Peter Armstrong et al. “Controls”
Handbook of Heating, Ventilation, and Air Conditioning
Ed. Jan F. Kreider
Boca Raton, CRC Press LLC. 2001

5
Controls

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5.1 Control Fundamentals

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A building energy system is the combination of the HVAC plant, heating and cooling distribution paths, process loop controllers, and building energy management systems (EMSs). All of these must act in concert to produce a comfortable and healthy environment for the people who work in these buildings. The physical HVAC system must achieve the goals listed here:

- The building must maintain an internal temperature within a range acceptable by the occupants.
- Fresh air must be drawn into the building and distributed efficiently.
- Conditioned air, water, and gas must travel throughout the building to locations where they are needed.
- Internally generated air- and water-borne pollutants must be flushed from the building.
- Temperatures, pressures, flows, light levels, and energy use must all be properly controlled and any adverse interactions accounted for.

To accomplish this, a control system should be used to provide adequate feedback of the many complex processes in the building and to satisfy a number of objectives.

The main objective of the control system is *process stabilization*. HVAC processes can generally be divided into three categories: *self-stabilizing*, *moderate self-stabilizing*, and *unstable*. An example of the former is a well-designed coal furnace in which the amount of heat given off is the same as that produced by the burning of the coal. A moderately self-stabilizing process is usually stable, but small perturbations can lead to unstable response. A cooling coil at design conditions can be operated with a simple on-off control on the valve, but, once the load decreases, the room temperatures downstream of the coil will not be controlled adequately. An electric boiler is a good example of an unstable process, as it needs to have controls in place to prevent the boiler from reaching dangerous pressures. Unstable processes usually require some way of measuring the process, some way of assigning a setpoint to the process, and some method of controlling the process.

Another objective is the *suppression of disturbances*. Buildings are inherently dynamic, subject to constant occupant- and weather-driven load disturbances. Feedback, feedforward, and anticipating controls are used to maintain desired setpoints during periods of external disturbances.

The control system should ideally also perform some degree of *process optimization* to minimize system energy use and operating cost. Process optimization and energy savings in HVAC systems are achieved in a number of ways. The easiest is through scheduling, that is, to simply turn off devices such as pumps and fans when not in use. Another method is supervisory control, where the setpoints of the various processes are modified depending on the current load conditions.

Finally, the control system should provide a high degree of *labor saving and personal safety* features. Manually changing setpoints or adjusting valves can be boring jobs and are tasks much better suited to a continually attendant control system. Also, an automatic control system will not "lose interest" or not notice when a process is approaching dangerous levels.

Overview of Control Systems

As in any science, the field of HVAC controls has its own jargon and definition of events. Before discussing control systems in any detail, it is helpful to know the nomenclature. Formal definitions of some of the control components follow.

Process: a coil, damper, fan, or other piece of equipment that produces a motion, temperature change, pressure, etc. as a function of the actuator position and external disturbances. The output of the process is called the process value. If a positive action in the actuator causes an increase in the process value, then the process is called ***direct-acting***. A heating coil is direct-acting. If positive action in the actuator decreases the process value, for example a cooling coil, it is called ***reverse-acting***.

Sensor: a device that produces some kind of signal indicative of the process value. Sensors use pneumatic, fluidic, or electric impulses to transmit information.

Setpoint: the desired value for a process output. The difference between the setpoint and the process value is called the ***process error***.

Controller: sends signals to an actuator to effect changes in a process. The controller compares the setpoint and the process value to determine the process error. It then uses this error to adjust the output and bring the process back to the setpoint. The controller *gain* dictates the amount that the controller adjusts its output for a given error.

Actuator: a pneumatic, fluidic, or electric device that moves a damper or a valve, activates a relay, or performs any physical action that will control a process.

External disturbance: any driving force that is unmeasured or unaccounted for by the controller.

Open-loop system: one in which there is no feedback. A whole-house attic fan is an example. It will continue to run even though the house may have already cooled. Also, timed on/off devices are open loops.

Feedback (closed-loop) system: contains a process, a sensor, and a controller. Figure 5.1.1 shows some of the components and terms used when discussing feedback loop systems. In this diagram, a setpoint is compared with the measured process value. The difference between the two values is the error. The controller uses the error to generate an output signal that is sent to an actuator. The actuator, in turn, translates the control signal into a physical change of the process. A sensor measures the change of the process, and the cycle begins anew.

These feedback loop components are illustrated in the reservoir level control example shown in Figure 5.1.2. Here a float sensor adjusts the flow of water out of the tank via an armature that acts like the controller and actuator.

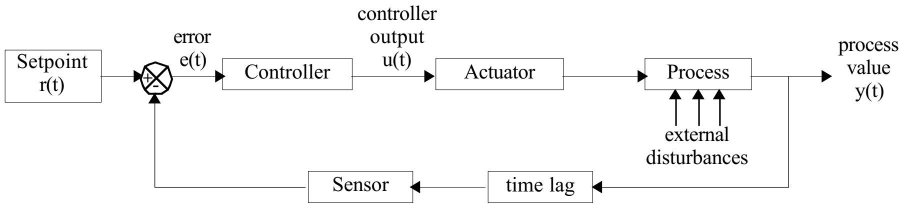

FIGURE 5.1.1 Typical components of a feedback loop.

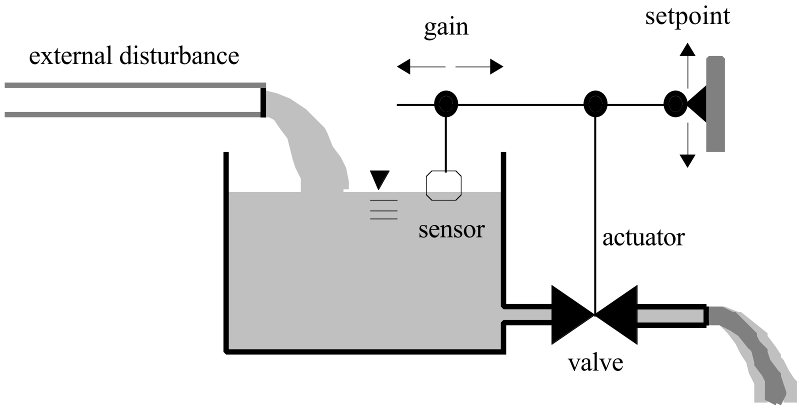

FIGURE 5.1.2 Control system example showing components.

Sensor and Process Characteristics

Sensors and processes have various characteristics that play a role in the ability of a feedback loop to maintain stable control of a system.

The *time constant* of a sensor or process is a quantity that describes the dynamic response of the device or system. Usually the time constant is related to the mass of the object. For example, the physical mass of a heating coil must first heat up before it can heat a stream of air passing through it. Likewise, a temperature sensor recording this change will probably have a protective sheaf around it that must first heat up before the sensor registers a change of temperature. The time constant of a coil can be several minutes, while for sensors it is typically tens of seconds.

The *dead time* or *lag time* of a process is the time between the change of a process and the time this change arrives at the sensor. The delay time is not related to the time constant of the sensor, although the effects of the two are similar. Large dead times must be properly treated by the control system to prevent unstable control.

Hysteresis is the nonlinear response of an actuator that results in different valve or damper positions depending on whether the control signal is increasing or decreasing. That is, a control signal of 50% may result in a valve position of 45% when the control signal is increasing from zero, but a valve position of 55% when the control signal is decreasing from 100%.

The *dead band* of a process is a range of the process value in which no control action is taken. A dead band is usually used in a 2-position control to prevent "chattering" or in split-range systems to prevent sequential control loops from fighting each other.

The *control point* is the actual, measured value of a process (i.e., the setpoint + steady state offset + compensation).

The *stability* of a feedback loop is an indication of how well the process is controlled or, alternatively, how controllable the process is. Stability is determined by any number of criteria, including overshoot, settling time, correction of deviations due to external disturbances, etc.

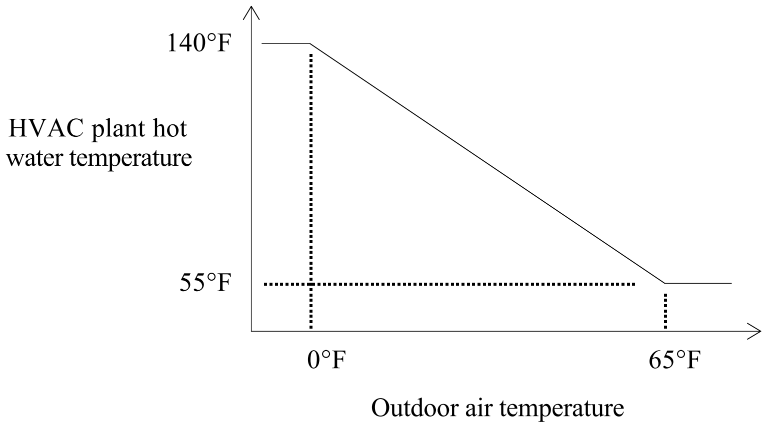

FIGURE 5.1.3 Outdoor air reset control.

Other Types of Control Loops

If the cause of a process disturbance is known, a control loop can be designed to counteract disturbances before their effects are seen at the end process. *Compensation control* (or *reset control*) is when the control point of a process is shifted upward or downward depending on the input from a second sensor. This is a subset of *feedforward control*, an example of which is outdoor-air reset control, as shown in Figure 5.1.3. In this example, as the ambient air temperature increases, the temperature of the hot water is reset upward in anticipation of a greater heating load.

Another type of feedforward control uses a model of the process to predict what the process value will be at some point in the future, based upon the current and past conditions. The controller then specifies a control action to be taken in the present that will reduce the future process error. This is called *predictive control*. Note that predictive controllers are different than *adaptive controllers*. Adaptive controllers are essentially feedback loop processes in which the gains are modified dynamically to adapt to the current process conditions.

Control Signals

There are several methods for passing control signals from one location to another. *Electric control* uses low voltages (typically 24 VAC) or line voltages (110 VAC) to measure values and effect changes in controlled variables. *Electronic control* is associated with the use of solid state, electronic components used for measurement and amplification of measured signals and the generation of proportional control signals. *Pneumatic controls* use compressed air as the medium for measuring and controlling processes. *Fluidic controls* are similar to pneumatic controls except that hydraulic fluid is used instead of compressed air.

5.1.1 Sensors

Closed-loop control of building systems is possible only if the control system is able to accurately measure the process. This section discusses some of the different types of sensors and sensing mechanisms that can be found in a building. As with the control loops, there are terms which must be defined prior to any discussion of the sensors.

Actual value: the true or actual value of a process. This value can never be known with absolute certainty since it must be determined by measurements that will always incorporate some error.

Measured value (or **process value**)**:** the estimate of the actual value. The measurement error is the difference between the actual and measured values.

Uncertainty: the possible value of the error. The uncertainty range is the probable range of the errors (for example, the process value = actual value ± uncertainty).

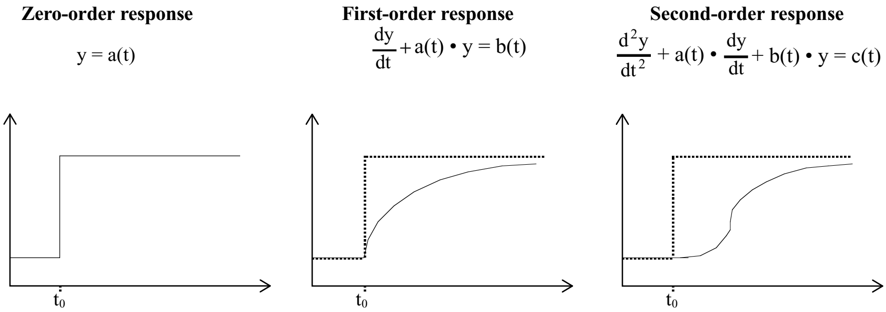

FIGURE 5.1.4 Different types of sensor response.

Process range: a process will vary between some lower and upper bounds relating to the dynamics of the physical process. This is called the process range.

Accuracy of a sensor: the expected uncertainty of measurement, usually specified by the manufacturer of the instrument. This can be given in engineering units (e.g., ± 1°F) or as a function of the range (e.g., ± 5% full scale).

Repeatability: the ability of a sensor to measure the same value during successive measurements. The systematic error is a constant error due to an inherent problem in the process or in the sensor. Sometimes a process or instrument will behave differently when the process value increases as opposed to when the process value is decreasing. This is called the hysteresis of the process.

Sensitivity: the ratio of the change in the sensor output corresponding to a unit change in the measured variable.

Calibration: the relationship between the sensor output and the corresponding engineering units is called the calibration of the sensor.

Resolution (of a sensor): the smallest readable change of the value of the measured variable.

Sensor Response

The sensor may not respond immediately if it has much mass or a small surface area in contact with the measured process. The sensor response also depends on the type of process measured. Figure 5.1.4 shows some of the different types of sensor response that may be experienced. A zero-order response is typical of sensors such as voltage and current transducers where there is an immediate response to a change in the measured process, while higher order responses are usually seen in the measurements of other processes. The first-order response is quite common and is quantified by the *time constant* of the sensor.

Sensor Time Constant — The time constant of a sensor is usually found from experimentation, although if the physical characteristics of the sensor are well known then it can be calculated. For example, consider a temperature sensor with the following known properties: mass m, specific heat c_p, surface area A, and surface conductance coefficient h (in units of Btu/hr·ft^2·°F or W/cm^2·°C). The overall heat capacitance of this sensor can be found from

$$C_{sensor} = m \cdot c_p$$

The heat capacity has units of energy per temperature change. Energy (in the form of heat) can pass into this sensor at a rate of

$$UA_{sensor} = A \cdot h$$

with units of power per temperature difference.

Suppose this sensor is allowed to reach a steady state temperature and is then placed into a large container of water at temperature T_{water}. The amount of energy transferred between the water and the sensor in a given time is

$$Q_{water \rightarrow sensor} = UA_{sensor} \cdot (T_{water} - T_{sensor}) \cdot \Delta t$$

The sign convention is that energy *into* the sensor is positive. The change of energy stored in the sensor over a given interval is

$$Q_{storage} = C_{sensor} \cdot [T_{sensor}(t) - T_{sensor}(t - \Delta t)] = C_{sensor} \cdot \Delta T_{sensor}$$

The energy balance is $Q_{storage} = Q_{water \rightarrow sensor}$ or

$$C_{sensor} \cdot \Delta T_{sensor} - UA_{sensor} \cdot (T_{water} - T_{sesnsor}) \cdot \Delta t = 0$$

For an infinitesimally small time interval, this can be written as

$$C_{sensor} \cdot \frac{dT_{sensor}}{dt} + UA_{sensor} \cdot (T_{sensor} - T_{water}) = 0$$

The *time constant* can now be defined. It is given as $\tau = C_{sensor}/UA_{sensor}$ in units of seconds. The energy balance is then

$$\frac{dT_{sensor}}{dt} + \frac{1}{\tau}T_{sensor} = \frac{1}{\tau}T_{water}$$

The general solution of this first-order, nonhomogeneous equation yields

$$T_{sensor}(t) = T_{water} + [T_{sensor}(0) - T_{water}]e^{-t/\tau}$$

Note that when $t = \tau$, the sensor will be e^{-1}, or 37%, of the total temperature change away from its final value.

Electronic Temperature Sensors

Almost all electronic temperature sensors use thermocouples, thermistors, or RTDs. The output of these sensors is often amplified or otherwise modified to provide a more meaningful signal to the control system.

Thermocouple — When any two dissimilar metals are in contact, a current is generated that corresponds to the temperature of the junction. This is the principle behind thermocouples. Advantages of thermocouples include

- Self-powered — no excitation voltage is necessary
- Simple — no electronics other than the constituent metals
- Rugged — difficult to break or damage
- Inexpensive — typically a few dollars per point
- Wide variety and temperature ranges — see thermocouple types in Table 5.1.1

Some of the disadvantages of thermocouples are

- Non-linear — polynomial conversion equations are required for full temperature range
- Low voltage — amplification of the signal may be necessary
- Reference required — independent measurement of the voltmeter temperature may be necessary
- Least sensitive — accuracy may be plus or minus several degrees

TABLE 5.1.1 Thermocouple Types and Ranges

Type	Metals +	Metals –	Average Seebeck Coefficient µV/°F	ref. °F	Std. Error °F	Range °F
B	94% Pt/6% Rh	70% Pt/30% Rh	3.3	1112	7.9–15.5	32 to 3200
E	90% Ni/10% Cr	Constantan	32.5	32	3.1–7.9	–450 to 1800
J	Iron	Constantan	27.9	32	2.0–5.2	–350 to 1400
K	90% Ni/10% Cr	Ni	21.9	32	2.0–5.2	–450 to 2400
R	87% Pt/10% Rh	Pt	6.4	1112	2.5–6.8	–60 to 3100
S	90% Pt/10% Rh	Pt	5.7	1112	2.5–6.8	–60 to 3100
T	Cu	Constantan	21.1	32	1.4–5.2	–450 to 800

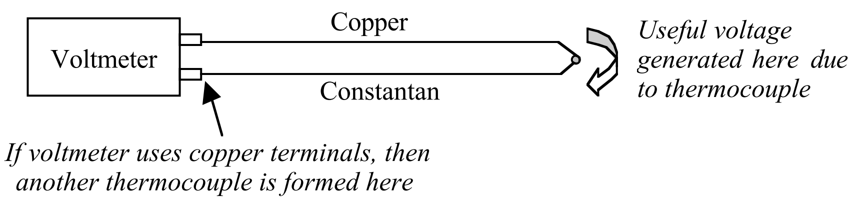

FIGURE 5.1.5 Measuring thermocouple with voltmeter.

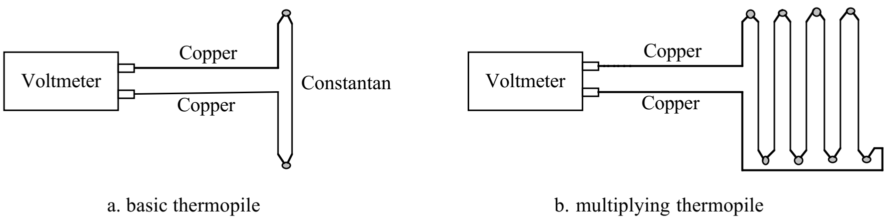

FIGURE 5.1.6 Examples of thermopiles.

Care must be exercised when using thermocouples. A standard copper-constantan thermocouple will produce a voltage proportional to the temperature at the junction of the two metals. However, it is not possible to measure this voltage directly because the connection to a voltmeter will also result in a thermocouple, as shown in Figure 5.1.5. However, if the temperature of the voltmeter terminal is known, then the necessary correction factor can be easily calculated and applied to the resulting signal.

If one wishes to measure the temperature *difference* between two points, then any even number of thermocouples can be arranged to produce a *thermopile* that can be measured with a standard voltmeter without a reference temperature. Figure 5.1.6a shows how a basic thermopile works. The two junctions produce opposing voltages; the temperature difference is proportional to the voltage difference. Figure 5.1.6b shows a thermopile that could be used for averaging purposes or to amplify the signal of a point measurement.

Resistance Temperature Device (RTD) — The resistance of most metals changes as the temperature of the metal changes. This principle is used in resistance temperature devices. Typically a thin wafer of platinum is laser-etched to provide a known resistance at a reference temperature. These types of sensors are quite stable and accurate and provide a more linear response than thermocouples. Disadvantages include

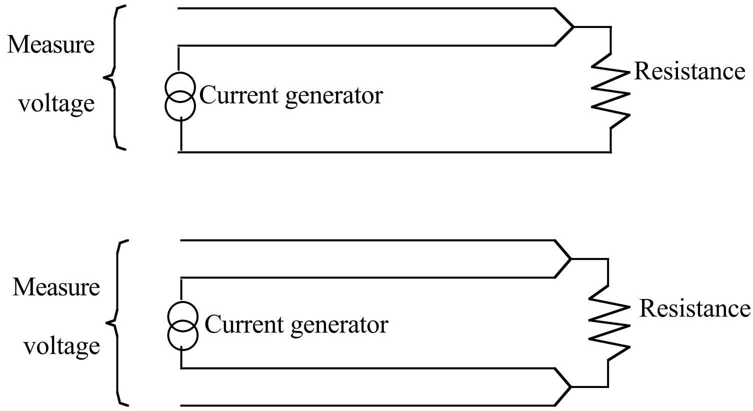

FIGURE 5.1.7 Three- and four-wire resistance measurements.

- Cost — RTDs are typically \$50–100 per point
- Current source required — an excitation voltage is required to measure the resistance
- Small resistance change — total range of temperature may be represented by 30 to 40 Ω resistance range
- Low absolute resistance — reference resistance typically 100 Ω
- Self-heating — excitation voltage can cause sensor to warm and provide false readings

The temperature of an RTD is calculated as

$$°C = (\Omega_{RTD} - \Omega_{ref})/(100 \cdot \alpha)$$

where α is the average slope of the Ω_{RTD} versus temperature line between 0 and 100°C. Typical values are $\alpha = 0.00385$ or $\alpha = 0.00392$ for a Ω_{ref} of 100 Ω at 0°C.

RTD sensors have nominal resistance values of 100 to 120 ohms under normal conditions. Standard 18-gauge wire has a resistance of about 0.67 ohms per 100 feet. It is therefore necessary to use 3- or 4-wire resistance measurements to avoid introducing too much error into the resulting signal. In such a measurement, a power source is used to send a small current (typically 1 to 10 mA) through the resistor, and the resulting voltage is measured (Figure 5.1.7). If the current is accurately controlled, then the resistance can be found through Ohm's law.

Thermistor — Certain semiconductors or metal oxides can be packaged into a small probe in which the electrical resistance through the probe varies inversely with the temperature. This is the basic principle behind thermistors. The sensors often have high reference resistances (in the kΩ range) and very fast response times. Disadvantages include a strong nonlinearity, limited operational temperature range, fragility of the sensor, and the same current requirements and self-heating problems found in RTDs. Thermistor temperatures are calculated from

$$1/T = A + B \cdot \ln(\Omega_{thermistor}) + C \cdot [\ln(\Omega_{thermistor})]^3$$

where T is the temperature in Kelvin, $\Omega_{thermistor}$ is the resistance of the thermistor, and A, B, and C are curve fitting constants. Typical resistance is 5000 ohms at 25°C.

