# Temperature Control Technologies & Home Automation


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## Chapter 1

# Thermostat


Honeywell's iconic "The Round" model T87 thermostat, one of which is in the Smithsonian.

A **thermostat** is a device for regulating the temperature of a system so that the system's temperature is maintained near a desired *setpoint* temperature. The name is derived from the Greek words thermos "hot" and statos "a standing". The thermostat does this by switching heating or cooling devices on or off, or regulating the flow of a heat transfer fluid as needed, to maintain the correct temperature.

A thermostat may be a control unit for a heating or cooling system or a component part of a heater or air conditioner. Thermostats can be constructed in many ways and may use a variety of sensors to measure the temperature. The output of the sensor then controls the heating or cooling apparatus.

The first electric room thermostat was invented in 1883 by Warren S. Johnson. Early technologies included mercury thermometers with electrodes inserted directly through the glass, so that when a certain (fixed) temperature was reached the contacts would be closed by the mercury. These were accurate to within a degree of temperature.

Common sensor technologies in use today include:

- Bimetallic mechanical or electrical sensors
- Expanding wax pellets
- Electronic thermistors and semiconductor devices
- Electrical thermocouples

These may then control the heating or cooling apparatus using:

- Direct mechanical control
- Electrical signals
- Pneumatic signals


A Honeywell electronic thermostat in a retail store

## *Mechanical*

This covers only devices which both sense and control using purely mechanical means.

### Bimetal

Domestic water and steam based central heating systems have traditionally been controlled by bi-metallic strip thermostats, and this is dealt with later here. Purely mechanical control has been localised steam or hot-water radiator bi-metallic thermostats which regulated the individual flow. However, Thermostatic Radiator Valves (TRV) are now being widely used.

Purely mechanical thermostats are used to regulate dampers in some rooftop turbine vents, reducing building heat loss in cool or cold periods.

Some automobile passenger heating systems have a thermostatically controlled valve to regulate the water flow and temperature to an adjustable level. In older vehicles the thermostat controls the application of engine vacuum to actuators that control water valves and flappers to direct the flow of air. In modern vehicles, the vacuum actuators may be operated by small solenoids under the control of a central computer.

### Wax pellet

### Automotive

Car engine thermostat

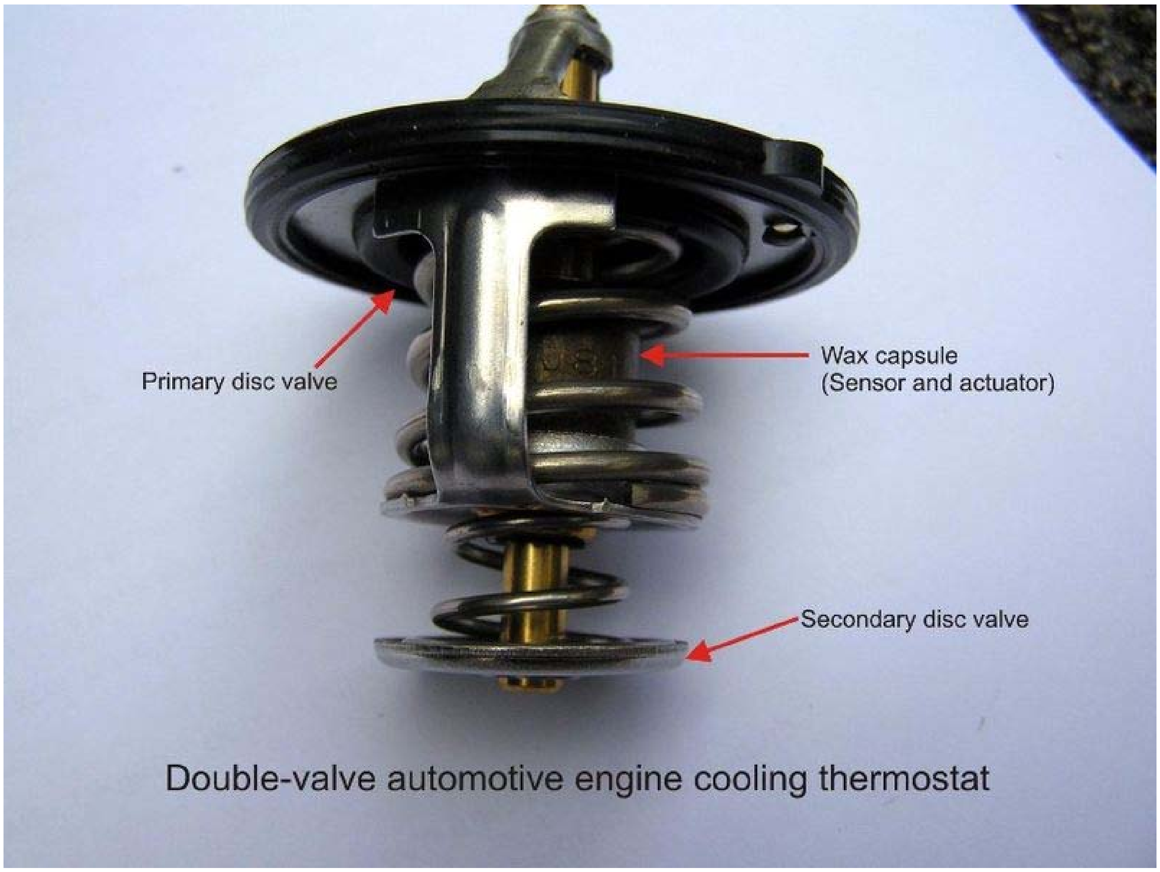
Perhaps the best example of purely mechanical technology in widespread use today is the internal combustion engine cooling thermostat. These are used to maintain the core temperature of the engine at its optimum operating temperature by regulating the flow of coolant to an external heat sink, usually an air cooled radiator. Also, research in the 1920s showed that cylinder wear was aggravated by condensation of fuel when it contacted a cool cylinder wall which removed the oil film, and the development of the automatic thermostat in the 1930s provided a solution to this problem by ensuring fast engine warm-up.

This type of thermostat operates mechanically. It makes use of a wax pellet inside a sealed chamber. The wax is solid at low temperatures but as the engine heats up the wax melts and expands. The sealed chamber has an expansion provision that operates a rod which opens a valve when the operating temperature is exceeded. The operating temperature is fixed, but is determined by the specific composition of the wax, so thermostats of this type are available to maintain different temperatures, typically in the range of 70 to 90°C (160 to 200°F). Modern engines run hot, that is, over 80°C (180°F), in order to run more efficiently and to reduce the emission of pollutants. Most thermostats have a small bypass hole to vent any gas that might get into the system, *e.g.*, air introduced during coolant replacement, which also allows a small flow of coolant past the thermostat when it is closed. This bypass flow ensures that the thermostat experiences the temperature change in the coolant as the engine heats up; without it a stagnant region of coolant around the thermostat could shield it from temperature changes in the coolant adjacent to the combustion chambers and cylinder bores.

While the thermostat is closed, there is no flow of coolant in the radiator loop, and water flow is instead redirected back through the engine, allowing it to warm up rapidly while also avoiding hotspots within the engine. The thermostat stays closed until the coolant temperature reaches the nominal thermostat opening temperature. The thermostat then progressively opens as the coolant temperature increases to the optimum operating temperature, increasing the coolant flow to the radiator. Once the optimum operating temperature is reached, the thermostat progressively increases or decreases its opening in response to temperature changes, dynamically balancing the coolant recirculation flow and coolant flow to the radiator to maintain the engine temperature in the optimum range as engine heat output, vehicle speed, and outside ambient temperature change. Under normal operating conditions the thermostat is open to about half of its stroke travel, so that it can open further or reduce its opening to react to changes in operating conditions. A correctly designed thermostat will never be fully open or fully closed while the engine is operating normally, or overheating or overcooling would occur. For instance,

- If more cooling is required, *e.g.*, in response to an increase in engine heat output which causes the coolant temperature to rise, the thermostat will increase its opening to allow more coolant to flow through the radiator and increase engine cooling. If the thermostat were already fully open, then it would not be able to increase the flow of coolant to the radiator, hence there would be no more cooling capacity available, and the increase in heat output by the engine would result in overheating.

- If less cooling is required, *e.g.*, in response to decrease in ambient temperature which causes the coolant temperature to fall, the thermostat will decrease its opening to restrict the coolant flow through the radiator and reduce engine cooling. If the thermostat were already fully closed, then it would not be able to reduce cooling in response to the fall in coolant temperature, and the engine temperature would fall below the optimum operating range.




Double valve engine thermostat

Engines which require a tighter control of temperature, as they are sensitive to "Thermal shock" caused by surges of coolant, may use a "constant inlet temperature" system. In this arrangement the inlet cooling to the engine is controlled by double-valve thermostat which mixes a re-circulating sensing flow with the radiator cooling flow. These employ a single capsule, but have two valve discs. Thus a very compact, and simple but effective, control function is achieved.

The wax product used within the thermostat requires a specific process to produce. Unlike a standard paraffin wax, which has a relatively wide range of carbon chain lengths, a wax used in the thermostat application has a very narrow range of carbon molecule chains. The extent of the chains is usually determined by the melting characteristics demanded by the specific end application. To manufacture a product in this manner requires very precise levels of distillation, which is difficult or impossible for most wax refineries.

### Shower and other hot water controls

These use wax pellets to control the mixing of hot and cold water see thermostatic mixing valve (TMV).

### Gas expansion

Thermostats are sometimes used to regulate gas ovens. It consists of a gas-filled bulb connected to the control unit by a slender copper tube. The bulb is normally located at the top of the oven. The tube ends in a chamber sealed by a diaphragm. As the thermostat heats up the gas expands applying pressure to the diaphragm which reduces the flow of gas to the burner.

### Pneumatic

A pneumatic thermostat is a thermostat that controls a heating and/or cooling system via a series of air-filled control tubes. This "control air" system responds to the pressure changes (due to temperature) in the control tube to activate heating or cooling when required. The control air typically is maintained on "mains" at 15-18psi (although usually operable up to 20psi). Pneumatic thermostats typically provide output/ branch/ post-restrictor(for single-pipe operastion) pressures of 3-15psi which is piped to the end device (valve/ damper actuator/ Pneumatic-Electric switch, etc.)

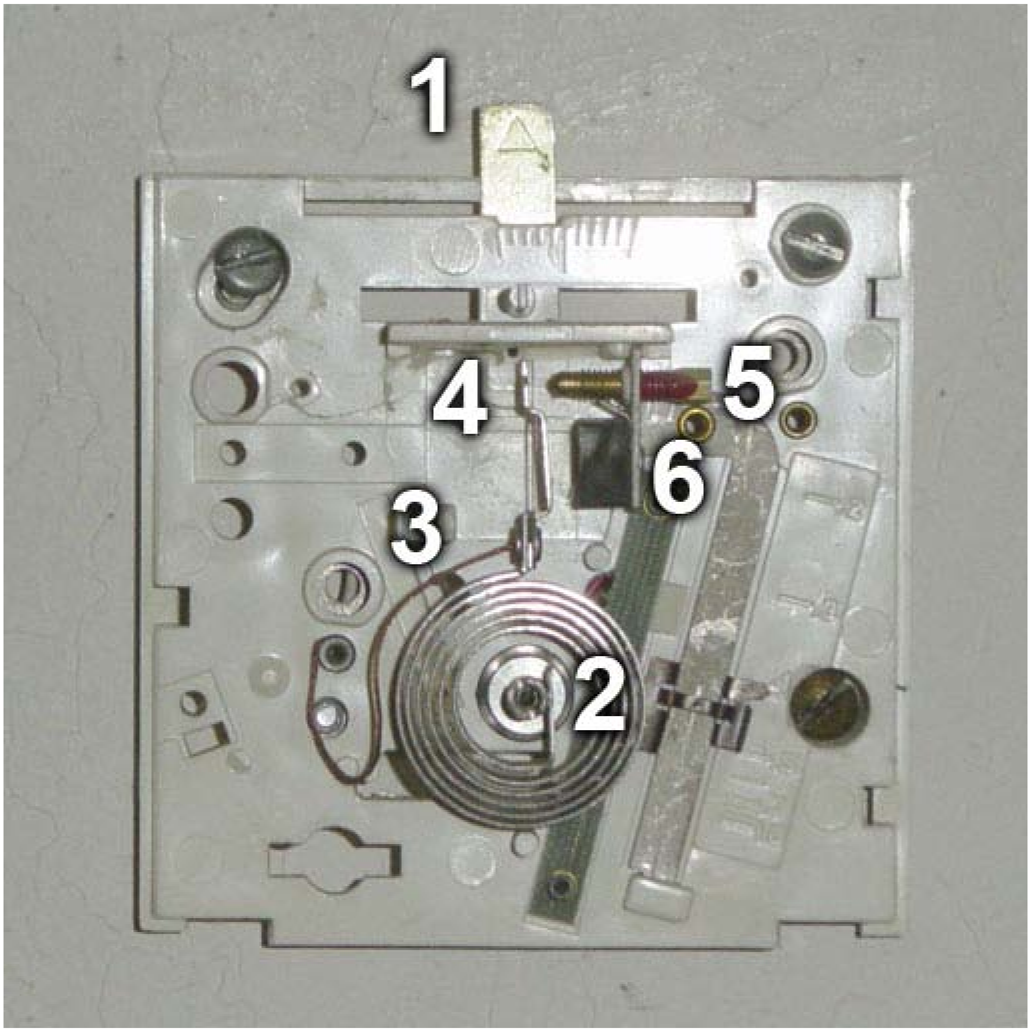
## *Electrical*

### Bimetallic switching thermostats


Bimetallic thermostat for buildings.

Water and steam based central heating systems have traditionally had overall control by wall-mounted bi-metallic strip thermostats. These sense the air temperature using the differential expansion of two metals to actuate an on/off switch. Typically the central system would be switched on when the temperature drops below the set point on the thermostat, and switched off when it rises above, with a few degrees of hysteresis to prevent excessive switching. Bi-metallic sensing is now being superseded by electronic sensors. A principal use of the bi-metallic thermostat today is in individual electric convection heaters, where control is on/off, based on the local air temperature and the set point desired by the user. These are also used on air-conditioners, where local control is required.

## Simple two wire thermostats




Milivolt thermostat mechanism

The illustration is the interior of a common two wire heat-only household thermostat, used to regulate a gas-fired heater via an electric gas valve. Similar mechanisms may also be used to control oil furnaces, boilers, boiler zone valves, electric attic fans, electric furnaces, electric baseboard heaters, and household appliances such as refrigerators, coffee pots, and hair dryers. The power through the thermostat is provided by the heating device and may range from millivolts to 240 volts in common North American construction, and is used to control the heating system either directly (electric baseboard heaters and some electric furnaces) or indirectly (all gas, oil and forced hot water systems). *Due to the variety of possible voltages and currents available at the thermostat, caution must be taken when selecting a replacement device.*

1. Set point control lever. This is moved to the right for a higher temperature. The round indicator pin in the center of the second slot shows through a numbered slot in the outer case.

2. Bimetallic strip wound into a coil. The center of the coil is attached to a rotating post attached to lever (1). As the coil gets colder the moving end — carrying (4) — moves clockwise.
3. Flexible wire. The left side is connected via one wire of a pair to the heater control valve.
4. Moving contact attached to the bimetal coil.thence to the heater's controller.
5. Magnet. This ensures a good contact when the contact closes. It also provides hysteresis to prevent short heating cycles, as the temperature must be raised several degrees before the contacts will open. As an alternative, some thermostats instead use a mercury switch on the end of the bimetal coil. The weight of the mercury on the end of the coil tends to keep it there, also preventing short heating cycles. However, this type of thermostat is banned in many countries due to its highly and permanently toxic nature if broken. When replacing these thermostats they must be regarded as chemical waste.
6. Fixed contact screw. This is adjusted by the manufacturer. It is connected electrically by a second wire of the pair to the thermocouple and the heater's electrically operated gas valve.

Not shown in the illustration is a separate bimetal thermometer on the outer case to show the actual temperature at the thermostat.

## Millivolt thermostats

As illustrated in the use of the thermostat above, the power is provided by a thermocouple, heated by the pilot light. This produces little power and so the system must use a low power valve to control the gas. This type of device is generally considered obsolete as pilot lights waste a surprising amount of gas (in the same way a dripping faucet can waste a large amount of water over an extended period), and are also no longer used on stoves, but are still to be found in many gas water heaters and gas fireplaces. (Their poor efficiency is acceptable in water heaters, since most of the energy "wasted" on the pilot light is still being coupled to the water and therefore helping to keep the tank warm). It also makes it unnecessary for an electrical circuit to be run to the water heater. For tankless (on demand) water heaters, pilot ignition is preferable because it is faster than hot-surface ignition and more reliable than spark ignition.)

Some programmable thermostats will control these systems.

## 24 volt thermostats

The majority of modern heating/cooling/heat pump thermostats operate on low voltage (typically 24 volts AC) control circuits. The source of the 24 volt AC power is a control transformer installed as part of the heating/cooling equipment. The advantage of the low voltage control system is the ability to operate multiple electromechanical switching devices such as relays, contactors, and sequencers using inherently safe voltage and current levels. Built into the thermostat is a provision for enhanced temperature control using anticipation. A heat anticipator generates a small amount of additional heat to the sensing element while the heating appliance is operating. This opens the heating contacts slightly early to prevent the space temperature from greatly overshooting the thermostat setting. A mechanical heat anticipator is generally adjustable and should be set to the current flowing in the heating control circuit when the system is operating. A cooling anticipator generates a small amount of additional heat to the sensing element while the cooling appliance is not operating. This causes the contacts to energize the cooling equipment slightly early, preventing the space temperature from climbing excessively. Cooling anticipators are generally non-adjustable.

