Title
Laboratory test of the Argon personal air-conditioning system (APACS)

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ARGON PERSONAL AIR CONTROL SYSTEM (APACS)

LABORATORY TEST[1]
UNIVERSITY OF CALIFORNIA, BERKELEY

The tests described in the subject report were performed at UC Berkeley by Research Specialist Fred Bauman, P.E., a very experienced researcher and writer in the field of air distribution (see References). The purpose of the tests was to measure and confirm the ability of APACS to provide the needed cooling to satisfy each and every individual occupant for total comfort control under all foreseeable conditions.

The test facility measured only dry (sensible) heat. As the report indicates, the cooling effect of skin moisture (latent cooling) is equal to or greater than sensible cooling. Especially at extremes when the occupant is very hot and perspiring, he can increase APACS air flow to remove all the heat generated, provide thermal equilibrium, and thus make himself comfortable.

The heat generated (metabolism) can vary from 360 to 3000 Btuh per person, a range of almost 10 to 1[2]. This is the reason for providing up to 70 CFM of personal air flow – even though this high heat output is rare in an office environment. The norm is 360 to 800 Btuh, which requires only 0 to 30 CFM, and maximum air velocity of 200 FPM (1 m/s), or 2.3 MPH, which is very comfortable (see Table 3, Pg. 11).

This study demonstrates the ability of APACS to remove variable amounts of heat with localized air flow instead of air temperature change, and to provide perceived temperatures for the individual through a range of 0° to 15°F (65° - 80°F) without affecting other people.

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LABORATORY TEST OF THE ARGON PERSONAL AIR-CONDITIONING SYSTEM (APACS)

Final Report

Submitted to
Argon Corporation
Naples, Florida

Submitted by
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Berkeley, California

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EXECUTIVE SUMMARY

The cooling effectiveness of the Argon Personal Air-Conditioning System (APACS) was investigated in a controlled environment chamber. The APACS Personal Air Outlet was installed and tested as an underdesk air terminal in both the horizontal and vertical positions with underfloor supply air at 21-25°C (70-77°F) in a standard partitioned office workstation. Its effect on the sensible heat loss from a thermal manikin with 16 heated sections was measured at two different room temperatures (26, 28°C [79, 82°F]) and a range of supply air volumes (10-70 cfm [5-33 L/s]). Individual cooling control provided by the APACS unit was measured in terms of reduction in room air temperature (without local air motion) that would have affected equivalent whole-body heat loss. For the test at 28°C (82°F), the range of maximum sensible cooling effect was 4°C (7°F), and for the test at 26°C (79°F), the maximum effect was 3°C (5°F). Although not part of this test program, previous wet manikin tests have investigated the rate of evaporative (latent) cooling provided by local air supply units. Evaporative heat loss from a person can be significant, and in most cases, would produce a total whole-body cooling rate (sensible plus latent) that was at least double the sensible cooling rates presented in the following report.

The segmented manikin also provided a measure of the thermal asymmetry caused by the APACS unit in terms of the rate of heat loss from each of its 16 body sections. The degree of asymmetry was substantial for some of the test conditions that produced the highest whole-body cooling rates.

The amount of cooling was dependent primarily on the air supply volume and direction, and to a lesser degree on the supply air temperature, the proximity of the supply device to the manikin, and the room air temperature. The above values were achieved with the supply air directed toward the manikin in such a way as to maximize the convective heat loss from the manikin.

DESCRIPTION OF APACS

The APACS Personal Air Outlet consists of five 4-way adjustable grills mounted in a small distribution box that can be mounted horizontally (Figure 1, 2) or vertically (Figure 3) in the kneespace of a typical office desk. Supply air is provided to the box through a flexible duct connected to an underfloor fan. The APACS nominally is designed to deliver 0-70 cfm (0-33 L/s) of supply air. The amount is adjustable by the occupant using a damper lever (Figure 2) and the position of the 4-way adjustable grills.

EXPERIMENTAL METHODS

Controlled Environment Chamber

This laboratory study was accomplished by mocking up a typical office space (modular partitioned workstations) in our full-scale controlled environment chamber (CEC). The CEC measures 18 ft x 18 ft x 8 ft 4 in. (5.5 m x 5.5 m x 2.5 m) and is designed to resemble a modern office space while still allowing a high degree of control over the test chamber's thermal and ventilation environment. The access 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. 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.

