Authors
Bauman, Fred
Arens, Edward

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THE DEVELOPMENT OF A CONTROLLED ENVIRONMENT CHAMBER FOR THE PHYSICAL AND SUBJECTIVE ASSESSMENT OF HUMAN COMFORT IN OFFICE ENVIRONMENTS

FRED BAUMAN, P.E., and EDWARD ARENS, Ph.D.
Building Science Laboratory
Department of Architecture
University of California
Berkeley, CA 94720

Introduction

This paper describes the development of a Controlled Environment Chamber (CEC) for the investigation of a wide range of physical and psychological aspects of thermal comfort in office environments. The unique capabilities of the CEC are presented and recommendations for future research are suggested.

The advantages and disadvantages of performing thermal comfort studies in laboratory versus real world settings are well known. Controlled environment laboratories provide consistent measurement conditions and the opportunity to precisely define the range of thermal parameters that will be investigated. However, compared to the work environment that subjects actually experience, many laboratory "test cells" provide a rather sterile, unnatural setting. On the other hand, field studies have the advantage that the subjects are responding to their natural environment, providing a more realistic representation of the non-thermal or psychological aspects of comfort. Humphreys (1976) presents a worldwide summary of a large number of field studies performed over many years, and Schiller, et. al. (1988) describe a recently completed extensive field study at the University of California, Berkeley. Field studies unfortunately often suffer from the limitation that measurement conditions are less consistent, and thermal environment parameters measured in a typical (HVAC-controlled) building vary over only a narrow range. Not surprisingly, thermal sensation and comfort assessment have been found in some studies to be quite insensitive to the range of thermal parameters encountered in realistic environments, while psychological parameters played a significant role [Howell and Kennedy (1979), Rohles (1980), Rohles, et. al. (1981), Howell and Stramler (1981)].

The importance of psychological issues combined with the experimental advantages of a controlled laboratory facility formed the basis for the development of the Controlled Environment Chamber. The CEC is designed to resemble a modern office building and to provide a high degree of control over the chamber's thermal environment. Recognizing that the perception of thermal comfort for largely sedentary workers in a nonstressful office environment can depend on a broad range of physical and psychological factors, the CEC will be capable of investigating many of these important environmental issues.

A reconfigurable air distribution system will allow the CEC to simulate not only the typical high-volume uniform air flows found in many laboratories, but

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also a variety of air flow configurations associated with modern office buildings, including 1) alternate air supply/return locations, 2) spot cooling and heating, as a solution to nonuniform thermal conditions produced by obstructing office layouts (partitions, cubicles, etc.), and local heat sources such as computers, and 3) low-volume ventilation strategies such as displacement ventilation. The realistic office appearance of the chamber will permit the effects of psychological issues to be more reliably assessed. In today's modern office buildings, such issues include 1) worker performance and productivity, 2) worker expectations for indoor climate control, and 3) worker satisfaction.

Chamber Design

The chamber, constructed within a larger existing laboratory space, measures 5.5 m x 5.5 m x 2.5 m (18 ft x 18 ft x 8 ft 4 in) and has a volume of 76 m^3 (2700 ft^3). The raised access floor system consists of 0.61 m (2.0 ft) square panels (steel shell with lightweight cementitious core) supported by galvanized steel pedestals. Floor registers, fan-powered supply modules, and other spot cooling air flow connections are installed directly into the floor panels permitting maximum flexibility in the selection of supply and return locations. The 0.6 m (2 ft) high sub-floor area serves as a supply or return plenum, while also providing adequate space for connecting ducted floor registers and running instrumentation, power, and communication cables. A 0.5 m (1.5 ft) high ceiling plenum is provided for similar purposes above the suspended ceiling, made up of 0.61 m (2.0 ft) square acoustical ceiling tiles. Each ceiling tile contains damper-adjustable slots which allow the supply or return air to be evenly distributed over the entire ceiling area.