Electromechanical thermostats use resistance elements as anticipators. Most electronic thermostats use either thermistor devices or integrated logic elements for the anticipation function. In some electronic thermostats, the thermistor anticipator may be located outdoors, providing a variable anticipation depending on the outdoor temperature.

Thermostat enhancements include outdoor temperature display, programmability, and system fault indication. While such 24 volt thermostats are incapable of operating a furnace when the mains power fails, most such furnaces require mains power for heated air fans (and often also hot-surface or electronic spark ignition) so no functionality is lost. In other circumstances such as piloted wall and "gravity" (fanless) floor and central heaters the low voltage system described previously may be capable of remaining functional when electrical power is unavailable.

## Ignition sequences in modern systems

- Gas

    1. Start drafting fan (if the furnace is relatively recent) to create a column of air flowing up the chimney
    2. Heat ignitor or start spark-ignition system
    3. Open gas valve to ignite main burners
    4. Wait (if furnace is relatively recent) until the heat exchanger is at proper operating temperature before starting main blower fan or circulator pump

- Oil

    1. Similar to gas, except rather than opening a valve, the furnace will start an oil pump to inject oil into the burner

- Electric

    1. The blower fan or circulator pump will be started, and a large electromechanical relay or TRIAC will turn on the heating elements

- Coal (including grains such as corn, wheat, and barley, or pellets made of wood, bark, or cardboard)

1. Generally rare today (though grains and pellets are increasing in popularity); similar to gas, except rather than opening a valve, the furnace will start a screw to drive coal/grain/pellets into the firebox

With non-zoned (typical residential, one thermostat for the whole house) systems, when the thermostat's R (or Rh) and W terminals are connected, the furnace will go through its startup rituals and produce heat.

With zoned systems (some residential, many commercial systems — several thermostats controlling different "zones" in the building), the thermostat will cause small electric motors to open valves or dampers and start the furnace or boiler if it's not already running.

Most programmable thermostats will control these systems.

## Line voltage thermostats

Line voltage thermostats are most commonly used for electric space heaters such as a baseboard heater or a direct-wired electric furnace. If a line voltage thermostat is used, system power (in the United States, 120 or 240 volts) is directly switched by the thermostat. With switching current often exceeding 40 amperes, using a low voltage thermostat on a line voltage circuit will result at least in the failure of the thermostat and possibly a fire. Line voltage thermostats are sometimes used in other applications, such as the control of fan-coil (fan powered from line voltage blowing through a coil of tubing which is either heated or cooled by a larger system) units in large systems using centralized boilers and chillers, or to control circulation pumps in hydronic heating applications.

Some programmable thermostats are available to control line-voltage systems. Baseboard heaters will especially benefit from a programmable thermostat which is capable of continuous control (as are at least some Honeywell models), effectively controlling the heater like a lamp dimmer, and gradually increasing and decreasing heating to ensure an extremely constant room temperature (continuous control rather than relying on the averaging effects of hysteresis). Systems which include a fan (electric furnaces, wall heaters, etc.) must typically use simple on/off controls.

## Combination heating/cooling regulation

Depending on what is being controlled, a forced-air air conditioning thermostat generally has an external switch for heat/off/cool, and another on/auto to turn the blower fan on constantly or only when heating and cooling are running. Four wires come to the centrally-located thermostat from the main heating/cooling unit (usually located in a closet, basement, or occasionally in the attic): One wire supplies a 24 volts AC power connection to the thermostat, while the other three supply control signals from the thermostat, one for heat, one for cooling, and one to turn on the blower fan. The power is supplied by a transformer, and when the thermostat makes contact between power and another wire, a relay back at the heating/cooling unit activates the corresponding function of the unit.

A thermostat, when set to "cool", will only turn on when the ambient temperature of the surrounding room is above the set temperature. Thus, if the controlled space has a temperature normally above the desired setting when the heating/cooling system is off, it would be wise to keep the thermostat set to "cool", despite what the temperature is outside. On the other hand, if the temperature of the controlled area falls below the desired degree, then it is advisable to turn the thermostat to "heat".

### *Heat pump regulation*

The heat pump is a refrigeration based appliance which reverses refrigerant flow between the indoor and outdoor coils. This is done by energizing a reversing valve (also known as a "4-way" or "change-over" valve). During cooling, the indoor coil is an evaporator removing heat from the indoor air and transferring it to the outdoor coil where it is rejected to the outdoor air. During heating, the outdoor coil becomes the evaporator and heat is removed from the outdoor air and transferred to the indoor air through the indoor coil. The reversing valve, controlled by the thermostat, causes the change-over from heat to cool. Residential heat pump thermostats generally have an "O" terminal to energize the reversing valve in cooling. Some residential and many commercial heat pump thermostats use a "B" terminal to energize the reversing valve in heating. The heating capacity of a heat pump decreases as outdoor temperatures fall. At some outdoor temperature (called the balance point) the ability of the refrigeration system to transfer heat into the building falls below the heating needs of the building. A typical heat pump is fitted with electric heating elements to supplement the refrigeration heat when the outdoor temperature is below this balance point. Operation of the supplemental heat is controlled by a second stage heating contact in the heat pump thermostat. During heating, the outdoor coil is operating at a temperature below the outdoor temperature and condensation on the coil may take place. This condensation may then freeze onto the coil, reducing its heat transfer capacity. Heat pumps therefore have a provision for occasional defrost of the outdoor coil. This is done by reversing the cycle to the cooling mode, shutting off the outdoor fan, and energizing the electric heating elements. The electric heat in defrost mode is needed to keep the system from blowing cold air inside the building. The elements are then used in the "reheat" function. Although the thermostat may indicate the system is in defrost and electric heat is activated, the defrost function is not controlled by the thermostat. Since the heat pump has electric heat elements for supplemental and reheats, the heat pump thermostat provides for use of the electric heat elements should the refrigeration system fail. This function is normally activated by an "E" terminal on the thermostat. When in emergency heat, the thermostat makes no attempt to operate the compressor or outdoor fan.

**Digital**


Residential digital thermostat


Lux Products' Model TX900TS Touch Screen Thermostat.

Newer digital thermostats have no moving parts to measure temperature and instead rely on thermistors or other semiconductor devices such as a resistance thermometer (resistance temperature detector). Typically one or more regular batteries must be installed to operate it, although some so-called "power stealing" digital thermostats use the common 24 volt AC circuits as a power source, but will not operate on thermopile powered "millivolt" circuits used in some furnaces. Each has an LCD screen showing the current temperature, and the current setting. Most also have a clock, and time-of-day and even day-of-week settings for the temperature, used for comfort and energy conservation. Some advanced models have touch screens, or the ability to work with home automation or building automation systems.

Digital thermostats use either a relay or a semiconductor device such as triac to act as switch to control the HVAC unit. Units with relays will operate millivolt systems, but often make an audible "click" noise when switching on or off.

More expensive models have a built-in PID controller, so that the thermostat knows ahead how the system will react to its commands. For instance, setting it up that temperature in the morning at 7 a.m. should be 21°C, makes sure that at that time the temperature will be 21°C, where a conventional thermostat would just start working at that time. The PID controller decides at what time the system should be activated in order to reach the desired temperature at the desired time. It also makes sure that the temperature is very stable (for instance, by reducing overshoots).

Most digital thermostats in common residential use in North America and Europe are programmable thermostats, which will typically provide a 30% energy savings if left with their default programs; adjustments to these defaults may increase or reduce energy savings. The programmable thermostat article provides basic information on the operation, selection and installation of such a thermostat.

### Household thermostat location

The thermostat should be located away from the room's cooling or heating vents or device, yet exposed to general airflow from the room(s) to be regulated. An open hallway may be most appropriate for a single zone system, where living rooms and bedrooms are operated as a single zone. If the hallway may be closed by doors from the regulated spaces then these should be left open when the system is in use. If the thermostat is too close to the source controlled then the system will tend to "short cycle", and numerous starts and stops can be annoying and in some cases shorten equipment life. A multiple zoned system can save considerable energy by regulating individual spaces, allowing unused rooms to vary in temperature by turning off the heating and cooling.

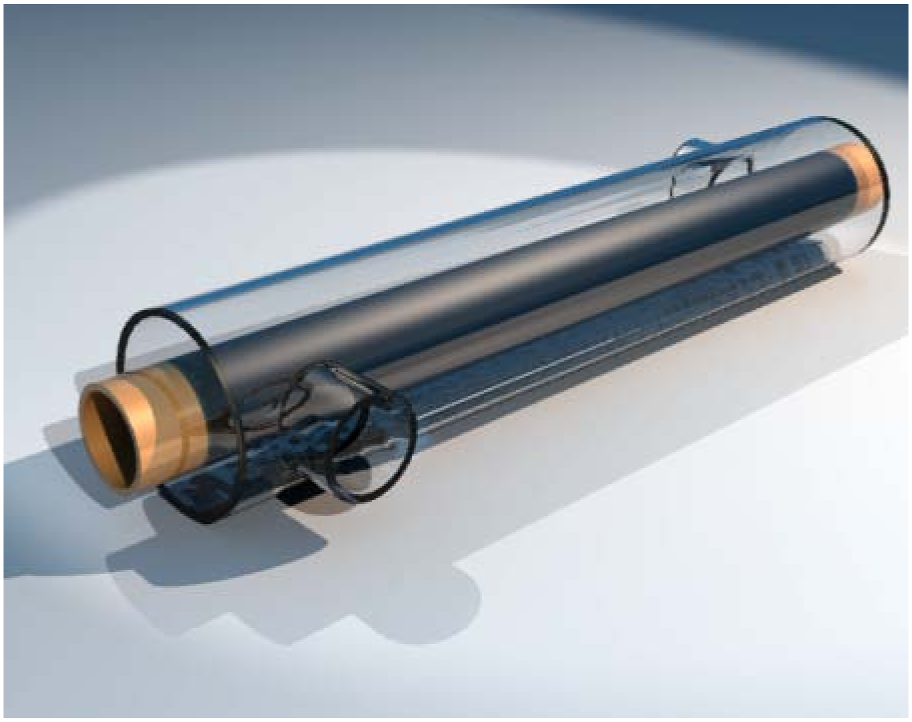
### *Dummy thermostats*

It has been reported that many thermostats in office buildings are non-functional dummy devices, installed to give tenants' employees an illusion of control. These dummy thermostats are in effect a type of placebo button.

## Chapter 2

# Heat Exchanger

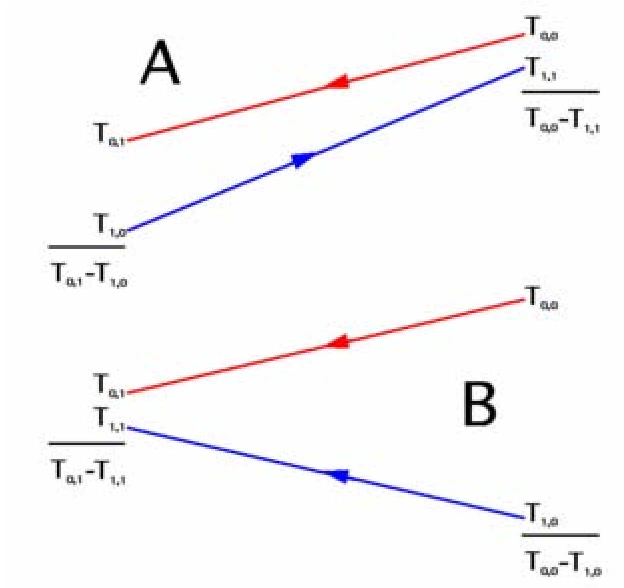
An interchangeable plate heat exchanger



Tubular heat exchanger.

A **heat exchanger** is a piece of equipment built for efficient heat transfer from one medium to another. The media may be separated by a solid wall, so that they never mix, or they may be in direct contact. They are widely used in space heating, refrigeration, air conditioning, power plants, chemical plants, petrochemical plants, petroleum refineries, natural gas processing, and sewage treatment. One common example of a heat exchanger is the radiator in a car, in which the heat source, being a hot engine-cooling fluid, water, transfers heat to air flowing through the radiator (i.e. the heat transfer medium).

### *Flow arrangement*




Countercurrent (A) and parallel (B) flows

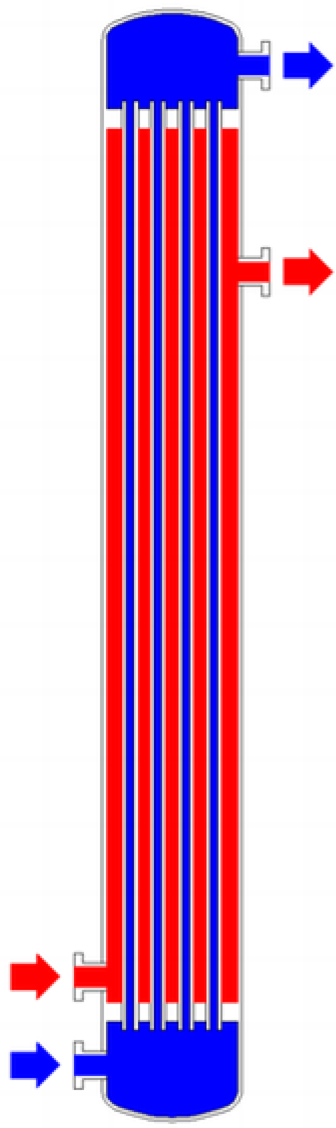


Fig. 1: Shell and tube heat exchanger, single pass (1-1 parallel flow)

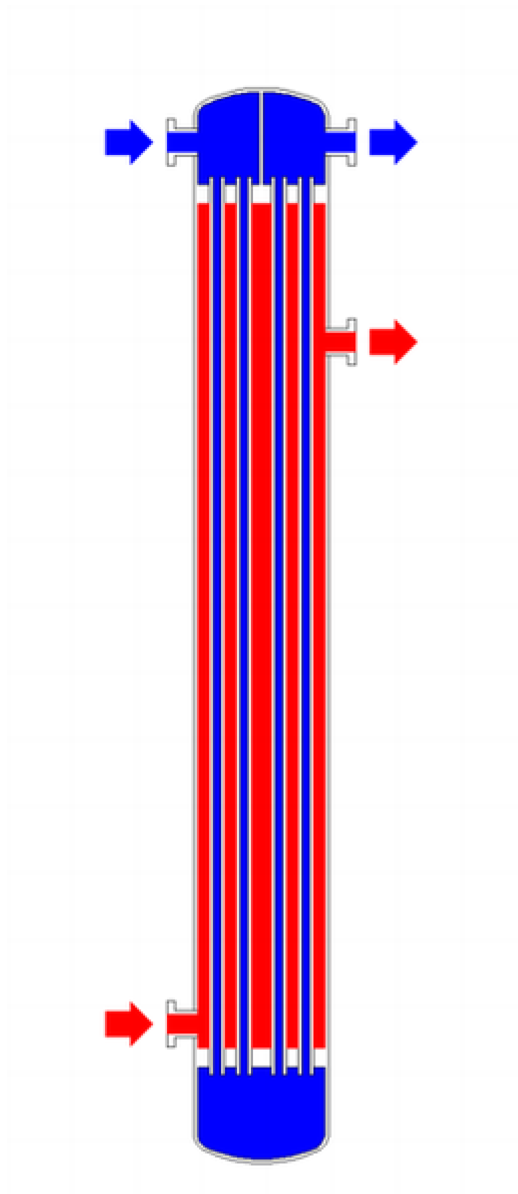


Fig. 2: Shell and tube heat exchanger, 2-pass tube side (1-2 crossflow)

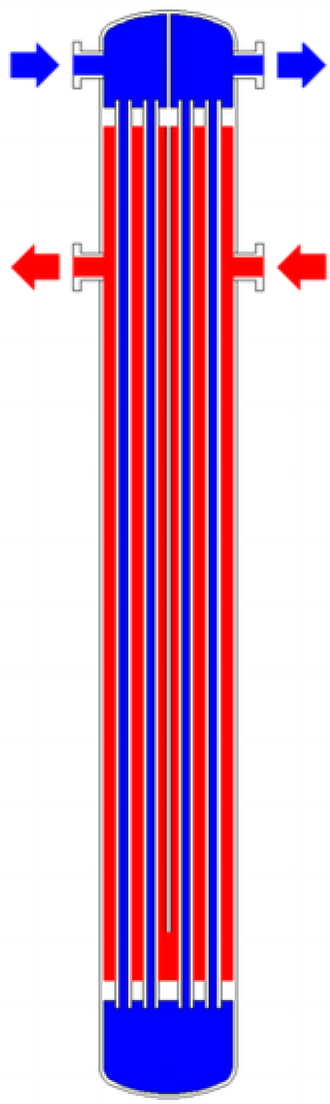


Fig. 3: Shell and tube heat exchanger, 2-pass shell side, 2-pass tube side (2-2 countercurrent)

There are two primary classifications of heat exchangers according to their flow arrangement. In *parallel-flow* heat exchangers, the two fluids enter the exchanger at the same end, and travel in parallel to one another to the other side. In *counter-flow* heat exchangers the fluids enter the exchanger from opposite ends. The counter current design is most efficient, in that it can transfer the most heat from the heat (transfer) medium. In a *cross-flow* heat exchanger, the fluids travel roughly perpendicular to one another through the exchanger.

