Title
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Authors
Fountain, M.
Brager, G. S.
Arens, Edward A
et al.

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Comfort control for short-term occupancy

Marc Fountain, Gail Brager, Edward Arens, Fred Bauman and Charles Benton
Center for Environmental Design Research, University of California, Berkeley, Berkeley, CA 94720 (USA)

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Abstract

This paper describes the logic of a microprocessor-controlled thermostat termed 'comfortstat' to address the needs of temporary room occupants such as hotel guests while reducing energy consumption. The 'comfortstat' design grew out of a study of thermal comfort control in a luxury hotel in San Francisco, California, USA. Hotel guests frequently arrive from widely disparate climates and have high expectations of the thermal environment. Their short-term occupancy (for periods ranging from one day to several weeks) provides a unique challenge for thermal comfort control. We examined the hotel complaint log, collected detailed physical measurements of the thermal environment in typical hotel rooms, assessed the HVAC (heating, ventilating and air-conditioning) system capacity and response time, and surveyed 315 hotel guests over a five-month period. The results of this study led to the design of a thermostat control system (the 'comfortstat') that would solve the most serious problems. The 'comfortstat' integrates an infrared occupancy sensor, door switch, radiant temperature sensor, and control logic to optimize room conditions while 'learning' about the occupant's preferred comfort zone. This paper focuses on how the joint requirements of the guests and the hotel management guided the design of the 'comfortstat' for increased occupant satisfaction and lower energy use in the hotel. The concepts are completely generic and could be applied to the design of comfort systems for other types of short-term occupancy. We present control logic flowcharts and typical examples of the action of the hotel 'comfortstat' in response to data received from the physical environment and/or human input.

Introduction

Guest satisfaction and comfort are critically important for hotels, where a successful business depends on return customers and positive recommendations from satisfied guests. Heating and cooling of guest rooms can represent a substantial fraction of a hotel's heating, ventilating and air-conditioning (HVAC) expenses [1]. A successful environmental control strategy for hotel guest rooms (or other short-term occupancies) is one that responds to the guests' immediate thermal needs while conserving energy over the long term.

Conventional environmental control strategies for hotels allow only limited occupant control, collect minimal or no data from the physical environment, and rarely use logic for interpreting guests' heating or cooling requests. As they grant control of the thermal environment to the occupant, they generally leave little opportunity for energy conservation. The typical fan-coil and wall units are in this category. Other strategies allow little or no control by the occupant and may significantly reduce comfort. An example would be central AC operation with externally imposed energy-conserving shutdown periods. The ideal circumstance would balance these two approaches, maximizing savings and satisfying guests' thermal needs through all phases of hotel occupancy. This objective can be achieved through three specific steps. First, adopt an operational scheme for hotel occupancy that recognizes and responds differently to three distinct conditions for a guest room: (1) occupied, when the guest is physically in the room; (2) unoccupied, when a registered guest is checked in but is not physically in the room; and (3) unregistered, when no guest is checked in for that room. Second, use a structured, logical sequence of HVAC operational choices to provide comfort and energy conservation while the guest is in the room. Third, use a room sensor that measures more than just air temperature, i.e., a sensor that incorporates a few more of the properties of the physical environment that are needed to evaluate human thermal comfort.

In establishing a hotel-room environmental control strategy, room occupancy patterns must be com-

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bined with the principle of running mechanical equipment only when needed, in order to conserve energy. The occupancy recognition feature is important, because registered hotel rooms are left unoccupied more than 50% of the time [2, 3]. While it is important to maintain guest satisfaction by providing the desired levels of heating and cooling while the room is occupied, leaving the HVAC operating in an unoccupied room translates into a significant waste of energy and money. Recent studies of air-conditioning control use patterns [4–6] have focused primarily on residential systems and residential needs. In a residential system, the user has ample opportunity to become familiar with operating the controls, and the system can eventually be tuned to satisfy any pattern of preference. In contrast, a hotel-room system or other system for short-term occupancy must require only minimal understanding of the controls, automatically gather sufficient data regarding the guest's preferences to provide comfort in a short period of time, and reset itself with each new room resident. These differences appear deceptively simple but have important consequences for controls design and system operation.

A hotel comfort study

The 'comfortstat' design presented here grew out of a year-long study of thermal comfort in a luxury hotel in San Francisco, California, USA [7]. In the study we pursued two major goals: (1) to investigate the existing thermal comfort conditions in a hotel environment, and (2) to define methods and devices for improving guest service and conserving energy in the hotel HVAC system. Our research approach involved several specific steps. We examined the hotel complaint log to obtain a rough estimate of the number of comfort-related complaints, their causes and possible solutions. We measured the thermal conditions and subjective responses in typical hotel rooms in order to define the thermal characteristics of the rooms and the response of the HVAC system. Our measurement program utilized the following methods:

(1) detailed measurements of physical environments taken over a week-long period in two rooms;

(2) measurements of air temperature and humidity in many rooms taken during the maids' daily rounds;

(3) long-term (three-month) measurements of air temperature and humidity collected in six occupied rooms;

(4) a questionnaire for guests concerning their thermal comfort, placed in guest rooms;

(5) occupancy sensors and various operational features of energy management systems for improving comfort and energy performance.

Based on an analysis of the promising features of available products, the results of our inquiries detailed above, and the unique requirements for comfort control in hotel rooms, we developed a prototype model for a new hotel 'comfortstat.' The 'comfortstat' is designed to provide optimal guest comfort while still taking advantage of available energy-conserving control strategies. The hotel comfortstat presented in this paper combines setback capabilities with an occupancy sensor, an environmental sensor, and logic for interactive setpoint adjustment with rapid response to guests' thermal requests.

Field measurements

Our field measurements included physical and subjective data on the existing thermal environments in guest rooms in a luxury hotel. The hotel's heating and cooling system relied on hot and cold water delivered to a thermostat-controlled fan-coil unit in each room. The individual rooms could be shut off remotely during unregistered periods by the clerk at the front desk. We measured room air temperatures, wall temperatures, air velocities, humidity, supply and return air temperatures, and heating and cooling water temperatures in two guest rooms. The measurement period of one week per room in both summer and winter seasons incorporated tests of the heating and cooling system capacity and tests under occupied and unoccupied conditions. Our subjective data included the thermal comfort of the guests charged with operating the equipment during the occupied tests and also a survey of 315 guests' thermal expectations and preferences during their stay.

Summary of results

We found that the centralized HVAC system operating practices for energy conservation had adverse effects on thermal comfort in the guest rooms. This was due primarily to the failure of the room thermostat to be activated upon guest check-in, the regular night-time chiller shutdown that caused temperatures to climb in the early morning hours, and the slow response of the system to thermostat setpoint changes. The energy-conserving night-time chiller shutdown had a detrimental effect on guest thermal comfort. Surveyed guests' HVAC complaints focused on several additional problems. The system controls were difficult to use, and there was an insufficient system response to specific commands. In addition, guests complained of poor air quality, uncomfortable thermal conditions upon entering the room, and the inability of the system to meet their thermal needs. Inasmuch as the system and its thermostatic controls are somewhat generic, we assume that these problems are not unique to this hotel.

Hotel comfortstat design

To avoid the comfort or energy consumption shortcomings observed in the hotel study, a hotel thermostat should have the following characteristics:

(1) It must be easily and intuitively operated by the guest, and not require a manual or other detailed instructions.