Figure 1. APACS Personal Air Outlet mounted horizontally under desk

Figure 2. Close-up of APACS in horizontal position

Figure 3. Close-up of APACS in vertical position

The chamber'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. To investigate the APACS unit during the well-controlled steady-state experiments described here, a separate supply line was ducted through the subfloor plenum and connected via flexible duct to the APACS unit located in the workstation, replacing the Argon fan normally used with the system. Figure 4 shows a photo of the APACS unit as mounted in the chamber with the thermal manikin sitting in front of the desk.

A separate conventional ducted ceiling-based air distribution system (in combination with space loads) was used during all thermal manikin tests to maintain the average room air temperature at the desired level. In this system, all supply air was delivered to the test chamber through a single centrally located perforated diffuser. All air from the chamber, including the volume supplied from the APACS device, was returned through a single ceiling-level return register. In addition, the chamber's air distribution system includes a separately controlled supply of air through the plenum-wall construction of the two exterior chamber walls. Air flow through this annular space allowed the interior window surface temperature to be controlled at the desired level (equal to the average room air temperature).

Figure 4. APACS unit mounted in test chamber with thermal manikin

A partitioned office configuration containing four-workstations was set up as shown in Figure 5. In this arrangement, each workstation measured 90 in. x 75 in. (2.3 m x 1.9 m), and the solid partitions measured 65 in. (1.65 m) high. The APACS unit was installed in workstation #2 (ws2) during all tests reported here. Heat loads were provided to simulate typical office load densities in workstation #2. The workstation had a personal computer and monitor (90 W total) located on the desk, and overhead lights provided a total power of 500 W, of which approximately 100 W directly entered the chamber. The advanced segmented thermal manikin released approximately 100 W and was located in workstation #2 during all APACS tests.

Temperatures and air velocities were measured at selected locations within the workstation containing the advanced thermal manikin with a series of thermisters and omnidirectional anemometers, connected to a dedicated data acquisition system. Additional thermistor elements were installed to measure supply air temperature in the APACS Personal Air Outlet and a reference temperature located at desk height in workstation #1 (Figure 5). These, along with other test parameters, were monitored, recorded, and used for control purposes by the PC-based direct digital control system for the chamber. At the beginning of the study, all supply air and reference temperature sensors were calibrated by comparison against two high quality laboratory sensors, and found to agree within 0.5°C (0.9°F).

Supply air volume to the APACS unit, as well as supply and return air volumes to the overhead air distribution system in the chamber, were monitored with a high-precision flow measurement setup consisting of a series of long, small-diameter, straight pipes with pitot tubes and venturi flow meters mounted to measure the fully developed flow. This measurement system has been previously described in reference [1].

All experiments were carried out under steady-state conditions in the test chamber. A number of combinations of room air temperature and supply air temperature were studied. Preliminary experiments were carried out at the highest supply volume to determine the focused air flow direction and manikin position that produced the maximum cooling of the manikin. This air flow direction and manikin position were then used in all subsequent tests for that device. For the horizontal APACS, the grills were adjusted to blow straight ahead. For the vertical APACS, even with the grills turned as far toward the manikin as possible, the supply air jet missed the manikin when seated centrally in front of the desk. For this test, we moved the manikin over toward the APACS unit until the air jet directly hit the side of the manikin.

Prior to each test, all heat loads in the chamber were turned on and the two air supply lines serving the overhead diffuser and the annular space between the inner and outer window panes were also turned on and allowed to reach equilibrium at their desired setpoint conditions. The setpoints for the next day's test were typically set at the end of a day of testing, and the chamber was then operated all night to ensure that steady-state conditions were achieved before beginning testing on the following day. The temperature of the constant volume (94 L/s [200 cfm]) of air supplied through the overhead diffuser was controlled to maintain the reference temperature sensor (Figure 5) at its setpoint. The annular space air supply temperature was controlled to maintain the interior window surface temperature at the same temperature as the room air setpoint. On the day of testing, the ducts and pipes serving the selected local supply device were opened and all others were closed off. A dedicated variable speed fan was then manually adjusted until the desired supply volume to the local device was obtained. The chamber's control system then maintained the desired supply air setpoint temperature during the subsequent steady-state experiment.