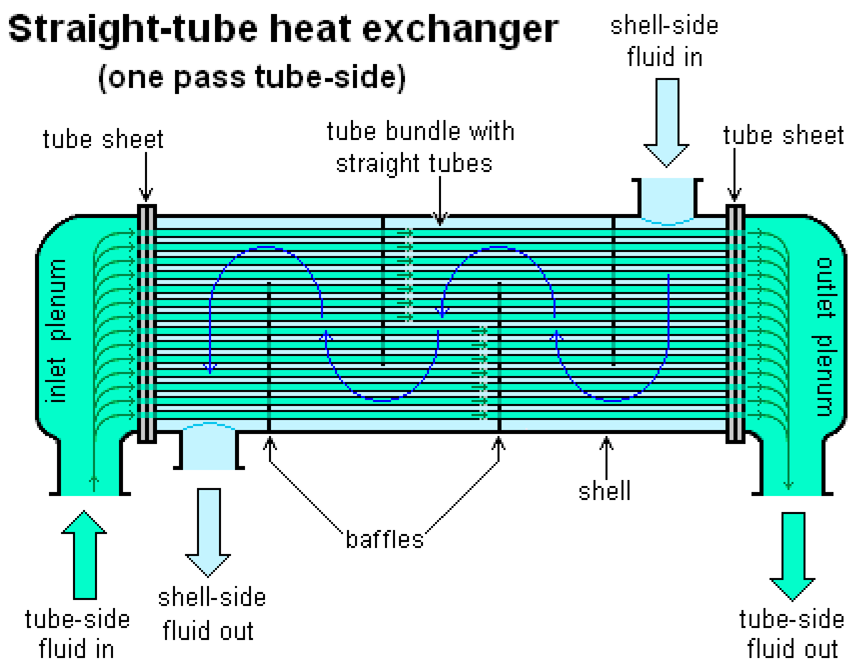
For efficiency, heat exchangers are designed to maximize the surface area of the wall between the two fluids, while minimizing resistance to fluid flow through the exchanger.

The exchanger's performance can also be affected by the addition of fins or corrugations in one or both directions, which increase surface area and may channel fluid flow or induce turbulence.

The driving temperature across the heat transfer surface varies with position, but an appropriate mean temperature can be defined. In most simple systems this is the "log mean temperature difference" (LMTD). Sometimes direct knowledge of the LMTD is not available and the NTU method is used.

## *Types of heat exchangers*

### Shell and tube heat exchanger

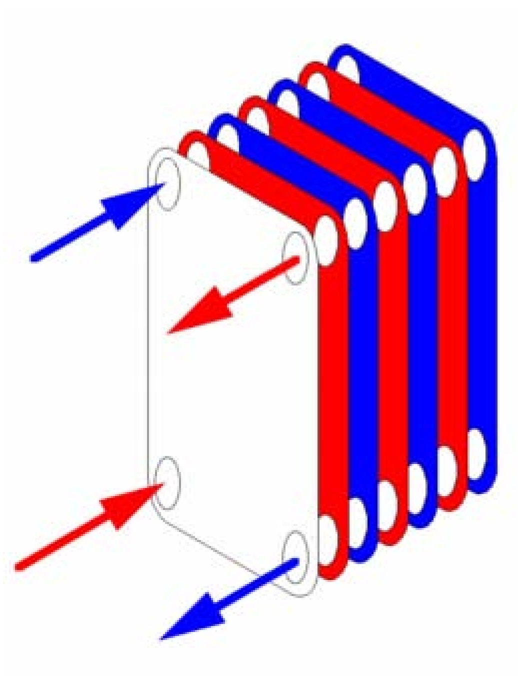



A Shell and Tube heat exchanger

Shell and tube heat exchangers consist of a series of tubes. One set of these tubes contains the fluid that must be either heated or cooled. The second fluid runs over the tubes that are being heated or cooled so that it can either provide the heat or absorb the heat required. A set of tubes is called the tube bundle and can be made up of several types of tubes: plain, longitudinally finned, etc. Shell and tube heat exchangers are typically used for high-pressure applications (with pressures greater than 30 bar and temperatures greater than 260°C). This is because the shell and tube heat exchangers are robust due to their shape.
There are several thermal design features that are to be taken into account when designing the tubes in the shell and tube heat exchangers. These include:

- Tube diameter: Using a small tube diameter makes the heat exchanger both economical and compact. However, it is more likely for the heat exchanger to foul up faster and the small size makes mechanical cleaning of the fouling difficult. To prevail over the fouling and cleaning problems, larger tube diameters can be used. Thus to determine the tube diameter, the available space, cost and the fouling nature of the fluids must be considered.
- Tube thickness: The thickness of the wall of the tubes is usually determined to ensure:
    - There is enough room for corrosion
    - That flow-induced vibration has resistance
    - Axial strength
    - Availability of spare parts
    - Hoop strength (to withstand internal tube pressure)
    - Buckling strength (to withstand overpressure in the shell)
- Tube length: heat exchangers are usually cheaper when they have a smaller shell diameter and a long tube length. Thus, typically there is an aim to make the heat exchanger as long as physically possible whilst not exceeding production capabilities. However, there are many limitations for this, including the space available at the site where it is going to be used and the need to ensure that there are tubes available in lengths that are twice the required length (so that the tubes can be withdrawn and replaced). Also, it has to be remembered that long, thin tubes are difficult to take out and replace.
- Tube pitch: when designing the tubes, it is practical to ensure that the tube pitch (i.e., the centre-centre distance of adjoining tubes) is not less than 1.25 times the tubes' outside diameter. A larger tube pitch leads to a larger overall shell diameter which leads to a more expensive heat exchanger.
- Tube corrugation: this type of tubes, mainly used for the inner tubes, increases the turbulence of the fluids and the effect is very important in the heat transfer giving a better performance.
- Tube Layout: refers to how tubes are positioned within the shell. There are four main types of tube layout, which are, triangular (30°), rotated triangular (60°), square (90°) and rotated square (45°). The triangular patterns are employed to give greater heat transfer as they force the fluid to flow in a more turbulent fashion around the piping. Square patterns are employed where high fouling is experienced and cleaning is more regular.
- Baffle Design: baffles are used in shell and tube heat exchangers to direct fluid across the tube bundle. They run perpendicularly to the shell and hold the bundle, preventing the tubes from sagging over a long length. They can also prevent the tubes from vibrating. The most common type of baffle is the segmental baffle. The semicircular segmental baffles are oriented at 180 degrees to the adjacent baffles forcing the fluid to flow upward and downwards between the tube bundle. Baffle spacing is of large thermodynamic concern when designing shell and tube heat exchangers. Baffles must be spaced with consideration for the conversion of pressure drop and heat transfer. For thermo economic optimization it is suggested that the baffles be spaced no closer than 20% of the shell's inner diameter. Having baffles spaced too closely causes a greater pressure drop because of flow

redirection. Consequently having the baffles spaced too far apart means that there may be cooler spots in the corners between baffles. It is also important to ensure the baffles are spaced close enough that the tubes do not sag. The other main type of baffle is the disc and donut baffle which consists of two concentric baffles, the outer wider baffle looks like a donut, whilst the inner baffle is shaped as a disk. This type of baffle forces the fluid to pass around each side of the disk then through the donut baffle generating a different type of fluid flow.



Conceptual diagram of a plate and frame heat exchanger.

A single plate heat exchanger

An interchangeable plate heat exchanger applied to the system of a swimming pool

### Plate heat exchanger

Another type of heat exchanger is the plate heat exchanger. One is composed of multiple, thin, slightly-separated plates that have very large surface areas and fluid flow passages for heat transfer. This stacked-plate arrangement can be more effective, in a given space, than the shell and tube heat exchanger. Advances in gasket and brazing technology have made the plate-type heat exchanger increasingly practical. In HVAC applications, large heat exchangers of this type are called *plate-and-frame*; when used in open loops, these heat exchangers are normally of the gasket type to allow periodic disassembly, cleaning, and inspection. There are many types of permanently-bonded plate heat exchangers, such as dip-brazed and vacuum-brazed plate varieties, and they are often specified for closed-loop applications such as refrigeration. Plate heat exchangers also differ in the types of plates that are used, and in the configurations of those plates. Some plates may be stamped with "chevron" or other patterns, where others may have machined fins and/or grooves.

## Adiabatic wheel heat exchanger

A third type of heat exchanger uses an intermediate fluid or solid store to hold heat, which is then moved to the other side of the heat exchanger to be released. Two examples of this are adiabatic wheels, which consist of a large wheel with fine threads rotating through the hot and cold fluids, and fluid heat exchangers.

## Plate fin heat exchanger

This type of heat exchanger uses "sandwiched" passages containing fins to increase the effectivity of the unit. The designs include crossflow and counterflow coupled with various fin configurations such as straight fins, offset fins and wavy fins.

Plate and fin heat exchangers are usually made of aluminium alloys which provide higher heat transfer efficiency. The material enables the system to operate at a lower temperature and reduce the weight of the equipment. Plate and fin heat exchangers are mostly used for low temperature services such as natural gas, helium and oxygen liquefaction plants, air separation plants and transport industries such as motor and aircraft engines.

Advantages of plate and fin heat exchangers:

- High heat transfer efficiency especially in gas treatment
- Larger heat transfer area
- Approximately 5 times lighter in weight than that of shell and tube heat exchanger
- Able to withstand high pressure

Disadvantages of plate and fin heat exchangers:

- Might cause clogging as the pathways are very narrow
- Difficult to clean the pathways
- Aluminum alloys are susceptible to Mercury Liquid Embrittlement Failure

## Pillow plate heat exchanger

A pillow plate exchanger is commonly used in the dairy industry for cooling milk in large direct-expansion stainless steel bulk tanks. The pillow plate allows for cooling across nearly the entire surface area of the tank, without gaps that would occur between pipes welded to the exterior of the tank.

The pillow plate is constructed using a thin sheet of metal spot-welded to the surface of another thicker sheet of metal. The thin plate is welded in a regular pattern of dots or with a serpentine pattern of weld lines. After welding the enclosed space is pressurized with sufficient force to cause the thin metal to bulge out around the welds, providing a space for heat exchanger liquids to flow, and creating a characteristic appearance of a swelled pillow formed out of metal.

### Fluid heat exchangers

This is a heat exchanger with a gas passing upwards through a shower of fluid (often water), and the fluid is then taken elsewhere before being cooled. This is commonly used for cooling gases whilst also removing certain impurities, thus solving two problems at once. It is widely used in espresso machines as an energy-saving method of cooling super-heated water to be used in the extraction of espresso.

### Waste heat recovery units

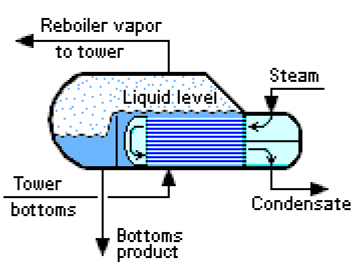
A Waste Heat Recovery Unit (WHRU) is a heat exchanger that recovers heat from a hot gas stream while transferring it to a working medium, typically water or oils. The hot gas stream can be the exhaust gas from a gas turbine or a diesel engine or a waste gas from industry or refinery.

### Dynamic scraped surface heat exchanger

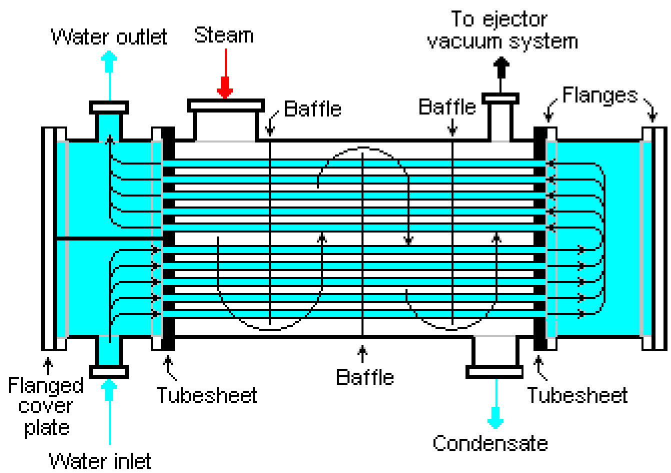
Another type of heat exchanger is called "(dynamic) scraped surface heat exchanger". This is mainly used for heating or cooling with high-viscosity products, crystallization processes, evaporation and high-fouling applications. Long running times are achieved due to the continuous scraping of the surface, thus avoiding fouling and achieving a sustainable heat transfer rate during the process.

The formula used for this will be Q=A*U*LMTD, whereby Q= amount of heat transferred; U= heat transfer coefficient; A=Heat Transfer Area; LMTD = Log mean temperature differential.

### Phase-change heat exchangers




Typical kettle reboiler used for industrial distillation towers




Typical water-cooled surface condenser

In addition to heating up or cooling down fluids in just a single phase, heat exchangers can be used either to heat a liquid to evaporate (or boil) it or used as condensers to cool a vapor and condense it to a liquid. In chemical plants and refineries, reboilers used to heat incoming feed for distillation towers are often heat exchangers.

Distillation set-ups typically use condensers to condense distillate vapors back into liquid.

Power plants which have steam-driven turbines commonly use heat exchangers to boil water into steam. Heat exchangers or similar units for producing steam from water are often called boilers or steam generators.

In the nuclear power plants called pressurized water reactors, special large heat exchangers which pass heat from the primary (reactor plant) system to the secondary (steam plant) system, producing steam from water in the process, are called steam generators. All fossil-fueled and nuclear power plants using steam-driven turbines have surface condensers to convert the exhaust steam from the turbines into condensate (water) for re-use.

To conserve energy and cooling capacity in chemical and other plants, regenerative heat exchangers can be used to transfer heat from one stream that needs to be cooled to another stream that needs to be heated, such as distillate cooling and reboiler feed pre-heating.

This term can also refer to heat exchangers that contain a material within their structure that has a change of phase. This is usually a solid to liquid phase due to the small volume difference between these states. This change of phase effectively acts as a buffer because it occurs at a constant temperature but still allows for the heat exchanger to accept additional heat. One example where this has been investigated is for use in high power aircraft electronics.

## *Direct contact heat exchangers*

Direct contact heat exchangers involve heat transfer between hot and cold streams of two phases in the absence of a separating wall. Thus such heat exchangers can be classified as:

- Gas – liquid
- Immiscible liquid – liquid
- Solid-liquid or solid – gas

Most direct contact heat exchangers fall under the Gas- Liquid category, where heat is transferred between a gas and liquid in the form of drops, films or sprays.

Such types of heat exchangers are used predominantly in air conditioning, humidification, water cooling and condensing plants.

| Phases | Continuous phase | Driving force | Change of phase | Examples |
|---|---|---|---|---|
| Gas – Liquid | Gas | Gravity | No | Spray columns, packed columns |
| | | | Yes | Cooling towers, falling droplet evaporators |
| | | Forced | No | Spray coolers/quenchers |
| | | Liquid flow | Yes | Spray condensers/evaporation, jet condensers |
| | Liquid | Gravity | No | Bubble columns, perforated tray columns |
| | | | Yes | Bubble column condensers |
| | | Forced | No | Gas spargers |
| | | Gas flow | Yes | Direct contact evaporators, submerged combustion |

## *HVAC air coils*

One of the widest uses of heat exchangers is for air conditioning of buildings and vehicles. This class of heat exchangers is commonly called *air coils*, or just *coils* due to their often-serpentine internal tubing. Liquid-to-air, or air-to-liquid HVAC coils are typically of modified crossflow arrangement. In vehicles, heat coils are often called heater cores.

On the liquid side of these heat exchangers, the common fluids are water, a water-glycol solution, steam, or a refrigerant. For *heating coils*, hot water and steam are the most common, and this heated fluid is supplied by boilers, for example. For *cooling coils*, chilled water and refrigerant are most common. Chilled water is supplied from a chiller that is potentially located very far away, but refrigerant must come from a nearby condensing unit. When a refrigerant is used, the cooling coil is the evaporator in the vapor-compression refrigeration cycle. HVAC coils that use this direct-expansion of refrigerants are commonly called *DX coils*.

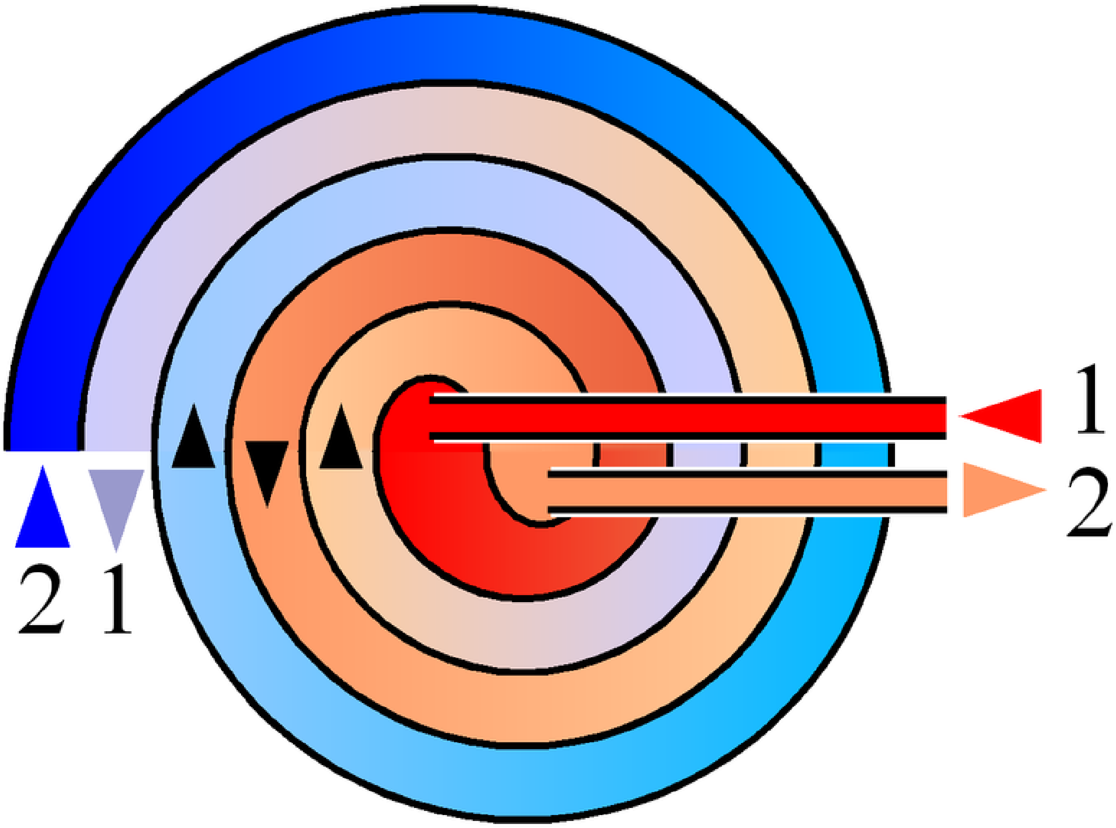
On the air side of HVAC coils a significant difference exists between those used for heating, and those for cooling. Due to psychrometrics, air that is cooled often has moisture condensing out of it, except with extremely dry air flows. Heating some air increases that airflow's capacity to hold water. So heating coils need not consider moisture condensation on their air-side, but cooling coils *must* be adequately designed and selected to handle their particular *latent* (moisture) as well as the *sensible* (cooling) loads. The water that is removed is called *condensate*.