Note that with both RTDs and thermistors, it is important not to allow current to flow through the sensor continuously, as this will lead to heating of the resistor and erroneous readings. This self heating is a function of both the current and the sensor resistance where the power converted to heat is given as i^2R. The self-heating effect will be attenuated by the mass of the sensor and any factors in the local

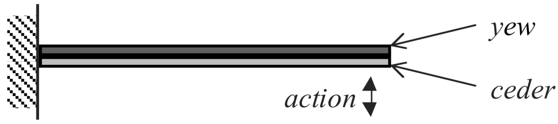

FIGURE 5.1.8 Schematic of a wood-based humidity sensor.

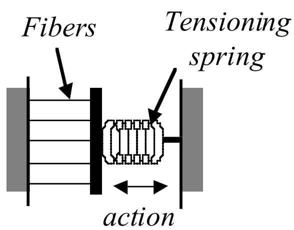

FIGURE 5.1.9 Schematic of a fiber-based humidity sensor.

FIGURE 5.1.10 Schematic of a thin-film humidity sensor.

environment that may transport heat away from the sensor, but usually it is best to provide power to the sensor only when a reading is taken.

Humidity Measurements

To determine all moist air properties, one needs only to know the two of the following: dry-bulb temperature, wet-bulb temperature, relative humidity, and humidity ratio. Some traditional ways of measuring moist air properties are listed below.

Two pieces of different types of wood can be used to determine the humidity ratio (Figure 5.1.8). A given humidity ratio will cause both pieces to absorb water, but in different amounts. The sensor will bend accordingly and generate a physical control action that can be transmitted to a controller.

In a similar fashion, fibers will contract or expand depending on the local humidity ratio and the corresponding absorption of water by the fibers (Figure 5.1.9). Both natural and synthetic fibers are available for this use. The tension of the fibers can be measured by sensors on the fiber supports.

Thin-film capacitors or resistors can be used to determine the relative humidity (Figure 5.1.10). These devices consist of a thin wafer or piece of foil that changes electrical properties as the relative humidity changes.

Chilled mirror systems use an electronically cooled reflective surface to determine the dew-point of an airstream (Figure 5.1.11). The mirror is cooled until it is no longer a specular surface (that is, until moisture in the air begins to condense on the mirror surface).

Perhaps the most standard method for measuring humid air properties is the use of a sling psychrometer (Figure 5.1.12). This device is simply two thermometers on a single base with a moistened absorbent material around the bulb of one of the thermometers. Air is forced across the absorbent material and, through evaporation, is forced to bring it to the wet-bulb temperature.

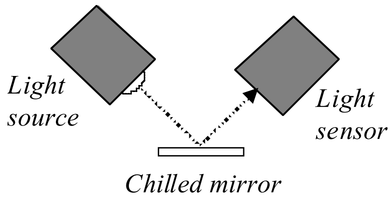

FIGURE 5.1.11 Schematic of a chilled mirror dew-point sensor.

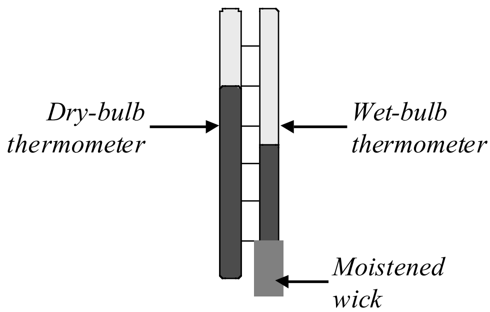

FIGURE 5.1.12 Schematic of a sling psychrometer.

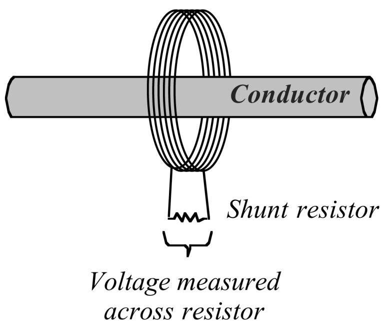

FIGURE 5.1.13 Schematic of a current transducer.

Current Measurements

Electrical current is usually measured with current transducers (sometimes called "current donuts" — (Figure 5.1.13). This kind of transducer is simply a long, continuous winding of wire that uses the induced magnetic field from current flow in a power line to generate a proportional measurement signal.

The current transducers can be solid core or split core. Solid core transducers are single coils of wire that must be installed on a conductor before the conductor is connected to the load. Split core transducers can be opened on one side to allow installation around a wire (see Figure 5.1.14) and are used for short-term monitoring or in situations where the existing conductor cannot be broken or disconnected.

Pressure Measurements

Pressure will often be cited in either *gauge* (sometimes *gage*) or *absolute* pressure. Gauge pressure refers to the pressure above the ambient atmospheric pressure, while absolute pressure uses a complete vacuum as the zero reference.

A *bulb and capillary* arrangement is often used to transmit temperature signals (Figure 5.1.15). The bulb is filled with a refrigerant or other material that changes pressure as a function of the temperature.

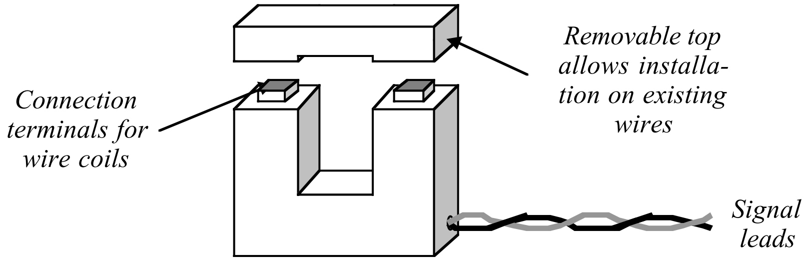

FIGURE 5.1.14 Schematic of a split core current transducer.

FIGURE 5.1.15 Schematic of a bulb and capillary sensor.

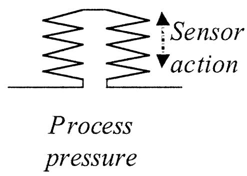

FIGURE 5.1.16 Schematic of a bellows pressure sensor.

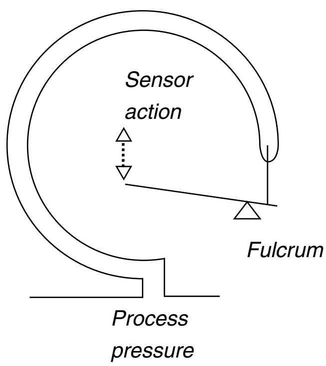

FIGURE 5.1.17 Schematic of a bourdon tube.

This kind of sensor is useful for taking average readings across a wide surface area and also for freeze protection.

A *bellows* sensor uses a flexible coupling to amplify changes in pressure and translate the pressure change into a physical motion (Figure 5.1.16). The opposite end of the bellows is attached to some kind of armature that will perform an action depending on the displacement of the bellows.

Bourdon tubes (Figure 5.1.17) are flattened pieces of pipe, capped at one end, which flex slightly when a pressure is applied to the open end. This motion is then translated into an actuator motion or dial adjustment through an armature connected to the pipe. Bourdon tubes are used in many dials and gauges.

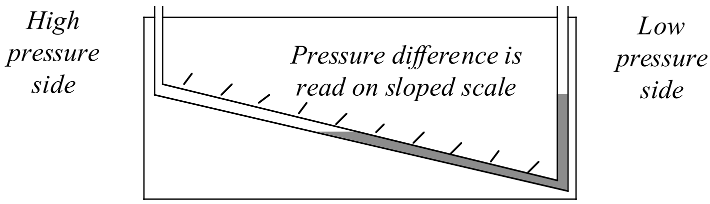

FIGURE 5.1.18 Schematic of a liquid manometer.

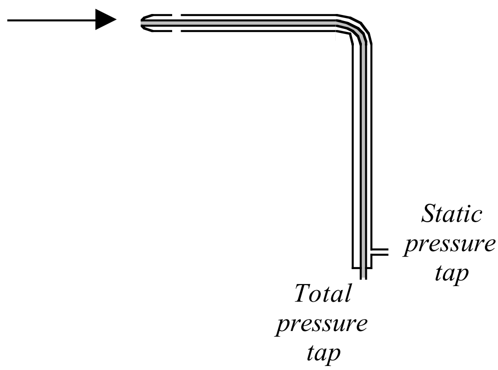

FIGURE 5.1.19 Schematic of a pitot tube.

A *manometer* (Figure 5.1.18) is often used to measure the difference between dynamic and static pressures. This is an inclined tube containing a fluid of a known and consistent specific gravity. The pressure measurements can be made by attaching a differential pressure probe to the ends of the tube.

Electronic sensors use a couple of different methods for determining the pressure applied to the sensor. Some incorporate a grid of thin wires with very specific electrical resistances. The grid is attached to a membrane that can develop a concavity under pressure, thus flexing the grid. As the grid is flexed, the resistance across the wires changes. This resistance can be measured by passing a small, constant current through the mesh and measuring the resulting voltage. *Piezoelectric* sensors rely on the physical properties exhibited by specific materials, specifically, crystals that produce a small current under pressure. This current can be measured and used as the basis for determining the pressure on the crystal.

Air Flow Measurements

Pitot tubes are most often used for hand measurements of the air flow rate in a duct. These probes consist of concentric tubes, one that is open to the oncoming air flow and the other with openings perpendicular to the air flow (Figure 5.1.19). The former measures the total pressure and the latter measure the static pressure. The difference between the two is the dynamic pressure from which the air speed can be determined from

$$v = \sqrt{\frac{2 \cdot P_d}{\rho} g_c}$$

where P_d is the dynamic pressure, ρ is the density of the air, and g_c is the acceleration of gravity (32.17 lbm·ft/lbf·s^2). Since there is no air flow through the tube, the length of the tube does not matter, and long pitot tubes can be used to take measurements deep inside very large ductwork.

The profile of the air velocity through a duct is usually not uniform across the face of the duct. For this reason, it is preferable to take multiple readings of the air flow in a duct and average the result. To

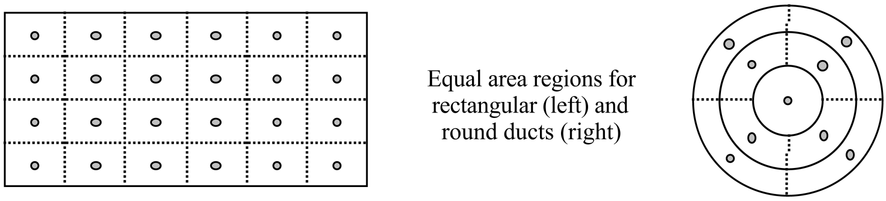

FIGURE 5.1.20 Examples of equal area duct measurements.

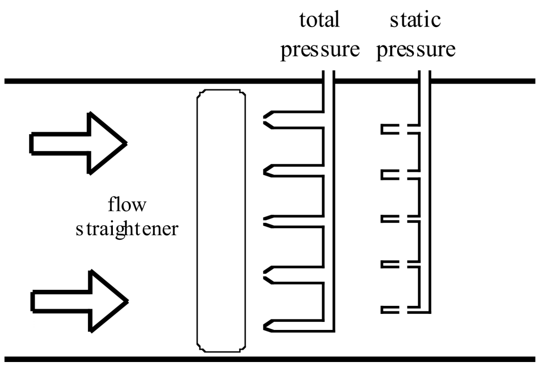

FIGURE 5.1.21 Schematic of an air flow station.

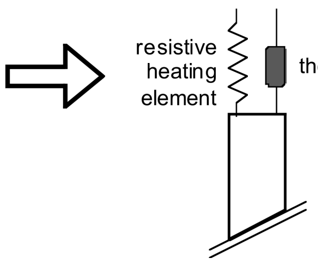

FIGURE 5.1.22 Schematic of a hot wire anemometer.

ensure that a true average is taken, the readings should be taken at equal area sections of a duct, as shown in Figure 5.1.20.

A *pitot-tube traverse* is often used to measure the air velocity because it is easy to navigate a pitot tube across the face of a duct.

Air flow stations are used to measure the average total and static pressures in a duct (Figure 5.1.21). In essence, they act like permanently installed pitot traverse measurements. The measurements are taken with many modified pitot tubes that span the cross section of the duct. Since the pressure will be adversely affected by any turbulence in the duct, flow straighteners are usually included just upstream of the pitot arrays. In addition, it is important to situate an air flow station in a long, straight region of duct, several duct diameters downstream of any kind of obstruction or elbow in the duct.

Hot wire anemometers (Figure 5.1.22) rely on heating an airstream to determine the air flow rate. The current passing through a resistive heating element is varied in order to maintain a constant temperature (around 200°F) at a downstream thermistor. Since the response of the thermistor will also depend on the air temperature, it is necessary to measure this value as well. A simpler device measures the heating element current while the resistance is held constant by a feedback controller using a wheatstone bridge.

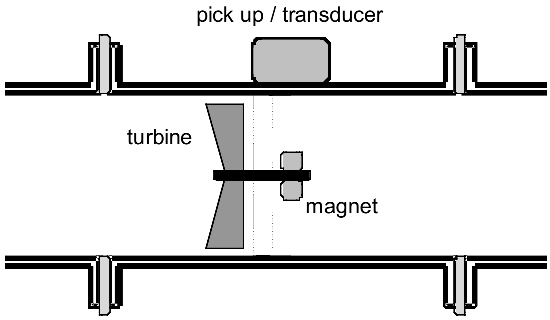

FIGURE 5.1.23 Schematic of a turbine flow meter.

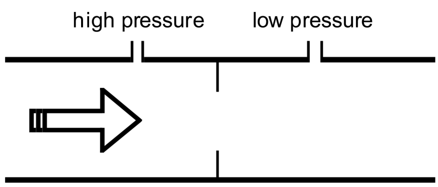

FIGURE 5.1.24 Schematic of an orifice plate meter.

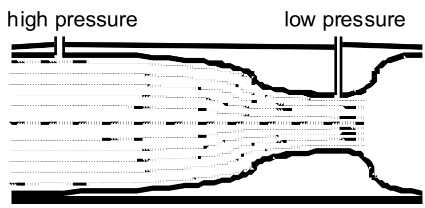

FIGURE 5.1.25 Schematic of a venturi meter.

Fluid/Gas Flow Measurements

A *turbine meter* (Figure 5.1.23) is a volumetric flow meter that consists of a propeller with a magnet attached to the shaft. The propeller makes a certain number of turns per volume of fluid that passes through the blades. A magnetic pick-up counts the number of times the propeller turns over a given time interval. The turns-to-volume ratio is called the k-factor of the turbine meter. The k-factor should remain constant but can tend to drop at low flow values due to friction in the turbine bearings.

Both *orifice plates* (Figure 5.1.24) and *venturi meters* (Figure 5.1.25) use constrictions in a fluid stream to induce a pressure drop. The pressure drop can then be correlated to a flow rate given the fluid's density and kinematic viscosity. The main difference between the two types of flow meters is that venturi meters attempt to preserve laminar flow while orifice plates usually produce turbulence. Orifice plates, therefore, create higher total system pressure drops than venturi meters, but they are also much less expensive.

Radiation Sensors

Typically, solar radiation is measured with a *pyranometer*. One type of pyranometer uses alternating black and white fields to measure radiation (see Figure 5.1.26). Sunlight striking the sensor causes the black surfaces to become warmer than the adjacent white surfaces; the temperature difference is then measured using a thermopile. The sensor is calibrated according to the correlation between the temperature difference and the intensity of the sunlight.

Other types of pyranometers use a *photovoltaic* chip (or *photodiode*) to produce (or allow) a current corresponding to the ambient radiation signal (Figure 5.1.27).

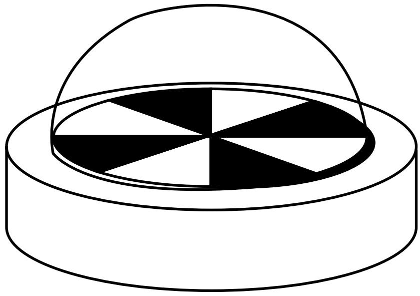

FIGURE 5.1.26 Temperature-based pyranometer.

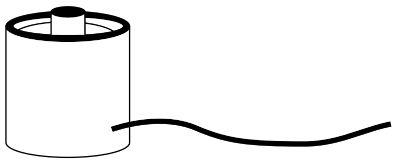

FIGURE 5.1.27 Illustration of a photocell-based radiation sensor.

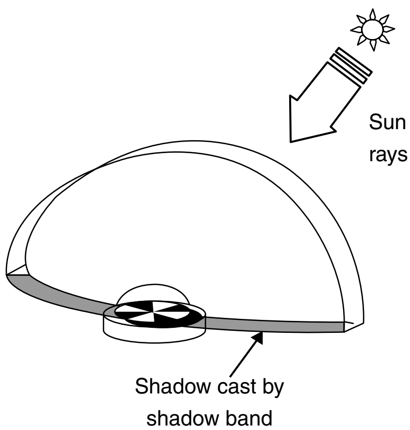

FIGURE 5.1.28 Pyranometer with shadow band.

A *pyrheliometer* is a pyranometer that tracks the sun and is shaded so that it views only a very small angle of the sky corresponding to the angular extent of the sun. These devices are used to measure only the beam radiation coming directly from the solar disk.

A *shadow band pyranometer* uses a suspended band that blocks out direct beam radiation (Figure 5.1.28). The reading from a shadow band pyranometer is usually used in conjunction with a standard pyranometer to determine both the beam and diffuse radiation.

A *multi-pyranometer array* uses several fixed pyranometers to measure the solar radiation on several surfaces simultaneously. A knowledge of solar geometry is then used to determine the individual radiation components.

5.1.2 Actuators

Electric and Electronic Actuators

Electronic actuators use a series of motors and reduction gears to move valves and dampers. They will accept control signals up to 20 VDC or 20 mA and translate a signal into an actuator position. Because

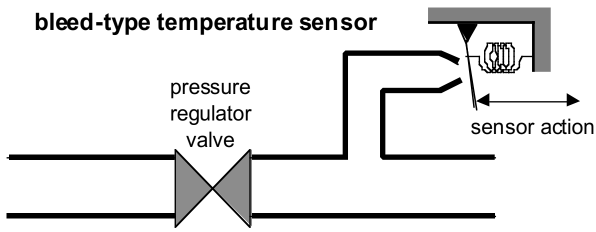

FIGURE 5.1.29 Schematic of a bleed type pneumatic sensor.

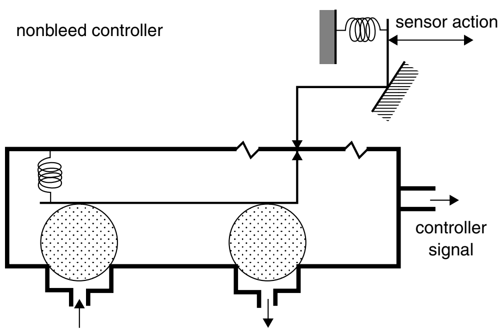

FIGURE 5.1.30 Schematic of a non-bleed controller.

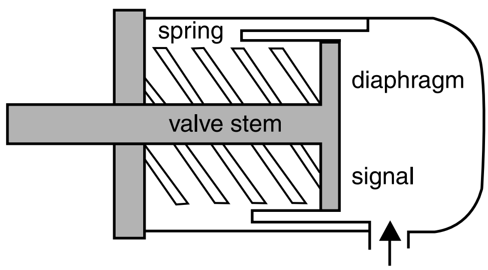

FIGURE 5.1.31 Schematic of a pneumatic valve actuator.

the motors are often geared down significantly to achieve the desired torque at the valve or damper shaft, the travel time of electronic actuators can be tens of seconds or even minutes.

Pneumatic Actuators

Pneumatic sensors and controllers are an important part of HVAC systems, particularly in older buildings. Pneumatic actuators use compressed air to generate force on diaphragms located within the actuators. With a relatively small surface area and modest air pressures, it is possible to generate sufficient forces to move valves, dampers, etc. Pneumatic actuators are generally much faster acting than electronic actuators since the full force is applied as soon as the signal is received by the actuator. It is, however, difficult to implement complex control algorithms using pneumatic components. Pneumatic actuators are also often more bulky than electronic actuators.

Pneumatic controllers can usually be divided into two different types: *bleed* (Figure 5.1.29) and *non-bleed* (Figure 5.1.30). Typical air pressures used in such systems vary from 3 to 20 psi. The signals from the controllers can be used to create a mechanical action. The force required by that action determines both the working pressure used and the size of the diaphragm used in the actuator.

Pneumatic actuators (Figure 5.1.31) take advantage of the energy inherent in the compressed air signal. The actuator body is sized so that the required torque or force will be achieved.

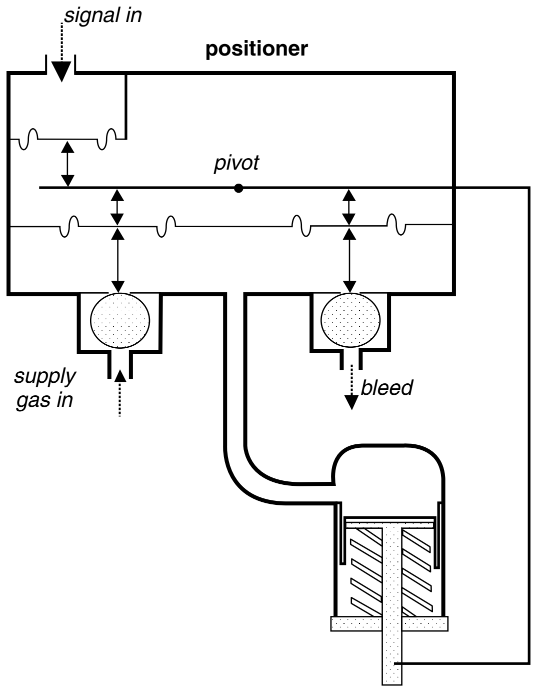

FIGURE 5.1.32 Schematic of a pneumatic positioner.

Of course, most actuators, valves, and dampers are subject to friction and sticking. This can be annoying if you are trying to obtain exact control of a process. To overcome this problem, many valves use a *positioner* to convert the pneumatic signal from the controller into the proper pressure sent to the actuator. Figure 5.1.32 shows the relation between an actuator and the positioner mechanics.

5.1.3 Steady State and Dynamic Processes

A process is basically a group of mechanical equipment in which something is put in that is changed or transformed somehow to produce an output. We are familiar with the action-reaction of processes from our every-day life experience, but to quantify these responses we need to put them in more mathematically rigorous terms. Many processes in a building will be at steady state, while others may be in a more-or-less constant state of change. Steady state processes are addressed first.