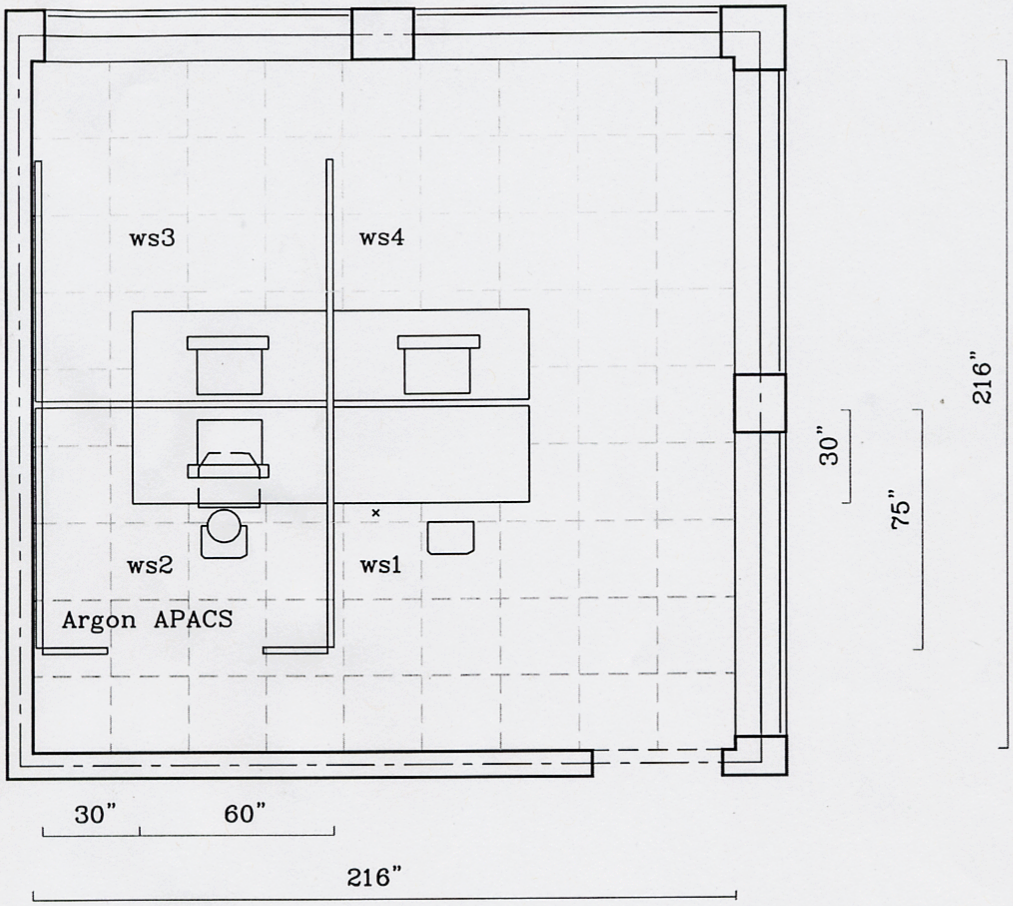

Figure 5. Test Chamber Plan

Key

Manikin

× Reference Temperature Sensor

Argon APACS (horizontal position)

Computer

For most test conditions, the supply air temperature was maintained to within ±0.2°C (0.4°F) of the setpoint. However, supply air temperature control was not as stable at the lowest flow rate (10 cfm [5 L/s]) tested for APACS. For these tests, variations of up to 1°C (2°F) were recorded. All reported supply air temperatures represent a 5-minute average coinciding with the manikin 5-minute measurement period.

Thermal Manikin

Thermal manikins are heated dummies that simulate the heat transfer between humans and their thermal environment. The advanced thermal manikin at UC Berkeley (Figures 4 and 6) contains several significant improvements over previous designs, including the following. (1) The heating elements are placed on the outside surfaces of the manikin to produce a relatively small time constant (less than 5 min.). This improves the accuracy and stability of the skin temperature control algorithm that is based on an iterative function of surface heat transfer rate. The manikin also has the ability to be controlled based on a fixed skin temperature, which produces an even smaller time constant. A fixed skin temperature of 33.0°C (91.4°F) was in fact used during all experiments of the present study to provide a consistent basis for comparison between the different test conditions. (2) The manikin is divided into sixteen body segments, each with its own individual computer-controlled heat source, permitting discrete heat transfer rates to be determined for different areas of the human body. The segmented manikin design is particularly well-suited to evaluate non-uniform environments. Table 1 lists the sixteen body parts and their respective surface areas. A PC-based data acquisition system records the manikin's skin temperature and heat loss for each body part at 1-minute intervals. Each data record represents the mean of 60 individual measurements; an average of five records (300 observations over 5 minutes) is used for data analysis.