For many climates, water or steam HVAC coils can be exposed to freezing conditions. Because water expands upon freezing, these somewhat expensive and difficult to replace thin-walled heat exchangers can easily be damaged or destroyed by just one freeze. As such, freeze protection of coils is a major concern of HVAC designers, installers, and operators.

The introduction of indentations placed within the heat exchange fins controlled condensation, allowing water molecules to remain in the cooled air. This invention allowed for refrigeration without icing of the cooling mechanism.

The heat exchangers in direct-combustion furnaces, typical in many residences, are not 'coils'. They are, instead, gas-to-air heat exchangers that are typically made of stamped steel sheet metal. The combustion products pass on one side of these heat exchangers, and air to be conditioned on the other. A *cracked heat exchanger* is therefore a dangerous situation requiring immediate attention because combustion products are then likely to enter the building.

### *Spiral heat exchangers*




Schematic drawing of a spiral heat exchanger.

A spiral heat exchanger (SHE), may refer to a helical (coiled) tube configuration, more generally, the term refers to a pair of flat surfaces that are coiled to form the two channels in a counter-flow arrangement. Each of the two channels has one long curved path. A pair of fluid ports are connected tangentially to the outer arms of the spiral, and axial ports are common, but optional.

The main advantage of the SHE is its highly efficient use of space. This attribute is often leveraged and partially reallocated to gain other improvements in performance, according to well known tradeoffs in heat exchanger design. (A notable tradeoff is capital cost vs operating cost.) A compact SHE may be used to have a smaller footprint and thus lower all-around capital costs, or an over-sized SHE may be used to have less pressure drop, less pumping energy, higher thermal efficiency, and lower energy costs.

### Construction

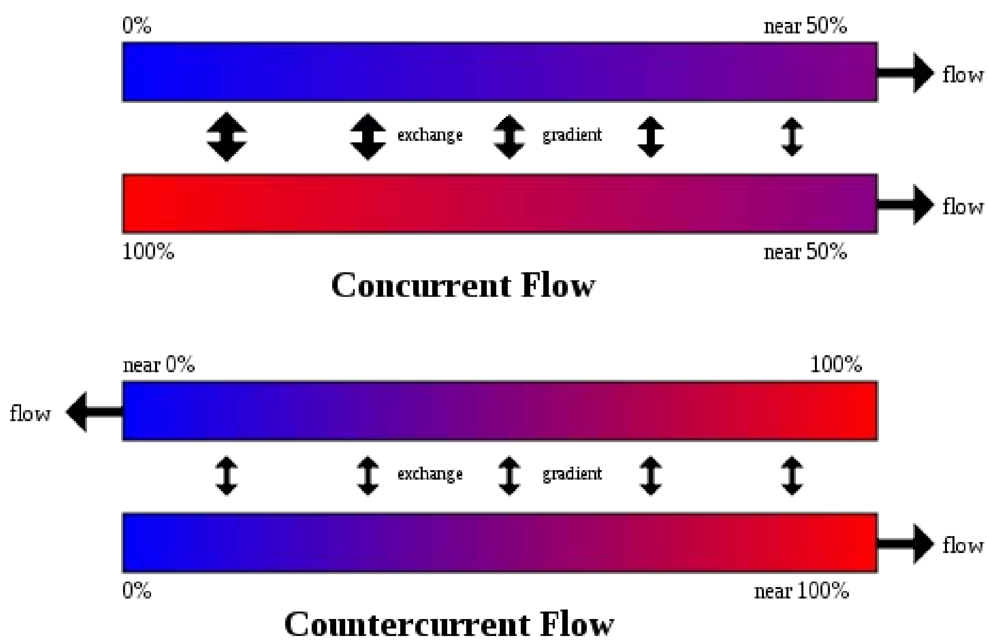
The distance between the sheets in the spiral channels are maintained by using spacer studs that were welded prior to rolling. Once the main spiral pack has been rolled, alternate top and bottom edges are welded and each end closed by a gasketed flat or conical cover bolted to the body. This ensures no mixing of the two fluids will occur. If a leakage happens, it will be from the periphery cover to the atmosphere, or to a passage containing the same fluid.

## Self cleaning

SHEs are often used in the heating of fluids which contain solids and thus have a tendency to foul the inside of the heat exchanger. The low pressure drop gives the SHE its ability to handle fouling easier. The SHE uses a “self cleaning” mechanism, whereby fouled surfaces cause a localized increase in fluid velocity, thus increasing the drag (or fluid friction) on the fouled surface, thus helping to dislodge the blockage and keep the heat exchanger clean. "The internal walls that make up the heat transfer surface are often rather thick, which makes the SHE very robust, and able to last a long time in demanding environments." They are also easily cleaned, opening out like an oven where any build up of foulant can be removed by pressure washing.

Self-Cleaning Water filters are used to keep the system clean and running without the need to shut down or replace cartridges and bags.

## Flow Arrangements




Concurrent and countercurrent flow.

There are three main types of flows in a spiral heat exchanger:

1. **Countercurrent Flow**: Fluids flow in opposite directions. These are used for liquid-liquid, condensing and gas cooling applications. Units are usually mounted

vertically when condensing vapour and mounted horizontally when handling high concentrations of solids.

2. **Spiral Flow/Cross Flow:** One fluid is in spiral flow and the other in a cross flow. Spiral flow passages are welded at each side for this type of spiral heat exchanger. This type of flow is suitable for handling low density gases which passes through the cross flow, avoiding pressure loss. It can be used for liquid-liquid applications if one liquid has a considerably greater flow rate than the other.
3. **Distributed Vapour/Spiral flow:** This design is a condenser, and is usually mounted vertically. It is designed to cater for the sub-cooling of both condensate and non-condensables. The coolant moves in a spiral and leaves via the top. Hot gases that enter leave as condensate via the bottom outlet.

### Applications

The SHE is good for applications such as pasteurization, digester heating, heat recovery, pre-heating (see: recuperator), and effluent cooling. For sludge treatment, SHEs are generally smaller than other types of heat exchangers.

## *Selection*

Due to the many variables involved, selecting optimal heat exchangers is challenging. Hand calculations are possible, but many iterations are typically needed. As such, heat exchangers are most often selected via computer programs, either by system designers, who are typically engineers, or by equipment vendors.

In order to select an appropriate heat exchanger, the system designers (or equipment vendors) would firstly consider the design limitations for each heat exchanger type. Although cost is often the first criterion evaluated, there are several other important selection criteria which include:

- High/ Low pressure limits
- Thermal Performance
- Temperature ranges
- Product Mix (liquid/liquid, particulates or high-solids liquid)
- Pressure Drops across the exchanger
- Fluid flow capacity
- Cleanability, maintenance and repair
- Materials required for construction
- Ability and ease of future expansion

Choosing the right heat exchanger (HX) requires some knowledge of the different heat exchanger types, as well as the environment in which the unit must operate. Typically in the manufacturing industry, several differing types of heat exchangers are used for just the one process or system to derive the final product. For example, a kettle HX for pre-heating, a double pipe HX for the 'carrier' fluid and a plate and frame HX for final cooling. With sufficient knowledge of heat exchanger types and operating requirements, an appropriate selection can be made to optimise the process.

## *Monitoring and maintenance*

Online monitoring of commercial heat exchangers is done by tracking the overall heat transfer coefficient. The overall heat transfer coefficient tends to decline over time due to fouling.

$U=Q/A\Delta T_{lm}$

By periodically calculating the overall heat transfer coefficient from exchanger flow rates and temperatures, the owner of the heat exchanger can estimate when cleaning the heat exchanger will be economically attractive.

Integrity inspection of plate and tubular heat exchanger can be tested in situ by the conductivity or helium gas methods. These methods confirm the integrity of the plates or tubes to prevent any cross contamination and the condition of the gaskets.

Mechanical integrity monitoring of heat exchanger tubes may be conducted through Nondestructive methods such as eddy current testing.

### Fouling

A heat exchanger in a steam power station contaminated with macrofouling.

Fouling occurs when impurities deposit on the heat exchange surface. Deposition of these impurities can be caused by:

- Low wall shear stress
- Low fluid velocities
- High fluid velocities
- Reaction product solid precipitation
- Precipitation of dissolved impurities due to elevated wall temperatures

The rate of heat exchanger fouling is determined by the rate of particle deposition less re-entrainment/suppression. This model was originally proposed in 1959 by Kern and Seaton.

**Crude Oil Exchanger Fouling**. In commercial crude oil refining, crude oil is heated from 70F to 650F prior to entering the distillation column. A series of shell and tube heat exchangers is typically used to exchange heat between the crude oil and other oil streams, in order to get the crude to 500F prior to heating in a furnace. Fouling occurs on the crude side of these exchangers due to asphaltene insolubility. The nature of asphaltene solubility in crude oil was successfully modeled by Wiehe and Kennedy. The precipitation of insoluble asphaltenes in crude preheat trains has been successfully modeled as a first order reaction by Ebert and Panchal who expanded on the work of Kern and Seaton.

**Cooling Water Fouling**. Cooling water systems are susceptible to fouling. Cooling water typically has a high total dissolved solids content and suspended colloidal solids. Localized precipitation of dissolved solids occurs at the heat exchange surface due to wall temperatures higher than bulk fluid temperature. Low fluid velocities allow suspended solids to settle on the heat exchange surface. Cooling water is typically on the tube side of a shell and tube exchanger because it's easy to clean. To prevent fouling, designers typically ensure that cooling water velocity is greater than 3 ft/s and bulk fluid temperature is maintained less than 140F. Other approaches to control fouling control combine the “blind” application of biocides and anti-scale chemicals with periodic lab testing.

## Maintenance

Plate heat exchangers need to be disassembled and cleaned periodically. Tubular heat exchangers can be cleaned by such methods as acid cleaning, sandblasting, high-pressure water jet, bullet cleaning, or drill rods.

In large-scale cooling water systems for heat exchangers, water treatment such as purification, addition of chemicals, and testing, is used to minimize fouling of the heat exchange equipment. Other water treatment is also used in steam systems for power plants, etc. to minimize fouling and corrosion of the heat exchange and other equipment.

A variety of companies have started using water borne oscillations technology to prevent biofouling. Without the use of chemicals, this type of technology has helped in providing a low-pressure drop in heat exchangers.

## *In nature*

### Humans

The human nasal passages serve as a heat exchanger, which warms air being inhaled and cools air being exhaled. You can demonstrate its effectiveness by putting your hand in front of your face and exhaling, first through your nose and then through your mouth. Air exhaled through your nose will be substantially cooler.

In species that have external testes (such as humans), the artery to the testis is surrounded by a mesh of veins called the pampiniform plexus. This cools the blood heading to the testis, while reheating the returning blood.

### Birds, fish, marine mammals

"Countercurrent" heat exchangers occur naturally in the circulation system of fish, whales and other marine mammals. Arteries to the skin carrying warm blood are intertwined with veins from the skin carrying cold blood, causing the warm arterial blood to exchange heat with the cold venous blood. This reduces the overall heat loss in cold waters. Heat exchangers are also present in the tongue of baleen whales as large volumes of water flow through their mouths. Wading birds use a similar system to limit heat losses from their body through their legs into the water.

## *In industry*

Heat exchangers are widely used in industry both for cooling and heating large scale industrial processes. The type and size of heat exchanger used can be tailored to suit a process depending on the type of fluid, its phase, temperature, density, viscosity, pressures, chemical composition and various other thermodynamic properties.

In many industrial processes there is waste of energy or a heat stream that is being exhausted, heat exchangers can be used to recover this heat and put it to use by heating a different stream in the process. This practice saves a lot of money in industry as the heat supplied to other streams from the heat exchangers would otherwise come from an external source which is more expensive and more harmful to the environment.

Heat exchangers are used in many industries, some of which include:

- Waste water treatment
- Refrigeration systems
- Wine-brewery industry
- Petroleum industry.

In the waste water treatment industry, heat exchangers play a vital role in maintaining optimal temperatures within anaerobic digesters so as to promote the growth of microbes which remove pollutants from the waste water. The common types of heat exchangers used in this application are the double pipe heat exchanger as well as the plate and frame heat exchanger.

### *In aircraft*

In commercial aircraft heat exchangers are used to take heat from the engine's oil system to heat cold fuel. This improves fuel efficiency, as well as reduces the possibility of water entrapped in the fuel freezing in components.

In early 2008, a Boeing 777 flying as British Airways Flight 38 crashed just short of the runway. In an early-2009 Boeing-update sent to aircraft operators, the problem was identified as specific to the Rolls-Royce engine oil-fuel flow heat exchangers. Other heat exchangers, or Boeing 777 aircraft powered by GE or Pratt and Whitney engines, are not affected by the problem.

## *A model of a simple heat exchanger*

A simple heat exchanger might be thought of as two straight pipes with fluid flow, which are thermally connected. Let the pipes be of equal length $L$, carrying fluids with heat capacity $C_i$ (energy per unit mass per unit change in temperature) and let the mass flow rate of the fluids through the pipes be $j_i$ (mass per unit time), where the subscript $i$ applies to pipe 1 or pipe 2.

The temperature profiles for the pipes are $T_1(x)$ and $T_2(x)$ where $x$ is the distance along the pipe. Assume a steady state, so that the temperature profiles are not functions of time. Assume also that the only transfer of heat from a small volume of fluid in one pipe is to the fluid element in the other pipe at the same position. There will be no transfer of heat along a pipe due to temperature differences in that pipe. By Newton's law of cooling the rate of change in energy of a small volume of fluid is proportional to the difference in temperatures between it and the corresponding element in the other pipe:

$$\frac{du_1}{dt} = \gamma(T_2 - T_1)$$
$$\frac{du_2}{dt} = \gamma(T_1 - T_2)$$

where $u_i(x)$ is the thermal energy per unit length and $\gamma$ is the thermal connection constant per unit length between the two pipes. This change in internal energy results in a change in the temperature of the fluid element. The time rate of change for the fluid element being carried along by the flow is:

$$\frac{du_1}{dt} = J_1 \frac{dT_1}{dx}$$
$$\frac{du_2}{dt} = J_2 \frac{dT_2}{dx}$$

where $J_i = C_i j_i$ is the "thermal mass flow rate". The differential equations governing the heat exchanger may now be written as:

$$J_1 \frac{\partial T_1}{\partial x} = \gamma(T_2 - T_1)$$
$$J_2 \frac{\partial T_2}{\partial x} = \gamma(T_1 - T_2).$$

Note that, since the system is in a steady state, there are no partial derivatives of temperature with respect to time, and since there is no heat transfer along the pipe, there are no second derivatives in $x$ as is found in the heat equation. These two coupled first-order differential equations may be solved to yield:

$$T_1 = A - \frac{Bk_1}{k} e^{-kx}$$
$$T_2 = A + \frac{Bk_2}{k} e^{-kx}$$

where $k_1 = \gamma / J_1$, $k_2 = \gamma / J_2$, $k = k_1 + k_2$ and $A$ and $B$ are two as yet undetermined constants of integration. Let $T_{10}$ and $T_{20}$ be the temperatures at x=0 and let $T_{1L}$ and $T_{2L}$ be the temperatures at the end of the pipe at x=L. Define the average temperatures in each pipe as:

$$\overline{T}_1 = \frac{1}{L} \int_0^L T_1(x)dx$$
$$\overline{T}_2 = \frac{1}{L} \int_0^L T_2(x)dx.$$

Using the solutions above, these temperatures are:

$$T_{10} = A - \frac{Bk_1}{k} \qquad T_{20} = A + \frac{Bk_2}{k}$$
$$T_{1L} = A - \frac{Bk_1}{k} e^{-kL} \qquad T_{2L} = A + \frac{Bk_2}{k} e^{-kL}$$
$$\overline{T}_1 = A - \frac{Bk_1}{k^2 L}(1 - e^{-kL}) \qquad \overline{T}_2 = A + \frac{Bk_2}{k^2 L}(1 - e^{-kL}).$$

Choosing any two of the above temperatures will allow the constants of integration to be eliminated, and that will allow the other four temperatures to be found. The total energy transferred is found by integrating the expressions for the time rate of change of internal energy per unit length:

$$\frac{dU_1}{dt} = \int_0^L \frac{du_1}{dt}\,dx = J_1(T_{1L} - T_{10}) = \gamma L(\overline{T}_2 - \overline{T}_1)$$
$$\frac{dU_2}{dt} = \int_0^L \frac{du_2}{dt}\,dx = J_2(T_{2L} - T_{20}) = \gamma L(\overline{T}_1 - \overline{T}_2).$$

By the conservation of energy, the sum of the two energies is zero. The quantity $\overline{T}_2 - \overline{T}_1$ is known as the "log mean temperature difference" and is a measure of the effectiveness of the heat exchanger in transferring heat energy.

# Chapter 3

# Insulated Shipping Container and Thermostatic Radiator Valve

## Insulated shipping container

**Insulated shipping containers** are a type of packaging used to ship temperature sensitive products such as foods, pharmaceuticals, and chemicals. They are used as part of a cold chain to help maintain product freshness and efficacy. The term can also refer to insulated intermodal containers or insulated swap bodies.