(2) It must provide rapid response to all guest requests.

(3) It must incorporate, in measuring the room thermal environment, the effects of thermal radiation in addition to air temperature.

(4) It should create a 'personal temperature range' by automatically adjusting its internal set-points for temperature control based on both the frequency and time of requests made by the guest for changes in environmental conditions.

(5) During unoccupied and unregistered periods, it must automatically control the room temperature in the most energy-efficient manner, while still satisfying minimum comfort conditions for guest arrival.

(6) After guest check-out, it must automatically reset itself to prevent the imposition of one guest's preference on the next guest.

A full-scale mock-up of the hotel comfortstat is shown in Fig. 1. The sensor incorporates a curved strip of thin copper with a gray paint finish. A thermocouple is mounted behind the copper strip, in the center, providing an approximation of the 'operative temperature'. The operative temperature is the arithmetic average of the air temperature and the mean radiant temperature and is a good predictor of thermal comfort [8]. Curving the sensor allows the sensing of obliquely positioned radiation sources. Copper was chosen for its excellent heat conduction properties, ensuring rapid response (aluminum would also provide good performance), and flat gray paint has appropriate absorptivity and emissivity for measuring the mean radiant temperature. This sensor does not measure the operative temperature exactly, but provides a better approximation than either a shielded air-temperature sensor or a flat plate. An exact operative temperature measurement would be provided by an air-temperature sensor in the center of a gray sphere freely suspended in the occupants position in the room at chest height (not

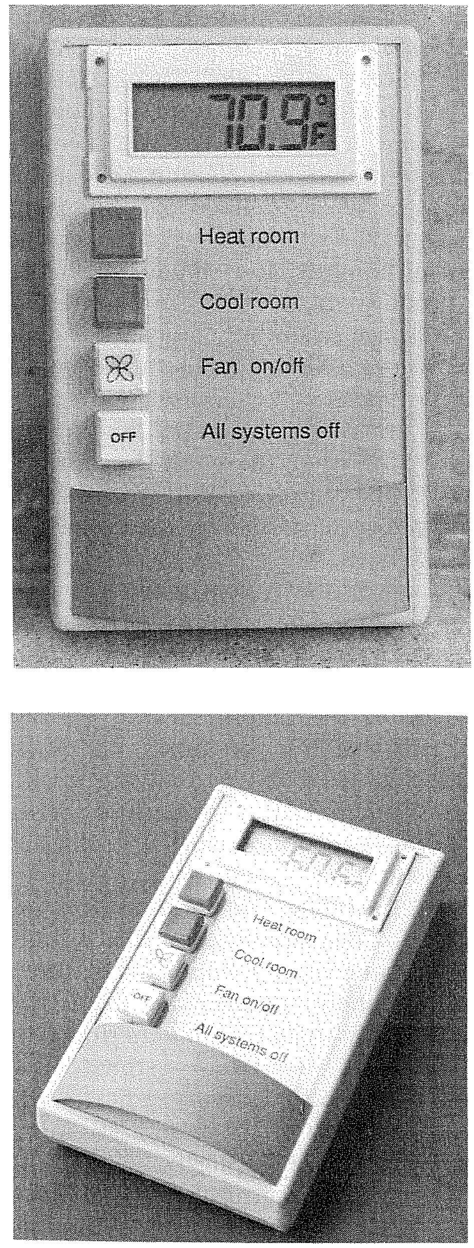


Fig. 1. Hotel comfortstat (mock-up).

feasible in a hotel room, for self-evident reasons). One parameter of the physical environment that is not measured or accounted for in the comfortstat design is the relative humidity (RH). Accounting for the effects of RH on thermal comfort would require a considerably more complicated design. Further refinements of the comfortstat should incorporate not only RH but a user-defined metabolic rate and clothing level as well.

Hotel comfortstat control principles

The main problems that the hotel comfortstat design addresses are the following: (1) providing a guest with rapid response to requests; (2) 'learning' a guest's personal thermal preferences in a short time; (3) making energy-saving decisions based on the guest's thermal preferences and the occupancy status. A key element in maintaining guest comfort is the designation of a 'personal comfort zone'. The 'personal comfort zone' is defined as the room temperature range within which a guest experiences acceptable thermal comfort. It is bounded on the low side by T_{heat}, the room setpoint temperature at which heating becomes desirable, and on the high side by T_{cool}, the room setpoint temperature under cooling conditions. Preset values in the comfortstat for T_{heat} and T_{cool} determine the initial room temperature control action when the guest first arrives in the room. These default temperature setpoints are based on thermal comfort research results from the literature [8, 9].

The comfortstat incorporates an occupancy sensor in its control operation. The primary purpose of the occupancy sensor is to reduce the HVAC operation when the room is vacant. An added benefit for this application is the ability to turn on the HVAC systems and maintain comfort conditions without requiring action on the part of the guest.

It should be noted here that a thermostat incorporating some of these concepts exists for residential use (called 'Touchstat' [10]), but it requires training and practice to use effectively. The hotel comfortstat utilizes algorithms for decision-making that render the learning process unnecessary. Important features that differentiate the hotel comfortstat from any currently available commercial building thermostats are its ability to sense occupancy, estimate the operative temperature, automatically adjust 'setpoints' (temperatures that the HVAC unit attempts to produce) and incorporate energy-saving temperature drifts. The control algorithms for the hotel comfortstat are presented in Figs. 2–5. The residential 'Touchstat' (mentioned above) incorporates all of the content of Fig. 2 but few of the features presented in Fig. 3 that specifically allow the hotel comfortstat to perform optimally in a short-term-occupancy situation. The notation used in these Figures for defining the system control parameters is given in Table 1.

Hotel comfortstat algorithms

A simplified flow diagram describing the operation of the hotel comfortstat is presented in Fig. 2. For certain system inputs, shown on the left, a series of basic control actions proceeds, as diagrammed on the right. System input consists of

(1) a request from the guest ('want warmer', 'want cooler', 'want fan', or 'system off';

(2) action from the guest – enter, exit, or check-out – as measured by the occupancy sensor or input by the hotel management.

Figure 3 presents an expanded comfortstat flow chart that explains in greater detail the various decision-making processes, including:

(1) how the system responds to occupancy sensor status;

(2) how the system responds to specific guest requests, and

(3) how the personal comfort zone is adjusted in response to guest input.

With the exception of the immediate response of the system to a guest request, all control actions are directly dependent on the current room temperature, and how it compares with the temperature control setpoints and setbacks.

Figure 4 presents a diagram of system control actions as a function of room temperature. Figure 5 illustrates how the comfort zone setpoints (T_{heat}, T_{cool}) would be adjusted when the personal comfort zone is raised or lowered.

When a request is made for the room to be either warmer or cooler (Fig. 3), the immediate response is to heat or cool the room for a specific length of time (QUICKHEAT or QUICKCOOL). A typical default value for QUICKHEAT and QUICKCOOL would be five minutes, depending on the ability of the room HVAC equipment to satisfy the guest's short-term comfort demands during this period. When the guest pushes the fan button, the fan will toggle on or off, depending on its previous operating condition. If the fan is turned on, it will continue to run independently of other system conditions until another request (or the occupancy sensor) overrides its operation. If the guest requests system off, all HVAC equipment is immediately turned off, and the comfortstat enters a mode of minimal operation in which no control of the room temperature is provided, except to maintain it within the energy-conserving deadband (see Fig. 4; see below for more discussion).

