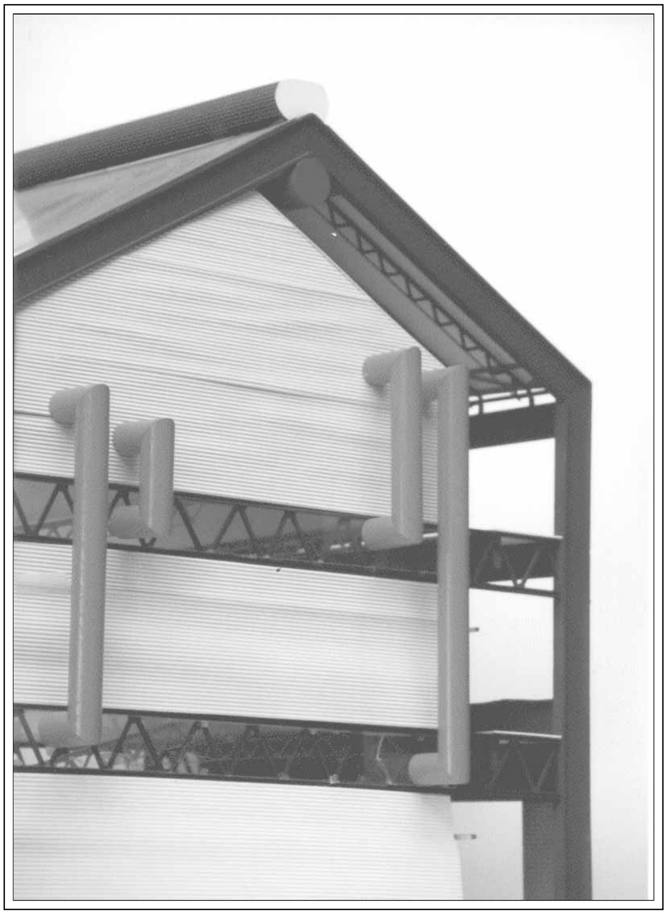
VITAL SIGNS

# HVAC COMPONENTS AND SYSTEMS



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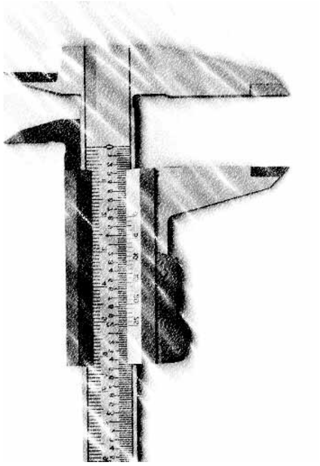

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The information and opinions presented herein are solely the responsibility of the module authors, and do not necessarily reflect the position of the Project sponsors or managers. Comments and suggestions from those who use this module are solicited.

# TABLE OF CONTENTS

# HVAC COMPONENTS AND SYSTEMS
# INTRODUCTION

This module of the Vital Signs curriculum package addresses HVAC systems. HVAC (pronounced as four separate letters) is an acronym that stands for “heating, ventilating and air-conditioning” and generally includes a variety of active mechanical/electrical systems employed to provide thermal control in buildings. Control of the thermal environment is a key objective for virtually all occupied buildings. For thousands of years such control may have simply been an attempt to ensure survival during cold winters. In the modern architectural context, thermal control expectations go far beyond survival and involve fairly complex thermal comfort and air quality concerns that will influence occupant health, satisfaction and productivity.

A heating system (“H” in HVAC) is designed to add thermal energy to a space or building in order to maintain some selected air temperature that would otherwise not be achieved due to heat flows (heat loss) to the exterior environment. A ventilating system (“V”) is intended to introduce air to or remove air from a space -- to move air without changing its temperature. Ventilating systems may be used to improve indoor air quality or to improve thermal comfort. A cooling system ("C" is not explicitly included in the HVAC acronym) is designed to remove thermal energy from a space or building to maintain some selected air temperature that would otherwise not be achieved due to heat flows (heat gain) from interior heat sources and the exterior environment. Cooling systems are normally considered as part of the “AC” in HVAC; AC stands for air-conditioning.

An air-conditioning system, by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) definition, is a system that must accomplish four objectives simultaneously. These objectives are to: control air temperature; control air humidity; control air circulation; and control air quality. Although the word “control” is often loosely construed, encompassing anything from pin-point control for central computer facilities to ballpark control for residences, the requirement that an air-conditioning system simultaneously modify four properties of air demands reasonably sophisticated systems. This module will focus on air-conditioning systems, as owner and occupant expectations for many common building types tend to require the use of this broad family of systems. Heating systems (such as portable electric heaters or fireplaces), ventilating systems (such as whole-house fans or make-up air units), and sensible-cooling-only systems are also used in buildings and will be discussed in this module. The emphasis, however, will be on multi-function air-conditioning systems.

HVAC systems are of great importance to architectural design efforts for four main reasons. First, these systems often require substantial floor space and/or building volume for equipment and distribution elements that must be accommodated during the design process. Table 1 suggests the extent of these requirements for a variety of building types. Second, HVAC systems constitute a major budget item for numerous common building types. Figure 1 summarizes HVAC cost percentages for selected building types. Third, the success or failure of thermal comfort efforts is usually directly related to the success or failure of a building’s HVAC systems (when passive systems are not used) -- even though the HVAC systems should be viewed as part of the larger architectural system. Table 2 summarizes causes for occupant complaints in existing commercial buildings and emphasizes the importance of HVAC systems to the satisfaction of occupants. Last, but not least, maintaining appropriate thermal conditions through HVAC system operation is a major driver of building energy consumption. Figure 2 provides a breakdown of energy uses for typical residences and commercial buildings in both hot and cold climates.

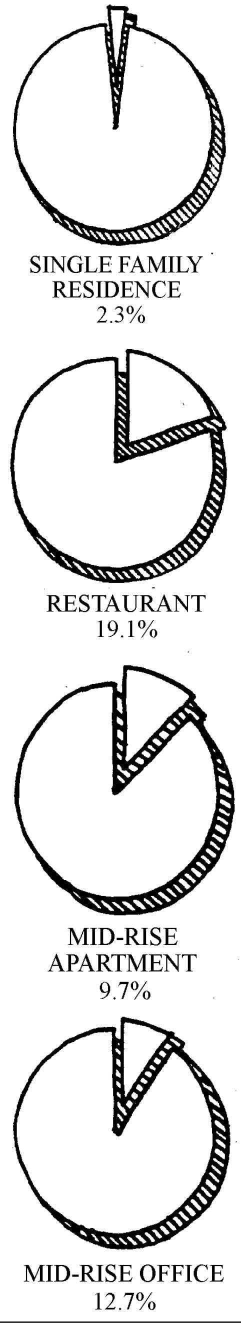


**Figure 1.** HVAC system cost as a percentage of total building construction cost for selected building types. (From various sources)

If an architect is to maintain any semblance of control over the total building design process, he or she must understand HVAC systems. HVAC systems consume an important part of the building construction budget, account for a major portion of a typical building's annual energy consumption, often require substantial space allocations (that may drive building organization schemes in larger buildings), and contribute to interior environments that are critically evaluated by building occupants on a day-by-day basis. Successful HVAC systems are often the key to successful buildings. Although it is unlikely that an architect will fully design an HVAC system, even for residential projects, it is critical that the architect manage the system design and component selection processes to retain control of the final building product. Such management requires an understanding of system objectives, the role of key system components, the types of systems that are available, and what such systems can and can not accomplish. Overseeing HVAC system development from a broad building-wide perspective, the architect can (and usually will) leave the specifics of system design to consulting engineers.

The organization of this module is based on a flow of concerns from basic principles, to components, to assemblies of components (termed systems), to applied examples of systems. Field studies to strengthen understanding of terminologies, concepts, and systems are provided following the case study examples. A glossary is included to provide easy access to the many technical terms encountered in this module. An annotated bibliography provides recommendations for other sources of information on building HVAC systems.

This module is not intended to be used as a stand-alone document. The design of HVAC systems is intimately related to other building concerns, including but certainly not limited to: lighting system design, building envelope design, thermal comfort, and indoor air quality. Cross references to other Vital Signs modules are indicated where appropriate.

TABLE 1.
HVAC System Space Requirements as a Percentage of Gross Building Floor Area

| Gross Floor Area (ft2) | Domicile-related Occupancies | Institutional Occupancies | Assembly-based Occupancies | Laboratory Occupancies |
|---|---|---|---|---|
| 10,000 | 6 % | 8 % | 9 % | 11 % |
| 50,000-100,000 | 4 % | 6 % | 7 % | 10 % |
| 500,000 | 3 % | 4 % | 5 % | 8 % |

Approximate values that include floor space for central equipment (chillers, boilers, pumps) and air circulation equipment (fans). As suggested, HVAC space requirements tend to increase with increased load density and complexity; percentage space requirements tend to decrease with increased building size. Derived from the Architect's Studio Companion (see Bibliography).

TABLE 2.
Management, Operation or Design Problems in Commercial Buildings

| Basis of Problem | Relative Frequency |
|---|---|
| Heating, ventilating and air conditioning | 5.4 |
| Elevators | 2.7 |
| Building design | 1.5 |
| Loading docks | 1.2 |
| Indoor air quality | 1.0 |
| Cleaning services | 1.0 |

Derived from the Office Tenant Moves and Changes research project conducted by the Building Owners and Managers Association International. Relative frequency suggests that problems with HVAC systems are twice as prevalent as with elevator system problems, and five times as prevalent as cleaning services problems.

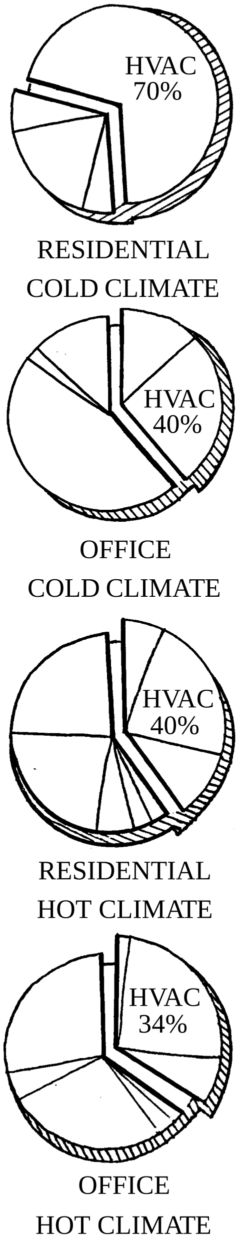


**Figure 2.** Relative percentage of total building energy use attributable to HVAC system operation in residential and office occupancies in hot and cold climates. (From various sources)

# HVAC COMPONENTS AND SYSTEMS
# HVAC COMPONENTS

## BACKGROUND

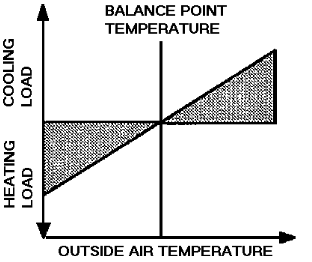


**Figure 3**. Concept of balance point temperature. (See Vital Signs module: Balance Point Temperature)

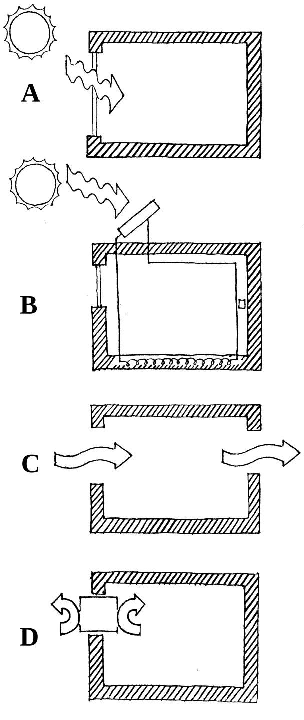


**Figure 4**. Active versus passive climate control: A - direct gain; B - solar collectors; C- cross-ventilation; D - window air-conditioner.

The basic purpose of an HVAC system is to provide interior thermal conditions that a majority of occupants will find acceptable. Occasionally this may simply require that air be moved at an adequate velocity to enhance convective cooling and evaporation from the skin. Much more commonly, however, providing for occupant comfort will require that an HVAC system add or remove heat to or from building spaces. In addition, it is normally necessary for moisture to be removed from spaces during the summer; sometimes moisture will need to be added during the winter. The heat and moisture control functions of HVAC systems provide the foundation for key system components. The additional functions of air circulation and air quality control establish further component requirements. In specific building situations, supplemental functions, such as controlling smoke from fires or providing background noise for acoustic privacy, may be imposed on an HVAC system -- along with a potential need for additional components. Before proceeding further, it is necessary to explain a number of the terms and concepts that help to define the character of an HVAC system.

Each building has a characteristic exterior air temperature, known as the balance point temperature, at which the building in use would be able to support thermal comfort without the need for a heating or cooling system. At the balance point temperature, which is strongly influenced by internal loads and envelope design, building heat gains and losses are in equilibrium so that an appropriate interior temperature will be maintained naturally and without further intervention. When the outside air temperature falls below the balance point temperature, heat losses through the building envelope will increase -- and interior air temperature will drop unless heat is added to the building to compensate. A system that provides such additional heat is called a space (or building) heating system. When the outside air temperature exceeds the balance point temperature, heat gain through the building envelope will upset thermal equilibrium and cause the interior air temperature to rise. A system that removes such excess heat is called a cooling system. Although the balance point temperature concept, Figure 3, is simplistic -- it ignores moisture flows and some solar radiation effects -- it is a convenient way of putting the basic need for HVAC systems in context. Those times of the year when heat gain is of concern are collectively termed the overheated period; the underheated period includes those times when heat loss is of concern.

Space heat may be added or removed by an electro-mechanical system, which is termed an active systems approach. An active system has the following general characteristics: it normally utilizes purchased energy for its operation, it requires special-purpose components that serve no other major building function, and it is generally relatively independent of the underlying architectural elements of the building. Alternatively, space heat may be added or removed by a system designed to make use of naturally occurring environmental forces. Such a system is termed a passive system. A passive system has the following general characteristics: it utilizes renewable site resources for energy inputs, it usually involves components that are integral parts of other building systems, and it is usually so tightly interwoven with the basic architectural fabric of a building that removal would be difficult. Figure 4 provides graphic examples of typical active and passive climate control systems. Although passive systems are valid (and perhaps preferred) for many applications, this module focuses exclusively on active HVAC systems.

Control of an HVAC system is critical to its successful operation. The issue of system control leads to the concept of HVAC zoning. During the design process, a zone is defined as a region of a building that requires separate control if comfort is to be provided for occupants. For example, it may not be possible to successfully condition a below ground office area and a glass enclosed atrium from a single control point. The dynamics of the thermal loads in the two spaces are simply not compatible. To provide comfort, each

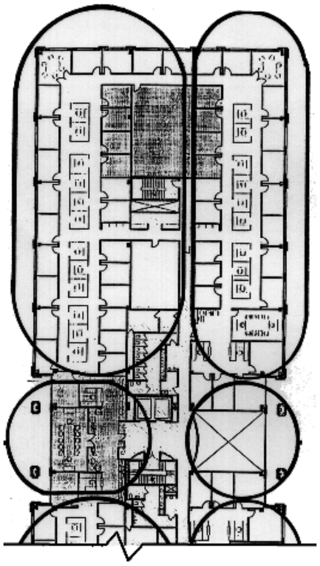


**Figure 5**. Example of thermal zoning.

space must be provided with its own control -- the climate control system must be designed to accommodate separate thermal zones. In an existing building, a zone is easily identified as an area operated from a single control point (typically a thermostat in an active system). Zoning is very much an architectural responsibility as it requires an understanding of building function and schedules. Typically the two key elements to consider when establishing thermal zones are differential solar radiation exposures (a north facade versus an east facade) and differential operating schedules and loading requirements (an occasionally used assembly hall versus a normally occupied office suite). Thermal zones must be established very early in the HVAC system design process. Figure 5 provides an example of thermal zoning for a mid-sized commercial building.

Active HVAC systems may be designed to condition a single space (or portion of a space) from a location within or directly adjacent to the space. Such a system is known as a local system. Other HVAC systems are designed to condition several spaces from one base location. Such a system, easily identified by components that distribute conditioning energy across space boundaries, is known as a central system. Figure 6 shows a building as conditioned by local systems and as conditioned by a central system. There are benefits and disadvantages to both local and central systems that are discussed in the following section.

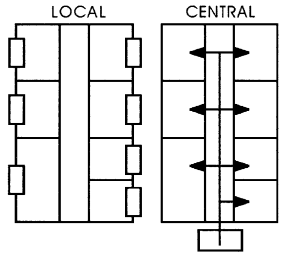


**Figure 6**. Local versus central air conditioning systems.

HVAC system components may be grouped into three functional categories: source components, distribution components, and delivery components. Source components provide or remove heat or moisture. Distribution components convey a heating or cooling medium from a source location to portions of a building that require conditioning. Delivery components serve as an interface between the distribution system and occupied spaces. Compact systems that serve only one space or zone of a building (local systems) often incorporate all three functions in a single piece of equipment. Systems that are intended to condition multiple spaces in a building (central systems) usually have distinctly different equipment elements for each function.

## SOURCE COMPONENTS

Four distinctly different types of heat sources are employed in buildings. Heat may be generated by the combustion of some flammable material (a fuel) such as coal or natural gas. Electricity may be converted to heat through the process of electric resistance. Solar radiation or other renewable energy resources may be collected on site and converted to heat. Heat may be removed from some material on site and transferred into a building. Figure 7 provides a graphic summary of these basic heat sources. All four of these fundamental heat sources find common use in all scales of buildings. The choice of a heat source for a given building situation is usually based upon source availability, required system capacity, and equipment and fuel costs.

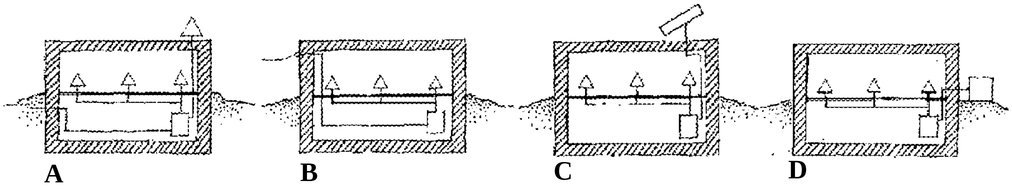


**Figure 7**. Basic sources for building heat: A - on-site combustion; B- electric resistance; C - solar collector on roof to furnace; D - heat pump in furnace.

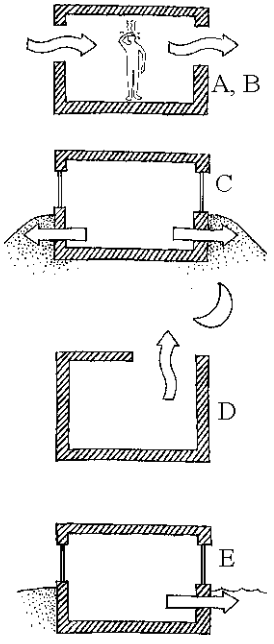


**Figure 8**. Natural heat sinks: A - outside sensible air temperature; B - outside latent air conditions; C - soil temperature; D - night sky radiation; E - on-site water body.

Although cooling is technically just a reverse heat flow -- the flow of heat into a sink, rather than from a source -- sources of cooling (heat sinks) are not always readily available. The term "coolth" is sometimes used to identify the product of heat flowing to a sink. Identification of coolth sources is actually the identification of available heat sinks. Heat sinks of interest to building design are either naturally occurring environmental phenomena or artificially induced phenomena. Naturally occurring heat sinks, noted in Figure 8, include outside air -- its sensible (temperature) and latent (humidity) conditions, the night sky, on-site water bodies, and on-site soil. Use of such natural sinks is the basis for passive cooling systems. Unfortunately, the availability and/or capacity of natural heat sinks is often exceptionally limited during overheated periods of the year, making passive cooling most difficult when most needed. Active system heat sinks are artificially established through the operation of some type of refrigeration device. There are three main refrigeration approaches employed in buildings: vapor compression (mechanical) refrigeration, absorption (chemical) refrigeration, and evaporative cooling. Figure 9 summarizes the active heat sinks in graphic format. The choice of a coolth source is usually based upon resource availability, energy and equipment costs, and appropriateness to the building context.

Although often driven by availability or consumer economics, the choice of a heat source and/or source of cooling will have architectural ramifications that must be considered during design. Table 3 provides a summary of heat sources and their potential applications in buildings. Table 4 provides a similar summary for cooling sources. Summaries of architectural considerations related to these heat and coolth source options are provided in Tables 5 and 6. A brief discussion of some of the most commonly encountered heating and cooling source components for active systems is given below.

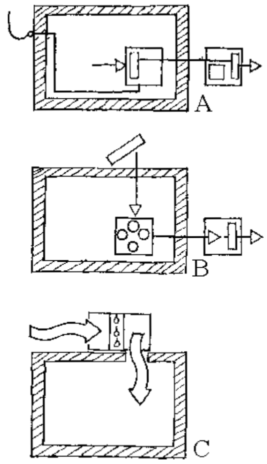


**Figure 9**. Active systems for building cooling: A - vapor compression; B - absorption; C - evaporative cooling.

Fireplace: a fireplace is, as its name suggests, a location where on-site combustion is used as a means of producing heat. A descendent of the campfire, the typical fireplace consists of a niche or well constructed of non-combustible materials that will withstand the temperatures generated during the combustion process. Although freestanding fireplaces are sometimes used, most fireplaces are installed in exterior walls as shown in Figure 10. By its design and scale a fireplace functions as a local heating system -- directly providing heat for a limited area of a building. As heat distribution from fireplaces is often totally by natural radiation and convection, many fireplaces act as passive heating systems. Adding fans to circulate heated air can move a fireplace into the realm of hybrid or active systems and increase efficiency.

Wood Stove: wood stoves, Figure 11, are sophisticated on-site combustion devices, normally self-contained and freestanding, that provide higher efficiency than fireplaces. Tight control of combustion air permits more substantially complete combustion, resulting in improved resource utilization and less potential for problems from infiltration. As with a fireplace, wood stoves are effectively a local heating device directly providing heat to a limited area of a building.

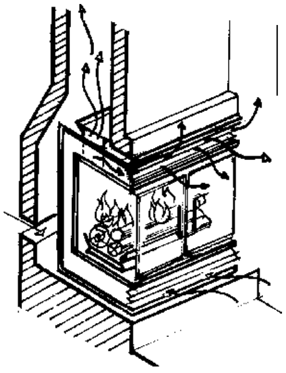


**Figure 10**. Fireplace as a local heating system

**Figure 11**. Wood stove as a local heating system

TABLE 3.
Building Heating Sources Matrix

| HEAT SOURCE | PASSIVE | | ACTIVE | | | |
|---|---|---|---|---|---|---|
| | LOCAL | CENTRAL | LOCAL | CENTRAL ............. | Distribution ........... | Delivery |
| On-Site Combustion | Fireplace, Stove | Convective Furnace | Unit Heater | Furnace | Ducts (air) | Diffusers or registers |
| | | | | Boiler | Pipes (water) | Baseboard radiators |
| | | | | Boiler | Pipes (steam) | AHU heating coils |
| Electrical Resistance | N/A | N/A | Unit Heater, Portable Heater, Electric Baseboard | Furnace or | Ducts (air) | Diffusers or registers |
| | | | | AHU | Ducts (air) | Diffusers or registers |
| | | | | Boiler | Pipes (water) | Radiant panels |
| Heat Transfer | N/A | N/A | Heat Pump— Window or Split | Central Heat Pump | Ducts(air)<br>Pipes (water) | Diffusers or registers<br>Coils or other devices |
| Heat Collection | Direct gain<br>Indirect gain | Isolated gain | N/C | Air Heating,<br>Water Heating | Ducts (air)<br>Pipes (water) | Diffusers or registers<br>Radiators or coils |

Notes: this table should in NO way be considered a comprehensive listing of all possible building heating options — it simply provides an overview of typical systems and common applications; N/A = not applicable; N/C = not common; AHU = air handling unit.

TABLE 4.
Building Cooling Sources Matrix

| HEAT SINK | PASSIVE | | ACTIVE | | | |
|---|---|---|---|---|---|---|
| | LOCAL | CENTRAL | LOCAL | CENTRAL ................ | Distribution ............ | Delivery |
| Ambient Outside Air (Sensible) | Local Ventilation [window] | Central Ventilation [stack] | Local Ventilation [window fan] | Central Ventilation [fan] | Ducts or building spaces | Diffusers/registers;<br>Openings/spaces |
| Ambient Outside Air (Latent) | Evaporative Cooling | N/C | Evaporative Cooler | Evaporative Cooler | Ducts or building spaces | Diffusers/registers;<br>Openings/spaces |
| Water from Site | N/A | N/A | N/C | AHU with water coil | Ducts | Diffusers/registers |
| Soil (Earth) | Indirect Contact | N/A | N/C | Ground source heat pump | Ducts | Diffusers/registers |
| Night Sky (Radiation) | Direct or Indirect | N/A | N/A | Ice-making system | Ducts (with AHU) | Diffusers/registers;<br>Fan coils |
| Active Heat Transfer | N/A | N/A | Refrigeration [vapcom] | Refrigeration [vapcom, abs] | Ducts (with AHU) [central A/C] | Diffusers/registers;<br>Fan coils |

Notes: this table should in NO way be considered a comprehensive listing of all possible building cooling options — it simply provides an overview of typical systems and common applications; N/A = not applicable; N/C = not common; AHU = air handling unit; vapcom = vapor compression; abs = absorption.