A plenum-wall construction of the two chamber walls facing the exterior allows a continuous stream of temperature controlled air to pass between the inner (single-pane) and outer (double-pane) glazings of the windows. Air flow through this annular space is used to control the interior window surface temperatures at desired levels. The windows are shaded from all direct solar gain by the building's overhanging sun shades, and by surrounding trees and buildings. All four chamber walls are heavily insulated with gypboard comprising the innermost layer. The two interior walls are of standard steel stud construction.

A major distinguishing feature of the chamber is its realistic office appearance (see Figure 1). The floor is fully covered with carpet tiles, finished gypboard walls are painted white, windows in the exterior walls provide a pleasant view to the outside, the suspended ceiling contains patterned acoustical tile, six 0.6 m (2 ft) square dimmable lighting fixtures are mounted in the ceiling, and it is furnished with typical office workstation furniture. By closely resembling a contemporary office, the chamber minimizes some of the unknown psychological effects associated with "test cell" experiments of human comfort.

Due to the greater thermal capacity of the chamber walls and furnishings compared to that of lightweight chamber designs [e.g., Kjerulf-Jensen, et. al. (1975)] it is expected that there will be some reduction in the chamber's ability to maintain uniform thermal conditions and in its speed of response to thermal changes. Nevertheless, the chamber will be able to effectively simulate a large majority of the realistic thermal conditions occurring in office buildings. The design control specifications of the CEC are discussed below.