After providing an immediate response to either a 'warmer' or 'cooler' request, the comfortstat must determine what personal comfort zone is best suited to the individual preferences of the current hotel guest. As indicated in Fig. 2, the personal temperature range that controls HVAC system action consists of either

(1) preset default values for initial check-in, or

(2) adjusted values – when the setpoint temperatures have been modified by a fixed amount (ΔT_{adj}) after the guest repeats a request under certain conditions.

TABLE 1. Definitions of system control parameters for the hotel comfortstat

ADAPT-TIME	Required period of time after arrival for guest to acclimate to room thermal conditions; adjustable seasonally
HOLD-TIME	Required period of time for guest in room to reach thermal neutrality with new room conditions; adjustable seasonally
QUICKCOOL	Period of time cooling will be provided as an immediate response to guest request; adjustable based on the room HVAC capacity
QUICKHEAT	Period of time heating will be provided as an immediate response to guest request; adjustable based on the room HVAC capacity
REPEAT-TIME	Period of time after guest request for thermal change (warmer or cooler) during which a repeat of the same request will cause an adjustment (upward or downward) of the personal comfort zone setpoint temperatures (T_{heat}, T_{cool}) by an amount ΔT_{adj}
T_{cool}	Cooling setpoint temperature, representing the upper limit of the personal comfort zone
T_{heat}	Heating setpoint temperature, representing the lower limit of the personal comfort zone
T_{max}	Maximum allowable room temperature, representing the upper limit of the energy-conserving deadband
T_{min}	Minimum allowable room temperature, representing the lower limit of the energy-conserving deadband
T_{room}	Room temperature, as measured by the comfortstat sensor
ΔT_{adj}	Magnitude of temperature adjustment by which the personal comfort zone setpoint temperatures can be raised or lowered in response to a guest request

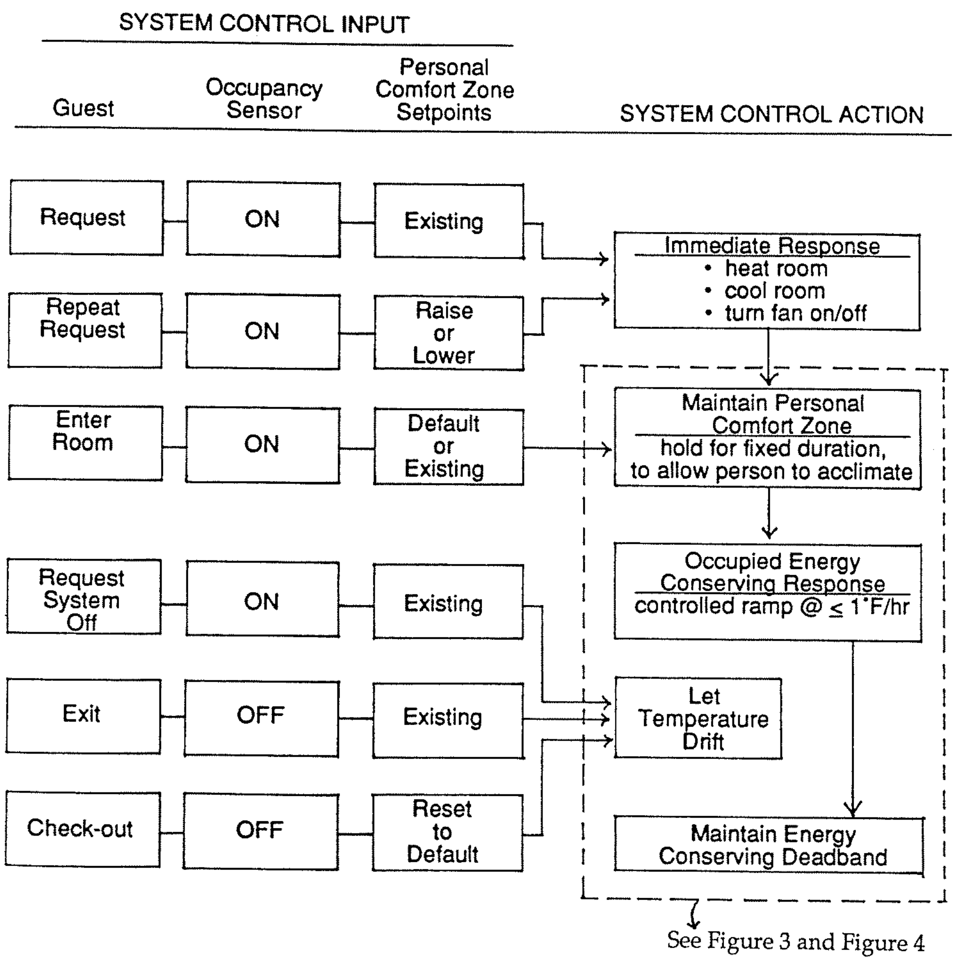


Fig. 2. Hotel comfortstat: system control inputs and actions.

