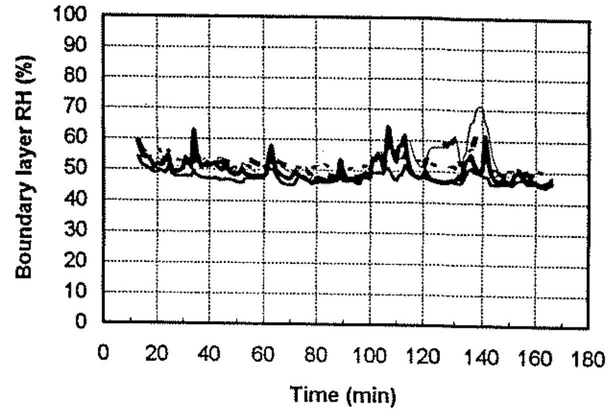


Individual Physiological Data
Subject No.37
Date: 06/09/94
Time: 1:00pm-4:00pm
RH = 70% T = 25.3°C

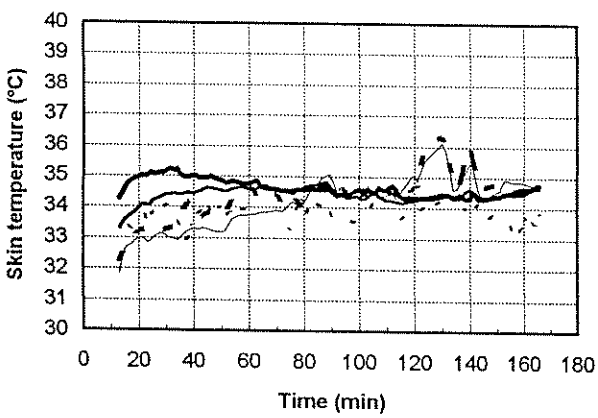
Boundary Layer Temperature



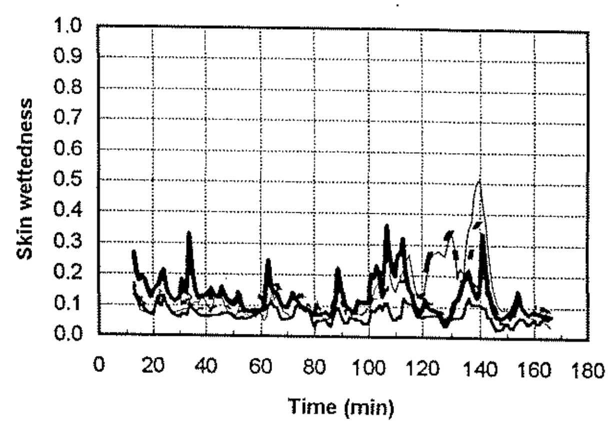
Boundary Layer RH



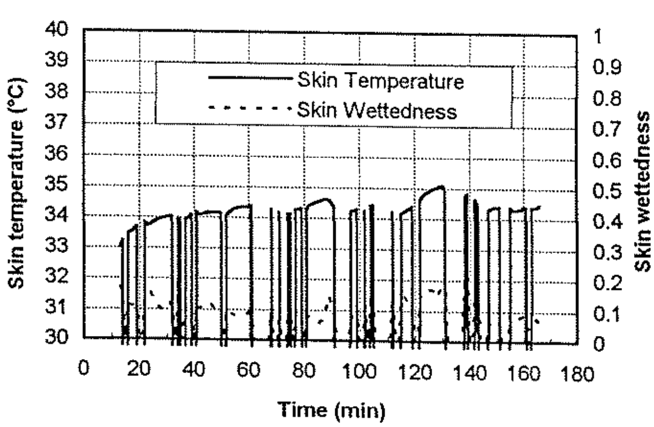
Skin Temperature

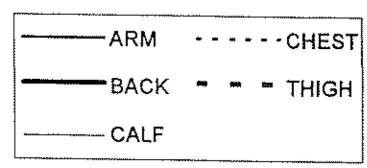


Skin Wettedness



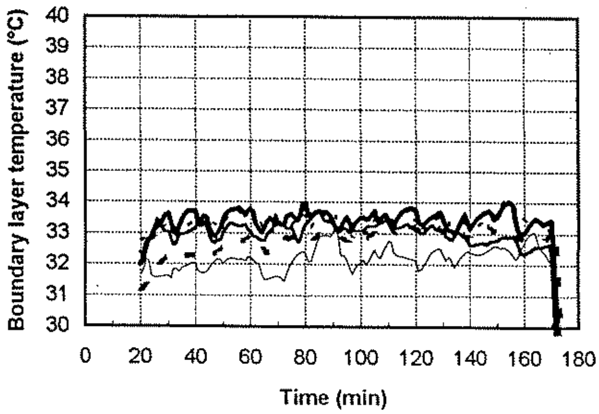
Mean Skin Temperature and Wettedness



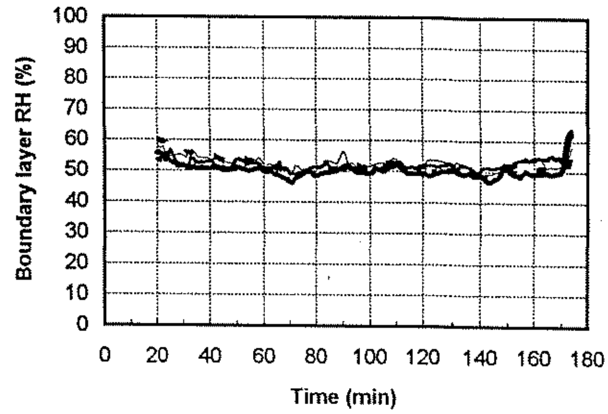


Individual Physiological Data
Subject No.78
Date: 07/06/94
Time: 7:00pm-10:00pm
RH = 70% T = 25.3°C

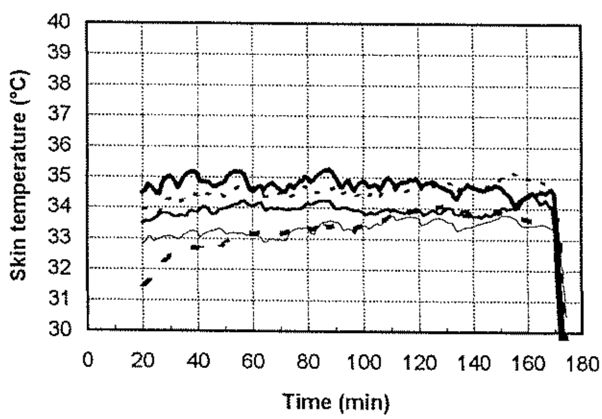
Boundary Layer Temperature



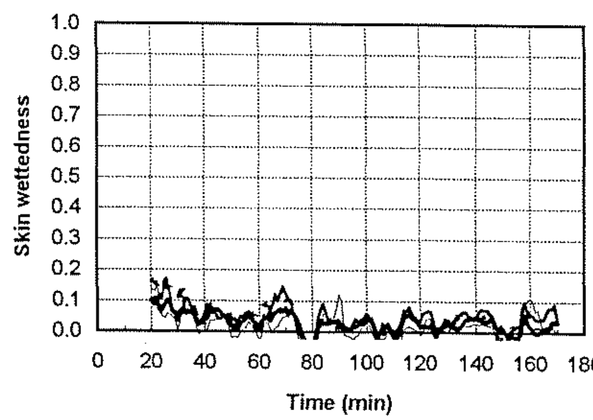
Boundary Layer RH

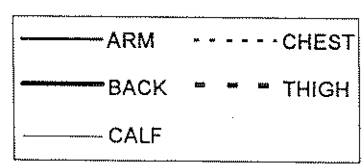


Skin Temperature

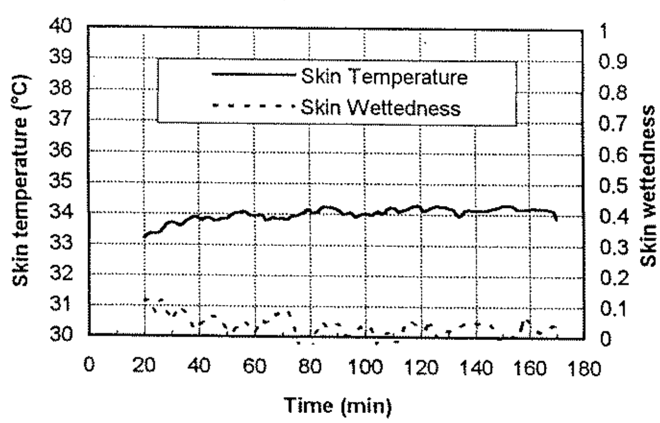


Skin Wettedness



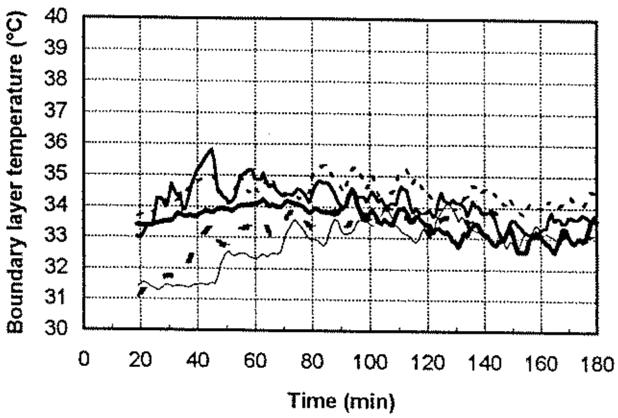


Mean Skin Temperature and Wettedness

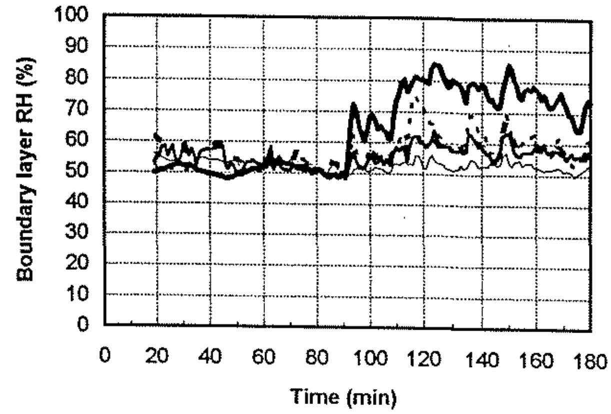


Individual Physiological Data
Subject No.24
Date: 06/03/94
Time: 1:00pm-4:00pm
RH = 80% T = 24.9°C

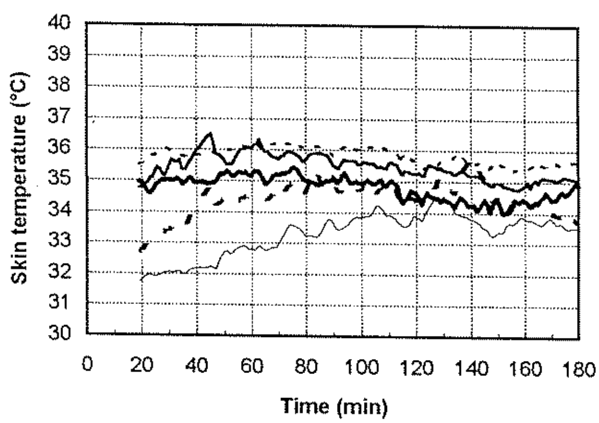
Boundary Layer Temperature



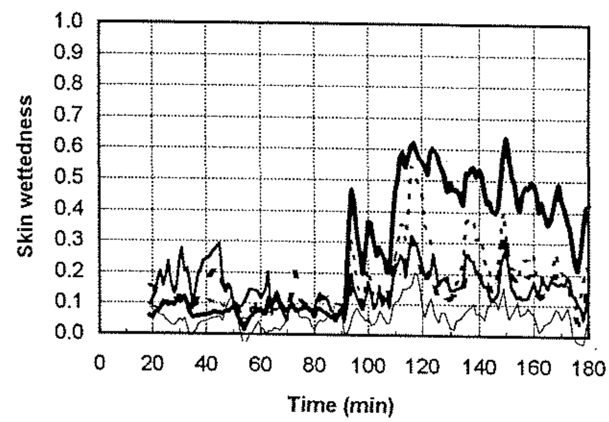
Boundary Layer RH

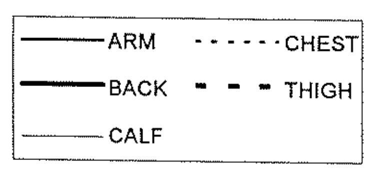


Skin Temperature

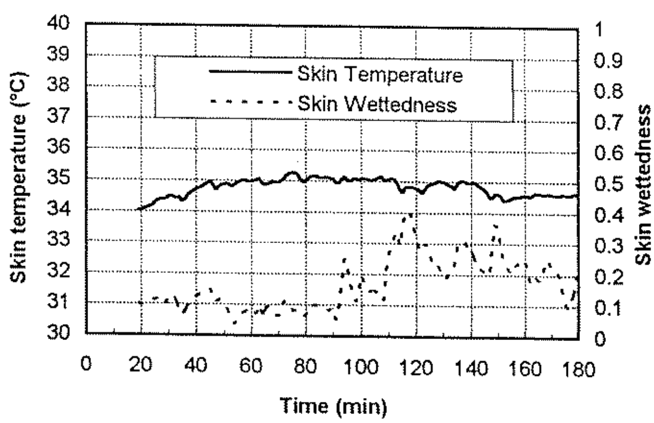


Skin Wettedness



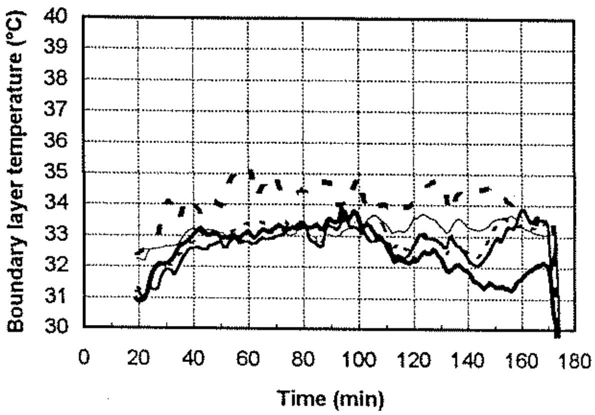


Mean Skin Temperature and Wettedness

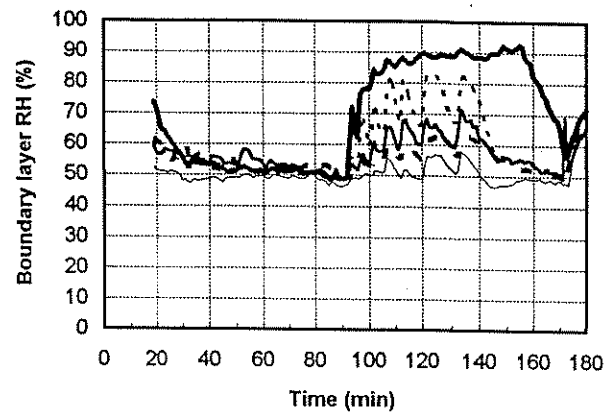


Individual Physiological Data
Subject No.27
Date: 06/07/94
Time: 1:00pm-4:00pm
RH = 80% T = 24.9°C

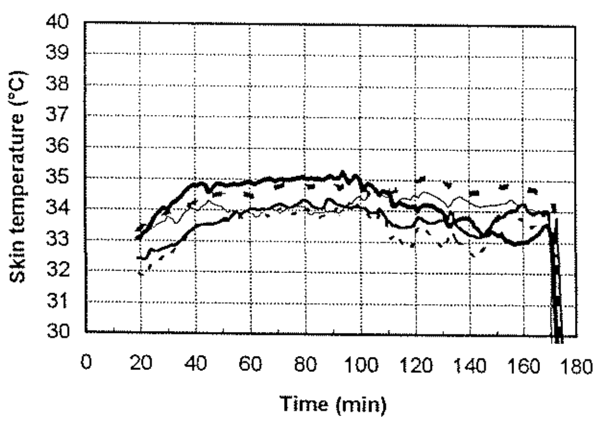
Boundary Layer Temperature



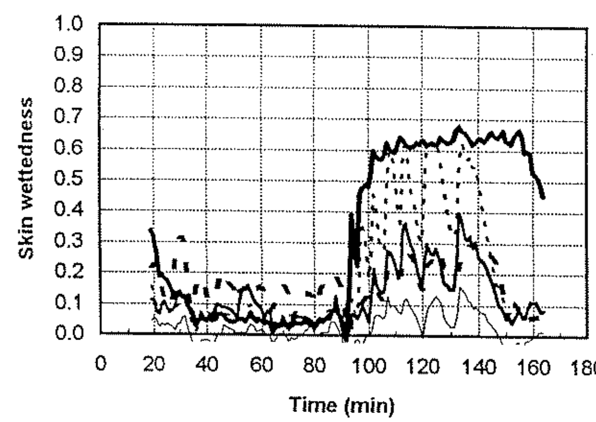
Boundary Layer RH

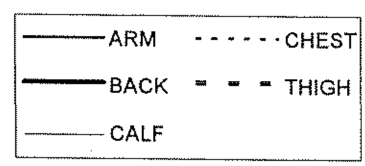


Skin Temperature

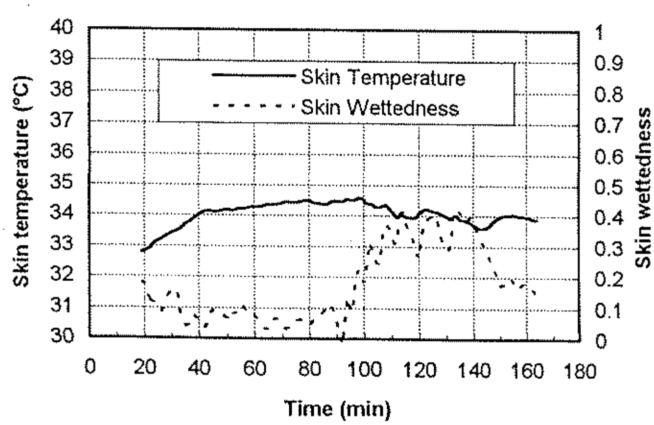


Skin Wettedness



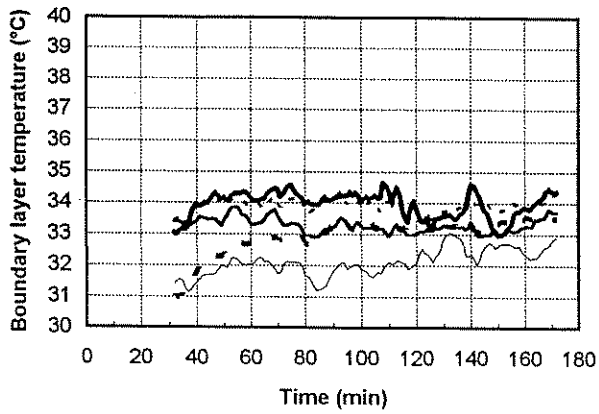


Mean Skin Temperature and Wettedness

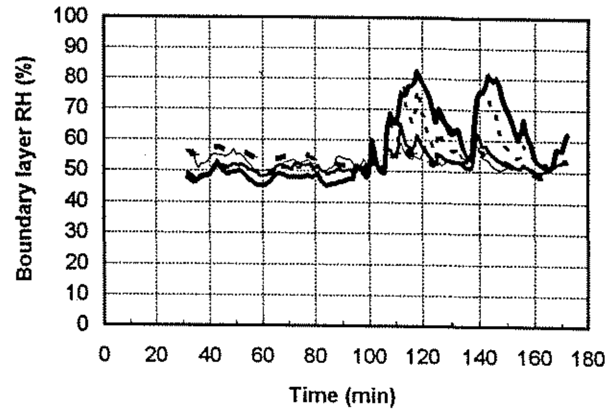


Individual Physiological Data
Subject No.28
Date: 06/07/94
Time: 7:00pm-10:00pm
RH = 80% T = 24.9°C

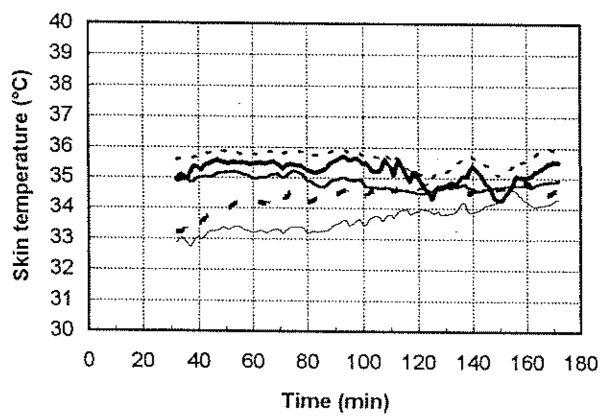
Boundary Layer Temperature



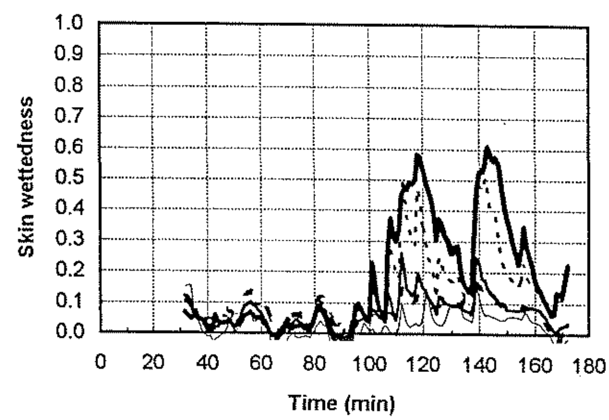
Boundary Layer RH

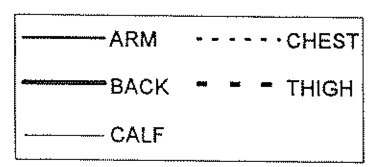


Skin Temperature

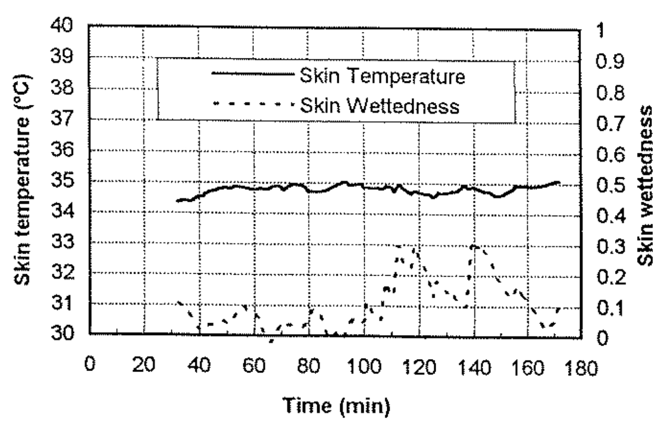


Skin Wettedness



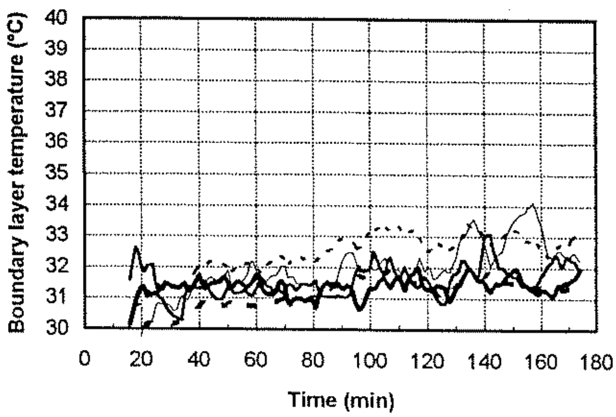


Mean Skin Temperature and Wettedness

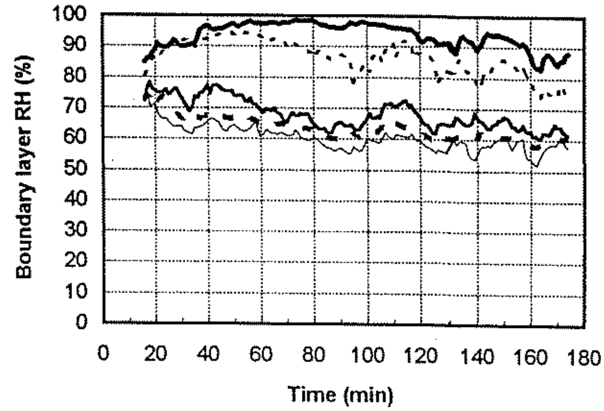


Individual Physiological Data
Subject No.34
Date: 06/08/94
Time: 7:00pm-10:00pm
RH = 80% T = 24.9°C