Steady State Operation

The true response of even the simplest function is actually quite complex. It is very difficult to identify and quantify every single input due to the stochastic nature of life. However, practically any process can be approximated by an equation which takes into account the known input variables and produces a reasonable likeness to the actual process output.

It is convenient to use differential equations to describe the behavior of processes. For this reason, the "complexity" of the function is denoted by the number of terms in the corresponding differential equation (i.e., the *order* or *degree* of the differential equation). In steady state analysis, we usually consider a step change in the control signal and observe the ensuing response. The following descriptions assume a step input to the function, as illustrated in Figure 5.1.33.

A step change such as this is highly unlikely in the field of HVAC controls and can be applied only to a digital event, such as a power supply being switched on or a relay being energized. Zero-order functions (also mostly theoretical) have a one-to-one correspondence to the input,

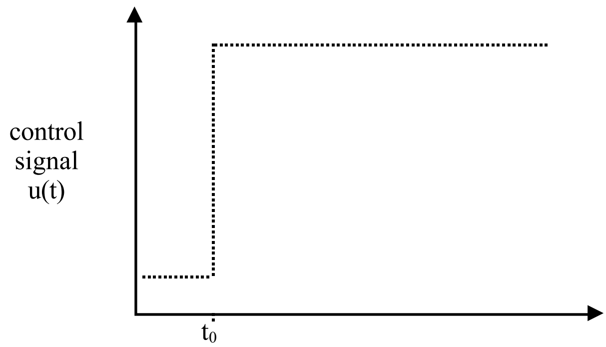

FIGURE 5.1.33 Step change function used in the explanations.

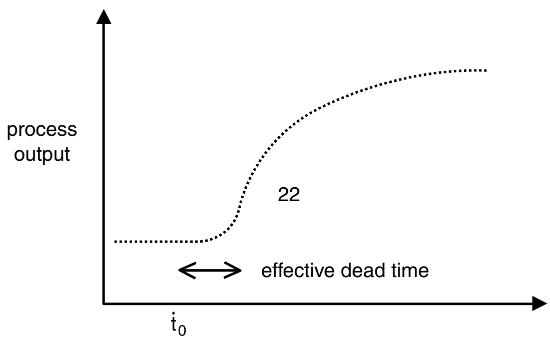

FIGURE 5.1.34 Response of second-order process to step change showing dead time.

$$y(t) = a_0 \cdot u(t)$$

First-order functions produce a curved line in the output with a step-change as input,

$$\frac{dy(t)}{dt} + a_1 \cdot y(t) = b_1 \cdot u(t)$$

and higher order functions produce lines with multiple curves.

The function that relates the process value to the controller input is called the *transfer function* of the process. The time between the application of the step change t_0 and the time at which the complete change in the process value has been achieved is called the *transfer period*. If there is a sufficient distance between the process output and the sensor, then you can observe the dead time during which the process is seemingly not affected by the control signal (see Figure 5.1.34).

The *process gain* (or *static gain* or *steady state gain*) is the ratio of the percentage change of the process to the percentage change of the control signal for a given response. The gain can be positive (as in a heating coil) or negative (as in a cooling coil).

To summarize, the transfer function of a process has several components: dead time, transfer function of the physical system, transfer period, and process gain.

Dynamic Response

In practice, very few processes are controlled in a steady-state fashion, i.e., by a series of step changes. Usually, the control signal is constantly modulating much like the way you constantly make small changes to the steering wheel of your car when driving down the highway. We now consider dynamic process changes by returning to buckets filled with water. Figure 5.1.35 shows two reservoirs of water connected by a thin tube. When water is added to the reservoir on the left, the water level in the reservoir on the

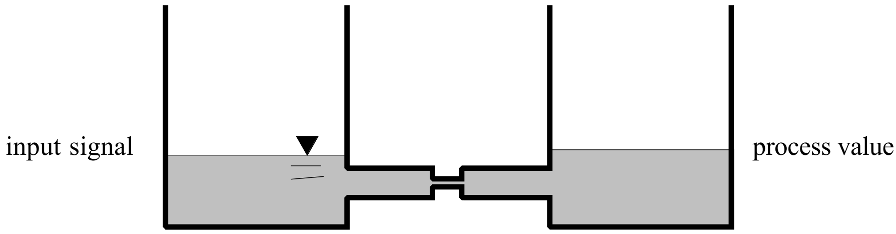

FIGURE 5.1.35 Example used in dynamic response explanation.

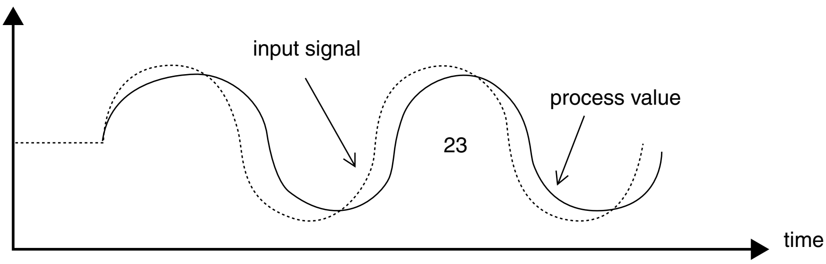

FIGURE 5.1.36 Dynamic response of water bucket example.

right will begin to rise, albeit slowly as the water must first pass through the thin constriction. In this sense, the level of water in the reservoir on the left can be considered the control signal that effects a process, i.e., the level of water on the right.

It is obvious that a step change in the control signal will bring about a first-order response of the process value. Suppose, however, that a periodic signal is applied to the level of the bucket on the left, that is, the water level increases and decreases at a constant time interval. If the frequency of the signal is small enough, we see a response in the level in the bucket on the right which varies as a function of this driving force, but with a delay and a small decrease in the amplitude, as shown in Figure 5.1.36.

Here the *dynamic process gain* is less than one even though the static process gain is 1. There is no dead time in this process; as soon as we begin to increase the control signal, the process value will also begin to increase. The dynamic process gain, therefore, can be defined similarly to that of the static gain — it is the ratio of the amplitude of the two signals, comparable to the normalized ranges used in the static gain definition.

The dynamic gain, as its name suggests, is truly dynamic. It changes not only according to the transfer function but also to the frequency of the control signal. As the frequency increases, the output lags even farther behind the input and the gain continues to decrease. At one point, the frequency may be exactly right to cancel any past effects of the input signal (i.e., the phase shift is 180°) and the dynamic gain approaches zero. If the frequency rises any higher, the process output may be decreasing as the control signal is increasing (this can easily be the case with a cooling or heating coil due to the mass effects) and the dynamic gain is negative.

5.1.4 Feedback Loops

In most houses, the furnace comes on based upon a relay activated in the thermostat. When the temperature falls below some user-set value, the furnace fires up and delivers heat to the space. This situation is an example of a feedback loop. Now, suppose the system designed knew the heat loss in the house as a function of the outdoor air temperature and the amount of heat that could be delivered by the furnace. In this case, the design may incorporate only the outside air temperature into the staging of the furnace. Such a situation is an example of feedforward control. This example illustrates the main differences between feedback and feedforward loops:

- Feedback loops use a direct measurement of the process under control.
- Feedforward (compensation) control measures the external disturbances and uses these values to control the process in anticipation of the process value.

The Control Loop

Recall that a control loop must have at least the following:

- An actuator that affects the process
- The process being controlled
- A sensor to measure the process value
- A controller that calculates the error and sends a signal to the actuator
- A setpoint input

The objective of the control loop is to maintain the process at the setpoint when

- The setpoint is changed
- The load on the process is changed
- The transfer function of the process is changed (e.g., clogged filters, fouled heat exchanged, degradation of equipment, and changes in the external disturbances)

In practice, most controllers look at three components of the error: the actual value of the error, the running sum of the error, and the change of error over time. Each of these components is multiplied by some gain, the products are summed, and the result is sent to the actuator.

Single feedback loops consist of one each of the elements of a control loop. This type of control can be applied to relatively simple control algorithms where the biggest disturbance is usually a load change, such as pressure and flow controls.

If a process consists of several subprocesses, each with a relatively different transfer function, it is often useful to use *cascaded control loops*. For example, consider a manufacturing line in which 100% outside air is used but which must also have very strict temperature control of the room air temperature. The room temperature is controlled by changing the position of a valve on a coil at the main air handling unit which feeds the zone. Typically, the time constant of the coil will be much smaller than the time constant of the room. A single feedback loop would probably result in poor control since there is so much dead time involved with both processes. The solution is to use two controllers: the first (the *master*) compares the room temperature to the thermostat setting and sends a signal to the second (the *slave*), which uses that signal as its own setpoint for controlling the coil valve. The slave controller measures the output of the coil, not the temperature of the room. The controller gain on the master can be set lower than that of the slave to prevent excessive cycling.

Sometimes control action is needed at more than one point in a process. The best example of this is an air-handling unit that contains both heating and cooling coils in order to maintain a fixed outlet air temperature no matter what the season is. Typically, a *sequential* (or *split range*) system in an air handling unit will have three temperature ranges of operation — the first for heating mode, the last for cooling mode, and a middle dead-band region where neither the cooling nor heating coils are operating. Most sequential loops are simply two different control loops acting off the same sensor. The term *sequential* refers to the fact that in most of these systems the components are in series in the air or water stream.

As noted earlier, feedforward loops (Figure 5.1.37) can be used when the effects of an external disturbance on a system are known. It can be useful to combine feedback and feedforward controllers in systems where the proper method for obtaining good control is, in part, to attack the problem at its root. An example of this is outside air temperature reset control used to modify supply air temperatures. The control loop contains both a discharge air temperature sensor (the *primary* sensor) and an outdoor air temperature sensor (the *compensation* sensor). The designer should have some idea about the influence of the outside temperature on the heating load and can then assign an *authority* to the effect of the

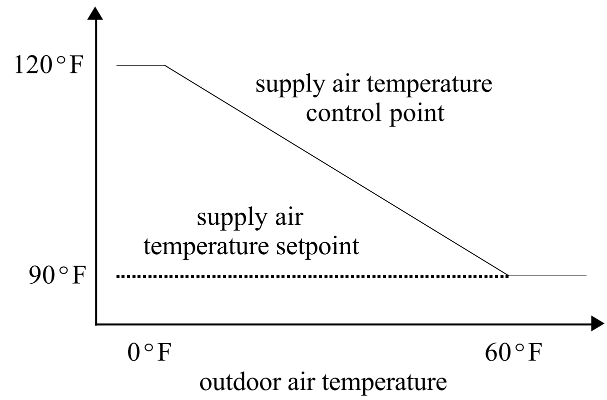

FIGURE 5.1.37 Example of feedforward control.

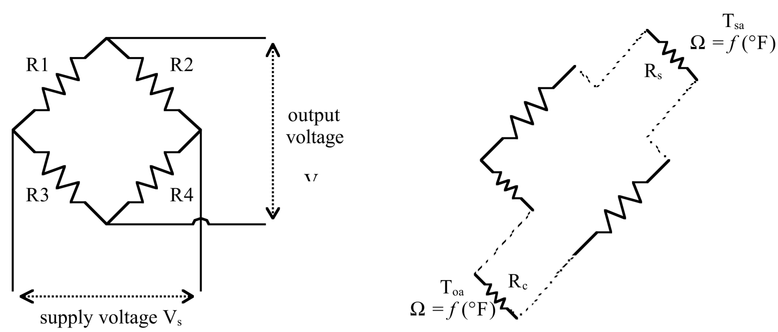

FIGURE 5.1.38 Bridge circuit used to bias the control point in feedforward loop example. Left shows standard bridge circuit; right shows location of outdoor and supply air temperature sensors.

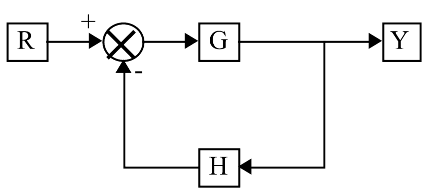

FIGURE 5.1.39 Block diagram of feedback loop.

outside air temperature on the controller setpoint. As the outdoor temperature increases, the control point decreases and vice versa.

The *authority* of each input can be defined using a bridge circuit (Figure 5.1.38).

If all resistances are equal, then $V_o = 0$. If R3 is the compensation resistor, R_c, plus some fixed resistors that bring the total up to approximately the discharge air sensor R2, and R1 and R4 are more or less the same as R2, then the authority of the compensation sensor is $R_c \div R2$.

Mathematical Representation of a Feedback Loop

For the purpose of analysis it is convenient to define a feedback loop mathematically. A general feedback loop is shown in Figure 5.1.39. The controller, actuator, and process have all been combined into the *forward transfer function* (or *open-loop transfer function*) **G** and the sensor and dead time have all been combined into the *feedback path* transfer function **H**. The *closed-loop transfer function* is defined as

$$\frac{Y}{R} = \frac{G}{1 + G \cdot H}$$

The right side of this equation is usually a fraction expressed in polynomials, in which case the roots of the numerator are called the "zeros" of the transfer function, and the roots of the denominator are called the "poles."

The denominator of the closed-loop transfer function, $1 + G \cdot H$, is called the *characteristic function.* Setting the characteristic function equal to zero gives the *characteristic equation*

$$1 + G \cdot H = 0$$

which can be used for determining the stability of the overall transfer function.

Sometimes it is necessary to express transfer functions in either the frequency or discrete time domains. Laplace and z-transforms are used, respectively, to do so.

Laplace Transforms **—** The transfer function of a closed-loop process is often written using Laplace transforms, a mapping of a continuous time function to the frequency domain and defined as

$$F(s) = \int_0^{\infty} f(t)e^{-st}dt$$

This formulation can greatly simplify problems involving ordinary differential equations that describe the behavior of systems. A transformed differential equation becomes a purely algebraic term that can be easily manipulated. The result needs to then be inverted back to the continuous time domain. The inverse Laplace transform is given by

$$f(t) = \frac{1}{2\pi j}\int_{\sigma - j\infty}^{\sigma + j\infty} F(s)e^{st}ds$$

where s is a real constant integer greater than the real part of any singularity of F(s).

If F(s) is the Laplace transform of f(t), then the Laplace transform of the n^{th} derivative of f(t) is

$$L\left\{\frac{d^n f}{dt^n}\right\} = s^n F(s) - s^{n-1}f(0^+) - s^{n-2}f(0^+) - \ldots - f^{n-1}f(0^+)$$

where $f(0^+)$ is the initial value of f(t) evaluated as $t \to 0$ from the positive region.

The Laplace transform of a time function f(t) delayed in time by T equals the Laplace transform of f(t) multiplied by e^{-sT}. This is applicable any time there is dead time between the process and the sensor. When investigating stability criteria, however, there are times when we wish to preserve the polynomial expression of the Laplace transform. For this reason, the time lag is often given by the Padé approximation:

$$e^{-sT} \approx \frac{2 - sT}{2 + sT}$$

If the Laplace transform of f(t) is F(s) and if there exists a limit of sF(s) as s goes to infinity, then the initial value of the time function is

$$\lim_{t \to 0} f(t) = \lim_{s \to \infty} sF(s)$$

Likewise, if sF(s) is analytic on the imaginary axis and in the right half-plane, then the final value of the time function is

$$\lim_{t \to \infty} f(t) = \lim_{s \to 0} sF(s)$$

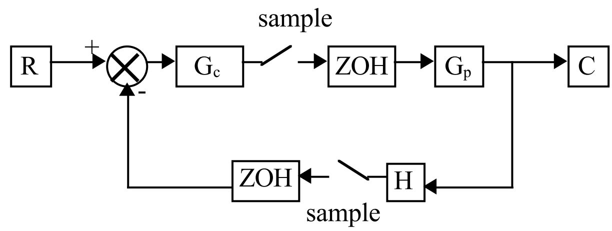

FIGURE 5.1.40 Feedback loop block diagram for discrete time controllers.

Example of Laplace Transform — Laplace transforms enable the calculations of complex differential equations to be reduced to algebraic manipulation. For example, consider a differential equation used to describe a process in the time domain:

$$\frac{d^n y}{dt^n} + a_1 \frac{d^{n-1} y}{dt^{n-1}} + a_2 \frac{d^{n-2} y}{dt^{n-2}} + \dots + a_{n-1} \frac{dy}{dt} + a_n y = b_0 \frac{d^m u}{dt^m} + b_1 \frac{d^{m-1} u}{dt^{m-1}} + \dots + b_{m-1} \frac{du}{dt} + b_m u$$

To express this relationship in the frequency domain, it is convenient to have a reference value as a constant offset and to use only the dynamic portion of the driving signal. This allows all but the first term of the Laplace transform of the derivative to be set to zero. The Laplace transform of the previous equation is then

$$s^n Y(s) + A_1 s^{n-1} Y(s) + \dots + A_{n-1} sY(s) + A_n Y(s) = B_0 s^m U(s) + B_1 s^{n-1} U(s) + \dots + B_{n-1} s U(s) + B_n U(s)$$

which can be rewritten as

$$Y(s)\cdot(s^n + A_1 s^{n-1} + \dots + A_{n-1} s + A_n) = U(s)\cdot(B_0 s^m + B_1 s^{n-1} + \dots + B_{n-1} s + B_n)$$

and the transfer function is found from

$$\frac{Y(s)}{U(s)} = \frac{s^m + B_1 s^{m-1} + \dots + B_{m-1} s + A_m}{s^n + A_1 s^{n-1} + \dots + A_{n-1} s + A_n}$$

Z-Transforms — A significant number of HVAC control applications are accomplished by computers and digital control systems. In such systems, the sampling is not continuous as required for something like a Laplace transform. The control loop schematic looks similar to Figure 5.1.40.

It would be prohibitively expensive to include a voltmeter or ohmmeter on each loop, so the controller employs what is called a *zero-order hold*. This basically means that the value read by the controller is "latched" until the next value is read. This discrete view of the world precludes the use of Laplace transforms for analyses, and it is therefore necessary to find some other means of simplifying the simulation of processes and controllers. The z-transform is used for this purpose.

Recall that the Laplace transform is given as

$$L\{f(t)\} = \int_0^{\infty} f(t)e^{-st}dt$$

Now suppose a process is sampled at a discrete, constant interval T. The index k will be used to describe the number of the interval, that is,

at time $t = 0$, $k = 0$,
at time $t = T$, $k = 1$,
at time $t = 2T$, $k = 2$,
at time $t = 3T$, $k = 3$,

and so forth. The equivalent Laplace transform of a process that is sampled at a constant interval T can be represented as

$$L\{f^*(t)\} = \sum_{k=0}^{\infty} f(kT)e^{-s \cdot kT}$$

By substituting the *backward-shift operator* z for e^{Ts} we get the definition of the z-transform:

$$Z\{f(t)\} = \sum_{k=0}^{\infty} f(kT)z^{-k}$$

Example of Using the Discrete Time Domain — The conversion from the continuous time domain to the discrete time domain is best seen through example. Consider a process described by

$$y(k) = a_1 y(k-1) + a_2 y(k-2) + a_3 y(k-3) + \ldots$$
$$+ b_1 u(k-1) + b_2 u(k-2) + b_3 u(k-3) + \ldots$$

The equivalent z-transform is given by

$$y(1 - a_1 z^{-1} - a_2 z^{-2} - a_3^{z-3} + \ldots) = u(b_1 z^{-1} - b_2 z^{-2} - b_3 z^{-3} + \ldots)$$

and the transfer function can now be found as

$$\frac{y}{u} = \frac{b_1 z^{-1} - b_2 z^{-2} - b_3 z^{-3} + \ldots}{1 - a_1 z^{-1} - a_2 z^{-2} - a_3 z^{-3} + \ldots}$$

Table 5.1.2 lists some of the more common transforms used in the analysis of building systems. More extensive tables can be found in most mathematics and numerical analysis reference books.

5.1.5 Controllers

Controllers are like processes in that they have gains and transfer functions. Generally, there is no dead time in a controller, or it is so small as to be negligible. Recall that the process static gain can be viewed as the total change in the process value due to a 100% change in the controller output. A proportional controller acts like a multiplier between an *error signal* and this process gain. Under stable conditions, therefore, there must be some kind of error to yield any controller output. This is called the steady state or static offset.

Ideally, a controller gain is chosen that compensates for the dynamic gain of the process under normal operating conditions. The total loop dynamic gain can be considered as the product of the process, feedback, and controller gains. If the total dynamic loop gain is one, the process will oscillate continuously at the natural frequency of the loop with no change in amplitude of the process value. If the loop gain is greater than one, the amplitude will increase with each cycle until the limits of the controller or process are reached, or something breaks. If the dynamic loop gain is less than one, the process will eventually settle into stable control.

The *controller bias* is a constant offset applied to the controller output. It is the output of the controller if the error is zero, $u = K \cdot e + M$, where M is the bias. This is useful for processes that become nonlinear at the extremes.

PID Control

Most control systems in HVAC processes use proportional-integral-derivative (PID) control where the controller output is given by

$$\text{Control output} = K_p \cdot [\text{error} + K_i \cdot \text{integral of error} + K_d \cdot \text{derivative of error}]$$

where K_p, K_i, and K_d are the controller gains.

TABLE 5.1.2 List of Some S- and Z-Transforms

Continuous Time Domain	Frequency Domain	Discrete Time Domain
1 $t = 0$ 0 $t \neq 0$	n/a	1
1 $t = k$ 0 $t \neq k$	n/a	z^{-k}
1	$\frac{1}{s}$	$\frac{z}{z-1}$
t	$\frac{1}{s^2}$	$\frac{Tz}{(z-1)^2}$
e^{-at}	$\frac{1}{(s+a)^2}$	$\frac{z}{z-e^{-aT}}$
$t\,e^{-at}$	$\frac{1}{s+a}$	$\frac{Tze^{-aT}}{(z-e^{-aT})^2}$
$1 - e^{-at}$	$\frac{a}{s(s+a)}$	$\frac{z(1-e^{-aT})}{(z-1)(z-e^{-aT})}$
$e^{-at} - e^{-bt}$	$\frac{b-a}{(s+a)(s+b)}$	$\frac{z(e^{-aT}-e^{-bT})}{(z-e^{-aT})(z-e^{-bT})}$

Proportional control action is the amount that the controller output changes for a given error. The proportional term, $K_p \cdot e$, has the greatest effect when the process value is far from the desired setpoint. Very large values of K_p will tend to force the system into oscillatory response. The proportional gain effect of the controller goes to zero as the process approaches setpoint. Purely proportional control should therefore be used only when (1) the time constant of the process is small so a large controller gain can be used, (2) the process load changes are relatively small so that the offset is limited, and (3) the offset is within an acceptable range.