Figure 6. Photo of Researchers with Thermal Manikin (Monika)

Table 1. Body Parts of Segmented Thermal Manikin

No.	Body Part	Area (m^2)	Area (ft^2)
1	head	0.130	1.40
2	left upper arm	0.073	0.79
3	right upper arm	0.073	0.79
4	left forearm	0.052	0.56
5	right forearm	0.052	0.56
6	left hand	0.038	0.41
7	right hand	0.037	0.40
8	chest	0.144	1.55
9	back	0.133	1.43
10	pelvis	0.182	1.96
11	left thigh	0.160	1.72
12	right thigh	0.165	1.78
13	left lower leg	0.089	0.96
14	right lower leg	0.089	0.96
15	left foot	0.043	0.46
16	right foot	0.041	0.44
total		1.501	16.17

Because the thermal manikin closely approximates a full-scale “human sensor,” as opposed to individual physical sensors that take measurements at a single point, the manikin can take into account such issues as the insulating value of clothing over different body parts and body positions, the insulating value of different chair configurations, variations in clothing insulation as a function of local air speed, and the effects of thermal stratification, radiant asymmetry, local jets of high speed air flow, and the convective plume formed around the body by its own heat.

In the current study, the manikin was used to simulate a person seated at a desk having an underdesk APACS unit. The manikin was dressed in typical lightweight slacks, long-sleeve shirt, shoes, socks, and underwear, covering all but head and hands, with a total (clothing plus air layer) whole-body insulation value of 0.208 m^2°K/W (1.34 Clo). The manikin simulates a female occupant with hair length just below the ears. In the current study, it maintained a constant skin temperature distribution (33.0°C [91.4°F]) characteristic of an occupant in thermal neutrality at all times. The electrical power per unit surface area (W/m^2 [$Btu/hr \cdot ft^2$]) that was supplied to each section to maintain the set skin temperature at equilibrium was an accurate and reproducible estimate of an occupant's rate of sensible heat loss from that body section in the same microclimate. An occupant's whole-body rate of heat loss is estimated as the area-weighted sum of the sectional rates of heat loss. The manikin was placed in front of the desk, with its face aligned about 15 cm (6 in.) back from the front edge of the desk, seated in an upright posture on a typical typist's chair, i.e. a minimally upholstered chair with a small lumbar support, whose effective insulation was equivalent to an additional 0.023 m^2°K/W (0.15 Clo), with arms slightly bent and hands and forearms resting on the desk surface.

After all setpoint temperatures and supply volumes in the test chamber had stabilized, the manikin was put into log mode. During the manikin tests, the manikin skin temperatures and heat flux rates were monitored for at least 30 minutes to ensure their stability before using the last 5 minutes of the log period to record the final data for that test condition.

Data Analysis

Prior to these experiments, the nude manikin was calibrated by exposing it passively (unheated) to two different steady-state homogeneous environments in the test chamber at temperatures covering the range of expected operation (20-33°C [68-91°F]). The calibrated manikin was then exposed using standard (heated) procedures to a homogeneous environment with and without the selected clothing ensemble, and with and without the desk chair. These reference exposures were used to determine the total insulation value (heat transfer coefficient) for each body segment of the manikin while fully clothed and sitting in the desk chair under constant temperature, still-air conditions. The whole-body insulation values for the clothing and chair, as reported above, were calculated using an area-weighting scheme. These coefficients were stored and used in all subsequent manikin tests to calculate Equivalent Homogeneous Temperature (EHT) [2]. EHT is defined as the temperature of a uniform space, in which all surface temperatures are equal to air temperature, there is no air movement other than the self-convection of the manikin, and the rate of heat loss would be the same as was actually measured. EHT is useful as a basis of comparison for complex and highly non-uniform thermal environments, such as automobiles [3]. For each body segment, EHT can be calculated using Equation (1) below when skin temperature, Ts (°C), total heat loss from skin surface, Qt (W/m^2), and total clothing insulation value, It (m^2°C/W), are known.