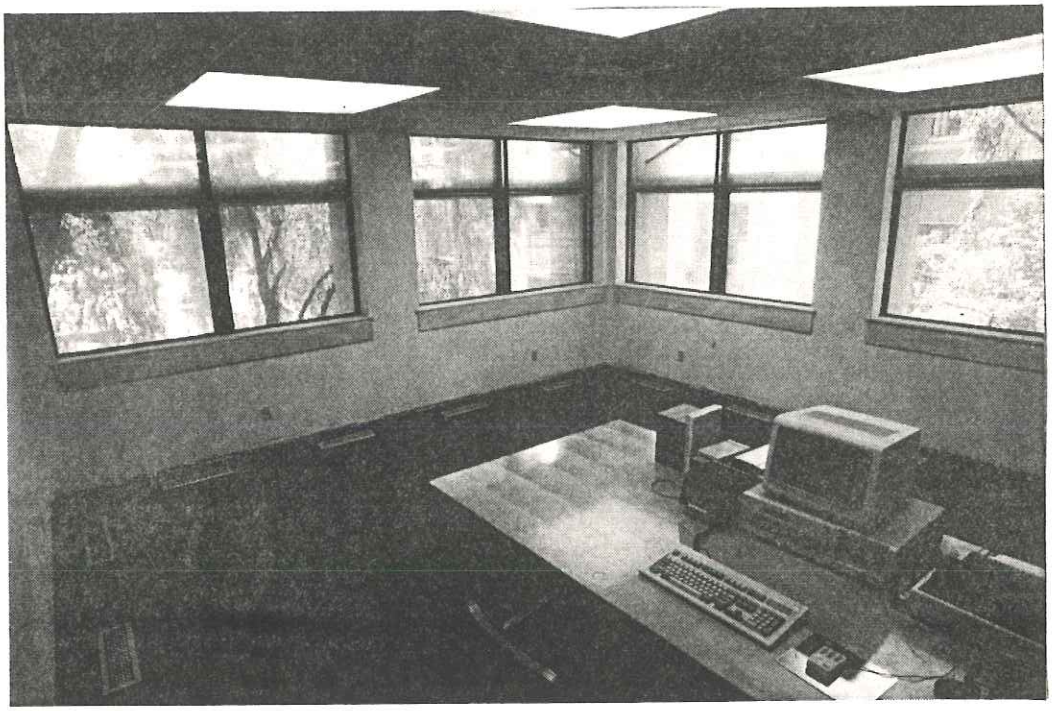
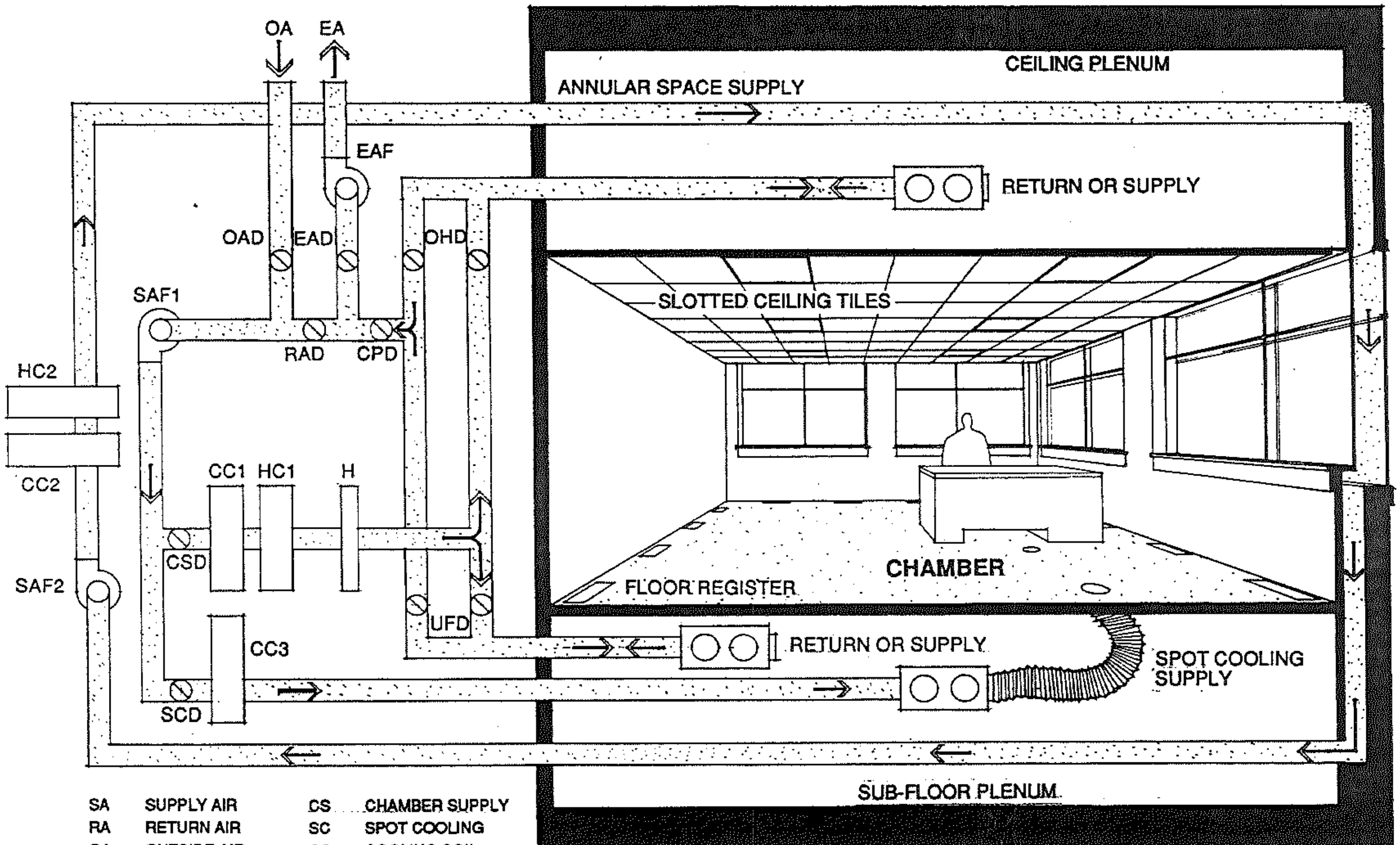


Figure 1: Photograph of Controlled Environment Chamber

Air Handling System

The air handling system (Figure 2) has been designed to provide three separately controllable air supplies to maintain desired conditions in the following areas: 1) main chamber, 2) annular space, and 3) spot cooling within the main chamber. Each is described briefly below.