Integral action is the rate at which the controller output changes for a given error sum. The integral term K_i is the reciprocal of the reset time, T_r, of the system. Integral control is used to cancel any steady state offsets that would occur using purely proportional control. This is sometimes called *reset* control.

Derivative action is the amount that the controller output changes for a given rate of change of the error. Derivative control is typically used in cases where there is a large time lag between the controlled device and the sensor used for the feedback. This term has the overall effect of preventing the actuator signal from going too far in one direction or another and can be used to limit excessive overshoot.

PID Controller in the Time Domain — The PID controller can be represented in a variety of ways. In the time domain, the controller output is given by

$$u(t) = K_p\left[e(t) + K_i\int_0^t e(t)dt + K_d\frac{de(t)}{dt}\right]$$

PID Controller in the Frequency Domain — It is relatively straightforward to derive the Laplace transform of the time domain PID equation. Recall that the Laplace transforms for the integral and derivative of a function are

$$L\left[\int_0^t f(u)du\right] = \frac{F(s)}{s} \qquad \text{and} \qquad L\left[\frac{df(t)}{dt}\right] = sF(s) - f(0)$$

The output of the PID controller can therefore be expressed as

$$U(s) = K_p\left\{E(s) + K_i\frac{E(s)}{s} + K_d[sE(s) - e(t_0)]\right\}$$

Note that we are using upper case letters for s-domain functions. If we assume that the error at time $t = t_0$ is zero (before any perturbations), this equation is equivalent to

$$U(s) = E(s)\left[K_p + \frac{K_pK_i}{s} + K_pK_ds\right]$$

and the transfer function of the controller is therefore

$$\frac{U(s)}{E(s)} = \left[K_p + \frac{K_pK_i}{s} + K_pK_ds\right]$$

PID Controller in the Z-Domain — If the data is measured discretely at time intervals Δt, the PID controller can be represented by

$$u(k) = K_p\left[e(k) + K_i\Delta t\sum_{i=0}^{k} e(i) + K_d\frac{e(k) - e(k-1)}{\Delta t}\right]$$

The change of the output from one time step to the next is given by $u(k) - u(k-1)$, so the PID *difference equation* looks like this:

$$u(k) - u(k-1) = K_p\left[\left(1 + \frac{K_d}{\Delta t}\right)e(k) + \left(K_i\Delta t - 1 - 2\frac{K_d}{\Delta t}\right)e(k-1) + \left(\frac{K_d}{\Delta t}\right)e(k-2)\right]$$

which simplifies as

$$u(k) - u(k-1) = q_0e(k) + q_1e(k-1) + q_2e(k-2)$$

where

$$q_0 = K_p\left(1 + \frac{K_d}{\Delta t}\right); \qquad q_1 = K_p\left(K_i\Delta t - 1 - 2\frac{K_d}{\Delta t}\right); \qquad q_2 = K_p\left(\frac{K_d}{\Delta t}\right)$$

The difference equation can then be written as

$$u(1 - z^{-1}) = e(q_0 + q_1z^{-1} + q_2z^{-2})$$

and the z-domain transfer function of the PID controller is therefore

$$\frac{u(z)}{e(z)} = \frac{q_0 + q_1z^{-1} + q_2z^{-2}}{1 - z^{-1}} = \frac{q_0z^2 + q_1z + q_2}{z^2 - z}$$

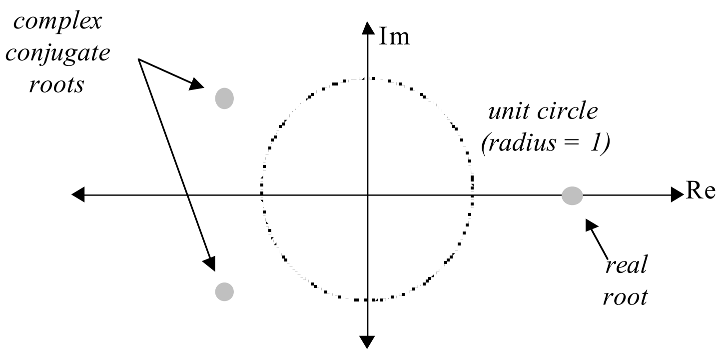

FIGURE 5.1.41 Plotting the roots of the characteristic equation.

5.1.6 Stability of Feedback Loops

Obviously, in HVAC feedback control one wishes to reduce the error. Control systems engineers can use different cost functions in the analysis of a given controller depending on the criteria for the controlled process. Some of these cost functions (or *performance indices*) are listed below:

ISE	integral of the square of the error	$\int e^2$
ITSE	integral of the time and the square of the error	$\int te^2$
ISTAE	integral of the square of the time and the absolute error	$\int t^2\|e\|$
ISTSE	integral of the square of the time and the square of the error	$\int t^2 e^2$

Stability in a feedback loop means that the feedback loop will tend to converge on a value as opposed to exhibiting steady state oscillations or divergence. Recall that the closed loop transfer function is given by

$$\frac{Y}{R} = \frac{G}{1 + GH}$$

and that the denominator, 1 + GH, is called the characteristic equation. Typically, this equation will be a polynomial in s or z depending on the method of analysis of the feedback loop. Two necessary conditions for stability are that all powers of s or z must be present in the characteristic equation from zero to the highest order, and all coefficients in the characteristic equation must have the same sign.

The roots of the characteristic equation play an important role in determining the stability of a process. These roots can be real and/or imaginary and can be plotted as shown in Figure 5.1.41. In the s-domain, if all the roots are in the left-hand plane (i.e., to the left of the imaginary axis), then the feedback loop is guaranteed to be asymptotically stable and will converge. If one or more roots are in the right-hand plane, then the process is unstable. If one or more roots lie on the imaginary axis and none are in the right-hand plane, then the process is considered to be marginally stable. In the z-domain, if all the roots lie within the unit circle about the origin, then the feedback loop is asymptotically stable and will converge. If one or more roots lie outside the unit circle, then the process is unstable. If one or more roots lie on the unit circle and none are outside the unit circle, then the process is marginally stable.

Routh-Hurwitz Criteria — The Routh-Hurwitz method is a tabular manipulation of the characteristic equation. If the characteristic equation is given by

$$a_0 s^n + a_1 s^{n-1} + \ldots + a_{n-1} s + a_n = 0$$

then the Routh-Hurwitz method constructs a table as follows:

$$\begin{array}{lllll} s^n & a_0 & a_2 & a_4 & \dots \\ s^{n-1} & a_1 & a_3 & a_5 & \dots \\ s^{n-2} & X_1 & X_2 & X_3 & \dots \\ s^{n-3} & Y_1 & Y_2 & Y_3 & \dots \\ : & : & : & : & : \end{array}$$

where

$$X_1 = \frac{a_1a_2 - a_0a_3}{a_1}; \qquad X_2 = \frac{a_1a_4 - a_0a_5}{a_1}; \qquad X_3 = \frac{a_1a_6 - a_0a_7}{a_1} \dots$$

$$Y_1 = \frac{X_1a_3 - a_1X_2}{X_1}; \qquad Y_2 = \frac{X_1a_5 - a_1X_3}{X_1} \dots$$

and so forth. Now consider the first column of coefficients. The number of roots in the right-hand plane is equal to the number of sign changes in the first column. In other words, if all the elements in the first column have the same sign, then there are no roots in the right-hand plane and the process is stable. A few considerations about the Routh-Hurwitz method:

- If the first element of any row is zero but the remaining elements are not, then use some small value ε and interpret the final column results as $\varepsilon \to 0$.
- If one of the rows before the final row is entirely zeros, then (1) there is at least one pair of real roots of equal magnitude but opposite signs, or (2) there is at least one pair of imaginary roots that lie on the imaginary axis, or (3) there are complex roots symmetric about the origin.

Tuning Feedback Loops — One method of obtaining the desired critically damped response of HVAC processes is to determine the closed-loop transfer function in the form

$$\frac{Y}{R} = \frac{(s + A_1)(s + A_2)\dots(s + A_m)}{(s + B_1)(s + B_2)\dots(s + B_n)}$$

The coefficients A and B depend on both the process characteristics and the controller gains. The objective of pole-zero cancellation is to find values for the controller gains that will set some numerator coefficients equal to those in the denominator, effectively canceling terms. As can be imagined, however, this can be a very difficult process, particularly when working with complex roots of the equations. This method is typically used only with very simple system models.

Often it is more convenient to test a feedback loop *in situ*. The *reaction curve technique* has been developed which allows one to field tune PID constants using open-loop response to a step change in the controller output. Consider the process response shown in Figure 5.1.42 where Δc is the change of process output, Δu is the change of controller, L is the time between change and intersection, and T is the time between lower intersection and upper intersection. We can define the following variables:

$$A = \Delta u \div \Delta c, \qquad B = T \div L, \qquad \text{and} \qquad R = L \div T$$

which can be used with the values in Table 5.1.3 to estimate "decent" control constants.

The *ultimate frequency* test involves increasing the proportional gain of a process until it begins steady state oscillations. K^*_p is defined as the proportional gain that results in steady oscillations of the controlled system, and T^* is the period of the oscillations. The desired controller gains are given in Table 5.1.4.

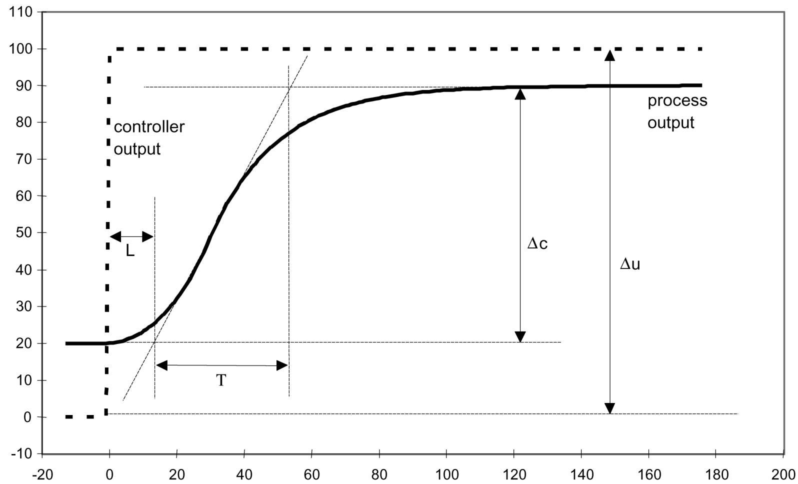

FIGURE 5.1.42 Response of process to step change in controller output.

TABLE 5.1.3 Recommended Control Constants from Reaction Curve Tests

Controller Components	Zeigler-Nichols			Cohen and Coontz		
	K_p	$\frac{K_p}{K_i}$	$\frac{K_d}{K_p}$	K_p	$\frac{K_p}{K_i}$	$\frac{K_d}{K_p}$
P	AB	—	—	$AB\left(1+\frac{R}{3}\right)$	—	—
P + I	0.9AB	3.3L	—	$AB\left(1.1+\frac{R}{12}\right)$	$L\frac{30+3R}{9+20R}$	—
P + D	—	—	—	$AB\left(1.25+\frac{R}{6}\right)$	—	$L\frac{6-2R}{22+3R}$
P + I + D	1.2AB	2L	0.5L	$AB\left(1.33+\frac{R}{4}\right)$	$L\frac{32+6R}{13+8R}$	$L\frac{4}{11+2R}$

TABLE 5.1.4 Recommended Control Constants from Ultimate Frequency Tests

Controller Components	K_p	$\frac{K_p}{K_i}$	$\frac{K_d}{K_p}$
P	$0.5\ K_p^*$	—	—
P + I	$0.45\ K_p^*$	$0.8T^*$	—
P + I + D	$0.6\ K_p^*$	$0.5T^*$	$0.125T^*$

5.1.7 Control Diagrams

Line diagrams are pictorial representations of components of a control loop. These schematics are useful for presenting information about subsystems or simple control diagrams. Figure 5.1.43 shows an example control line diagram for a motor starter. When starting a large motor, it is desirable to minimize the initial current draw. This circuit in the diagram is a *wye-delta* starter, common in many large motors. At start-up, the relays 1S and 1M1 are energized and the motor windings are energized in a wye configuration. This allows the motor to start with low voltage and current draw. After an acceleration period, relay 1A

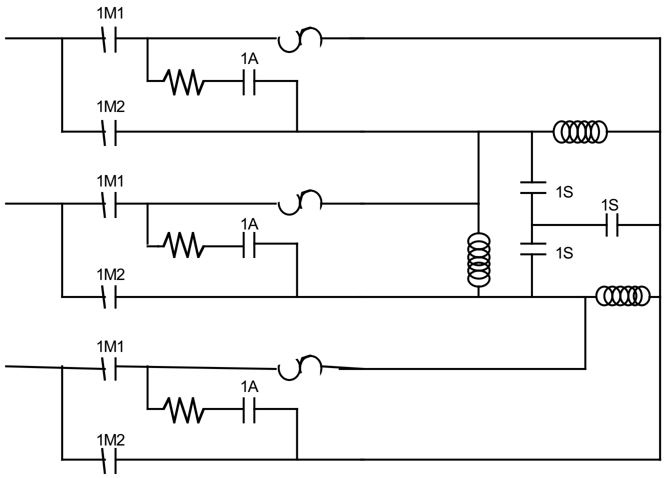

FIGURE 5.1.43 Control line diagram for a motor starter.

is energized allowing current to be shunted across the resistors, then 1S is de-energized, 1M2 is energized, and the motor is running in a delta configuration.

Ladder diagrams are used frequently to describe the logic flow of complex control systems. Figure 5.1.44 shows a ladder diagram for the start-up and safety features of a chiller and condenser combination. Each of the rungs of the ladder is labeled to indicate the function of that rung.

5.1.8 Control of Air Distribution Systems

In larger buildings, air handlers are used to push air through ductwork until it arrives at zones that need to be conditioned. The zones use their own equipment to provide localized heating or cooling to meet the thermostat setpoint. To ensure that there is sufficient air pressure at the zones to provide adequate control and air circulation, the pressure in the supply air ducts is usually controlled to a fixed setpoint. The supply air duct static pressure is typically measured at a point about 75% of the total duct length downstream from the fan, although some researchers have indicated that this is not the ideal location (Figure 5.1.45). The pressure in the supply duct will be controlled to between 3 and 20 in of equivalent water pressure depending on the building size. In optimal control, the duct pressure setpoint will be dynamically adjusted to ensure that at least one terminal box supply air damper is fully open. That is, the duct pressure will be set to the minimum value allowed by the zone or zones with the maximum supply air demand.

Supply fans usually control to maintain duct static pressure with a high-limit cutout safety. Return fans are controlled as either speed tracking (open loop), direct building static (reset to zero when no OA), air flow tracking (requires air flow sensor), or return duct static pressure. Relief fans are used to control direct building static pressure or to track the amount of outside air brought into the building.

Most buildings are pressurized, which helps control infiltration and dirt intake. The pressure rise across the fan is controlled using inlet vanes or outlet dampers. Certain zones are depressurized, such as laboratories and zones under *smoke evacuation mode*. With these strategies, the exhaust fan tracks above the supply fan to guarantee a net loss of conditioned air from a zone.

There are several different ways to vary the pressure rise across a fan. *Outlet dampers* restrict the air leaving the fan, while *inlet vanes* restrict the air entering the fan and can also "pre-swirl" the air to improve fan efficiency. *Variable frequency drives* (VFDs or sometimes *variable speed drives*, *VSDs*) change the actual speed of the motor by decomposing the standard 50 or 60 Hz signal and rebuilding it at a desired frequency through a process called *pulse width modulation*. Since the motor is not operating at the design frequency,

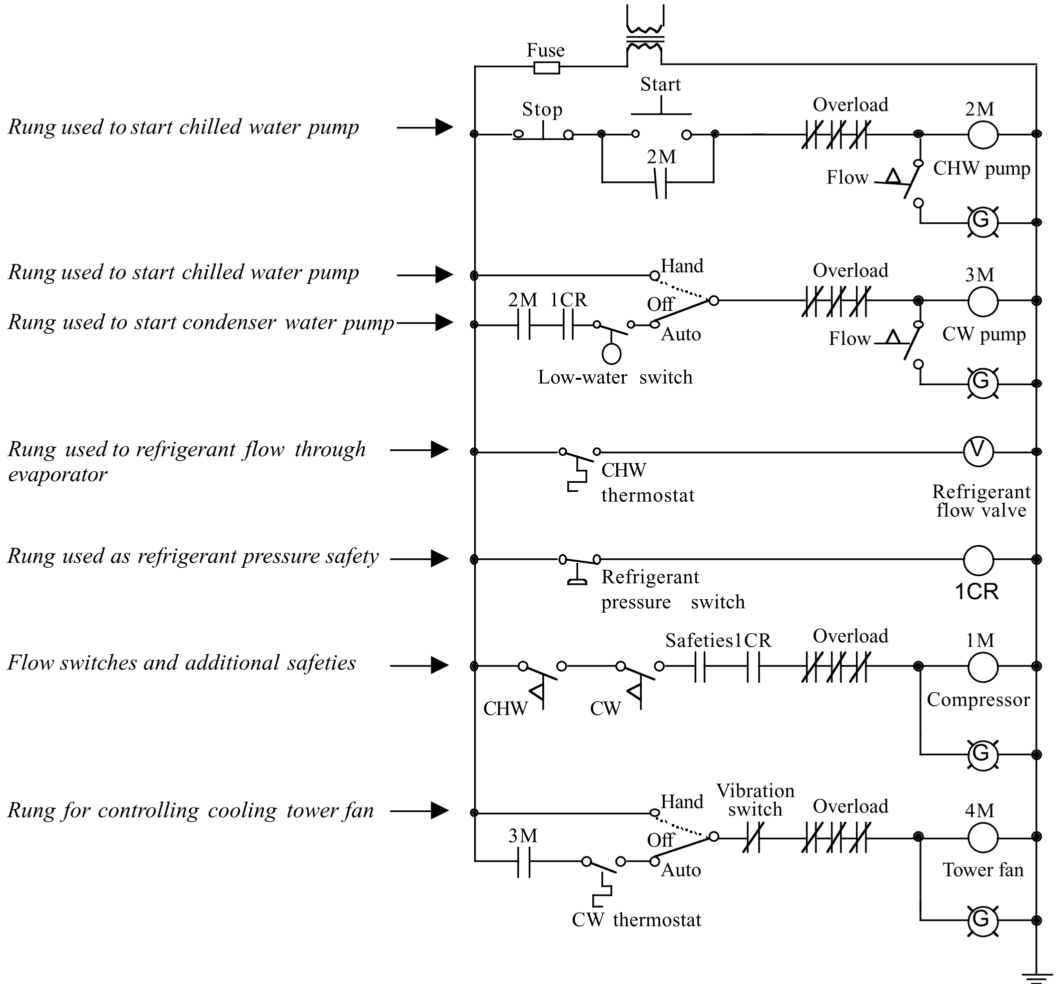

FIGURE 5.1.44 Ladder diagram showing chiller start-up sequence.

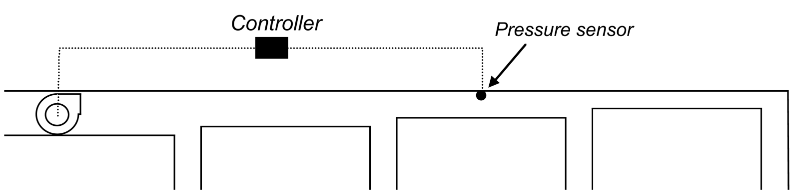

FIGURE 5.1.45 Supply air duct showing location of static pressure sensor.

however, there may be certain frequencies that cause undue vibration or harmonics in the fan. Most VFDs have *critical speed step-over* circuits that are adjustable ranges that can be locked out to avoid any resonant speeds. Two step-over ranges of individually adjustable width will be sufficient for nearly all applications. Figure 5.1.46 shows the location of each of these methods of pressure modulation.

Figure 5.1.47 shows the principle behind the operation of a variable frequency drive. The standard line frequency (left) is decomposed and then used to generate a series of impulses that "blend together" to create a new periodic wave at a different frequency. Figure 5.1.47 shows how 60 Hz power is converted to a 40 Hz signal.

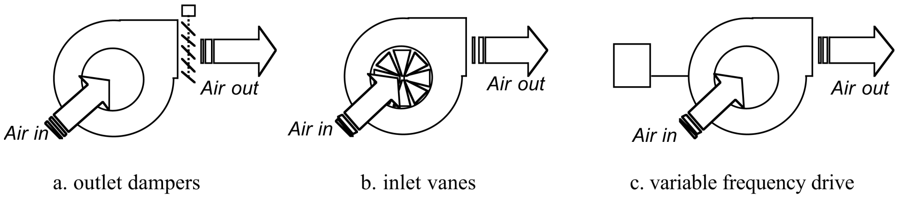

FIGURE 5.1.46 Different methods of fan pressure modulation.

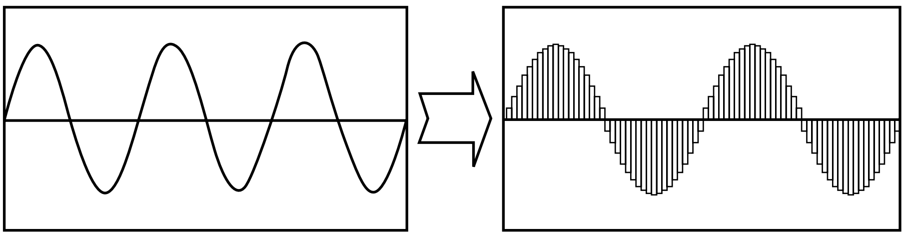

FIGURE 5.1.47 Variable frequency modulation.

Terminal Box Control

The terminal box provides the endpoint control of the zone temperature. It is connected to the local thermostat or central control system and provides the fine adjustment of the local temperature (see Figure 5.1.48). Terminal boxes can have many different configurations, including induced air return from the plenum, reheat coils (usually only in perimeter zones), and fans to pull air in from the plenum. In the case of fan-powered mixing boxes with reheat, the control of the boxes is similar to that shown in Figure 5.1.49. The damper closes as the room cools until it reaches a minimum value allowed for indoor air quality. The fan and heaters come on in succession to provide recirculation and heating of room air, respectively.