$$Qt = (1/It)(Ts - EHT) \tag{1a}$$

or

$$EHT = Ts - It \cdot Qt \tag{1b}$$

In the current series of tests, the manikin was tested in a reference exposure for each room temperature setpoint (26 and 28°C [79 and 82°F]). During each reference test, the manikin was clothed and seated in the office chair in front of the desk with all heat sources (computer, monitor, etc.) turned on in the space. No air flow was supplied from the APACS unit, so all convective heat exchange with the surrounding environment took place under still-air conditions (local air velocities were measured to be less than 0.1 m/s [20 fpm]). The magnitude of individual control in terms of cooling could then be calculated as the relative change in sectional or whole-body EHT during all subsequent tests of air flow from the APACS unit. The change in EHT from reference (no flow) conditions was calculated according to the following formula:

$$\Delta EHT_{adj} = (EHT - EHT_{nf}) - (Tref - Tref_{nf}) \tag{2}$$

where:

ΔEHT_{adj} = change in EHT from reference conditions, adjusted for room temperature (°K)

EHT = Equivalent Homogeneous Temperature (°C)

EHT_{nf} = EHT measured for reference (no flow) conditions at same room temperature setpoint (°C)

Tref = reference temperature used to control room setpoint (°C)

$Tref_{nf}$ = reference temperature used to control room setpoint for reference (no flow) conditions at same room temperature setpoint (°C)

In the above equation, the change in EHT is adjusted to account for any shift in the average room air temperature between tests, as measured by the reference temperature sensor (Tref). Throughout the remainder of this report, ΔEHT will always refer to the adjusted change in EHT shown in Equation (2), unless otherwise noted.

Test Conditions

Table 2 lists all experiments, their setpoint (desired) and measured test conditions, and whole-body manikin results for the APACS unit. The tests covered two room temperature setpoints (26 and 28°C [79 and 82°F]) and two mounting positions of the APACS (horizontal and vertical). As described above, for each room temperature, a reference test was first performed in which the manikin was tested with no air flow from the APACS unit. Cooling tests were performed at different air supply volumes and temperatures at both the 26°C (79°F) and 28°C (82°F) room temperatures. The majority of tests were done at the 26°C (79°F) room temperature with horizontal position of the APACS, for which the supply temperatures studied were 21°C, 23°C, and 25°C (70°F, 73°F, and 77°F). At 28°C (82°F) room temperature with horizontal position and 26°C (79°F) room temperature with vertical position, only the 21°C (70°F) supply temperature was studied. Four air supply volumes were tested to cover the range of supply rates expected from the APACS unit. The volumes tested were 10, 30, 50, 70 cfm (4.7, 14.2, 23.6, 33.0 L/s). All volumes were tested at the 26°C (79°F) room temperature setpoint with horizontal position, while only the 30 and 70 cfm (14.2 and 33.0 L/s) rates were tested for the 28°C (82°F)/horizontal and 26°C (79°F)/vertical tests. The APACS unit was tested under focused air flow direction, meaning the air supply was directed toward the manikin in a way that maximized the overall (whole-body) cooling rate. All experiments were conducted using a dry manikin, thereby assessing cooling impacts in terms of sensible heat loss.

RESULTS

Sectional and whole-body rates of heat loss from the manikin were measured for the test conditions listed in Table 2. Table 2 also reports whole-body values for EHT and ΔEHT for the APACS unit. Complete manikin measurement data for all tests are listed in *Appendix A*. In Appendix A, total (whole-body) and sectional results are shown for EHT (°C), heat loss (W/m^2), and ΔEHT_{adj} (°K). Heat loss and surface temperature data are directly measured by the manikin. EHT is calculated from these values using Equation (1). Note that surface temperatures, although not reported here, were always equal to the 33.0°C (91.4°F) setpoint. ΔEHT_{adj} values are calculated according to Equation (2), and as previously described, are adjusted for any change in room temperature.

Velocity Measurements

Variations in flow rate have a direct effect on the speed of air hitting the manikin. These velocities can also be used to make quick estimates of the overall flow rate during field installations. For each of the four different supply volumes tested, we recorded the average velocity at a distance of one foot in front of the supply grills. The anemometer was centrally positioned to obtain the maximum velocity, as the grills were oriented to blow the air straight ahead. The results are summarized below in Table 3.