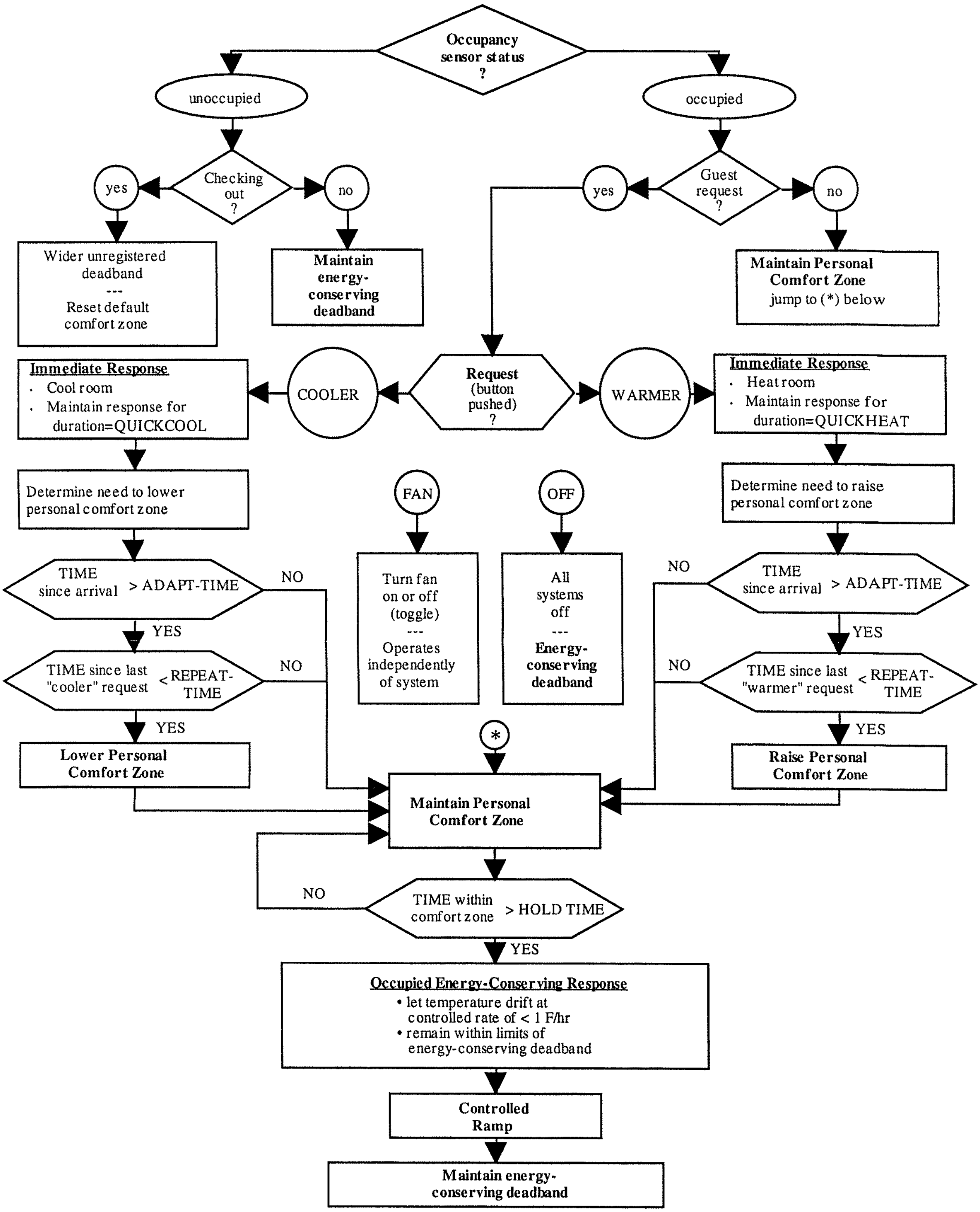


Fig. 3. Flow diagram for the hotel comfortstat. See Fig. 4.

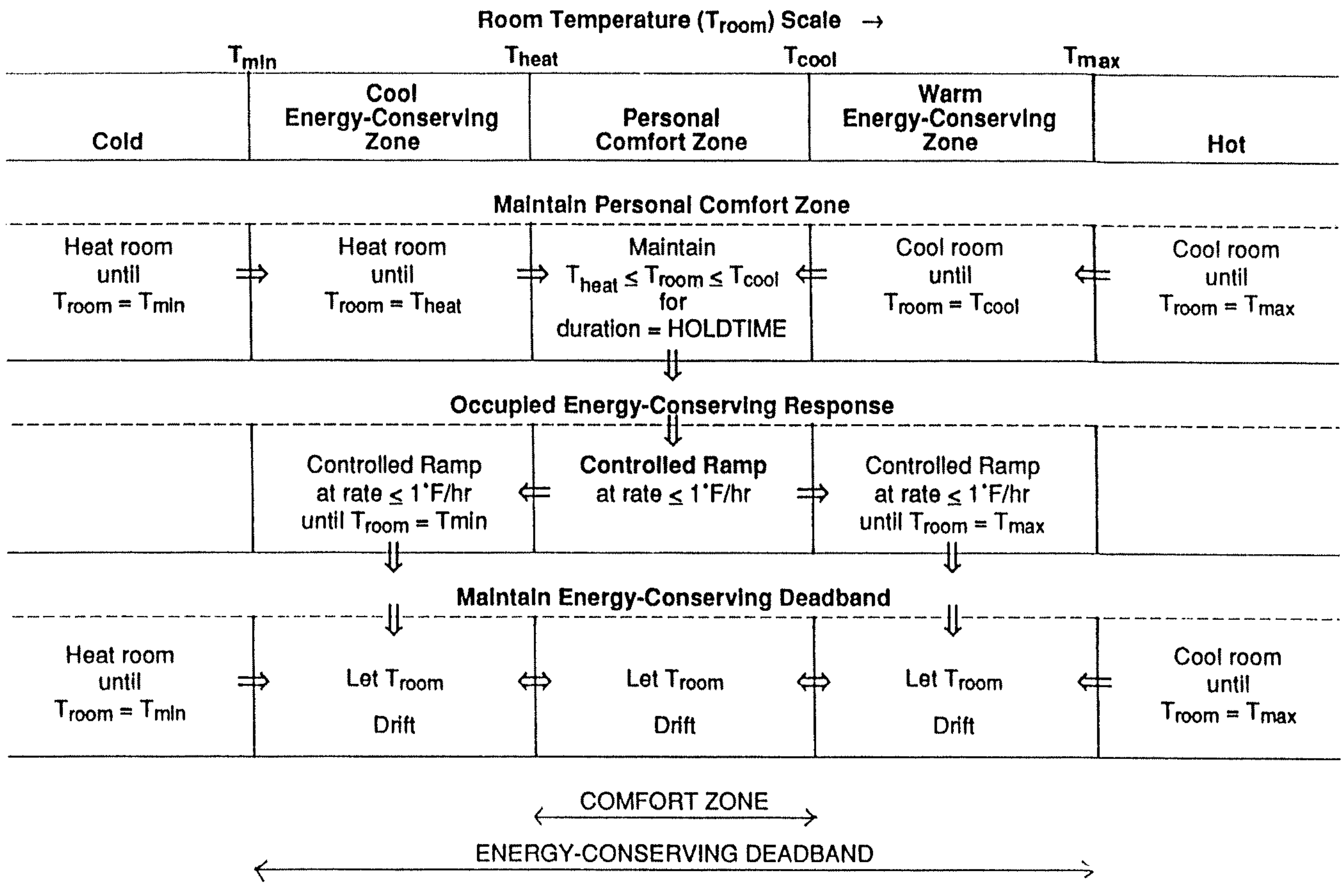


Fig. 4. System control actions of the hotel comfortstat as a function of room temperature. Temperature is on the horizontal scale, and time proceeds downward in stages from the top.

When the room occupancy sensor registers that a person has entered the room, the HVAC system will operate to heat or cool the room as required to maintain the personal temperature range. These will remain the default values, until the guest indicates that the personal temperature range should be adjusted to meet his or her preferences.

Figure 3 shows how the decision to adjust the comfort setpoints is based on the time elapsed since the guest arrived in the room and the frequency of repeat requests for thermal change. The parameters affecting the control logic are ADAPT-TIME and REPEAT-TIME, respectively. The parameter ADAPT-TIME represents the period of time necessary for a guest to acclimate to the room thermal conditions after arrival. A guest may often experience thermal discomfort upon first entering the room owing to factors unrelated to room conditions (e.g., the guest has just walked up a flight of stairs and feels excessively warm, or the guest has just come inside from a long walk out in the cold and feels excessively chilled). The value of the parameter ADAPT-TIME determines the length of time after arrival during which no long-term changes will be made to the comfort zone temperatures.