Air Temperature Control

The supply air temperature in a single-deck system is usually maintained at about 50 to 60°F. One controller can be used to modulate both the CHW and HW valves on the air handler. Valves on the chilled and hot water coils are modulated to maintain the air setpoint temperature (see Figure 5.1.50). If the outdoor air is below 32°C, then a preheat coil might be activated to prevent water in the cooling or heating coils from freezing.

If the outdoor air temperature is close to the desired supply air temperature, then the exhaust and outdoor air dampers are fully opened and the return air damper is completely closed, as shown in Figure 5.1.51. Under these conditions, 100% outside air enters the building and the chiller can be shut off because there is no need for cooling the air. This is called *economizer mode*. Strictly speaking, the economizer mode should be used whenever the enthalpy difference between the outdoor air and the supply air is less than the enthalpy difference between the return air and the supply air. However, it is difficult to measure enthalpy, so usually only the air temperatures are used.

A similar damper configuration is used at night to cool a building mass in preparation for the next day's cooling load. This is called *night purging*. The idea with night purging is to precool the building so the peak cooling loads the next day are reduced. However, in some very humid locations it is claimed that the introduction of humid air into the building leads to the absorption of water by the interior building materials, office paper, etc. and that this can actually lead to an increase in the latent load during the next day.

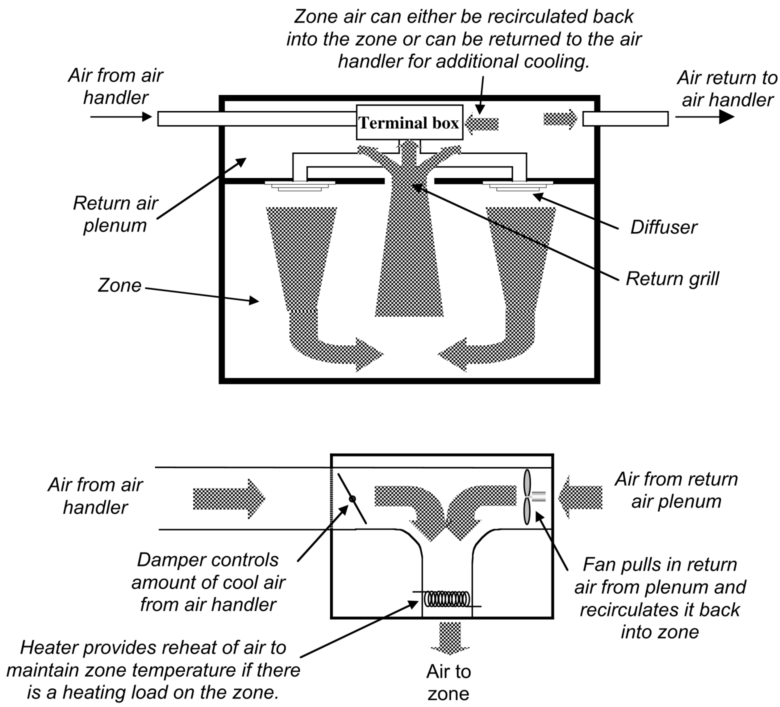

FIGURE 5.1.48 Components of terminal boxes.

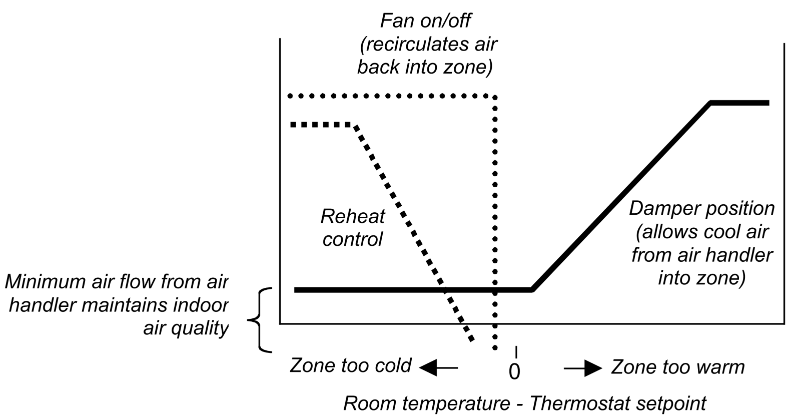

FIGURE 5.1.49 Typical control of fan-powered terminal box.

5.1.9 Control of Water Distribution Systems

Water distribution systems are the combination of pumps, pipes, and other apparatus that move hot and chilled water throughout a building. The control schemes implemented in water distribution systems must maintain controllable pressure across control valves, maintain required flow through a heating or cooling source, maintain desired water temperature to terminal units, maintain minimum flow through pumps, properly stage multipump systems, and prevent cavitation in pumps.

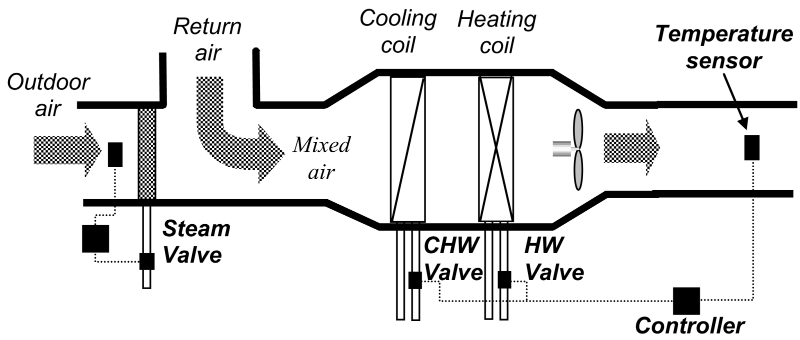

FIGURE 5.1.50 Typical air handler showing preheat, cooling, and reheat coils.

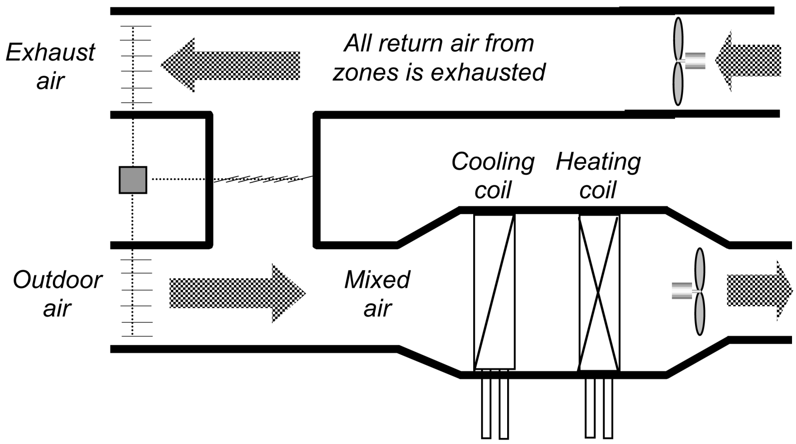

FIGURE 5.1.51 Air handler showing dampers in economizer mode.

Water flows in HVAC systems are controlled through valves. Valves have many different arrangements, depending on the needs and function of the system. Three typical valve types are shown in Figure 5.1.52.

Linear valves are good for steam flow because the steam is at a constant temperature, and the latent heat of condensation is uniform with the change of pressure. Equal percentage valves are good for cooling and heating coils because the combination of the typical coil with an equal percentage valve provides effectively linear control of the coil heating or cooling. When multiple valves are installed in a system, some will be responsible for causing greater pressure drops in the system than others. The *authority* of a valve is the ratio of the valve pressure drop to the total system pressure drop.

While, ideally, a valve will exhibit linear behavior even at very low flows, it is more likely that there is a significant step change in the flow when the valve plug first separates from the seal. The actual minimum flow when a valve is cracked open is about 3 to 5% of maximum possible flow. This value is known as the *turndown ratio*. A typical commercial valve might have a turndown ratio of 5% (20:1), while industrial process control valves may have a turndown ratio of 50:1 to 100:1. Such fine precision, however, is generally not needed in HVAC applications.

The actual flow rate through a valve is determined by the *flow coefficient*, C_v, which is the number of gallons per minute of 60°F water that will flow through the valve with a pressure drop of 1 psi when the valve is fully open. The flow under any other condition can be found from $GPM = C_v \cdot \Delta P^{0.5}$ where ΔP is the pressure drop across the valve.

Often a valve's purpose is not only to shut off the flow but to redirect flow from one pipe to another. This is accomplished through *three-way mixing and diverting valves*. The two types of valves are constructed differently as shown in Figure 5.1.53, so they should not be used interchangeably. Mixing and

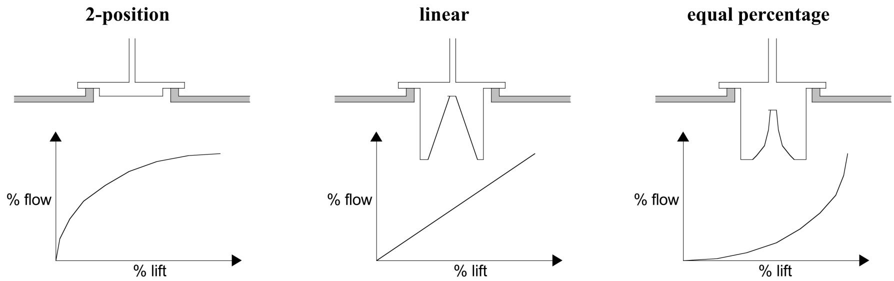

FIGURE 5.1.52 Valve configurations and corresponding flow versus lift charts.

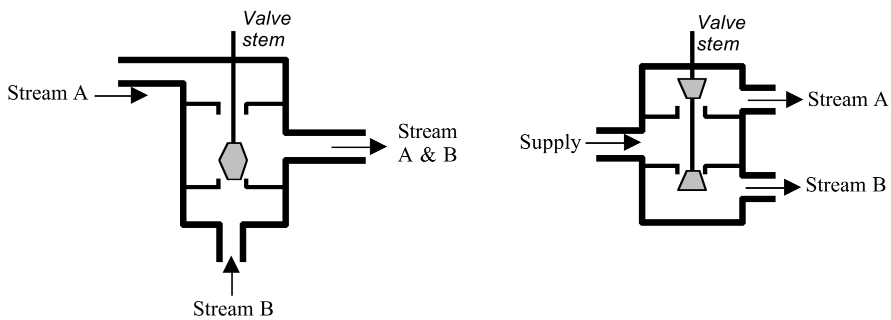

FIGURE 5.1.53 Schematics of three-way mixing (left) and diverting (right) valves.

diverting valves are particularly useful on coils because it allows the flow to remain relatively constant through a particular water loop branch over the operating range of the coil. This helps maintain the water distribution system pressure at a fixed value. A *balancing valve* is used to make the pressure drop through the bypass loop similar to the pressure drop through the coil.

Water Temperature and Pressure Control

Most water distribution systems use a primary/secondary loop configuration as shown in Figure 5.1.54. In such a system, the primary loop is often used to obtain gross control of the water temperature, and the valve to the secondary loop is used to maintain more precise temperature control of the distributed water.

The pressure across the supply and return lines of a water distribution system must be maintained above a minimum threshold in order for the control valves in that system to work properly. Consider the extreme: if there were no pressure drop in the system (i.e., no water flow), the valves would do absolutely nothing. The problem is compounded if three-way valves are not used on the system and the pressure control must be accomplished through other means. One way to aid the maintenance of a minimum pressure drop across the system is to use reverse-return plumbing. Compared with a direct return system, the reverse-return provides for a roughly equal pressure drop across all loads. In large systems, however, the extra capital cost of the piping may need to be considered. Figure 5.1.55 illustrates direct and reverse return piping.

With a fixed-speed pump and widely varying loads with two-way valves, a pressure drop across the water distribution supply and return can be maintained using a bypass valve controlled by a differential pressure sensor (Figure 5.1.56). Care must be taken when choosing the gains for the control loop, however, since water is not compressible and small changes in the valve position can lead to large changes in the system pressure drop.

In a variable-flow system (Figure 5.1.57), the pump speed is varied to maintain a fixed pressure drop across the supply and return branches. As with the bypass loop, however, care must be taken not to set the control loop gains too high because excessive system pressure oscillations can occur rapidly.

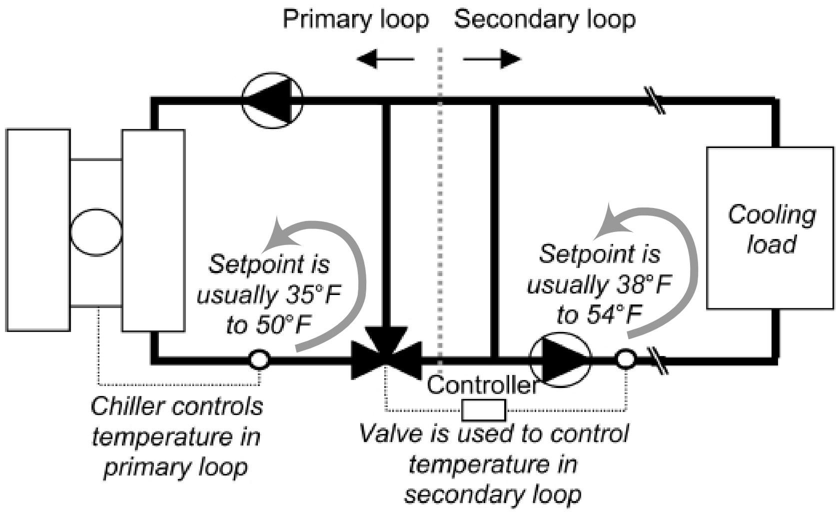

FIGURE 5.1.54 Schematic of chilled water primary and secondary loops.

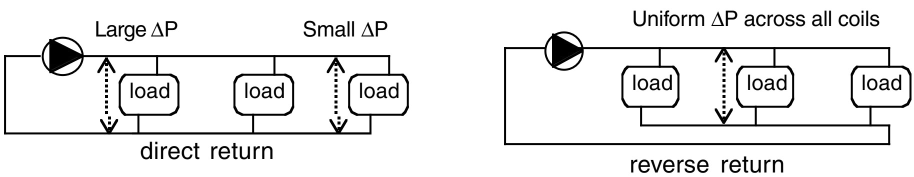

FIGURE 5.1.55 Direct and reverse return piping schematics.

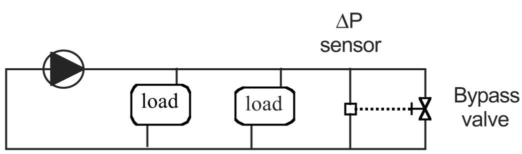

FIGURE 5.1.56 Flow bypass sensor position.

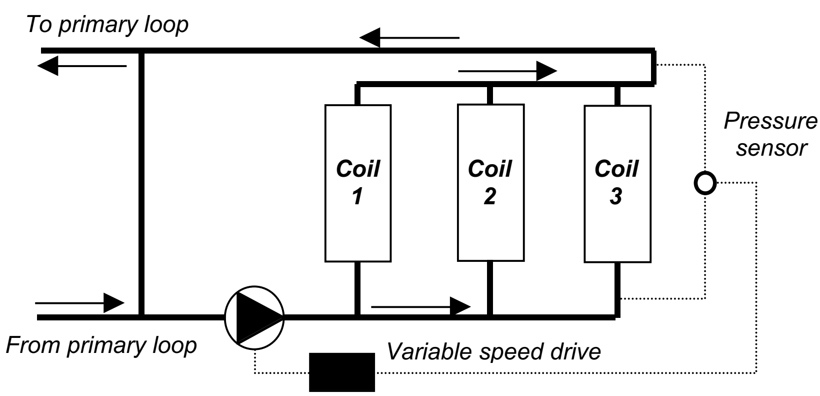

FIGURE 5.1.57 Variable flow water distribution system showing location of a pressure sensor.

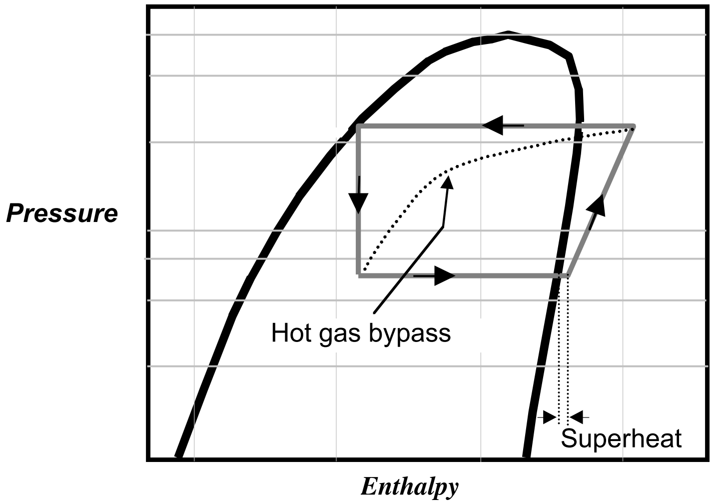

FIGURE 5.1.58 Pressure-enthalpy diagram showing superheat and hot gas bypass.

5.1.10 Control of Chillers

Chillers are used to cool water or air by means of a vapor compression cycle. Methods for modulating the capacity of a chiller depend on the type of compressor used in the cycle.

A *centrifugal* compressor acts like a water pump. Refrigerant enters the compressor and is subject to the centrifugal forces of an impeller, increasing both the velocity and the pressure of the refrigerant. Centrifugal compressors can also use inlet vanes to preswirl the refrigerant or to impede the refrigerant flow. The chiller controller operates a pneumatic or electric actuator to reposition the inlet vanes as a function of the chiller water temperature. If speed control is available, the controller sequences the motor or rotor speed with the position of the inlet vanes.

A *reciprocating* compressor behaves like a car engine in reverse. Refrigerant enters the cylinders and is compressed by pistons that are driven from a central shaft. Valves at the top of the cylinders allow the refrigerant to enter or leave the cylinders at the proper stages of the cycle. To reduce the capacity of the chiller, some of the valves are forced open so that no compression takes place. These types of compressors, therefore, have very distinct operating capacities (for example, 0, 25%, 50%, 75%, and 100% of rated peak capacity)

A *screw-type* compressor forces the refrigerant into a series of interlocking screws. The farther along the meshing screws the refrigerant travels, the greater the compression. Modulation of capacity occurs with a pneumatic or electric actuator used to position a sliding bypass valve. The valve allows refrigerant to leave the mesh at various points along the screws. As a result, these kinds of compressors have good modulating characteristics.

With all types of compressors, it is desirable to have only gaseous refrigerant enter the compressor. Liquid refrigerant in the compressor cannot be compressed and can cause pitting of the compressor surfaces. To avoid this *slugging* of the compressor, chillers usually operate with some amount of *superheat* where the evaporator outlet temperature is slightly outside the saturation curve. A typical value for superheat is about 5 to 10°F, meaning that the refrigerant is 5 to 10°F above the saturation temperature at the compressor inlet pressure. The thermal expansion valve on a chiller is often controlled to maintain the superheat setpoint.

Hot gas bypass is sometimes used to modulate the capacity of reciprocating chillers. A solenoid valve is used to let hot refrigerant flow directly from the compressor outlet back into the evaporator inlet. Figure 5.1.58 shows both the superheat and hot gas bypass processes on a pressure-enthalpy diagram.

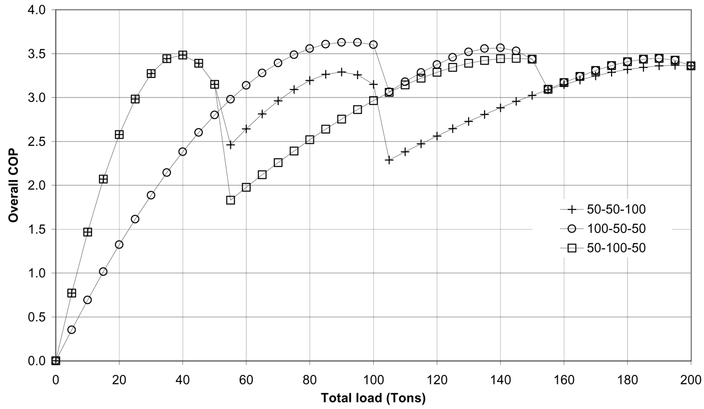

FIGURE 5.1.59 Total cooling plant COP as a function of cooling load and different chiller staging orders.

Most chillers are operated on a primary/secondary distribution loop system which guarantees flow through the evaporator barrel and insures against freezing. There are a number of other safety controls on a chiller designed to protect it from freezing or high refrigerant pressures. Some of these safeties are listed here. Most if not all of these safeties will cause the chiller to shut off and will not reset automatically; human intervention is usually required.

- High condenser pressure
- Low refrigerant pressure or temperature
- High motor temperature
- Motor current overload
- Low oil sump temperature
- High oil sump temperature
- Evaporator water flow interlock
- Condenser water flow interlock

Large buildings may have several chillers of different sizes that are brought on-line according to the load on the cooling plant. Since the part-load performance of a chiller may not be very good, it is often desirable to operate the chillers at 80 to 100% of their rated capacities to ensure that the kW/ton ratio is sufficiently small. A number of issues are associated with multiple chiller operation, however, particularly if the chillers are of different capacities. If the morning load is small but the afternoon load is expected to be large, it may be advantageous to bring the large chiller on-line in the morning even at a low part-load ratio. This procedure will prevent the large chiller from doing a "warm-start" in the afternoon, when the start-up transient power consumption can be high enough to reset the demand load for the building.

If the building has more than two chillers, it may be necessary to include some intelligence in the start-up algorithm that can identify the proper combination of chillers to obtain the highest overall plant COP. Figure 5.1.59 shows the effects of different starting dispatch orders for a building with two 50-ton chillers and one 100-ton chiller. Clearly, some combinations are better than others, particularly at low loads.

The CHW outlet setpoint should be the same on each chiller in a multiple chiller plant. The condenser and evaporator flows through each chiller should be in proportion to the relative capacity of each chiller.

Some chillers have built-in control circuitry that limits the current draw. This is useful if one is trying to manage the utility demand charges. Under current limiting control, the chiller will unload capacity rather than trying to meet the setpoint if the current limit is reached.