TABLE 5.
Building Heating Systems - Architectural Implications Matrix

| HEAT SOURCE | TYPE | EXTERIOR ISSUES | INTERIOR ISSUES | OTHER ISSUES |
|---|---|---|---|---|
| On-Site Combustion | Wood | Wood storage, flue, combustion air | Dry storage, flue, equipment | Ash removal |
| | Gas | Meter, flue, combustion air | Flue, equipment | |
| | Oil | Fuel inlet, flue, combustion air | Storage tank, flue, equipment | |
| | Coal | Fuel inlet, flue, combustion air | Storage bin, flue, equipment | Ash removal |
| Electrical Resistance | Various | Normal service entrance | Equipment, circuitry | |
| Heat Transfer | Air source | Condenser unit | Equipment | |
| | Water source | Cooling tower, well | Equipment, (integration) | |
| | Ground source | Heat "field" | Equipment | |
| Heat Collection | Active | Collectors (area, tilt, orientation) | Equipment (additional) | Back-up system |
| | Passive | Aperture (area, orientation) | Storage, controls, distribution | User intervention |
| District Heating | Water | Connection to off-site source | Pumps, equipment (less source) | |
| | Steam | Connection to off-site source | Heat exchanger, equipment (" ") | |

Note: this table should in NO way be considered a comprehensive listing of all possible building heating concerns - it simply provides an overview of typical systems and common architectural integration issues.

TABLE 6.
Building Cooling Systems - Architectural Implications Matrix

| HEAT SINK | TYPE | EXTERIOR ISSUES | INTERIOR ISSUES | OTHER ISSUES |
|---|---|---|---|---|
| Ambient Outside Air (Sensible) | Local vent (P)<br>Central vent (P)<br>Local vent (A)<br>Central vent (A) | Inlet/outlet openings, orientation<br>Inlet/outlet openings, orientation<br>Inlet opening, outlet, possibly fan<br>Inlet opening, outlet | Spatial layout w/r/t air flow<br>Air circulation paths, layout<br>Spatial layout w/r/t air flow<br>Equipment space, layout/ducts | Comfort ventilation<br>Structural ventilation<br>Security, privacy, dust |
| Ambient Outside Air (Latent) | Evap. cooling (P)<br>Evap. cooler (A) | Inlet-water source arrangement<br>Equipment location/inlet | Spatial layout w/r/t air flow<br>Spatial layout or ductwork | Materials selections<br>Maintenance |
| Water from Site | AHU/water coil | Water source | Equipment space, distribution potential | Latent cooling |
| Soil (earth) | Earth contact (P)<br>Ground source (A) | Soil depth, type, vegetation<br>Soil type, vegetation | Spatial layout<br>Equipment space, distribution | Regional issues |
| Night Sky Radiation | Building parts (P)<br>Equipment (A) | View of sky, surface area<br>Location, area | Spatial layout<br>Equipment space | Seasonal issues<br>Experimental |
| Heat Transfer | Refrigeration | Condenser location | Evaporator location, equipment | Local/central |

Note: this table should in NO way be considered a comprehensive listing of all possible building cooling concerns — it simply provides an overview of typical systems and common architectural integration issues; (P) indicates passive; (A) indicates active; w/r/t means with respect to; AHU = air handling unit; Evap. = evaporative.

**Figure 12**. Exterior view of a gas furnace.

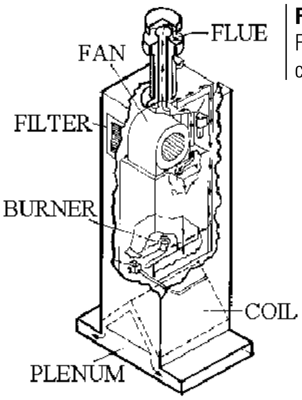


**Figure 13**. Furnace components.

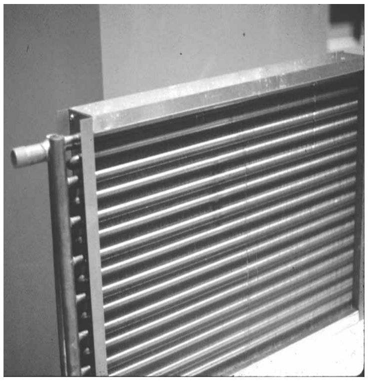


**Figure 14**. A coil.

Furnace: a furnace, Figure 12, is a heating system component designed to heat air for distribution to various building spaces. Small-capacity furnaces that rely on natural convection for heat distribution would be classified as local systems and usually effectively condition only one space. Furnaces equipped with fans to circulate air over greater distances or to several rooms would be found in central systems. All four heat source categories are used with furnaces, including on-site combustion (coal, oil, natural gas, propane), electric resistance, on-site energy collection (solar energy), and heat transfer (heat pumps). A furnace is a packaged assembly of components that normally includes a heat-source element (burner or coil), a fan (for central units), and an air filter -- as illustrated in Figure 13. A burner consists of an arrangement of nozzles that permits the efficient combustion of liquid or gaseous fuels by providing good mixing between the fuel and the oxygen necessary for combustion. A coil, Figure 14, consists of a series of heat exchange surfaces that are either the heat source (electric resistance coils) or provide close thermal contact with a heat distribution medium (hot water or steam coils in air handling units or fan-coils).

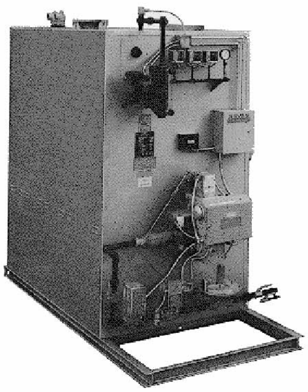


**Figure 15**. Exterior view of a boiler.

Boiler: a boiler (shown in Figure 15) is a heating system component designed to heat water for distribution to various building spaces. As water can not be used to directly heat a space, boilers are only used in central systems where hot water is circulated to delivery devices (such as baseboard radiators, unit heaters, convectors, or air-handling units). Boilers are commonly designed to utilize two of the four basic heat sources: on-site combustion (coal, oil, natural gas, propane) and electric resistance. Boilers are a packaged assembly of components that normally includes a heat-source element (burner or electric resistance coil) and some volume of water storage. Depending upon design intent, a boiler may produce either hot water or steam. An on-site solar energy collection system may serve in lieu of a boiler. Heat transfer systems (heat pumps) likewise may serve as a substitute for a boiler.

**Figure 16**. Portable electric resistance heater.

Portable Heaters: numerous consumer appliances are available to provide spot heat wherever needed. Portable heaters are normally occupant selected and “installed”, often to supplement conditions provided by another (presumably less than successful) heating system. Such portable devices, however, might collectively constitute a complete building heating system. Portable electric resistance heaters, Figure 16, are more common than portable combustion heaters as they involve fewer air quality and safety concerns. Portable heaters are designed to operate as local systems serving a fairly small area. Small-scale electric resistance heaters are also available as built-in units (as in Figure 17), to provide a permanent, localized source of heat.

**Figure 17**. Built-in electric resistance heater.

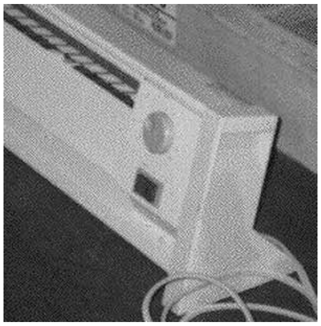


**Figure 18**. Electric baseboard radiator.

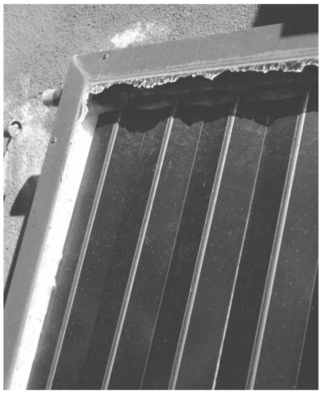


**Figure 19**. Active solar collector.

Electric Baseboard Radiation: sometimes called electric strip heaters, baseboard radiation is a fairly common heat source and heating system. Compact heating elements enclosed in protective and decorative linear housings, as shown in Figure 18, are permanently installed along the lower part of one or more room walls -- near the intersection with the floor. Room air heated by the resistance element rises and is replaced by cooler room air, establishing a continuous convective flow of warm air while in operation. Although various control schemes are possible, baseboard radiation would typically function as a collection of local heating systems -- although the collection might be considered a central system by building occupants.

Solar Thermal Collector: solar collectors may be used to heat air or water for building heating purposes. Water-heating collectors may replace or supplement a boiler in a water-based heating system. Air-heating collectors may replace or supplement a furnace. As solar energy in an active solar system is typically collected at a location remote from the spaces requiring heat, solar collectors are normally associated with central systems. Solar water-heating collectors may also provide heated water that can be used for space cooling in conjunction with an absorption refrigeration system. Figure 19 provides a view of a water-based solar collector (with glass cover removed).

Heat Pump: a heat pump is a reversible cycle vapor compression refrigeration unit. Through the addition of a special control valve, heat flow in a mechanical refrigeration loop can be reversed so that heat is extracted from the outside air (or ground water or soil) and rejected into a building. As described in detail below, the purpose of a conventional refrigeration cycle is to establish heat flow in the opposite direction (from cool to warm). Figure 22 illustrates the operation of a vapor compression unit in heat pump mode.

Vapor Compression Refrigeration Unit: the most commonly used active cooling approach involves the operation of a vapor compression refrigeration cycle to induce heat to move in a direction contrary to gross environmental temperature differences. During the overheated period, the outside air temperature is usually not just above the balance point temperature but also above the indoor air temperature. Under such conditions, heat flow will be from higher to lower temperature (from outside to inside). Maintaining thermal comfort during the overheated period requires that heat be removed from a building, not added to it. Through a series of artificially maintained temperature and pressure conditions in a heat transfer fluid (refrigerant), established through the action of four primary components, a refrigeration system can induce heat to flow from inside a cooler building to a warmer outside environment.

A vapor compression unit establishes a heat sink through the flow of a refrigerant in a fixed loop between a compressor, a condenser, an expansion valve, and an evaporator -- shown schematically in Figure 20. The compressor (in centrifugal, reciprocating, or screw configurations) adds energy to the refrigerant that increases its pressure. From the compressor, high-pressure, high-temperature refrigerant is circulated to a condenser. The condenser indirectly exposes the refrigerant to air or water of lower temperature. The

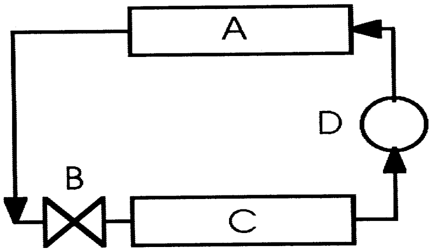


**Figure 20**. Components of vapor compression refrigeration cycle:
A - condenser; B - expansion valve;
C - evaporator; D - compressor.

**Figures 21 & 22**. Schematic operation of vapor compression refrigeration system and reverse-cycle vapor compression heat pump, respectively: A - condenser; B - expansion valve; C - evaporator; D - compressor; 1 - hot refrigerant gas; 2 - air or water heated by refrigerant gas; 3 - hot liquid refrigerant; 4 - cold mixture of refrigerant gas and liquid; 5 - air or water cooled by refrigerant; 6 - warmed refrigerant gas. In heat pump (heating) mode, a valve changes flow patterns so inside coil becomes condenser and outside coil becomes evaporator.

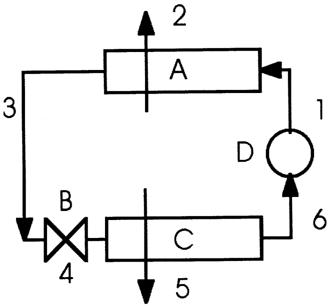


**Figure 21**.

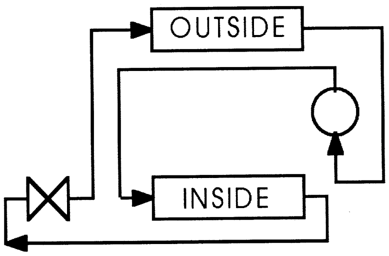


**Figure 22**.

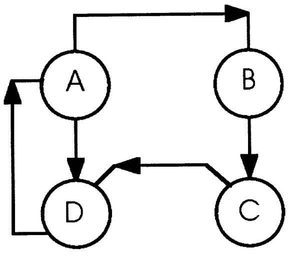


**Figure 23**. Absorption refrigeration cycle: A - generator; B - condenser; C - evaporator; D - absorber.

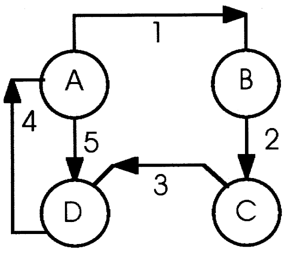


**Figure 24**. Schematic operation of absorption refrigeration cycle:
A - generator; B - condenser;
C - evaporator; D - absorber;
1 - refrigerant gas (water vapor);
2 - liquid refrigerant (water);
3 - refrigerant gas; 4 - mixture of refrigerant and salt solution;
5 - concentrated salt solution.

exchange of heat from the refrigerant to air or water permits the refrigerant to condense from the vapor state to the liquid state. This change of state releases a substantial amount of heat that is also absorbed by the air or water flowing through the condenser. Liquid refrigerant with a lower energy content is then circulated to an expansion valve. The expansion valve produces a pressure drop large enough to cause part of the liquid refrigerant to evaporate (due to reduced pressure -- not due to elevated temperature). The change from the liquid to vapor state (known as evaporation) requires energy input. As a small percentage of the refrigerant evaporates after passing through the expansion valve, the temperature of the refrigerant is reduced as heat is removed to drive the evaporation process. The cooler refrigerant mixture (vapor and liquid) is then circulated to the evaporator. Room air or chilled water brought into indirect contact with the refrigerant provides heat for the complete evaporation of all remaining liquid refrigerant. The transfer of this heat from the air or water to the refrigerant reduces the temperature of the air or water. The cooled air or water may then be used as a heat sink for the building. Figure 21 summarizes the operation of a vapor compression refrigeration cycle.

<u>Absorption Refrigeration Unit</u>: the basic concept behind an absorption refrigeration unit is the same as that for a vapor compression unit; the means of execution, however, is substantially different. Water, acting as the refrigerant, is circulated between a generator, a condenser, an evaporator, and an absorber. Heat is added to the generator, which causes the refrigerant to evaporate. The vapor-state refrigerant is conveyed to the condenser where heat is removed by transfer to condenser water or air and the refrigerant is condensed to liquid. The refrigerant is then transferred to the evaporator where it accepts heat from room air or chilled water. The fully evaporated (gaseous) refrigerant then travels to the absorber and from the absorber to the generator where the cycle continues. The driving force in the absorption refrigeration cycle is chemical -- as opposed to the mechanical driving force in a vapor compression unit. A desiccant salt is used to attract water (the refrigerant) and induce its flow through the components that comprise the cycle. Water vapor is pulled to the absorber by the desiccant. In order to continue the cycle, the desiccant must be continuously regenerated (dried) so it may continue to attract refrigerant. The drying of the desiccant occurs in the generator, where water is driven off the desiccant-water mixture that was produced in the absorber. Heat, often from a solar collector or waste heat from an industrial process, is used as an external energy input to power the cycle. The components of the absorption refrigeration process are shown in Figure 23; Figure 24 illustrates the operation of this type of refrigeration cycle.

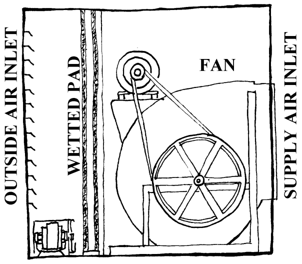


**Figure 25**. Diagram of an evaporative cooler.

Evaporative Cooling Unit: in hot dry climates, usable cooling effect may be obtained from the evaporative cooling process. Evaporative cooling is a basic psychrometric process in which air is sensibly cooled while it is simultaneously humidified. An evaporative cooler is a packaged unit that contains components to govern this process in a manner that can produce reasonable cooling capacities. Dry air is pulled into the evaporative cooler by a fan. The dry air is passed through some porous media that is wetted with water. As the air contacts the water spread over the media, much of the water evaporates. The energy required to evaporate the water comes from the air. As the air passes through the cooling unit it is humidified -- but also cooled. A schematic diagram of an evaporative cooler is shown in Figure 25. The evaporative cooling process is basically an exchange of latent energy (humidity) for sensible energy (temperature). Where climate permits, as per Figure 26, evaporative cooling can provide an energy-efficient (but water-consumptive) means of building cooling. Indirect and 2-stage evaporative cooling units are also available.

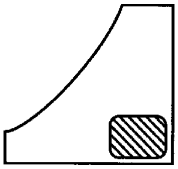


**Figure 26**. Climatic range of evaporative cooling.

DX Systems: in a DX (direct expansion) system the evaporator of the refrigeration cycle (in the form of a cooling coil) is placed in an air handling unit so that the room cooling effect is produced directly by room air flowing across the evaporator. Window air-conditioners, unitary or through-the-wall air conditioners, rooftop package units, and split systems are typically DX systems. A limitation of approximately 100 feet for maximum separation between compressor and evaporator applies to all DX system installations. Capacity control in DX systems is most commonly accomplished by cycling the refrigeration compressor on and off.

Chiller: a chiller is a refrigeration unit designed to produce cool (chilled) water for space cooling purposes. The chilled water is then circulated to one or more cooling coils located in air handling units, fan-coils, or induction units. Chilled water distribution is not constrained by the 100 foot separation limit that applies to DX systems, thus chilled water-based cooling systems are typically used in larger buildings. Capacity control in a chilled water system is usually achieved through modulation of water flow through the coils; thus, multiple coils may be served from a single chiller without compromising control of any individual unit.

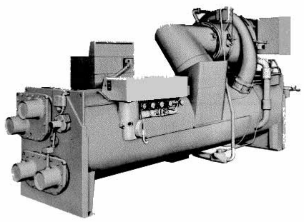


**Figure 27**. Vapor compression chiller.

Chillers may operate on either the vapor compression principle or the absorption principle. Vapor compression chillers may utilize reciprocating, centrifugal, screw, or rotary compressor configurations. Reciprocating chillers are commonly used for capacities below 200 tons; centrifugal chillers are normally used to provide higher capacities; rotary and screw chillers are less commonly used, but are not rare. Heat rejection from a chiller may be by way of an air-cooled condenser or a cooling tower (both discussed below). Vapor compression chillers may be bundled with an air-cooled condenser to provide a packaged chiller, which would be installed outside of the building envelope. Vapor compression chillers may also be designed to be installed separate from the condensing unit; normally such a chiller would be installed in an enclosed central plant space. Absorption chillers are designed to be installed separate from the condensing unit. Figure 27 illustrates a typical vapor compression chiller, Figure 28 an absorption chiller.

**Figure 28**. Absorption chiller.

Air-Cooled Condenser: an air-cooled condenser, Figure 29, is a heat rejection device, installed outside of the building envelope, through which refrigerant is circulated. As the refrigerant comes into indirect

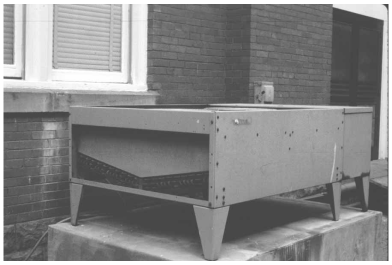


**Figure 29**. Air-cooled condenser.

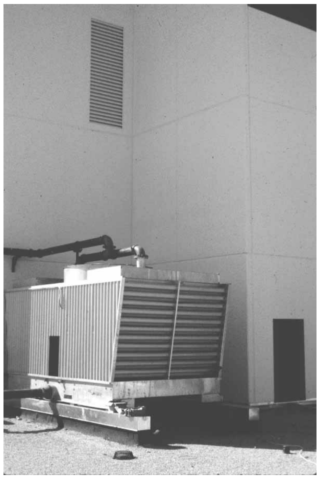


**Figure 30**. Cooling tower.

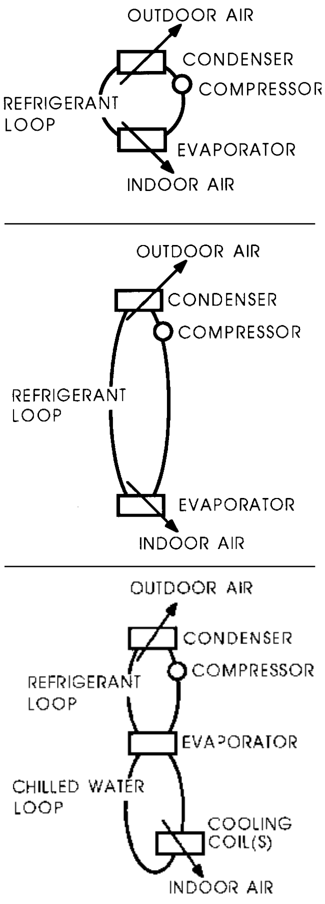
contact with outside air, heat is exchanged from the relatively hot refrigerant to the relatively cooler air. Heat exchange is enhanced by fan-forced flow of large volumes of air across the heat exchange coils. An air-cooled condenser is a sensible heat exchange device, where the magnitude of heat flow is a function of the temperature difference between the refrigerant and the outside air dry bulb temperature.

Cooling Tower: a cooling tower, Figure 30, is a heat rejection device, installed outside of the building envelope, through which condenser water is circulated. Refrigerant in the refrigeration cycle is condensed in a refrigerant-to-water heat exchanger. Heat rejected from the refrigerant increases the temperature of the condenser water, which must be cooled to permit the cycle to continue. The condenser water is circulated to the cooling tower where evaporative cooling causes heat to be removed from the water and added to the outside air. The cooled condenser water is then piped back to the condenser of the chiller. A cooling tower is a latent heat exchanger, where the magnitude of heat flow is a function of the quantity of water that is evaporated -- which is primarily a function of the relative humidity of the outside air.

As suggested by the above discussion of DX units, chillers, and condenser units, numerous refrigeration configurations are available for building applications. Figure 31 illustrates many of these configuration options. The appropriate configuration for any particular building situation will be determined by building scale, required cooling capacity, economics, and climate.

Energy Efficiency Measures: because of their central role in HVAC systems operation, source components commonly play an instrumental role in overall system energy efficiency. There are a number of ways by which to express the efficiency of a heating or cooling source. Understanding these efficiency measures is critical to the design of energy-efficient systems. The instantaneous performance of a heat source is expressed in terms of efficiency. Efficiency is defined as output divided by input, where output and input are in the same units. A simple statement of efficiency usually implies full load (peak) efficiency. Throughout the year, heating equipment operates more often at off-peak (less than maximum load) conditions than at full load, so that peak efficiency is deceptive. Seasonal efficiencies that consider a typical range of operating conditions and loads are more representative of the real world.

Cooling sources are not comfortably represented by efficiency. The energy input to a cooling system serves as a catalyst for the movement of heat from one location to another; thus, apparent efficiency values can exceed 1.0 if output effect is compared to driving energy input. As stating efficiencies greater than 100% is potentially confusing (and theoretically impossible), a different measure -- the coefficient of performance -- is used to rate cooling system performance. The coefficient of performance (COP) is



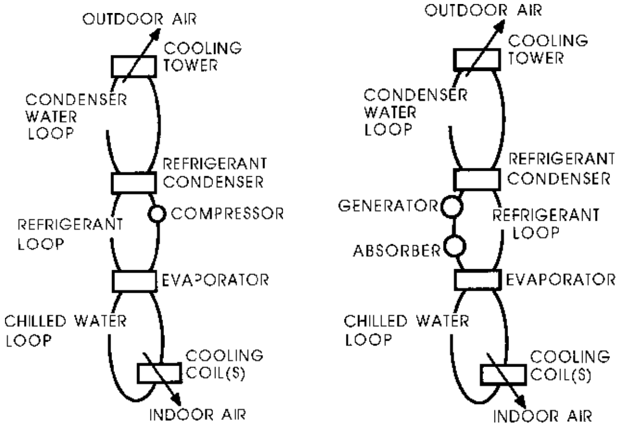


**Figure 31**. Configuration options for active building cooling.

defined as the cooling output divided by the energy input, where output and input are in the same units. As with efficiencies, COP may be expressed on either an instantaneous basis or a seasonal basis. Several secondary efficiency measures have been developed to express equipment efficiency over time and under normal operating conditions. Table 7 summarizes commonly specified equipment efficiency measures and presents typical heating and cooling source efficiency and coefficient of performance magnitudes extracted from ASHRAE Standard 90.1. Standard 90.1 is cited by the U.S. Energy Policy Act of 1992 (EPACT) as the reference standard for non-residential buildings. Similar efficiency measures are used with residential-scale equipment. The choice of heating/cooling source may greatly affect HVAC system efficiency. Appropriate system selection, skillful design, commissioning, and proper operation and maintenence practices will also play a major role in system efficiency.