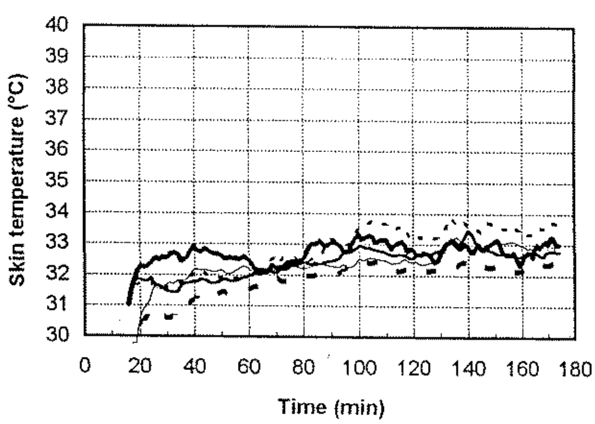
Boundary Layer Temperature



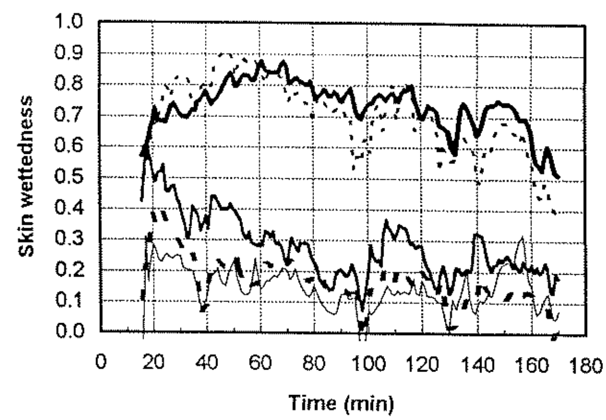
Boundary Layer RH



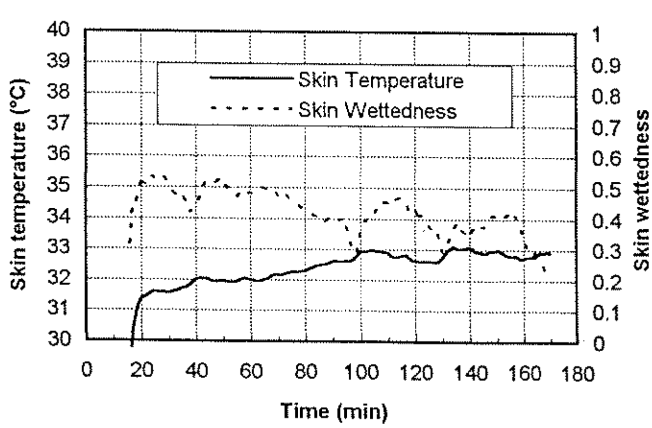
Skin Temperature

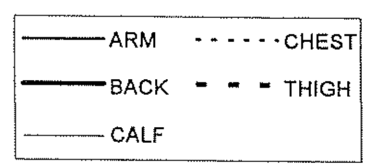


Skin Wettedness



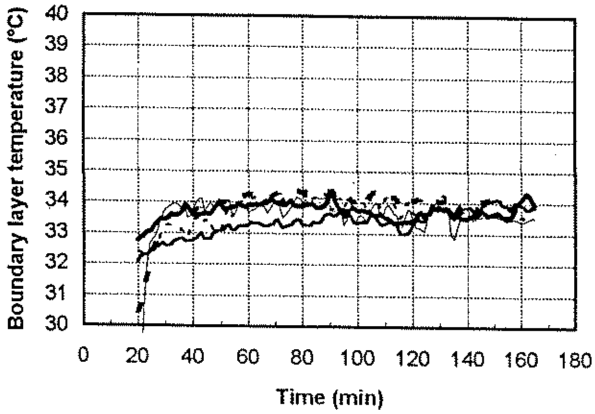
Mean Skin Temperature and Wettedness



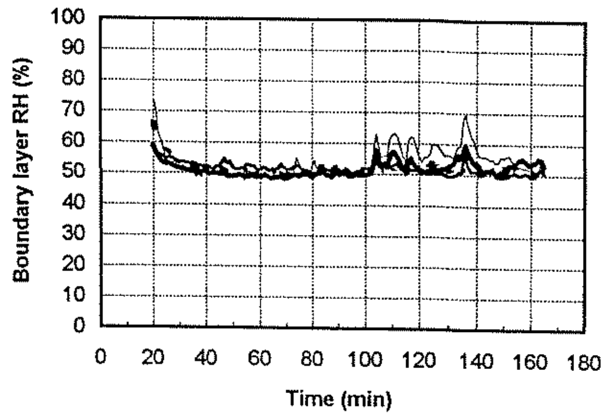


Individual Physiological Data
Subject No.40
Date: 06/09/94
Time: 7:00pm-10:00pm
RH = 80% T = 24.9°C

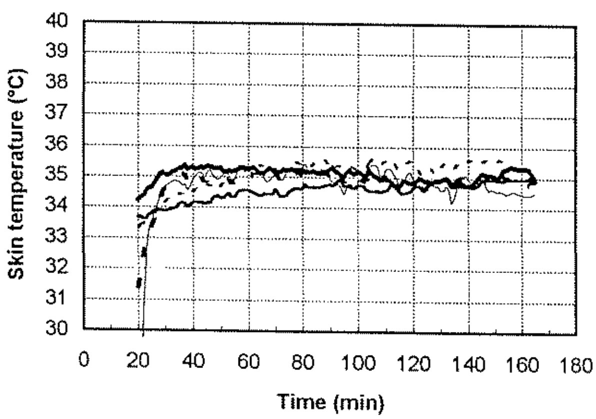
Boundary Layer Temperature



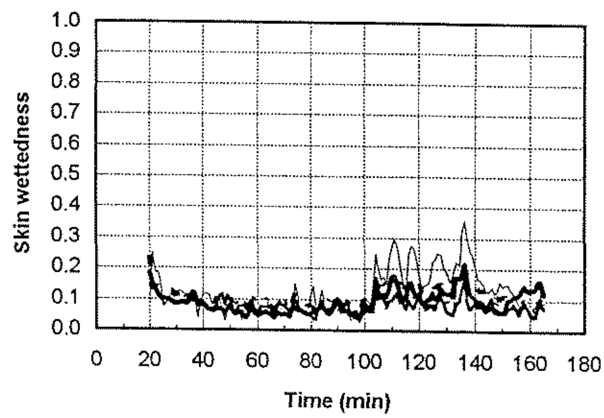
Boundary Layer RH

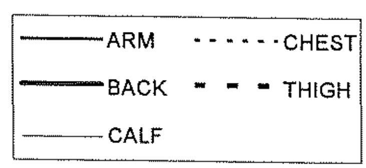


Skin Temperature

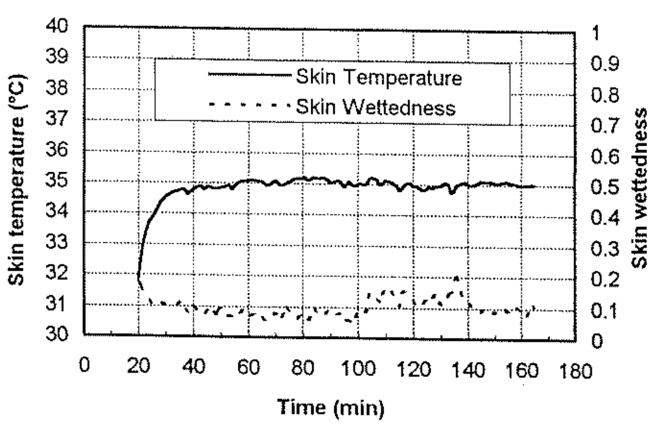


Skin Wettedness



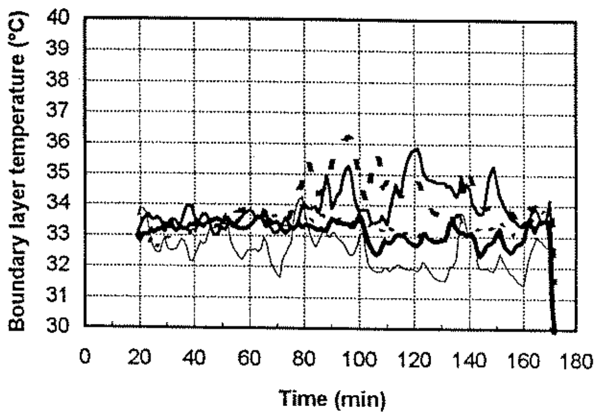


Mean Skin Temperature and Wettedness

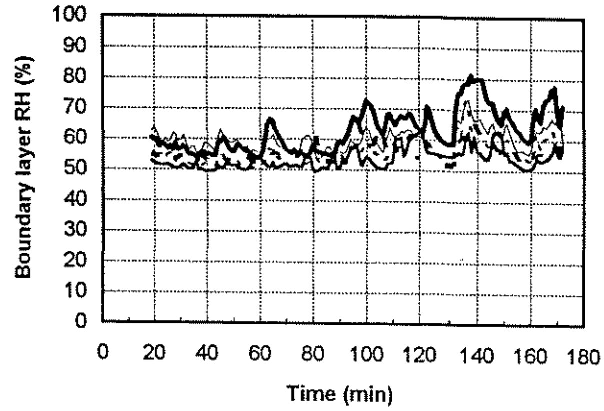


Individual Physiological Data
Subject No.73
Date: 07/05/94
Time: 7:00pm-10:00pm
RH = 80% T = 24.9°C

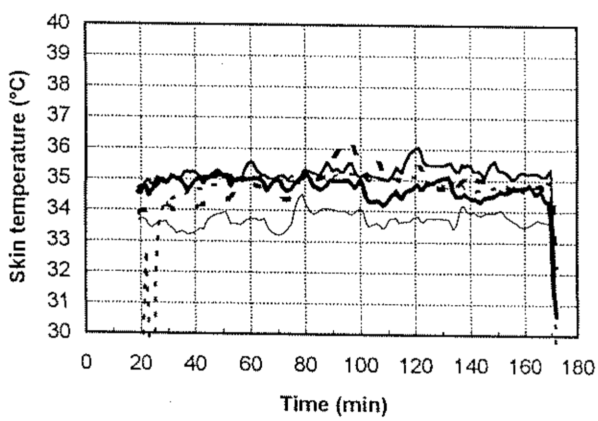
Boundary Layer Temperature



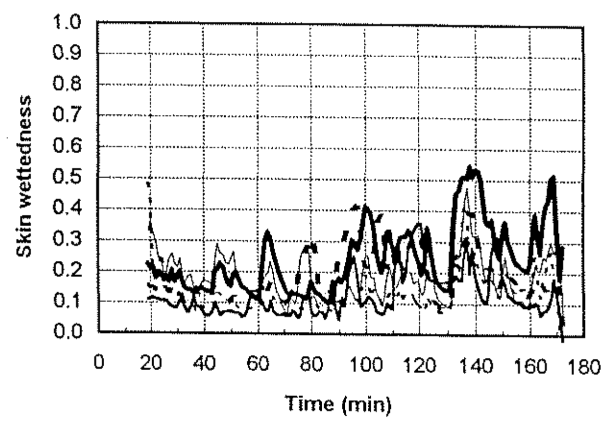
Boundary Layer RH

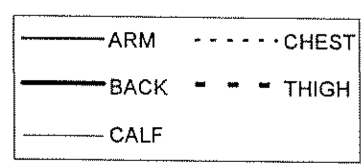


Skin Temperature

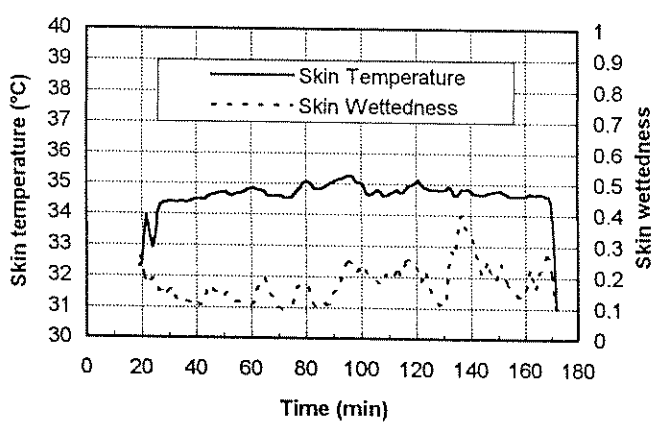


Skin Wettedness





Mean Skin Temperature and Wettedness



Individual Physiological Data
Subject No.75
Date: 07/06/94
Time: 1:00pm-4:00pm
RH = 80% T = 24.9°C

APPENDIX C

General Comments from Subjects

Appendix C

Test Condition: RH=50%, Temp=26.1°C

Comments
This experiment is making me very hungry and thirsty. I am somewhat tired due to the humidity. It did not feel that humid when I first started but after exercising, I could feel the humidity become a factor, although I did not perspire. This is because I do not perspire easily.
It's probably worth mentioning I came into the experiment feeling hot and damp. Today was hot and humid, and I had just walked quickly across campus.
This seems to be a very interesting study - perhaps afterwards you could tell the participants a little bit what it was about. I am curious why the subjects were so isolated from each other. Also, I think you should ask about the moisture of the palms (hands) this part of my body seemed to be feeling quite a bit of moisture. (Maybe because I was writing so much!) To me the overall atmosphere didn't seem to change noticeably - I'm curious to see if there actually were many variable factors.
I define "acceptable" as what I can handle. The room /air quality/humidity certainly is too warm and stale and humid for comfort. Yet I did feel alert throughout. This I think is due to regular exercises and interruptions and the unfamiliar surroundings.
I marked acceptable in all the questionnaires, because I felt that the atmosphere was tolerable. However, in the environment of an office which demands productivity and alertness, the air quality was far too muggy and stuffy. I cannot see how an eight hour day would be pleasant in such an atmosphere, but for a three hour session, it was tolerable with the last twenty minutes more comfortable than previous periods.
This experiment has been very interesting but there are a few suggestions. During this experiment restless even though I had a book to occupy my mind. Maybe if activities were provided besides doing the twelve/twenty steps, my restlessness would not increase. Also I was extremely curious about the other people and the experiment. Because of the barriers, I could not interact with the others. I understand that the experiment is kept low profiled for your purposes but it would have been appreciated if it was explained to me more thoroughly.
It's hard for me to perceive the air humidity. I can feel hot, warm, humidity on my body. But not in term of "air" humidity. I guess because my skin is not that sensitive as other animals.
One factor that can raise body temperature and therefore cause the subject to feel uncomfortable is if the subject habitually and unconsciously shakes, moves a leg or foot. Also if subject is listening to music the rhythm may cause him/her to move around and be restless thereby increasing body temperature.
Smoothly run, very intriguing. Good luck.
I have nothing to comment about the experiment itself - but I feel I should note that I was already very tired/fatigued going into the experiment.

Test Condition: RH=60%, Temp=25.8°C

Comments
Although "tolerable" or "acceptable", I would not want to work a full day every day at this heat/humidity level. Had this been my own home, I would have immediately opened all the windows to get some air moving. Any changes in the environment were subtle, perhaps even imagined. I'd be interested in seeing a sketch of room parameters vs. time (temp, humidity, whatever else you have control of) now that it's over.
Any adjustment in temperature or humidity seemed inconsequential to me, as the room seemed fine the whole time, even after exercise. I only thought the room was stuffy when I first entered, but it may have been because the air outside was so much cooler and dryer. But inside, it was fine.
Too many steps. Room is a bit stuffy. Maybe fresh air?
I find this experiment quite interesting. But I think that music plays a factor in our comfort. If you're thinking about an ideal office, then you should allow us to drink water. Oh, I would like to know more about your experiment and your results. Why are we not allowed to face each other?
I have a slight headache as we approach the end of this experiment. It may be due to lack of sleep last night and may not be directly linked to this experiment. I'm not sure. The music and chatting helped me stay awake. So did the little exercises we did throughout the experiment. I also drank a small cup of water. This kept my throat from drying. The air in the room is quite dry.
The reminder of a book, something to do would have been great. I was not so engaged in magazines and so the questions of acceptability and fatigue might be connected to some boredom I felt. At the times of the questionnaires, I felt as though the conditions may have been changing.
My feelings varied according to what I was doing: when writing (approximately first hour, and last half-hour) I was much more alert than when reading (middle period). This is usually the case with my work. Also, only one armpit was perspiring - the one without the sensor (experimental shyness).
I found it a little difficult to distinguish between levels of dryness and humidity.
For the most part, I felt comfortable throughout the entire experiment. The only times I felt somewhat hot were periods right after the exercises. Overall, I hope my participation will help you with your research.
I have much hair on my head, legs, chest, etc. I'm hairy therefore I sweat a lot easier than some.
Overall: temperature were too high, fan sound was very annoying, air humidity was too high,

fluorescent lighting was annoying, room smelled like mold slightly, air movement was too low/little.

Being in a room where there is no fresh air and where the windows don't open is very uncomfortable - I could not work in such a place. I would be sick if I had to work in an office like this. Where there is too high a temperature and a lack of fresh air, people tend to get cranky and not perform their work well.

I think it was very nice to participate in a "personalized" experiment, as all of us were addressed by our first names.

Air "quality" is hard to define, especially when so many other adjectives and descriptors are isolated and used elsewhere (words like stuffy, fresh, stale, warm can limit word choices for "quality".

Mostly throughout the experiment, I was slightly uncomfortable because of the heat. The quality of air bothered me a little, but overall the environment was acceptable.

Without the step exercise, I'm sure I would have fallen asleep.

I found it very difficult to distinguish between whether or not the conditions were humid or dry. I did not feel any extreme differences . I did my best to distinguish between the conditions. Good Luck with your findings!

Could leaning against the seat back have an effect on the reading from the sensor on my back? I tried not to lean during the experiment.

One area I thought needed to be perceived was more air flow or circulation. Not only will circulation provide more fresh air, but also the perceived feeling of having air moving helps the comfort and alertness levels.

I didn't feel too much variation in humidity readings. The air in general seemed very still and hard to judge. It felt too isolated and dampened. The hum of the fan and machines in adjacent rooms also contributed to a feeling of numbness and fatigue.

Usually I find that I feel most comfortable immediately after activity and I wonder if having a "cool down" time between stopping and filling out the questionnaire affects your study or at least pinpointing when and how people feel uncomfortable. Otherwise, the experiment seems well thought out and carefully done.

I noticed that while I was relaxing - the air seemed stuffier, and I felt a somewhat oppressive heat/humidity/stuffiness coming from above and to my left, but when I leaned forward to write in the responses I picked up on the fresher, cooler air coming from vent above and straight ahead of me. I also sensed a coolness rising from the empty desk and the cool desk pulling heat from my arm as I leaned them on the table to write. So, I felt more comfortable while I was actually writing the answers than while I was just sitting back. I reported how I felt just as I was answering the questionnaires.

Usually I do not sweat much. I am used to the dry air here in California (been here 14 years).

Usually in office environments, I have been plagued by drafty air conditioner vents blowing cold air on me. I usually don't like drafts, but found the flow of air in this experiment a bit too <u>low</u>. I enjoyed the breeze from the fan in the beginning but I found the direct draft annoying (since I 'm generally hyper-sensitive to drafts). For my maximum comfort, I would have directed the fan to bounce off the cubicle wall - to keep flow of air without direct draft.

Test Condition: RH=70%, Temp=25.3°C

Comments
The air was very dry in the beginning, but then got very humid. My feeling throughout the experiment was a will to open a window and get some air moving through the room. I did not enjoy the clamminess of my hands, and was too hot overall.
More energy with more exercise - not sure if it's actual fatigue or just boredom the steps help with. I felt great at 80th minute - felt fresher. I really felt much more comfortable at the beginning when the fans were on. I like the cool breeze. I've been having a lot of hay fever this month, but I didn't have any symptoms (sneezing, watery eyes) the whole time I was here. The researcher was very kind.
When I work here at Wurster or at home, I usually have the window open. By sitting in this room for just a few hours I cannot say that the air quality is ever truly acceptable unless I spent more time in here and became accustomed to a room with no operable windows.
I felt somewhat tired throughout the experiment. For the most part I could not perceive any changes in temperature and air quality.
It is interesting to note that when the researcher leading the experiment would tell us to fill the questionnaires, the temperature/climate would change as I was filling it out. Now I don't know if I filled it out too fast and caught the previous feelings or waited long enough to note the latter feelings, but there was a definite Δ as I was filling out the lines. The experiment was painless and I thank you for allowing me to participate. I hope my answers help to better serve whatever purpose you have.
Just a thought- you might want to add a section: one on irritability.
The heat made me feel quite sleepy and as a result, I was reading at a slower pace then usual. Basically the lack of air motion and humidity was much harder to deal with than the heat itself.
Thermal comfort involves both a quantitative and qualitative analysis of the human being's comfort level. The qualitative aspect of analysis needs to be more clearly defined and interpreted since it is not an exact science. The clues to the many problems and difficulties of thermal comfort lie within the subjective state of the mind. In this experiment when I was asked what I found "acceptable" I was quite uncomfortable mentally. The word "acceptable" implies many different levels of meaning within each circumstance. Comfort does not depend on tolerance. Maybe a better measure of each subjective state would be a sentence or two that best explains the state of comfort within the conditioned environment. Through this procedure individual, phenomenological feeling would be better understood thereby creating a humane context cognizant of the environment and earth upon which it exists.
The questionnaires are too subjective. I liked the quiet in the room.

Comments
It was pretty okay and normal, but I think it needs to have a little more fresh air.
I am wearing hiking boots because of some heavy work I did before I came here. This makes my hot, but my socks kept my feet dry. Probably I would have taken my boots off if I was in my office, but I did not feel like doing so in a room with strangers. All of this is to say I wish I wore my usual tennis shoes instead.
I became more uncomfortable when I thought about the conditions.
I found the directions clear and the experience positive. Thanks.
I think towards the end I began getting more irritated with how the experiment was taking more than anything else. It is also an unusually very hot day in Berkeley.
Something interesting happened when we were doing all the steps. I would feel winded and tired a little once I finished, and then by the time I filled out the questionnaire I felt fine, cool even. So it seemed that something about the air cooled me down. Though in general the air is much more humid than Berkeley weather, but I felt comfortable with it because I'm used to weather like that (I'm from the East Coast). After a while I felt we were getting a workout. Too much exercise.
Interesting. However I really feel like there was a time when I was completely comfortable.

Test Condition: RH=80%, Temp=24.9°C

Comments
It was kind of stuffy/humid in here during most of the experiment. The fan at the beginning of the experiment helped, although it was only a slight breeze. The typical set up and smell of the room is very typical of an ordinary office. But the air quality needs to be carefully planned. If it's too hot or if the air motion is too little, then people won't be able to work efficiently and properly. Overall, the experiment was long, but somewhat interesting.
This experiment was interesting. We did get some exercise with all the stepping exercises. Maybe after you're done analyzing the surveys, you can send us your conclusions.
For the most part I felt the conditions were stuffy. Except for some occasion the temperature was acceptable, but I never felt as though there was enough circulation. The humidity did not cause too much body dampness, but contributed to the stuffiness.
During most of the experiment, I was warmer than I'd like to be. If I were in an environment like this everyday, though, (and if I weren't confined by a dress code), then I would wear cooler clothing and be quite comfortable. Still I would like better air circulation, even if I weren't so warm.
It seemed to me that the environment throughout the experiment was hot and stuffy. It was too hot and stuffy for my comfort.
In this experiment I felt the most comfortable with the cool air motion and slightly dry air motion. Humidity is very uncomfortable adding to the stuffiness and stale air. The heat also

seems to make me more sleepy and fatigued while cooler air leaves me more alert. Cooler air also helps my skin from becoming damp.

Sometimes I felt my body temperature was warm, although the air felt cool. The question about temperature applies only to body temperature - perhaps you should add one about air temperature.

I answered "no" to the question, "Is this .....acceptable" when I decided that, if I were at home, I would do something to change my surroundings. That is how I interpreted the question.

Overall I felt the room temperature was always too warm. It would have felt quite comfortable had I been wearing a short sleeved shirt or short pants.

Hearing an air conditioning sound was somewhat deceiving in that I had the impression that air was flowing, though I couldn't really feel air moving and wished the temperature was cooler.

Seeing trees outside the window was soothing, although it did not make me feel cooler.

A lot of the time I felt like the conditions were changing in the middle of filling out the questionnaire. Generally I did not change the answer, but this was difficult because the way I felt changed so rapidly - a few seconds- that I felt I should change my answer so that the whole page would be consistent with one general feeling of my comfort at that time. In general I thought it never got cool enough (except once, but not at questionnaire time). There was never enough air movement and it was usually too humid. I guess I am just hard to please.

The room was acceptable when I came in and was at its least acceptable state a little bit before the part where I had to do the 40 steps. I would quit a job if I was required to work conditions that existed during most of the experiment.

All my responses were based on a "starting value "that was very humid, uncomfortable, and warm. Thus all of my other responses were based on that than an overall feeling of comfort ("starting value" that would have been comfortable. (i.e. that air was always humid and stale, but the feeling was relative to how it felt at the beginning). Along the same lines, my body was almost always at least a little damp and uncomfortable, but I am used to it to a certain degree. Even if the air got better, the overall feeling was one of "yuckiness" due to the humidity. If it didn't feel so humid, air quality and temperature might not have mattered so much.

I think that room temperature was often (especially in the beginning of the experiment) slightly higher that I would have liked it (I would normally have worn a short-sleeved shirt at that temperature). Also , it would have been more comfortable (for me anyway) if it would have been slightly less humid. Also the movement of the air was very pleasant, and the air seemed remarkably fresh for an indoor environment (especially a closed one).

I wish there had been a more formal explanation of what we were supposed to be doing, and the relativity of the scale. "Acceptable" is a rather vague word. I often thought the sensors were going to come off my body, but they did not. Otherwise, I enjoyed it.

I was raised in Minnesota, where it snows 7 out 12 months a year. So I have always preferred cold, crisp air.

The room felt stuffy; not much air flow. Initially when I got into the room, it felt slightly humid. As the exercise got progressively more laborious, the air felt humid.

Although I felt warm and humid in this room, I did feel comfortable in the chair. When I study and read, I need a good comfortable chair, one that's firm but soft enough. Needless to say, the chair in this room was very comfortable and the table spacious.

Throughout this experiment, most of the time, I felt wet between my fingers, which was very uncomfortable. You should have included questions not only about feet but also about hands.

In general, I found the air quality to be somewhat humid overall. The only time it became unbearable and uncomfortable was after the heaviest exercise. I found the room to be somewhat stuffy as well.

I found that the longer I sat still, the more uncomfortable I became, because I became more aware of the humidity and stuffiness.

Environment: In this kind of thermal environment my comfort would have been much greater if I could have used a controllable source of cool air - I imagine that my feeling of well-being would have been increased with even a slight flow of distinctly cooler air over my head and around my feet.

Experiment: The research assistants were very courteous and friendly which made it more enjoyable.

I think that if you are attempting to collect data that will be effective in giving an accurate description of peoples' responses to a given office environment , that it is important to allow for greater variations in movement than allowed at present.

This environment was very unpleasant for me. Ordinarily, I would have left after the first 45 minutes and found a cooler environment w/more air circulation.

My body temperature fluctuated greatly throughout the experiment and I found it very hard to concentrate after the first 30-40 minutes. Also the lighting had a very strong effect on my eyes and I had a headache throughout.

I'm not sure whether I felt incredibly uncomfortable due to the fact that I have my period and am therefore feeling weaker or whether it was simply the heat and stuffiness of the room that was making me drowsy - there were a few times that I felt it very difficult to keep myself awake.

It seems a little strange to have the scales juxtaposed with the "yes" "no" kinds of answers. But perhaps you make a distinction between "acceptable" and "comfortable" - this I don't quite get. i.e. I perceive the air as acceptable but not comfortable.

Do you keep (rate) afternoon subjects differently from morning ones? I know I always have a "low" in the afternoon which would mean that some part of my sleepiness would be due to that.

The changes in temperature and humidity over the course of the test were much less than I expected. I am really looking forward to fresh air.