The parameter REPEAT-TIME represents the period of time after a request for thermal change within which a repeat of the same request constitutes a strong preference on the part of the guest to adjust the personal comfort zone accordingly. This parameter anticipates the situation in which an occupant desiring a large change will press the button repeatedly (as people do when waiting for elevators or 'walk' signals). Since the HVAC system operates at its maximum heating or cooling capacity for the period QUICKHEAT or QUICKCOOL when a button is pushed, the REPEAT-TIME parameter acts as a 'low-pass filter' and ignores rapidly repeated button pushes. The only time that T_{heat} and T_{cool} will be raised or lowered by the amount ΔT_{adj} is when the following two conditions are satisfied:

(1) the time since arrival > ADAPT-TIME

(2) the time elapsed between repeated requests for 'warmer' or 'cooler' < REPEAT-TIME

Given a set of values for T_{heat} and T_{cool}, as determined above, the comfortstat must first ensure

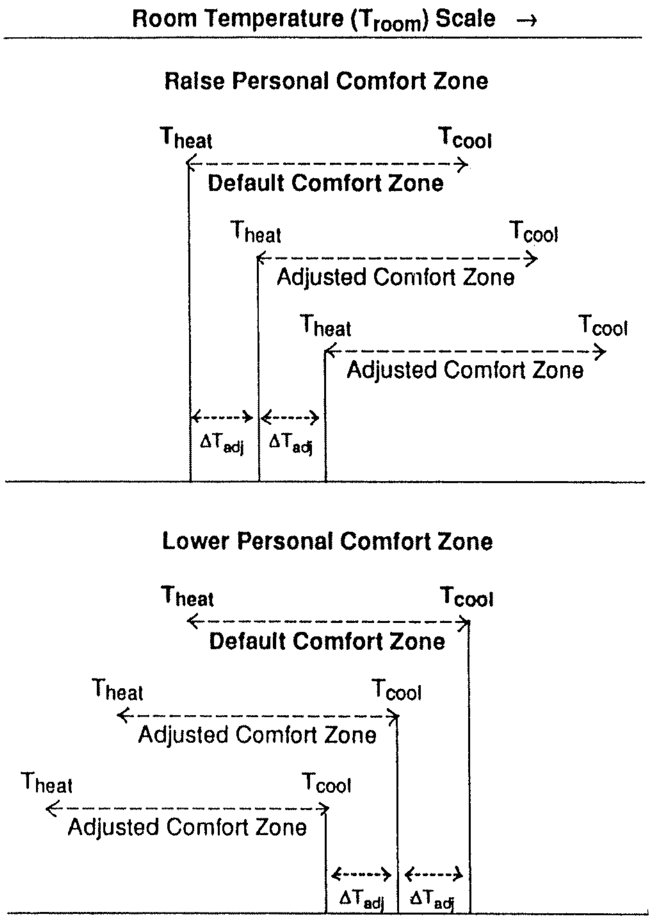


Fig. 5. Adjusting the personal comfort zone on the hotel comfortstat.

that the room temperature is within the personal comfort zone. As shown in Fig. 4, this is done by either heating the room (if T_{room} is within the cold or cool energy-conserving zones) or cooling the room (if T_{room} is within the hot or warm energy-conserving zones). The comfortstat will then maintain the guest's personal temperature range for a long-enough period of time (HOLDTIME) to allow the guest to reach thermal equilibrium with the room conditions. Note in Figs. 2 and 3 that the control logic activates the 'maintain personal temperature range' mode of operation whenever the guest enters the room but makes no request to the comfortstat. In this situation, the occupancy sensor initiates the control action of the comfortstat.

After the period HOLDTIME has elapsed, the comfortstat proceeds with its occupied energy-conserving response, in which the room temperature is allowed to drift at a rate of not greater than one degree Fahrenheit per hour (see Fig. 4). This drift is called a 'controlled ramp', and the direction of the room temperature ramp is determined on the basis of maximizing energy savings. The ramp rate is limited to the rate that is thermally indistinguishable to the guest [11], in order to maximize energy savings during the occupied period without loss of comfort.

The controlled ramp proceeds until the room temperature reaches the outer limits of the energy-conserving deadband, or setback temperatures (T_{min} or T_{max}). T_{min} and T_{max} are defined as the minimum and maximum temperatures the room is allowed to reach, respectively. Their values are based on acceptable temperature limits for short-term exposure (i.e., upon entry), and on maximum heating or cooling recovery times for the room in question. The comfortstat will maintain the energy-conserving deadband indefinitely, until a new system control input calls for another action. T_{room} is allowed to drift as long as it remains within the energy-conserving deadband. Heating or cooling is provided only when T_{room} drifts outside the energy-conserving deadband limits.

During unoccupied periods, signaled by the occupancy sensor, the comfortstat removes any tight control of the room temperature and allows it to drift within the energy-conserving deadband. When the guest checks out, the room status becomes 'unregistered', the allowable temperature drift range is widened, and the personal temperature range values are reset to their default values in preparation for the next guest's arrival.

Hotel comfortstat examples

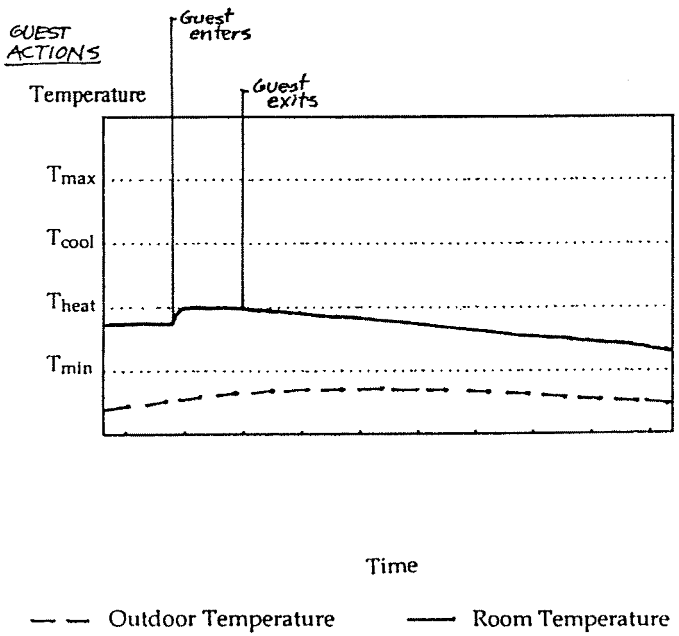
Several scenarios are presented (Fig. 6(a)–(d)) that illustrate how the comfortstat operates to control room temperature in response to various actions by the guest. For each scenario, a hypothetical plot of temperature versus time is presented, along with the comfortstat flow diagram (Fig. 3). The path of control operation through the flow diagram is shaded in each example. The scenarios are for the following conditions: (a) a simple situation; (b) a cold winter day; (c) a hot summer day; (d) transient human response due to a change in activity.