There is potential controversy surrounding system efficiencies, as the definition of a system's boundary will affect the outcome of the analysis. For example, electric resistance systems are 100% efficient if the analysis boundary is considered to be the building envelope. If the boundary is expanded to include the electrical transmission and generation systems, efficiency will drop to perhaps 20% due to energy losses inherent in those processes. Providing an even playing field for energy-efficiency comparisons is not an easy task. Energy-efficiencies typically used for building design purposes are exclusively site efficiencies.

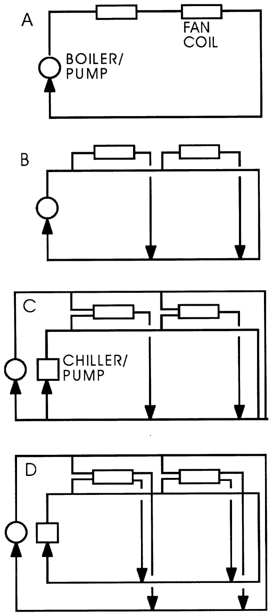


**Figure 32**. Typical distribution configurations for HVAC piping: A - series; B - parallel; C - parallel 3-pipe; D - parallel 4-pipe.

## DISTRIBUTION COMPONENTS

Central systems produce a heating and/or cooling effect in a single location. This effect must then be transmitted to the various spaces in a building that require conditioning. Three transmission media are commonly used in central systems: air, water, and steam. Hot air can be used as a heating medium, cold air as a cooling medium. Hot water and steam can be used as heating media, while cold water is a common cooling medium. A central system will always require distribution components to convey the heating or cooling effect from the source to the conditioned locations.

In a water-based central system, pipes are used to convey water from the source to the final delivery components. A minimum of two pipes is necessary, one for supply water and one for return water, to establish a distribution loop. Closed circuit loops are universally employed as it is more economical to heat or cool water in a closed loop than in an open system. When both heating and cooling are required in a building, 3-pipe and 4-pipe distribution systems may be used to increase system flexibility. A 2-pipe system can only heat or cool, simultaneous heating and cooling -- not an uncommon requirement in large buildings -- is not possible with a 2-pipe system. A 3-pipe system has two supply pipes (hot and cold water) and a single return. The mixing of heating and cooling water in a single return is not energy efficient and is not recommended. A 4-pipe distribution system has two supply pipes and two separate return pipes (hot and cold). The 4-pipe arrangement provides the greatest control flexibility in the most energy-efficient manner. Figure 32 summarizes common HVAC system piping configurations.

Several piping materials are used in HVAC distribution systems. Steel pipes are by far the most common, although copper may be used when economic or environmental conditions dictate. Hot and cold (chilled) water pipes in HVAC distribution systems are normally insulated. Minimum insulation requirements are prescribed in energy codes and standards. Numerous accessories will be found in typical HVAC piping systems. Valves are used to control water flow as a means of adjusting system heating or cooling capacity to the demands of the building thermal zones. Valves are also used to shut off water flow so that equipment may be maintained. Common valve types are shown in Figure 33. A range of gauges, Figure 34, is used to balance system flows and verify temperature and pressure conditions. Such instrumentation provides a means to check the vital signs of an operating system and becomes increasingly important if systems are to be commissioned.

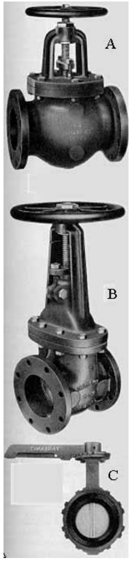


**Figure 33**. Common valves for HVAC applications.

TABLE 7.
Efficiency Measures for HVAC System Components

| MEASURE | MEANING | DEFINITION | TYPICAL VALUES |
|---|---|---|---|
| AFUE | ANNUAL FUEL UTILIZATION EFFICIENCY | ANNUAL OUTPUT ENERGY OF EQUIPMENT DIVIDED BY ANNUAL INPUT ENERGY (IN CONSISTENT UNITS AND INCLUDING ALL PILOT LOSSES) | 80 - 85 % |
| COP | COEFFICIENT OF PERFORMANCE | HEATING OR COOLING OUTPUT OF SYSTEM EQUIPMENT DIVIDED BY ENERGY INPUT (IN CONSISTENT UNITS) | 2 - 4 |
| E | THERMAL EFFICIENCY | EQUIPMENT OUTPUT DIVIDED BY ENERGY INPUT (IN CONSISTENT UNITS) | 75 - 85 % |
| EER | ENERGY EFFICIENCY RATIO | EQUIPMENT COOLING CAPACITY IN BTUH DIVIDED BY ENERGY INPUT IN WATTS (EER = COP X 3.41) | 8 - 10 |
| HSPF | HEATING SEASONAL PERFORMANCE FACTOR | TOTAL HEATING OUTPUT OF A HEAT PUMP DURING NORMAL OPERATING SEASON (IN BTU) DIVIDED BY THE TOTAL ELECTRIC INPUT DURING THE SAME PERIOD (IN W-H) | 7 |
| IPLV | INTEGRATED PART LOAD VALUE | A SINGLE NUMBER VALUE THAT EXPRESSES PART-LOAD EFFICIENCY OF AIR CONDITIONING EQUIPMENT (BASED ON EER OR COP) WEIGHTED BY OPERATION AT VARIOUS PART-LOAD CAPACITIES | 3 - 8 |
| SEER | SEASONAL ENERGY EFFICIENCY RATIO | TOTAL COOLING OUTPUT OF AIR CONDITIONING EQUIPMENT DURING NORMAL OPERATING SEASON (IN BTUH) DIVIDED BY THE TOTAL ELECTRIC INPUT DURING THE SAME PERIOD (IN W-H) | 10 |

Some typical equipment efficiency values are as follows: electric resistance -- 100% (site basis only); gas-fired furnace/boiler -- 90 to 98%; fireplace/wood stove -- -10% to 50% (very dependent upon design); vapor compression refrigeration -- 2.0 to 3.5 COP; absorption refrigeration -- 0.6 to 0.8 COP.

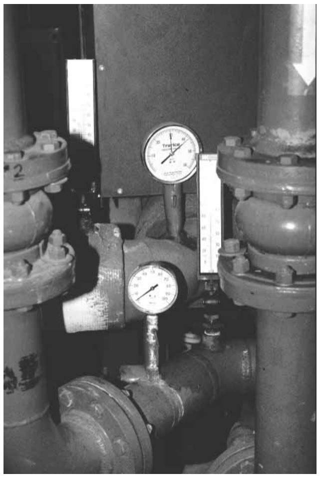


**Figure 34**. Gauges for HVAC applications.

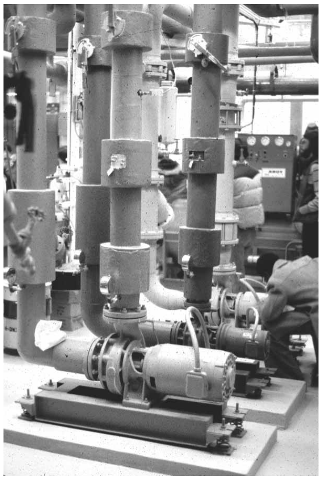


**Figure 35**. Centrifugal pumps.

Water will not normally flow through a complex distribution system without the assistance of some driving force -- friction losses through the piping, accessories, and equipment are simply too extensive. A pump is used to provide the energy input required to overcome friction losses and circulate water through a system. The typical central HVAC system may require the use of several pumps: for hot water, for chilled water, and often for condenser water. Pumps come in a variety of designs and capacities and can be driven by electric motors, combustion engines, or steam. Electric motor driven centrifugal pumps, Figure 35, are by far the most commonly used for HVAC system applications.

In an air-based central system, ducts (ductwork) are used to convey air from a primary or secondary source to the final delivery components. Typically, two duct paths are necessary, one for supply air and one for return air. Air distribution loops often recirculate as much indoor air as possible, as it is more economical to heat or cool return air than outdoor air. In practice, outside air should always be brought into the air circulation loop to assist in providing acceptable indoor air quality (refer to the Vital Signs module: Health in the Built Environment). The air that is displaced by such outdoor air is either allowed to leak out of the building envelope, is exhausted by bathroom and kitchen exhaust fans, or is exhausted to the outside by dedicated exhaust fans provided to maintain building pressure balances. Return air is often channeled back to the source through building voids such as a plenum or a chase. Using the building fabric itself as a return air path can provide economies of space and cost when properly done. Supply air is rarely distributed without ductwork containment due to the high likelihood of uncontrolled distribution. Figure 36 illustrates common supply and return air distribution configurations.

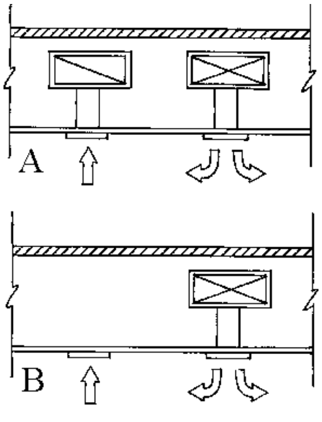


**Figure 36**. Common ductwork configurations: A - ducted supply and return; B - ducted supply with plenum return.

Ductwork systems are classified as either high-pressure or low-pressure systems and as high-velocity or low-velocity systems, depending on their static pressure and air speed design parameters, respectively. Supply ductwork will usually be designed to operate at low-velocity and low-pressure unless building constraints dictate otherwise. Increasing air flow velocity allows the use of smaller duct cross sections, which may be necessary in buildings with constricted distribution spaces. Higher pressures are required as the pressure loss in the distribution system increases; a long distribution path or the use of system-powered terminal devices may necessitate increased distribution pressures. Increasing distribution system pressure, however, increases HVAC system energy consumption. Return ductwork is usually low-velocity and low-pressure. ASHRAE Standard 90.1 places efficiency restrictions on duct distribution systems in the form of Watt per cfm (cubic feet per minute, a measure of volumetric air flow) limits for fan power.

Several materials, as illustrated in Figure 37, are commonly used to construct ducts. Sheet metal (galvanized steel) is probably the most common material. Glass fiber insulation board, which provides containment and insulation in a single material, is also a common duct material for low-pressure systems. Flexible ducts, comprised of plastic wrap over a spiral metal framework, are often used to connect terminal or delivery devices to main distribution ducts. Duct shapes include square or rectangular, circular, and flat oval cross sections, as shown in Figure 38. A circular cross section is most economical with respect to material and friction losses. A rectangular cross section, however, is often more likely to fit in the types of spaces available for duct placement. Supply ducts are insulated to reduce heat gain from unconditioned spaces and warm plenums through which they may be routed. Minimum insulation requirements are specified by energy codes and standards (such as ASHRAE Standard 90.1). Return air ductwork is normally uninsulated.

Accessories found in many duct distribution systems include dampers, splitters, and turning vanes. Dampers are used to control air flow, either to balance flows throughout a system or to adjust air flow in response to changing building loads. Specialized fire dampers and smoke dampers are used to reduce the spread of fire and smoke through the building air distribution system. Splitters and turning vanes are used to reduce friction losses by reducing turbulence within the ductwork; they also can reduce noise generated within the ducts. Figures 39, 40 and 41 depict typical ductwork accessories.

As with water, air flowing through a duct system will encounter friction losses through contact with the duct walls and in passing through devices such as dampers, diffusers, filters, and coils. A fan is used to provide the energy input required to overcome friction losses and circulate air through a system. The typical central HVAC system may require the use of several fans: for supply air, for return air, and for exhaust air. Fans come in a variety of capacities and designs, including centrifugal (Figure 42) and axial (Figure 43). Fans are normally driven by electric motors.

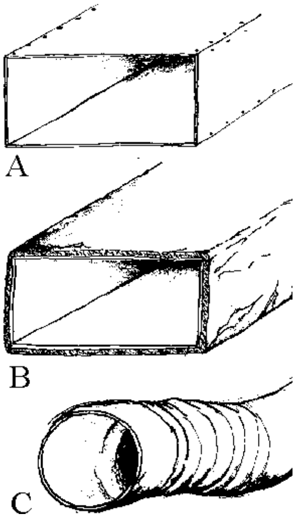


**Figure 37**. Typical duct materials: A - sheet metal; B - fiberglass ductboard; C - flex duct.

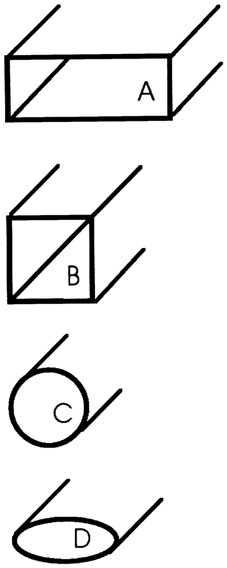


**Figure 38**. Typical ductwork shapes: A - rectangular; B - square; C - circular; D - flat oval.

**Figure 39**. Air flow control dampers.

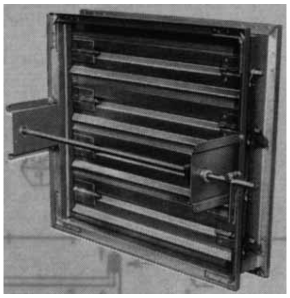


**Figure 40**. Fire dampers.

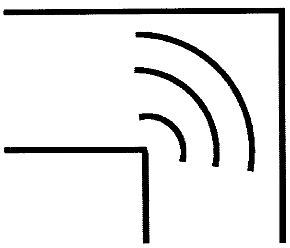


**Figure 41**. Turning vanes.

**Figure 42**. Centrifugal fan.

**Figure 43**. Axial fan.

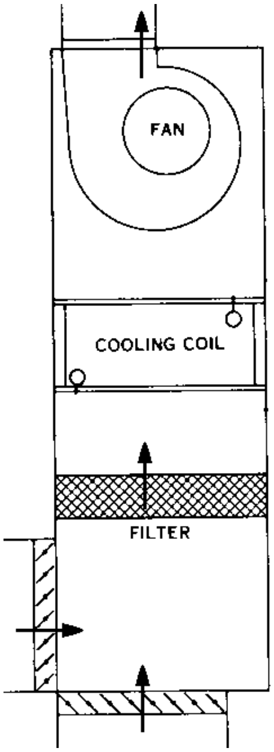


**Figure 44**. Schematic view of air handling unit (AHU).

Air handling units are equipment packages, usually pre-assembled but sometimes site-built, that house several major components necessary for the operation of air-based central HVAC systems. As noted in Figure 44, an air handler consists of a sheet metal enclosure, a fan, a heating coil or heat source and/or a cooling coil (as required), an air filter, occasionally a humidifier, and necessary control devices. The fan provides the motive energy for air circulation. A filter is provided to remove indoor pollutants from the air stream (refer to Vital Signs module: Health in the Built Environment). The heating or cooling coil act as secondary sources -- receiving heating or cooling media from a boiler or a chiller and transferring the conditioning effect to the air stream. Electric resistance coils may also be used as a heat source. On-site combustion at the air handling unit (typically a gas burner) serves as a common heat source for rooftop air handling units. A humidifier may be required to add moisture to the air under certain conditions. Dehumidification (moisture removal) is accomplished through the cooling coil. Control devices such as mixing dampers and valves are often part of an air handling unit. Figure 45 illustrates a typical air handling unit.

**DELIVERY COMPONENTS**

The heating or cooling effect produced at a source and distributed by a central system to spaces throughout a building needs to be properly delivered to each space to promote comfort. In air-based systems, heated or cooled air could theoretically just be dumped into each space. Such an approach, however, does not provide the control over air distribution required of an air-conditioning system. In water-based systems, the heated or cooled media (water or steam) can not just be dumped into a space. Some means of transferring the conditioning effect from the media to the space is required. Devices designed to provide the interface between occupied building spaces and distribution components are collectively termed delivery devices. A brief discussion of some common delivery devices is given below.

Diffuser: a diffuser is a device designed specifically to introduce supply air into a space, to provide good mixing of the supply air with the room air, to minimize drafts that would discomfort occupants, and to integrate with the ceiling system being used in the space in question. Diffusers are intended for ceiling installation and are available in many shapes, sizes, styles, finishes, and capacities. In many buildings, the only portions of an HVAC system seen by occupants on a day-by-day basis are the supply diffusers and return air registers or grilles. Although inherently simple devices, diffusers should be selected with care as they are the point where the effect of an HVAC system is implemented. In addition, they are normally the HVAC system component with the most aesthetic impact. Common diffuser designs are shown in Figure 46.

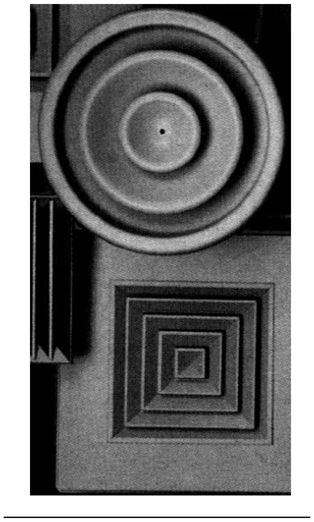


**Figure 46**. Common diffuser designs.

**Figure 45**. Exterior view of air handling unit

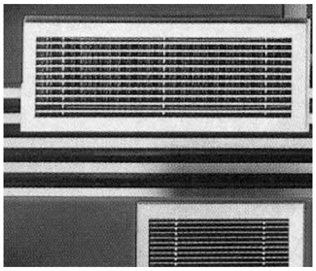


**Figure 47**. Common register designs.

Register: registers, Figure 47, are similar to diffusers except that they are designed and used for floor or sidewall air supply applications or as return air inlets.

Grille: grilles, Figure 48, are simply decorative covers for return air inlets; they are used to block sightlines so that occupants can not see directly into return air openings.

Baseboard Radiator: a hydronic baseboard radiator may be used as the delivery device in a hot water or steam heating system. Hydronic baseboard units are similar in general appearance to electric resistance baseboard units. Finned tube heat exchange elements transfer heat from the hot water distribution system to the room air. Baseboard radiators induce natural convection as an important means of heat distribution within a space, with warmer air exiting at the top of the unit and cooler air entering at the bottom. Figure 49 shows a typical hydronic baseboard radiator.

Convector: a convector, Figure 50, is basically a high capacity heat exchange element consisting of one or more finned-tube heat exchange elements, a housing, and possibly a fan. Convectors are used in steam or water (hydronic) central heating systems to provide high capacity heat delivery.

Unit Heater: a unit heater, Figure 51, is an industrial style heat delivery device, consisting of a fan and coil packaged in a housing, used in water or steam central heating systems.

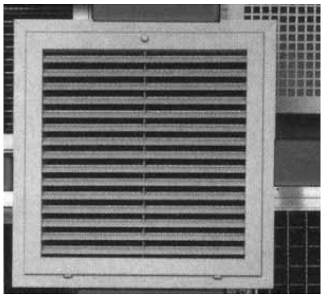


**Figure 48**. A typical grille.

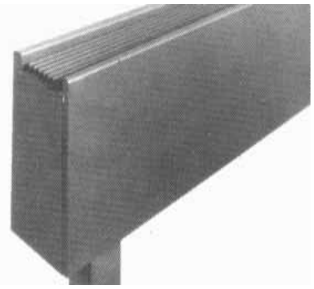


**Figure 49**. Hydronic baseboard radiator.

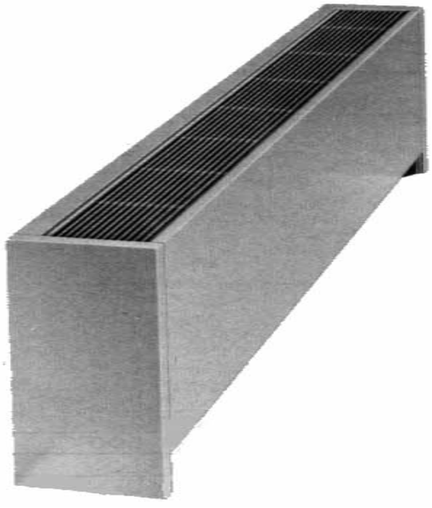


**Figure 50**. Hydronic convector.

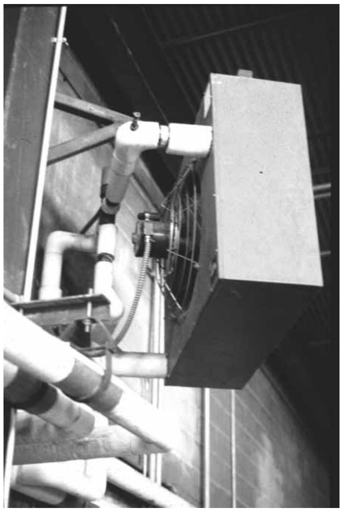


**Figure 51**. Unit heater.

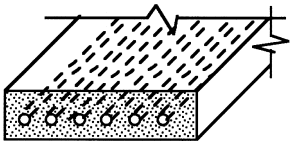


**Figure 52**. Hydronic radiant heating installation.

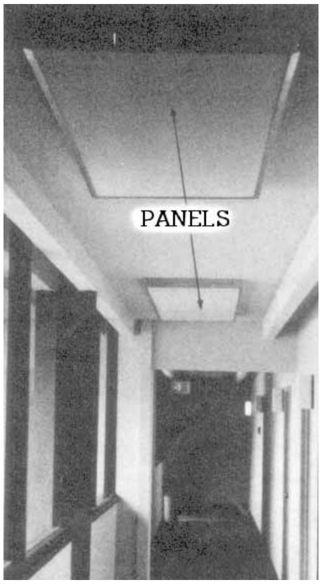


**Figure 53**. Electric resistance radiant ceiling panel installation.

Radiant Panels: it is possible to embed pipes in wall or floor constructions to develop a radiant heat delivery approach for steam or water central heating systems. Radiant heat delivery is generally considered to provide an exceptionally comfortable environment. Packaged electric resistance radiant panels are also available; such units would normally be used to provide supplemental heating for a localized area of a building. Electric resistance cables can also be used with gypsum board construction to provide large-area radiant heating systems. Figure 52 depicts a hydronic radiant floor installation; Figure 53 an electric resistance radiant ceiling panel installation.

Valance Units: occasionally, retrofit space cooling installations are required in buildings with no floor space for equipment in the conditioned zones and no room for duct routing. Valance units are finned-tube heat exchangers installed high on a wall near the intersection with the ceiling that are designed for use with an all-water cooling system.

Workstation Personal Climate Control: rather than delivering conditioned air generally into a space or providing radiant surfaces at some distance from occupants, several manufacturers have developed workstation climate control systems that produce individualized micro-climates tailored to an individual's needs. A personalized control approach allows very accurate control of the thermal environment at a particular area in a building (for example, at a particular desk). Such systems have a potential for increased energy efficiency through the delivery of climate control energy at a specific point of need. In addition, the ability to exercise more individual control over one's environment may improve perceptions of thermal comfort among occupants. Typically these workstation systems are similar to the delivery systems used in automobiles, with adjustable air supply louvers and easily reachable control settings.

Heat Recovery Devices: a number of heat recovery approaches may be used to reduce energy consumption in buildings. Common heat recovery devices include heat wheels, run-around coils, and heat pipes. The purpose of a heat recovery device is to capture some of the energy contained in air about to be exhausted from a building -- normally so that the heat may be used to pre-heat incoming ventilation air. A similar approach may be used in hot climates to pre-cool ventilation air. Some types of heat recovery equipment can transfer both sensible and latent energy.

# HVAC COMPONENTS AND SYSTEMS
## HVAC SYSTEMS

HVAC systems may be generally classified as heating only, ventilating only, cooling only, or air-conditioning systems. As discussed in the previous chapter, most building situations and occupant expectations will typically demand the application of air-conditioning systems. Such systems provide the focus for this chapter, although systems with more limited capabilities will also be discussed. HVAC systems may also be classified as either local or central systems. District systems, those serving more than one building, are also encountered -- but such systems revert to central systems at the single building level. The distinction between local and central systems is critical from an architectural perspective and will serve as the organizing theme for this chapter. The distinction between active and passive systems was discussed in the previous chapter; active systems are the focus of this discussion.