Some variable speed drives also have circuitry that automatically controls the maximum output current of the drive. This is necessary to protect the current carrying components. Typically, a drive's rating is

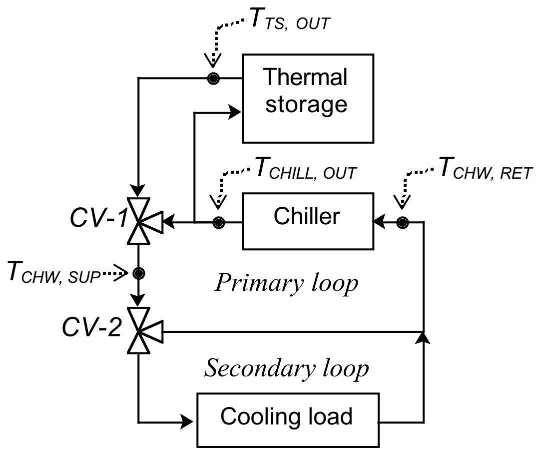

FIGURE 5.1.60 Schematic of thermal storage flows.

at 100% current. Constant torque drives typically have a maximum current limit of 150% and variable torque drives have a maximum current limit of 100 to 115%.

Thermal Energy Storage

It is becoming more common to use thermal energy storage (TES) to shed daytime peaking loads to the evening hours when overall electrical demand is low and the cost of electricity is usually cheaper. The "coolth" is stored either by creating ice or by cooling a large volume of water. A simplified schematic of ice storage is shown in Figure 5.1.60. At night, the three-way mixing valve CV-2 is closed to force all the water from the chiller back into the primary loop. If ice is used as the thermal storage medium, then the chiller setpoint $T_{CHW, SUP}$ is set somewhere around 25 to 30°F. The water is used to cool the thermal storage tank. During the daytime the CV-2 will modulate to maintain a desired setpoint temperature in the secondary loop. To retrieve the stored energy, one of the following methods is usually used.

The simplest method for thermal storage control is the *chiller-priority* strategy. The chiller is sized for a capacity less than the building peak load. During the evenings, the chiller is used to make chilled water or ice. During the day the chiller operates at full capacity and the difference between the chiller output and the building load is made up with the cold storage. This technique maintains a high chiller efficiency and provides for a known demand curve in case demand limiting is implemented. The main disadvantage of this method is that the chiller still operates during the daytime hours and incurs both consumption and demand charges.

Storage-priority control attempts to use as much of the stored energy as possible and to minimize the chiller operation during the hours when electricity is most expensive. The clear advantages of this strategy are that the chiller can quite possibly be turned off during these on-peak hours and the cost savings are significant. The main disadvantage is that a control scheme is required that can predict the next-day building loads and generate enough ice to handle that load. If the storage is depleted during the day, then the chiller may need to be placed on-line during periods of high energy cost.

Constant proportional control of thermal storage refers to a technique in which the ratio of the cooling provided by the chiller and the storage is a constant. In other words, the proportion of cooling provided by either device remains constant throughout the day regardless of the load. This combines the simplicity of chiller-priority control with the demand limiting potential of storage-priority control. When using constant proportion control, the outlet temperatures of the chiller and storage tank remain constant. The chiller outlet temperature setpoint is given as

$$T_{CHILL, OUT} = T_{CHW, RET} - \boldsymbol{f} \cdot (T_{CHW, RET} - T_{SUP})$$

where $\boldsymbol{f}$ is the fraction of cooling that is to be handled by the chiller.

Cooling Tower Control

Cooling towers are typically controlled to maintain the condenser return water temperature, i.e., the temperature of the water that goes back into the chiller condenser. This is done by either staging multiple cooling tower fans or by varying the fan speeds with variable frequency drives. Since cooling towers take advantage of evaporative cooling, *the setpoint of the cooling tower can be no lower than the wet-bulb temperature of the ambient air*. Thus, ambient temperature data is needed both in the design and control of cooling towers. Also, note that cooling towers tend to create their own microclimates, so any measurement of the ambient conditions must be made in the vicinity of the cooling tower. The *approach temperature* of a cooling tower is the difference between the design outlet temperature and the design wet-bulb temperature. As the approach temperature decreases, the available cooling also decreases. If the approach temperature is below about 5°F, the cooling capacity of the tower will be effectively negligible.

If the cooling tower has multiple cells (i.e., fan and draft columns) and the fans are controlled using variable frequency drives, then the fans in all cells should be operated at the same speed. This will provide the correct amount of cooling at the minimum fan energy cost. If the cooling tower has multiple cells and the fans are controlled with multiple speed fans, then the lowest speed fans should be put on-line first as additional capacity is needed.

Tower ("Free") Cooling — In tower cooling mode, the chiller is turned off and the water bypasses the chiller altogether. If the building cooling load is small and the outside conditions are within the right range, it is possible to achieve "free" cooling by sending the cooling tower water directly to the load (Figure 5.1.61).

Heat Recovery

Some chiller models allow for the recovery of condenser heat for relatively low-temperature hot water applications (Figure 5.1.62). Heat from the condenser can be used to provide some or all of the heating energy for hot water distribution loops in the range of 100 to 130°F. Temperatures above this are not possible since the condenser would then be too hot for efficient chiller operation. The temperature controls for the heat recovery loop are usually installed by the manufacturer. The condenser heat recovery can be placed before or after the conventional heating source. Note that it is always necessary to have conventional refrigerant cooling equipment in case the chiller is operating when the demand for hot water is low.

5.1.11 Control of Boilers and Steam Systems

Boilers are used to generate steam for use in larger buildings. Steam is a convenient "prime mover" since it does not require an additional pumping power to circulate. The boiler produces steam, and the steam expands into the distribution system. Of course, there will be some condensation within the distribution system as some of the steam cools. This condensate is removed using steam traps that feed to a condensate receiver tank. A float switch in this tank closes when the tank is full and activates a pump that returns the condensate back to the boiler. Figure 5.1.63 illustrates a steam distribution system and condensate return.

Boilers use electricity, natural gas, or oil to heat water and produce steam. *Hydronic* boilers do not produce steam but rather pressurized hot water. Most of the control circuitry for boilers is installed by the manufacturer, although often the user will have the ability to change the outlet pressure setpoint. Low pressure steam systems operate in the 10 to 20 psig range.

As with all large HVAC equipment, boilers have safety controls that will shut off the boiler (or prevent ignition) if a condition exists that is hazardous to the equipment or the facilities personnel. Some boiler combustion safeties include shutting off the gas flow if the flame is unintentionally extinguished, purging the combustion chamber of any unburnt gases before ignition, purging the combustion chamber of any unburnt gases after flame shut-off, and ensuring flame integrity upon startup before increasing gas flow to maximum. Of course, there will always be a water flow interlock to prevent boiler operation when there is no water flow. In addition, many large boilers (greater than 1 million Btu/hour) monitor flue gas conditions to estimate combustion efficiency. Ideally, CO_2 concentrations in the flue gas will be

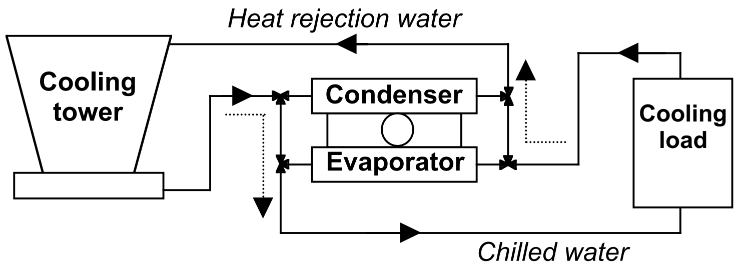

FIGURE 5.1.61 Chilled water plumbing needed for "free" cooling.

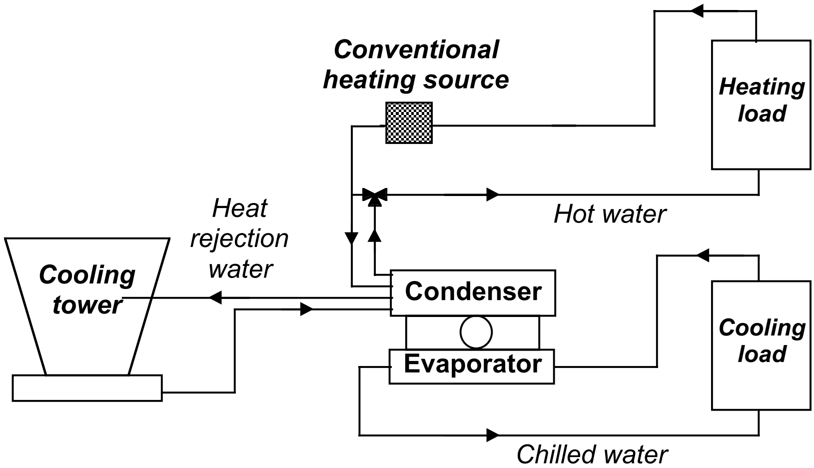

FIGURE 5.1.62 Piping schematic for chiller with heat recovery.

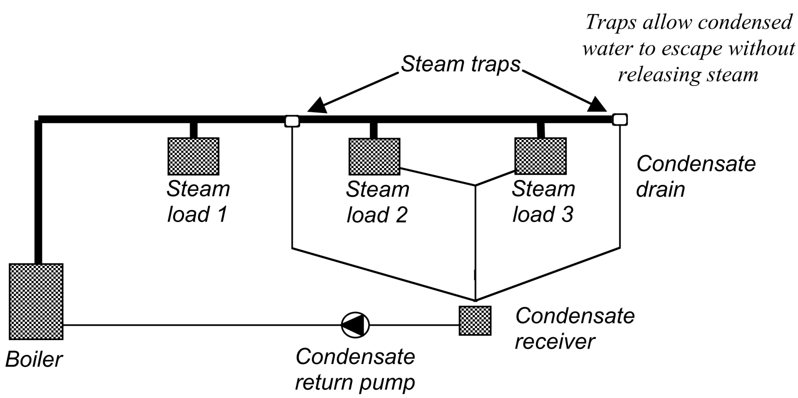

FIGURE 5.1.63 Schematic of steam distribution system and condensate return.

10 to 12 percent, while O_2 concentrations should be around 3 to 5 percent. Lower concentrations of O_2 are impractical and unsafe, while higher concentrations imply that too much air is entering the combustion chamber and must be warmed.

Boilers are rated in terms of their efficiency or in terms of the annual fuel utilization efficiency (AFUE). The efficiency is a simple, steady state ratio of input energy to output energy while the AFUE efficiency takes cycling into account. The problem with cycling a boiler is that the pressure vessel must first reach boiler temperatures before steam is produced. During cycling (see Figure 5.1.64), a considerable amount of energy is lost during the transient conditions.

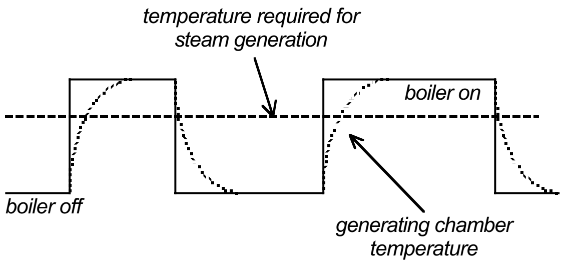

FIGURE 5.1.64 Boiler pressure chamber temperature versus time during boiler cycling.

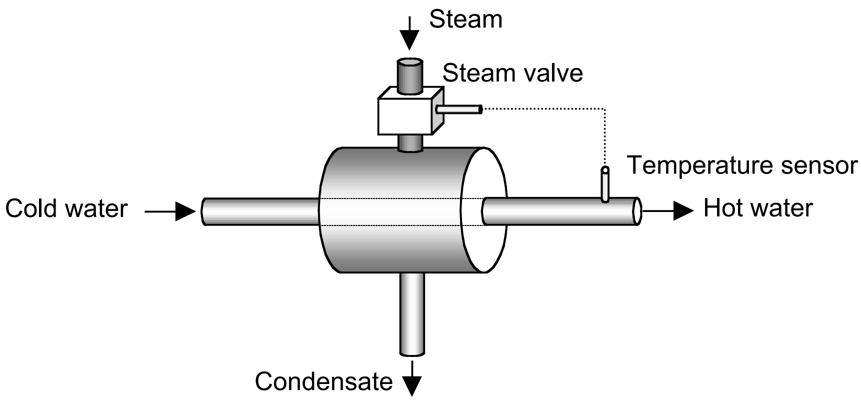

FIGURE 5.1.65 Schematic of a steam/hot water converter showing steam valve.

Steam/Hot Water Converter

A converter is like a heating coil, except that it is much smaller and heats water, not air. The water and steam never mix; they just exchange energy. Converters are used for generating hot water at remote points in a building. They are used instead of multiple water heaters. The steam flow is controlled to maintain the hot water temperature setpoint. Figure 5.1.65 shows a schematic of a steam/hot water converter and its steam valve.

Radiant Heating

Floor panels are often controlled by outside air temperature. Maximum allowable temperatures are about 85°F. Wall and ceiling panels have less mass and can operate at temperatures up to 100°F and 120°F, respectively. Walls and ceilings can also be used for radiant cooling, but care must be taken to avoid condensation. Note that radiant heating temperatures are good matches to solar collector temperatures. Temperature sensors for radiant heating should be located away from the panels so that the control maintains the proper air temperature and is not biased by direct heating from the panels.

Building Warm-up/Cool-down

Many buildings are allowed to "float" at night, which means that the HVAC equipment is turned off and the building temperature can drift up or down depending on the difference between the inside and outside temperature. Of course, the building must be at a comfortable temperature when the occupants arrive, so it is necessary to start the HVAC system beforehand. The key is to have an understanding of the building time constant so that the morning warm-up (or pull-down, if in cooling mode) can start so the building reaches the desired setpoint without wasting energy. Figure 5.1.66 shows the effect of different start times on the building temperature. During warm-up mode, any exhaust fans and relief fans are turned off, the building pressure control and the air flow tracking differential are reset to zero (if used), and the thermostat control is overridden or reset.

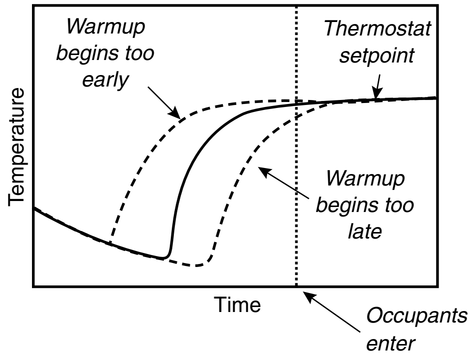

FIGURE 5.1.66 Effect of different HVAC warm-up start times on building temperature.

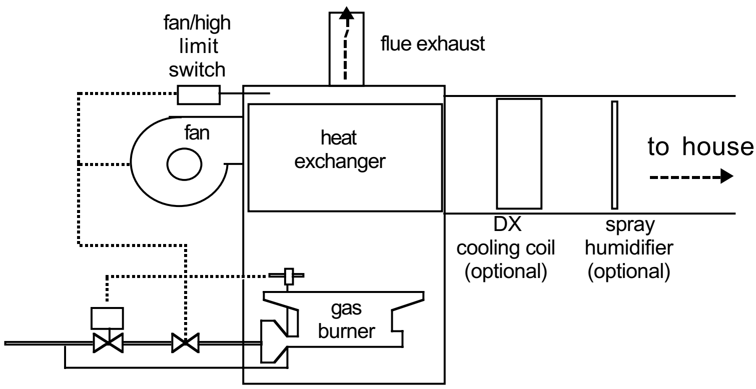

FIGURE 5.1.67 Schematic of residential furnace showing location of components and sensors.

Control of Furnaces

Furnaces are gas- or oil-fired devices (most often residential) that combine combustion elements with a fan to circulate warm air throughout a house. The flame safeguard controls on most residential furnaces are thermocouples protected by a metal sheath. Other methods of flame detection include bimetal sensors (slow response) and ultraviolet flame sensing (fast and reliable but expensive). Figure 5.1.67 shows a residential furnace and its components.

5.1.12 Supervisory Control

Supervisory controllers are used to govern the operation of the entire HVAC plant and/or building climate control. This type of controller attempts to minimize a cost function associated with the operation of the building under the current conditions. The controller will vary setpoints, perform load shedding, switch cooling modes from mechanical to storage, etc. A basic diagram of a supervisory controller is given in Figure 5.1.68.

The principle behind the plant-wide optimization is to have a supervisory controller that can be used to predict the behavior of the plant over a wide range of operating conditions. This is accomplished by any number of modeling techniques from simple regression to neural networks to sophisticated building simulations. Once the model has been developed and calibrated, it can be used to examine a number of “what-if” scenarios to determine the economically optimum operating conditions. The two examples in Figure 5.1.69 show the results of a building model that has been used to look at the effects of (a) chilled water temperature control, and (b) chilled water and supply air temperature control on the hourly cost of operating the HVAC plant.

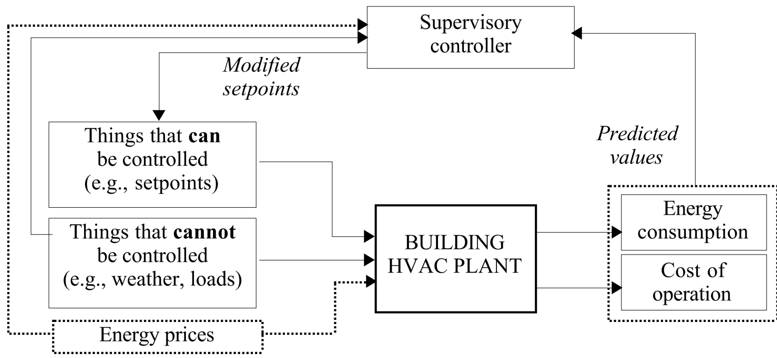

FIGURE 5.1.68 Supervisory controller information paths.

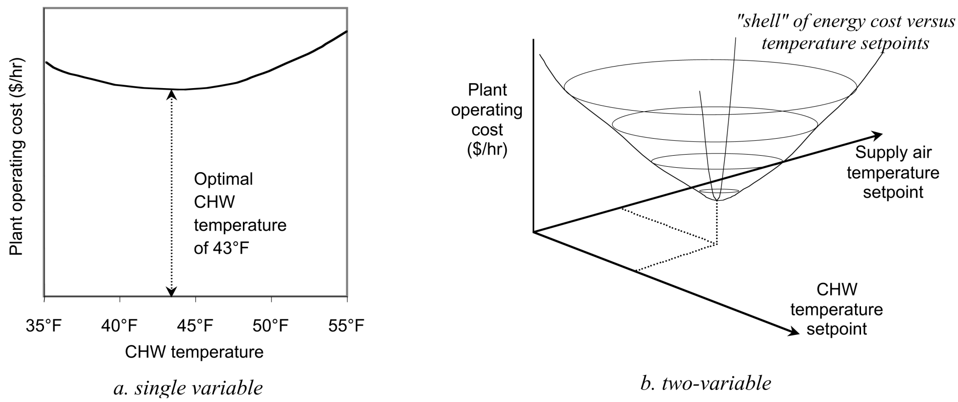

FIGURE 5.1.69 Supervisory optimization decision charts.

5.1.13 Advanced System Design Topics — Neural Networks for Commercial Building Controls

Neural networks (NNs), offer considerable opportunity to improve control achievable in standard PID systems. This section provides a short introduction to this novel approach to control which has been used in a number of commercial products. For the basis of NNs, see Section 6.2.3.

A proof of concept experiment in which NNs were used for both local and global control of a commercial building HVAC system was conducted, in the JCEM laboratory at the University of Colorado, in which full-scale testing of multizone HVAC systems can be done repeatably. Data collected in the laboratory were used to train NNs for both the components and the full systems involved (Curtiss, 1993a, 1993b). Any neural network-based controller will be useful only if it can perform better than a conventional PID controller. Figures 5.1.70 and 5.1.71 show typical results for the PID and NN control of a heating coil. The difficulty that the PID controller experienced is due to the highly nonlinear nature of the heating coil. A PID controller tuned at one level of load is unable to control acceptably at another whereas the NN controller does not have this difficulty. With the NN controller we see excellent control — minimal overshoot and quick response to the setpoint changes.

In an affiliated study, Curtiss et al. (1993b) showed that NNs offered a method for global control of HVAC systems as well. The goal of such controls could be to reduce energy consumption as much as possible while meeting comfort conditions as a constraint. Energy savings of over 15% were achieved by the NN method vs. standard PID control.

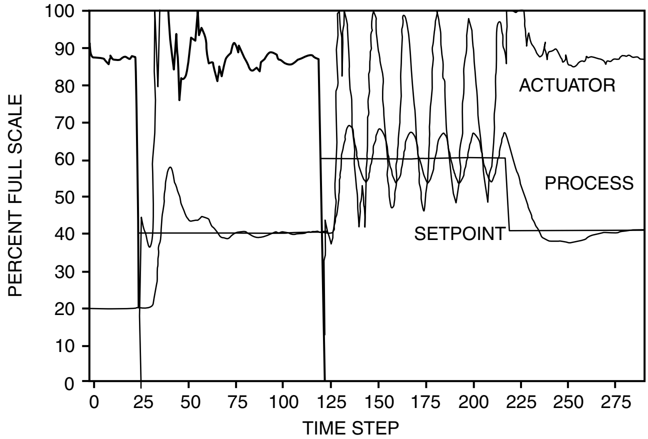

FIGURE 5.1.70 PID controller response to step changes in coil load. Proportional gain of 2.0 (from Curtiss et al., 1993a.)

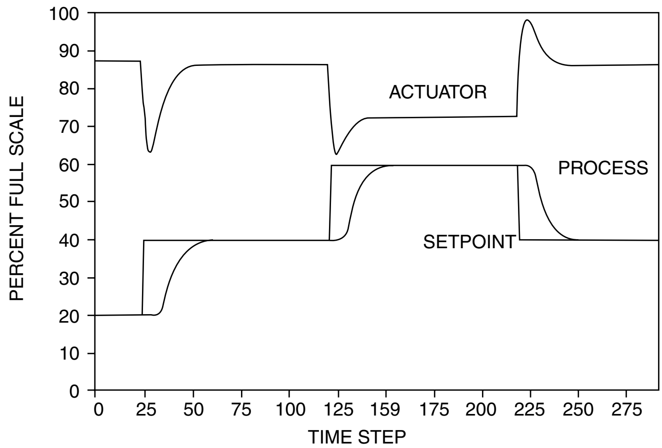

FIGURE 5.1.71 NN controller with learning rate of 1.0 and window of 15 time steps (from Curtiss et al., 1993a.)

References

ASHRAE, 1989. *Handbook of Fundamentals*. American Society of Heating Refrigeration and Air Conditioning Engineers, 1791 Tullie Circle NE, Atlanta, GA.

Curtiss, P.S., Kreider, J.F., and Brandemuehl, M.J., 1993a. Adaptive Control of HVAC Processes Using Predictive Neural Networks. *ASHRAE Transactions,* Vol. 99, Pt. 1.