SECTION 2

Impact of Humidity Standards on Commercial Building Energy Use

The Impact of Humidity Standards on Commercial Building Energy Use

Final Report
CIEE Exploratory Project

Charlie Huizenga
Zhang Hui
Fred Bauman
Edward Arens, *Principal Investigator*

INTRODUCTION

The upper and lower limits of humidity defined by ASHRAE Standard 55 impact not only the energy required by a specific HVAC system to maintain thermal comfort but also the selection of an HVAC system by a designer. The California Energy Commission estimates that commercial buildings in California use over 13,583 GWh annually for space cooling, 8,626 GWh for fans and pumps and over $2{,}700 \times 10^9$ Btu of natural gas for space cooling (CEC 1991). If we conservatively assume that 50% of the fan and pump energy is used by fans during cooling operation, this represents over $1.4 billion dollars spent annually on commercial space cooling and fan energy[1]. Given the magnitude of this expenditure, it is clear that the impact of Standard 55 on the selection and design of cooling systems needs to be well understood.

There is not universal agreement on the appropriate upper humidity limit of the comfort zone (Berglund 1995). ASHRAE has published three different limits since 1981, each with a very different shape to the upper limit based on three different criteria (dew point, relative humidity, and wet bulb). Table 1 and Figure 1 show the upper humidity limits of the comfort zone as described by these three revisions of Standard 55. Standard 55-92 (ASHRAE 1992) placed a much more severe restriction on this upper limit than 55-81 (ASHRAE 1981), with the exception of the extreme upper-right corner of the summer comfort zone, where slightly higher humidities were permitted. Laboratory studies completed as part of this research project suggest that the 60% RH limit of Standard 55-1992 is too low with respect to thermal comfort. Standard 55-92-Revised (ASHRAE 1995) uses wet bulb temperature as the basis for the upper limit of humidity. The use of wet bulb temperature is much more consistent with our understanding of human physiology, and is also more tolerant of direct evaporative cooling systems, which trade cooler temperatures for higher humidity levels.

The purpose of this work is to examine the potential impact of Standard 55 on building energy use in California commercial buildings. Of particular interest is the impact of the

[1] Using an average electricity cost of $0.08/kWh and a gas price of $0.60/therm

standard on the use of non-compressor-based cooling strategies. Evaporative cooling is one such strategy that is well-suited to many regions of California. Direct and two-stage evaporative coolers lower the temperature of the supply air at the cost of increasing the humidity. These coolers can use significantly less energy than traditional compressor-based air-conditioners and chillers, but their use could be impacted significantly by the maximum humidity specified by Standard 55.

Table 1. Upper Humidity Limits of ASHRAE Standards

	Upper Humidity Limit	
	Summer	Winter
Standard 55-81	62 °F dew point	62 °F dew point
Standard 55-92	60% RH	60% RH
Standard 55-92 Revised	68 °F wet bulb	64 °F wet bulb

TECHNICAL APPROACH

Two independent analyses are presented in this report: one evaluating the impact of indoor design criteria on the selection of evaporative cooling systems and the other evaluating system operation using DOE-2 simulations. The design criteria analysis is important because mechanical designers presumably will only make use of evaporative cooling strategies when they can meet the indoor design conditions specified by ASHRAE. The simulations are useful in examining the energy consumption implications of evaporative cooling and demonstrating the indoor conditions produced by evaporative systems over the broad range of conditions found during a typical year of operation.

Three types of evaporative cooling systems are considered in this report: *direct* evaporative cooling, *indirect* evaporative cooling, and *two-stage* evaporative cooling. Direct systems add moisture directly to the supply air, raising its humidity and lowering its temperature in a constant enthalpy process. The advantage to such a system is its simplicity and its ability to lower the air temperature quite close to the wet bulb temperature. Indirect systems evaporate water on the outside of a heat exchanger through which the supply air passes. This results in lowering the supply air temperature without adding moisture to it, though indirect systems typically do not lower the supply air temperature as much as direct systems. Two-stage systems use an indirect stage followed by a direct stage, and offer the advantages of both systems.

INDOOR DESIGN CRITERIA

Our first approach was to evaluate the impact of humidity standards on the design process for evaporative cooling strategies. To do this, a spreadsheet model was developed to estimate the cooling potential of a two-stage evaporative cooler based on outdoor and indoor design conditions. The ASHRAE 0.5% outdoor design conditions (based on total annual hours) were used for each of the climate zones, and the indoor conditions were evaluated using three levels of relative humidity: 60%, 70% and 80%. The use of relative humidity was chosen only as a way of representing humidity levels at the warm side of the comfort zone rather than suggesting that relative humidity is the appropriate basis for the upper limit from the perspective of human comfort. In this analysis, an indirect stage efficiency of 60% and a direct stage efficiency of 90% was modeled.

The model uses the following algorithm:

1. Start with outside air at the ASHRAE 0.5% design condition (based on annual hours).
2. Cool using the indirect stage (60% effectiveness*).
3. Cool using the direct stage (90% effectiveness*) until the minimum achievable temperature is reached or the maximum allowable humidity is reached.
4. Determine the temperature difference between the post-direct stage conditions and the upper ET* limit of the comfort zone. This temperature difference is directly proportional to the cooling capacity of the system.

*effectiveness is defined as:

(Tdb - Tcool)/(Tdb - Twb)

where:

Tdb is the entering dry bulb temperature
Twb is the entering wet bulb temperature
Tcool is the cool temperature of the evaporatively cooled air

Two kinds of analyses were done for this report. The first is consistent with Standard 55 as written, and assumes that the cooling *supply* air humidity can rise above the maximum limit as long as the *return* air humidity (assumed to be the same as the room air) is within the standard. The second analysis assumes that *supply* air humidity is not allowed to rise above the upper limit of the standard. Such a restriction could be proposed as being consistent with concerns of microbial growth in ductwork at high humidities, and is included here to demonstrate the dramatic effect that such a change in the standard would have.

An example of the model process for Santa Rosa (climate zone 2) is shown in Figure 2. Air starts at the outdoor design condition of 96°F dry bulb and 68°F wet bulb (❶). It is then cooled by the indirect stage by 60% of the difference between the dry bulb and wet bulb to 79°F (❷). The direct stage than adds moisture and lowers the temperature, following a line of constant wet bulb temperature to 90% of the difference between the dry bulb and wet bulb, or 64.2°F and 91% RH (❸). The supply air is then heated and some moisture added by occupants as it cools the conditioned space, and returns at the maximum temperature allowed by the standard, 78.8° and 56% RH (❹) The heat removal potential of the system is based on the difference between the air temperature at steps 3 and 4, in this case 14.6°F.

The evaporative cooling can provide supply air at 64.2°F using the first interpretation of the standard, but it can be seen from Figure 2 that the humidity rises well above 60% RH during the direct stage. If the humidity limit is applied to the supply air, only 72°F supply air can be produced by the system (❸'). For this climate, there is no difference in the cooling capacity of the system with the three relative humidity limits, though it is interesting to note that if the system maintained the space at 75°F the relative humidity would rise above 60%, and if the space was maintained at 73°F, the relative humidity would approach 70%. This is an important consideration if relative humidity rather than wet bulb or absolute humidity (dew point) is used as the upper limit for the standard.

The maximum cooling potential is a function of the delta T and the air flow rate. Table 2 shows the maximum heat removal for each climate zone in Btu/hr-cfm. This can be thought of in terms of (Btu/hr-ft^2)/(cfm/ft^2). Our DOE-2 simulations indicate that air flows of 2.5 to 3 cfm/ft^2 are the upper limit before compressor savings from an evaporative cooling system are outweighed by increased fan energy consumption. However, with a smart fan control scheme that uses a multi-speed or variable-speed fan controller, this limit could be raised considerably.

Table 2. Heat Removal Potential of Two Stage Evaporative Cooling System (Btu/hr-cfm)

Climate Zone	0.5% ASHRAE Outdoor Design Conditions (annual basis)		Humidity Restriction on Supply Air			No Humidity Restriction on Supply Air		
	DB	WB	60%RH	70% RH	80%RH	60%RH	70% RH	80%RH
1	69	59	16.0	18.5	20.7	23.8	23.8	23.8
2	96	68	8.2	11.0	13.4	15.9	15.9	15.9
3	84	64	11.9	14.5	16.9	19.6	19.6	19.6
4	88	66	9.5	12.2	14.6	17.4	17.4	17.4
5	83	64	11.6	14.2	16.6	19.4	19.4	19.4
6	90	69	4.7	7.6	10.2	11.6	13.2	13.2
7	83	69	2.9	5.8	8.4	7.1	12.0	12.0
8	89	69	4.5	7.4	9.9	11.0	13.1	13.1
9	94	68	7.6	10.4	12.9	15.5	15.5	15.5
10	100	69	7.5	10.3	12.8	15.1	15.1	15.1
11	104	69	8.6	11.4	13.8	15.8	15.8	15.8
12	100	70	5.7	8.5	11.1	13.5	13.5	13.5
13	101	71	4.1	7.1	9.6	10.2	12.2	12.2
14	108	69	9.8	12.5	14.9	16.6	16.6	16.6
15	111	73	3.1	6.1	8.7	7.7	10.8	10.8
16	89	61	18.9	21.2	23.4	25.2	25.2	25.2

Table 3 and Figure 3 show the heat removal potential for evaporative cooling systems based on 2.5 cfm/ft^2. Typical office building heat loads are of the order of 24 Btu/hr-ft^2(500 ft^2/ton). The shaded boxes indicate conditions where an evaporative cooling system would meet this typical load. Note that if the supply air humidity restriction is enforced, the upper limit is quite significant in determining whether an evaporative cooling system can meet the building load. At 60% RH, evaporative cooling systems meet this typical criterion in only four climate zones, while at 80% RH, an evaporative cooling system would be sufficient in fourteen of the sixteen climate zones.

Table 3. Heat Removal Potential (Btu/hr-ft^2) of Two Stage Evaporative Cooling System supplying 2.5 cfm/ft^2. Shaded boxes indicate conditions where heat removal is above 24 Btu/hr-ft^2 (equivalent to 500 ft^2/ton).

Climate Zone	Humidity Restriction on Supply Air			No Humidity Restriction on Supply Air		
	60%RH	70% RH	80%RH	60%RH	70% RH	80%RH
1	40.1	46.3	51.8	59.6	59.6	59.6
2	20.5	27.4	33.5	39.7	39.7	39.7
3	29.7	36.3	42.1	48.9	48.9	48.9
4	23.8	30.6	36.6	43.4	43.4	43.4
5	29.0	35.6	41.4	48.4	48.4	48.4
6	11.8	19.1	25.5	29.0	33.1	33.1
7	7.1	14.6	21.1	17.7	30.0	30.0
8	11.2	18.4	24.8	27.4	32.6	32.6
9	19.1	26.1	32.2	38.7	38.7	38.7
10	18.8	25.8	31.9	37.7	37.7	37.7
11	21.6	28.5	34.6	39.6	39.6	39.6
12	14.2	21.4	27.7	33.8	33.8	33.8
13	10.3	17.6	24.0	25.4	30.4	30.4
14	24.5	31.3	37.2	41.5	41.5	41.5
15	7.8	15.2	21.7	19.3	27.1	27.1
16	47.2	53.1	58.4	63.0	63.0	63.0

In more general terms, the cooling capacity of an evaporative cooling system is a function of the outdoor and indoor design criteria. Figures 4-6 show the cooling capacity of the two-stage system used in this study as a function of design wet bulb for three outdoor design dry bulb conditions (85°F, 95°F, and 105°F). The cooling capacity is most sensitive to the outdoor humidity, shown by the steep slope of the capacity line in these graphs. In each graph, the impact of different indoor humidity criteria was considered in calculating the capacity as described in the model above. What the graphs clearly show is that the indoor criteria become important only as the outdoor wet bulb reaches a critical level, in this case ranging from 67°F for the 85°F design dry bulb case to 71°F for the 105°F design dry bulb case. It is important to note that this impact is dependent on the type of evaporative system evaluated and its operating characteristics. For example, a direct evaporative cooler would be much more sensitive to the relative humidity limits at lower design wet bulbs.

One conclusion that can be drawn from figures 4-6 is that the humidity limits under consideration should only be an issue for climates with a wet bulb above a critical level. This can be seen in Table 3 by observing that the humidity limits only impact climate zones 6, 7, 8, 13 and 15, all of which have a high design wet bulb relative to their design dry bulb. Figure 7 shows the design conditions for each of the sixteen climate zones. For each climate zone, design dry bulb is plotted vs mean coincident wetbulb. For nine of the climate zones, design wet bulb temperature plotted vs mean coincident dry bulb (Colliver 1994).

CALIFORNIA COMMERCIAL BUILDING LOADS

Now that we have established the cooling capacity of the two-stage evaporative cooling system in each of the CEC climate zones, it is possible to compare the capacity with typical loads of a variety of building types in each zone. To establish these typical loads, we used CEC Building Prototypes (CEC, 1994) that have been used to estimate the impacts of conservation technologies in California. In this report, 16 commercial building types and three vintages are defined for five climate zones. The three vintages "Old", "T24", and "New" represent buildings constructed prior to 1978 (pre-Title-24), between 1978 and 1991, and after 1991 respectively. Tables 4-8 show the cooling capacity (Btu/hr-ft^2) for each building type and vintage for each of the five climate zones used in the CEC evaluation.

Table 4. Climate Zone 4 Cooling System Capacities (Btu/hr-ft^2) (CEC 1994)

		Construction Vintage		
	Gross sq ft	Old	T24	New
Small Office	10,000	55	52	52
Large Office	175,000	38	32	27
Small Retail	8,000	38	38	38
Large Retail	120,000	23	17	15
Restaurant	4,000	66	51	42
Fast Food	2,000	120	78	78
Grocery	15,000	48	36	31
Storage/office	7,000	17	12	12
Hospital	250,000	69	64	54
Nursing Home	60,000	30	29	20
Primary	50,000	58	54	49
Secondary	150,000	22	21	16
Hotel	200,000	25	23	20
Motel	29,000	27	21	21
College	300,000	35	35	26

Table 5. Climate Zone 7 Cooling System Capacities (Btu/hr-ft^2) (CEC 1994)

		Construction Vintage		
	Gross sq ft	Old	T24	New
Small Office	10,000	48	40	40
Large Office	175,000	38	29	25
Small Retail	8,000	30	30	30
Large Retail	120,000	23	16	15
Restaurant	4,000	39	36	30
Fast Food	2,000	78	66	60
Grocery	15,000	48	44	24
Storage/office	7,000	26	12	10
Hospital	250,000	64	59	54
Nursing Home	60,000	33	30	19
Primary	50,000	43	41	40
Secondary	150,000	21	21	14
Hotel	200,000	26	23	18
Motel	29,000	21	17	17
College	300,000	38	34	22

Table 6. Climate Zone 9 Cooling System Capacities (Btu/hr-ft^2) (CEC 1994)

		Construction Vintage		
	Gross sq ft	Old	T24	New
Small Office	10,000	64	46	46
Large Office	175,000	40	33	26
Small Retail	8,000	45	45	23
Large Retail	120,000	25	18	16
Restaurant	4,000	69	48	24
Fast Food	2,000	126	60	54
Grocery	15,000	52	48	44
Storage/office	7,000	26	15	14
Hospital	250,000	69	64	54
Nursing Home	60,000	32	29	21
Primary	50,000	56	50	49
Secondary	150,000	28	26	22
Hotel	200,000	28	24	20
Motel	29,000	37	33	31
College	300,000	47	43	35

Table 7. Climate Zone 12 Cooling System Capacities (Btu/hr-ft^2) (CEC 1994)

		Construction Vintage		
	Gross sq ft	Old	T24	New
Small Office	10,000	59	50	53
Large Office	175,000	37	31	25
Small Retail	8,000	38	45	38
Large Retail	120,000	24	16	15
Restaurant	4,000	66	66	45
Fast Food	2,000	120	84	78
Grocery	15,000	52	44	36
Storage/office	7,000	26	14	12
Hospital	250,000	54	49	40
Nursing Home	60,000	38	32	23
Primary	50,000	58	52	47
Secondary	150,000	22	21	17
Hotel	200,000	28	26	21
Motel	29,000	27	23	23
College	300,000	43	38	26

Table 8. Climate Zone 15 Cooling System Capacities (Btu/hr-ft^2) (CEC 1994)

		Construction Vintage		
	Gross sq ft	Old	T24	New
Small Office	10,000	66	48	48
Large Office	175,000	43	34	29
Small Retail	8,000	53	45	38
Large Retail	120,000	30	20	17
Restaurant	4,000	66	66	51
Fast Food	2,000	126	120	54
Grocery	15,000	64	52	48
Storage/office	7,000	26	15	14
Hospital	250,000	69	64	55
Nursing Home	60,000	37	34	24
Primary	50,000	56	49	48
Secondary	150,000	29	27	21
Hotel	200,000	36	34	29
Motel	29,000	41	35	33
College	300,000	47	47	31

The data presented in Tables 4-8 can be used to determine if the two-stage evaporative cooler could be used to provide the equivalent capacity as the compressor-based system used in the CEC models. Tables 9-12 show the results of this analysis for four of the building prototypes: Small Office, Large Office, Small Retail, and Large Retail. In each table, the words "New", "T24", and "Old" indicate whether the evaporative cooling system can provide the CEC capacity for the each of the construction vintages, respectively. This has been calculated for the same humidity restrictions discussed above.

In a smaller building, the system pressure is much lower than a large building, and an increased air volume can be supplied at a lower penalty than in a larger building. For this analysis, 3 cfm/ft^2 was used for the maximum supply flow in the Small Office and Small Retail prototypes, and 2.5 cfm/ft^2 was used for the Large Office and Large Retail prototypes. The "Small" prototypes tend to have much higher loads per unit floor area then the "Large" prototypes, and therefore appear to offer less of an opportunity for evaporative cooling. However, it is important to note that we have not carefully studied the maximum supply air flow rate for these prototypes, and a higher supply air flow rate will make evaporative cooling work for a higher cooling load.

Since construction practices have been improving with respect to energy efficiency, newly constructed buildings tend to have lower cooling loads than older buildings. This is due to improvements in the envelope as well as reduce internal gains from more efficient lighting and office equipment. As a result, if the evaporative cooling system is sufficient to meet the load of an older vintage construction, it will also meet the load of the newer construction for the same building prototype.

With the exception of the Large Office building prototype, the three room air humidity limits do not have an impact on the applicability of the evaporative cooling system for the New construction vintage, and only a minor impact on the other building vintages. When the same humidity limits are applied to supply air, however, they do have a significant impact on the applicability of evaporative cooling for each of these four prototypes.

Table 9. Small Office Evaporative Cooling Applicability by Climate Zone and Construction Vintage

Climate Zone	Humidity Restriction on Supply Air			No Humidity Restriction on Supply Air		
	60%RH	70% RH	80%RH	60%RH	70% RH	80%RH
4	--	--	--	New/T24	New/T24	New/T24
7	--	--	--	New/T24	New/T24	New/T24
9	--	--	--	--	--	--
12	--	--	--	--	--	--
15	--	--	--	--	--	--

Table 10. Large Office Evaporative Cooling Applicability by Climate Zone and Construction Vintage

Climate Zone	Humidity Restriction on Supply Air			No Humidity Restriction on Supply Air		
	60%RH	70% RH	80%RH	60%RH	70% RH	80%RH
4	--	New	New/T24	New/T24/Old	New/T24/Old	New/T24/Old
7	--	--	--	--	New/T24	New/T24
9	--	New	New	New/T24	New/T24	New/T24
12	--	--	New	New/T24	New/T24	New/T24
15	--	--	--	--	--	--

Table 11. Small Retail Evaporative Cooling Applicability by Climate Zone and Construction Vintage

Climate Zone	Humidity Restriction on Supply Air			No Humidity Restriction on Supply Air		
	60%RH	70% RH	80%RH	60%RH	70% RH	80%RH
4	--	--	New/T24/Old	New/T24/Old	New/T24/Old	New/T24/Old
7	--	New/T24/Old	New/T24/Old	New/T24/Old	New/T24/Old	New/T24/Old
9	--	New	New	New	New	New
12	--	--	--	--	--	--
15	--	--	--	--	--	--

Table 12. Large Retail Evaporative Cooling Applicability by Climate Zone and Construction Vintage

Climate Zone	Humidity Restriction on Supply Air			No Humidity Restriction on Supply Air		
	60%RH	70% RH	80%RH	60%RH	70% RH	80%RH
4	New/T24/Old	New/T24/Old	New/T24/Old	New/T24/Old	New/T24/Old	New/T24/Old
7	New/T24	New/T24/Old	New/T24/Old	New/T24/Old	New/T24/Old	New/T24/Old
9	--	New/T24	New/T24/Old	New/T24/Old	New/T24/Old	New/T24/Old
12	--	New	New/T24	New/T24	New/T24/Old	New/T24/Old
15	--	--	New/T24	New	New/T24	New/T24

DOE-2 SIMULATIONS

To examine the impact Standard 55 could have on the use of evaporative cooling strategies in California, DOE-2 simulations were done for a prototypical mid-size commercial building using CEC weather data for five locations: Santa Rosa (CTZO2c), El Toro (CTZ08c), Pasadena (CTZ09c), Riverside (CTZ10c) and Sacramento (CTZ12c). These simulations were done to assess both the comfort and energy implications of evaporative cooling strategies. It should be understood that the weather data used in this study were developed to examine annual energy consumption issues rather than peak cooling performance, and the peak days in the weather data may not be well represented.

PROTOTYPE BUILDING

The prototype building is a 21,500 ft^2 two-story building above a 10,750 ft^2 unconditioned parking space. Building envelope and internal load characteristics are show in Table 13. For each location, thirteen HVAC systems were simulated as shown in Table 14. These systems represent the two most commonly used systems, VAV and packaged single zone, in combinations reflecting the use of air-side economizers and evaporative pre-coolers.

Table 13. Prototype Building Characteristics

	Climate Zone 2	Climate Zones 9, 10, 12
Conditioned Floor Area	21,500	21,500
Glazing Area	2,285 ft^2	2,285 ft^2
Wall R-Value	4	7
Glazing Area	2,285 ft^2	2,285 ft^2
Glazing U-Value	1.03 Btu/h-ft^2-°F	1.03 Btu/h-ft^2-°F
Glazing SC	0.60	0.60
Lighting Density	2.0 W/ft^2	2.0 W/ft^2
Equipment Density	1.0 W/ft^2	1.0 W/ft^2

Table 14. Simulated HVAC Systems

System	Base System	Economizer	Evaporative Precooler
1	Two Stage Evaporative Cooler	Yes	--
2	Indirect Evaporative Cooler	Yes	--
3	Direct Evaporative	Yes	--
4	Packaged Single Zone	No	None
5	Packaged Single Zone	Yes	None
6	Packaged Single Zone	Yes	Two Stage
7	Packaged Single Zone	Yes	Indirect
8	Packaged Single Zone	Yes	Direct
9	VAV	No	None
10	VAV	Yes	None
11	VAV	Yes	Two Stage
12	VAV	Yes	Indirect
13	VAV	Yes	Direct

SIMULATION RESULTS- THERMAL COMFORT

A post processor was written to read DOE-2 hourly binary files and evaluate the dry bulb and humidity ratio of the conditioned zones relative to each of three comfort zones: Standard 55-81, Standard 55-92, and Standard 55-92 Revised. Figures 8 through 31 show the indoor conditions during occupied hours for the months of March through September plotted in psychrometric chart format. Each of the three comfort zones is also shown on each chart. In all of the analyses done in this report, no consideration was given to effects of mean radiant temperatures or air motion. Unless otherwise noted, comfort zones are shown for typical office worker clothing (0.9 clo winter, 0.5 clo summer) and activity levels (1.2 met). The comfort zones shown are the combined summer and winter zones rather than the summer only zone. The only difference in the winter and summer zones is the assumption about clothing (0.9 clo winter, 0.5 clo summer), and in many of the mild California climates, clothing levels vary enough during the period of March through September that it is appropriate to consider the range of the ASHRAE comfort zones. This in no way implies that the ASHRAE comfort zones should be merged when evaluating thermal comfort. However, the variations in outdoor conditions during this period will result in shifts in clothing from one period of time to another, requiring different comfort zones to be included in the depiction of the data.

Figures 8 through 31 give a very clear picture of the general trend of conditions provided by different systems. Evaporative cooling systems have higher humidities than conventional systems, and systems with economizers have some hours with higher humidities than systems without economizers. What is very clear is that when using the two-stage evaporative cooling system, there are a significant number of hours that fall above the limit set by Standard 55-92 (60% RH), yet are well within the standard set by 55-92 Revised. Figures 36 through 39 show for each climate zone the percentage of occupied hours when the humidity in the conditioned space was above the maximum as defined by each of the three standards. This data is presented numerically in Tables 15 through 18. For this analysis, the building was assumed to be at least partially occupied from 7 am through 8 pm every day for a total of 4745 occupied hours. Full occupancy was 9 am to 5 pm on weekdays.

The simulation results clearly show that systems using evaporative coolers often create conditions that would fall above the maximum humidity of 60% RH imposed by Standard 55-92, yet are below the maximum humidity levels of Standard 55-81 and Standard 55-92 Revised. In all four climate zones studied, even a direct evaporative cooler is able to provide conditions within the comfort zone as defined by Standard 55-92 Revised for 90% of the occupied hours, and a two-stage cooler can meet the humidity criteria for at least 95% of the occupied hours.

Although this study focused on the upper humidity level of Standard 55, it is interesting to note that there are many hours during the year when the humidity is below the lower limit of the standard. The use of evaporative coolers in California can be beneficial in reducing exposure to air which is too dry, known to increase the incidence of respiratory infection, asthmatic symptoms, and bacterial and viral growth.