A system may be defined as an assembly of components with a particular structure and a defined function. The structure and function of a system determine the nature of the system's response to a given input. Depending upon where one begins an analysis of any given system, it is usually quite easy to zero in and look at the system in more detail -- to consider subsystems and subsystem components. It is also equally easy to zoom out and take a broader view -- to consider the original system of interest as merely a subsystem in some larger system. An understanding and definition of system boundaries is critical to the consideration of any system.

The components addressed in the previous chapter constitute the subsystems from which building-scale HVAC systems are assembled. Mechanical or industrial engineers and equipment manufacturers focus on the component and system scales. Architects tend to, and must, focus on building-scale systems. Utilities engineers and energy planners are likely to see individual building systems primarily as subsystems in larger conglomerate systems. This chapter views systems from the building-scale perspective. Even at this scale, there are literally hundreds of ways in which basic HVAC components may be assembled into systems. The purpose of this chapter is explore some of the most commonly encountered system configurations.

### LOCAL SYSTEMS

A local HVAC system serves a single thermal zone and has its major components located within the zone itself, on the boundary between the zone and the exterior environment, or directly adjacent to the zone. In general, space conditioning energy (heat or coolth) from a local system will not pass through another zone on its way to the space being conditioned. Serving only a single zone, local HVAC systems will have only one point of control -- typically a thermostat for active systems. A portable electric heater being used to heat a living room represents a local space heating system -- the equipment is located in the room being heated, the heater realistically serves no other building space, and the output enters the room directly without passing through other building spaces. Each local system generally does its own thing, without regard to the performance or operation of other local systems. Although a local system is truly an isolated system, it is common to view a collection of such independent elements as part of a larger full-building HVAC system. This view is not unreasonable -- even though there is no formal structure connecting the separate units to forge a larger system.

There are a number of advantages associated with the use of local HVAC systems. Local systems tend to be distributed systems; a building conditioned using local systems may have a dozen (or a hundred) individual and independent units located throughout the building. Distributed systems tend to provide greater collective reliability than do centralized systems. The failure of one of 12 heating units, for example, may cause discomfort in one room of a building but there are still 11 operating units that can provide heat for the rest of the building. Because local systems are likely to be of small capacity and are not complicated by interconnections with other units, maintenance of local systems tends to be simple and available through numerous service providers. In a building where a large number of spaces may be unoccupied at any given time, such as a dormitory or hotel, local systems may be totally shut off in the unused spaces, thus providing potential energy savings. As a self-contained system, a local HVAC system may provide greater occupant comfort through totally individualized control options -- if one room needs heating while an adjacent one needs cooling, two local systems can respond without conflict.

With advantages often come disadvantages. Local system units can not be easily connected together to permit centralized energy management operations. Local systems can usually be centrally controlled with respect to on-off functions through electric circuit control, but more sophisticated central control (such as night-setback or economizer operation) is not possible. Local systems can not benefit from economies of scale. The coefficient of performance (COP) of a refrigeration system generally increases with capacity; as each local unit is normally of low capacity, local system COPs are relatively low. Lack of interconnection between units also means that loads can not be shared on a building-wide basis. Several central HVAC systems deliver improved efficiency and lower first cost by sharing load capacity across an entire building. Although local system maintenance may often be relatively simple, such maintenance may have to occur directly in occupied building spaces.

Local heating systems: a local heating system will consist of one or more self-contained equipment units containing heat source, distribution, and delivery functions in a single package. Portable electric heaters, built-in electric resistance heaters, electric resistance baseboard radiators, infrared heaters, fireplaces, and wood stoves (discussed in the previous chapter) are examples of local heating-only systems.

Local cooling systems: local cooling-only systems tend to be passive in nature, for example an open window for convective cooling or a fountain for evaporative cooling. Active local cooling systems tend to also provide control of air humidity, distribution, and quality (at least at a rudimentary level) and would be considered air-conditioning systems.

Local ventilating systems: a local ventilating system will consist of some device that will move air into or out of a space without changing the air's thermal properties. A window fan is a local ventilating system. A local ventilating system may provide the only active thermal comfort modification in an otherwise passive cooling system. Air circulation devices, such as paddle or desk fans, may be used to improve occupant comfort in a space with an air-conditioning system.

Local air-conditioning systems: a local air-conditioning system will consist of one or more self-contained equipment units containing a heat and/or coolth source (depending on climate and occupancy demands), a fan, a filter, and control devices. The most common local air-conditioning system comprises one or more window air-conditioning units.

**Figure 54**. A window air-conditioning unit with cover removed (the compressor is at bottom, condenser coil on the left and evaporator on the right).

A window air conditioner, Figure 54, is a packaged unit consisting of a vapor compression refrigeration cycle (a compressor, condenser, evaporator, and expansion valve), with a fan, a filter, appropriate controls, and a housing. Window air-conditioners are designed for installation in a framed or unframed opening in a vertical building enclosure element, and take their name from the fact that they are often installed in window openings. Window air-conditioning units are designed for installation without ductwork and can effectively distribute air only within a few feet of the unit. As the unit contains both an exterior heat exchange element (condenser) and an interior heat exchange element (evaporator) it must be located partly inside and partly outside of the building. This location can lead to several architectural concerns including aesthetics, noise, space utilization, and leakage (infiltration and water). Heating may be provided by electric resistance coils or by a reversible refrigeration cycle (heat pump).

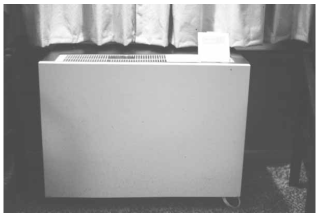


**Figure 55**. A unitary air - conditioning unit in a motel room.

Unitary air-conditioners, Figure 55, are similar to window air-conditioners, but are designed for commercial applications. Unitary units will normally be installed in a rough-in sleeve and tend to be located near the floor-wall intersection. Many hotel and motel air-conditioning systems consist of a unitary air-conditioner in each guest room. The components and operation of a unitary air-conditioner are the same as for a window air-conditioner; these units are also intended for installation in an exterior wall.

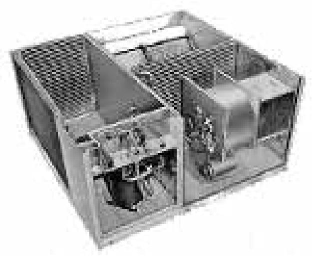


**Figure 56**. A packaged roof-top air-conditioning unit.

A packaged rooftop air-conditioner, Figure 56, may function as a local air-conditioning system if it is not connected to substantial distribution ductwork. A rooftop unit typically consists of a vapor compression refrigeration cycle and a heat source (electric resistance, heat pump, or on-site combustion), an air handler (fan, filter, dampers), and control devices. The typical capacity for a rooftop packaged unit is greater than for a window or unitary air-conditioner. Packaged rooftop units are also commonly used with distribution ductwork in central systems.

Split systems: the close coupling of evaporator and condenser components in small-scale single-zone systems using window, unitary or packaged equipment is often too restrictive for many architectural applications. Window and unitary units, for example, must penetrate vertical elements of the building envelope -- with substantial impact on aesthetics and envelope integrity. Having all system components in a single location also limits installation flexibility. A through-wall air-conditioner, for example, can only be installed where there is a wall available; interior spaces can not be reasonably conditioned with such equipment. Rooftop units work well for single-story buildings, but don't fit into multistory schemes. The split system provides a solution to these potential problems.

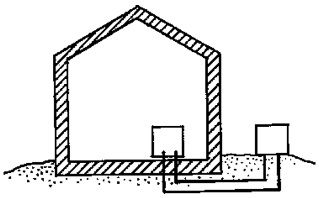
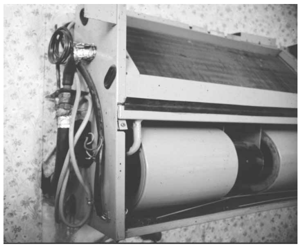


**Figure 57**. Schematic diagram of a split system.

A split system, shown schematically in Figure 57, generally consists of an exterior unit (consisting of compressor and condenser elements, Figure 58) and an interior unit (consisting of evaporator and expansion valve elements, Figure 59). The two halves of the system are connected by refrigerant tubing. This arrangement permits much greater installation flexibility than possible with unitary equipment. For example, the evaporator unit might be located in a basement, interior closet or attic while the compressor/condenser unit might be located on the side, rear or roof of a building. Such an arrangement provides enhanced architectural and thermal opportunities -- HVAC equipment may be easily concealed and interior spaces easily conditioned. Separation distance between exterior and interior elements is usually limited to around 100 feet. The evaporator unit may be installed in a furnace or an air handling unit or be provided as



**Figures 58. and 59**. Exterior and interior (without cover) units of a split-system.

a self-contained unit similar in appearance to a fan-coil unit. Some manufacturers make small-to-moderate capacity split systems with multiple evaporator units.

## CENTRAL SYSTEMS

A central HVAC system may serve one or more thermal zones and has its major components located outside of the zone or zones being served -- usually in some convenient central location in, on, or near the building. Space conditioning (thermal) energy from a central system must pass through zone boundaries on its way to the space or spaces being conditioned. Central HVAC systems will have as many points of control (thermostats) as there are zones. The nature of the thermal energy transfer medium used by a central system provides a means of sub-classifying central HVAC systems. If conditioning is transferred only by means of heated or cooled air, the system is termed an all-air system. If conditioning is transferred only by means of hot or chilled water, the system is termed an all-water system. If conditioning is transferred by a combination of heated/cooled air and hot/chilled water, then the system is termed an air-water system.

There are a number of advantages associated with the use of central HVAC systems. Central systems allow major equipment components to be isolated in a mechanical room. Grouping and isolating key operating components allows maintenance to occur with limited disruption to building functions. It is also easy to locate a central mechanical space in such a way as to reduce noise and aesthetic impacts on building occupants. Central HVAC systems also offer opportunities for economies of scale. Larger capacity refrigeration equipment is usually more efficient than smaller capacity equipment. Larger systems can utilize cooling towers, which can improve system efficiencies in many climates. Some central systems permit building-wide load sharing; this may result in reduced equipment sizes (and costs) and the ability to shift conditioning energy from one part of a building to another. Central systems are also amenable to centralized energy management control schemes that, properly done, can reduce building energy consumption. It is also possible that a central system may be appropriate from other than a climate control perspective; active smoke control, for example, is best accomplished by a central all-air HVAC system.

Central HVAC systems also have disadvantages. As a non-distributed system, failure of any key equipment component (such as a pump or chiller) may affect an entire building. As system size and sophistication increase, maintenance may become more difficult and may be available from fewer providers if specialists are needed. Large, centralized systems tend to be less intuitive than smaller, local systems, which can make central systems analysis and understanding more difficult. The conditioning effect from a central HVAC system must be conveyed throughout a building. The need to transfer conditioned air or water imposes space and volume demands on a building. Large duct sizes, for example, may require an increase in floor-to-floor height and, consequently, building cost.

Nationally, all-air systems are the most commonly used central HVAC systems. There is a simple reason for this popularity. The purpose of an air-conditioning system is to control selected air properties -- this is most easily accomplished directly, through an all-air system. Any conditioning effect embodied in water must be subsequently transferred to air to provide air-conditioning, which adds to system complexity. Unfortunately, air is not an efficient heat transfer medium, thus, all-air systems may require extensive building volume for ductwork distribution. In situations where ductwork can not be reasonably accommodated in the building design, air-water or all-water approaches may be considered. Escalating concerns for acceptable indoor air quality may suggest the increasing use of all-air systems. Air-water systems may find greater popularity in certain regions of the U.S., in renovation projects, or where a dedicated ventilation air scheme is used for indoor air quality purposes. More specific advantages and disadvantages for the various types of central HVAC systems will be presented in concert with discussions of individual systems.

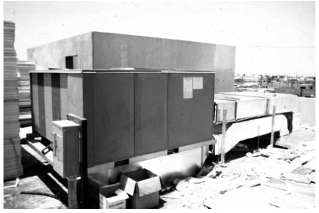


**Figure 60**. An integrated package, single-zone air-conditioning system.

### All-Air Systems

Single zone: a single zone system consists of an air handling unit, a heat source and coolth source, distribution ductwork, and appropriate delivery devices. A completely integrated equipment approach may be used, as in Figure 60, where the heat and coolth sources are an integral part of the air handler package; or separate heat and coolth sources may provide heating and cooling effect to a remote air handler as illustrated in Figure 61. The integrated package is most commonly a rooftop unit, as access to the exterior environment for heat rejection or combustion air is readily available. Separate source and distribution equipment is typically chosen when air handlers need to be installed in interior locations and/or where source equipment may serve several air handlers.

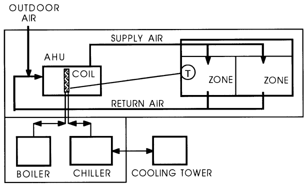


**Figure 61**. Schematic diagram of an all-air, single zone HVAC system with a separate air handler, boiler and chiller.

In a single zone all-air HVAC system, one control device (most commonly a thermostat) located in the zone controls the operation of the system. Control may be either modulating or on-off in nature. A modulating control adjusts system output in increments to match heating or cooling loads. Modulating control may be achieved by varying the flow of hot or chilled water to a coil or by staging the output of a heating or cooling source packaged with the unit. On-off control is all-or-nothing, it simply starts and stops the heating or cooling effect; air circulation may also start and stop along with heating/cooling or may be set for continuous operation. As this type system serves only one zone, control is normally effected at the air handling unit (AHU) through a change in supply air temperature or the stopping/starting of the system. Figure 62 is a schematic diagram of a single zone HVAC system.

Although very few buildings are truly just a single thermal zone, single zone systems actually find many applications. Most central HVAC systems serving one-family residential units are single zone systems. Although the typical residence would be best treated as a multiple zone building, the cost of installing a multiple zone system versus a single zone system is usually prohibitive. In a residence, occupants can move about rather freely and select those spaces that are most comfortable at any given time of day. In larger residences, two (or more) single zone systems may be used to provide thermal zoning. In low-rise apartments, each apartment unit may be conditioned by a separate single zone system. Many large single-story buildings -- supermarkets, discount stores, and the like -- can be effectively conditioned by a series of single zone systems, each system serving a loosely defined region of the building. The central (or interior) zones of large office buildings are sometimes conditioned by a series of separate single zone systems.

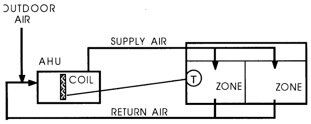


**Figure 62**. Schematic diagram of a single-zone system.

The primary advantage of a single zone central system is its simplicity. Single zone systems are the most basic and least complex of central all-air systems. Because of this simplicity, they are usually the lowest-first-cost all-air system, the easiest to maintain, and the simplest to design. The primary disadvantage of a single zone system is that it can effectively condition only one zone. This is only a disadvantage when improperly applied. As control is achieved at the air handling unit, single zone systems are not easily modified to serve multiple zones should building usage change with time.

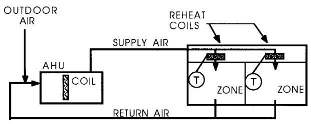


**Figure 63**. Schematic diagram of a terminal reheat system.

Terminal reheat: as shown in Figure 63, a terminal reheat HVAC system is basically a multiple zone adaptation of a single zone HVAC system layout. Some type of heating device (electric or hot water coil) is located downstream of the air handling unit near each zone. A thermostat in each zone controls the heat output of the reheat coil to produce comfortable conditions. The supply air leaving the central air handling unit is conditioned to cool the zone with the greatest cooling load. Any zone that requires less than maximum cooling will have its supply air temperature increased by its terminal reheat device. The terminal reheat system is flexible; reheat devices can be added or removed to accommodate changes in zoning. Such a system is capable of providing excellent control of thermal conditions. Unfortunately, cooling all supply air to some lowest common denominator temperature and then reheating most of the air to produce comfortable conditions is very wasteful of energy. For this reason, use of reheat systems is strictly regulated by most energy codes and standards. Were it not for this restriction, terminal reheat systems would likely find application in most multiple zone buildings where an all-air approach is chosen.

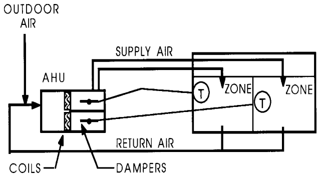


**Figure 64**. Schematic diagram of a multi-zone system.

Multi-zone: in a multi-zone all-air system, Figure 64, individual supply air ducts are provided for each zone in a building. Cool air and hot (or return) air are mixed at the air handling unit to suit the needs of each zone. Once mixed at the air handler, air for a particular zone can not be intermingled with air for any other zone -- thus the need for separate supply ducts. A special air handling unit, with parallel air flow paths at the heating and cooling coils and internal mixing dampers, is used for this type system. Due to physical restrictions on duct connections and damper size, the normal commercial multi-zone air handler is limited to a maximum of around 12 zones. If more zones are required, additional air handlers may be used.

A key advantage of the multi-zone control approach is that it provides the ability to adequately condition several zones without the energy waste associated with a terminal reheat system. Only as much cooling and heating effect as required to provide comfortable conditions need be provided. In practice, leakage between the "decks" (the hot and cold sections) of the air handler tends to induce some energy inefficiencies. An important potential disadvantage of a multi-zone system is the need for multiple supply air ducts. Six separate supply ducts will occupy a greater volume than would one duct carrying the same total air quantity. In many building situations, space for such multiple ducts is simply not available.

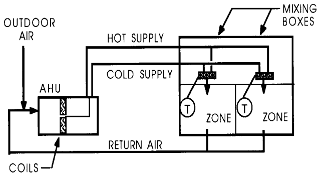


**Figure 65**. Schematic diagram of a dual duct system.

Dual duct: the dual duct all-air HVAC system, illustrated in Figure 65, is a terminal-controlled adaptation of the multi-zone concept. A central air handling unit provides two conditioned air streams (a "cold" deck and a "hot" deck). These air streams are distributed throughout the area served by the air handling unit in separate and parallel ducts (not necessarily of equal size, depending upon building heating and cooling loads). A terminal mixing box is provided for each zone. Under the control of the zone thermostat, the air streams are mixed in the terminal box to provide a supply air temperature that will properly condition the zone. A dual duct system generally exhibits advantages and disadvantages similar to those experienced with a multi-zone system. The primary difference is that the dual duct system, using terminal control, is more flexible with respect to changes in zoning requirements.

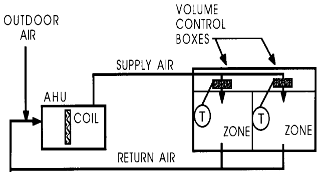


**Figure 66**. Schematic diagram of a VAV system.

Variable volume: a variable air volume (VAV) HVAC system changes the quantity of air supplied to a space in response to changes in loads. This is a major operational difference from the four constant volume systems discussed above -- and opens up a number of energy-efficiency options. A central air handling unit supplies air through a common duct pathway to all spaces conditioned by the unit. As shown in Figure 66, each zone is provided with a VAV box (terminal control box) that adjusts air supply volume in response to the zone thermostat. The temperature of air supplied by the air handling unit may be varied occasionally to adapt to building-wide changes in loads, but day-to-day control of each zone is achieved through modulation of supply air flow rate. A basic VAV system can not provide simultaneous heating and cooling.

A VAV system can be exceptionally energy efficient, but may also present serious indoor air quality concerns. Depending upon building load patterns, it is often possible to shift air flow from one zone to another throughout the day, thus reducing the design capacity of air circulation equipment and main ducts. As air flow is reduced from design quantities under part-load conditions, a VAV system can be controlled so that fan power is substantially reduced (resulting in energy savings). On the other hand, reduced supply air flow under part-load conditions will often mean reduced ventilation air flow as well, which is potentially problematic from an indoor air quality perspective -- a set minimum air flow is often recommended.

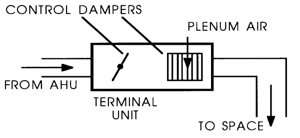


**Figure 67**. Schematic diagram of an induction terminal unit.

All-air Systems Summary: five primary types of all-air systems are commonly encountered in new and existing buildings. Single zone and multi-zone systems are constant volume, variable supply-temperature systems that are controlled at the central air handler. Terminal reheat and dual duct systems are constant volume, variable temperature systems that are terminally controlled -- a control approach that increases system flexibility and adaptability. The variable air volume system is a variable flow, constant temperature system with terminal control. The dual duct and multi-zone systems are multiple path systems with two or more separate supply air ducts, while the single zone, terminal reheat, and variable volume systems are single path systems with one common main supply duct. Numerous variations and hybrids of these systems may be encountered. For example, induction terminal units (Figure 67) that supply a constant air volume to a space by mixing variable quantities of conditioned air and plenum air are quite common. All-air systems require that the majority of air supplied to a space is returned to the air handling unit for reconditioning or exhausted from the building. This "return" air may be conveyed in a return air duct system or through plenums formed by various elements of a building, such as a suspended ceiling and the building structure.

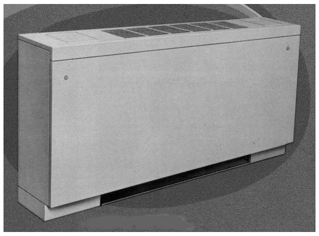


**Figure 68**. A vertically-oriented fan-coil unit.

### All-water Systems

In an all-water system, conditioning effect is distributed from a central plant to conditioned spaces via heated or cooled water. Water is an effective heat transfer medium, thus distribution containers (pipes) generally may be of relatively small volume (compared to air ducts). On the other hand, water can not be directly dumped into a space through a diffuser, requiring a more sophisticated delivery device. All-water heating-only systems employ a variety of delivery devices, including baseboard radiators, convectors, unit heaters, and radiant floors. All-water cooling-only systems are rare; valance units (a ceiling-located counterpart of a baseboard radiator) are the most common delivery device for such systems. If full air-conditioning is considered, the most common delivery device is the fan-coil unit.

**Figure 69**. A horizontally-oriented fan-coil unit.

Fan-coil: a fan-coil unit is a small-scale air handling unit with circulation fan, cooling and/or heating coil, filter, and appropriate controls. Fan-coil units are available for vertical installation (typically along a wall at the intersection with the floor, Figure 68) or horizontal installation (typically suspended from the ceiling, Figure 69). Fan-coil housings may be exposed to occupants (with appropriate styling and finishes), or may be concealed in a plenum or soffit, as shown in Figure 70. As a central system, individual fan-coil units are supplied with conditioning effect produced at a central location (a central plant); in an all-water system, the heating effect is produced by a boiler and the cooling effect by a chiller.

Fan-coil control is typically achieved through control of water flow through the coil using a control signal from the zone thermostat. Further control is sometimes provided by a multi-speed fan option. Occupants can usually adjust supply air louvers to provide some control over air distribution patterns. The most critical performance issue facing an all-water fan-coil system is ventilation air. Fan-coil units installed on an exterior wall can be equipped with an outdoor air connection so that ventilation may be provided. Fan-coils installed in interior zones can not easily provide such outdoor air ventilation. An air-water fan-coil system can overcome this constraint. In a fan-coil system, a major system component (the fan-coil unit itself) is installed in or adjacent to occupied spaces, requiring that filter changes and maintenance of fans and coils occur in these spaces. Fan noise may be a concern in some critical occupancies.

**Figure 70**. Supply and return grilles for a concealed fan-coil unit.

## Air-water Systems

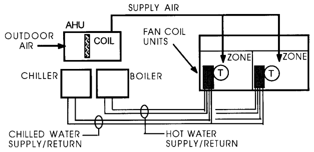


**Figure 71**. Schematic diagram of an air-water fan-coil unit.

An air-water system incorporates the main benefits of all-air and all-water approaches in a hybrid system. The volume-saving advantages of an all-water system are combined with the outdoor ventilation benefits of an all-air system. Usually, the majority of space load is carried by conditioned water with just enough central air supply to meet ventilation demands. Historically this has resulted in a system where 80-90 % of the space load is dealt with by heated or cooled water and 10-20% by heated or cooled air. Two main delivery approaches are used in air-water systems; the fan-coil and the induction unit.

Fan-coil: an air-water fan-coil system is similar in most respects to an all-water fan-coil with one major difference. Supply air from a central air handler is provided to each space as well as conditioned water. This supply air is usually intended to meet the ventilation needs of the space, and can either be delivered independently of the fan-coil unit (through conventional diffusers or registers) or can be introduced at the fan-coil unit itself. Figure 71 provides a schematic illustration of an air-water fan-coil system.

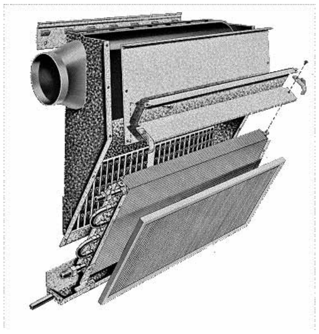


**Figure 72**. A typical induction unit.

Induction: externally, an induction unit looks very much like a fan-coil unit; the difference is internal. An induction unit employs high velocity air flow from a central air handling unit to induce a flow of room air into and through the cabinet. This induction effect replaces the motive force provided by the fan in a fan-coil unit. The mixture of central air (termed primary air) and room air (secondary air) passes through a coil in the unit and is conditioned to suit the needs of the zone. Filtration of the secondary room air at the induction cabinet is common. Figure 72 shows a typical induction unit, while Figure 73 provides a schematic diagram of an air-water induction system.