### *Construction*

An insulated shipping container might be constructed of:

1. a vacuum flask, similar to a "thermos" bottle
2. fabricated thermal blankets or liners
3. molded expanded polystyrene foam (EPS, styrofoam, etc), similar to a cooler
4. other molded foams such as polyurethane, polyethylene, etc
5. sheets of foamed plastics
6. reflective materials: (metallised film, etc)
7. bubble wrap or other gas filled panels
8. other packaging materials and structures

Some are designed for single use while others are returnable for reuse. Some empty containers are sent to the shipper disassembled or “knocked down”, assembled and used, then knocked down again for easier return shipment.

### *Use*

Insulated shipping containers are part of a comprehensive cold chain which controls and documents the temperature of a product through its entire distribution cycle. The containers may be used with a refrigerant or coolant such as :

- block or cube ice, slurry ice, etc
- dry ice
- Gel or ice packs (often formulated for specific temperature ranges)
- Some products (such as frozen meat) have sufficient thermal mass to contribute to the temperature control
- etc

A temperature data logger or time temperature indicator is often enclosed to monitor the temperature inside the container for its entire shipment.

Labels and appropriate documentation (internal and external) are usually required.

Personnel throughout the cold chain need to be aware of the special handling and documentation required for some controlled shipments. With some regulated products, complete documentation is required.

## *Design and Evaluation*

The use of "off the shelf" insulated shipping containers does not necessarily guarantee proper performance. Several factors need to be considered :

- the sensitivity of the product to temperatures (high and low) and to time at temperatures
- the specific distribution system being used: the expected (and worst case) time and temperatures
- regulatory requirements
- the specific combination of packaging components and materials being used
- etc

In specifying an insulated shipping container, the two primary characteristics of the material will be the insulation properties of the matieral known as the "K Value" and the thickness of the material. These two attributies determine that majority of the functionality of the component. One should attempt to control the latent heat of any insultated shipping container when is use, as this will affect the overall performance of the component when integrated into a system (closed system with refrigerant & product).

It is wise (and sometimes mandatory) to have formal verification of the performance of the insulated shipping container. Laboratory package testing might include ASTM D3103-07, Standard Test Method for Thermal Insulation Performance of Packages, ISTA Guide 5B: Focused Simulation Guide for Thermal Performance Testing of Temperature Controlled Transport Packaging, and others. In addition, validation of field performance is extremely useful.

Specialists in design and testing of packaging for temperature sensitive products are often needed. These may be consultants, independent laboratories, universities, or reputable vendors.

# Thermostatic radiator valve

A **Thermostatic Radiator Valve** (TRV) is a self-regulating valve fitted to hot water heating system radiators. The TRV controls the temperature of a room by regulating the flow of hot water to the radiator. Thermostatic radiator valves (air vent valves) also exist for steam radiators.

## *Short history of the TRV*

Many years ago the first ideas for heating controls saw the light of day, but it was not until 1943 when Mads Clausen, founder of Danfoss, invented the first radiator thermostat that the development of TRVs became serious. However, from the first invention to mass production to the European market it took almost 15 years, and it was not until 1973 when the first oil crisis hit the world that the installation of TRVs really took speed.

Today TRVs have a wide market distribution and acceptance worldwide as an energy efficient and competitive technology. In spite of this there is still a huge potential for further implementation of TRVs as replacement of old manual valves to benefit the environment and reduce the energy costs for people around the world.

## *Product design and functionality*

A TRV consists of two parts: a valve that opens or closes to control the hot water flow and a sensor that controls the opening of the valve. The sensor contains an actuator with a sensing substance, which adjusts the valve opening based on the temperature in the room and via a physical connection between the actuator-spindle and the valve-spindle/cone.

The sensors are for the most part made of plastic in many different designs and shapes. The actuator usually contains a sensing substance, such as wax, liquid or gas.

The valves are mainly made by brass or bronze and have different sizes, shapes and connections to the radiator. The majority of valves are mounted on the piping connected to the radiator; however, the valves may also be mounted as an integrated part of the radiator.

## *Operation*

TRVs are self-regulating devices, which control the temperature in the room based on an individually set temperature and heat load. TRVs can work together with outdoor temperature controls, supply flow temperature controls, pressure controls and time set-back devices.

The self-regulating principle is shown in this animation. The overall principle can be described in this way:

1. The actuating device in the sensor is a steel container containing a sensing substance, either wax, liquid or gas. All three substances expand or contract depending on the temperature in the room.
2. A spindle system in the sensor transfers the axial movement from the actuator to the valve by interaction between the sensor spindle and the valve spindle. In the valve a rubber cone fixed on the valve spindle interacts with the valve seat and thereby regulates and controls the flow of hot water through the valve to the radiator inlet.

The process is completely self-contained and without complex electronic controls. The TRV keeps the room temperature at a desired level even through fairly wide swings in indoor temperature due to external conditions such as sudden temperature drops, solar radiation, wind velocity or wind direction.

After installing TRVs, owners have to get used to the self-regulating principle which means that they do not have to turn the thermostat up and down. When room temperatures vary, the valve automatically opens or closes to regulate the flow of hot water until the desired temperature is achieved. Only if the desired room temperature has to be changed or if windows are opened or closed for ventilation does the sensor setting need to be adjusted.

A TRV should not be fitted on a radiator where it is in the same room as the main house/rooms thermostat, as this can lead to inaccurate overall house temperature control. Refer to BS5449 or equivalent.

## *Applications and $CO_2$ savings*

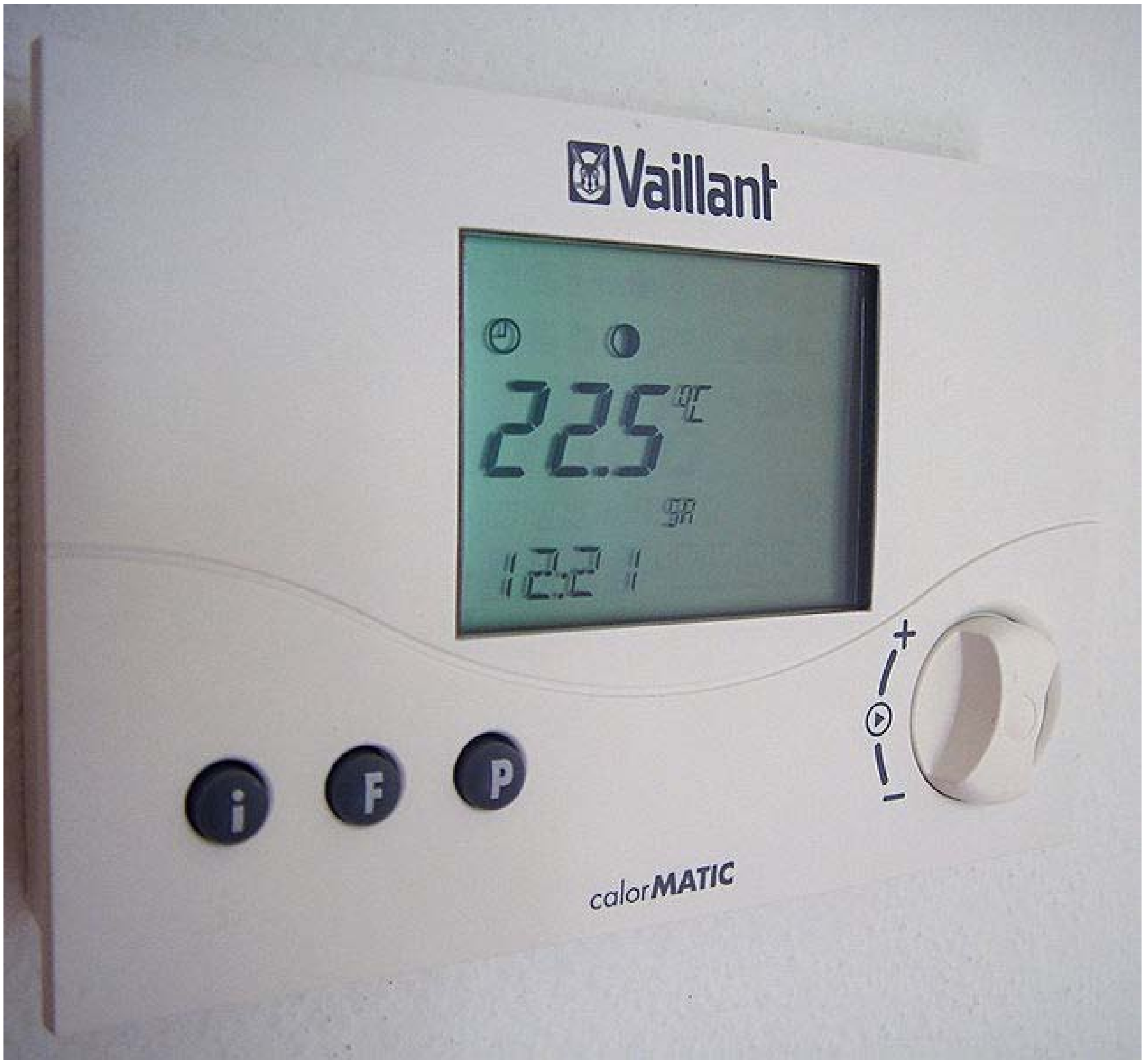
TRVs are suitable for all kind of radiator systems, radiators, convectors and towel dryers. Designs of the sensors can be tailored to suit the specific applications. TRVs are cheap and easy solutions with a significant potential for energy savings and $CO_2$ reductions from heating installations. In fact the replacement of a manual heating control with a TRV can save at least 100 kg $CO_2$ per year.

When dimensioning a heating system in a building, it is necessary to perform a precise calculation of the total system. As part of this calculation it is important to secure proper hydraulic balancing of the complete heating system. For this balancing, the presetting feature in the valve or a special hydraulic balancing valve can be used.

## Chapter 4

# Programmable Thermostat


Lux Products' Model TX900TS Touch Screen Thermostat.




Vaillant digital room thermostat

A **programmable thermostat** is a thermostat which is designed to adjust the temperature according to a series of programmed settings that take effect at different times of the day. Programmable thermostats may also be called **setback thermostats** or **clock thermostats**.

### *Benefits*


Honeywell electronic thermostat in a store

Heating and cooling losses from a building (or any other container) become greater as the difference in temperature increases. A programmable thermostat allows reduction of these losses by allowing the temperature difference to be reduced at times when the reduced amount of heating or cooling would not be objectionable.

For example, during cooling season, a programmable thermostat used in a home may be set to allow the temperature in the house to rise during the workday when no one will be at home. It may then be set to turn on the air conditioning before the arrival of occupants, allowing the house to be cool upon the arrival of the occupants while still having saved air conditioning energy during the peak outdoor temperatures. The reduced cooling required during the day also decreases the demands placed upon the electrical supply grid.

Conversely, during the heating season, the programmable thermostat may be set to allow the temperature in the house to drop when the house is unoccupied during the day and also at night after all occupants have gone to bed, re-heating the house prior to the occupants arriving home in the evening or waking up in the morning. Since most people sleep better when a room is cooler and the temperature differential between the interior and exterior of a building will be greatest on a cold winter night, this reduces energy losses.

Similar scenarios are available in commercial buildings, with due consideration of the building's occupancy patterns.

## *Construction and features*

### Clock thermostats


Honeywell office thermostat

The most basic clock thermostats may only implement one program with two periods (a hotter period and a colder period), and the same program is run day after day. More sophisticated clock thermostats may allow four or more hot and cold periods to be set per day. Usually, only two distinct temperatures (a hotter temperature and a colder temperature) can be set, even if multiple periods are permitted. The hotter and colder temperatures are usually established simply by sliding two levers along an analogue temperature scale, much the same as in a conventional (non-clock) thermostat.

This design, while simple to manufacture and relatively easy to program, sacrifices comfort on weekends since the program is repeated each of the seven days of the week with no variation. To overcome this deficit, a push-button is sometimes provided to allow the user to explicitly switch (once) the current period from hot period to a cold period or vice-versa; the usual use of this button is to over-ride a "set back" that takes place during the workday when the home is normally unoccupied.

The clock mechanism is electrical, and two methods have commonly been used to drive it:

- A separate, continuous source of 24 volts AC is provided to the thermostat, or
- A rechargeable battery in the thermostat operates the clock. The battery charges when the thermostat is not calling for heat and 24 VAC is available across the thermostat's terminals, and discharges to operate the clock when the thermostat is commanding heating or cooling.

### Digital thermostats


A touch-screen programmable thermostat in programming mode.

Digital thermostats may implement the same functions, but most provide more versatility. For example, they commonly allow setting temperatures for two, four, or six periods each day, and rather than being limited to a single "hotter" temperature and a single "colder" temperature, digital thermostats usually allow each period to be set to a unique temperature. The periods are commonly labeled "Morning", "Day", "Evening", and "Night", although nothing constrains the time intervals involved. Digital thermostats usually allow the user to override the programmed temperature for the period, automatically resuming programmed temperatures when the next period begins. A function to "hold" (lock-in) the current temperature is usually provided as well; in this case, the override temperature is maintained until the user cancels the hold or a programmed event occurs to resume the normal program. More-sophisticated models will allow for the release of the hold to take place at a set time in the future.

As with clock thermostats, basic digital thermostats may have just one cycle that is run every day of the week. More-sophisticated thermostats may have a weekday schedule and a separate weekend schedule (so-called "5-2" setting) or separate Saturday and Sunday schedules (so-called "5-1-1" settings), while other thermostats will offer a separate schedule for each day of the week ("7 day" settings). The selection of which days are defined as the "weekend" is arbitrary, depending on the user's heating and cooling schedule requirements. Often, a manufacturer will sell three similar thermostats offering each of those levels of functionality, and there is no obvious difference in the thermostats other than the factory programming and the price.

Most digital thermostats have separate programs for heating and cooling, and may feature a digital or manual switch to turn on the furnace blower for air circulation, even when the system isn't heating or cooling. More-sophisticated models may be programmed to run the circulating fan for a brief 5-10 minute period in the event a heating or cooling cycle has not taken place during the previous hour. This is particularly useful in buildings subject to stratification where without frequent air circulation, hot air rises and separates from the cooler air that falls.

Digital thermostats may also have a user-programmable air filter change reminder; this counts the accumulated run-time of the heating/cooling system and reminds the user when it is time to change the filter. The feature often displays the accumulated run-time either as an aggregate of both heating and cooling or displaying each time separately.

Some digital thermostats have the capability of being programmed using a touch-tone telephone or over the Internet.

Digital thermostats are usually powered one of three ways:

- A sophisticated power circuit operates from the 24 VAC supply when the thermostat is *not* calling, and operates from the current flowing in the thermostat circuit when the thermostat *is* calling. A battery is used to provide back-up during power failures.
- A rechargeable battery operates the thermostat just as in the clock thermostat, charging when the thermostat is not calling and discharging while the thermostat is calling.
- A non-rechargeable battery always powers the thermostat. To limit the amount of power drawn from the battery, such thermostats use an impulse relay that does not require the continuous application of power to the relay's coil. These thermostats can be used on millivolt circuits, as well as conventional 24 VAC circuits. Battery life is typically one to two years.

## Digital thermostats with PID controller

More expensive models have a built-in PID controller, so that the thermostat learns how the system will react to its commands. Programming the morning temperature to be 21° C at 7:00 AM, for instance, makes sure that at that time the temperature will be 21° C. A standard programmable thermostat would simply start working toward 21° at 7:00 AM. The PID controller decides at what time the system should be activated in order to reach the desired temperature at the desired time. It knows this by remembering the past behavior of the room, and the current temperature of the room. This is called optimal start.

It also makes sure that the temperature is very stable (for instance, by reducing overshoots at the end of the heating cycle) so that the comfort level is increased.

## Commercial thermostats

In commercial applications, the thermostat may not contain any clock mechanism. Instead, another means may be used to select between the "hotter" and "colder" settings. For example, if the thermostat uses pneumatic controls, a change in the air pressure supplied to the thermostat may select between the "hotter" and "colder" settings, and this air pressure is determined by a central regulator. With electronic controls, a specific signal may indicate whether to operate at the "hotter" or "colder" setting.

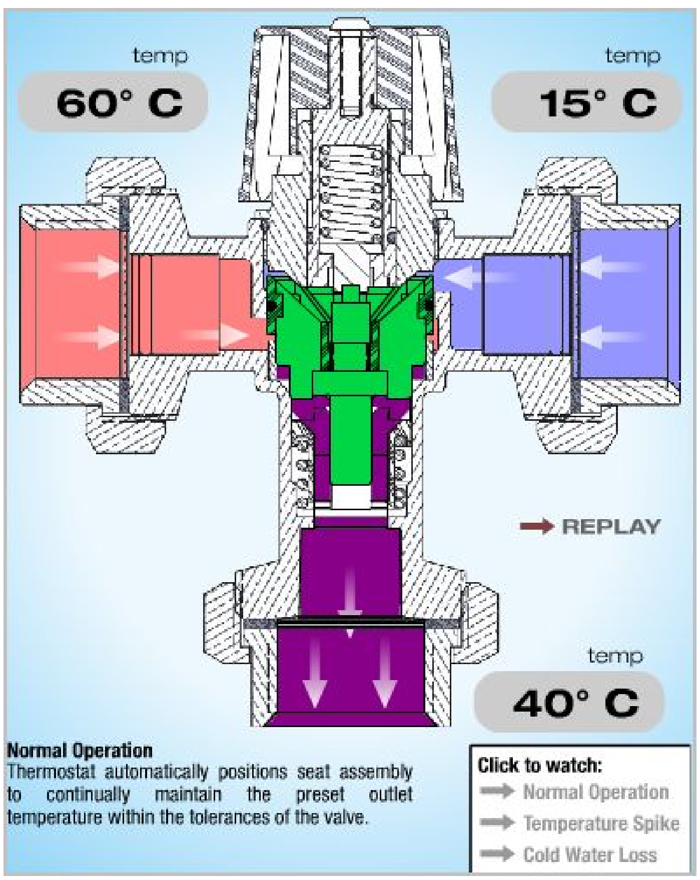
## Terminal types

| Terminal Code | Color | Description |
|---|---|---|
| R | Red | 24 volt |
| RH / RC | Red | 24 volt HEAT / COOL load |
| C / X | | 24 volt Common |
| W / W1 | White | Heat |
| W2 | White | Backup Heat |
| Y / Y1 | Yellow | Cool |
| G | Green | Fan |
| O / OB | Orange | Reversing valve (Heat Pump) |
| E | | Emergency Heat (Heat Pump) |

Chapter 5

# Thermostatic Mixing Valve and Wax Thermostatic Element

## Thermostatic mixing valve




A **Thermostatic Mixing Valve** (TMV) is a valve that blends hot water with cold water to ensure constant, safe outlet temperatures preventing scalding.