Outside air (OA) is combined with return air and is supplied to the chamber by the main supply air fan (SAF1). The following system components are used to condition the chamber supply air. The main cooling coil (CC1) is used for both cooling and dehumidification purposes. A 20% glycol-water mixture is supplied to CC1 from a chilled water storage tank attached to a packaged water chiller. The main heating coil (HC1) receives hot water from an electric water heater. A self-contained electrode humidifier (H) provides humidification through a steam jacket distribution manifold. Four manual control dampers (two overhead dampers (OHD) and two underfloor dampers (UFD) can be set to obtain one of two possible chamber supply/return air flow config-



SA	SUPPLY AIR	CS	CHAMBER SUPPLY
RA	RETURN AIR	SC	SPOT COOLING
OA	OUTSIDE AIR	CC	COOLING COIL
EA	EXHAUST AIR	HC	HEATING COIL
D	DAMPER	H	HUMIDIFIER
F	FAN	OH	OVERHEAD
CP	CHAMBER PRESSURE	UF	UNDER FLOOR

FIGURE 2: CONTROLLED ENVIRONMENT CHAMBER - AIR FLOW SCHEMATIC

urations: 1) ceiling supply with floor return, or 2) floor supply with ceiling return.

A separate supply of conditioned air is provided to the annular space by a closed-loop system containing a second supply air fan (SAF2), cooling coil (CC2), and heating coil (HC2). In this system a constant volume of air is ducted through the ceiling plenum to the top of the exterior window-wall plenum. The return air is collected at the bottom of the windows and is ducted back through the sub-floor plenum.

A third air supply is provided to the chamber at floor level through a spot cooling line which is split off from the main supply line just after SAF1. The volume of spot cooling air supply is controlled by a spot cooling damper (SCD) in tandem with the chamber supply damper (CSD), and a third cooling coil (CC3) provides cool air for this application. Supply air is ducted through the sub-floor plenum to the inlet locations.

The design of the air distribution system allows a variety of chamber air flow configurations to be investigated. The main supply/return lines in both ceiling and sub-floor plenums terminate in manifold boxes containing damper-controlled stub-outs. Under conditions of plenum supply or return, air flows directly out of or into the stub-outs. Alternatively, ducted supply or return can be studied by using flexible ducting to connect the stub-outs to supply diffusers or return registers at selected locations. The paneled floor and ceiling allow inlet and outlet locations to be placed anywhere on these surfaces. For ducted ceiling air flows the unused slotted ceiling tiles are closed off.

Design Control Specifications

Table 1 lists the design control specifications for the chamber. The chamber dry bulb temperature will be controlled to within $\pm$ 0.5°C of the set point during both steady state and dynamic (pull-down or pull-up) conditions. Dew point temperature will be controlled as specified under steady state conditions only. Start-up calibration tests will be used to determine the accuracy of control under dynamic humidity conditions. The specified pull-down and pull-up rates are less than those possible in a lightweight chamber, but are still expected to be large enough to adequately address the significant temperature variations typically encountered in office environments, as described in ASHRAE Standard 55-1981. Independent control of the annular space dry bulb temperature will be provided at the same range and stability as those for the chamber dry bulb temperature. Spot cooling air supply will be provided over a relatively narrow range of cool temperatures.

The chamber supply air volume can be varied from a minimum of 0.5 air changes per hour (40 m^3/hr) to a maximum of 20 air changes per hour (1520 m^3/hr). Outside ventilation air can also be provided over the full range of 0 to 100%.