## Water-source Heat Pumps

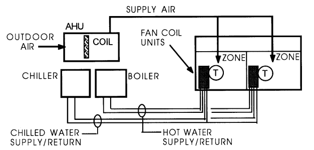


**Figure 73**. Schematic diagram of an air-water induction system.

Water-source heat pumps are a system option that can provide substantial energy benefits in appropriate applications. In this system numerous individual heat pumps are provided for the various zones in a building. Zone control is accomplished through individual control of these heat pumps. A centralized water circulation loop is provided as a heat source and heat sink for the heat pumps -- as shown in Figure 74. As each heat pump contains a full compliment of vapor compression components, the heat pumps act as the primary source of heating and cooling. The water loop serves as a convenient place for the heat pumps to reject heat or accept heat (just as an air-source heat pump uses the outside atmosphere for the same purposes). The heat pumps may be located very much as fan-coil units might in an all-water system. Water-source heat pumps do not neatly fall into the all-air, all-water, air-water categories described above, but in terms of architectural impact are most closely akin to an all-water system. The ventilation air concerns of all-water systems also apply to water-source heat pump systems.

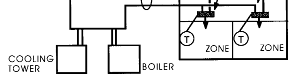


**Figure 74**. Schematic diagram of a water-source heat pump.

If all spaces in a building require heating at a particular time, a boiler (or waste heat or solar collectors) will be used to supply heat to the water circulation loop. The heat pumps will then draw upon this resource as needed. If all spaces require cooling, a cooling tower can be used to reject heat collected from the heat pumps to the outside atmosphere. A chiller is not required as each heat pump acts as its own refrigeration system. Neither of these application scenarios is particularly energy efficient. If, however, part of a building requires heating and another part cooling, the water loop may serve to simply redistribute heat from one part of the building to another -- with no need for boiler or cooling tower operation. Under such a circumstance, not at all uncommon in large buildings in cold climates, a water-source heat pump system can provide energy savings. As with other systems that have distributed mechanical/electrical equipment throughout a building, maintenance will occur in or near occupied spaces and equipment noise may be of concern.

# HVAC COMPONENTS AND SYSTEMS APPLICATION EXAMPLES

The following case studies are provided to illustrate the application of various types of HVAC systems to commonly encountered building types. Building scales range from single-family residential to a multi-building office complex. System scales include local, central and district systems. Introductory information is provided for each project, along with floor plans and elevations. The thermal zoning of each building is noted, as are the locations of all major HVAC equipment components, and the supply and return air distribution layouts. Basic information for major items of equipment is provided. Reference figures-of-merit for several aspects of HVAC system design are provided.

The four case studies include a single-family residence in Tallahassee, Florida, a branch bank facility in Tallahassee, Florida, a church in Tallahassee, Florida, and a state office complex in Tallahassee, Florida. Although all the case studies are located in Tallahassee, which represents a decidedly warm and humid climate (30 degrees North latitude, 1721 heating degree days @ base 65 degree F, 2401 cooling degree days @ base 65 degree F, 91 degree F 2.5% summer design temperature, 75 degree F coincident wet bulb design temperature, 30 degree F 97.5% winter design temperature), the components and systems arrangements that are illustrated are fairly common throughout much of the United States.

These examples are all recently constructed buildings without records of utility usage. As energy consumption data are collected for these buildings, an attempt will be made to make such data available via the Vital Signs World Wide Web pages (http://www.ced.berkeley.edu/cedr/vs).

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A

B

C

D

**Figure 75.** The following four buildings/projects will be used as examples in this section:

A - single-family residence

B - Premier Bank

C - Wildwood Presbyterian Church

D - Capital Circle Office Center

## SINGLE-FAMILY RESIDENCE

Background: this two-story, two-bedroom house with study, gallery, and detached garage was constructed in 1995 on a heavily wooded infill lot in Southeast Tallahassee. The house is of wood frame construction with wood siding and asphalt shingle roof. Primary climate control is provided by a split system central air-conditioning system; secondary means of climate control are afforded by a fireplace and ceiling fans. An exhaust fan is installed in the kitchen. Gross conditioned floor area is 1388 square feet.

HVAC System: The entire building is treated as one thermal zone. The split system is comprised of an air handling unit installed in a mechanical closet on the first floor and a condenser/compressor unit located near the north-east corner of the house. Supply air distribution is through the interstices of the second floor structure. Floor registers are used to supply air to the second floor, while high-wall registers are used to supply air to the first floor. This supply arrangement, somewhat unusual for a cooling-load dominated climate, requires minimal distribution volume and coordination, and keeps all supply ducts within the conditioned volume of the building. Cooling system capacity is 4 tons. Heating system capacity is 100,000 Btuh. Cooling is by electrically-driven vapor compression; heating is by reverse cycle vapor compression (heat pump) with supplemental electric resistance heat in the air handling unit. The thermostat, which provides on-off control of the compressor, is located in the entry hall.

Ceiling fans are 42 inch diameter, 4080 cfm capacity. The fireplace is intended as an aesthetic element, and will not be expected to contribute to space heating capabilities. Kitchen exhaust is of unknown capacity with a local on-off control. There are no bathroom exhaust fans.

Sequence of Operation: operation is manually sequenced by the building occupant. Thermostat set point and heating or cooling mode selection are manually entered. In the "auto" setting, heating or cooling system operation cycles on-off as the thermostat set point is satisfied. The occupant can opt to disable heating/cooling operation by selecting the "off" control position. There are no interlocks to other equipment. Ceiling fan operation is by manual wall switch.

Major Equipment Details:

compressor/condenser:
    cooling capacity: 48,000 Btuh
        applicable efficiency measure: see notes
    heating capacity: 100,000 Btuh
        applicable efficiency measure: see notes
air handling unit: residential split-system type, located in closet
supply air registers: residential-style floor and wall registers

Figures of Merit:

number of zones = 1
cooling capacity, square foot per ton = 347
heating capacity, Btuh per square foot = 72
supply air cfm per square foot = 1.4
size of largest supply air duct = 20 x 16 inches
percentage of gross conditioned floor area dedicated to HVAC equipment = 0.5%
HVAC cost as a percentage of total construction cost = 1.8% (approximate)

Special Notes: the owner of this residence was heavily involved in the design and construction processes; as a result some decisions regarding mechanical elements (lack of bathroom exhaust fans, for example) may differ from community norms. Although minimum efficiency ratings for the heating and cooling equipment for this residence are fixed by the Florida Energy-Efficiency Code for Building Construction, it is difficult to determine the actual equipment efficiencies due to the various combinations of components that can be assembled to construct a residential air-conditioning unit and the relatively poor documentation of those options.

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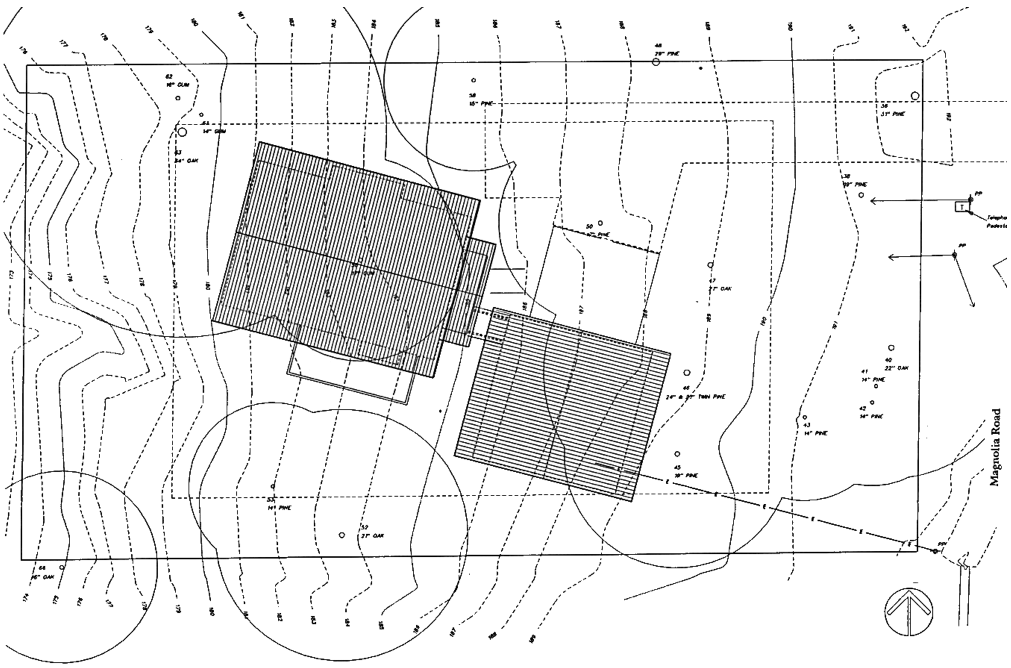


**Figure 76.** Site plan of the single-family residence in Tallahassee, FL.

**Figure 77.** North elevation of the single-family residence.

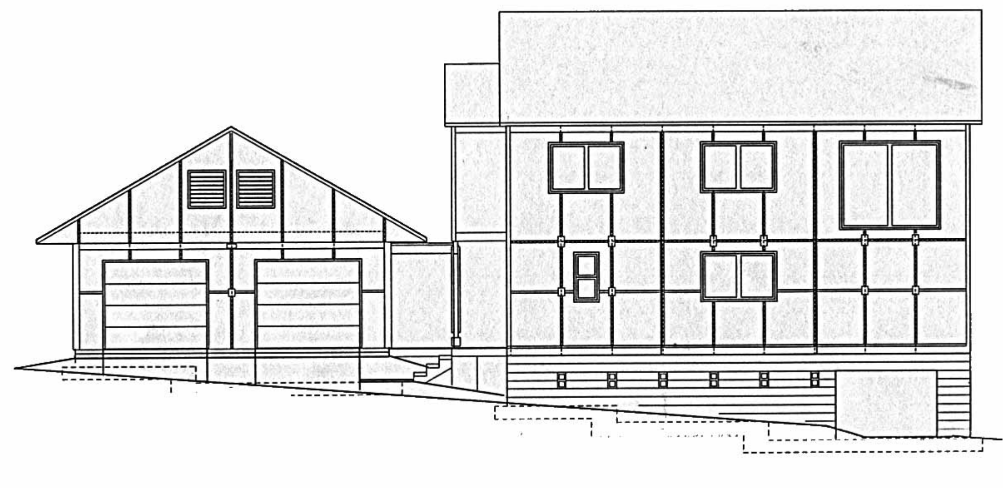
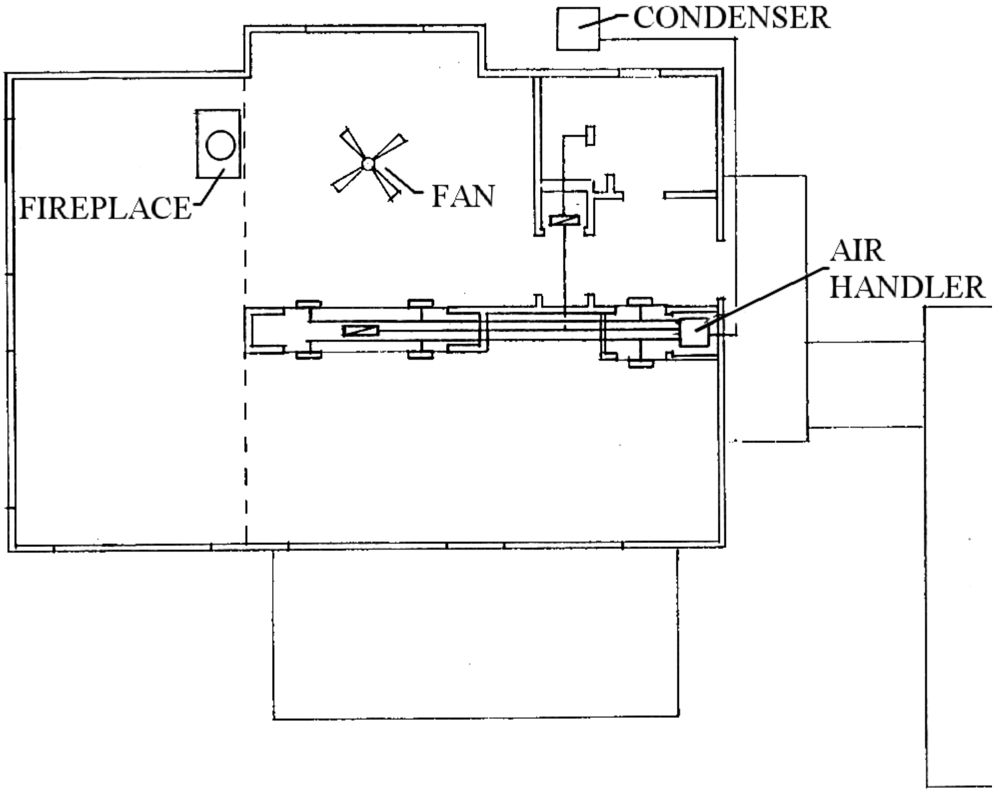


**Figure 78.** A mechanical plan of the single-family residence.



## BRANCH BANK

Background: this three-story banking facility was constructed in 1995 on a moderately wooded lot fronting on a major commercial thoroughfare in Northeast Tallahassee. The bank is of wood frame construction with brick veneer and asphalt shingle roof. The first floor contains a public banking lobby, a private banking hall, several private offices, a vault, and bathrooms; the second floor contains private offices, conference room, computer room, and bathrooms; the third floor contains a fan room and storage rooms. Gross conditioned floor area is 9871 square feet.

HVAC System: The building is treated as two thermal zones, each conditioned by a separate split system air-conditioning system. The first floor comprises one zone, the second and third floors comprise the second zone. Each of the split systems is comprised of an air handling unit installed in a third floor mechanical room (fan room) and a condenser/compressor unit located along the southeast facade of the bank. Supply air distribution for the first floor is through the interstices of the second floor structure; distribution for the second floor is via ducts dropping down from the third floor (which is used primarily for storage). Ceiling diffusers are generally used on both the first and second floors, while high-wall registers are used to supply the third floor storage areas and the main banking lobby. Return air is collected from registers in each space and ducted back to the respective air handling units. A central exhaust fan serves first and second floor bathrooms and exhausts through the roof. A dedicated ventilation air intake provides outdoor air to both air handling units.

Cooling system capacity for unit one is 14 tons; for unit two 18 tons. Heating system capacity is 91,800 Btuh for unit one and 98,700 Btuh for unit two. Cooling is by electrically-driven vapor compression; heating is by reverse cycle vapor compression (heat pump) with supplemental electric resistance heaters in the supply ducts. The thermostats, which provide on-off control of the compressors, are located in the first floor reception area and in the second floor corridor.

Sequence of Operation: the operation of the HVAC system for this building is fundamentally the same as for a residence. Building occupants select appropriate set points for the two thermal zones. The heating and cooling equipment operates in an on-off cycling mode to satisfy the thermostat setpoints. The two air-conditioning units function as totally independent systems, except for thermal interactions between zones. To save energy, bathroom exhaust fan operation is interlocked with one of the air-conditioning systems, so that the exhaust fan will not operate when the heating/cooling system is in the manual "off" position and the building is unoccupied.

Major Equipment Details

compressor/condenser one:
    cooling capacity: 170,000 Btuh
        applicable efficiency measure: EER = 8.25 (including air handler)
    heating capacity: 91,800 Btuh
        applicable efficiency measure: COP = 2.75
air handling unit one: 5,712 cfm capacity, located in 3rd floor mechanical room
compressor/condenser two:
    cooling capacity: 217,300 Btuh
        applicable efficiency measure: EER = 8.2 (including air handler)

heating capacity: 98,700 Btuh
applicable efficiency measure: COP = 2.85
air handling unit two: 7,651 cfm capacity, located in 3rd floor mechanical room
supply air devices: include supply and return registers, rectangular and linear bar diffusers
exhaust fan: 690 cfm, located in 3rd floor mechanical room, discharge through roof
outside air intake: 580 cfm (AHU one) and 600 cfm (AHU two), brought in through roof

Figures of Merit:

number of zones = 2
cooling capacity, square foot per ton = 306
heating capacity, Btuh per square foot = 19
supply air cfm per square foot = 1.4
size of largest supply air duct = 66 x 14 inches
percentage of gross conditioned floor area dedicated to HVAC equipment = 2.7%
HVAC cost as a percentage of total construction cost = information not available

Special Notes: in construction details and HVAC system design and operation, this bank is more closely related to a single-family residence than to larger commercial building types. The character of the HVAC systems is typical of smaller commercial buildings, which account for a substantial percentage of the number of buildings constructed in the United States.

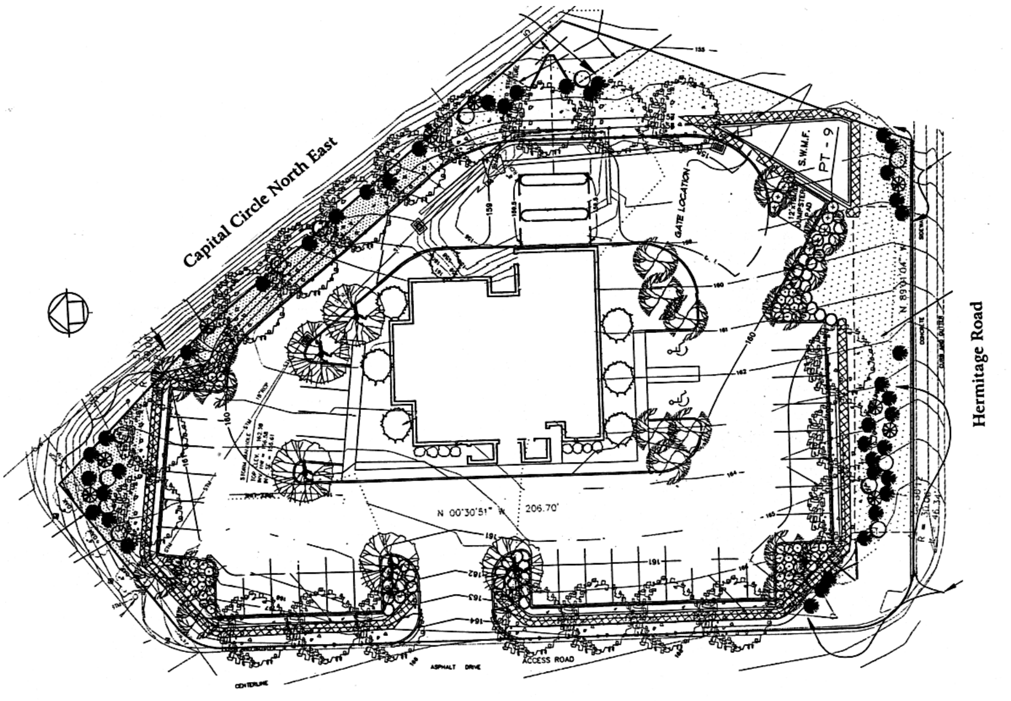


**Figure 79.** Site plan of the Premier Bank building in Tallahassee, FL.

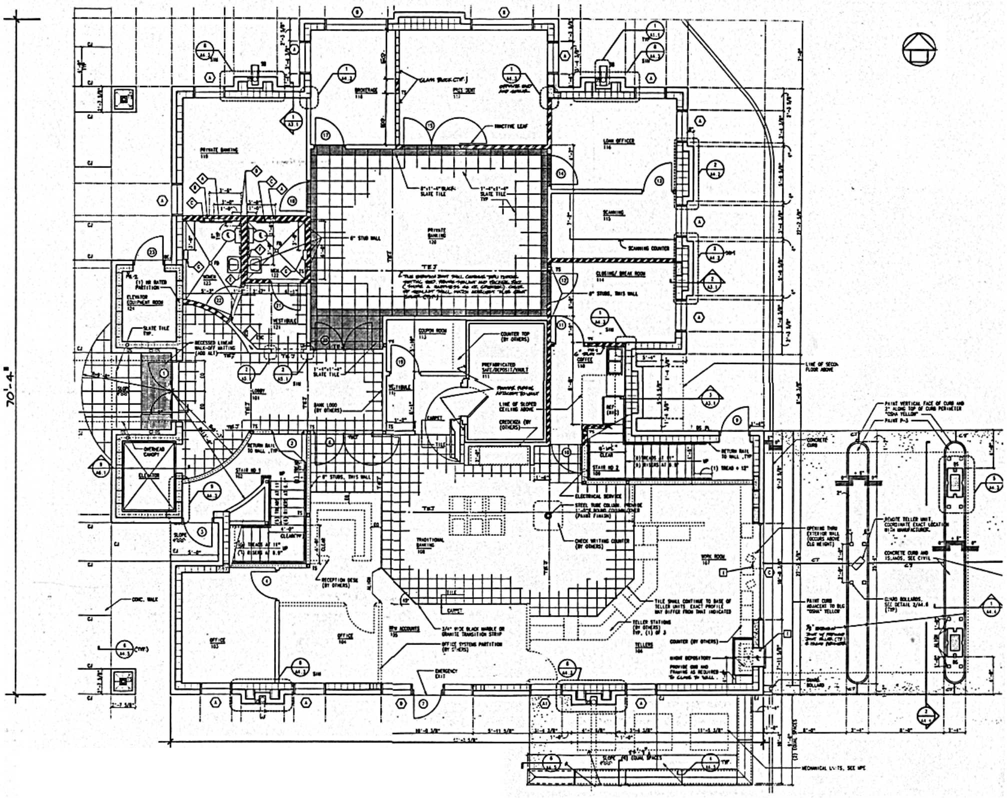
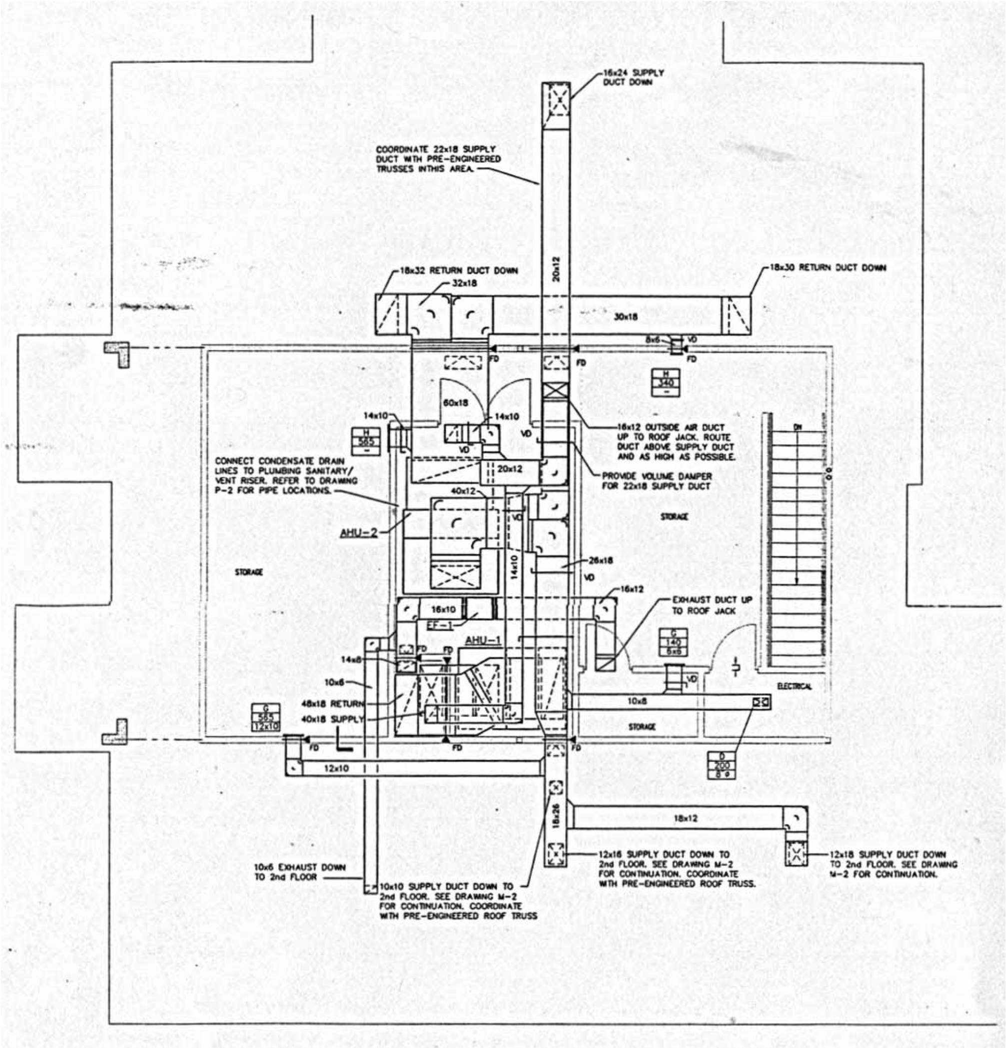


**Figure 80.** Ground floor plan of the Premier Bank.

**Figure 81.** West elevation of the Premier Bank.

**Figure 82.** Third floor mechanical plan of the Premier Bank .



## CHURCH

Background: this single-story church facility was constructed in 1995 on a lot in a suburban location in Northeast Tallahassee. Most vegetation (including shade trees) was removed from the site. The church is of wood frame construction with brick veneer and asphalt shingle roof. The facility includes a sanctuary, fellowship hall, choir rehearsal room, numerous classroom and nursery spaces, offices, a kitchen, and bathrooms. Climate control is provided by ten split system central air-conditioning systems located throughout the building. Four units serve the sanctuary, with air handling units located in mechanical rooms along each of the four walls and compressor/condenser units located directly adjacent to these rooms along four facades. A separate split system serves the choir rehearsal spaces. Another unit serves offices, library and lobby spaces. The fellowship hall, southeast classrooms, nursery rooms, and north classrooms are each served by separate split systems. Six exhaust fans serve various bathrooms, an electric room, and the fellowship hall. A fresh air supply fan is provided for the fellowship hall. Gross conditioned floor area will total 27,596 square feet when all construction is completed (the east portion of the facility, 14,185 square feet, is complete; the west portion, 13,411 square feet, is to be completed later). This case study addresses the full facility (both east and west portions).