Table 2. Test Conditions and Whole-Body Manikin Results: Argon Corporation

Set Point Conditions					Measured Conditions			Whole-Body	
Position	Room Temp (°C)	Supply Temp (°C)	Vsupply (CFM)	Test #	Tref (°C)	Tws (°C)	Tsupply (°C)	EHT (°C)	Delta EHTadj (°C)
	26	REF.	REF.	1	26.1	26.8	n/a	27.2	n/a
Horizontal	26	21	70	2A	25.8	26.4	21.0	23.8	-2.9
Horizontal	26	21	70	2B	26.0	26.5	20.9	23.8	-3.1
Horizontal	26	23	70	3B	26.0	26.6	22.8	25.2	-1.7
Horizontal	26	25	70	4A	26.1	26.9	25.0	25.5	-1.4
Horizontal	26	25	70	4B	26.2	27.0	25.0	25.6	-1.4
Horizontal	26	25	50	5A	26.2	26.8	25.0	25.7	-1.4
Horizontal	26	25	50	5B	26.3	27.2	25.0	25.8	-1.3
Horizontal	26	23	50	6A	26.1	26.7	22.9	24.9	-2.0
Horizontal	26	23	50	6B	25.9	26.8	23.0	25.1	-1.6
Horizontal	26	21	50	7A	26.0	26.6	21.1	24.6	-2.3
Horizontal	26	21	50	7B	26.0	26.6	21.0	24.6	-2.3
	26	REF.	REF.	8A	26.0	26.9	n/a	27.5	n/a
	26	REF.	REF.	8B	26.1	26.9	n/a	27.6	n/a
Horizontal	26	21	30	9A	26.2	26.8	21.0	25.5	-2.1
Horizontal	26	21	30	9B	25.8	26.5	21.0	25.3	-1.9
Horizontal	26	23	30	10A	26.0	26.7	23.0	26.1	-1.4
Horizontal	26	23	30	10B	26.0	26.7	23.0	26.1	-1.4
Horizontal	26	25	30	11A	25.9	26.8	25.0	26.5	-0.8
Horizontal	26	25	30	11B	26.0	26.9	25.0	26.5	-1.0
Horizontal	26	21	10	12A	26.0	26.8	21.2	26.5	-1.0
Horizontal	26	23	10	13A	26.1	26.9	23.0	27.0	-0.5
Horizontal	26	23	10	13B	26.0	26.8	23.1	27.1	-0.4
Horizontal	26	25	10	14A	26.0	26.9	24.8	27.4	-0.1
	28	REF.	REF.	15	28.0	28.5	n/a	29.0	n/a
Horizontal	28	21	30	16A	28.0	28.2	21.0	26.7	-2.3
Horizontal	28	21	30	16B	28.1	28.4	21.0	26.5	-2.6
Horizontal	28	21	70	17A	28.0	28.1	n/a	25.0	-4.0
Horizontal	28	21	70	17B	28.0	28.1	n/a	24.8	-4.2
	26	REF.	REF.	18A	26.1	26.7	n/a	27.7	n/a
	26	REF.	REF.	18B	26.1	26.7	n/a	28.1	n/a
Vertical	26	21	30	19A	26.1	26.6	21.1	27.3	-0.6
Vertical	26	21	30	19B	25.8	26.7	20.9	27.4	-0.3
Vertical	26	21	70	20A	26.1	26.8	20.9	27.5	-0.4
Vertical	26	21	70	20B	26.1	26.8	21.0	27.4	-0.5

Table 3. Measured Air Velocities One Foot in Front of Supply Grills

Supply Volume (cfm [L/s])	Maximum Velocity (m/s [fpm])
70 [33.0]	2.90 [570]
50 [23.6]	2.20 [430]
30 [14.2]	1.04 [200]
10 [4.7]	0.31 [61]

Evaporative Cooling

Under typical sedentary metabolic rates for office workers (1-1.2 met), sensible heat loss will make up approximately 80% of the total heat loss under still air conditions. Although not part of this test program, a series of wet manikin tests were previously conducted under similar circumstances to provide an estimate of the rate of evaporative (latent) cooling provided by local air supply units when the manikin had wet clothing [4]. The evaporative cooling rates were very large in comparison to the sensible cooling (dry) manikin results, with ∆EHT values ranging from -20°K to -29°K (-36°F to -52°F) for the flow rates tested. If 0.20 is taken as a representative skin wettedness value for a typical person, these evaporative cooling rates would contribute on the order of -4°K to -6°K (-7°F to -11°F) of whole-body cooling, which is similar in magnitude to the sensible cooling rate measured for the same flow rates. The net effect is that the evaporative heat loss from a person can significantly increase the overall cooling impact of a local supply device like the APACS, and in most cases, would at least double the total whole-body cooling rate that was measured for dry clothing.

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