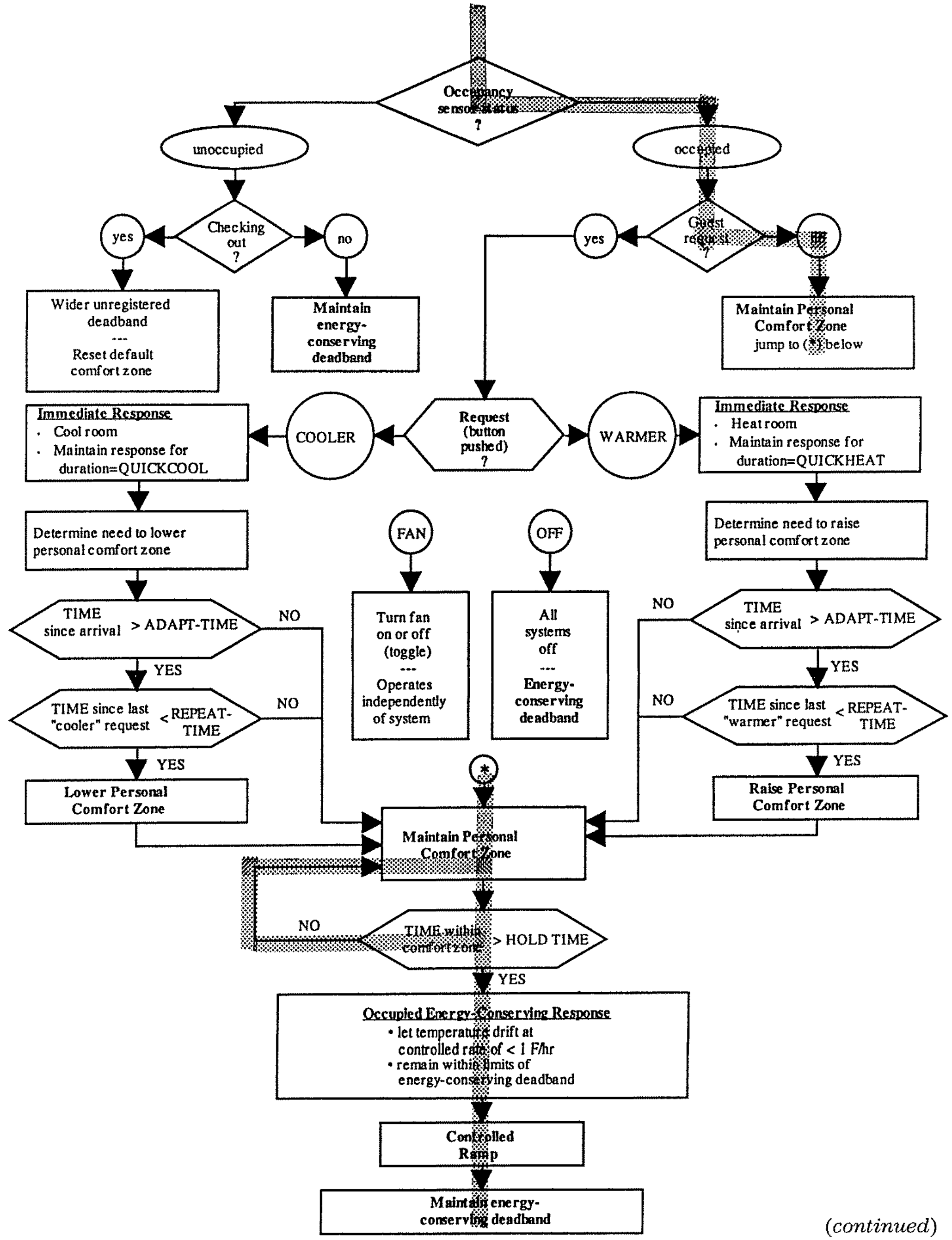
(a) In the simple situation, the guest does not request a change in the default comfort zone. When the guest exits the room, the occupancy sensor signal tells the system to turn off and the room temperature slowly drifts downward.

(b) In the cold winter day situation, the occupancy sensor's input turns on the system and calls for heating. When the bottom of the personal temperature range is reached, heating is maintained for HOLDTIME and then the room temperature is allowed to drift downward again. Since subsequent requests for heating are sufficiently far apart, i.e.,

Scenario #1: A simple situation

Outside conditions are cool, but not extreme. The guest arrives and the occupancy sensor triggers the comfortstat to move the room into the default comfort zone. The guest is satisfied with the default comfort zone and does not attempt to change it. The guest remains only a short time. After leaving, the occupancy sensor turns off the HVAC system and the temperature drifts downward. (The system will heat if necessary, to maintain indoor temperatures above T_{min}).





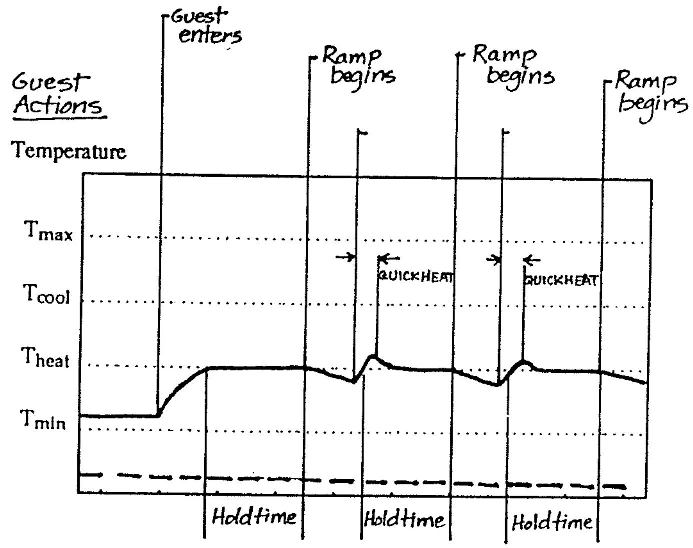
(a)

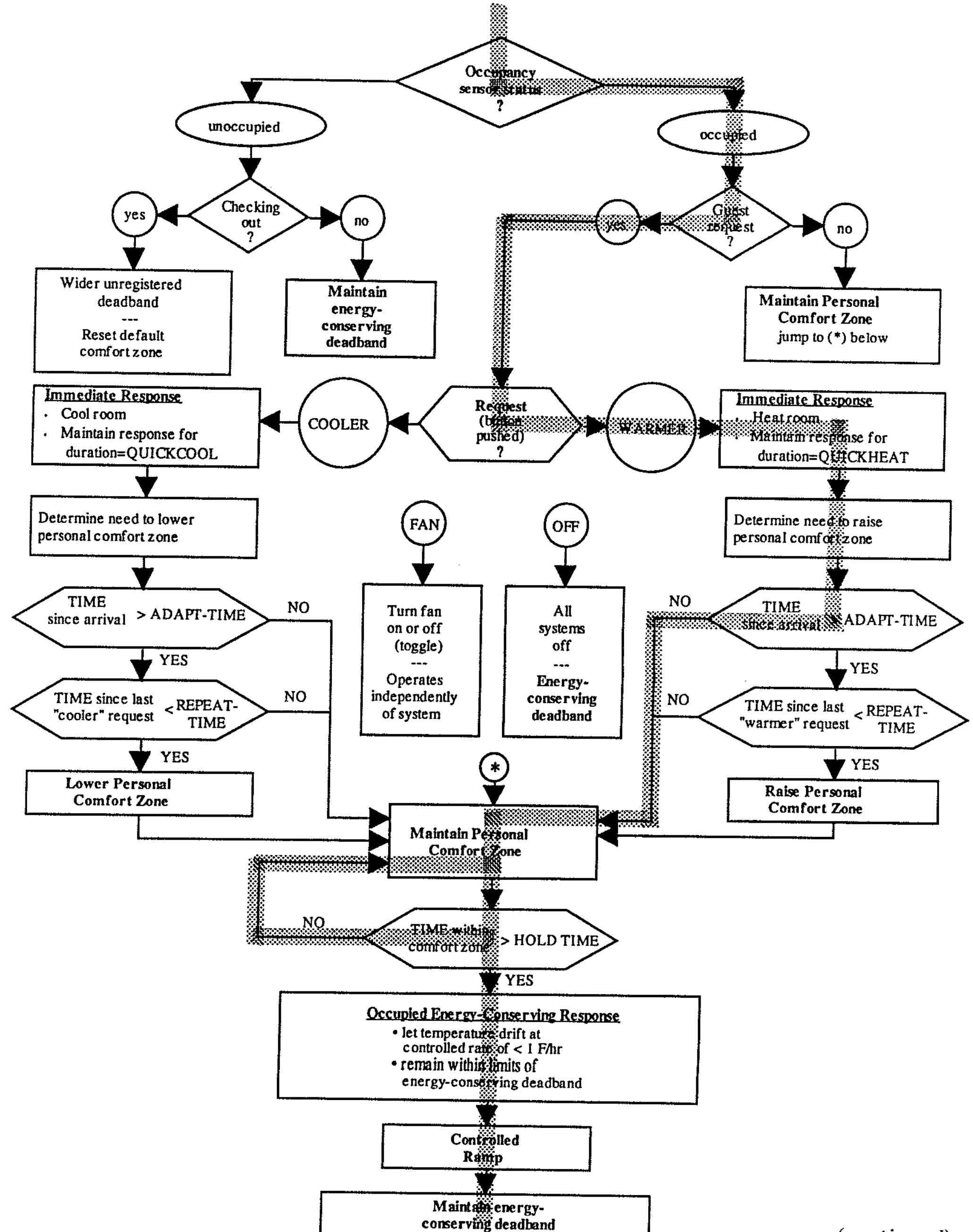
Fig. 6.