Table 15. Percent of occupied hours when humidity is above comfort zone. Climate Zone 2 (4745 total occupied hours)

	Std 55-81	Std 55-92	Std 55-92 Revised
Two Stage Evaporative Cooler	3%	19%	1%
Indirect Evaporative Cooler	0%	10%	0%
Direct Evaporative	11%	37%	5%
Packaged Single Zone, no econo.	0%	0%	0%
Packaged Single Zone	0%	1%	0%
Packaged Single Zone w/ 2 stage	0%	20%	0%
Packaged Single Zone w/ indirect	0%	1%	0%
Packaged Single Zone w/ direct	1%	28%	0%
VAV, no econo.	0%	1%	0%
VAV	0%	1%	0%
VAV w/ 2 stage	0%	4%	0%
VAV w/indirect	0%	1%	0%
VAV w/direct	0%	10%	0%

Table 16. Percent of occupied hours when humidity is above comfort zone. Climate Zone 9 (4745 total occupied hours)

	Std 55-81	Std 55-92	Std 55-92 Revised
Two Stage Evaporative Cooler	11%	29%	4%
Indirect Evaporative Cooler	4%	22%	2%
Direct Evaporative	20%	43%	10%
Packaged Single Zone, no econo.	0%	0%	0%
Packaged Single Zone	0%	1%	0%
Packaged Single Zone w/ 2 stage	5%	31%	1%
Packaged Single Zone w/ indirect	0%	1%	0%
Packaged Single Zone w/ direct	9%	43%	3%
VAV, no econo.	0%	0%	0%
VAV	0%	1%	0%
VAV w/ 2 stage	0%	10%	0%
VAV w/indirect	0%	1%	0%
VAV w/direct	2%	28%	0%

Table 17. Percent of occupied hours when humidity is above comfort zone. Climate Zone 10 (4745 total occupied hours)

	Std 55-81	Std 55-92	Std 55-92 Revised
Two Stage Evaporative Cooler	7%	26%	3%
Indirect Evaporative Cooler	1%	13%	1%
Direct Evaporative	18%	50%	9%
Packaged Single Zone, no econo.	0%	0%	0%
Packaged Single Zone	0%	0%	0%
Packaged Single Zone w/ 2 stage	2%	36%	0%
Packaged Single Zone w/ indirect	0%	0%	0%
Packaged Single Zone w/ direct	7%	46%	2%
VAV, no econo.	0%	0%	0%
VAV	0%	1%	0%
VAV w/ 2 stage	0%	9%	0%
VAV w/indirect	0%	1%	0%
VAV w/direct	2%	30%	0%

Table 18. Percent of occupied hours when humidity is above comfort zone. Climate Zone 12 (4745 total occupied hours)

	Std 55-81	Std 55-92	Std 55-92 Revised
Two Stage Evaporative Cooler	3%	17%	1%
Indirect Evaporative Cooler	1%	10%	0%
Direct Evaporative	15%	40%	6%
Packaged Single Zone, no econo.	0%	1%	0%
Packaged Single Zone	0%	1%	0%
Packaged Single Zone w/ 2 stage	2%	21%	0%
Packaged Single Zone w/ indirect	0%	0%	0%
Packaged Single Zone w/ direct	6%	31%	2%
VAV, no econo.	0%	1%	0%
VAV	0%	1%	0%
VAV w/ 2 stage	0%	9%	0%
VAV w/indirect	0%	1%	0%
VAV w/direct	0%	21%	0%

SIMULATION RESULTS- ENERGY IMPACTS

Evaporative cooling systems have the potential to provide significant energy and peak demand reductions for buildings in California. The DOE-2 simulations carried out for this project were intended to examine not only the impact on indoor humidity levels, but also the potential savings that evaporative coolers could produce in mid-size commercial buildings.

Figures 40-43 show for each climate zone the fan and cooling energy consumption of each HVAC system. The simulations indicate that a two-stage evaporative cooler can save up to 70% of the fan and cooling energy used by the quite commonly used packaged single zone system. This represents a 20% savings in total energy consumption of the building.

Table 19. Cooling and Fan Energy for Climate Zone 2 (kWh/ft2-yr)

System	Cooling Energy	Fan Energy	Fan and Cooling
2 Stage EC	0.67	1.73	2.40
Indirect EC	0.57	1.91	2.48
Direct EC	0.21	1.38	1.59
PSZ	4.51	1.46	5.97
PSZ w/ econ	3.35	1.61	4.96
PSZ w/ 2 Stage EC	2.45	2.34	4.79
PSZ w/ Indirect EC	2.62	2.20	4.82
PSZ w/ Direct EC	3.67	1.76	5.43
VAV	4.22	0.90	5.11
VAV w/ econ	3.30	0.96	4.27
VAV w/ 2 Stage EC	2.67	1.29	3.97
VAV w/ Indirect EC	2.87	1.23	4.10
VAV w/ Direct EC	2.77	1.02	3.79

Table 20. Cooling and Fan Energy for Climate Zone 9 (kWh/ft2-yr)

System	Cooling Energy	Fan Energy	Fan and Cooling
2 Stage EC	0.86	2.20	3.07
Indirect EC	0.67	2.22	2.89
Direct EC	0.23	1.51	1.75
PSZ	4.66	1.71	6.37
PSZ w/ econ	3.89	1.88	5.77
PSZ w/ 2 Stage EC	2.89	2.74	5.62
PSZ w/ Indirect EC	3.05	2.56	5.62
PSZ w/ Direct EC	4.36	2.05	6.42
VAV	4.78	1.02	5.80
VAV w/ econ	4.48	1.09	5.58
VAV w/ 2 Stage EC	3.84	1.47	5.31
VAV w/ Indirect EC	4.13	1.40	5.53
VAV w/ Direct EC	3.94	1.16	5.10

Table 21. Cooling and Fan Energy for Climate Zone 10 (kWh/ft2-yr)

System	Cooling Energy	Fan Energy	Fan and Cooling
2 Stage EC	1.04	2.61	3.65
Indirect EC	0.90	2.94	3.84
Direct EC	0.32	2.05	2.37
PSZ	5.36	1.71	7.07
PSZ w/ econ	4.67	1.88	6.55
PSZ w/ 2 Stage EC	3.61	2.74	6.35
PSZ w/ Indirect EC	3.63	2.56	6.19
PSZ w/ Direct EC	5.44	2.05	7.49
VAV	5.18	1.07	6.24
VAV w/ econ	4.75	1.15	5.90
VAV w/ 2 Stage EC	3.87	1.53	5.40
VAV w/ Indirect EC	4.11	1.46	5.57
VAV w/ Direct EC	4.09	1.21	5.30

Table 22. Cooling and Fan Energy for Climate Zone 12 (kWh/ft2-yr)

System	Cooling Energy	Fan Energy	Fan and Cooling
2 Stage EC	0.75	1.93	2.67
Indirect EC	0.64	2.15	2.79
Direct EC	0.23	1.47	1.69
PSZ	3.96	1.71	5.67
PSZ w/ econ	3.28	1.88	5.16
PSZ w/ 2 Stage EC	2.34	2.74	5.08
PSZ w/ Indirect EC	2.69	2.56	5.26
PSZ w/ Direct EC	3.44	2.05	5.49
VAV	4.81	1.02	5.82
VAV w/ econ	3.98	1.09	5.08
VAV w/ 2 Stage EC	3.26	1.47	4.73
VAV w/ Indirect EC	3.58	1.40	4.98
VAV w/ Direct EC	3.27	1.16	4.43

The upper humidity limit could also technically have an impact on the energy consumption of compressor-based cooling systems, particularly in humid climates. In practice, however, this impact would only occur with systems providing supply air at or above 60°F or using a significant amount of coil by-pass. Otherwise, due to the removal of moisture by the cooling coil, the moisture content of the supply air would rarely be high enough to be close to the upper humidity limits of the standard. The use of air-side economizers also is not very sensitive to the humidity limit, particularly in California.. Tables 15-18 show that the use of economizers does not result in a significant number of hours out of the comfort zone. This is due to the fact that if the outside air is cool enough to trigger economizer operation, the absolute humidity is low enough that as the air is warmed in the space the relative humidity drops to well below the standard.

CONCLUSIONS

The thermal comfort zone defined by ASHRAE Standard 55 is used by designers as a basis for selecting and sizing HVAC equipment. If a system cannot provide conditions within the comfort zone during a significant portion of the year, it is logical to assume that such a system will not be selected by HVAC designers. Although a detailed forecast of the impact of Standard 55 on system selection is beyond the scope of this study, we have presented the general energy implications of discouraging the use of evaporative cooling systems.

The DOE-2 simulations done for this study show that evaporative coolers could save an average of 40% of the cooling and fan energy for the mid-size commercial building. If they were used in 25% of all commercial buildings in the state, this would result in annual energy savings of approximately 2,220 GWh of electricity and 2.7 million therms of natural gas.

Huang (Huang, et al 1994) has examined the energy impacts of evaporative air conditioners on residential buildings in the same four California climate zones used in this study. He found that two-stage evaporative coolers could keep house temperatures at or below 78°F and save 51% to 66% in cooling and fan energy over a typical air-conditioner. Huang's result is consistent in magnitude with the results of this study, and suggests that any barriers that may be unnecessarily discouraging designers from implementing evaporative cooling in appropriate applications should be thoroughly evaluated.

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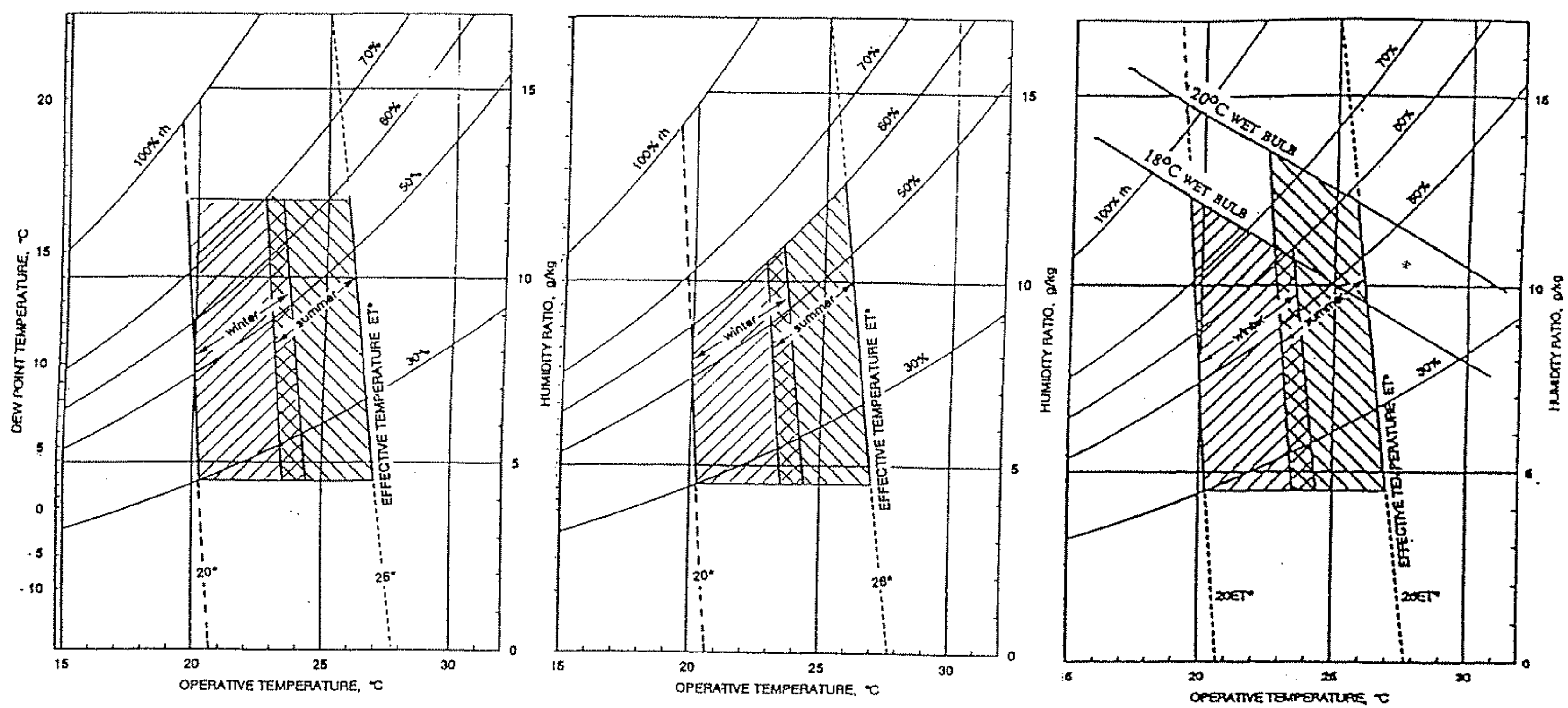
Huang, Y.J., J.W. Hanford, and H.F. Wu, "Preliminary Evaluation of the Performance, Water Use, and Current Application Trends of Evaporative Coolers in California Climates", CIEE Report, 1992.



1981 1992 1994

Figure 1. Comfort zones of ASHRAE Standard 55 from 1981 to present.

Figure 2. Psychrometric Process Chart for Santa Rosa (Climate Zone 2)

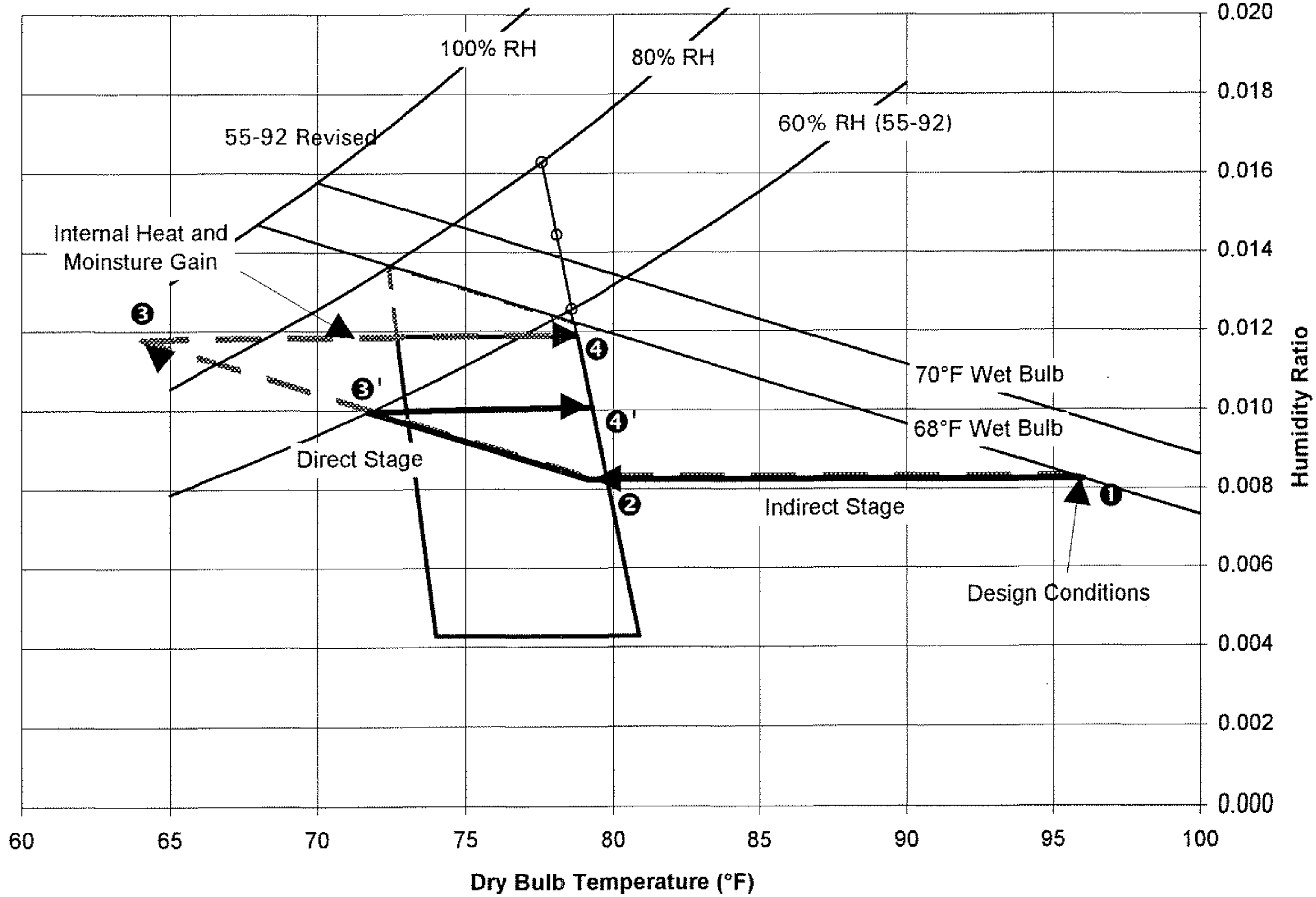


Figure 3. Two-Stage Evaporative Cooling Capacity for Three Supply Air Relative Humidity Limits Based on 2.5 cfm/ft2

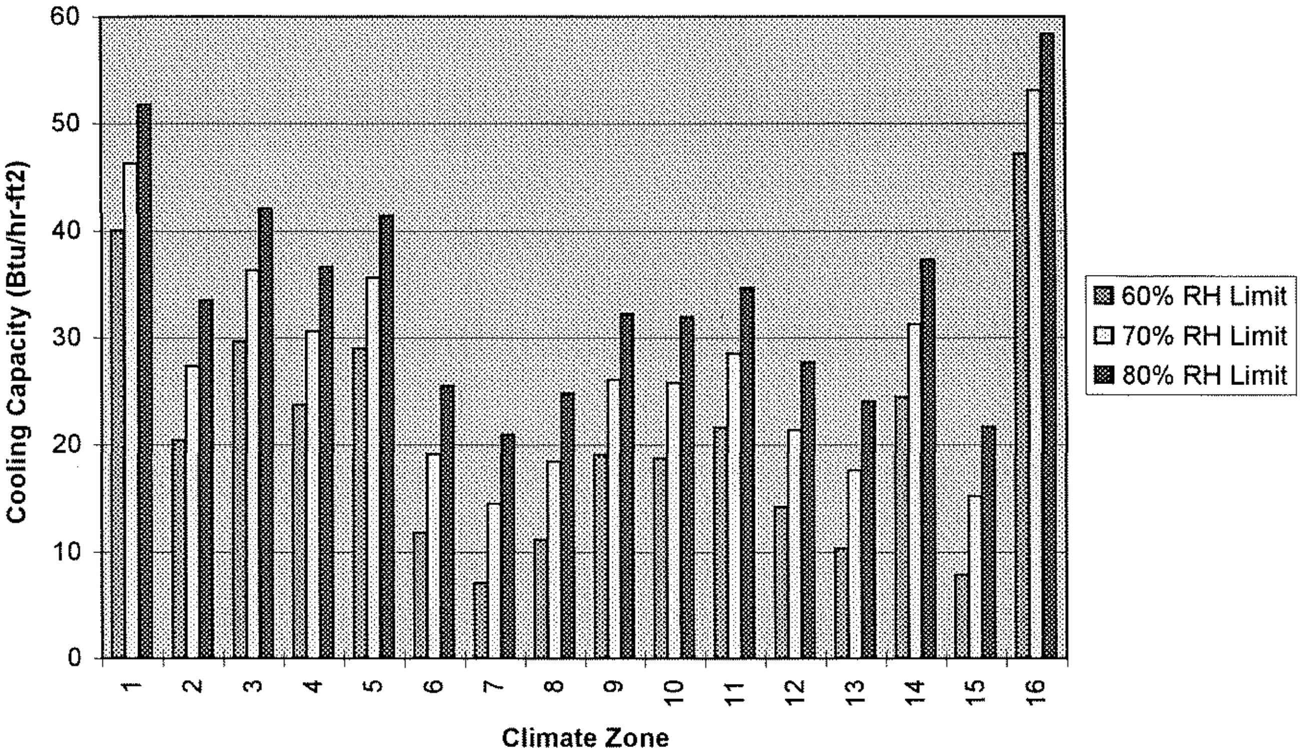


Figure 4. Two-Stage Evaporative Cooling Capacity for Three Relative Humidity Limits
Outdoor Design Dry Bulb: 85°F, Supply Air Flow: 2.5 cfm/ft2

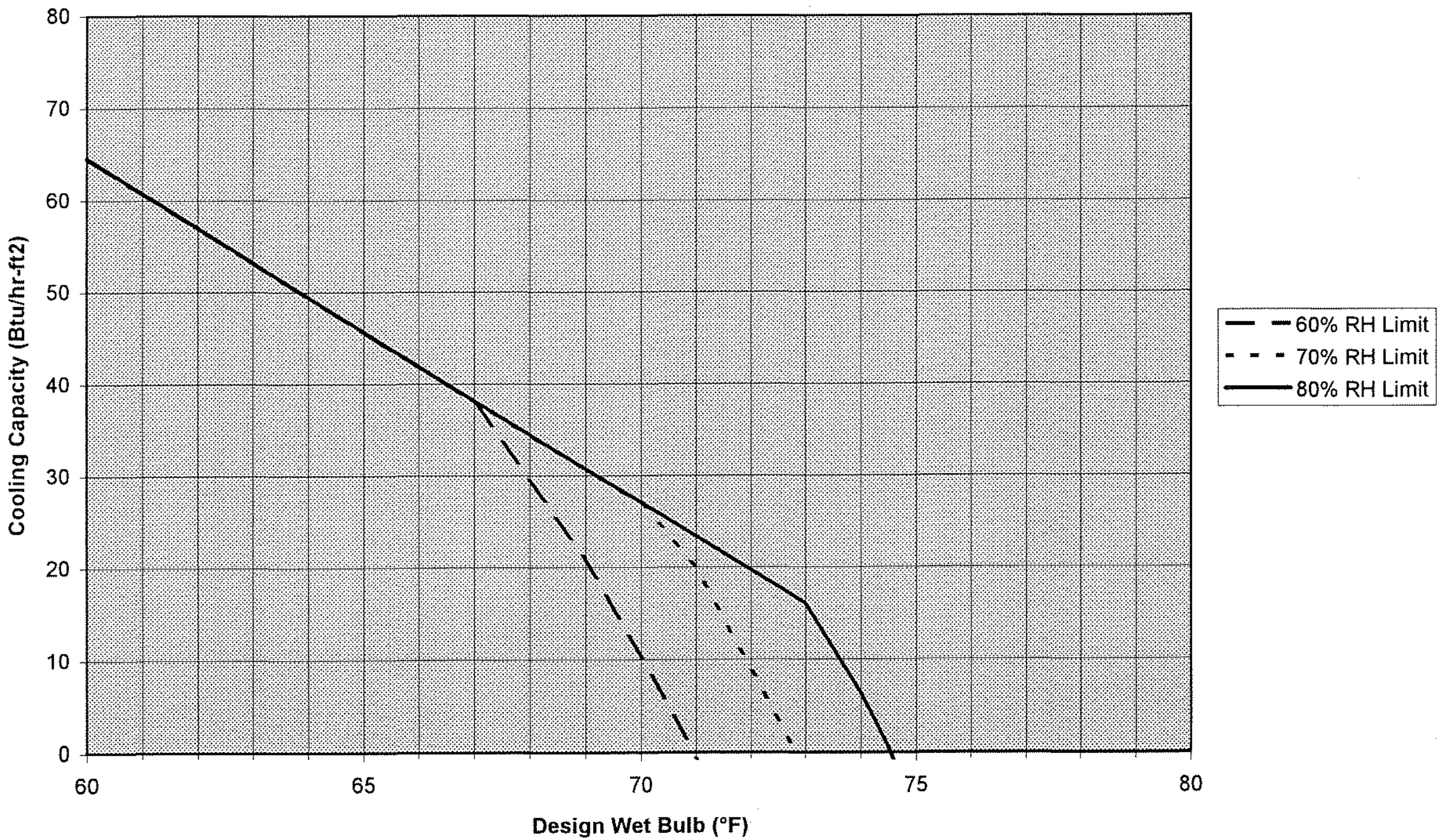


Figure 5. Two-Stage Evaporative Cooling Capacity for Three Relative Humidity Limits
Outdoor Design Dry Bulb: 95°F, Supply Air Flow: 2.5 cfm/ft2

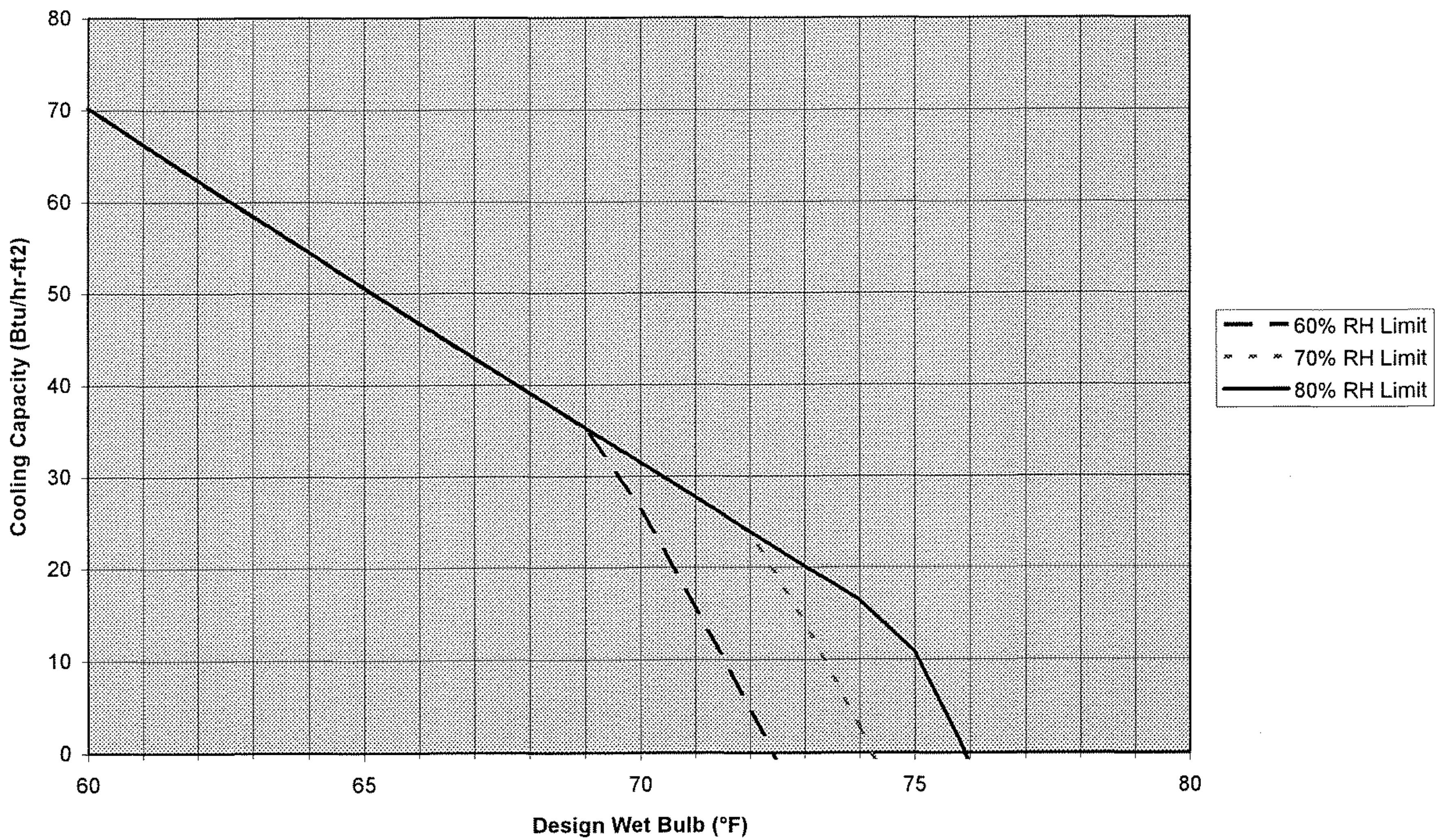


Figure 6. Two-Stage Evaporative Cooling Capacity for Three Relative Humidity Limits
Outdoor Design Dry Bulb: 105°F, Supply Air Flow: 2.5 cfm/ft2