The storage of water at high temperature removes one possible breeding ground for Legionella; the use of a thermostat rather than a static mixing valve provides increased safety against scalding, and increased user comfort because the hot-water temperature remains constant.

Many TMVs use a wax thermostat for regulation. They also shut-off rapidly in the event of a hot or cold supply failure to prevent scalding or thermal shock.

It is increasingly common practice around the world to regulate the storage water temperature to above 60 °C (140 °F), and to circulate or distribute water at a temperature less than 50 °C (122 °F). Water above these temperatures can cause scald injuries. Many countries, states, or municipalities now require that the temperature of all bath water in new build and extensively refurbished domestic properties be controlled to a maximum of 48 °C (118 °F). Installing Thermostatic Mixing Valves (TMVs) can ensure that water is delivered at the required temperature thereby reducing the risk of scalding accidents; it also reduces hot water consumption relative to a supply that is maintained at a higher temperature.

There are three main categories for water temperature controlling devices: Heat Source, Group Control, and Point of Use.

Heat Source:

These are used with central heating systems that use water as a medium.

- tempering valves for use on hot water heat distribution systems
- High flow rates suitable for use in under floor (radiant) heating applications
- Allows water to be stored at a higher temperature

Group Control:

These provide a uniform distribution temperature for all hot water outlets in a household.

- Designed for multi-point applications
- High flow rates (from 14gpm to 51gpm at 45psi)
- Temperature stability

Point of Use:

These are single Outlet Thermostatic Mixing Valves, often called "thermostatic faucets", "thermostat taps" or "thermostat valves".

- Designed for single point applications such as Individual Showering, Hand Wash Basin Mixers, Bath or Tub fillers
- High level protection against scalding and thermal shock

# Wax thermostatic element

The **wax thermostatic element** was invented by Sergius Vernet (USA) in 1936 . The principal application of the wax element technology is for the production of automotive thermostats. The first applications of this technology in the plumbing and heating industries were in Sweden (1970) and in Switzerland (1971).

Wax thermostatic elements permit the transforming of thermal energy into mechanical energy. Their working principle is based on the large increase in the thermal expansion of waxes when they pass from the solid to the liquid state. The range of application includes but is not limited to the automotive industry, military and civil aviation, domestic heating (eg. thermostatic radiator valves), plumbing, industrial, fire, and agriculture.

## *Types of elements*

### Flat diaphragm element

The temperature sensing material contained in the cup transfers pressure to the piston by means of the diaphragm and the plug, held tightly in position by the guide. On cooling, the initial position of the piston is obtained by means of a return spring. Flat diaphragm elements are particularly noted for their high level of accuracy, and therefore mainly used in sanitary installations and heating.

### Squeeze-push elements

Squeeze-Push elements contain a synthetic rubber sleeve-like component shaped like the 'finger of a glove' which surrounds the piston. As the temperature increases, pressure from the expansion of the thermostatic material moves the piston with a lateral squeeze and a vertical push. As with the flat diaphragm element, the piston returns to its initial position by means of a return spring. These elements are slightly less accurate but provide a more powerful stroke.

## *Piston stroke*

The stroke is the movement of the piston in relation to its starting point. The ideal stroke corresponds to the temperature range of the elements. According to the type of element, it can vary from 1.5 mm to 16 mm.

## *Temperature range*

The temperature range lies between the minimum and maximum operating temperature of the element. Elements can cover temperatures ranging from -15°C to +120°C.

The temperature curve represents the movement of the piston in relation to the temperature. It can be a continuous or broken line. The angle varies according to the composition of the waxes.

### *Hysteresis*

Hysteresis is the difference noted between the upstroke and down stroke curve (i.e. heating and cooling of the element). Hysteresis is caused by the thermal inertia of the element and by the friction between the parts in motion.

# Chapter 6

# OpenTherm

**OpenTherm** (short: OT) is a protocol used in central heating systems between a central heating boiler and a thermostat or controller. It is a point to point protocol where one device (thermostat) is the master and the other the slave (boiler). Multiple devices can be linked by using the Multi Point to Point specification.

OpenTherm is manufacturer independent. A controller of manufacturer A can be used to control a boiler of manufacturer B.

## *How OpenTherm works*

Communication is digital and bi-directional between the thermostat (master) and the boiler (slave), many different commands, status reports and requests for information between the two devices is possible. However the most basic command is to control the boiler water temperature. The boiler when it has received a temperature control setpoint command will modulate (reduce or increase the heating power) to maintain this temperature setpoint. The thermostat constantly calculates what temperature the boiler water should be to maintain control of the room temperature, this results in a greater energy efficiency.

## *Communications media*

Physically OpenTherm is a 2 wire connection allowing the existing wiring to be re-used. OpenTherm not polarity sensitive: wires can be swapped. The maximum wiring length is 50m up to maximum 2 x 5 ohm resistance.

## *OpenTherm/Plus (OT/+)*

When referring to OpenTherm/Plus (OT/+) most of the time the “Plus OT+” part is left out.

The two wires are used for both communications and power supply. In this point-to-point connection the controller is the master and the boiler the slave. The master requests by changing the voltage level, and the slave responds by changing the current. Power supply for the controller is supplied by the slave. The minimal available power is 35 mW. When using OpenTherm Smart Power this can, by master request, also be 136 mW (medium power) or 255 mW (high power).

When short circuiting the OpenTherm connection on the boiler, the boiler will start heating.

OpenTherm specifies a minimal communications interval of one second. The data in the communication packet is functionally specified and is called OpenTherm-ID (OT-ID). 256 OT-IDs are available, 128 are reserved for OEM use. The other 128 are reserved, 90 of them are functionally specified. (OT specification v3.0)

### *OpenTherm/Lite (OT/-)*

When OT/- is used the master generates a PWM voltage signal, representing the boiler water temperature set point. The boiler current signal indicates the status of the boiler: error, no error.

When short circuiting the OpenTherm connection on the boiler, the boiler will start heating.

Due to the limited possibilities OT/- is hardly used.

### *OpenTherm Smart Power*

On June 16 2008 OpenTherm specification 3.0 is approved by the association. This version introduces OpenTherm Smart Power. The master can request the slave to change the available power to low, medium or high power. With this master manufacturers can add more functionality to their products (backlight or extra sensors).

### *Multi Point to Point*

Specification 3.0 also describes how more than two devices can be connected by OpenTherm. Whilst OpenTherm is a point-to-point connection, an extra device (gateway) is added between the master and the slave. This gateway has 1 slave and 1 (or more) master interfaces. The gateway controls which data is passed to each slave. An application example is a room temperature controller connected to a heat recovery unit, which is connected to a boiler. The heat recovery unit is then functioning as gateway.

## Certifying products

Manufacturers are allowed to market OpenTherm products when they comply with some rules of the OpenTherm association. Most importantly the manufacturer has to be an OpenTherm member, and the product must be tested by an independent testing body.

By handing over the test report and a Declaration of Conformity to the association, the manufacturer is allowed to use the OpenTherm logo.

## History

OpenTherm was founded because multiple manufacturers needed a simple-to-use communicating system between room controller and boiler. It had to run, like the existing controllers, over the existing two wires, not polarity sensitive, without the use of batteries.

For one British Pound, Honeywell sold the first specification to the OpenTherm Association on November 1996. Shortly after the first products appeared on the market. The Association has grown since then to around 42 members (2008) and has regularly updated and improved the specification. Furthermore, the Association is also active in lobbying for the interests of its members and is also present at exhibitions like the ISH (Frankfurt) and the Mostra Convegno (Milan)

## Specification documents

The protocol specifications document: **Protocol specification** (v2.2).

Document used for certification: **Test Specification**.

The document **Application Functional Specification** describes different applications and how the OpenTherm ID's are to be used. In addition implementation tips are given.

## Chapter 7

# Radiator (Heating)

**Radiators** and **convectors** are heat exchangers designed to transfer thermal energy from one medium to another for the purpose of space heating. The heating radiator was invented by Franz San Galli, a Polish-born Russian businessman living in St. Petersburg, between 1855–1857.

### *Radiation vs. convection*

In practice, the term "radiator" refers to any of a number of devices in which a fluid circulates through exposed pipes (often with fins or other means of increasing surface area), notwithstanding that such devices tend to transfer heat mainly by convection and might logically be called convectors.

The term convection heater or *convector* refers to a class of devices in which the source of heat is not directly exposed. As domestic safety and the supply from water heaters keeps temperatures relatively low, radiation is inefficient in comparison to convection.

For homes with radiators, Energy Star recommends placing heat-resistant reflectors between radiators and exterior walls to help retain heat in a room.

### *Types*

A cast iron household radiator

### Hot water

A hot-water radiator consists of a sealed hollow metal container filled with hot water by gravity feed, a pressure pump, or convection. As it gives out heat the hot water cools and sinks to the bottom of the radiator and is forced out of a pipe at the other end. Anti-hammer devices are often installed to prevent or minimize knocking in hot water radiator pipes.

## Hot water baseboard

Traditional cast iron radiators are no longer common in new construction, replaced mostly with forced hot water baseboard style radiators. They consist of copper pipes which have aluminum fins to increase their surface area. In the U.K., modern domestic radiators tend to be of sheet steel construction (often with steel fins), though copper/aluminium is often found in industrial Air Handling System heat exchangers.

### Steam

Single-pipe steam radiator

Steam has the advantage of flowing through the pipes under its own pressure without the need for pumping. For this reason, it was adopted earlier, before electric motors and pumps became available. Steam is also far easier to distribute than hot water throughout large, tall buildings like skyscrapers. However, the higher temperatures at which steam systems operate make them inherently less efficient, as unwanted heat loss is inevitably greater.

Steam pipes and radiators are prone to producing banging sounds often incorrectly called water hammer. The bang is created when some of the steam condenses into water in a horizontal section of the steam piping. Subsequently, steam picks up the water, forms a "slug" and hurls it at high velocity into a pipe fitting, creating a loud hammering noise and greatly stressing the pipe. This condition is usually caused by a poor condensate drainage strategy and is often caused by buildings settling and the resultant pooling of condensate in pipes and radiators that no longer tilt slightly back towards the boiler.

## Fan assisted heat exchanger

A fan-assisted radiator contains a heat exchanger fed by hot water from the heating system. A thermostatic switch energises an electric fan which blows air over the heat exchanger to circulate it in a room. Its advantages are small relative size and even distribution of heat. Disadvantages are fan noise and the need for both a source of heat and a separate electrical supply.

## Underfloor

In underfloor heating, tubing is placed on the floor throughout the room and later covered with a concrete layer during construction.

Underfloor heating uses a network of pipes, tubing or heating cables is buried in or attached beneath a floor to allow heat to rise into the room. Best results are had with conductive flooring materials such as tile. The large surface area of such room-sized radiators allows them to be kept just a few degrees above desired room temperature, minimizing convection. Underfloor heating is more expensive in new construction than less efficient systems. It also is generally difficult to retrofit into existing buildings.

The Roman hypocaust employed a similar principle of operation.

### Electric baseboard

Similar in configuration to forced hot water baseboard - low profile units running along the base of a wall with a central heating element surrounded by radiating fins - electric baseboard heaters are inexpensive to produce and install. They offer instant heat and great reliability, but may be more or less cost-effective relative to other forms of heat depending on electricity prices.

### Portable

Electrically powered portable radiators come in two basic forms:

- Electric elements, which either heat directly or radiate heat to a heat-conducting solid such as quartz
- Liquid filled, which employ an electric element to warm a fluid such as oil held within metal tubing, which circulates via convection.

# Chapter 8

# Storage Heater

A **storage heater** is an electrical home appliance which stores thermal energy during the evening, or at night when base load electricity is available at lower cost, and releases the heat during the day as required. Heat banks may be composed of clay bricks or other ceramic material, of concrete walls, or of water containers

In Australia, storage heaters are often called *heat banks*.

## *Application*

Storage heaters are usually used in conjunction with a two-tariff electricity meter which records separately the electricity used during the off-peak period so that it can be billed at a lower rate. In order to derive any benefit from a storage heater, the house must be on a special electricity tariff. In the United Kingdom the Economy 7 tariff is appropriate.

Storage heaters usually have two controls - a charge control (often called "input"), which controls the amount of heat stored, and the draught control (often called "output"), which controls the rate at which heat is released. These controls may be controlled by the user, or may operate automatically once the user selects the target room temperature on a thermostat.

Storage heaters may also incorporate an electric heater (utilizing either resistance heaters or heat pumps), which can be used to increase heat output. Such added heating is expensive, as it occurs during the high-tariff time of day.

## *Advantages*

- Storage heaters allow electrical heating, which is often more expensive than equivalent gas- or oil-fired heating systems, to be used without as much operating cost

- If the storage heater is incorporated into the building's floorplan (i.e. as dividing walls between areas, or underfloor), they take up less area than a gas- or oil-fired heating system
- Users of gas central heating & some other systems often turn off the heating during the night as an economy measure, with the result that the house is cold at night and early morning; but because night storage heaters are on at night, the house is still warm at those times
- Using storage heaters allows houses to be sited in areas where natural-gas distribution systems are not available, without forcing the homeowners to pay high electrical-heating bills
- The capital cost of night storage heating is relatively low; and installation is far easier than the initial installation of gas fired boilers, piping and radiators
- As compared to gas central heating systems, night storage heaters require next to no maintenance, with a consequent reduction in running costs.

### *Disadvantages*

- Sizing a storage heater is a compromise between the maximum expected cold-spell intensity and duration, and the cost and space requirement of the heater. If the heater is too large, its cost will be excessive and it will impact on the building's available area; if too small, the cost of supplemental (daytime) electrical heating will be excessive
- The heat stored during the night will be released into the living area during the next day, regardless of need (due to the inevitable heat transfer through the storage heater's insulation). Thus if the homeowner is unexpectedly absent that day (and therefore does not need the house to be warmed) or is only at home for a small part of the day, the heat has already been purchased and is already there, and eventually comes out
- Many users do not fully understand the controls, and a common error is leaving the output (or boost) control open at night, so that the heaters dissipate heat when they should be storing it, with a consequent increase in electricity consumption and cost
- Storage heaters are very heavy and somewhat bulky, due to the material used to store heat

### *Using storage heaters*

Storage heaters can be cost-effective if used properly, but they require more attention than fuel-fired systems.

## Power switches


Off peak and peak power supplies to storage heater

Storage heaters usually provide two power circuits, one for on-peak and one for off-peak electricity, and two power switches, which are switched off during the summer when heat is not required. During other months the off-peak switch can be left on at all times, with the on-peak switch being used when insufficient energy has been stored during off-peak times. The amount of heat that is stored can be altered using the controls on the storage heater unit. Normally the on-peak will have a fuse as it is part of another circuit. The off-peak will just be a switch as it has a dedicated circuit.

## Basic controls


Input and Output switches on a basic storage heater

Basic storage heaters have an input switch, and an output switch, called *heat boost* on some models.

The position of the input switch should be changed to reflect how cold the next day is predicted to be. The input switch is normally thermostatic, controlling the maximum temperature that the bricks will be heated to overnight. The exact setting needed will depend on the size of the storage heater, the desired room temperature, the number of hours that this needs to be maintained, and the room's rate of heat loss under a given set of circumstances. Some experimenting may be needed to find the relationship between forecast outside temperature and best input setting for a particular room. Most storage heater users follow simpler guidelines; for example, in the middle of winter, it is often appropriate to turn the input switch to its maximum setting. There is no need to touch the input switch on a daily basis if the same sort of weather prevails for weeks at a time. There is no need to touch the input switch during the day, as storage heaters only use electricity at night.

The output switch does require attention throughout the day. Before going to bed, the operator should switch the output to its minimum setting. This keeps as much heat in the bricks as possible. Enough will leak out into the room to make it warm in the morning. Only in exceptionally cold circumstances will the operator require output overnight. The operator may wish to slowly increase the output switch during the day to try and maintain the temperature in the house. Increasing the output will allow the heat to convect out of the heater. If the house is empty during the day because the operator is at work, the output should be left at a minimum all day and then switched up when returning from work in order to let more heat escape into the house.

### Thermostatic controls


Thermostatic controls on a more advanced storage heater

A thermostatic storage heater will automatically regulate the temperature in a room throughout the day. However, the operator may wish to switch the thermostatic switch to the minimum setting overnight to lower the room temperature. If the room is empty during the day, it is better to keep the thermostat at the mimimum setting and then increase the setting when the room is occupied in the evening. Some thermostatic heaters also make use of on-peak electricity when there is not enough stored heat to maintain the requested temperature; the user may wish to be aware of this and lower the settings.