(continued)

Scenario #2: A cold winter day

The second scenario presents a somewhat more extreme situation, a cold winter day. Upon entry, the comfortstat heats the room into the default comfort zone and holds it for HOLDTIME. After the controlled 1°F/hr ramp has begun, when the guest requests warmer air. Immediate short-term heating is provided followed by another hold of the temperature within the comfort zone for HOLDTIME. The guest's subsequent requests are not close enough together in time to warrant changing the comfort zone setpoints (i.e. time elapsed > REPEAT-TIME). Extra warmth has been provided to compensate for external conditions, not as a result of unusual preferences.





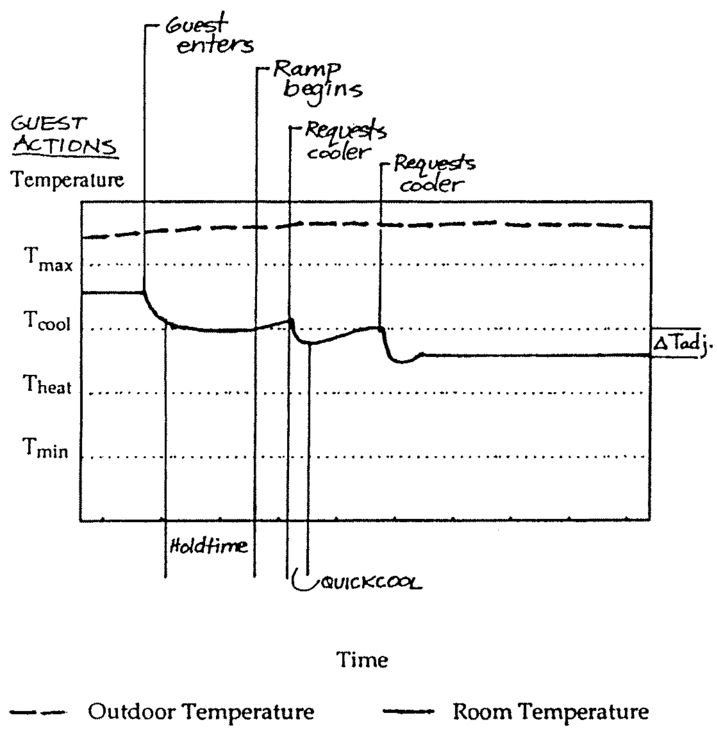
(b)

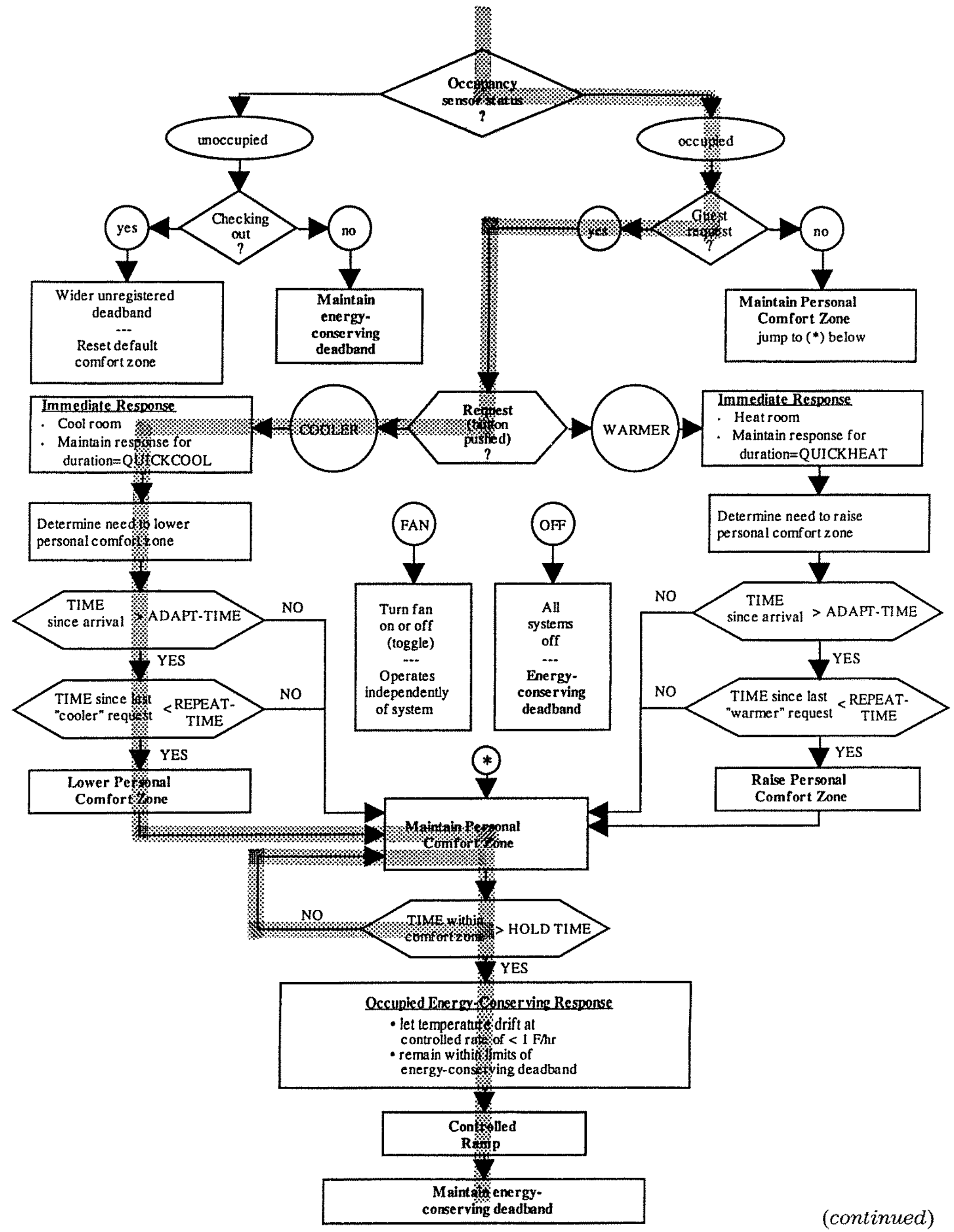
Fig. 6.