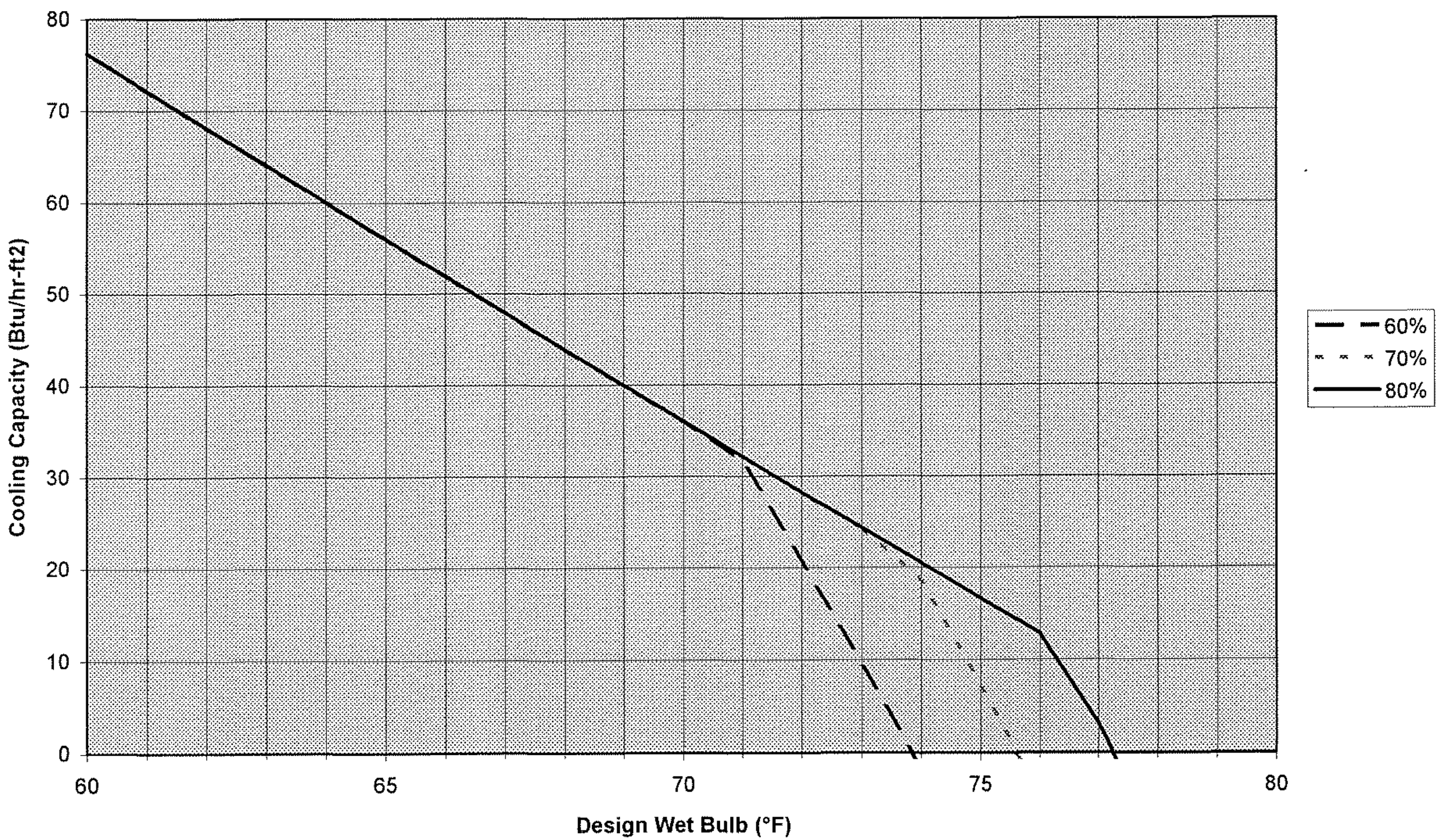
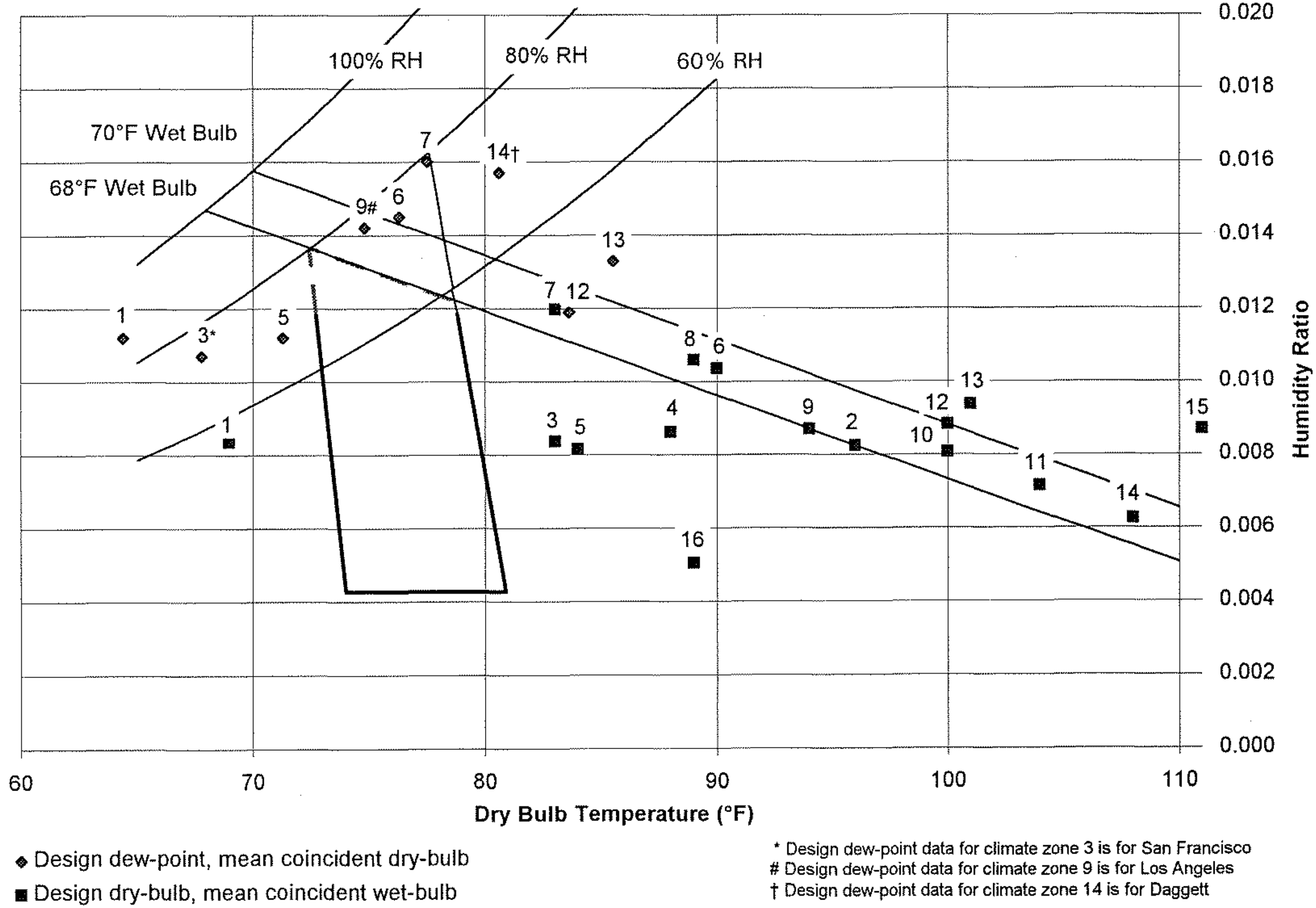


Figure 7. California Climate Zone Design Conditions

Sources: Design dry-bulb data, ASHRAE 0.5% conditions (annual hours)
Design dew-point data, Colliver 1994 1% conditions (summer hours)



* Design dew-point data for climate zone 3 is for San Francisco
\# Design dew-point data for climate zone 9 is for Los Angeles
† Design dew-point data for climate zone 14 is for Daggett

Figure 8. Indoor Conditions for 2 Stage EC
Climate Zone 2, March - September

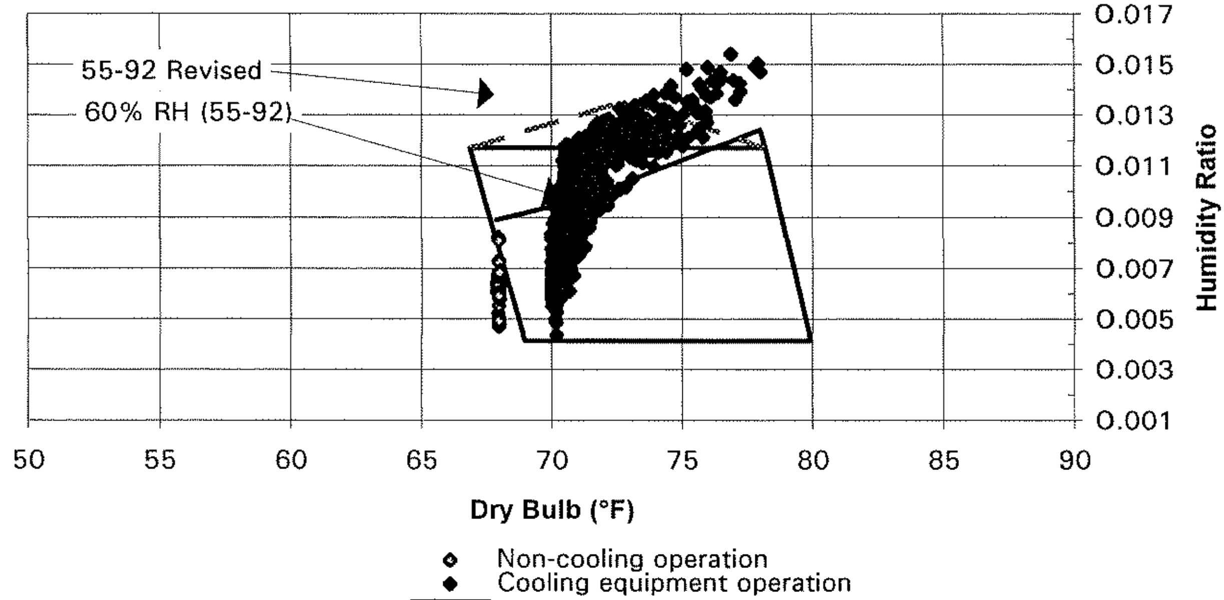
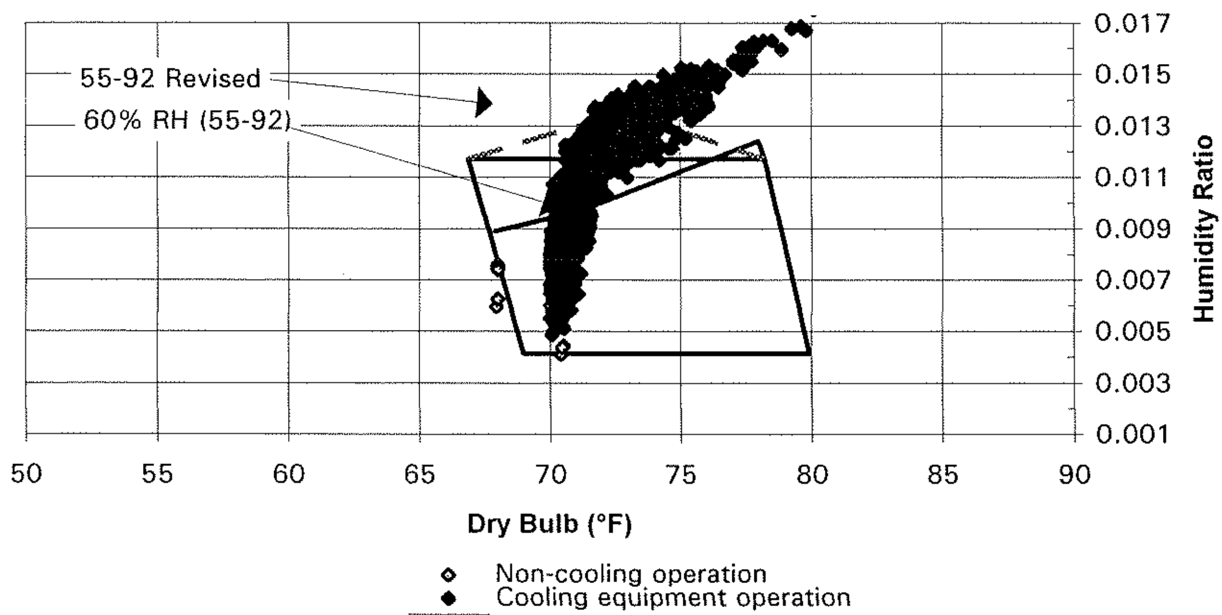


Figure 9. Indoor Conditions for 2 Stage EC
Climate Zone 9, March - September



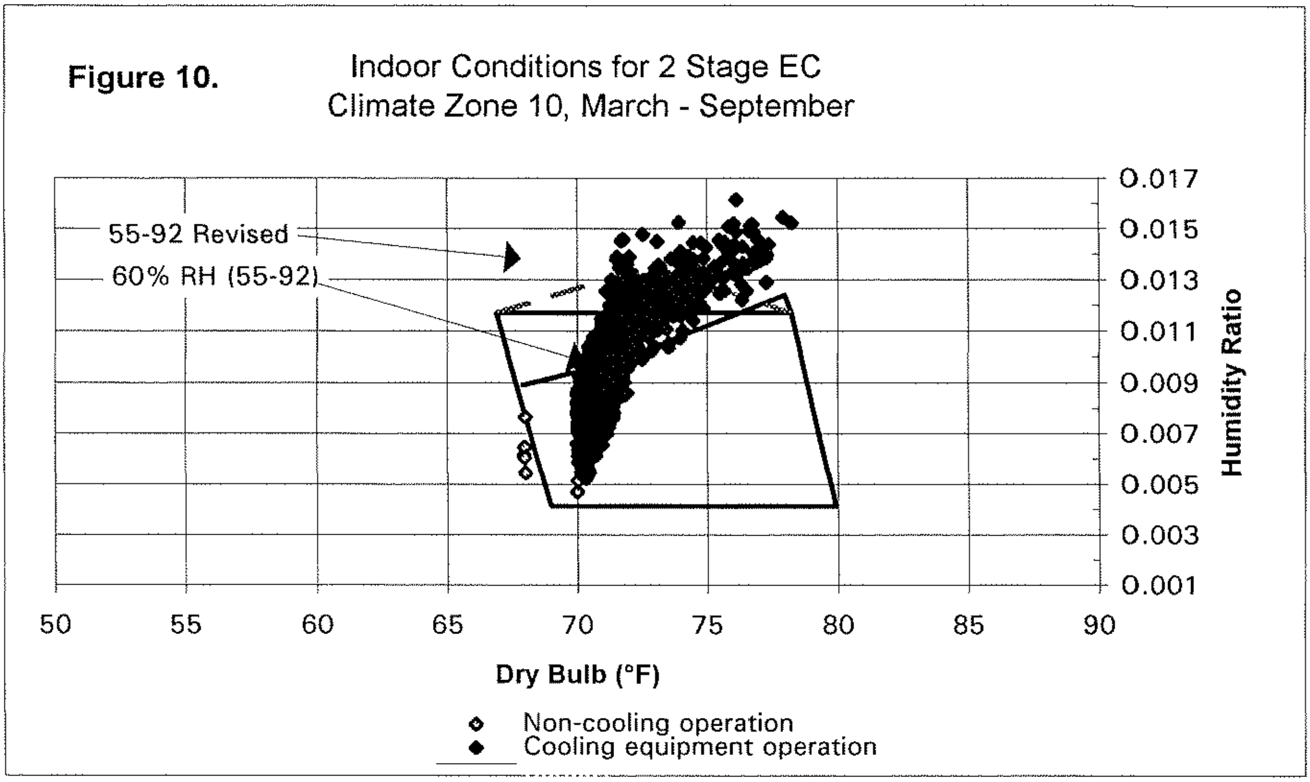


Figure 10.
Indoor Conditions for 2 Stage EC
Climate Zone 10, March - September
55-92 Revised
60% RH (55-92)
0.017
0.015
0.013
0.011
0.009
0.007
0.005
0.003
0.001
Humidity Ratio
50
55
60
65
70
75
80
85
90
Dry Bulb (°F)
Non-cooling operation
Cooling equipment operation

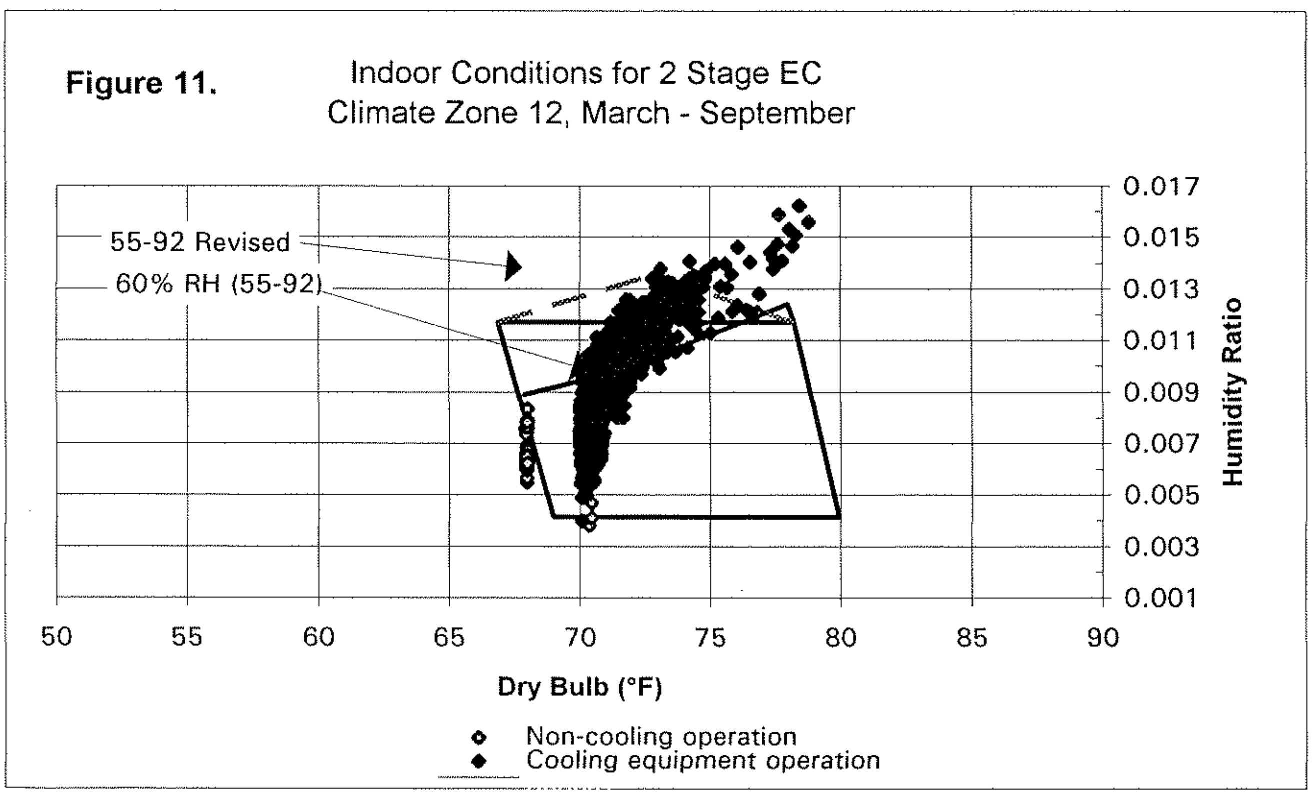


Figure 11.
Indoor Conditions for 2 Stage EC
Climate Zone 12, March - September
55-92 Revised
60% RH (55-92)
0.017
0.015
0.013
0.011
0.009
0.007
0.005
0.003
0.001
Humidity Ratio
50
55
60
65
70
75
80
85
90
Dry Bulb (°F)
Non-cooling operation
Cooling equipment operation