HVAC System: The building is effectively treated as ten thermal zones, each conditioned by a separate split system air-conditioning system -- with the exception of the fellowship hall which is served by dual split systems and the southeast classroom/nursery area which is zoned from a single split system through the use of variable volume terminal boxes. Each of the split systems is comprised of an air handling unit installed in a fan room or space and a condenser/compressor unit located in the vicinity of the air handling unit. Because of the HVAC system choice and size of the building, there are 10 externally located compressor/condenser packages surrounding the building on various facades. Supply air distribution is via ceiling diffusers for all spaces except the sanctuary; distribution for the sanctuary is through sidewall registers. Air is returned from the fellowship hall to the air handling unit through a louvered door. Sanctuary air is returned directly to the four air handling units through sidewall registers. Return air from all other spaces is collected via ceiling registers and ducted back to the respective air handling units.

Cooling and heating capacities vary as summarized under Major Equipment Details. Cooling is by electrically-driven vapor compression; heating is by electric resistance heaters in the supply ducts. The zone thermostats are located as shown in the mechanical plans.

Sequence of Operation: for the majority of the church facility, the sequence of operation is very similar to that of a residence. Thermostat set points are established by the building users, and the heating/cooling equipment serving the particular zone controlled by that thermostat cycles on and off to satisfy the set point requirements. In the classroom/nursery area, thermostats for multiple zones control air flow from variable volume control boxes connected to a single air handling unit. Exhaust fan control varies from unit to unit; some fans are time-clock controlled, two are interlocked with air handling units, the electrical room and attic fans are thermostatically controlled.

Major Equipment Details: there are a total of 10 split system air conditioning units distributed throughout the church; details for selected equipment components are provided below.

largest compressor/condenser unit:
- cooling capacity: 183,000 Btuh
  - applicable efficiency measure: 9.1 EER
- heating capacity: 54,600 Btuh
  - applicable efficiency measure: 100% efficiency (electric resistance)

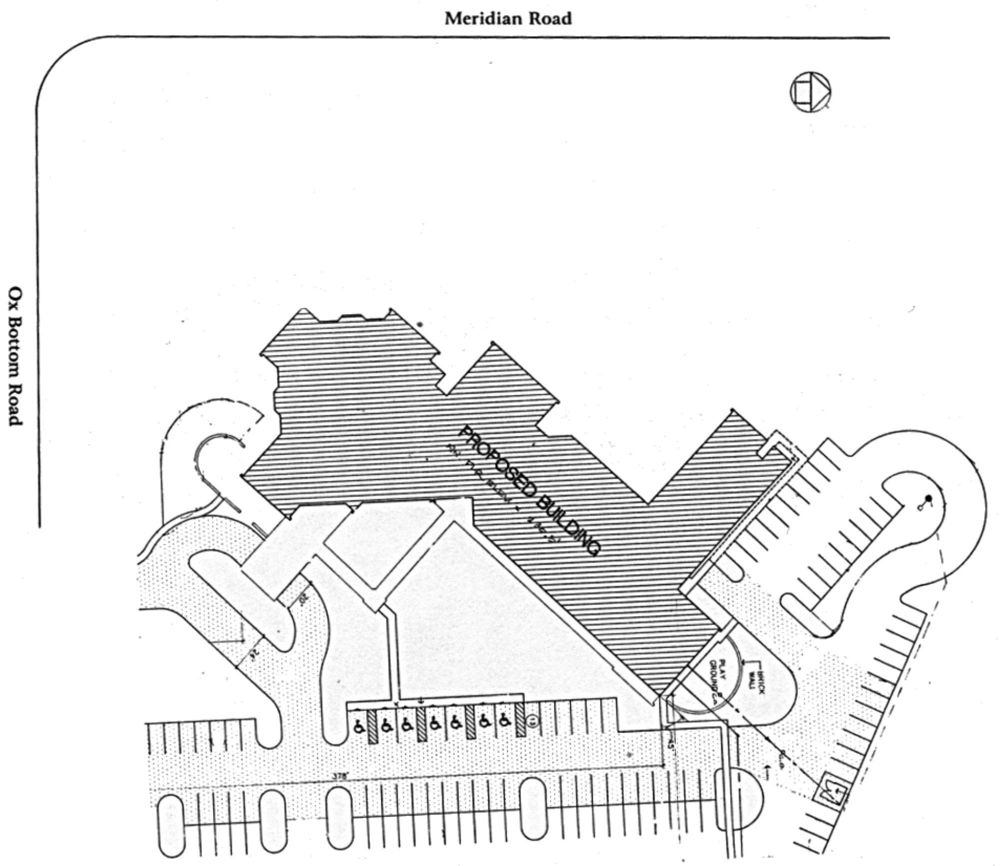
air handling unit: 6,538 cfm
smallest compressor/condenser unit:
    cooling capacity: 55,000 Btuh
        applicable efficiency measure: 11.1 EER
    heating capacity: 25,600 Btuh
        applicable efficiency measure: 100% efficiency (electric resistance)
air handling unit: 2,000 cfm
variable volume boxes: 8 VAV boxes, the smallest @ 30 - 200 cfm, the largest @ 615 - 4,100 cfm
supply/return air devices: 151 units;
    83 @ supply (ceiling and sidewall) with capacities from 50 to 615 cfm
    48 @ return (ceiling and sidewall) with capacities from 90 to 10,000 cfm
    20 @ miscellaneous (intake, exhaust) of various capacities
exhaust fans: 7 fans (4 @ toilet exhaust , 1 attic exhaust, 1 electric room, 1 fellowship hall)
    total toilet exhaust = 2,300 cfm
    fellowship hall exhaust (2,500 cfm) is balanced by equal size fresh air supply fan

Figures of Merit:

number of zones = 10
cooling capacity, square foot per ton = 250
heating capacity, Btuh per square foot = 17
supply air cfm per square foot = 1.7 overall average; (1.9 in classrooms, 1.3 in sanctuary)
size of largest supply air duct = 60 x 18 inches
percentage of gross conditioned floor area dedicated to HVAC equipment = 2.5%
HVAC cost as a percentage of total construction cost = approximately 10% of building cost (less land)

Special Notes: although a large facility, this church has retained a decidedly small-scale and distributed approach to HVAC systems. In part this is likely due to maintenance concerns and lack of a building operator who might be able to run a more centralized plant with chiller and boiler. It is also, however, likely due to the individualized nature of the operation schedule for the different components of the facility -- the fellowship hall, for example, may be in use at times when the classrooms and nurseries are not occupied. Much as occurs in a hotel setting, the use of separate systems for this facility may be a wise choice from an energy perspective, if the multiple systems are properly maintained. The decision to use multiple split systems has a major architectural impact as compressor/condenser units seem to dot the site. Even for this moderate size facility, there is a lot of HVAC equipment to be located and architecturally integrated (see for example, the listing of supply/return air devices above).

**Figure 83.** Site plan for the Wildwood Presbyterian Church in Tallahassee, FL.



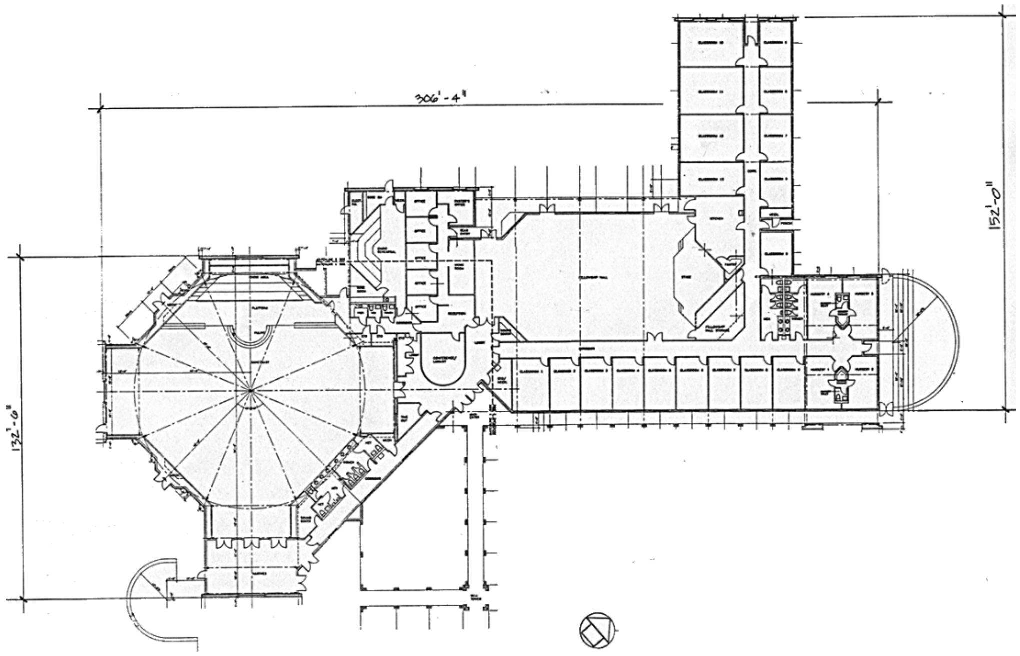


**Figure 84.** Plan of the Wildwood church.

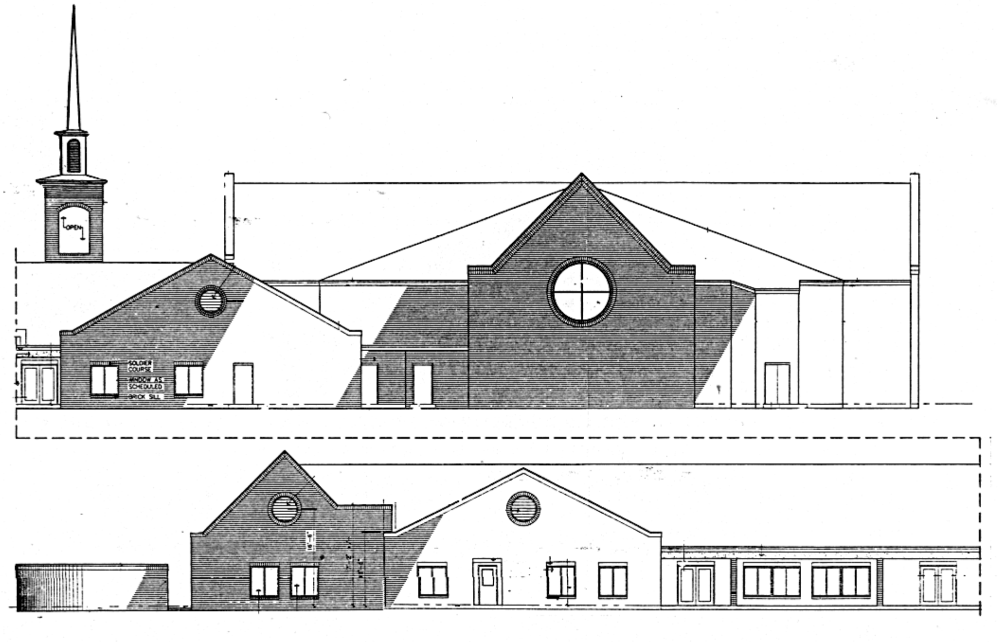


**Figure 85.** South elevation of the Wildwood church.

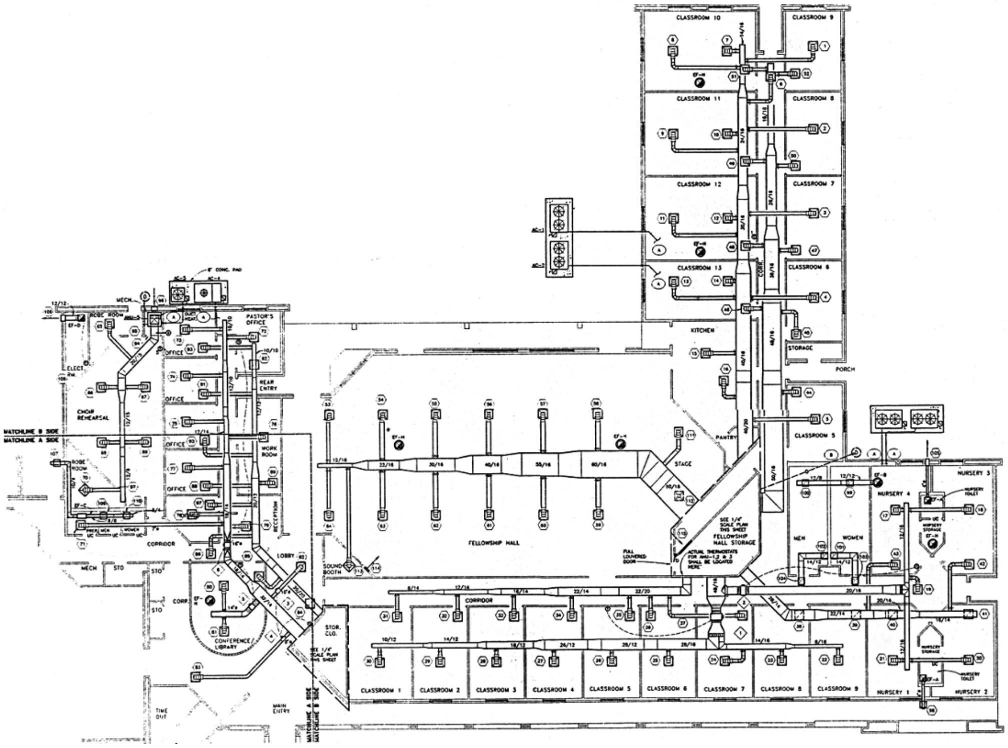


**Figure 86.** Mechanical plan (north wing only) of the Wildwood church; note the many air-cooled condensers located adjacent to the building.

## REGIONAL SERVICE CENTER / GOVERNMENT OFFICE BUILDING

Background: space for many State of Florida government offices in the Tallahassee area is being consolidated in the Capital Circle Office Center currently under development in Southeast Tallahassee. When fully developed, the Center will include around 20 separate buildings serving most state agencies and departments. The first of these office buildings was occupied in 1995, with future buildings coming on line over the next ten to twenty years. The buildings are based on prototype designs of various floor areas; the intention is that lessons learned from constructed buildings will be imparted to design teams in order to improve the performance of subsequent buildings. A district system is used to provide cooling for all buildings in the complex. Each building contains air handling equipment to distribute conditioned air to the spaces within the building. Thus, the complex uses a district system, while individual buildings use a central system. This case study will focus on the Department of Management Services (DMS) Building, the first building in the complex to be occupied.

HVAC System: Cooling is generated in a central plant housed in a separate building. Gas-fired absorption chillers produce chilled water that is piped to individual buildings through a utility tunnel. A secondary pumping system in each building circulates the chilled water to air handling units located in an “attic” space. Condenser heat from the chillers is rejected to atmosphere through a bank of cooling towers located adjacent to the central plant building. A gas-fired boiler in each building provides heat.

The DMS Building consists of three occupied floors (with a total of 100,000 square feet of space) and a mechanical attic. Air from two air handlers is ducted vertically through chases and horizontally through a ceiling plenum to individual spaces. Zoning is accomplished through variable volume terminal boxes located throughout the building. Air is supplied through ceiling diffusers. Return air is collected via ceiling plenums, then ducted back to the air handlers. Fan-coils are provided in some locations, such as corridors. Central exhaust fans are used to provide bathroom exhaust.

Sequence of Operation: the two air handling units in the DMS Building are controlled by an energy management control system using direct digital control. Supply air flow is modulated by supply-duct pressure-based control of variable frequency fan drives. Occupied and unoccupied control modes are identified. Outdoor air and fan-coil unit operational states are determined by occupancy status. Smoke detectors will stop the supply air fans in the event that smoke is detected. Variable volume fan terminal units are individually thermostatically controlled to adjust zone supply air flow to cooling demand. When required, heating is provided by hot water coils located at the terminal units. The fan terminal units are controlled to establish a night "set-back" condition.

Operation of the fan-coil units is enabled by a signal from the energy management control system. A digital controller at each fan-coil modulates chilled water flow through the action of a control valve. The fan-coils do not provide heating. The toilet exhaust fan is interlocked to the operation of either of the air handling units. Building secondary chilled water pumps are controlled by a variable frequency drive system that responds to water system pressure. Only one of the two pumps operates at any given time; the pumps are operated in sequence to equalize run time. The space heating boiler is controlled by a packaged control system that is an integral part of the boiler. The boiler control system is activated at an outside air temperature of 60 degrees F, along with the hot water supply pumps. One supply pump operates at any given time. A freeze-protection control strategy circulates heating water to all heating coils when the outside air temperature reaches 32 degrees F during an unoccupied period. Chilled water is provided to the DMS Building by a central chiller plant which operates under an independent controls scheme.

Major Equipment Details:

Central Plant:
- chillers: 2 absorption chillers at 400 tons capacity each;
  one vapor compression chiller at 125 tons capacity
- cooling towers: modular, expandable capacity to meet loads
- primary chilled water pumps: modular, expandable capacity

DMS Building:
- air handling units: two virtually identical units
  - cooling capacity: 1,590,000 Btuh each
  - heating capacity: none at central AHUs
  - supply air: 45,180 cfm each; 3.5 inches w.g. static pressure
- supply/return air devices: a variety of ceiling and sidewall diffusers, registers and grilles
- fan-coil units: 15 units, ranging from 450 cfm/9,700 Btuh capacity to 1600 cfm/51,600 Btuh
- secondary chilled water pumps: two @ 510 gpm; one auxiliary @ 25 gpm
- heating water pumps: two @ 55 gpm each
- boiler: 182,000 Btuh
- exhaust fan: 12,500 cfm toilet exhaust fan

Figures of Merit:

number of zones = 137
cooling capacity, square foot per ton = 377
heating capacity, Btuh per square foot = 1.8
supply air cfm per square foot = 1.1
size of largest supply air duct = 64 x 28 inches
percentage of gross conditioned floor area dedicated to HVAC equipment = 5%
HVAC cost as a percentage of total construction cost = information not available

Special Notes: gas-fired chillers were selected based upon a highly competitive natural gas tariff provided by the local utility. A district cooling system was selected as most appropriate and efficient for this scale office campus. A campus-wide energy management system will be used to monitor and control all buildings. The DMS Building was commissioned by an independent commissioning agent.

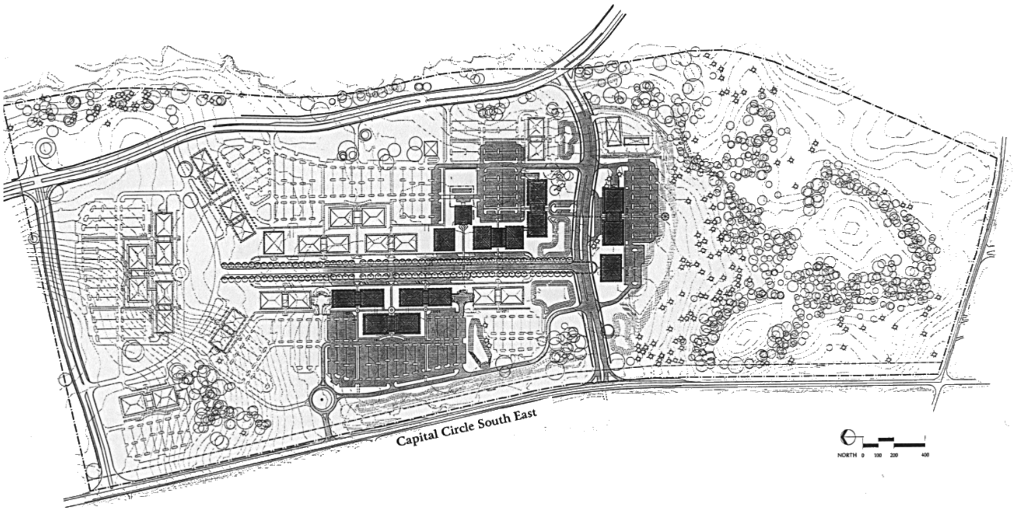


**Figure 87.** Site plan of the DMS office building, Tallahassee, FL.

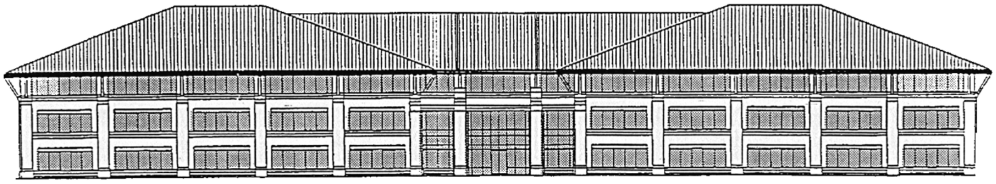


**Figure 88.** West elevation of the DMS office building.

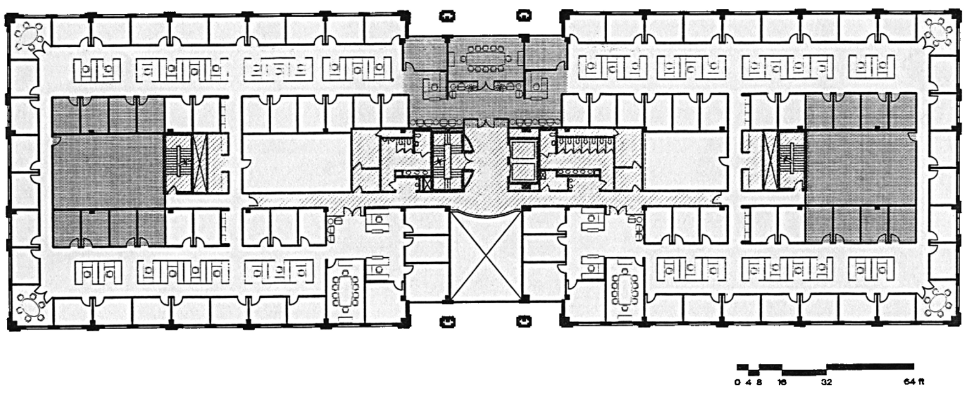


**Figure 89.** Ground floor plan of the DMS office building.

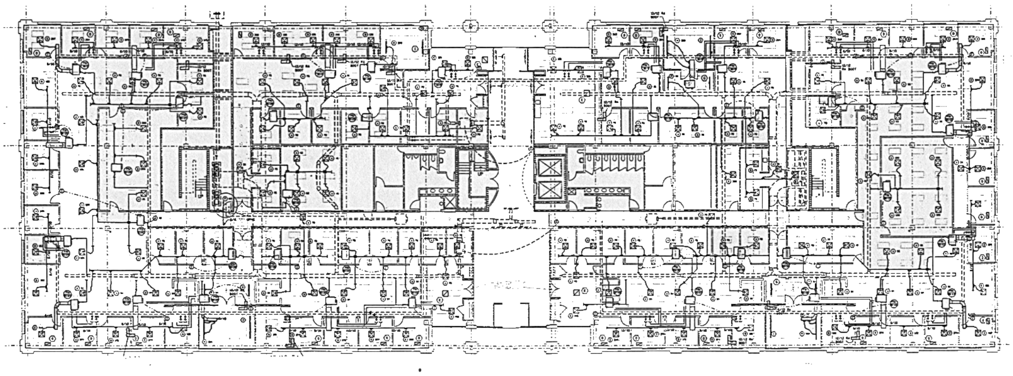
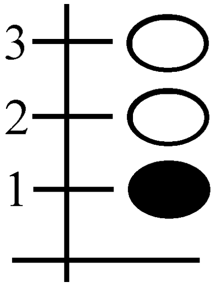


**Figure 90.** Ground floor mechanical plan of the DMS office building; illustrative of the complexity of HVAC systems in this scale of building.