(continued)

Scenario #3: A hot summer day

It is a hot summer day. The guest arrives and requests cooling. The guest remains in the room for a period longer than ADAPT-TIME. After HOLDTIME has expired, and the comfortstat has begun its energy-conserving ramp response, the guest requests cooling twice within REPEAT-TIME. The comfort zone setpoints are lowered to adjust for the guest's personal preferences.





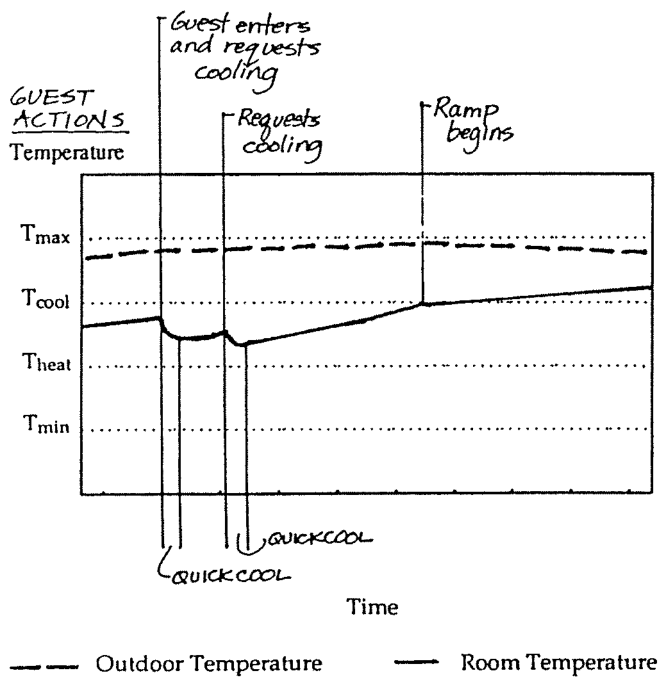
(c)

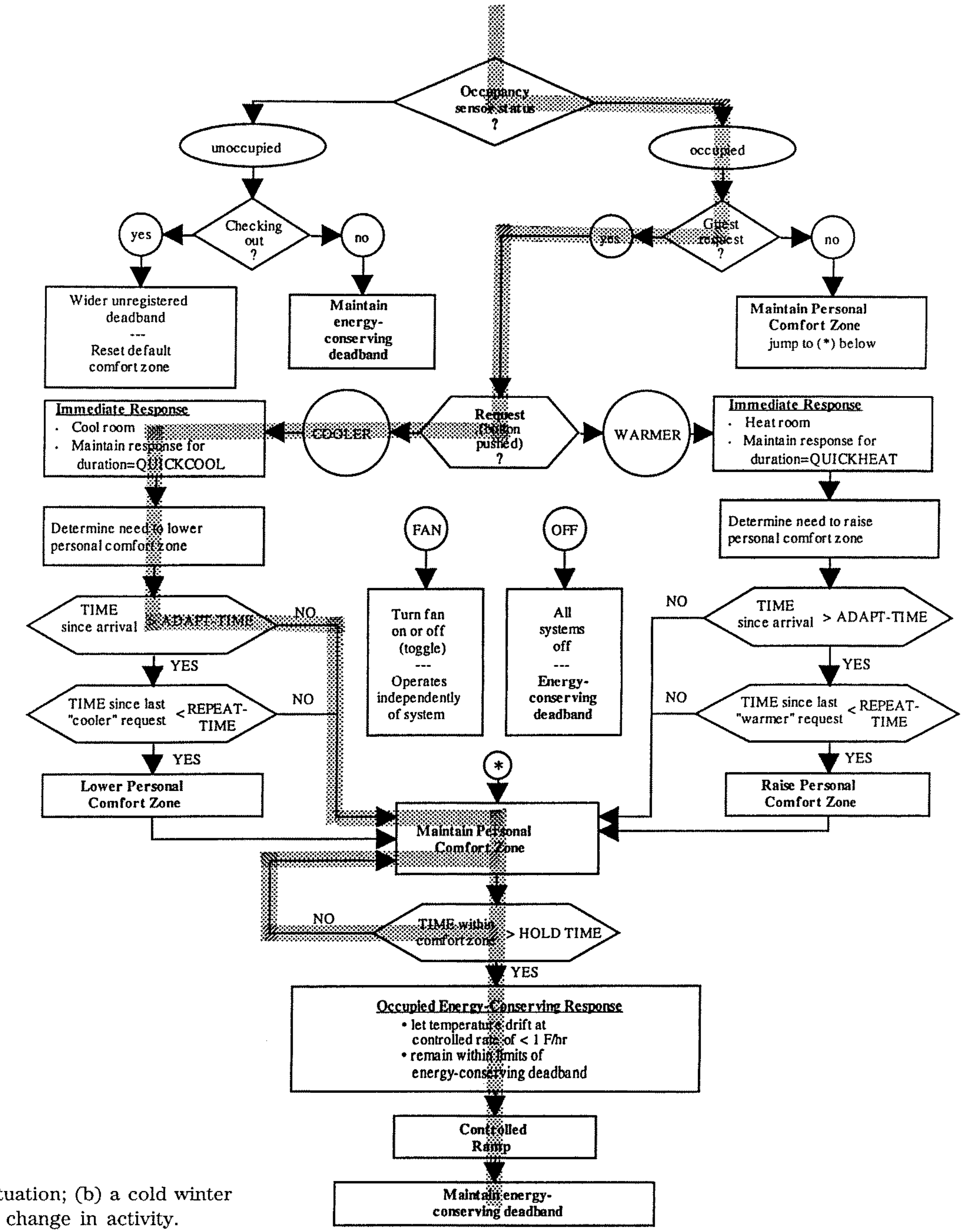
Fig. 6.

(continued)

Scenario #4: Transient human response, due to a change in activity

It is a warm afternoon. After the guest returns from shopping, his metabolic rate is elevated. Cool relief is desired promptly even though the room temperature is already within the comfort zone. After the immediate short-term cooling response of the system ends, the room temperature begins to drift upward and the guest again requests cooling. Since the two requests occur within ADAPT-TIME, a lowering of the comfort zone is not appropriate. There is no basis for assuming the immediate desire for cooler temperatures is related to his long term thermal preferences. He receives cool relief without changing setpoint.





(d)

Fig. 6. Four examples of hotel comfortstat operation: (a) a simple situation; (b) a cold winter day; (c) a hot summer day; (d) transient human response due to a change in activity.

greater than REPEAT-TIME, the personal temperature range is not adjusted.

(c) The hot summer day situation is the reverse of the cold winter day example, with the exception that the guest's request for cooling is repeated within REPEAT-TIME and the personal temperature range is lowered.

(d) The fourth situation illustrates a transient response to increased metabolic activity. The guest makes two requests for cooling in a period less than the adaptation period, ADAPT-TIME. The requests are granted, but the personal temperature range is not altered.

Conclusions

In this paper, we have presented the logic for a microprocessor-based environmental controller applicable to short-term occupancy. The algorithms were developed for a hotel environment but are applicable to other short-term occupancy situations where energy conservation must be balanced with the need for occupant satisfaction and comfort. The key features are the immediate response to guest requests while incorporating controlled ramps within continuously adjustable 'personal temperature ranges'. A prototype 'comfortstat' was developed integrating an occupancy sensor, setback capabilities, an environmental sensor, and logic for interactive setpoint adjustment with immediate response to thermal requests.

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