Figure 12. Indoor Conditions for Indirect EC
Climate Zone 2, March - September

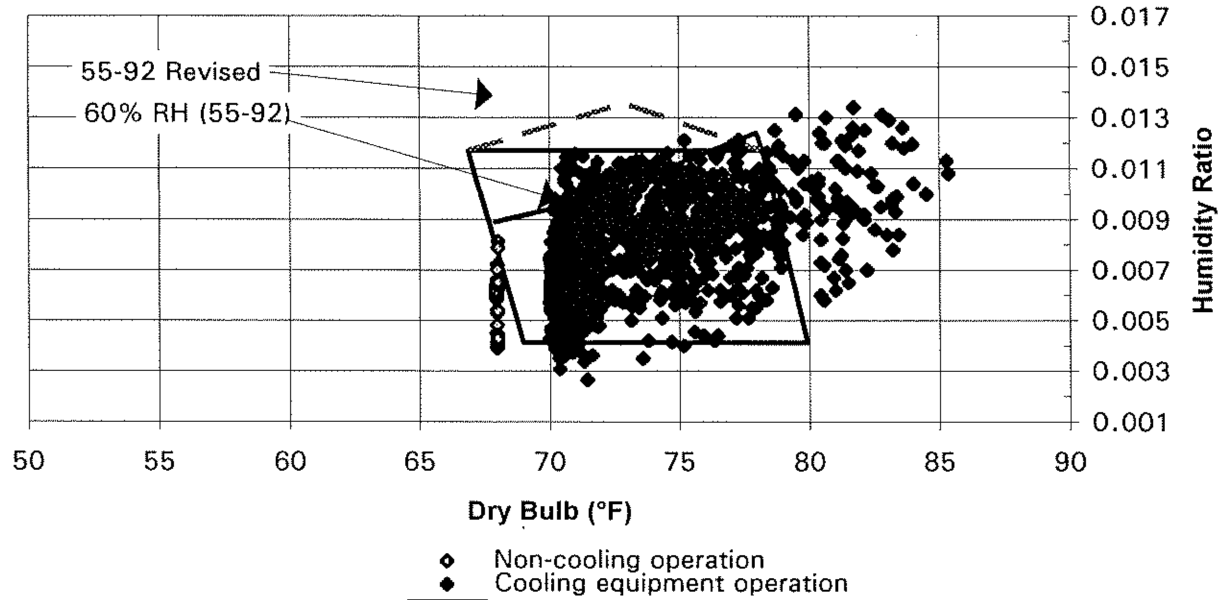


Figure 13. Indoor Conditions for Indirect EC
Climate Zone 9, March - September

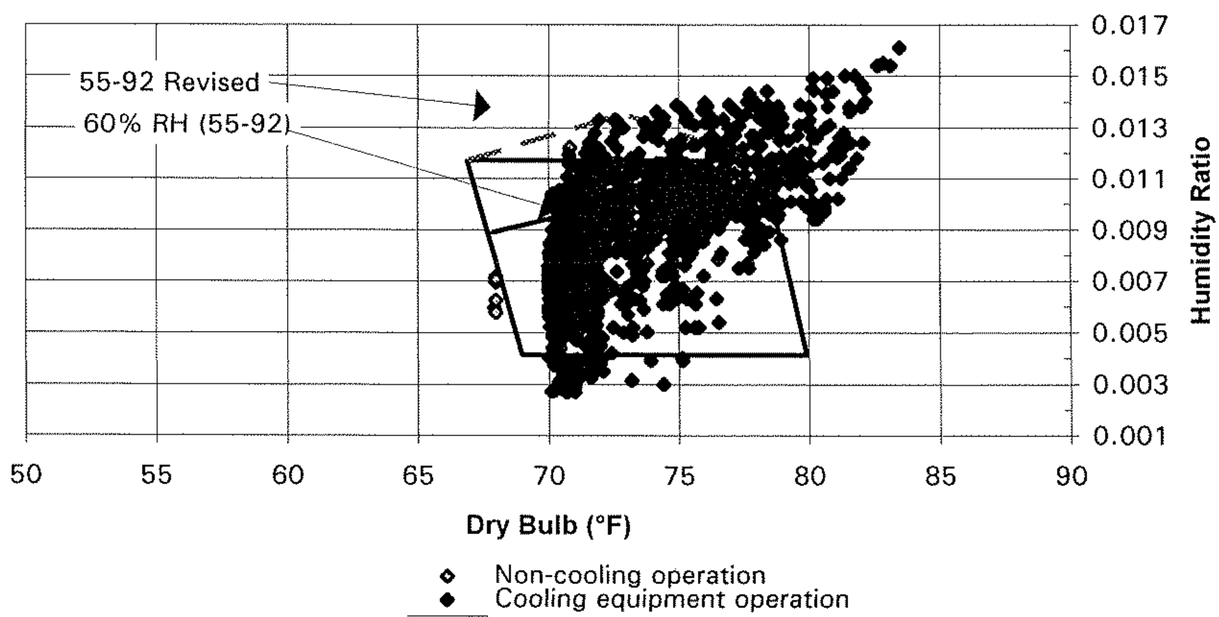


Figure 14. Indoor Conditions for Indirect EC Climate Zone 10, March - September

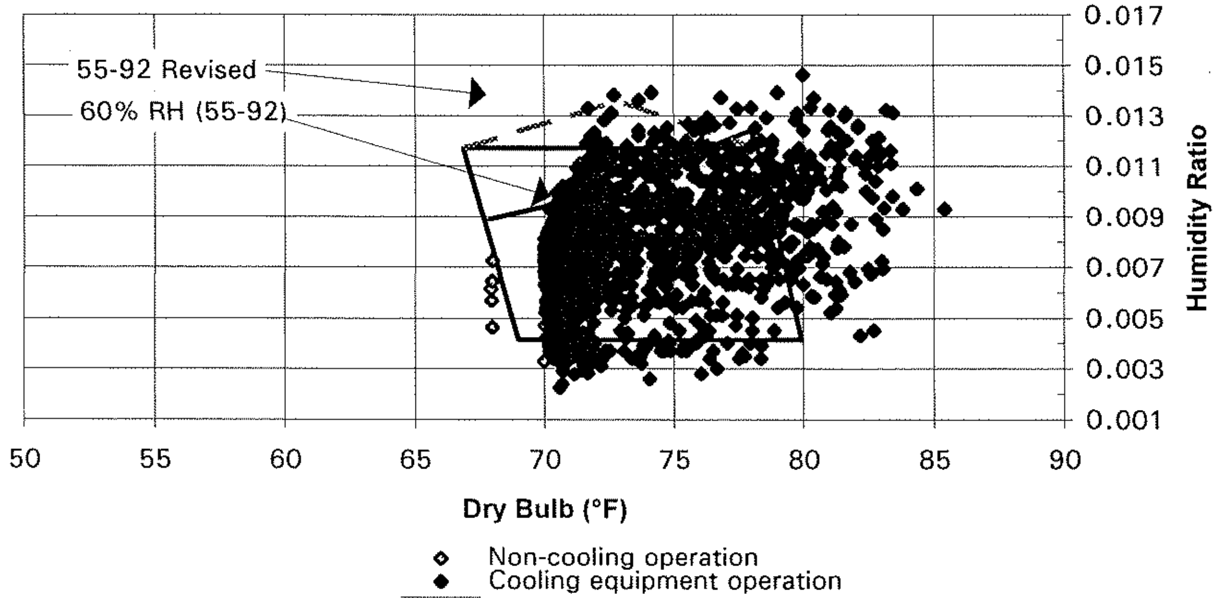


Figure 15. Indoor Conditions for Indirect EC Climate Zone 12, March - September

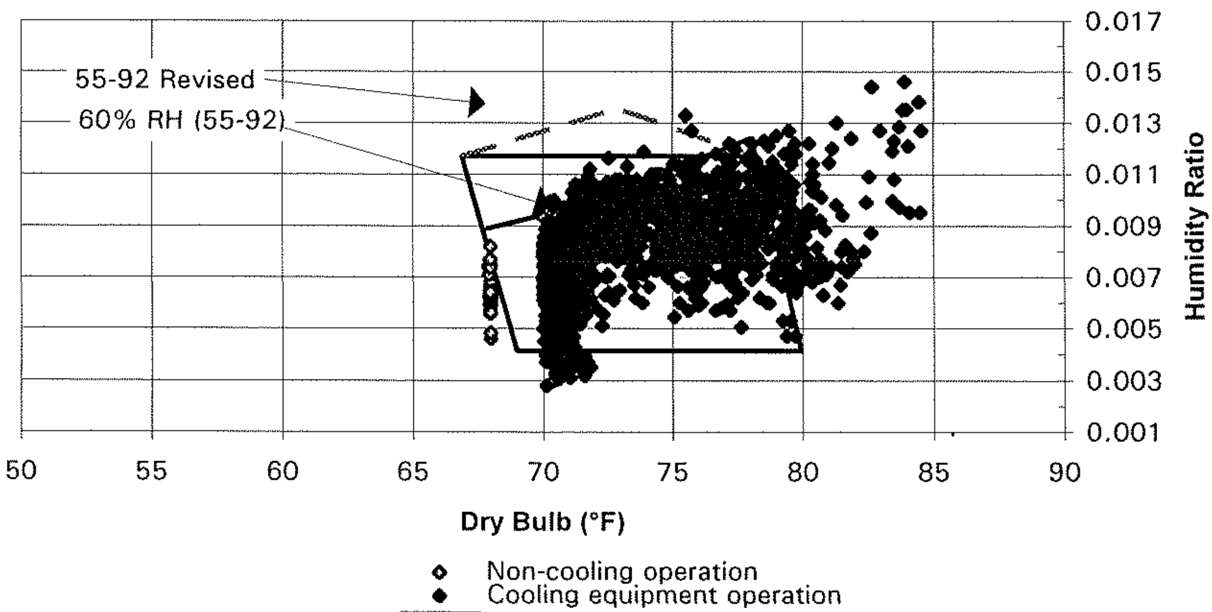


Figure 16. Indoor Conditions for Direct EC Climate Zone 2, March - September

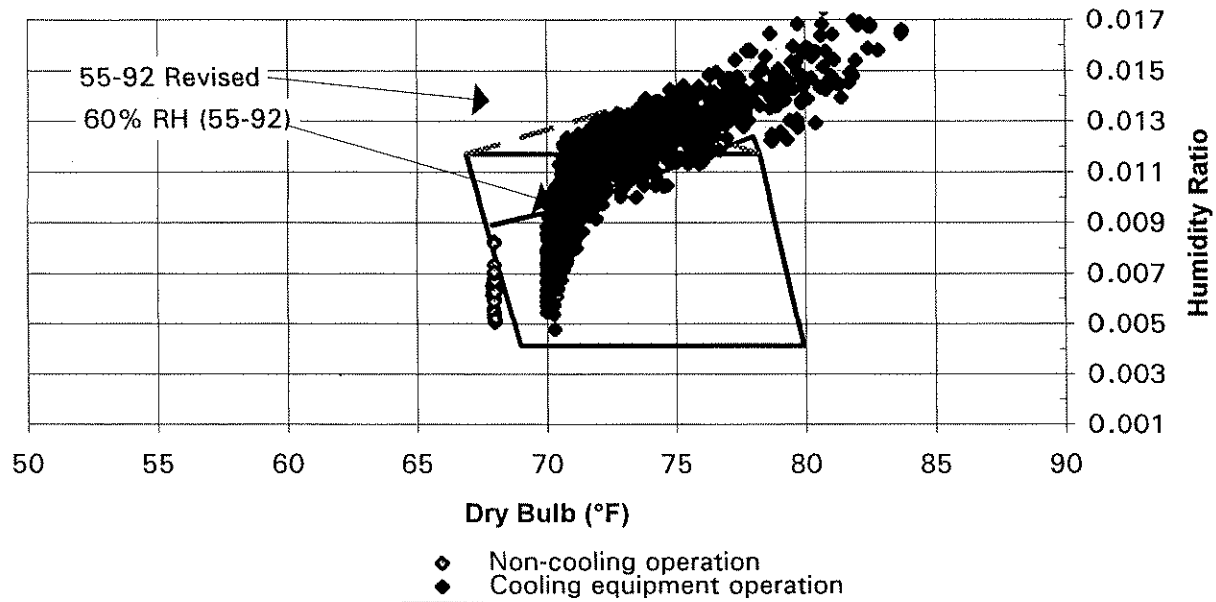


Figure 17. Indoor Conditions for Direct EC Climate Zone 9, March - September

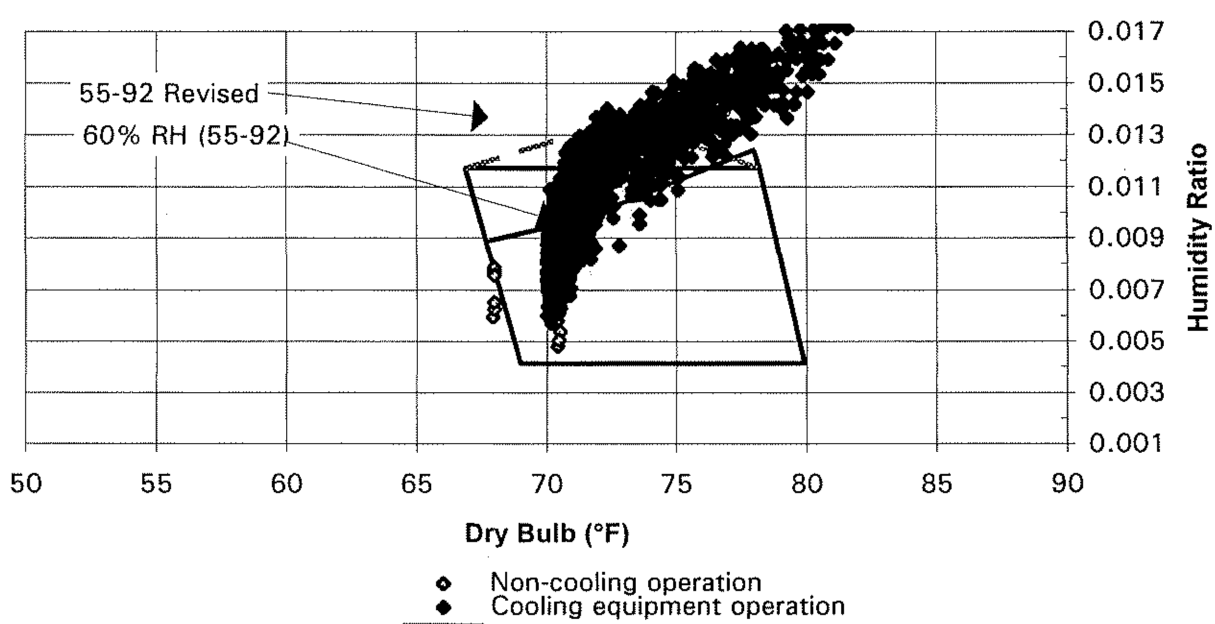


Figure 18.

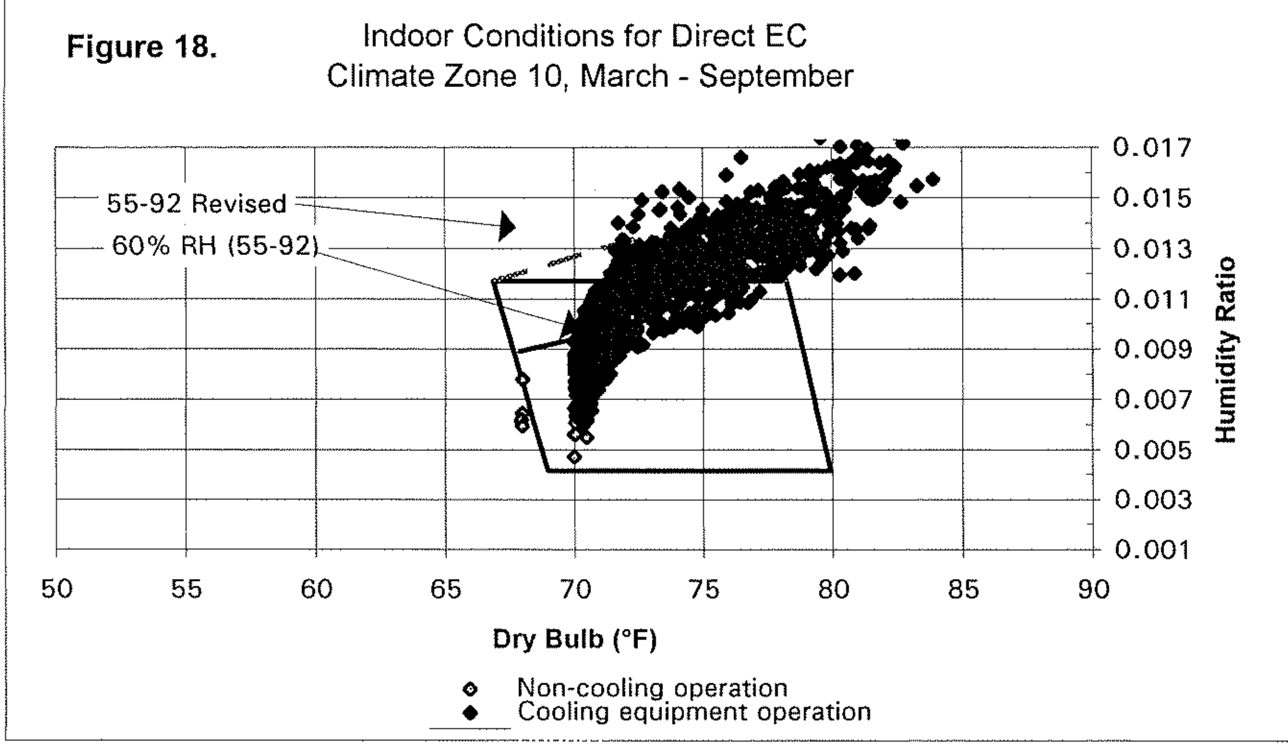


Figure 19.

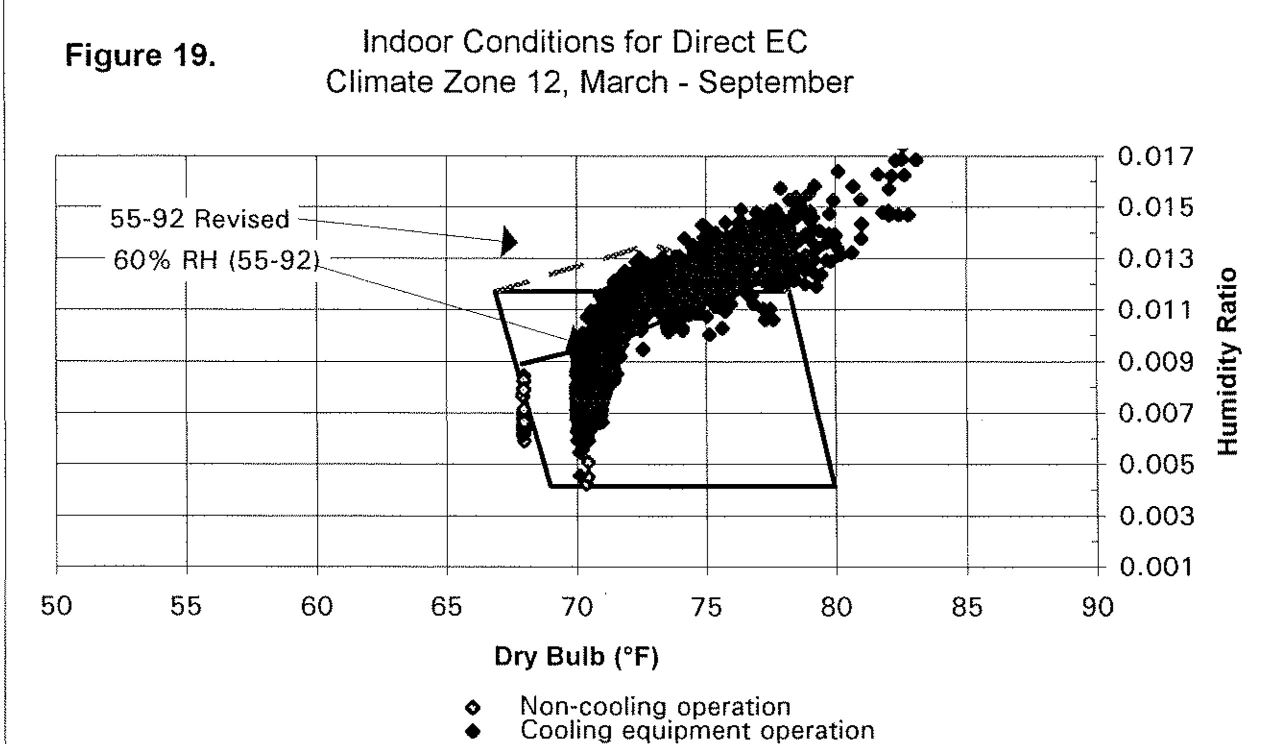


Figure 20. Indoor Conditions for PSZ
Climate Zone 2, March - September

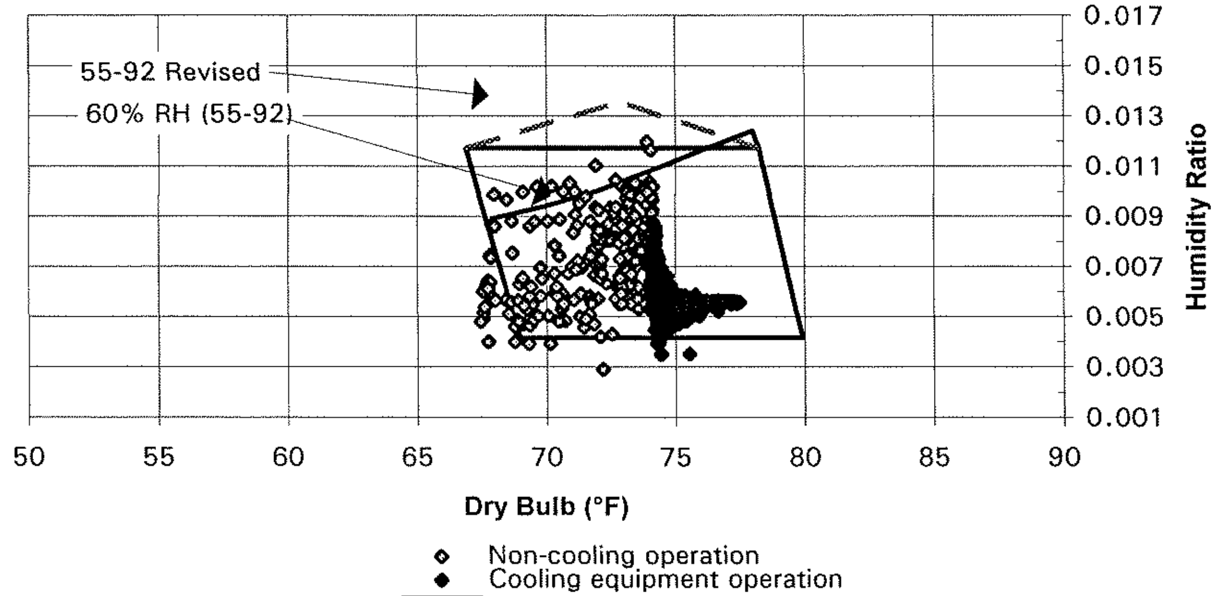


Figure 21. Indoor Conditions for PSZ
Climate Zone 9, March - September

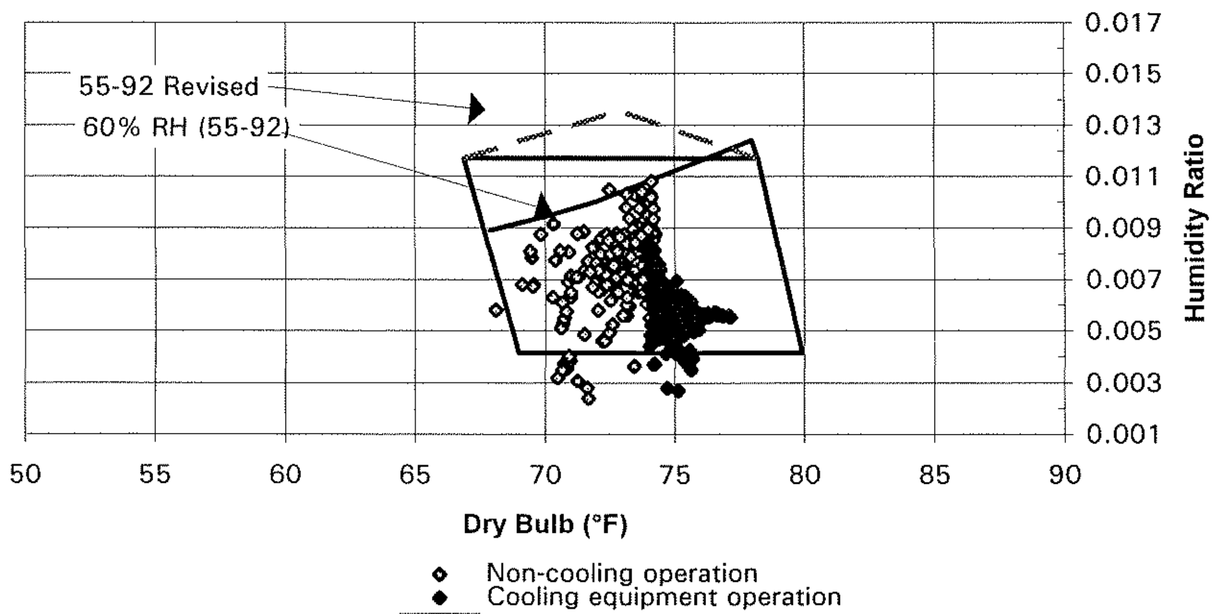


Figure 22. Indoor Conditions for PSZ Climate Zone 10, March - September

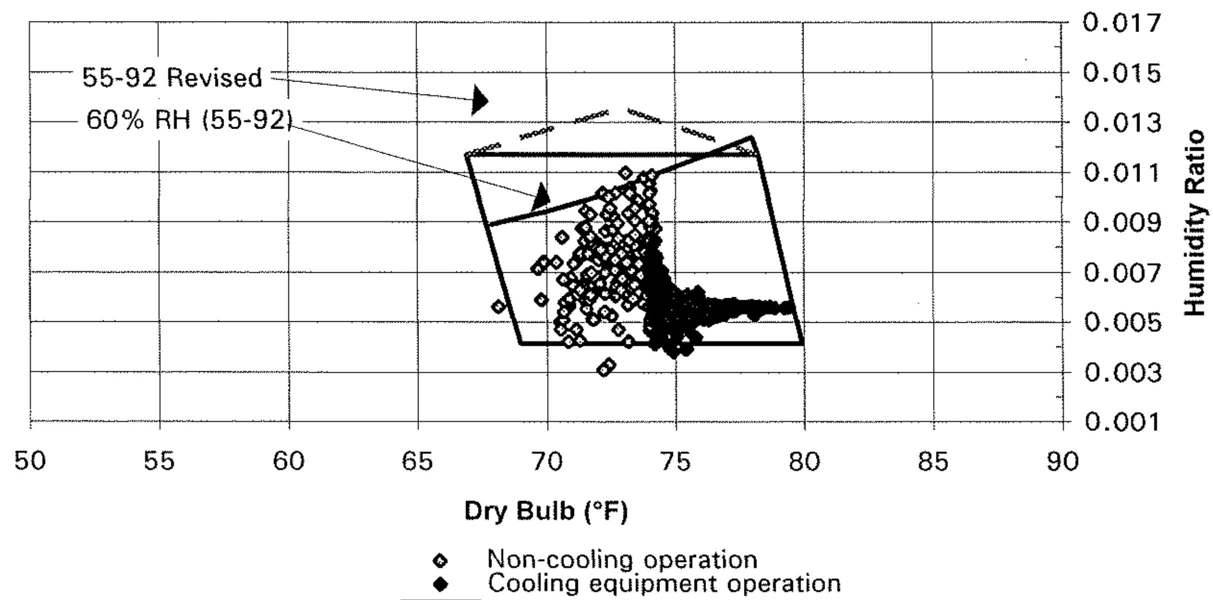


Figure 23. Indoor Conditions for PSZ Climate Zone 12, March - September

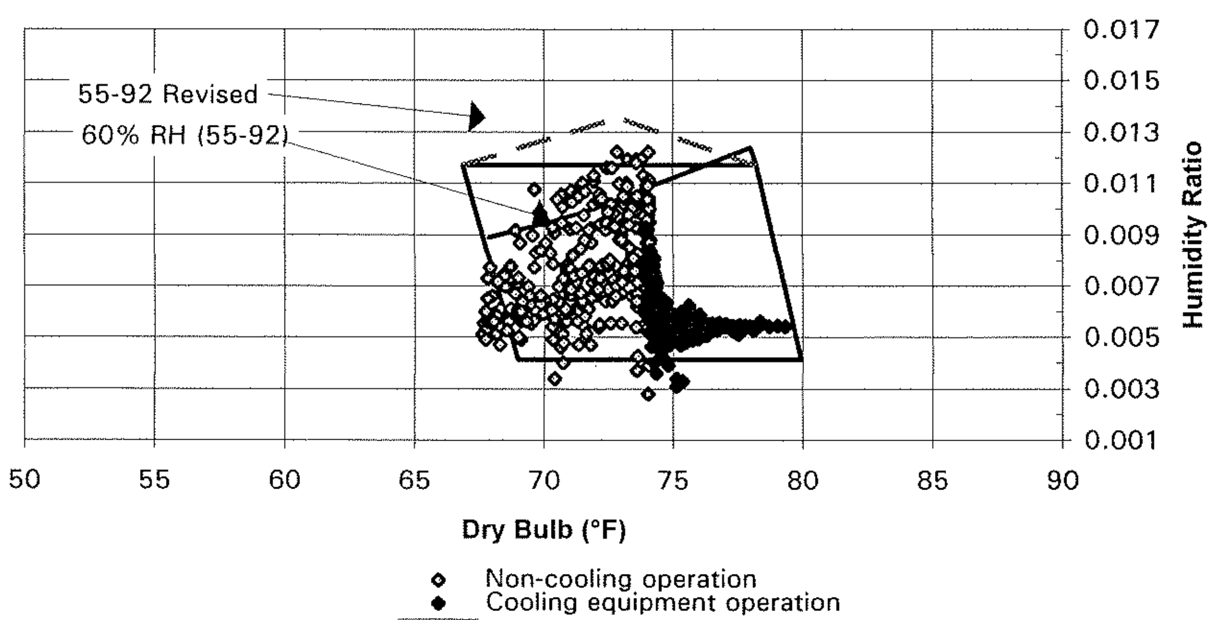


Figure 24. Indoor Conditions for PSZ w/ econ Climate Zone 2, March - September

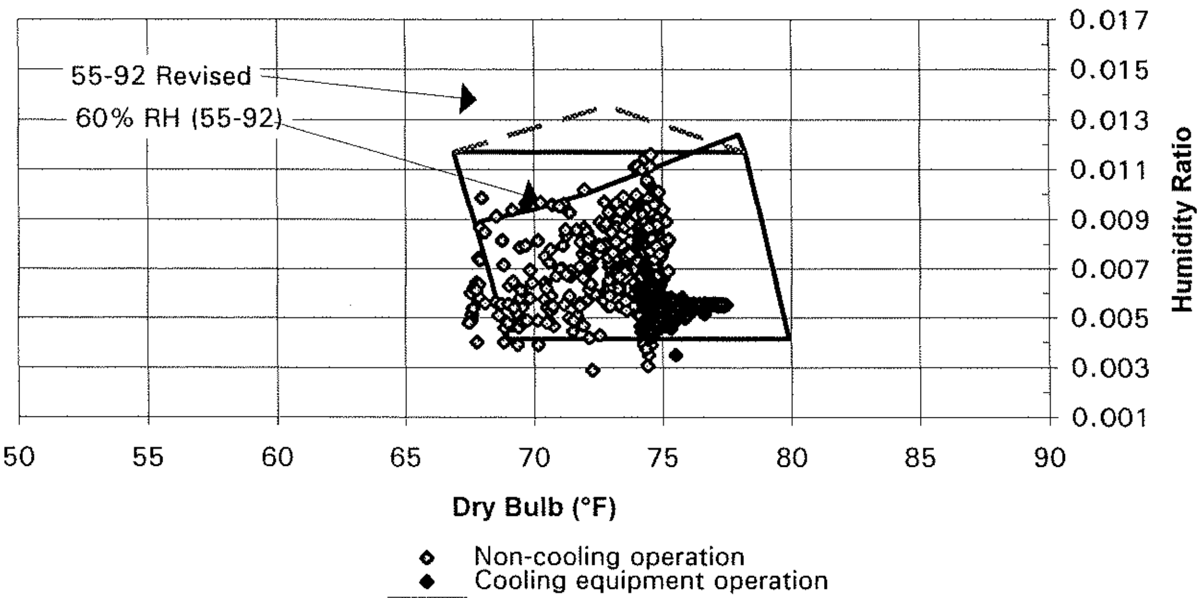


Figure 25. Indoor Conditions for PSZ w/ econ Climate Zone 9, March - September

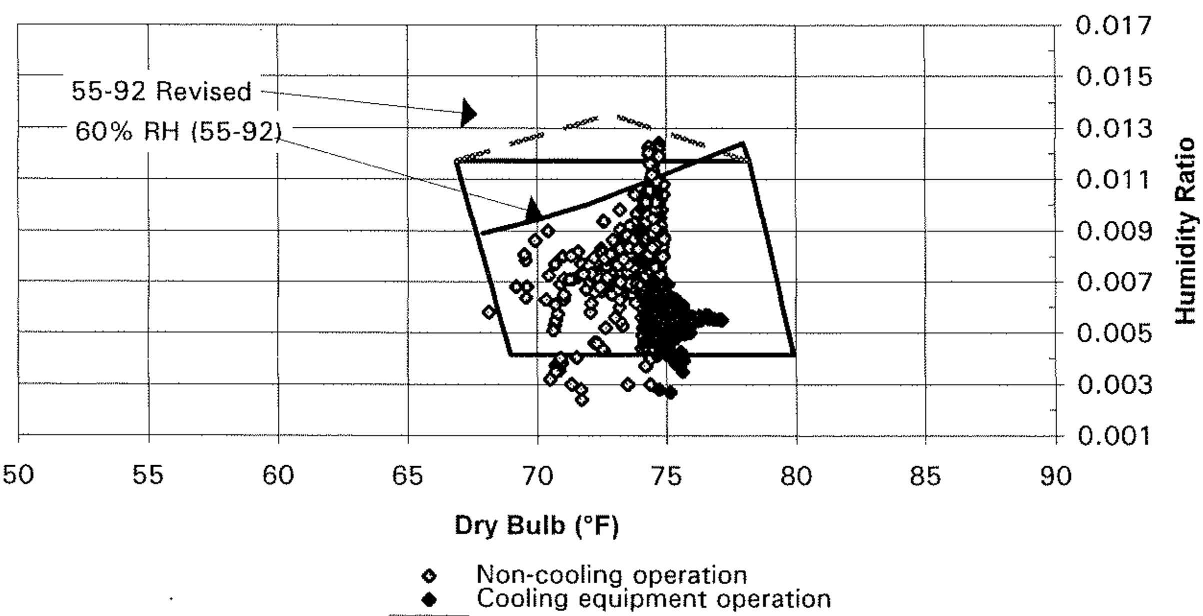


Figure 26.