# HVAC COMPONENTS AND SYSTEMS FIELD EXERCISES

The following field exercises are organized by level of detail and stage of design. Level One exercises are intended to address HVAC systems as a static element influencing building organization, are primarily conceptual in nature, and deal with issues that would normally be confronted during schematic design. Level Two exercises address HVAC systems as a dynamic element affecting building operations, require a more detailed understanding of system components and their functions, and deal with issues that would typically be considered by a consultant during design development. Level Three exercises consider the role of HVAC systems in the long-term functioning of a building, their impact on the consumption of energy resources, and deal with issues that would normally be addressed after building occupancy.

These exercises are intended to be applied in a group educational setting, as part of a lecture class or laboratory dealing with HVAC systems. The give and take between students and instructor likely to develop in such a setting can provide rich opportunities for the sharing of opinions regarding the character and role of HVAC systems in buildings. It is also possible, however, for an individual to undertake completion of these exercises in a more individualized setting. Physical access to appropriate buildings and supporting documentation is necessary for completion of the exercises. Objectives and instrumentation and documentation requirements for the three levels of exercises are outlined below.



## Level One

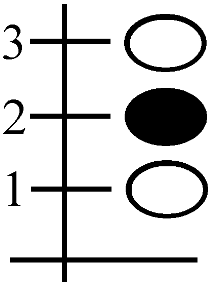
Level One exercises are based upon the "declare-and-compare" approach, wherein students are asked to make predictions regarding various aspects of HVAC systems and then to compare those predictions with actual system characteristics found in a sample building. Although it may be comforting to find that such comparisons support original suppositions, attempting to reconcile differences between predictions and field findings may be exceptionally educational.

Objectives: to consider HVAC systems from a conceptual and static viewpoint, addressing issues of space, location, size, and organization -- much as an architect might do during schematic design; to provide exposure to basic concepts and components of building HVAC systems.

Background Preparation: identify applicable building(s) for use with these exercises and obtain necessary documentation (site plan, floor plans, elevations, HVAC plans and schedules).

Instrumentation: none required.

Materials: building site plan, floor plans and elevations with all references to HVAC systems and equipment removed; a second set of these documents with references to the HVAC systems retained; exercise forms.



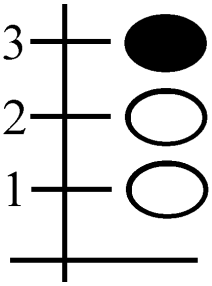
**Level Two**

Objectives: to consider HVAC systems from a dynamic perspective; to provide exposure to the characteristics of HVAC systems in operation.

Background Preparation: identify applicable building(s) for use with these exercises and obtain necessary documentation (site plan, floor plans, elevations, HVAC plans and schedules); ensure that access to the building and its mechanical spaces is available.

Instrumentation: portable activity loggers (Hobo temperature loggers or similar); site-installed systems instrumentation.

Materials: building floor plans and elevations, HVAC drawings and schedules; HVAC sequence of operations; operation and maintenance manuals for HVAC equipment and system; exercise forms.



**Level Three**

Objectives: to consider HVAC systems from the perspective of energy consumption, much as a building operations director or energy manager might; to understand the role of HVAC systems in building energy utilization.

Background Preparation: identify applicable building(s) for use with these exercises and obtain necessary documentation; ensure that information on the operation of building HVAC systems and equipment is available; obtain energy consumption information for building.

Instrumentation: varies with depth of investigation and selected building.

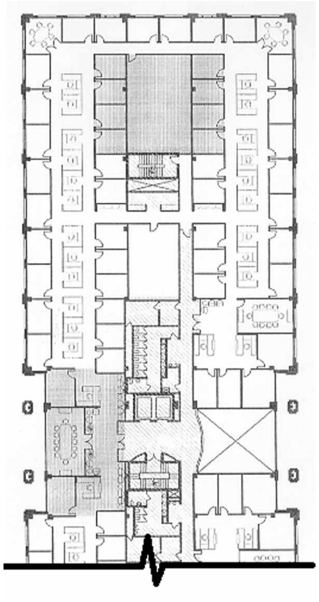
Materials: building documentation; equipment operations logs; energy management system reports; utility billing data; exercise forms.

Note: the consideration of dynamic system operation over time can be an extremely complex undertaking. Level Three exercises are most appropriate for advanced or graduate course settings. The energy usage issues addressed in Level Three relate closely to two other Vital Signs modules: Whole Building Energy Use -- Residential and Whole Building Energy Performance -- Simulation and Prediction. Reference to these modules is strongly recommended prior to beginning Level Three analysis.

## SUMMARY OF FIELD EXERCISES

| LEVEL | NO. | KEY ISSUE | PROCEDURE | MATERIALS/EQUIPMENT |
|---|---|---|---|---|
| 1 | ALL | GENERAL | SELECT BUILDING<br>OBTAIN DRAWINGS<br>TEAMS MAKE PROPOSALS<br>"DECLARE"<br>DEBATE TEAM PROPOSALS<br>"CONSENSUS"<br>REVIEW ACTUAL SITUATION<br>"COMPARE" | SITE PLAN, FLOOR PLAN(S), ELEVATIONS<br>MECHANICAL PLANS |
| 1 | 1 | THERMAL ZONING | AS DESCRIBED ABOVE | AS DESCRIBED ABOVE |
| 1 | 2 | SYSTEM SELECTION | AS DESCRIBED ABOVE | AS DESCRIBED ABOVE |
| 1 | 3 | COMPONENT LOCATION | AS DESCRIBED ABOVE | AS DESCRIBED ABOVE |
| 1 | 4 | SYSTEM "SIZES" | ESTIMATE KEY CAPACITIES, SIZES, AND EFFICIENCIES | AS PER ABOVE, PLUS TEXT RESOURCES |
| 1 | 5 | SITE VISIT | EXPERIENCE SYSTEM "ON-SITE" | ACCESS TO BUILDING AND MECHANICAL SPACES |
| 2 | 1 | OPERATION SEQUENCE | AS PER LEVEL 1 GENERAL | AS PER LEVEL 1 GENERAL |
| 2 | 2 | COMPONENT CYCLES | AS DESCRIBED ABOVE<br>MEASURE OPERATION STATUS | AS DESCRIBED ABOVE<br>OPERATIONS LOGS<br>DATA LOGGERS |
| 2 | 3 | PART-LOAD OPERATION | RECORD FLOWS AND TEMPERATURES | SYSTEM INSTRUMENTATION<br>ENERGY MANAGEMENT LOGS |
| 3 | 1 | ANNUAL ENERGY USE | ESTIMATE HVAC ENERGY CONSUMPTION<br>COMPARE ESTIMATES WITH ACTUAL USAGE | AS PER LEVELS 1 AND 2<br>OPERATIONS LOGS<br>UTILITY BILLS<br>ENERGY MANAGEMENT SYSTEM RECORDS |

## LEVEL ONE -- EXERCISE ONE



Objective: to explore the importance of thermal zoning to comfort and HVAC systems development.

Procedure:

A. Review the site plan, floor plan(s), and building elevations that are provided. Considering overall building function, form and orientation, the functions and uses of individual spaces, and anticipated building occupancy schedules, markup the provided floor plan(s) to indicate what you believe to be the most appropriate thermal zoning scheme.

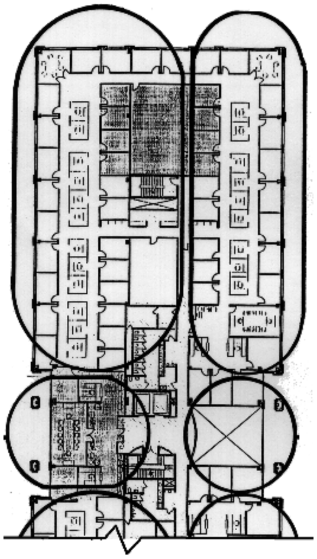
B. Suggest a thermostat location for each identified zone.

C. If the number of zones you proposed had to be reduced by one, specify the specific zone you would recommend deleting and note the anticipated effect on occupant comfort in the affected area. What effects would be expected if two zones had to be removed from your original zoning proposal?

D. Compare zoning schemes and thermostat locations developed by different individuals or groups in the class. Attempt to come to a class consensus regarding the most appropriate thermal zoning scheme for the building.

E. Compare the class consensus zoning arrangement with the zoning provided for the actual building.

F. Attempt to provide explanations for differences between the actual zoning arrangement and the proposed consensus zoning arrangement. What effect would these differences likely have on occupant comfort?



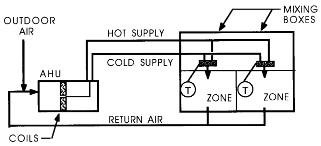
Discussion: a thermal zone is an area of a building that must be separately controlled if comfort is to be provided for occupants of that area. The key element in zoning analysis is differential thermal response over time. Two spaces with very different cooling or heating loads may be reasonably placed on the same zone -- as long as their loads follow a similar pattern over time. Solar radiation and occupancy schedules are normally the deciding factors in thermal zoning. Each zone will be controlled from a single control point (normally a thermostat). If you can not envision a thermostat in room "A" successfully controlling conditions in room "B", you have probably identified a need for a separate zone.

The zoning arrangement for an existing building will usually have to be deduced from the layout of system components. Rarely is thermal zoning included as an explicit element of the building design documents. In an all-air system, it is recommended that you use the ductwork layout (usually shown in mechanical plans) to identify points of thermal control (mixing boxes, VAV boxes, or air handling units) and, thus, portions of the building that are controlled from a common point (a zone). In an air-water system, locating the delivery devices (fan-coils, induction cabinets) should identify the thermal zones. In a local system, locating source equipment (air conditioning units) will provide similar information.

## LEVEL ONE -- EXERCISE TWO

Objective: to select an appropriate HVAC system for a given building situation.

Procedure:



A. Review the site plan, floor plan(s), and building elevations that are provided. Considering building functions, architectural design intent, anticipated budget (meager, average, lavish), proposed thermal zoning requirements, and other applicable factors, specify the general type of active HVAC system (local or central) and the specific system type and name you believe to be most appropriate for this building.

B. List and explain the six factors (related to selection criteria) that most influenced your decision. Note why you believe these factors to be most important in this particular context.

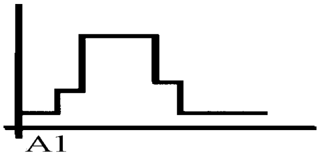
C. If for some reason your first-choice HVAC system could not be used for this building, what system would you select as your second choice? Explain why this "fallback" system is acceptable -- but not as desirable as the system selected in (A) above.

D. Compare HVAC system choices made by different individuals or groups in the class. Attempt to come to a class consensus regarding the most appropriate HVAC system for the building.

E. Through analysis of HVAC plans and equipment schedules, determine the type of HVAC system actually provided for the building in question. If differing opinions exist regarding the type of system indicated by the building documentation, come to a consensus through group discussions.

F. Compare the class consensus system selection with the system actually provided for the building.

G. Attempt to provide explanations for differences between the system actually selected for the building and the consensus system selection. What effect would these differences likely have on occupant comfort and building energy consumption?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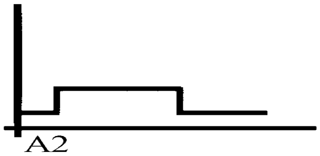
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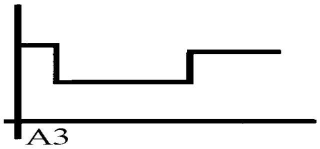
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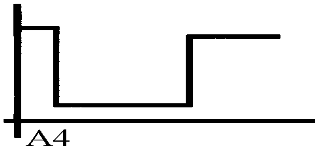

A4

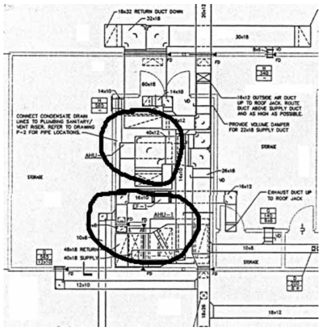
Discussion: any number of issues may influence the selection of an appropriate HVAC system -- first cost, appearance, energy efficiency, smoke control capabilities, and the like. The conversion of issues into targets that must be met by a system being considered -- first cost less than 10% of total construction cost, pleasing appearance, COP equal to or greater than 3.0, etc. -- provides selection criteria that may be used to sort system capabilities. As the typical selection process may consider 10 or more such criteria, and look at 3 or more potential systems, a matrix analysis approach (using weighted scores to account for the importance of each criterion and each system's score on that issue) can be of use. A clear understanding of the context of a building project is critical to successful system selection.

Usually, the type of HVAC system provided for an existing building will have to be deduced from information provided in the construction documents. System "names" are seldom included as an explicit element of the construction documents. Key information (clues) on the mechanical drawings, however, usually make it relatively easy to identify the particular system being used. VAV terminal boxes in a ductwork layout, for example, signal a VAV system.

## LEVEL ONE -- EXERCISE THREE

Objective: to consider how and why HVAC system components are located in a building.

Procedure:



A. Review the site plan, floor plan(s), and building elevations that are provided. Considering building context, zoning arrangement and the HVAC system chosen in Exercise Two, determine where you believe the major components (condenser, boiler, air handling unit, variable volume boxes, etc. -- as appropriate to your system) should be placed. Mark their locations on the building floor plan(s) provided.

B. Annotate the marked-up plan(s) from part (A) above to indicate the key reason why each system component is to be located where shown.

C. Compare component locations proposed by different individuals or groups in the class. Attempt to come to a class consensus regarding the most appropriate locations for all major equipment components.

D. Compare recommended class consensus equipment locations with the equipment locations established for the actual building.

E. Attempt to provide explanations for differences between the actual equipment locations and the proposed consensus locations. What effect would these differences likely have on construction cost (increase, decrease, no change) and process (simplifies, makes more complex, no effect), aesthetics, and other possible concerns?

| FAN SCHEDULE | | |
|---|---|---|
| UNIT # | CFM | STATIC |
| | | |
| F-1 | 2,500 | 1.50" |
| F-2 | 4,350 | 3.25" |
| F-3 | 1,370 | 1.25" |
| F-4 | 1,000 | 1.00" |
| F-5 | 2,900 | 2.50" |
| | | |
| E-1 | 500 | 0.50" |
| E-2 | 750 | 0.50" |

Discussion: ideally, the locations for all major equipment items would be thought out early in the design process and coordinated with the overall architectural design of the building. In practice, HVAC stuff seems to often just be plopped down here or there. Equipment locations can have serious effects on building aesthetics, performance, cost, and energy efficiency. Fan rooms should normally be located so as to minimize the length and size of duct distribution systems. Condensers must be located outside the building envelope. Adequate access to equipment is critical if systems are to be properly maintained. Maintenance without great difficulty is the key to continued efficient operation and equipment cleanliness.

Major equipment is usually clearly noted on mechanical drawings, although it may often be noted under a "tag" number (such as AC-1). Equipment schedules and legends provide a means for converting a symbol, tag number or abbreviation into a defined type of equipment. Often, equipment may not be shown in smaller-scale floor plans, but will be shown in larger-scale plans or details. Drawing cross references will indicate when such enhanced details are available.

## LEVEL ONE -- EXERCISE FOUR

Objective: to provide experience in estimating system capacities and efficiency measures.

Procedure:

A. Using the rule-of-thumb sizing charts in *The Architect's Studio Companion* and/or the sizing tables found in *Mechanical and Electrical Equipment for Buildings*, estimate the size or capacity of the following HVAC system elements:

Total cooling load = _________ tons Total heating load = _________ Btuh
Total supply air flow rate = _________ cfm (if an all-air system)
Minimum area for central plant room = __________ square feet (if required)
Minimum area for satellite fan rooms = ____________ square feet (if required)
Area allocation for condensers = ___________ square feet (if required)
Area of supply air duct where largest = _________ (units = ___________)
Proposed dimensions of largest duct = _______ x ________ (units = ________)

B. From the building energy-efficiency standard or code in force for the location of the building, determine the applicable efficiency measure and minimum permissible value of that measure for the following equipment (as applicable):

Refrigeration source equipment: the measure is ___________________________
minimum permissible value = ______________
Heating source equipment: the measure is ________________________________
minimum permissible value = ______________

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C. Using equipment schedules and mechanical plans from the building documentation set, determine the actual size or capacity of the following HVAC system elements:

Total cooling capacity = _________ tons Total heating capacity = _________ Btuh
Total supply air flow rate = _________ cfm (if an all-air system)
Minimum outside air supply = _________ cfm
Area for central plant room = __________ square feet (if required)
Area for fan rooms = ____________ square feet (if required)
Area allocation for condensers = ___________ square feet (if required)
Area of supply air duct where largest = _________ (dimensions = _______ x _______)

D. Compare the estimated values from (A) above with the actual values from (C). Attempt to provide explanations for any substantial differences encountered.

Discussion: it is important to get a feel for equipment space and capacity requirements early in the design process for coordination efforts to be successful. The rule-of-thumb information provided in the cited references is intended for use during preliminary design. Actual calculated values for cooling capacity, air flow, and the like would be expected to be somewhat different from estimated values -- but not substantially so if the estimates are to have any practical use. The area and size of supply ducts may be estimated by dividing the anticipated air flow through the duct (in cfm) by the proposed air flow velocity (in fpm -- usually between 1000 and 1500 fpm for main ducts).

## LEVEL ONE -- EXERCISE FIVE

Objective: to experience HVAC systems and components in their native habitat.

Procedure:

A. Walk through the building that has been used for Level One Exercises One through Four. Observe the locations, size, sound, and appearance of all major HVAC system components. Make a record of the manufacturer, model number, and capacity of all major equipment components. Take notes that will permit you to develop a statement or written report regarding the aesthetics and architectural integration of the HVAC systems and components. Make notes on any HVAC issue you encounter that raises questions or seems to substantially deviate from the impressions you formed as you reviewed the building documentation.

B. Identify the type of HVAC system used in the building. Draw a schematic diagram tracing the path of conditioning energy (in the form of air, water, or both) from source equipment, through distribution components, and to the zones through delivery components. Identify all major components by name. Find air intake and exhaust locations.

C. Prepare a summary report (written and/or oral) on the findings of your site visit.

D. Compare and discuss impressions gained and questions raised as a result of the site visit.

Discussion: viewing HVAC systems and components in an actual building setting is usually a great way to improve your understanding of systems and their application. As you walk through the building look for equipment that you know should be installed in a given location. Make a note of questions that come up as you view the systems. Attempt to name, and ascribe a purpose to, system components that you encounter during the walk-through but with which you may be unfamiliar. Consider how large items of equipment were installed, how they might be removed if they had to be replaced, and how they can be maintained. Much of the equipment you will see during the visit will be in operation, be careful around rotating equipment and electrical panels and connections. Be sure to record your impressions of the equipment in operation -- especially as regards noise and potential energy efficiency issues.

HVAC equipment is typically tagged with a nameplate that indicates manufacturer, model number and selected operational data (particularly as related to electrical characteristics). Much of the mechanical equipment you encounter in a building will not display information related to its HVAC capacity. Pumps, for example, do not have a tag indicating water flow rate. Information regarding the capacity -- and energy efficiency -- of equipment must usually be obtained from manufacturer's catalogs for the specific equipment in question.

## LEVEL TWO -- EXERCISE ONE

Objective: to consider HVAC systems as dynamic entities, rather than simply as a conglomeration of equipment footprints on a floor plan.

Procedure:

A. Develop a sequence of operation for the major elements of the HVAC system (chiller, boiler, cooling tower or air-cooled condenser, air handlers, pumps, exhaust fans -- as applicable) under the following conditions:

A.1: underheated period, normal occupancy hours
A.2. underheated period, evening hours
A.3 underheated period, late night/early morning hours
A.4 overheated period, normal occupancy hours
A.5. overheated period, evening hours
A.6 overheated period, late night/early morning hours

B. Discuss and compare various sequences of operation developed by individuals or groups. Come to a consensus on the sequence of operation that best fits the building context and intent.

C. If available, compare the sequence of operation developed for the actual building with the proposed consensus sequence of operation. Discuss substantial differences between the sequences and their likely impact on occupant comfort and energy usage.

Discussion: a sequence of operation is a verbal description of how the various equipment components are intended to function under a variety of situations. This description forms the basis for design of an appropriate control system. A well-written sequence of operation will capture the design intent of a system -- what the system designer intended a system to do under a given set of circumstances. As this statement will be used to control specific devices, it is usually prescriptive (“fan will turn on”) rather than performance-based (“sufficient air will be available”). Typically the HVAC sequence of operation will be found in the mechanical section of the project specifications. A small section of a hypothetical sequence of operation might go as follows: "during unoccupied summer hours, zone thermostats shall be reset to 85 deg F, exhaust fans shall be shut off, and outdoor air dampers shall be closed".

How and when HVAC equipment operates can have a great effect on a building’s energy consumption. Review of operating sequences and related control strategies is a rich area for energy conservation efforts in existing buildings. Occasionally, original operating intent will be seen to be flawed in the context of today’s expectations for building performance; more commonly, how a building is actually operated has diverged over time from how it was intended to be operated. Periodic re-commissioning of systems to match reality with intent is recommended.

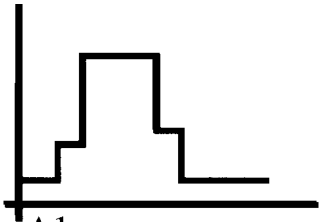
## LEVEL TWO -- EXERCISE TWO

Objective: to relate equipment operating profiles to sequence of operation intentions.

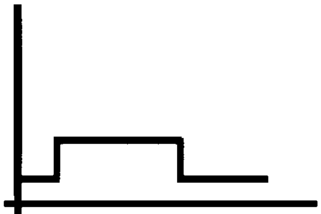
Procedure:

A. Plot a graphic depiction (a profile) of the operational status (on, off, or part-load -- including percentage of full load) you would expect (or propose) for all major energy-consuming components (chiller, boiler, air handling units, pumps, exhaust fans, etc.) of the building HVAC system for a 24-hour period during each of the following occupancy situations:

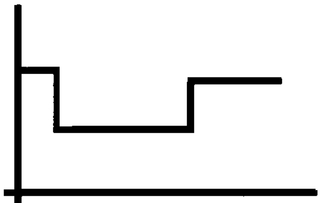
A.1: underheated period, weekday
A.2. underheated period, weekend-holiday
A.3. overheated period, weekday
A.4. overheated period, weekend-holiday



A1



A2



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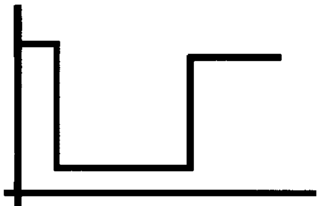


A4

B.1. If available, obtain equipment operation logs to develop similar profiles for equipment as actually operated in the building . Discuss substantial differences between the proposed and documented profiles and their likely impact on occupant comfort and energy usage.

B.2. If operational logs are not available, utilize portable data loggers to develop similar profiles for equipment as actually operated in the building. Discuss substantial differences between the sequences and their likely impact on occupant comfort and energy usage.

Discussion: the energy consumption of HVAC equipment is a function of the energy draw of the equipment times the hours of operation of the equipment. Energy draw (or consumption) is determined by the capacity (size) of the equipment, its efficiency, and its loading state (fully loaded, half-loaded). Accurately tracking these variables over time is termed metering and monitoring -- a potentially complex and expensive endeavor. This exercise asks you to estimate equipment loading status versus time for a limited number of "typical" days in the life of the building -- based on your understanding of system intentions and building performance. It is suggested that you start with "terminal" equipment first, then move to more central equipment. A suggested format for the operational profiles is shown adjacent.

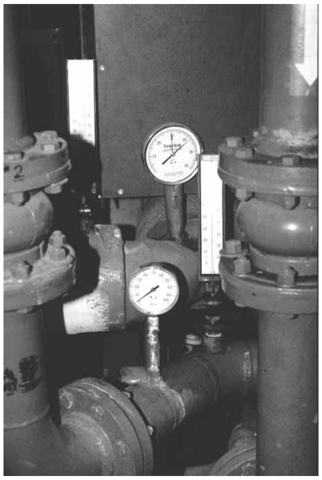
It may be possible (but not necessarily likely) to obtain operations logs for major equipment that will document actual time in use for defined time periods. If such logs are available, use them to plot operations profiles as described in Part (A) for comparison with your projected profiles. If the example building has an energy management system, it should be able to provide this type of information.