Curtiss, P.S., Brandemuehl, M.J., and Kreider, J.F., 1993b. Energy Management in Central HVAC Plants using Neural Networks. *ASHRAE Transactions,* Vol. 100, Pt. 1.

Haines, R.W., 1987. *Control Systems for Heating, Ventilating, and Air Conditioning*, 4th ed., Van Nostrand Reinhold, New York, NY.

Kreider, J.F., Rabl, A., and Curtiss, P.S., 2001. *Heating and Cooling of Buildings*, 2nd ed., McGraw-Hill, New York, NY.

McClelland, J.L. and Rumelhart, D.E., 1988. *Exploration in Parallel Distributed Processing,* MIT Press, Cambridge, MA.

Shinners, S., 1972. *Modern Control System Theory and Application*, 2nd ed., Addison-Wesley Publishing Company, Reading, MA.

5.2 Intelligent Buildings

Michael R. Brambley, Peter Armstrong, Michael Kintner-Meyer, Robert G. Pratt, and Srinivas Katipamula

The topic of "intelligent buildings" (IBs) emerged in the early 1980s. Since then, the term has been used to represent a variety of related yet differing topics, each with a slightly different focus and purpose. Wiring and networking infrastructure companies emphasize the cabling requirements for communication in intelligent buildings and the need to accommodate future needs for higher speed broadband. Lucent (Lucent 2000) for example, defines an IB as "… one with a completely integrated wiring architecture. A single cabling system that handles all information traffic — voice, data, video, even the big building management systems."

Developers focusing on advanced technologies for use as parts of buildings, furnishings, or structural members emphasize intelligent building technology, such as smart windows, active walls, ergonomic furniture, or furnishings with built-in computing technology or network/communication connections (see, for example, Ambient 2000).

Other organizations define intelligent buildings in the context of the overall performance of the building or how successfully the occupants of the building conduct business. The European Intelligent Buildings Group (EIBG 2000) uses the following definition: "An intelligent building incorporates the best available concepts, materials, systems, and technologies, integrating these to achieve a building that meets or exceeds the performance expectations of the building's stakeholders. These stakeholders include the building's owners, managers, and users, as well as the local and global community."

Dexter (1996) provided an excellent discussion of heating, ventilation, and air conditioning systems for intelligent building systems.

Finally, the U.S. Department of Energy (2000) defines intelligent building systems as follows:

> Intelligent building systems (IBSs) will use data from design, together with sensed data, to automatically configure controls, commission (i.e., start up and check out) and operate buildings. Control systems will use advanced, robust techniques and will be based on smaller, cheaper, and more abundant sensors than today. Intelligent devices will use this wealth of data to ensure optimal building performance continuously by controlling building systems and continuously recommissioning them using automated tools that detect and diagnose performance anomalies and degradation. Intelligent building systems will provide much more than today's rudimentary control. They will optimize operation across building systems, inform and implement energy purchasing, guide maintenance activities, and report building performance, while ensuring that occupant needs for comfort, health, and safety are met at lowest possible cost.

Although these definitions differ, they share a common goal of providing better services to building occupants to make them more productive, more comfortable, healthier, safer, more secure, and better able to conduct business using modern technology to provide better building services.

Webster's Dictionary (1999) defines *intelligent* as "having intelligence" and *intelligence* as "1.a. The capacity to acquire and apply knowledge. b. The faculty of thought and reason." By these definitions, few, if any, building technologies are intelligent. Yet, the infrastructure in which intelligence could be deployed has grown rapidly: high speed communication by audio, video, and other data, high speed processing, soon to exceed 1 GHz in home computers, and enormous data storage capabilities at lower cost than ever before. Application of building automation technology has become commonplace, yet building automation systems do not satisfy these definitions of "intelligent."

For purposes of this chapter, we adopt a slight variation of the definitions provided by Dexter and the USDOE. We define intelligent building technologies (IBT) as technologies incorporated into the building structure, external shell, or building systems that contribute to progress in moving buildings and building systems toward an ultimate vision of buildings that possess intelligence and display at least some characteristics that satisfy Webster's definition of intelligent. We also adapt the definition provided by the USDOE as the ultimate vision of intelligent buildings — buildings that set up and operate themselves.

Intelligent buildings will provide

- High-quality, personalized, and localized environmental control, including all aspects of the environment — heat, cooling, light, ventilation, and acoustics.
- Highly reliable, cost effective building services and environmental control — levels of reliability that far exceed today's at minimal costs, as automated learning systems that adapt to changing conditions are introduced into buildings.
- High speed multimode communication for voice, data, graphics, audio, and video — these technologies will provide services for tenants but will also provide the foundation on which intelligent building technology will be built.
- Flexible, reconfigurable workspaces and services — the increasing pace and changing styles of work in today's and tomorrow's rapidly growing economy require building spaces that can accommodate change. Flexible work spaces and the services provided to them (telephony, data, video, electricity, comfort conditioning, ventilation, and lighting) that can be reconfigured overnight or during lunch will make the space more adaptable to the needs of business.
- Efficient, robust, cost effective building operation — better control, provided by intelligent technology, will optimize building operation with respect to cost, while meeting occupants needs.
- Sustainable building practices — intelligent buildings will provide solutions for making our building stock higher performing and more sustainable.

Despite the advancement of technology, particularly in information technology, over the last 20 years, buildings and the technologies in them still do not display intelligent characteristics. While the concept of an intelligent building (IB) has been evolving for almost 20 years, relatively few buildings completed by the year 2000 would be considered intelligent. IB-enabling building automation (BA) technologies, however, have developed at an unprecedented rate in these same two decades. This seeming irony is easily explained by industry observers: the building industry is very conservative and is slow to adopt any new technology, let alone one that is rapidly changing. There is, nevertheless, little doubt that building automation technologies will be widely adopted — it is only a question of when. The fact that we can, at this time, paint a rather clear picture of "what" and "how" may be taken as evidence that "when" is not too far off.

This section, therefore, differs from others in this handbook because it summarizes the best estimate of IB technologies expected to be seen before long. It does not represent the certainty of historical experience and scientific inevitability embodied in other chapters that treat more mature technologies. However, because wide adoption appears to be imminent, we have decided to discuss the advanced concepts involved in IB technology.

The remainder of this section provides a discussion of drivers for the continued emergence of IBT, more detailed descriptions of technologies that the authors believe will be important to realizing the vision of intelligent buildings, and suggestions for how building designers, owners, and operators can prepare for intelligence in their buildings. Our focus is on building environmental systems that ensure comfortable and healthy indoor environments.

5.2.1 Why Intelligent Buildings Are Needed — Demand and Benefits

A survey of office tenants by the Building Owners and Managers Association International in 1999 revealed building features that tenants consider important (BOMA 1999). The most highly desired services and amenities were

- Comfortable temperatures
- Good indoor air quality
- High-quality building maintenance

- Responsive building management
- Building management's ability to meet tenant needs
- Effective noise control

BOMA also asked which of a set of thirteen intelligent building features were considered most important. The results were

- HVAC systems that provide comfortable temperatures
- Ability for tenants to control comfort
- Built-in wiring for the Internet
- High-speed LAN/WAN connectivity
- Fiber optics capability
- Conduits for power, data, and voice cabling
- Controlled access security system with monitoring
- Redundant power source

A number of political, economic, sociologic, and technologic factors contribute to the evolving demand for higher quality, more sophisticated, more reliable building services. These drivers include

- *Building owners searching for ways to cut costs of ownership and increase value.* Buildings owners are concerned with retaining tenants, and employers are concerned with retaining employees, especially in a tight labor market. Providing quality office space is more important than ever before for retaining tenants and employees. Tenants are demanding premium services, like high-speed Internet access, that were not required even five years ago. Owners are seeking ways to reduce costs, often looking to operations and maintenance (O&M) for cost reductions. This often means decreases in O&M staffing, even when tenants are demanding better service. Intelligent building technologies should provide solutions to this problem by providing tools that help operation and maintenance staff target their efforts more effectively. For example, if a sensor has failed and is causing poor control of an air-handler, an automated diagnostician could identify that a specific sensor has failed, provide estimates of the cost and comfort impacts of this problem, and direct staff to replace that specific sensor. In some cases, like poor control, an intelligent system could correct itself, learning from a record of complaints as well as past performance resulting in decreased costs while increasing performance. In addition to these evident costs, the risk of litigation related to indoor environmental conditions has increased in significance over the last decade. Indoor air quality and its effects on health have been the cause of notable legal action. Intelligent monitoring and control systems will help alleviate problems in the future.
- *The information technology revolution spurred by growth of the Internet.* Owners are struggling to meet tenant demands for access to rapidly changing information technology (IT) services. Keeping up with changes in information technology and providing for upgrades as technology evolves is increasingly important for retaining tenants. From the perspective of providing enhanced building environmental control, advances in IT (e.g., wireless, broadband, distributed processes, data mining, rapid widespread information sharing, etc.) provide new technologies by which high quality, flexible environmental control could be ensured. Information technology provides the new foundation on which intelligent building technologies can be built.
- In recent years, a global trend in *utility deregulation* has occurred. Deregulation will open new opportunities to building owners by providing increased customer choice in energy supply. New full service energy and O&M performance contracts are emerging in the energy services sector, and new, nontraditional services, such as air quality, comfortable temperatures, and continuous building commissioning, are likely to provide a new way of valuing energy and the services it provides.
- A shift is also occurring from central generating plants to *distributed power generation.* The economies of scale that existed for decades are giving way to economies of mass production. Smaller,

modular power generation systems, tailored, on-site, power solutions, and "green" power are emerging alternatives for building owners. These technologies may provide the answer to tenant desires for reliable, backed-up power sources, while also potentially leading to lower energy costs.

- In recent years, *carbon management* has emerged as a global scientific and political issue. After decades of investigation and discussion among the scientific community, the potential dangers of global climate change resulting from anthropogenic carbon emissions have become recognized as an important global issue. Sustainable energy policy is viewed by many as the solution to this problem. Currently, international political pressure is driving the U.S. towards policy that will address this issue. Premium tenants increasingly want "sustainable" or "green" buildings. Intelligent building technologies are likely to provide a major contribution toward using energy more efficiently in buildings and controlling the contribution of the buildings sector to atmospheric carbon concentrations. Government is likely to be a catalyst in this area through research, incentives, taxes, or potentially even regulation.
- In the U.S. and many of the industrialized countries of the world, c*hanging demographics* will influence the needs and desires of building occupants. This is particularly true for the U.S. where the "baby boomers" are now reaching middle age and will become seniors in the next decade or two. Meeting the needs of an aging population, such as increased demand for health care, changing needs with respect to housing, and changing work arrangements, could drive the need for changes to the building stock and create a role for intelligent buildings to help meet these needs.

Other factors make the time opportune for the development of intelligent building technologies. Building automation systems are likely to provide the mechanism for delivery of intelligent building technology for indoor environmental control. They currently provide a network of control and monitoring equipment that coordinates (or could coordinate) the functions of HVAC, security, fire protection, and other building services, while facilitating and automating the building management. These capabilities are clearly desirable. Increasing interest in IBs is driven by falling costs and growing capabilities of the underlying information technology. Let's consider some of these costs and functions.

Hardware costs. Moore's Law (Intel 2000) rings true for most of the technologies upon which building automation relies. Modems, bit drivers, hardware protocol converters (e.g., RS232 to RS485), communication protocol converters (bridges, routers, gateways), microprocessors, memory, computers-on-a-chip, analog components, PLAs, mixed ASICs, etc. have faithfully doubled in power and speed every 18 months for about three decades. Costs have generally followed a downward trend all the while. Lower cost and higher speed, capacity, and computing power mean that increased functionality is ever more cost effective.

Network media are well established. TCP/IP, CEBus™, BACnet™, Lon Talk™, Profibus™, and Fieldbus™ protocol standards are used at the supervisory level, field panel level, and in some cases at the device level in building automation systems. HART, one-wire, and similar multidrop standards are used for simple devices. All of these standards have achieved widespread acceptance in terms of their hardware/electrical requirements.

Communications standards have passed the critical threshold of multivendor acceptance. Third-party providers of control components and systems compatible with existing proprietary standards (e.g., Delta for Honeywell) have been very successful for a couple of decades. BACnet and Lon Works now provide open standards which show that the trend towards multi-vendor interoperability continues.

Enterprise management has shifted from cautious acceptance to embracing network information sharing technologies. The networks that tie a BAS with the rest of the enterprise and the intelligent software applications that manage the BAS are the keys for the next generation of distributed facilities management systems (Bayne 1999). Controls manufacturers, engineers, and researchers are developing software solutions that take advantage of integrated networks to provide easy access to operating and control data (Olken et al., 1996; O'Neill 1998; Brambley et al., 1998; Katipamula et al., 1999; Chassin 1999). Use of state-of-the-art controls that facilitate distributed processing, coupled with gateways that provide interfaces between the control networks and the data networks (Internet and intranet, respectively), will provide better monitoring and control of building systems and enable management of distributed facilities from either a central or remote location.

Operational efficiency is being pushed ever harder as skilled labor costs rise and the competition to provide services increases. This provides an opportunity to bring benefits by embedding knowledge and the ability to reason in building automation systems.

Improved operation is also a strong driver. Conditions that lead to complaints should be avoided, and response, when complaints are voiced, should be fast and their resolution appropriate and permanent. Occupants expect good lighting, thermal comfort, and a clean and adequate supply of fresh and recirculated air that is free of odors as well as contaminants. Automated systems can respond quicker than a human operator or engineer manually identifying problems and compensating for them. Meeting occupant's needs in a timely, consistent manner may require intelligent systems.

Maintenance managers are beginning to expect BASs to include tracking and scheduling features. These capabilities have been a part of BASs for years, but they have been difficult or inconvenient to use, and the knowledge required to convert raw data to information has been largely absent. These problems are likely to be addressed by the next generation of BASs that should include the capability to interpret data into useful information. Automatic fault detection is also becoming an expected, if limited, BAS feature; extension to automated diagnosis promises substantial labor savings for operation and maintenance.

Efficient infrastructure is the corollary to operational efficiency. Owners prefer to invest in building systems that are efficient in the first place and adaptable to changing building use. Standards, such as BACnet, emerged from building owners' dissatisfaction for years with being "hostage" to the vendor of their BAS. Standards are a step toward remedying this problem. True "plug and play" is the ultimate Intelligent Building solution to this problem, where system components can be removed, new ones installed and automatically set up and operated.

5.2.2 Intelligent Building Technologies

Intelligent building HVAC technologies will include advanced control systems, automated diagnostics, and flexible systems that can be easily reconfigured to adapt to reconfiguration of building spaces. Adaptive control systems will require plentiful, accurate, reliable, long-lived sensors. Today, sensors in buildings are generally low quality and unreliable. Sensor drifting, complete failure, and even improper placement are commonplace in buildings. Intelligent building systems will require better, more abundant sensors. But cost is often cited as a major impediment to adding more sensors to a new design or retrofit. This will require sensor costs to decrease, so the intelligence of control systems can correspondingly increase. Intelligence without information (data) is of little use — sensor technology will be a key to realizing IBT.

Intelligent environmental control systems will provide localized, personalized comfort control. Initially this might be done by providing work stations or seating stations in conference rooms with individualized controls for ventilation and air temperature. In the longer term, this will involve the system automatically recognizing that a specific individual is sitting at a specific location and then providing the conditions necessary to keep that person comfortable and productive.

Advanced control systems will provide intelligent power management. Energy will not be used when not needed. Environmental control systems will automatically respond to occupancy levels — not just whether a space is occupied or not, but how many occupants are present in each space and what activities are taking place (e.g., exercising compared to sitting at a desk working at a computer).

To provide these capabilities, advanced control systems will need levels of intelligence not present in today's systems. They will need to recognize changes in conditions both inside the building and outside (e.g., outdoor air temperature, humidity levels, solar insulation, wind conditions) and adapt accordingly to minimize the cost of operation while meeting the requirements of the occupants. This will require capabilities that are adaptive, predictive, and learning.

Automated diagnostics will also play an important role in intelligent building systems. These systems can "observe" the operation of environmental control systems and identify when problems in operation occur and then identify the causes of a problem. This capability is much more than a simple alarm. It requires embedded knowledge of the building systems, both control systems and physical components, how they should operate, and how they behave when degraded or failing. Automated diagnostics will lead to better maintenance that helps continuously ensure proper indoor conditions and minimal costs to meet those conditions. Automated diagnostics will also play an important role in automating the commissioning process. Coupled with "plug and play," automated diagnostics will enable automatic set up and operation of many building systems.

Flexible building systems will be important to buildings of the future. They will include rapidly reconfigurable spaces, reconfigurable services for those spaces, robust, self-balancing HVAC systems, reconfigurable lights, electric, and communication services, and "plug and play" components that can be inserted and rapidly placed into service. Part of providing flexible spaces may involve changes in the types of systems used to provide comfort. An example is the potential use of modular, miniature heat pumps in place of large, centralized HVAC systems. New technologies, like this, will most likely find a role in intelligent buildings of the future.

This introduction has provided an overview of some generic types of intelligent building technologies. The following sections discuss specific intelligent building technologies in more detail.

Smart Windows

The window has a truly profound effect on many aspects of a building's existence. Operable windows admit air, light, and sound. Windows contribute a large, if not dominant share of the cooling load and, depending on climate and other aspects of building design, can also represent a large share of the heating load.

Careful, large sample studies have demonstrated very convincingly, if not conclusively, that daylighting increases occupant performance and satisfaction. Retail sales were found to be up 30–50% per unit floor area at the 99.9% confidence level in a recent analysis of sales in 108 almost identical stores (Heschong 1999a). Elementary school students' performance in fully daylit classrooms was found to be 7–15% better than in windowless classrooms in a recent analysis of 21,000 students in three geographically and climatologically disperse school districts (Heschong 1999b). Operable windows were also shown to have a positive effect on students' standardized test scores. Another "finding suggests that *control* of light and/or diffusion of direct sunlight are important features to include in a classroom skylight system" (Heschong 1999b).

Poorly designed fenestration can cause many problems. Even well-designed window systems usually involve tradeoffs. However, proper control of window light transmittance and other window aspects — *smart windows* — can eliminate most of the design compromises while retaining all of the potential benefits. Note that fixed shading and diffusing elements are often called "solar control elements"; here we refer only to active elements as controls.

Daylight control mechanisms include chromogenic glazings, manual and automatic window shades, moveable insulation, and moveable diffusing screens. Thermochromic and photochromic glazings provide a simple form of control based on just one variable, that is, of preventing excessive daylight under direct or bright sky, thus preventing excessive heat gain. Electrochromic windows with electrically controllable transmission characteristics enable greater control and can become part of an integrated building temperature, lighting, and energy control strategy.

Much of the benefit of daylighting is attributed to the subtle visual stimulation of light levels, patterns of light and shade, and spectral distribution that change throughout the day. A similar effect may explain occupants' preference for operable windows. Mechanical delivery of fresh air provides the basic requirement for reasonably clean air with sufficient oxygen and no objectionable odors. The stimulation of naturally occurring changes in air movement, however, is missing with mechanical ventilation.

Switchable Window Technologies

For this discussion, we refer to a switchable technology as one that uses materials applied to (coated on) glass and has the ability to change tinting level (transmission) or opacity when subjected to an outside influence, specifically heat, light, or electricity. We then split this broader category into two groups: electrochromic (EC) and non-electrochromic (non-EC). The non-EC variety includes liquid crystal and suspended particle technologies. These technologies physically operate quite differently from EC, and in some cases their application is also different. For instance, "polymer dispersed liquid crystal" has been used in windows where privacy is desired because it turns opaque in its un-electrified state. Otherwise, in its electrified state PDLC is clear.

Electrochromic technologies are part of the larger chromogenic family which includes photochromic and thermochromic materials. These are materials that change their tinting level or opacity when exposed to light (*photo*chromic), heat (*thermo*chromic), and electricity (*electro*chromic). Within the EC category, there are several types. The primary three are

- Inorganic thin film
- Organic polymer
- Organic solution phase

While these three are all considered electrochromic, the materials and processes that comprise and form the EC systems as well as the resulting performance, appearance, durability, and application vary greatly. For example, with organic polymer electrochromics, the EC films are applied to the inside surfaces of facing panes of glass, and the panes are then adhered together sandwich-style using a polymer electrolyte material between the films. The polymer material must perform not only as one of the layers critical to a functioning electrochromic system, i.e., the electrolyte, but it also must hold the two pieces of glass together.

On the other hand, inorganic ceramic thin-film EC is made of ceramic materials that are sputter-coated onto one pane of glass (similar to how low-E glass is formed) and fired at high temperatures. The heating "bakes" the thin films onto the glass something like the way glazing is fired onto pottery. The pane can then be fabricated into industry-standard dual-pane windows, or, if desired, into a conventional laminated glass structure for situations where extra strength and safety are required.

Source: From SAGE Electrochromics Inc., 2000. With permission.

Operable windows also present the designer with potential problems. Filtration and intelligent controls that ensure energy efficient operation (especially when the occupant goes home without shutting windows) are essential elements of the smart windows concept.

In summary, design with smart windows provides occupants stimulation and personal control of light and ventilation while also providing the potential for energy efficiency. Proper integration with all other building systems and their controls ensures realization of that energy potential and long-term, reliable, and economic building operation.

Plug and Play Control Concepts

Plug and play functionality is broadly forecast to be a key feature of building controls in the future. The term *plug and play* is adopted from personal computer operating systems that detect newly installed hardware, establish communications with it, determine its type and function, and select and install the drivers it requires from a library of possibilities. The analog for building HVAC systems and controls is a system by which the hardware is installed and networked, the hardware announces its presence and preferred operating conditions over the network, and the control system automatically develops the algorithms and control code needed to operate the systems. Ultimately, the only inputs required from the designer might be the set of desired operating modes, or overrides to default decisions such as utilization of night/weekend setbacks, selection of the basis for controlling the economizer (temperature or enthalpy), utilization of a supply temperature reset schedule, etc.