## *Environmental aspects*

In common with other forms of direct electric heating, storage heaters are not normally considered environmentally friendly because most electricity is generated remotely using fossil fuels, with up to two-thirds of energy in the fuel lost at the power station and in transmission losses. In Sweden the use of direct electric heating has been restricted since the 1980s for this reason, and there are plans to phase it out entirely - while Denmark has banned the installation of electric space heating in new buildings for similar reasons. In the UK, a storage heater earns a "Poor" rating for Environmental Performance on an Energy Performance Certificate. Many progressive countries are developing their electricity generating system, principally, to incorporate 'greener', more sustainable and renewable energy sources.

In some countries, the current design of the electrical generating system may result in a surplus of electricity from base load power stations during off-peak periods, and storage heaters may then be able to make use of this surplus to increase the net efficiency of the system as a whole. However, future changes in supply and demand - for example as a result of energy conservation measures or a more responsive generating system - may then reverse this situation, with storage heaters preventing a reduction in the national base load. Other future technologies may incorporate electricity-supply-sensitive electronics to sense when there is a change in supply and demand. Thereby, they ensure that these loads only use off-peak electricity. Further advances in supply technology could provide for a more bespoke 'supply and demand' tariff system to make these sensing technologies a more viable financial prospect.

Compared to other forms of electric heating, storage heaters are cheaper to run and they impose lower peak loads. The highest peak loads come from instantaneous electric heating, such as immersion water heaters, which create heavy loads for short durations, although instantaneous water heaters may use less electricity overall. High-efficiency ground source heat pumps are able to use up to 66% less electricity than storage heaters in heating by recovering heat from the ground, and are regarded as preferable even though they use electricity throughout the day. These are not to be confused with air conditioning (A/C) heat pumps which are now considered to be an environmental liability in some, (in particular hotter climate), countries.

Where alternatives to electricity exist, hot-water central heating systems can use water heated in or close to the building using high-efficiency condensing boilers, biofuels, heat pumps or district heating. Ideally wet underfloor heating should be used. This can be converted in the future to use developing technologies such as solar panels, so also providing future-proofing. In the case of new buildings, low-energy buildings such as those built to the Passive House standard can eliminate the need for conventional space heating systems.

## Chapter 9

# Underfloor Heating

**Underfloor heating and cooling** is a form of central heating and cooling which achieves indoor climate control for thermal comfort using conduction, radiation and convection. The terms *radiant heating* and *radiant cooling* are commonly used to describe this approach because radiation is responsible for a significant portion of the resulting thermal comfort but this usage is technically correct only when radiation composes more than 50% of the heat exchanged between the floor and the rest of the space.

### *History*

Underfloor heating has a long history extending back into the Neoglacial and Neolithic periods. Archeological digs in Asia and the Aleutian islands of Alaska reveal how the inhabitants drafted smoke from fires through stone covered trenches which were excavated in the floors of their subterranean dwellings. The hot smoke heated the floor stones which then radiated into the living spaces. These early forms have evolved into modern systems using fluid filled pipes or electrical cables and mats. Below is a chronological overview of under floor heating from around the world.

| Time period, c. BC | Description |
|---|---|
| 10,000 | From China, the word kang, can be traced back to the 11th century B.C. and originally meant, “to dry” before it became known as a heated bed. |
| 5,000 | Evidence of “baked floors” are found foreshadowing early forms of kang and dikang “heated floor” later ondol meaning “warm stone” in China and Korea respectively. |
| 3,000 | Korean fire hearth, was used both as kitchen range and heating stove. |
| 1,000 | Ondol type system used in the Aleutian islands, Alaska and in Unggi, Hamgyeongbuk-do (present-day North Korea). |

| | |
|---|---|
| 1,000 | More than two hearths were used in one dwelling; one hearth located at the center was used for heating, the others at the perimeter was used for cooking throughout the year. This perimeter hearth is the initial form of the budumak (meaning kitchen range), which composes combustion section of the traditional ondol in Korea. |
| 500 | Greeks and later Romans scale up the use of conditioned surfaces (floors and walls) with the hypocausts. |
| 200 | Central hearth developed into gudeul (meaning heat releasing section of ondol) and perimeter hearth for cooking became more developed and budumak was almost established in Korea. |
| 50 | China, Korea and Roman Empire use kang, dikang/ondol and hypocaust respectively. |

| **Time period, c. AD** | **Description** |
|---|---|
| 500 | Asia continues to use conditioned surfaces but the application is lost in Europe where it is replaced by the open fire or rudimentary forms of the modern fireplace. Anecdotal literary reference to radiant cooling system in the Middle East using snow packed wall cavities. |
| 700 | More sophisticated and developed gudeul was found in some palaces and living quarters of upper class people in Korea. Countries in the Mediterranean Basin (Iraq, Algeria, Turkey, Afghanistan et al.) use various forms of hypocaust type heating in public baths and homes (ref.: tabakhana, atishkhana, sandali) but also use heat from cooking (see:tandoor, also tanur) to heat the floors. |
| 1000 | Ondol continues to evolve in Asia. The most advanced true ondol system was established. The fire furnace was moved outside and the room was entirely floored with ondol in Korea. Europe uses various forms of the fireplace with the evolution of drafting combustion products with chimneys. |
| 1400 | Hypocaust type systems used to heat Turkish Baths of the Ottoman Empire. |
| 1500 | Attention to comfort and architecture in Europe evolves; China and Korea continue to apply floor heating with wide scale adoption. |
| 1600 | In France, heated flues in floors and walls are used in greenhouses. |
| 1700 | Benjamin Franklin studies the French and Asian cultures and makes note of their respective heating system leading to the development of the Franklin stove. Steam based radiant pipes are used in France. Hypocaust type system used to heat public bath (Hammam) in the citadel town of Erbil located in modern day Iraq. |
| 1800 | Beginnings of the European evolution of the modern water heater/boiler and water based piping systems including studies in thermal conductivities and specific heat of materials and emissivity/reflectivity of surfaces (Watt/Leslie/Rumford). Reference to the use of small bore pipes used in the John Soane house and museum. |

| | |
|---|---|
| 1864 | Ondol type system used at Civil War hospital sites in America. Reichstag building in Germany uses the thermal mass of the building for cooling and heating. |
| 1899 | The earliest beginnings of polyethylene-based pipes occur when German scientist, Hans von Pechmann, discovered a waxy residue at the bottom of a test tube, colleagues Eugen Bamberger and Friedrich Tschirner called it polymethylene but it was discarded as having no commercial use at the time. |
| 1904 | Liverpool Cathedral in England is heated with system based on the hypocaust principles. |
| 1905 | Frank Lloyd Wright makes first trip to Japan, later incorporates various early forms of radiant heating in his projects. |
| 1907 | England, Prof. Barker granted Patent No. 28477 for panel warming using small pipes. Patents later sold to the Crittal Company who appointed representatives across Europe. A.M. Byers of America promotes radiant heating using small bore water pipes. Asia continues to use traditional ondol and kang—wood is used as the fuel, combustion gases sent under floor. |
| 1930 | Oscar Faber in England uses water pipes used to radiant heat and cool several large buildings. |
| 1933 | Explosion at England's Imperial Chemical Industries (ICI) laboratory during a high pressure experiment with ethylene gas results in a wax like substance—later to become polyethylene and the re-beginnings of PEX pipe. |
| 1937 | Frank Lloyd Wright designs the radiant heated Herbert Jacobs house, the first Usonian home. |
| 1939 | First small scale polyethylene plant built in America. |
| 1945 | American developer William Levitt builds large scale developments for returning GI's. Water based (copper pipe) radiant heating used throughout thousands of homes. Poor building envelopes on all continents require excessive surface temperatures leading in some cases to health problems. Thermal comfort and health science research (using hot plates, thermal manikins and comfort laboratories) in Europe and America later establishes lower surface temperature limits and development of comfort standards. |
| 1950 | Korean War wipes out wood supplies for ondol, population forced to use coal. Developer Joseph Eichler in California begins the construction of thousands of radiant heated homes. |
| 1951 | Dr. J. Bjorksten of Bjorksten Research Laboratories in Madison, WI, announces first results of what is believed to be the first instance of testing three types of plastic tubing for radiant floor heating in America. Polyethylene, vinyl chloride copolymer, and vinylidene chloride were tested over three winters. |
| 1953 | The first Canadian polyethylene plant is built near Edmonton, Ab. |

| | |
|---|---|
| 1960 | NRC researcher from Canada installs underfloor heating in his home and later remarks, "Decades later it would be identified as a passive solar house. It incorporated innovative features such as the radiant heating system supplied with hot water from an automatically stoked anthracite furnace." |
| 1965 | Thomas Engel patents method for stabilizing polyethylene by cross linking molecules using peroxide (PEx-A) and in 1967 sells license options to a number of pipe producers. |
| 1970 | Evolution of Korean architecture leads to multistory housings, flue gases from coal based ondol results in many deaths leading to the removal of the home based flue gas system to a central water based heating plants. Oxygen permeation becomes corrosion issue in Europe leading to the development of barriered pipe and oxygen permeation standards. |
| 1980 | The first standards for floor heating are developed in Europe. Water-based ondol system is applied to almost all of residential buildings in Korea. |
| 1985 | Floor heating becomes a traditional heating systems in residential buildings in Middle Europe and Nordic countries and increasing applications in non-residential buildings. |
| 1995 | The application of floor cooling and thermal active building systems (TABS) in residential and commercial buildings are widely introduced into the market. |
| 2000 | The use of embedded radiant cooling systems in middle of Europe becomes a standard system with many parts of the world applying radiant based HVAC systems as means of using low temperatures for heating and high temperatures for cooling. |
| 2010 | Radiant conditioned Pearl River Tower in Guangzhou, China, topped out at 71-stories. |

## *Description*

Modern underfloor heating systems use either electrical resistance elements ("electric systems") or fluid flowing in pipes ("hydronic systems") to heat the floor. Either type can be installed as the primary, whole-building heating system or as localized floor heating for thermal comfort. Electrical resistance can only be used for heating so when space cooling is also required, hydronic systems are used. Other applications for which either electric or hydronic systems are suited include snow/ice melting for walks, driveways and landing pads, turf conditioning of football and soccer fields and frost prevention in freezers and skating rinks.

Electric heating elements or hydronic piping can be cast in a concrete floor slab ("poured floor system" or "wet system"). They can also be placed under the floor covering ("dry system") or attached directly to a wood sub floor ("sub floor system" or "dry system").

Some commercial buildings are designed to take advantage of thermal mass which is heated or cooled during off peak hours when utility rates are lower. With the heating/cooling system turned off during the day, the concrete mass and room temperature drift up or down within the desired comfort range. Such systems are known as thermally activated building systems or TABS.

## Hydronic systems

Hydronic systems use water or a mix of water and anti-freeze such as propylene glycol as the heat transfer fluid in a "closed loop" that is recirculated between the floor and the boiler.

Various types of pipes are available specifically for hydronic underfloor heating and cooling systems and are generally made from polyethylene including PEX, PEX-Al-PEX and PERT. Older materials such as Polybutylene (PB) and copper or steel pipe are still used in some locales or for specialized applications.

Hydronic systems require skilled designers and tradespeople familiar with boilers, circulators, controls, fluid pressures and temperature. The use of modern factory assembled sub-stations, used primarily in district heating and cooling, can greatly simplify design requirements and reduce the installation and commissioning time of hydronic systems.

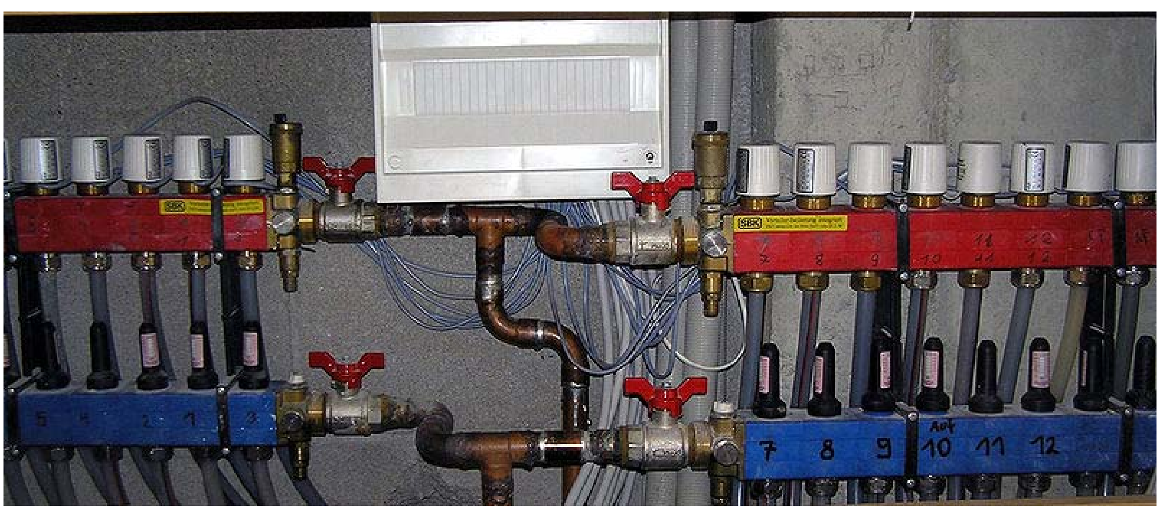
Hydronic systems can use a single source or combination of energy sources to help manage energy costs. Hydronic system **energy source** options are:

- Boilers (heaters) including Combined heat and power plants] heated by:
  - Natural gas, coal, oil or waste oil
  - Electricity
  - Solar thermal
  - wood or other biomass
  - bio-fuels
- Heat pumps and chillers powered by:
  - Electricity
  - Natural gas

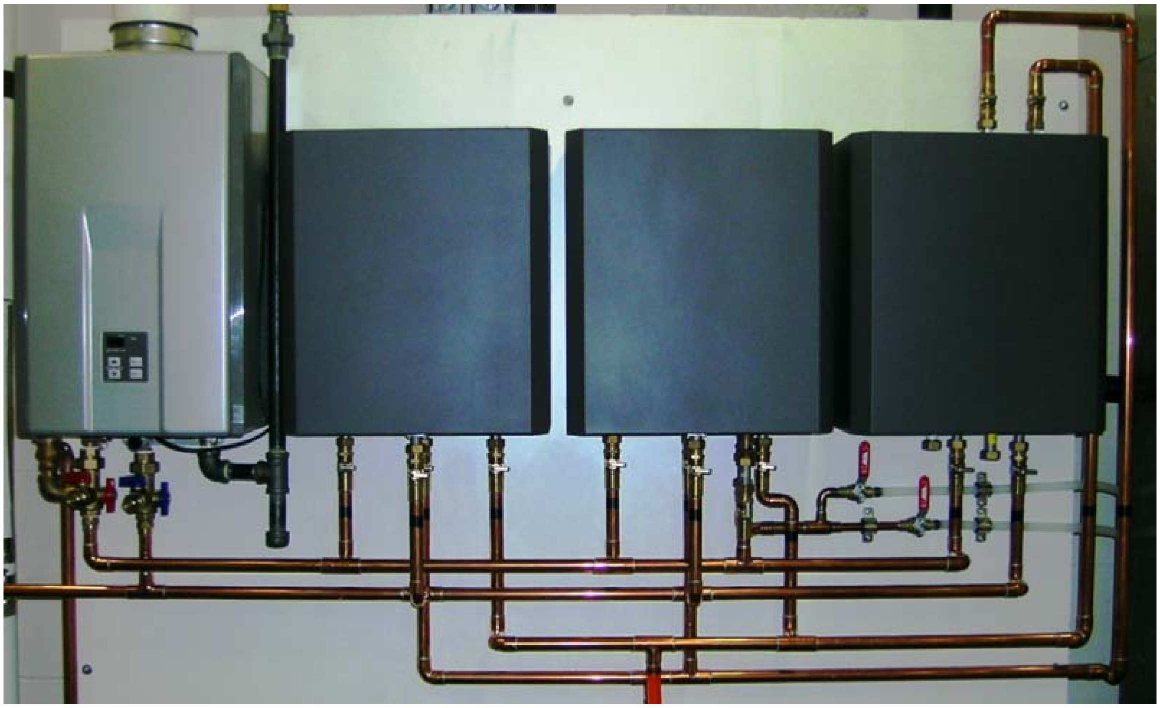
Underfloor heating pipes, before they are covered by the screed

Underfloor heating pipes, before they are covered by a concrete garage slab


Radiant tubing layout, Project: BCIT Aerospace Hangar, Vancouver, British Columbia, Canada




Manifold assembly



Modern factory assembled hydronic control appliances for underfloor heating and cooling, shown with covers on.

Modern factory assembled hydronic control appliances for underfloor heating and cooling, shown with covers off.

### Electric systems

Electric floor heating installation, cement being applied

Electric systems are used only for heating and employ non-corrosive, flexible heating elements including cables, pre-formed cable mats, bronze mesh, and carbon films. Due to their low profile they can be installed in a thermal mass or directly under floor finishes. Electric systems can also take advantage of time-of-use electricity metering and are frequently used as carpet heaters, portable under area rug heaters, under laminate floor heaters, under tile heating, under wood floor heating, and floor warming systems, including under shower floor and seat heating. Large electric systems also require skilled designers and tradespeople but this is less so for small floor warming systems. Electric systems use fewer components and are simpler to install and commission than hydronic systems. Some electric systems use line voltage technology while others use low voltage technology. Power consumption of an electric system is not based on voltage but rather wattage output produced by the heating element.

## *Features*

### Thermal comfort quality

As defined by ANSI/ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy, thermal comfort is, “that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation.” Relating specifically to underfloor heating, thermal comfort is influenced by floor surface temperature and associated elements such as radiant asymmetry, mean radiant temperature and operative temperature. Research by Nevins, Rohles, Gagge, P. Ole Fanger et al. show that humans at rest with clothing typical of light office and home wear, exchange over 50% of their sensible heat via radiation.