Table 1: Design Control Specifications

Chamber Thermal Conditions

Dry Bulb Temperature
Range: 13°C (55.4°F) $\leq T_{db} \leq$ 35°C (95°F)
Stability: ± 0.5°C (0.9°F)

Dew Point Temperature
Range: 8°C (46.4°C) $\leq T_{dp} \leq$ 25°C (77°F)
Stability: ± 2% RH

Pull-down (Air or Globe Temperature)
Rate: 0.125°C/min (0.225°F/min)
Range: 18°C to 28°C (64.4°F to 82.4°F)

Pull-up (Air or Globe Temperature)
Rate: 0.25°C/min (0.45°F/min)
Range: 15°C to 30°C (59°F to 86°F)

Annular Space Dry Bulb Temperature
Range: 13°C (55.4°F) $\leq T_{db} \leq$ 35°C (95°F)
Stability: ± 0.5°C (0.9°F)

Air Flow

Minimum Chamber Supply: 40 m^3/hr (25 cfm)
Maximum Chamber Supply: 1520 m^3/hr (900 cfm)
Outside Ventilation Air: 0 to 1520 m^3/hr (900 cfm)
Minimum Annular Space Supply: 850 m^3/hr (500 cfm)
Maximum Spot Cooling Supply: 850 m^3/hr (500 cfm)

Control System

The selection of a commercially available direct digital control (DDC) system was based on its sophisticated and broad ranging capabilities combined with the user-friendliness of its personal computer-based software. This highly accurate DDC system is expected to provide good performance in terms of stability, no control offset, and rapid response time. The system is designed to operate in a stand-alone mode or to communicate directly with the PC-based operator's workstation. Elaborate color graphic displays significantly improve the ease of use for the system operator, and also serve as a valuable teaching aid for HVAC-related instruction.

The DDC system allows separate control of the three CEC air supplies described earlier. In particular, the main chamber air supply can be controlled over a full range of operating modes, including any combination of the following control methods: 1) variable volume, 2) variable temperature, 3) variable dewpoint, and 4) reheat. Variable volume control of the main chamber air supply is provided by the variable speed fans, SAF1 and EAF (DC motor and drive), and the operation of the chamber pressure damper (CPD) (see Figure 2). System operation can be based on a variety of chamber control sensors, including 1) single or multiple room air temperature, 2) single or multiple globe temperature, and 3) dewpoint temperature. Additional details of the control system will be made available after the completion of initial performance tests of the chamber.

Research Agenda and Future Directions

Research activities in a facility similar to the CEC can address many important issues related to thermal comfort and worker productivity in office environments. Recommendations for a planned research agenda and future directions are outlined briefly below.

Thermal Comfort Requirements and Worker Productivity

A major component of all research activities should be the investigation of worker satisfaction and productivity in an office environment. Measured results should be analyzed to identify significant correlations and the relative importance of physical and psychological parameters. Studies can address the following topics:

1. Extended range of acceptable human comfort.
2. Human response to temperature drifts.
3. Human response to radiant asymmetry.
4. Thermal comfort modeling.
5. Development of improved physical and subjective measurement techniques for comfort and productivity.

Air Flow Studies

The versatility and reconfigurability of the chamber air distribution system are based on the fact that comfort and satisfaction in the built environment can be strongly affected by air flows. The CEC has been designed to provide close to uniform air flow and thermal conditions throughout the chamber (a typical design objective for many "controlled environment chambers"), as well as nonuniform chamber air distribution that represents alternative realistic office air flow conditions. Given these unique capabilities air flow studies can address the following areas of interest:

1. Supply/return air flow configurations and diffuser design.
2. Spot cooling and individualized comfort control.
3. Internal obstructions to air flow.
4. Ventilation and indoor air quality.

Summary

The design objectives of the Controlled Environment Chamber (CEC) have been to: 1) replicate the appearance of a modern office environment in order to eliminate some of the unwanted psychological variables associated with "test cell" experiments, and 2) retain the advantages and versatility of a controlled laboratory facility. The CEC will be used to investigate many of the important issues related to thermal comfort and worker productivity in office environments.

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