Achieving this vision of plug and play controls will bring a number of benefits to building owners, contractors, and operators. By automatically configuring the equipment, controllers, sensors, and actuators, inappropriate or incomplete control strategies can be virtually eliminated. Proactive, continuous commissioning procedures can be automatically generated that calibrate sensors against one another (or manual readings where necessary), test all operating modes, check for proper equipment installation (backwards flows, etc.), ensure proper actuation of controlled devices, and detect unacceptable valve and damper leakage. Cross-wiring of sensors and actuators can be discovered and corrected automatically by simply remapping them. These and related capabilities will

- Reduce the manual labor in setting up control systems and crafting control algorithms
- Ensure compatibility of control strategies with equipment characteristics
- Utilize the best appropriate control strategies
- Provide a degree of standardization for control strategies and algorithms that assists with their maintenance
- Reduce callbacks by detecting errors at the time of installation
- Generally result in a higher quality product

Intelligent buildings with plug and play controls will exhibit lower startup costs, fewer problems, increased comfort, lower O&M costs, greater adaptability to changing needs, and increased energy efficiency.

This vision of plug and play controls will not be achieved overnight. At its most primitive level, initial plug and play capability might be achieved by quasi-manual methods. For example, equipment manufacturers would specify equipment model numbers, characteristics, embedded sensors, optimal and limiting operating conditions, and preferred and alternative operating strategies on a Web site. Similarly, controls manufacturers would specify controller model numbers and characteristics and maintain a library of typical control strategies and algorithms on their Web site. The installed equipment and controllers would have bar codes, identifying the make and model, that are scanned by the installer and mapped to an electronic blueprint of the HVAC system schematic. This would link the equipment and associated controllers and their characteristics with the HVAC system topology. The controls designer would specify operating strategies and modes in electronic form also mapped to the equipment to be controlled via the HVAC blueprints. The plug and play system would then retrieve all relevant information and algorithms from the Web sites, automatically assemble the control software (specifying algorithms and setpoints), and generate automated and manual test procedures for commissioning and on-going diagnostics. The system also could retrieve and generate all relevant documentation for the control system and HVAC equipment that would be needed for on-going maintenance.

At the next level of plug and play functionality, the equipment and controllers might be networked via an intranet so that they automatically announce their presence and even might contain their own Web sites with all the relevant information. They also could utilize some form of location system so that their physical location could be mapped to the HVAC system layout, and hence the system topology automatically determined, eliminating most of the manual labor for creating this mapping.

Ultimately, plug and play controls might truly mimic computer system functionality in that the topology of the equipment, the controllers, and their sensors would be created and tested automatically through a mechanism of automatically exploring what is connected to what. This would provide added diagnostic capability (such as detecting that "the pump is installed backwards") and would eliminate the need for a direct link between the system physical layout and the system schematic.

Wireless Controls

As the tremendous growth* over the last several years in the wireless telephony area has affected almost everyone, there is very little reason to believe that this trend will not change the traditional HVAC controls industry. Major inroads of wireless technologies have been observed in the automatic meter reading (AMR) industry where increasing competition in retail electricity and gas markets has spurred the adoption of low cost radio frequency (RF) applications for reading electrical and gas meters. Wireless sensor technology has recently appeared on the HVAC controls market. The first application was a wireless sensor for a variable air volume (VAV) distribution system commercially available in 1997. At the AHR Exhibition held in February 2000, another controls vendor showcased a wireless temperature sensor for VAV and other controls applications. Both technologies are intended to communicate sensor data relatively short distances within a building. They were not intended for use as wireless communication applications across office buildings or other concrete and steel structures.

Recently, a new school of thought for wireless controls for buildings proposed to use wireless communications exclusively for entire buildings or sections of buildings. This is a departure from the previously adopted notion that wireless communications bridges only short distances to a control device. Novel radio frequency techniques would be used to achieve communications of approximately 1500 ft in typical commercial buildings while still complying with Federal Communications Commission (FCC) regulations** that limit RF signal power output of license-free RF operations. While this technology may provide a viable and cost effective option to wired control networks, the earliest adoption of wireless controls in building automation are expected to be the low cost RF technology designed to communicate short distances within a building's structure.

Wireless control technologies are becoming increasingly more attractive on the basis of cost savings compared to a wired control system. Other benefits include the following.

Extensibility of Control System — Wireless sensors and control devices can be readily added as retrofits to accommodate the changing needs of the occupants. As interior office space layout undergoes frequent changes to respond to organizational changes of the tenant, the controls technology can simply move with the walls. For instance, wall thermostats might be attached to a wall using Velcro. This thermostat could then easily be re-attached to a new wall of a reconfigured space. Likewise, the lighting control could be reconfigured easily as small office spaces are consolidated into larger conference rooms, or larger rooms are subdivided into small individual offices.

Enabling Advanced Diagnostics and Controls — Wireless controls technology is also an enabling technology that provides new economically viable controls enhancements or retrofit opportunities in those cases where using conventional wired technology would not be economically justifiable. Low-cost wireless sensors could significantly improve the information on thermal and environmental conditions in buildings, which would enable advanced diagnostics procedures and optimal control techniques to be developed and deployed. For instance, if several IAQ sensors could be inexpensively deployed to take real-time measurements, root causes of indoor air problems could be more easily detected.

First Cost Savings Opportunities — It is generally the communication and integration of many sensors into the existing control architecture that is cost-prohibitive when done using existing wiring practice. In particular, the labor component of the installation of additional wires is expensive. According to RS Means Mechanical Cost Data, communication cables for HVAC control applications installed in cable conduits are approximately $3.50 per linear foot of wiring, with the cost for ANSI/TIA/EIA category 5

*28 million subscribers to wireless telephony services in June of 1995, 61 million in mid 1998, *Progress Report: Growth and Competition in U.S. Telecommunications 1993–1998*, Council of Economic Advisers, February 1999. National Telecommunications and Information Administration, U.S. Department of Commerce.

**Federal Communications Commission Regulation Part 15. Radio Frequency Devices. Federal Communications Commission, Washington, DC.

cables for telecommunication at $0.15/ft and approximately $0.07/ft for #18 AWG cable used for thermostat connections (RS Means 1999).

Wireless controls in commercial buildings contribute to cost savings opportunities in the following three ways:

- *Cost for the physical wires and wiring conduits.* This is by far the least significant cost component. Communication cables for horizontal copper wiring in plenums are $0.15–0.20/linear ft or less. Noncommunication wiring for devices such as thermostats is approximately half the cost of communication wiring.
- *Cost of accessibility to wiring conduits.* This cost component is site specific. Issues may arise, for example in older buildings with asbestos ceilings, which may require specialists to be at the site to supervise or perform some of the work. Furthermore, there could be a high premium for inconveniencing tenants or customers in office buildings where the wiring work can be done only during the regular work schedule.
- *The cost of labor.* Accessibility to the wiring conduits or places in which wires can be laid determines the labor hours for wiring and, thus, the labor cost. Complicated wiring with short runs is generally more time intensive than long, straight runs. Depending on the location, labor cost, and whether or not union labor is employed, the labor for a linear foot may vary significantly. Means suggests $3/ft for labor as an average cost estimate.

Special Considerations with Wireless Controls

Wireless controls have been deployed successfully for several years. Most applications represented building-to-building communications or combined telemetry and control tasks with outdoor transceivers. The environment in which the wireless communication was performed was generally not subject to changes. Furthermore, outdoor environments generally cause less interference with wireless communications.

Early attempts to deploy wireless controls in commercial building environments with concrete structures yielded mixed results. Although there are no comprehensive studies published on the engineering issues for successful deployment of RF controls in office environments, there is anecdotal evidence of interference, signal attenuation, and battery lifetime problems. Interference problems have been addressed with frequency hopping and spread-spectrum techniques. Attenuation problems may still exist and require some engineering tasks for properly locating the RF transceivers. Depending on the signal strength, frequency, and surrounding environments, repeater stations have been deployed to robustly communicate the control signals to the intended receiver.

Full advantage of wireless controls can be achieved if the device is battery powered or, in other words, does not require electrical wiring for the power supply. A lifetime of 5 years or more is generally required for building controls applications to be acceptable. Data rate requirements and the RF signal power output determine the energy consumption of the control device. The power requirements for the device processing circuitry are generally significantly less than the RF communication energy consumption. Therefore, sophisticated power management techniques have been deployed to conserve electric energy whenever possible. The RF transceivers can be switched into a "sleep" mode and can "wake up" at a set time to communicate updated information, or they can be device-initiated when, for instance, the system properties above a threshold value are sensed. Therefore, applications such as remote thermostats or temperature sensors are now early wireless applications. The power requirements for closed loop controls with update rates of a second or less are relatively power intensive and place a real challenge to meet the acceptable lifetime requirement.

Automated Diagnostics in Intelligent Buildings

Commissioning is traditionally viewed as the process of manually testing an HVAC system to ensure that it performs as designed and as expected, in terms of function, capacity, efficiency, and ability to maintain thermal comfort. Diagnosis is commonly viewed as a passive process of observing system performance after installation and identifying problems. Although increasing numbers of buildings are being commissioned today, overall the number of commissions remains small. The number of buildings that receive either post-construction diagnostic or re-commissioning services is miniscule. As a result, when combined with the complexity of modern HVAC systems and a lack of routine maintenance, operational problems in commercial buildings are rampant.

Widespread adoption of automated diagnostic and commissioning procedures will help drive the cost of these services down and increase availability of the expertise in software packages. This is the subject of Chapters 7.1 and 7.2 of this handbook.

Automated diagnostic and commissioning procedures are directly linked to plug and play controls' functionality, with mutual and synergistic benefits. The automated procedures benefit from plug and play because the available sensors to support diagnostics are known; the control actions that should result under any conditions can be checked against the intended control strategy. This vastly reduces or eliminates the need to manually obtain and enter this information when setting up diagnostic or commissioning tools. Further, special operating modes, sometimes called proactive diagnostics, can be used to create operating conditions under which sensors can be checked against one another for consistency or to highlight correct or incorrect performance. These operating modes can be both designed and promulgated through plug and play functions, reducing cost. Where automated procedures must be supplemented by manual measurements and observations, the plug and play control system in intelligent buildings could generate the procedures and forms automatically, as well as set the system to the appropriate operating conditions on command.

Automated diagnostic procedures also bring added value to plug and play controls' functionality. The plug and play controls could automatically adjust or compensate for some problems, for example by changing a setpoint, substituting one sensor for another that is out of service, or adjusting PID loop parameters to enhance stability. These actions might be temporary until a repair is made or permanent if the adjustment is in response to changed building needs. Further, intelligent buildings could maintain records of design intent, control strategies, maintenance actions, and equipment specifications that will greatly simplify and reduce the cost of correcting or repairing problems found by automated diagnostic procedures.

Integrating Alternate Generation Technologies: Fuel Cells, Microturbines, and Solar Power

On-site generation technologies provide redundancy and power quality in almost all installations. In some installations, energy cost is an additional driver, and in others the "green" statement itself motivates the building owner. Deriving the full potential benefits of on-site power generation usually requires a level of integration and control coordination not found in conventional buildings. Important differences among the available solar, fuel-cell, and microturbine technologies should be considered during initial planning of on-site generation. These technologies for distributed generation are described in Chapter 3.1.

Automated Real-Time Energy Purchasing Capabilities

The Electric Power Research Institute (EPRI), in its *Electricity Technology Roadmap*, describes a future technology scenario, in which smart homes of the not-too-distant future will be equipped with Internet devices and controllers that could automatically search the Internet for access to the lowest cost power or seek power with other valued attributes, such as "green" power or high reliability power for critical applications (EPRI, 1998). While the scenario for the residential customer may appear to be far in the future, the earliest adopters will most likely be the commercial and industrial customers in deregulated energy markets. To date, the regulatory framework for the dynamic procurement of electric power already exists. California, for instance, offers nonresidential end-users the option to bid their load directly into the California Power Exchange for the purchase of wholesale electric power at hourly spot-market prices (demand bidding) [PBEP, 1997; PSCP, 1997]. Realizing this future scenario would require the integration of the facility management system with the bidding communication technology. With an integration of facility management, company accounting, and the bidding system, bid scenarios could be generated automatically based on load forecasts, the flexibility to manage electric power demands, and the assessment of the economic value of consuming electric energy at each hour of the day.

The growth of the Internet has drastically increased the interest in and relevance of electronic commerce. There are already electronic auction servers operating on the Internet, such as APX (Automated Power Exchange) providing opportunities to buy and sell power. Web-based intelligent agents are emerging to facilitate the searching task for an optimal power portfolio that meets the customer's cost and risk requirements. These agents work autonomously, scanning the Web for power offerings that meet a set of requirements — cost, date of delivery, and other characteristics that are important to the customer (EPRI, 1999; Reticular, 1999). It remains uncertain whether or not residential customers will ultimately use this technology and engage in power e-commerce over the Internet or whether this commerce will remain in the domain of energy service companies and large corporate energy managers.

Optimized Dynamic Building Systems

Optimal use of part-load efficiency, building thermal capacitance, and off-peak utility rates requires use of a number of simple concepts that collectively represent a very challenging problem. The key to this challenge is the high level coordinated control of various plant and distribution elements based on robust on-line, building-specific (i.e., adaptive) models of building thermal response, internal gain profiles, and equipment performance. A corollary requirement is on-line fault detection and diagnosis (FDD), described in Chapter 7.2.

Programmed (fixed) schedules for HVAC start/stop are no longer acceptable. To optimize performance, start-stop must function at zone level, must learn occupancy schedules at the zone level, and must use thermal set-up and set-back response models that adapt to changing building characteristics, including rezoning, and changing schedules of the occupants in any given zone.

In a well-designed building that has very efficient lighting and office equipment, life-cycle cost-optimized insulation, solar gain/shading/reflecting elements, and personal control of local temperature and humidity, the daily cooling loads may be quite modest. The possibility of reducing these loads further, or at least reducing the cost of meeting them, by nocturnal precooling of available building mass has been studied by a number of researchers.

Precooling can be achieved at night by operating a chiller near its most efficient part-load capacity, or by operating air handlers in economizer mode. Occupied zones are generally cooled at least to the lowest comfortable temperature during the night. Best use of thermal mass is obtained by cooling below the comfort band and then allowing zones to recover to just the minimum acceptable temperature by the time occupants arrive. Zones are maintained at the minimum temperature until the marginal cost of power crosses some threshold at which time cooling is modulated to stop or reduce the rate of rise at the building electric meter. This threshold must be carefully and dynamically selected (changing even up to the instant that it is crossed) to maximize savings at the meter without allowing zone conditions to rise above the comfort band. Modulation of the plant during the building demand-limiting period is also critical to success of the precooling strategy. Precooling also may involve significant latent load by absorption/desorption of water from the building fabric and contents.

Achieving the full potential of such dynamic control requires short-term (12–24 hour) forecasts of weather and occupant loads, a realistic and seasonally adaptive model of the building's thermal response to indoor and outdoor conditions, and real-time communication of utility rates.

Control of ice or chilled water storage is conceptually much simpler than control involving the thermal mass of the building fabric, but the need to justify the higher cost of discrete storage, and the desire to save (or at least minimize any increase) in plant energy use while pursuing the "easy" demand-related savings can also be quite challenging. Real-time pricing (RTP) adds yet another layer of complexity (Henze, et al., 1997).

5.2.3 How to Prepare for IB Technologies

This chapter has explained how improved control and monitoring can reduce labor costs, improve occupant satisfaction and productivity, and save energy. Future buildings will take maximum advantage of IB enabling technologies by using fundamentally new design criteria and processes. Existing buildings, however, can also benefit.

Upgrading Communication and Information Infrastructure

Two important elements of IBs can be retrofit incrementally to existing buildings: networks and sensors.

Communications Infrastructure — Typical office buildings have multiple tenants who maintain their own internal networks. The building owner, however, provides — and frequently must upgrade — high speed Internet access. The communications infrastructure needed for IBs is, ideally, designed and installed as part of the tenant-driven Internet access upgrades. The design should ensure that the appropriate network topology is installed and that sufficient data bandwidth is extended to key locations, including mechanical and electrical rooms and other equipment locations (e.g., rooftop, elevator, penthouse). Collection nodes serving HVAC and lighting distribution must also be considered, however. Multidrop lines will eventually extend to every room, and the drop density over open-plan office areas will at least equal that extended to small individual offices. In individual offices a single local controller will provide, minimally, the interface to an occupant control device, lighting sensors and actuators, HVAC sensors (IAQ and MRT as well as air temperature), and an HVAC terminal box.

Information infrastructure — Plans for upgrades should be reviewed to ensure adequate provisions for sensors whenever system upgrades of any type — communications, HVAC, lighting, tenant finish — are made. The decision to install a local controller should be based on cost, features, and technically useful life. Local controllers must be fully compatible with standard communications protocols, such as LonTalk, BACnet, or TCP/IP, and should also be compatible with application level software standards (XML, Java, OLE). Compatibility means that all features should be available and fully functional without requiring use of the manufacturer's software.

Upgrading HVAC Infrastructure

Current models of most air handlers and packaged equipment include microprocessor-based controls as a standard or optional feature. Most controller original equipment manufacturers (OEMS) offer a line of generic controllers that are configured to each equipment manufacturers specifications by firmware. The trend is towards control boards that (1) conform to BACnet, LonTalk, TCP/IP, or one of the half dozen widely accepted industrial control or building automation communications standards, and (2) allow firmware upgrades via the communications port. It is desirable to select equipment that uses controller hardware/firmware/communications protocols so that migration toward full integration of building controls can proceed smoothly and economically. It is also a good idea to consider the sensor suite included in each type of package and the provision for adding additional sensors and monitoring equipment in the future. The number and type of expansion inputs provided by the controller are factors that must be considered in selecting competing equipment. The ability of the controller microprocessor and associated architecture to support future FDD algorithms appropriate to the equipment type is also important but much more difficult to assess.

References

Brambley, M.R. et al., 1998. Automated diagnostics for outdoor air, ventilation, and economizers, *ASHRAE Journal*, vol. 40, no. 10, 49–55.

Braun, J.E., 1992, A comparison of chiller-priority, storage-priority and optimal control of an ice-storage system, *ASHRAE Trans*. vol. 98, part 1, AN-92-8-1, 893–902.

Building Owners and Managers Association International (BOMA), 1999, *What Tenants Want: 1999 BOMA/ULI Office Tenant Survey Report*, BOMA, Washington, DC.

Chassin, D.P., Computer software architecture to support automated building diagnostics, *Proceedings of the 1999 CIB W78 Workshop on Information Technologies in Construction*, Vancouver, Canada, vol.4, May 31–June 3, 1999.

Dexter, A.L., 1996, Intelligent buildings: fact or fiction?, *Int. J. HVAC&R Res.*, vol. 2, no. 2.

Electric Power, Revision 1, August 1999, Reticular Systems, Inc., San Diego.

EPRI, 1998, The electricity technology roadmap. *EPRI J.* November/December 1998, 25–31.

EPRI, 1999, Prototype intelligent software agents for trading electricity: competitive/cooperative power scheduling in an electronic marketplace, *EPRI Report* TR-113366.

European Intelligent Buildings Group (EIBG), June, 2000, The intelligent building, available at URL: http://www.eibg.org./.

GMD. June, 2000, Ambiente workspaces of the future, GMD — German National Research Center for Information Technology, Darmstadt, Germany, available at URL: http://www.darmstadt.gmd.de/ambiente/.

Henze, G.P., Dodier, R.H., and Krarti, M. 1997, Development of a predictive optimal controller for thermal energy storage systems, *Int. J. HVAC&R Res.*, ASHRAE, vol. 3, no. 3, 233–264.

Heschong, L., 1999, *Daylighting in Schools: An Investigation into the Relationship Between Daylighting and Human Performance*, Heschong Mahone Group for PG&E/CBEE Third Party Program, Fair Oaks, CA.

Heschong, L., 1999, *Skylighting and Retail Sales: An Investigation into the Relationship Between Daylighting and Human Performance*, Heschong Mahone Group for PG&E/CBEE Third Party Program, Fair Oaks, CA.

Intel Corporation, 2000, Intel's processor hall of fame, what is Moore's law. Available at URL: http://www.intel.com/intel/museum/25anniv/hof/moore.htm.

Katipamula, S. et al., Facilities management in the 21st century, *HPAC Heating/Piping/Air Conditioning Engineering*, July 1999, pp. 51–57.

Keeney, K.R., and Braun, J.E., 1997, Application of building precooling to reduce peak cooling requirements, *ASHRAE Trans.*, vol. 103, part 1 (PH-97-4-1), 463–469.

Keeney, K., and Braun, J.E., 1996. A simplified method for determining optimal cooling control strategies for thermal storage in building mass, *Int. J. HVAC&R Res.*, ASHRAE, vol. 2, no. 1, 59–78.

Lucent Technologies, 2000, SYSTIMAX intelligent buildings, Available at URL: http://www.lucent.com/systimax/buildings.html.

Morris, F.B., Braun, J.E., and Treado, S.J., 1994, Experimental and simulated performance of optimal control of building thermal performance, *ASHRAE Trans.*, vol.100, part 1, paper no. 3776, 402–414.

Olken, F. et al., 1996. Remote building monitoring and control, *Proceedings of the ACEEE 1996 Summer Study on Energy Efficiency in Buildings*, American Council for an Energy-Efficient Economy, Washington, D.C.

O'Neil, P., 1998. Opening up the possibilities, *Engineered Systems*, vol 15, no. 6.

PBEP, 1997, Power exchange bidding and bid evaluation protocol (PBEP), PX Tariff, Californian Power Exchange, 1997.

PSCP, 1997, Power exchange scheduling and control protocol (PSCP), PX Tariff, Californian Power Exchange, 1997.

Reticular, 1999, Using intelligent agents to implement an electronic auction for buying and selling electric power, Revision 1, August 1999, Reticular Systems, Inc., San Diego, CA.

Rossi, T.M., and Braun, J.E., 1996, Minimizing operating costs of vapor compression equipment with optimal service scheduling, *Int. J. HVAC&R Res.*, ASHRAE, vol. 2, no. 1, 3–26.

RS Means, 1999, *Mechanical Cost Data 1999.* 15 Mechanical, 157 — Air-Conditioning and Ventilation, 420–5000, RS Means Company, Inc., Kingston, MA.

SAGE Electrochromics, Inc. 2000. Sage Glass® Explained. Available at URL: http://sage.ec.com/pages/.sgexplained.html.

Seem, J.E., and Braun, J.E., 1992, The impact of personal environmental control on building energy use, *ASHRAE Trans.*, vol. 98, part 1, AN-92-8-2, 903-909.

U.S. Dept. of Energy (DOE) 2000. Recommended Future Directions for R&D in Intelligent Buildings Systems. Available at URL: http://www.eren.doe.gov/buildings/systemsfuture.html.

Webster's II New College Dictionary, Houghton Mifflin Company, Boston, 1999, p. 576.