If the example building has neither operating logs nor energy management system, it is suggested that low-cost temperature data loggers (such as a HOBO -- see the Vital Signs Tool Lending Library module for further information) be used to explore equipment operation. Virtually all HVAC equipment will change temperature with changes in operation. The housing of a pump, surface temperature of a chilled water line, outlet air temperature of a condenser, etc. will change as the equipment cycles on and off or substantially changes output. A plot of such temperatures over a 24-hour period should provide ample evidence upon which to construct a reasonably accurate operations profile. In most cases, such temperature measurements can be made in a manner that is non-intrusive, non-destructive, and safe for the investigator.

## LEVEL TWO -- EXERCISE THREE

Objective: to explore part-load operation characteristics of operating HVAC equipment..

Procedure:



A. If the building under consideration is fairly well-instrumented with permanently installed, remotely located gauges, use these devices to monitor temperature, pressure, and/or flow for major HVAC equipment components -- including air handling units, chillers, boilers, cooling towers/condensers, and large pumps. If available, obtain records from an energy management system to provide a picture of part-load operations. Use the results of such performance observations to plot part-load operating profiles of the components for the following typical situations:

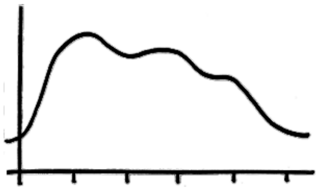
A.1: underheated period, weekday
A.2. underheated period, weekend-holiday
A.3. overheated period, weekday
A.4. overheated period, weekend-holiday

B. Compare the operating profiles developed in Part (A) above with those developed (more intuitively and with less input data) in Level Two, Exercise Two. What differences are found in these two portraits of equipment operation and how did such differences come about?

Discussion: the range of opportunities presented by this exercise and the specific techniques utilized to tap those opportunities will vary substantially from building to building. The following discussion is a generic introduction to basic underlying issues. A site-specific procedure will have to be developed for each building being considered.

The operational state of any given HVAC system component at a particular time is a result of the interaction of building internal and external loads with the building's control scheme (defined by a sequence of operation). In central systems, this interaction can be quite complex and dynamic. Monitoring actual output characteristics of equipment over time can provide insight into part-load operations -- which for many items of equipment is a much more common state of operation than the full-load condition. It may be possible to record and analyze data on selected equipment output parameters to establish an understanding of this system performance issue.

Local systems typically utilize on-off control schemes. The temporal performance of such systems is typically well-defined by recording operational time periods versus time periods when the equipment is dormant. There would seldom be instrumentation available on site from which to record such information. A day-long plot of output air temperature, derived from a portable temperature logger (for example a HOBO) would easily provide data on operational patterns.



Central systems commonly employ modulating control schemes, wherein equipment may be operating at any point between full and no load. Often, a part-load condition will be reflected in some measure of equipment output -- supply air temperature, cfm delivered by a fan, chilled water or condenser water temperature, for example. It is not uncommon to find that instrumentation that is readable by the casual observer (thermometer, pressure gage, etc.) has been installed near major equipment. This analog instrumentation may be used to track equipment performance over time (for example, readings every 15 minutes for a 24-hour period -- best done by a team!). Although possible, it will require a substantial investment of time to collect data. Similar recordings over a more limited time frame (6 am to 6 pm, perhaps) may yield almost equally valuable data. If an energy management control system is installed in a building, it should be able to provide detailed information on equipment operation over time. Such information should be accessible in electronic or printed format from the facility manager.

Information regarding the operating state (part-load status) of equipment -- supply air flow or chilled water temperature, for example -- will have to be correlated with manufacturer's catalog data for the equipment in question to determine the relationship of part-load status to energy consumption. Catalogs may be available as part of the Operating and Maintenance Manual for the system, or can be obtained from the manufacturer.

## LEVEL THREE -- EXERCISE ONE

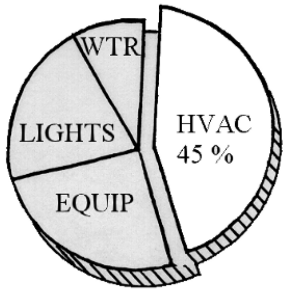
Objective: to predict annual energy consumption for the building that was used for Level One and Level Two analyses.

Procedure:

A. Utilize estimated (or, better yet, documented) equipment operation profiles and nameplate energy-consumption data to estimate annual HVAC system energy consumption. Consider the various operating states that have been discussed in other exercises (underheated, overheated, weekday, weekend) when developing this estimate.

B. Obtain utility bill or energy management system records to establish actual building energy consumption for a typical annual cycle. If utility bills are used, the consumption of non-HVAC elements (lights, computers, elevators, and the like) will have to backed out of the bills.

C. Compare the estimated annual energy consumption and estimated monthly consumption values to the measured energy consumption data. Note differences between the measured and predicted energy usages and discuss possible reasons for such differences.



D. Using the information you developed in Part (A) above, develop a pie chart showing percentages of annual HVAC system energy use attributable to each major system component.

E. Using either estimated or measured energy consumption data, calculate the annual energy budget (expressed as Btu per square foot per year) for the building in question. If similar data for comparable buildings in the same region are available, compare the energy budgets for these buildings to that of the building in question. How does this building compare relative to the others? What factors may influence this comparison?

Discussion: although building energy analysis software is becoming more accessible, it is not commonly used for the majority of today's building design projects. The ability to get a "back-of-an-envelope" type estimate of HVAC system energy consumption is a useful design skill. Part (A) above asks you to develop just such an estimate.

If available, an energy management system may be able to provide ready access to building energy consumption records for a one-year period. Comparison of estimated and actual energy consumption will serve as a reality check for your estimates. If your estimated and measured values are very close, you have great reason for suspicion. A building's energy consumption will vary from year to year as weather and building usage change. Such annual changes can sometimes be substantial. If the estimated and measured consumption values are in the same ballpark, you are probably on the right track.

If utility billing records are available, they can provide insight into HVAC system energy consumption. They will, however, reflect the consumption of all electrical and/or fuel driven devices and equipment -- including computers, lights, hot water heaters, cooking equipment, and the like. It is usually possible (although time-consuming and not necessarily simple) to estimate such non-HVAC consumption and back it out of the total consumption to derive HVAC energy consumption.

# HVAC COMPONENTS AND SYSTEMS GLOSSARY

Selected terms that may be unfamiliar to someone first exploring building HVAC systems are presented here in alphabetical order. The explanations in this glossary are intended to suggest a meaning and context for the terms; they are not technically rigorous definitions.

Absorption chiller: refrigeration equipment that generates chilled water via a chemically driven process using water and a desiccant salt as refrigerant; comprised of four major components: a generator, condenser, absorber, and evaporator; operating energy is input as heat.

Air: a mixture of gases (including oxygen, nitrogen, argon, carbon dioxide, and water vapor) and suspended solid and liquid materials.

Air changes: the number of times per hour that a volume of air equal to room volume is replaced; one air change per hour (ACH) represents the supply and return of air equal to the volume of the room in question once every hour.

Air conditioning: a process that simultaneously controls the temperature, moisture content, distribution, and quality of air.

Air filter: a device designed to remove contaminants and pollutants from air passing through the device.

Air handling unit: an assembly of air-conditioning components that normally includes a fan, a filter, heating and cooling coils, and control elements.

Air-water HVAC system: a category of central HVAC systems that distribute conditioning effect by means of heated or chilled water and heated or cooled air.

All-air HVAC system: a category of central HVAC systems that distribute conditioning effect solely by means of heated or cooled air.

All-water HVAC system: a category of central HVAC systems that distribute conditioning effect solely by means of heated or chilled water.

ASHRAE: the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; the primary professional organization in North America involved with HVAC systems design; developer of many HVAC system standards and guidelines.

Axial fan: a fan, usually with a propeller-type design, that moves air along a consistent axis without substantial change in direction; occasionally used in air handling units and commonly used for return and exhaust air applications.

Balance point temperature: that outside air temperature at which a particular building will be in thermal equilibrium, requiring neither heating nor cooling to support thermal comfort.

Boiler: equipment designed to heat water or generate steam.

British thermal unit: (Btu) a measure of thermal energy (heat); quantity of energy required to raise the temperature of one pound of water by one degree Fahrenheit.

Central HVAC system: a system that produces a heating or cooling effect in a central location for subsequent distribution to satellite spaces that require conditioning; see also all-air, all-water, and air-water HVAC systems.

Centrifugal: a particular type of fluid moving device that imparts energy to the fluid by high velocity rotary motion through a channel, fluids enter the device along one axis and exit along another axis; see also centrifugal chiller, centrifugal fan, centrifugal pump.

Centrifugal chiller: a vapor compression chiller that utilizes a centrifugal compressor; most commonly used in systems with cooling capacities of from 80 to 10,000 tons.

Centrifugal fan: a fan that utilizes a centrifugal air flow design; most common fan design for air handling unit applications.

Centrifugal pump: a pump that utilizes a centrifugal water flow design; most common pump design for general purpose HVAC applications (chilled water, condenser water, hot water).

Chiller: equipment designed to produce chilled water; see also vapor compression chiller (centrifugal, reciprocating) and absorption chiller.

Coefficient of performance: an efficiency measure for cooling source equipment; the ratio of cooling effect (output) to energy input -- with cooling effect and energy input in consistent units.

Coil: a liquid-to-air heat exchanger consisting of tubes through which the liquid flows and multiple fins (attached to the tubes) across which the air flows; an electric resistance element used to heat air or water.

Combustion: an oxidation process that releases heat; on-site combustion is a common heat source for buildings.

Comfort: an expression of satisfaction with a particular environment; see also thermal comfort.

Commissioning: a systematic process to verify that building components and systems function as intended and required; systems may need to be re-commissioned at intervals during a building's life cycle.

Compressor: a device designed to compress (increase the density) of a compressible fluid; a component used to compress refrigerant; a component used to compress air.

Condenser: a device designed to condense a refrigerant; an air-to-refrigerant or water-to-refrigerant heat exchanger; part of a vapor compression or absorption refrigeration cycle.

Control: a means of regulating the operation of a device or system; equipment or systems designed to regulate the operation of an HVAC system.

Cooling: a process that removes sensible and/or latent heat from a material or space.

Cooling load: the magnitude of heat removal required to maintain a building at appropriate thermal conditions.

Cooling tower: equipment designed to reject heat from a refrigeration cycle to the outside environment through an open cycle evaporative process; an exterior heat rejection unit in a water-cooled refrigeration system.

Damper: a device designed to regulate the flow of air in a distribution system.

Dehumidifier: equipment designed to remove moisture from the air; in the generally used sense of this term, a freestanding moisture removal device.

Design conditions: a set of interior and/or exterior environmental parameters used for the design of HVAC systems.

Dew point: that temperature at which the moisture in air at a given state point would begin to condense due to the air reaching saturation conditions.

Diffuser: a device designed to supply air to a space while providing good mixing of supply and room air and avoiding drafts; normally ceiling installed.

Dual duct HVAC system: a central air-all HVAC system that utilizes two supply air streams, one warm and one cool, that are mixed in a terminal device at each zone to provide appropriate thermal conditions; a dual duct system requires the use of two separate supply air ducts.

Duct: a container for the distribution of air.

Economizer: a means of providing space cooling through the introduction of outside air rather than through refrigeration; an economizer cycle allows outside air to be used for cooling when exterior conditions are appropriate.

Efficiency: the ratio of energy output to energy input of a device or system.

Energy: a measure of the capacity to do work.

Enthalpy: a measure of the relative heat content of air (Btu per pound of dry air).

Fan: a device designed to impart energy (velocity and/or pressure) to air in a supply, return, exhaust, or circulation system.

Fan coil: a small-scale "air handling unit" (including a fan, a coil or coils, and a filter) that is normally located in or directly adjacent to a conditioned space; serves as a delivery device in an all-water or air-water central HVAC system.

Filter: a device designed to remove impurities from a fluid passing through the device; see also air filter.

Fin tube: a linear water-to-air heat exchanger, used in baseboard radiators; a delivery device in all-water central heating systems.

Fire damper: a control device that will block air flow when triggered by high temperatures; installed wherever ducts or air transfer openings pass through fire-rated constructions.

Fuel: an easily burned material with high energy content (coal, wood, natural gas, propane, fuel oil).

Furnace: equipment designed to heat air; comprised of a heat source, fan and filter; normal usage of this term is for residential-scale equipment.

Grille: a device designed to permit air flow while restricting sightlines; a decorative cover for an air flow opening.

Heat exchanger: a device designed to efficiently transfer heat from one medium to another (for example, water-to-air, refrigerant-to-air, refrigerant-to-water, steam-to-water) .

Heating: a process that adds sensible heat to a material or space.

Heat pump: a device that uses a reversible cycle vapor compression refrigeration circuit to provide cooling and heating from the same unit (at different times).

Heat recovery: a process whereby heat is extracted from exhaust air before the air is dumped to the outside environment, the recovered heat is normally used to preheat incoming outside air; may be accomplished by heat recovery wheels or heat exchanger loops.

Hermetic compressor: a compressor and drive motor packaged in a factory sealed housing.

Humidifier: a device designed to add moisture to the air.

Hydronic system: a system using water or steam for heat distribution.

Indoor air quality: the state of air in a space -- with particular reference to detectable odors and non-detectable substances that may affect occupants' health.

Latent heat: thermal energy (heat) that is related to moisture content or a change of material state.

Local HVAC system: a system that produces a heating or cooling effect in or adjacent to a space that requires conditioning; distribution of the heating or cooling effect is effectively limited to a single space.

Makeup air: outside air brought into a building to compensate for indoor air that must be exhausted.

Multizone HVAC system: a central air-all HVAC system that utilizes an individual supply air stream for each zone; warm and cool air are mixed at the air handling unit to provide supply air appropriate to the needs of each zone; a multizone system requires the use of several separate supply air ducts.

Outdoor air: air from outside of the building envelope.

Packaged air-conditioner: a self-contained unit designed to provide control of air temperature, humidity, distribution, and quality; see also unitary air-conditioner.

Perimeter: those portions of a building adjacent to exterior walls; thermal zones adjacent to the building exterior.

Pipe: a container for distribution of water or steam.

Pressure: a measure of the force exerted by a fluid; static pressure is a measure of the force exerted by a fluid at rest; velocity pressure is a measure of the force exerted by the momentum of a fluid in motion; total pressure is the sum of static and velocity pressures.

Pump: a device designed to impart energy (velocity and/or pressure) to water in an HVAC system; found in chilled water, hot water, and condenser water circuits; see also centrifugal pump.

Psychrometric chart: a graphic means of displaying multiple properties of moist air, used to plot air-conditioning processes.

Reciprocating: a particular type of fluid moving device that imparts energy to the fluid by a positive displacement, piston-like action.

Reciprocating chiller: a vapor compression chiller that utilizes a reciprocating compressor; most commonly used in systems with cooling capacities up to approximately 200 tons.

Refrigerant: a heat transfer fluid employed by a refrigerating process, selected for its beneficial properties (stability, low viscosity, high thermal capacity, appropriate state change points).

Refrigeration: a process whereby a heat sink is artificially established by action of some electro-mechanical device; equipment used to establish an artificial heat sink.

Reheat HVAC system: a central air-all HVAC system with a single supply air stream that is heated by a terminal device (reheat coil) at each zone to provide appropriate thermal conditions.

Relative humidity: a measure of moisture content in the air; the ratio of moisture contained by an air sample to the maximum amount of moisture the air could hold at the same temperature.

Space heating: a process whereby sensible heat is introduced to a room or building.

Static pressure: the force exerted by a fluid not considering the energy equivalent of fluid velocity.

System: an assembly of components with a specific structure and intended function.

Temperature: a measure of the density of heat in a substance.

Terminal box: a device used to provide thermal control in an all-air central HVAC system and located adjacent to the zone being served; common types include reheat terminals, dual duct terminals, and variable volume terminals.

Thermal comfort: individually, an expression of satisfaction with the thermal environment; statistically, such expression of satisfaction from at least 80% of the occupants in a space.

Ton: a capacity measure for cooling equipment; equivalent to 12,000 British thermal units per hour.

Tube: a relatively small diameter pipe, usually of non-ferrous material.

Unitary air-conditioner: a self-contained unit designed to provide control of air temperature, humidity, distribution, and quality; see also packaged air-conditioner.

Unit heater: equipment designed to deliver heat to a space from an all-water heating system; a packaged unit consisting of a water or steam heating coil, a fan, and a housing.

Valve: a device designed to control water flow in a distribution system; common valve types include globe, gate, butterfly, and check.

Vapor compression chiller: refrigeration equipment that generates chilled water via a mechanically driven process using a specialized heat transfer fluid as refrigerant; comprised of four major components: a compressor, condenser, expansion valve, and evaporator; operating energy is input as mechanical motion.

Variable air volume (VAV) HVAC system: a central air-all HVAC system that utilizes a single supply air stream and a terminal device at each zone to provide appropriate thermal conditions through control of the quantity of air supplied to the zone.

Ventilation: a process whereby outdoor air is brought into a building as a means of maintaining acceptable indoor air quality, to control building pressurization, or to provide thermal comfort.

Zone: during design -- an area of a building that must be separately controlled if conditions conducive to thermal comfort are to be provided by an HVAC system; in existing buildings -- an area that is controlled from a single control point (thermostat).

# HVAC COMPONENTS AND SYSTEMS BIBLIOGRAPHY

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*How Buildings Work* provides a complete, introductory level look at all components of a building. The chapter on air temperature and humidity control (pp. 75-90) gives a general introduction to HVAC systems.

☐ ALLEN, EDWARD AND JOSEPH IANO: *THE ARCHITECT'S STUDIO COMPANION*, 2ND EDITION, JOHN WILEY AND SONS, NEW YORK, 1995.

An extremely useful reference manual for the introductory stages of building design. Provides an introduction to basic concepts and rule-of-thumb sizing data to assist with the planning of building systems. Addresses HVAC systems, as well as structures, codes, circulation, and other building elements.

☐ ASHRAE: *1995 ASHRAE HANDBOOK -- HVAC APPLICATIONS*, AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC., ATLANTA, GA, 1995.

A reference-manual compendium of information on HVAC system applications. Provides detailed coverage of comfort conditioning (for a variety of building occupancies), industrial HVAC applications, operations and maintenance concerns, and general issues (such as solar energy usage, thermal storage, smoke control, and noise and vibration). Chapters are written with the practicing HVAC design professional in mind. The ASHRAE Handbook series is updated on a four-year cycle, so information in the most recent edition is quite current.

☐ ASHRAE: *1992 ASHRAE HANDBOOK -- HVAC SYSTEMS AND EQUIPMENT*, AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC., ATLANTA, GA, 1992.

A reference-manual compendium of information on systems and equipment for heating, ventilating, and air-conditioning systems. Provides detailed coverage of system components (compressors, chillers, cooling towers, boilers, etc.) and system arrangements (all-air, air-water, all-water). Chapters are written with the practicing HVAC design professional in mind and are updated every four years.

☐ ASHRAE: *AIR-CONDITIONING SYSTEMS DESIGN MANUAL*, AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC., ATLANTA, GA, 1993.

This manual was developed to provide assistance to entry-level engineers and students who are just beginning to design HVAC systems. Written to bridge the gap between theory and practice, it provides a comprehensive review of HVAC systems analysis and design. Chapters address the design process, components, a range of central system types, special considerations, and controls; several example applications are presented.

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The definitive reference for technical terms related to HVAC systems; also includes information on abbreviations, acronyms, and symbols, basic information on physical and mathematical relationships, and policy for SI usage in HVAC applications.

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A benchmark energy efficiency standard for non-residential buildings. Standard 90.1 is cited by the Energy Policy Act of 1992 as a reference standard for compliance with the provisions of the Act. The standard addresses building envelope design, electric power and lighting systems, HVAC systems and equipment, service water heating, and energy management.

☐ ASHRAE: "VENTILATION FOR ACCEPTABLE INDOOR AIR QUALITY" (ASHRAE/ANSI STANDARD 60.2-1989), AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC., ATLANTA, GA, 1989.

The reference U.S. standard for indoor air quality, Standard 62 presents prescriptive and performance-based requirements for ventilation. The focus is on active control of indoor air quality via ventilation using HVAC systems.

☐ COLEN, HAROLD: *HVAC SYSTEMS EVALUATION*, R.S. MEANS COMPANY, INC., KINGSTON, MA, 1990.

This is a comprehensive guide to HVAC systems, written mainly for use by design professionals, but offering a wealth of information to any user. Part I features 17 chapters that list the basic characteristics of commonly used HVAC systems, their advantages and disadvantages in use, and installation, operation and maintenance trends for each system. Part II addresses operational problems of existing HVAC systems. Part III covers the electrical requirements of HVAC systems. Excellent quality explanatory diagrams are found throughout this book.

☐ GRIMMS, NILS AND ROBERT ROSALER: *HANDBOOK OF HVAC DESIGN*, MCGRAW-HILL, INC., NEW YORK, NY, 1990.

The objective of this book is to "provide a practical guide and a reliable reference for designing and operating HVAC systems. It details the necessary steps for planning, design, equipment selection, operation and maintenance" of HVAC systems. The Handbook provides an extensive examination of all issues necessary for a broad understanding of HVAC systems.

☐ HAINES, ROGER AND C. LEWIS WILSON: *HVAC SYSTEMS DESIGN HANDBOOK*, 2ND EDITION, MCGRAW-HILL, INC., NEW YORK, NY, 1994.

This volume gives a complete look at HVAC systems, functions, components, and applications, and includes discussion of basic theories behind the procedures. Written mainly for use by practicing professionals, it nevertheless can offer a wealth of information to all readers. Basic concerns are covered briefly, but the primary concentration is on applications. A review of thermodynamics, fluid dynamics and psychrometric principles is also featured.

☐ HAINES, ROGER: *ROGER HAINES ON HVAC CONTROLS*, MCGRAW-HILL, INC., NEW YORK, NY, 1991.

This book covers the philosophy, theory, systems, and devices related to conventional and computerized control applications for HVAC systems. Although not truly a design guide for control systems, this book is a source of ideas for control applications.

☐ HARTMAN, THOMAS: *DIRECT DIGITAL CONTROLS FOR HVAC SYSTEMS*, MCGRAW-HILL INC., NEW YORK, NY, 1993.

A valuable reference for current trends and future directions in computerized control technologies. Requiring prior knowledge of HVAC systems terminology, this book covers a variety of applications and systems and addresses control system programming. Direct digital controls are of special interest as they are a critical part of most current building energy management systems as well as utility metering and monitoring programs.

☐ LECHNER, NORBERT: *HEATING, COOLING, LIGHTING*, JOHN WILEY AND SONS, NEW YORK, NY, 1991.

An extremely valuable resource for beginning building designers, this book provides a concise, introductory-level summary of climate control systems. Fundamental issues are well-covered and illustrated with graphic examples. Energy efficiency and conservation are emphasized throughout.

☐ MANN, PETER: *ILLUSTRATED RESIDENTIAL AND COMMERCIAL CONSTRUCTION*, PRENTICE-HALL, INC., ENGLEWOOD CLIFFS, NJ, 1989.

Although primarily a guide to construction practices, this book offers a lot of good information on residential HVAC systems. Many excellent axonometric drawings show system layouts in building settings.

☐ MCQUISTON, FAYE AND JERALD PARKER: *HEATING, VENTILATING, AND AIR CONDITIONING*, 4TH EDITION, JOHN WILEY AND SONS, NEW YORK, NY, 1994.

This is a reference text for the analysis and design of HVAC systems that is used in many engineering curricula. The book covers all aspects of HVAC systems, with detailed information on system components. The focus is on mechanical engineering aspects.

☐ RUSH, RICHARD (ED.): *THE BUILDING SYSTEMS INTEGRATION HANDBOOK*, JOHN WILEY AND SONS, NEW YORK, NY, 1986.

This book focuses on the integration of building structural, envelope, interior, and mechanical systems. The attention given to HVAC systems is only moderate, but there are many excellent examples of carefully-documented, well-diagrammed buildings.

☐ STEIN, BENJAMIN AND JOHN REYNOLDS: *MECHANICAL AND ELECTRICAL EQUIPMENT FOR BUILDINGS*, 8TH EDITION, JOHN WILEY AND SONS, NEW YORK, NY, 1992.

A vital reference book for students and practitioners alike, the latest edition provides comprehensive information on building HVAC systems and components. Information on energy efficiency, conservation strategies, and passive approaches to climate control abounds. Although encyclopedic in scope, the excellent illustrations and discussions regarding HVAC systems and applications makes this a must-have reference.

☐ TRAISTER, JOHN: *RESIDENTIAL HEATING, VENTILATING, AND AIR CONDITIONING*, PRENTICE-HALL, INC., ENGLEWOOD CLIFFS, NJ, 1990.

This book provides a complete, yet concise, look at the analysis and design of residential HVAC systems. Its primary value lies in the range of topics covered, rather than in the depth of coverage.