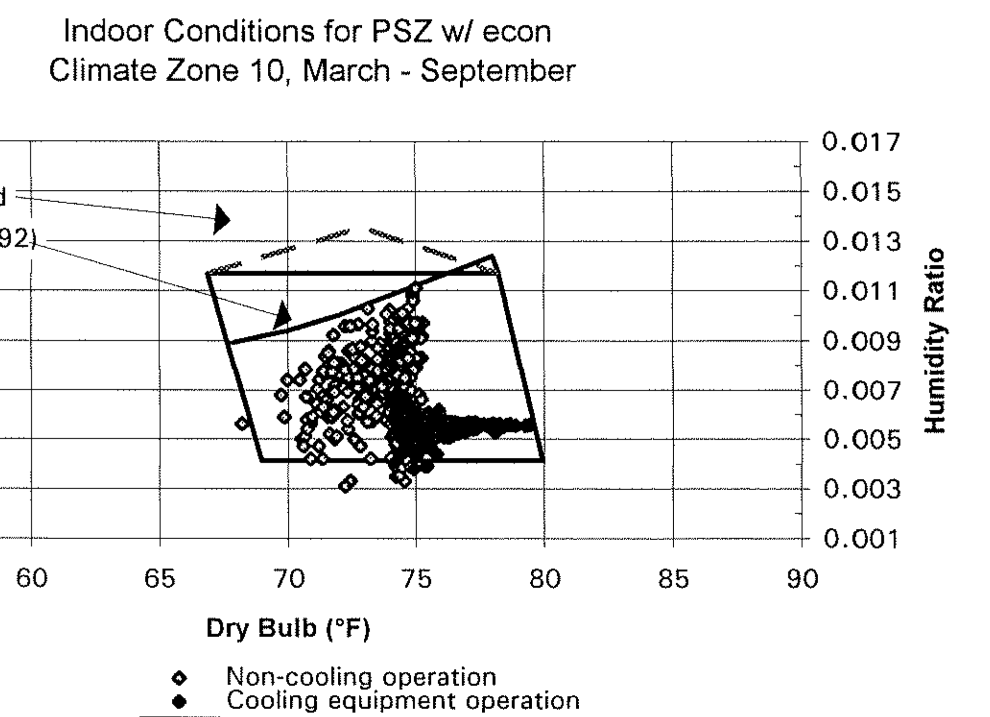


Figure 27.

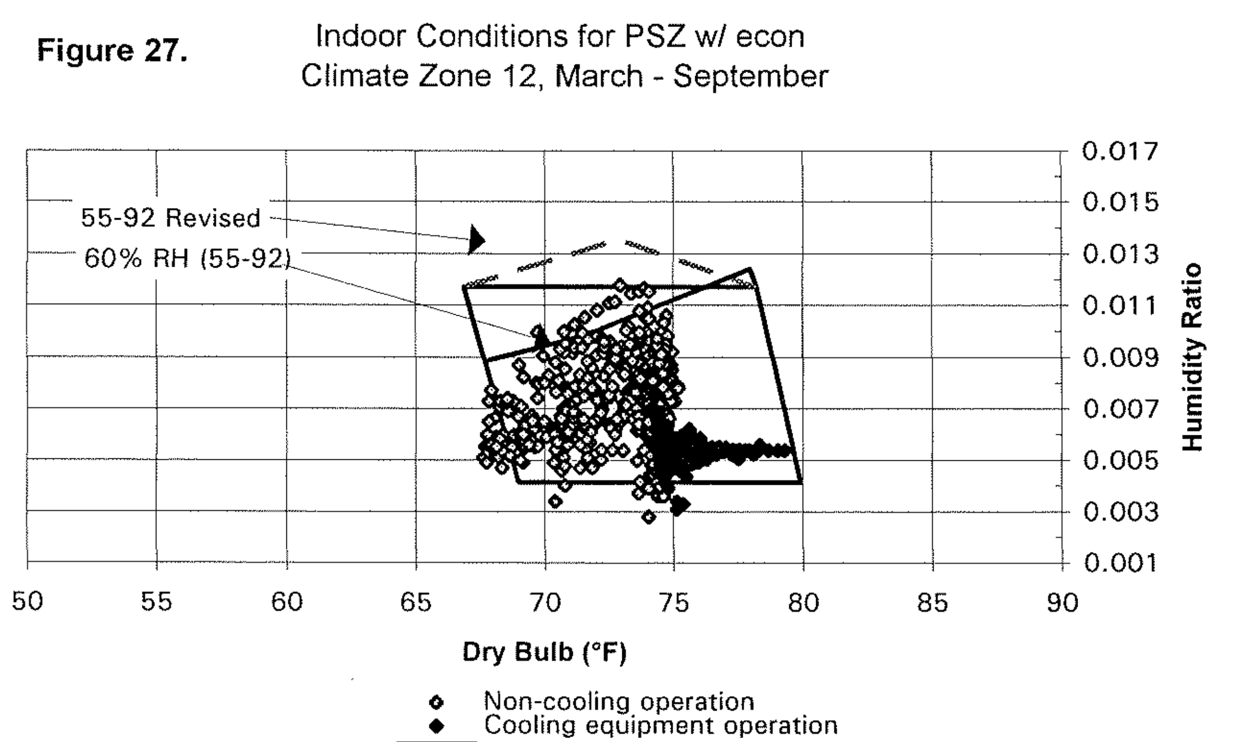


Figure 28.

Indoor Conditions for VAV
Climate Zone 2, March - September

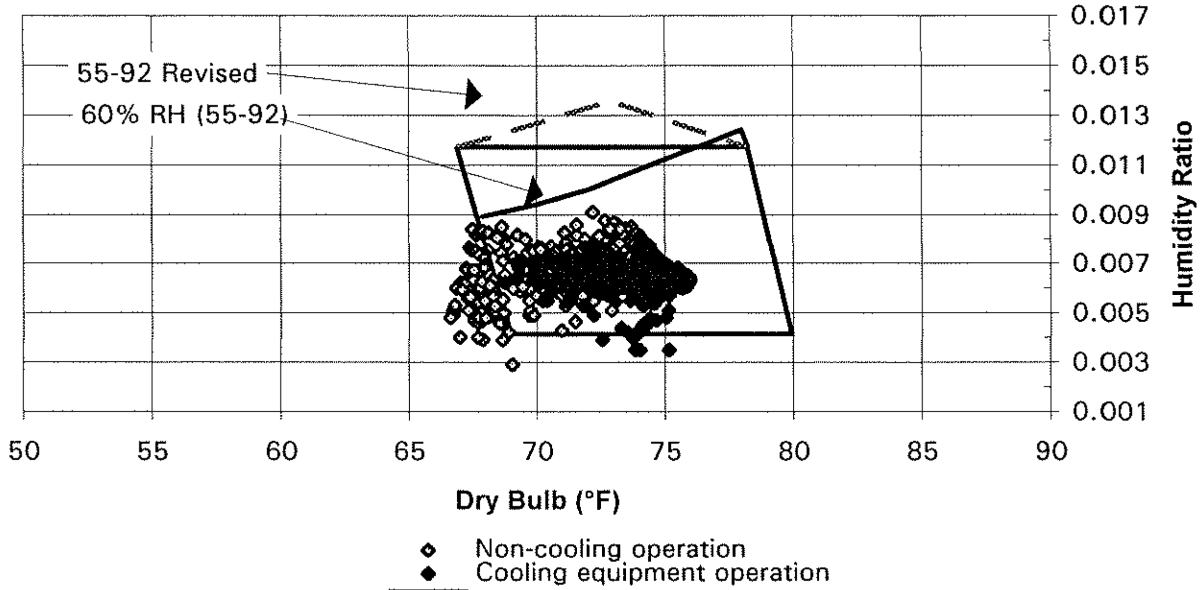


Figure 29.

Indoor Conditions for VAV
Climate Zone 9, March - September

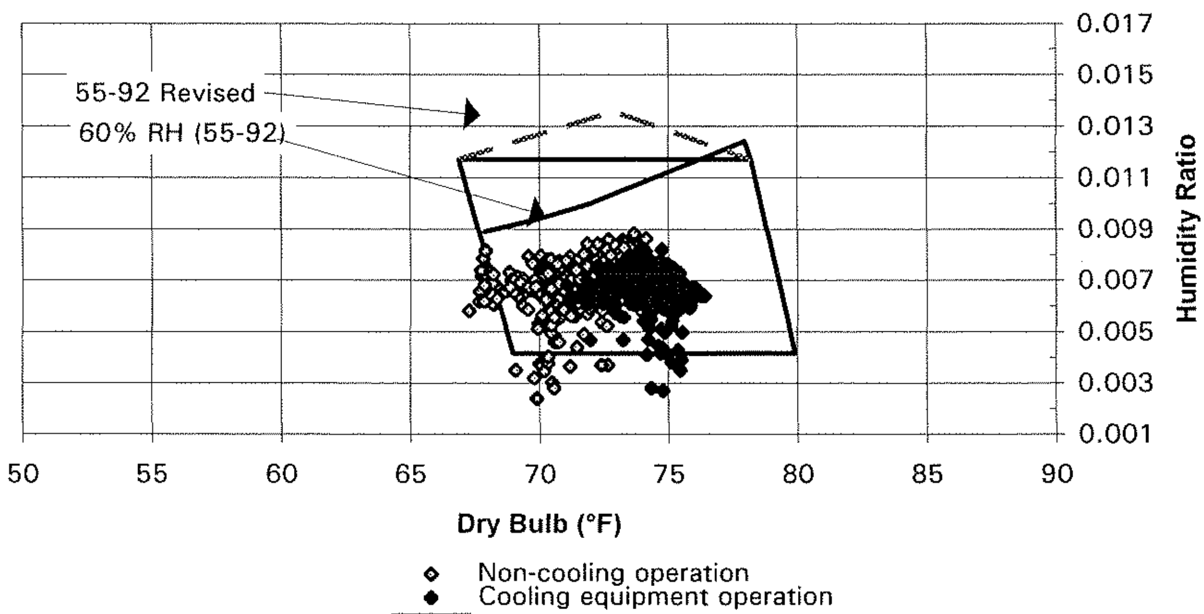


Figure 30. Indoor Conditions for VAV
Climate Zone 10, March - September

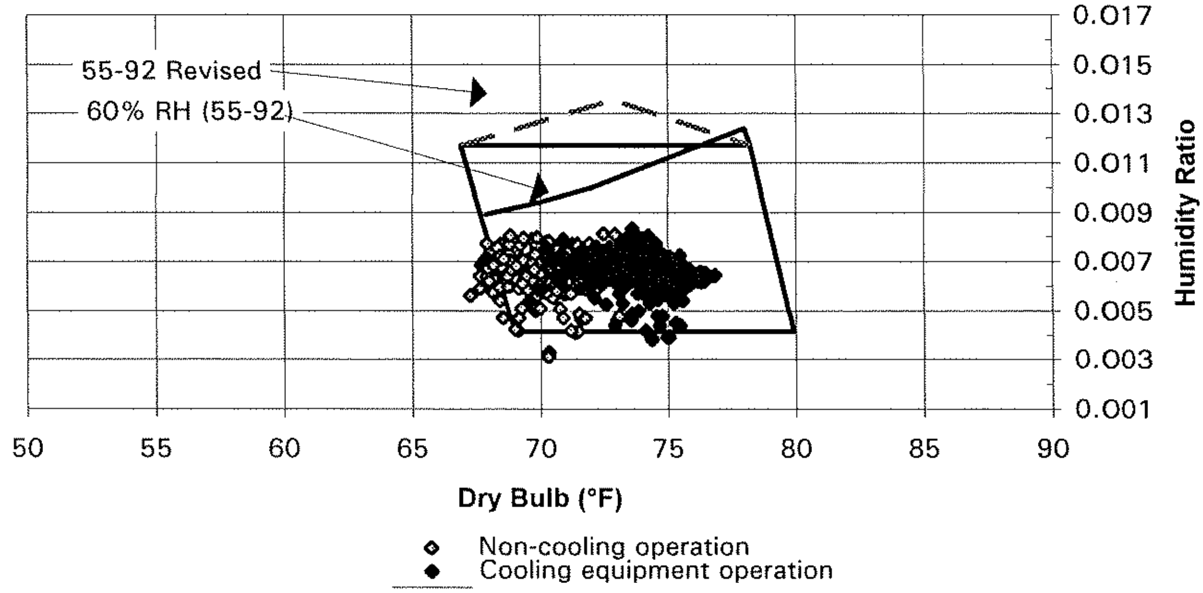


Figure 31. Indoor Conditions for VAV
Climate Zone 12, March - September

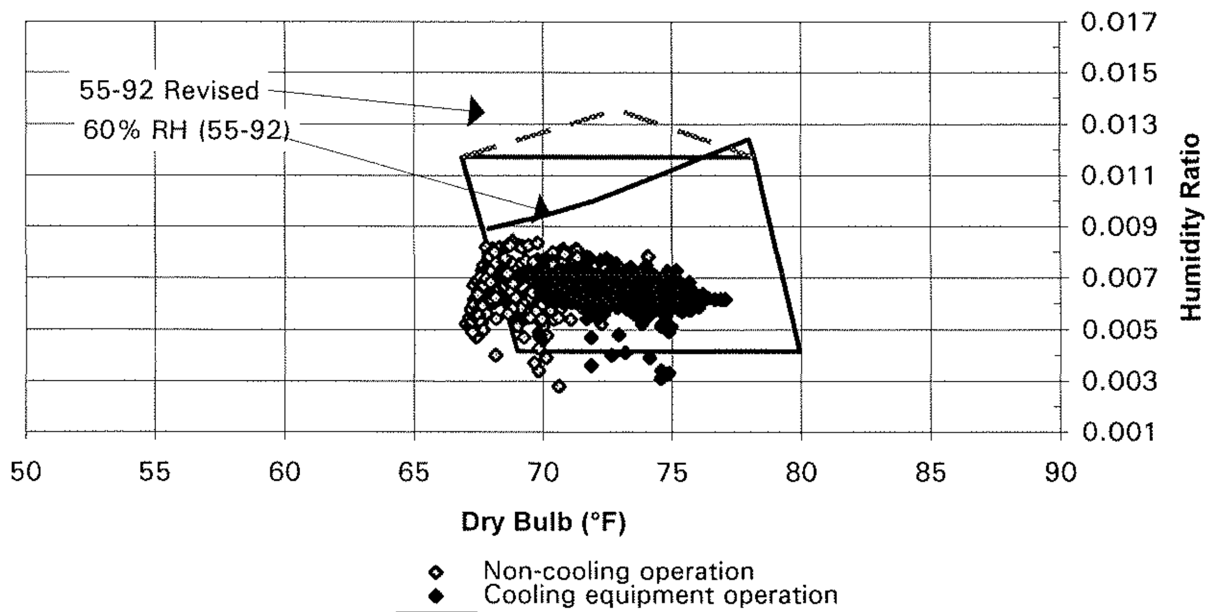


Figure 32. Indoor Conditions for VAV w/ econ Climate Zone 2, March - September

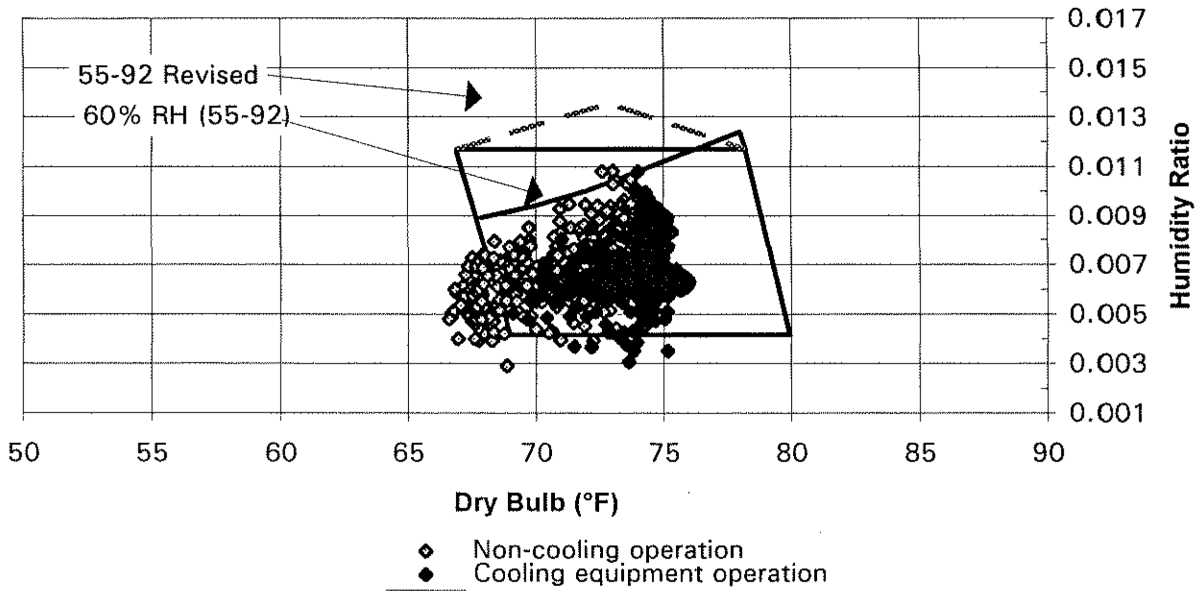


Figure 33. Indoor Conditions for VAV w/ econ Climate Zone 9, March - September

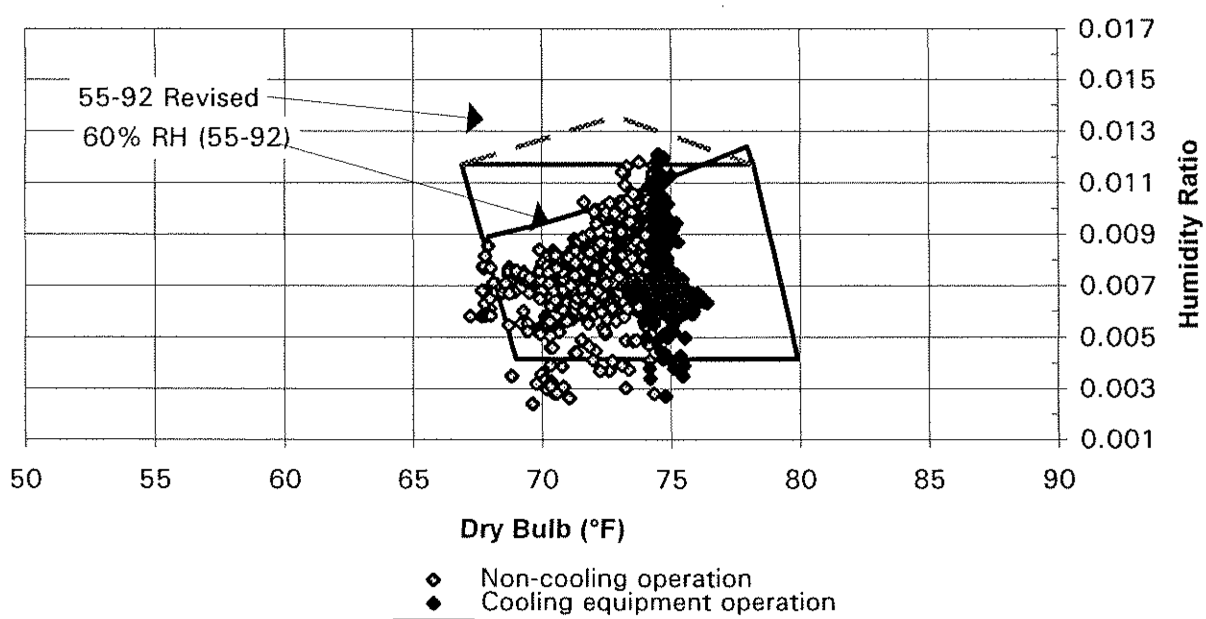


Figure 34. Indoor Conditions for VAV w/ econ Climate Zone 10, March - September

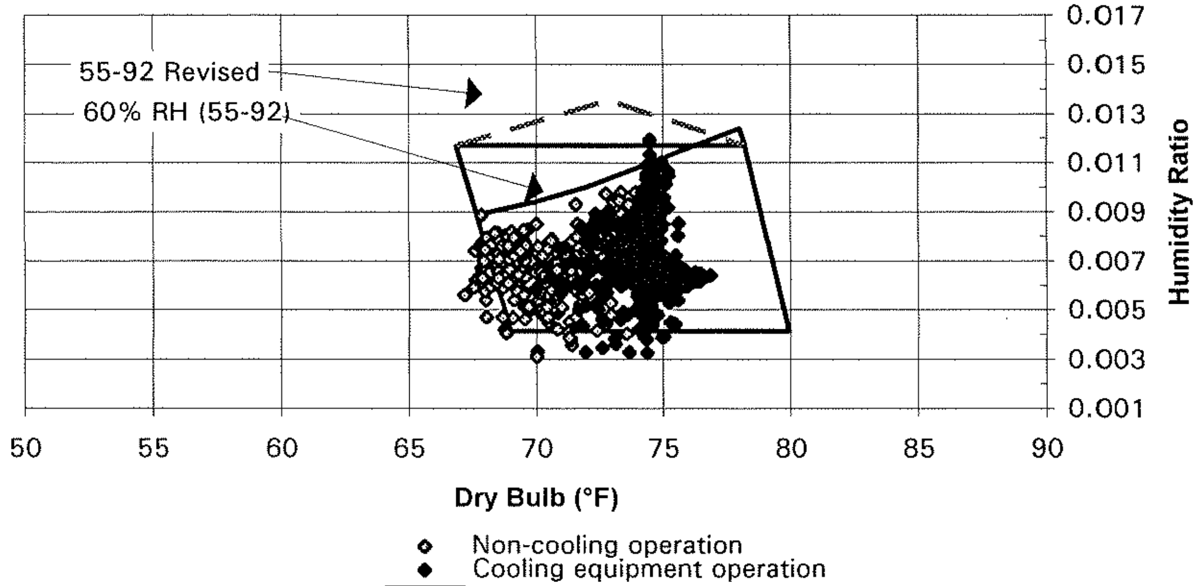


Figure 35. Indoor Conditions for VAV w/ econ Climate Zone 12, March - September

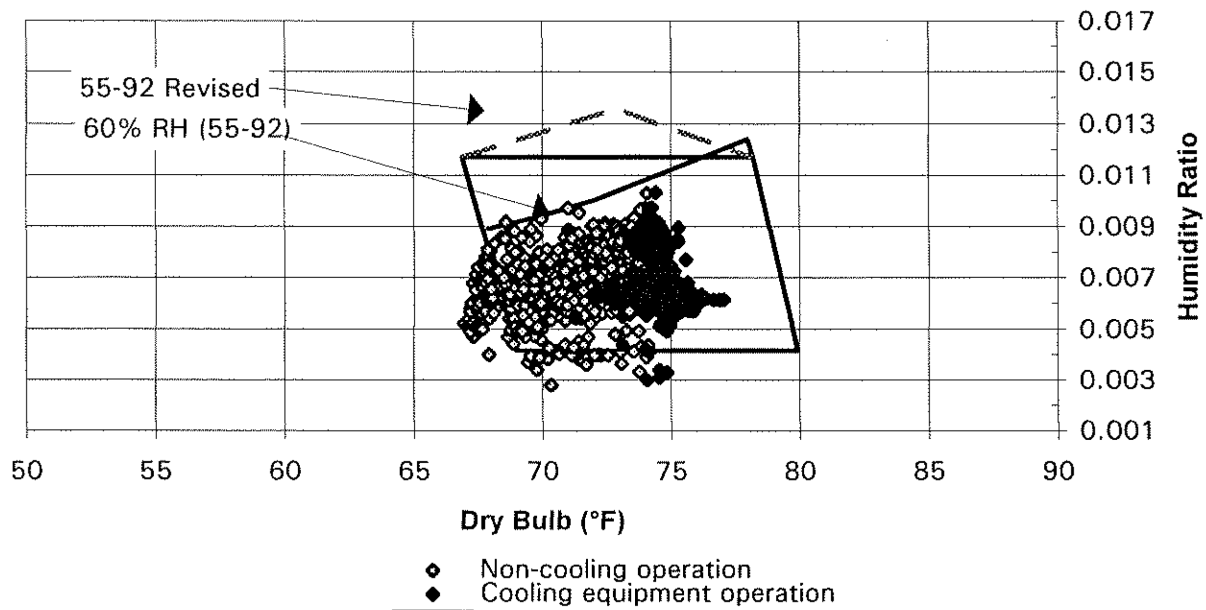


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Figure 36.
% of Occupied Hours with Humidity Above ASHRAE Comfort Zone
Climate Zone 2

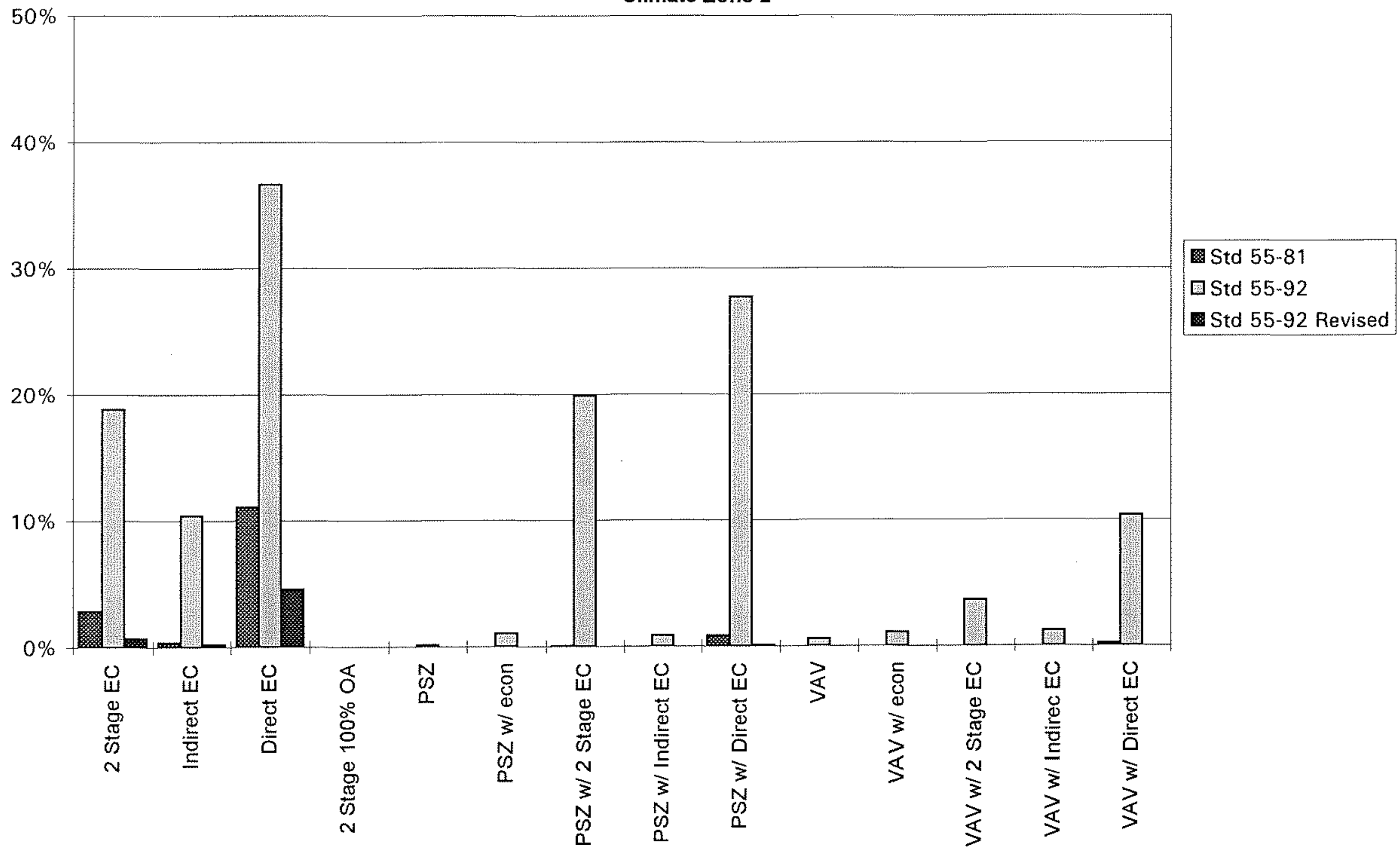


Figure 37.
% of Occupied Hours with Humidity Above ASHRAE Comfort Zone
Climate Zone 9

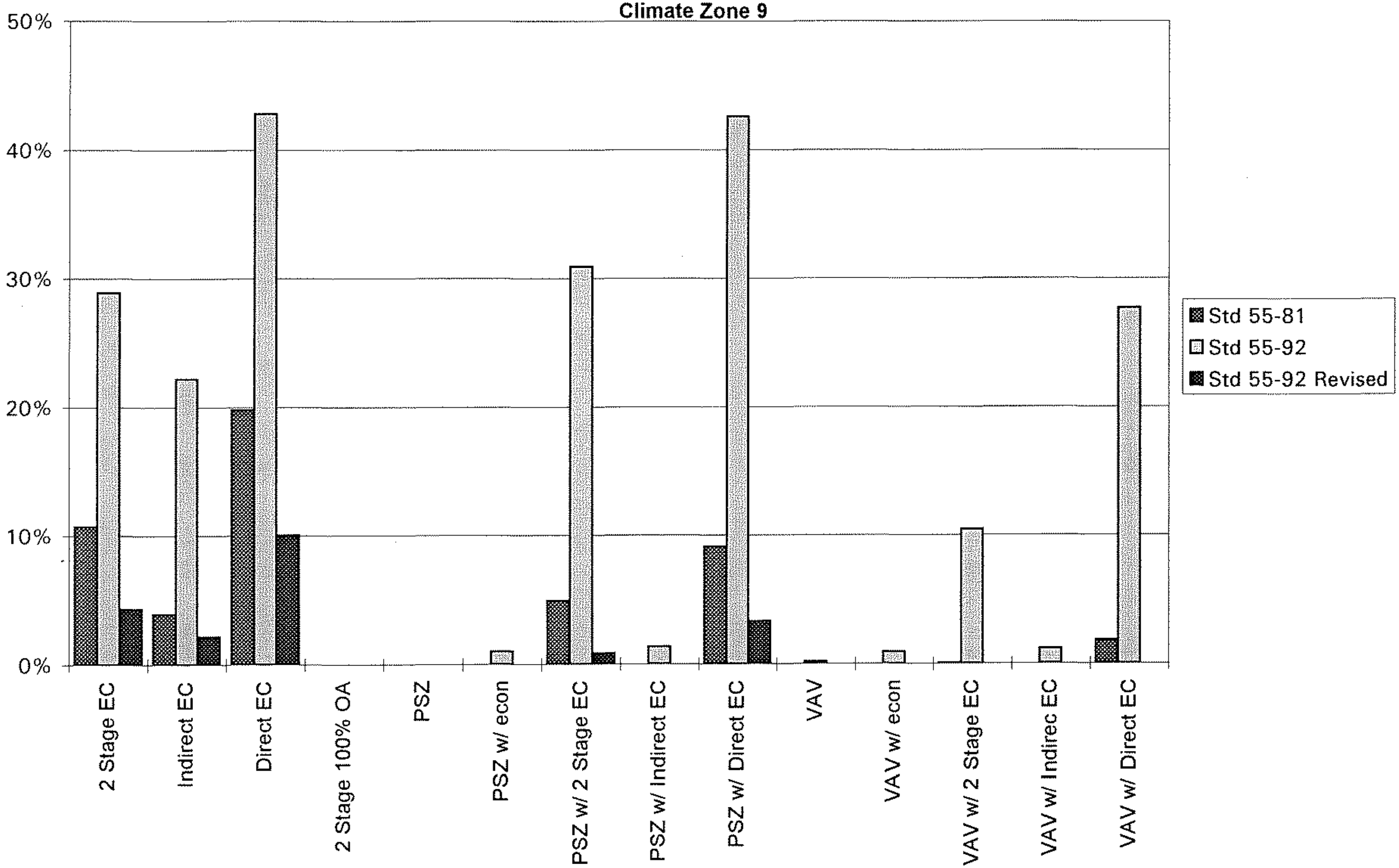


Figure 38.
% of Occupied Hours with Humidity Above ASHRAE Comfort Zone
Climate Zone 10

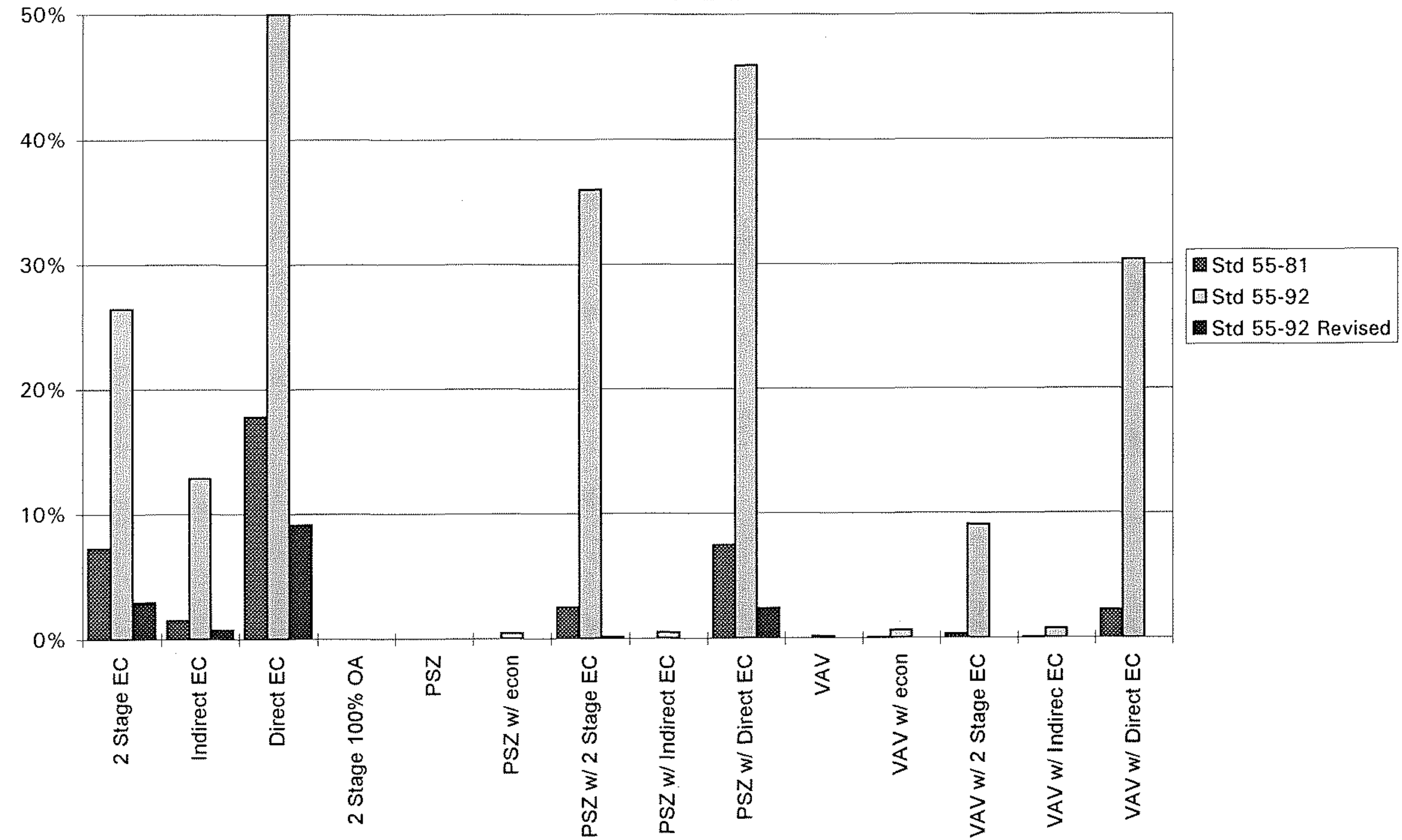
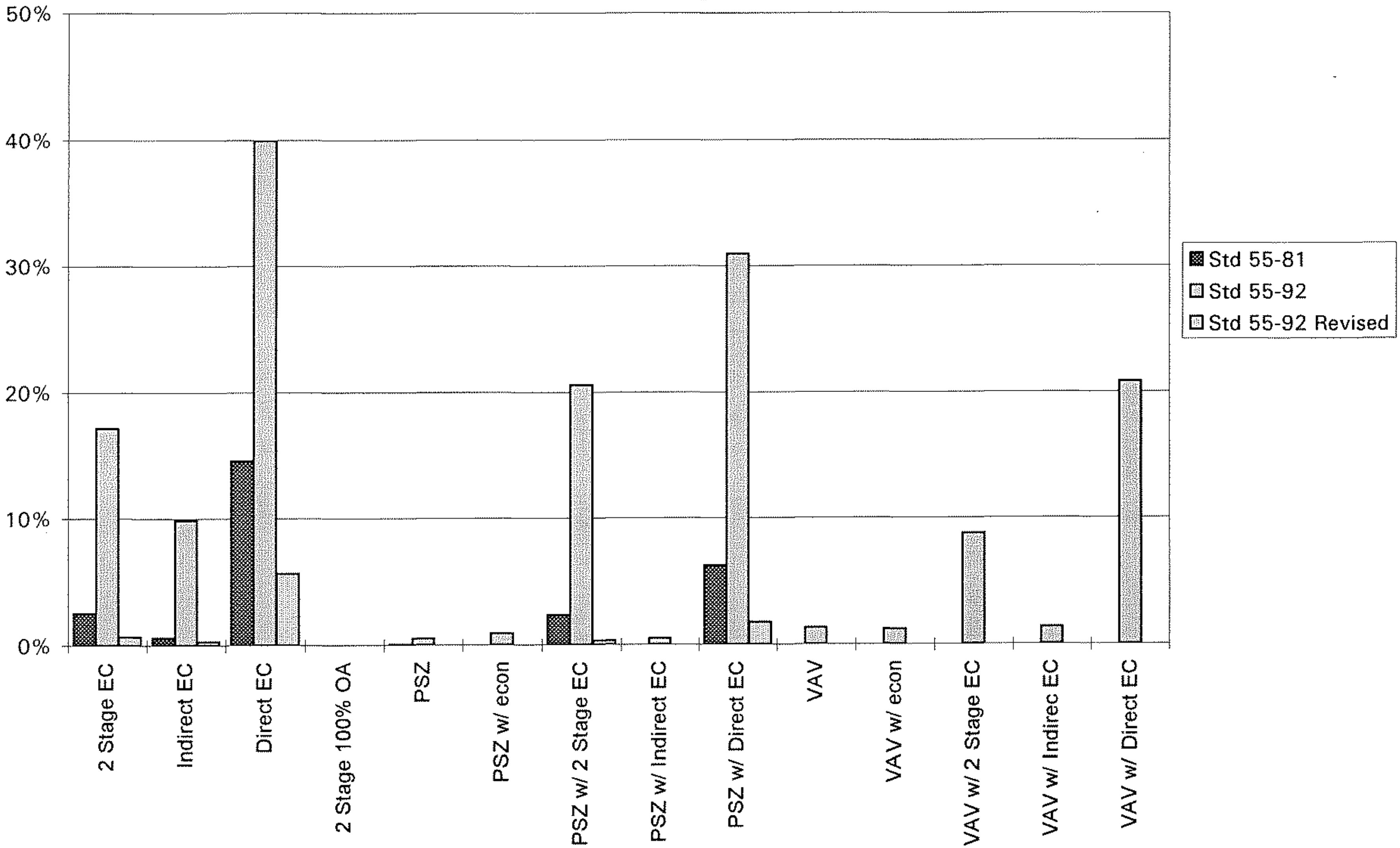


Figure 39.
% of Occupied Hours with Humidity Above ASHRAE Comfort Zone
Climate Zone 12



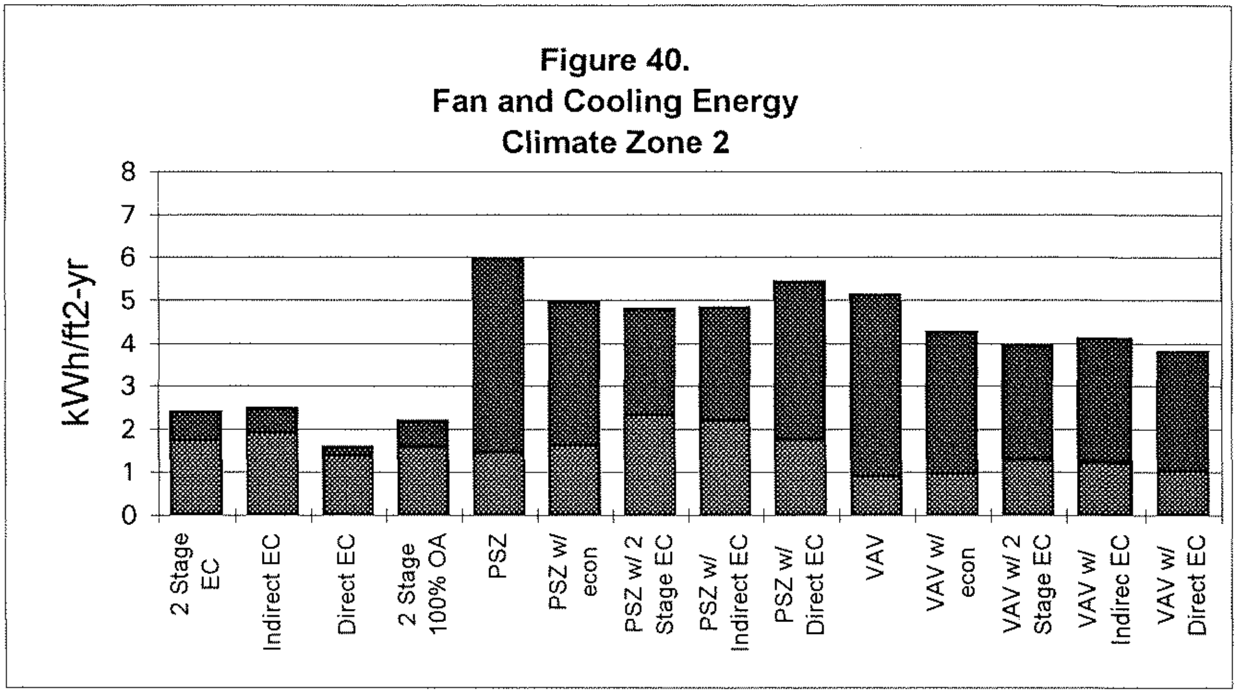


Figure 40.
Fan and Cooling Energy
Climate Zone 2
kWh/ft2-yr
8
7
6
5
4
3
2
1
0
2 Stage EC
Indirect EC
Direct EC
2 Stage 100% OA
PSZ
PSZ w/ econ
PSZ w/ 2 Stage EC
PSZ w/ Indirect EC
PSZ w/ Direct EC
VAV
VAV w/ econ
VAV w/ 2 Stage EC
VAV w/ Indirec EC
VAV w/ Direct EC

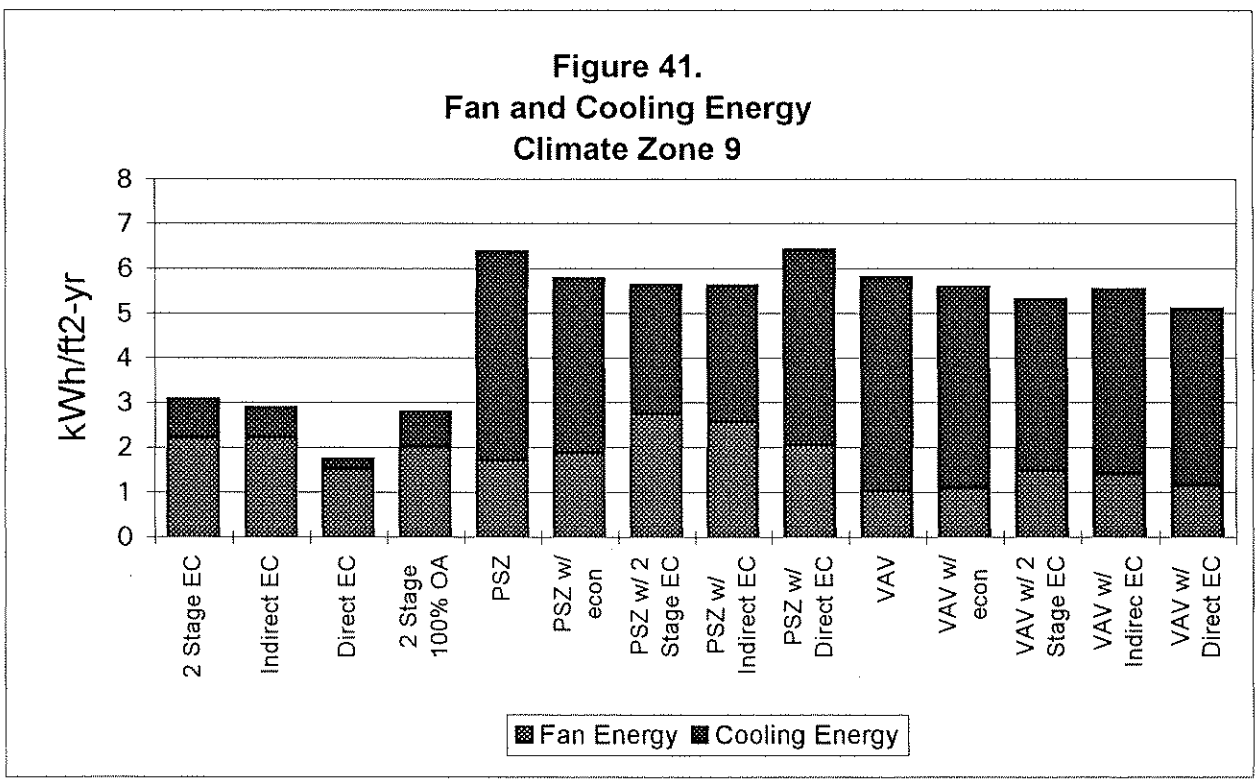


Figure 41.
Fan and Cooling Energy
Climate Zone 9
kWh/ft2-yr
8
7
6
5
4
3
2
1
0
2 Stage EC
Indirect EC
Direct EC
2 Stage 100% OA
PSZ
PSZ w/ econ
PSZ w/ 2 Stage EC
PSZ w/ Indirect EC
PSZ w/ Direct EC
VAV
VAV w/ econ
VAV w/ 2 Stage EC
VAV w/ Indirec EC
VAV w/ Direct EC
Fan Energy
Cooling Energy

Figure 42.
Fan and Cooling Energy
Climate Zone 9

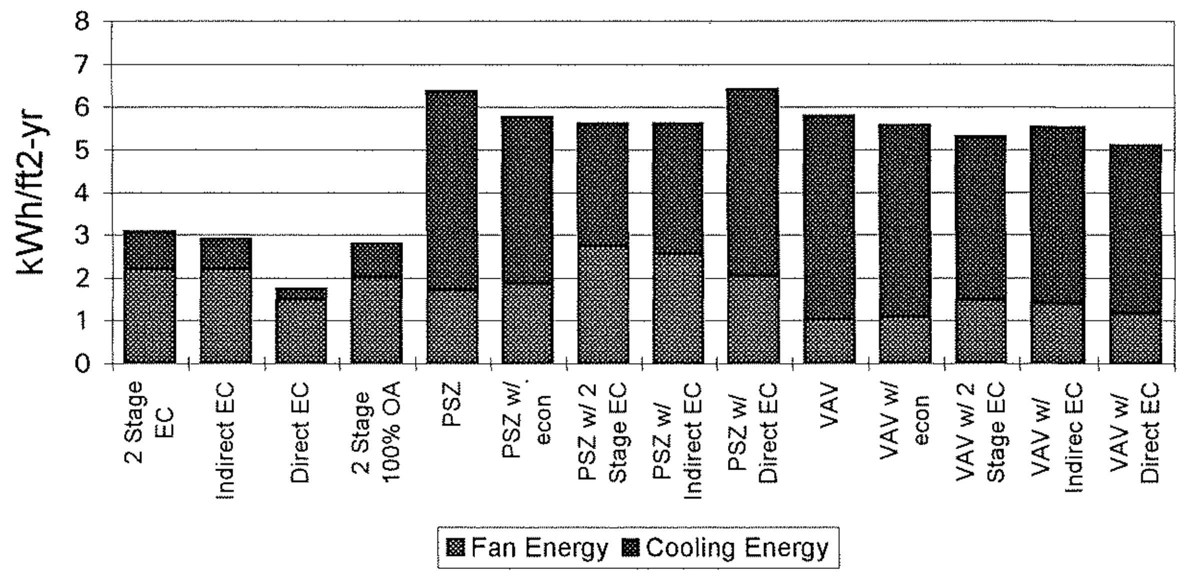


Figure 43.
Fan and Cooling Energy
Climate Zone 12