Underfloor heating influences the radiant exchange by thermally conditioning the interior surfaces with low temperature long wave radiation. The heating of the surfaces suppresses body heat loss resulting in a perception of heating comfort. This general sensation of comfort is further enhanced through conduction (feet on floor) and through convection by the surface's influence on air density. Underfloor cooling works by absorbing both short wave and long wave radiation resulting in cool interior surfaces. These cool surfaces encourage the loss of body heat resulting in a perception of cooling comfort. Localized discomfort due to cold and warm floors wearing normal foot wear and stocking feet is addressed in the ISO 7730 and ASHRAE 55 standards and ASHRAE Fundamentals Handbooks and can be corrected or regulated with floor heating and cooling systems.

## Indoor air quality

Underfloor heating can have a positive effect on the quality of indoor air by facilitating the choice of otherwise perceived cold flooring materials such as tile, slate, terrazzo and concrete. These masonry surfaces typically have very low VOC emissions (volatile organic compounds) in comparison to other flooring options. In conjunction with moisture control, floor heating also establishes temperature conditions that are less favorable in supporting mold, bacteria, viruses and dust mites. By removing the sensible heating load from the total HVAC (Heating, Ventilating, and Air Conditioning) load, ventilation, filtration and dehumidification of incoming air can be accomplished with dedicated outdoor air systems having less volumetric turnover to mitigate distribution of airborne contaminates. There is recognition from the medical community relating to the benefits of floor heating especially as it relates to allergens.

## Sustainability—energy

Under floor radiant systems are evaluated for sustainability through the principles of efficiency, entropy, exergy and efficacy. When combined with high performance buildings, under floor systems operate with low temperatures in heating and high temperatures in cooling in the ranges found typically in geothermal and solar thermal systems. When coupled with these non combustible, renewable energy sources the sustainability benefits include reduction or elimination of combustion and green house gases produced by boilers and power generation for heat pumps and chillers, as well as reduced demands for non renewables and greater inventories for future generations. This has been supported through simulation evaluations and though research funded by the U.S. Department of Energy, Canada Mortgage and Housing Corporation, Fraunhofer Institute as well as ASHRAE.

## Safety

Low temperature underfloor heating is embedded in the floor or placed under the floor covering. As such it occupies no wall space and creates no burn hazards, nor is it a hazard for physical injuries due to accidental contact leading to tripping and falling. This has been referenced as a positive feature in healthcare facilities including those serving elderly clients and those with dementia. Anecdotally, under similar environmental conditions, heated floors will speed evaporation of wetted floors (showering, cleaning, and spills). Additionally, underfloor heating with fluid filled pipes is useful in heating and cooling explosion proof environments where combustion and electrical equipment can be located remotely from the explosive environment.

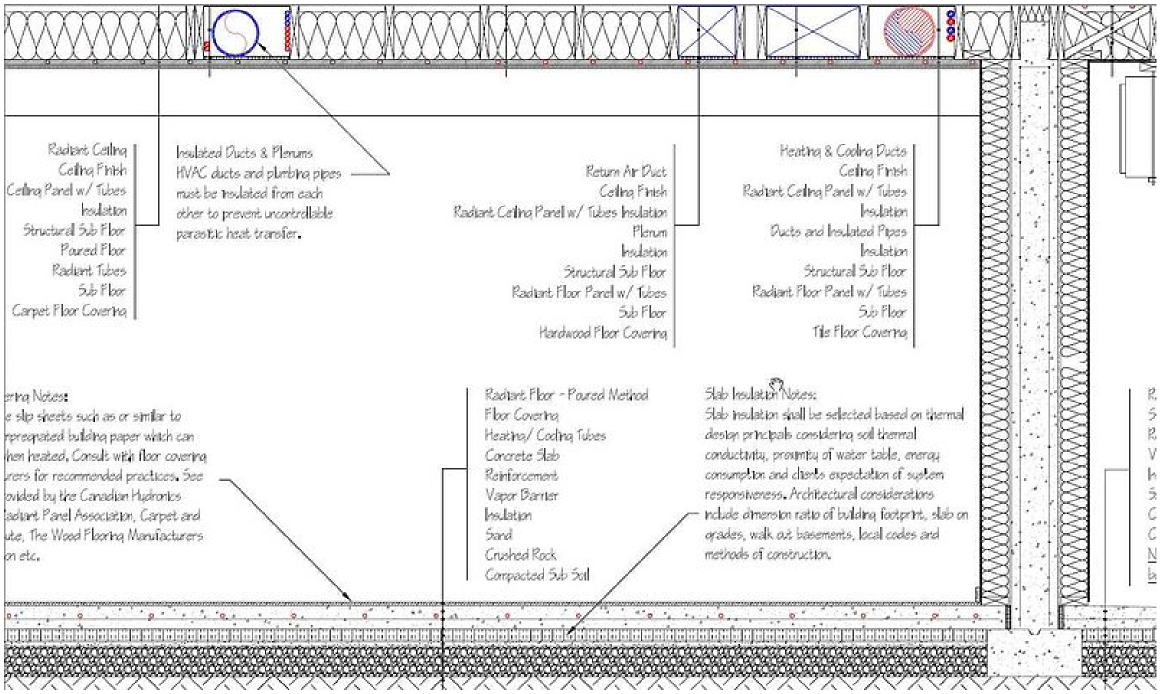
## Longevity, maintenance and repair

Equipment maintenance and repair is the same as for other water or electrical based HVAC systems except when pipes, cables or mats are embedded in the floor. Early trials (for example homes built by Levitt and Eichler, c. 1940-70's) experienced failures in embedded copper and steel piping systems as well as failures assigned by the courts to Shell, Goodyear and others for polybutylene and EPDM materials. There also have been a few publicized claims of failed electric heated gypsum panels from the mid 90's.

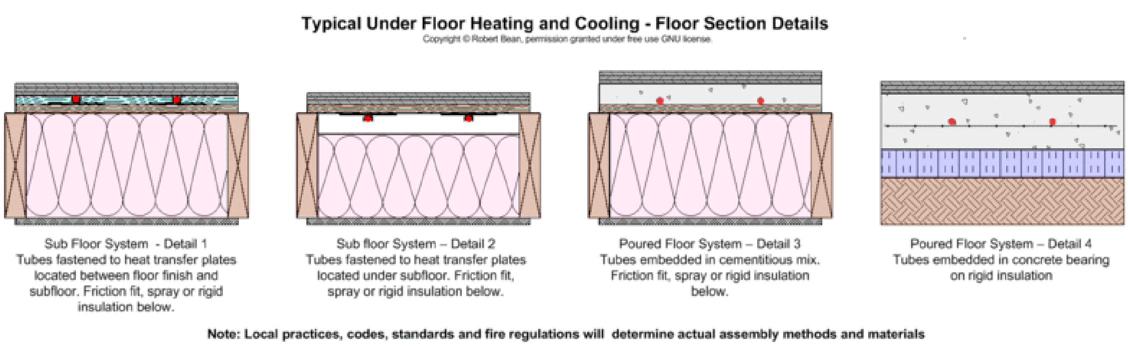
Failures associated with most installations are attributable to job site neglect, installation errors and product mishandling such as exposure to ultraviolet radiation. Pre-pour pressure tests required by concrete installation standards and good practice guidelines for the design, construction, operation and repair of radiant heating and cooling systems mitigate problems resulting from improper installation and operation.

Fluid based systems using Cross-linked polyethylene (PE-x) a product developed in the 1930s and its various derivatives such as PE-rt, have demonstrated reliable long term performance in harsh cold-climate applications such as bridge decks, aircraft hangar aprons and landing pads. Since the materials are produced from polyethylene and its bonds are cross-linked, it is highly resistant to corrosion or the temperature and pressure stresses associated with typical fluid based HVAC systems.

## *Typical installation details*




General considerations for placing radiant heating and cooling pipes in flooring assemblies where other HVAC and plumbing components may be present.




Typical under floor heating and cooling assemblies. Local practices, codes, standards, best practices and fire regulations will determine actual materials and methods.

## *Design and installation considerations*

The engineering of underfloor cooling and heating systems is governed by industry standards and guidelines.

### Technical design

The amount of heat exchanged from or to an underfloor system is based on the combined radiant and convective heat transfer coefficients.

- Radiant heat transfer is constant based on the Stefan–Boltzmann constant.
- Convective heat transfer changes over time depending on
    - the air's density and thus its buoyancy. Air buoyancy changes according to surface temperatures and
    - forced air movement due to fans and the motion of people and objects in the space.

Convective heat transfer with underfloor systems is much greater when the system is operating in a heating rather than cooling mode. Typically with underfloor heating the convective component is almost 50% of the total heat transfer and in underfloor cooling the convective component is less than 10%.

## Heat and moisture considerations

When heated and cooled pipes or heating cables share the same spaces as other building components, parasitic heat transfer can occur between refrigeration appliances, cold storage areas, domestic cold water lines, air conditioning and ventilation ducts. To control this, the pipes, cables and other building components must all be well insulated.

With underfloor cooling, condensation may collect on the surface of the floor. To prevent this, air humidity is kept low, below 50%, and floor temperatures are maintained above the dew point, 66°F(19°C).

## Building systems and materials

- Heat losses to below grade

    - The thermal conductivity of soil will influence the conductive heat transfer between the ground and heated or cooled slab-on-grade floors.
    - Soils with moisture contents greater than 20% can be as much as 15 times more conductive than soils with less than 4% moisture content.
    - Water tables and general soil conditions should be evaluated.
    - Suitable underslab insulation such as rigid extruded or expanded polystyrene is required by Model National Energy Codes.

- Heat losses at the exterior floor framing

    - The heated or cooled sub-floor increases the temperature difference between the outdoors and the conditioned floor.
    - The cavities created by the framing timbers such as headers, trimmers and cantilevered sections must then be insulated with rigid, batt or spray type insulations of suitable value based on climate and building techniques.

- Masonry and other hard flooring considerations

    - Concrete floors must accommodate shrinkage and expansion due to curing and changes in temperature.
    - Curing times and temperatures for poured floors (concrete, lightweight toppings)must follow industry standards.
    - Control and expansion joints and crack suppression techniques are required for all masonry type floors including;

    - Tile
    - Slate
    - Terrazzo
    - Stone
    - Marble
    - Concrete,stained, textured and stamped

- Wood flooring

    - The dimensional stability of wood is based primary on moisture content, however, other factors can mitigate the changes to wood as it is heated or cooled, including;

    - Wood species
    - Milling techniques, quarter sawn or plane sawn
    - Acclimation period
    - Relative humidity within the space

- Piping standards

## Control system

Underfloor heating and cooling systems can have several control points including the management of:

- Fluid temperatures in the heating and cooling plant (e.g. boilers, chillers, heat pumps).

    - Influences the efficiency

- Fluid temperatures in distribution network between the plant and the radiant manifolds.

    - Influences the capital and operating costs

- Fluid temperatures in the PE-x piping systems, which is based on;

    - Heating and cooling demands
    - Tube spacing

- Upward and downward losses
- Flooring characteristics

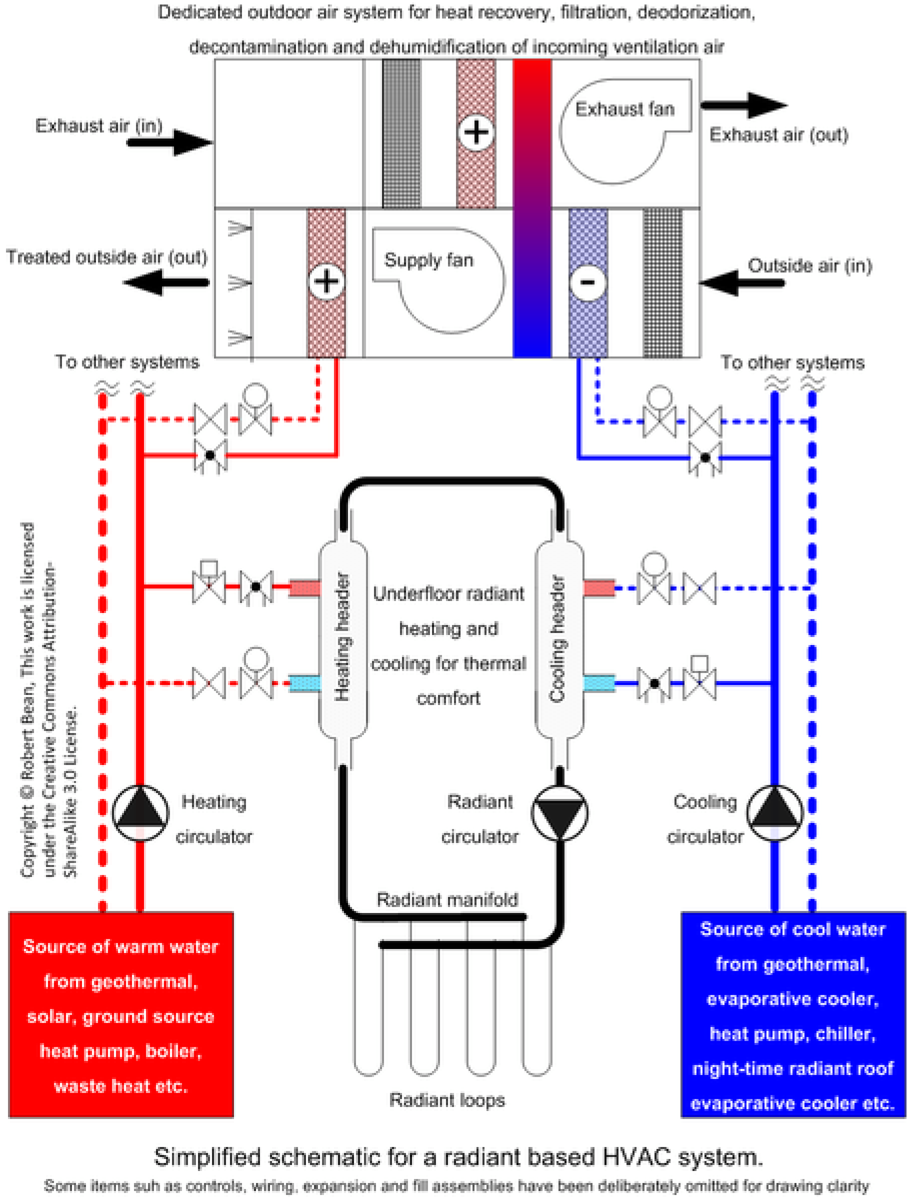
- Operative temperature

    - Incorporates the mean radiant and dry bulb

- Surface temperatures for;

    - Comfort
    - Health and safety
    - Material integrity
    - Dew point (for floor cooling).

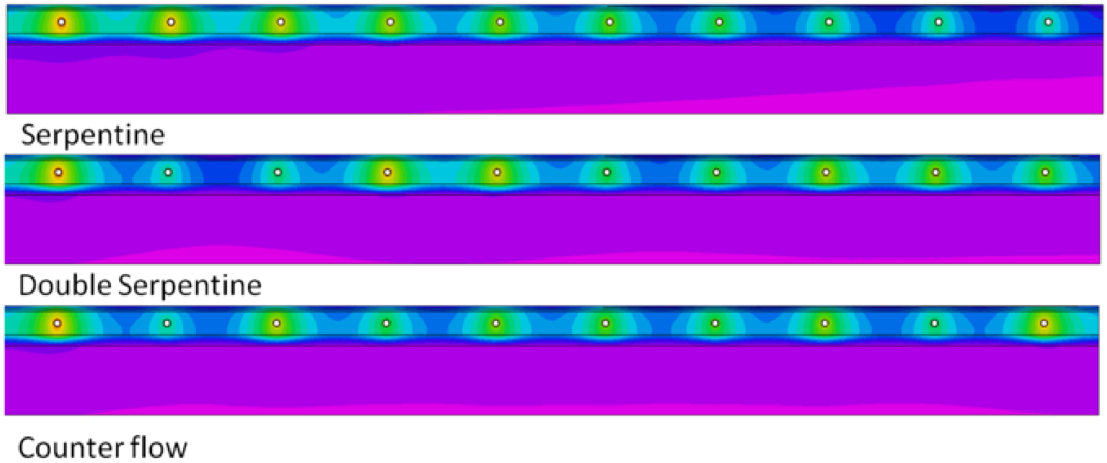
### *Sample - mechanical schematic*

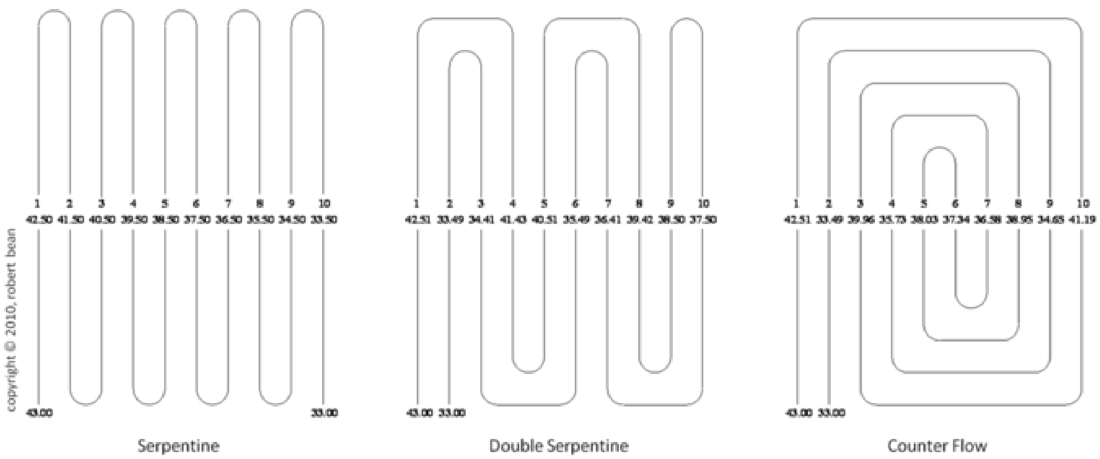



Example of a radiant based HVAC schematic.

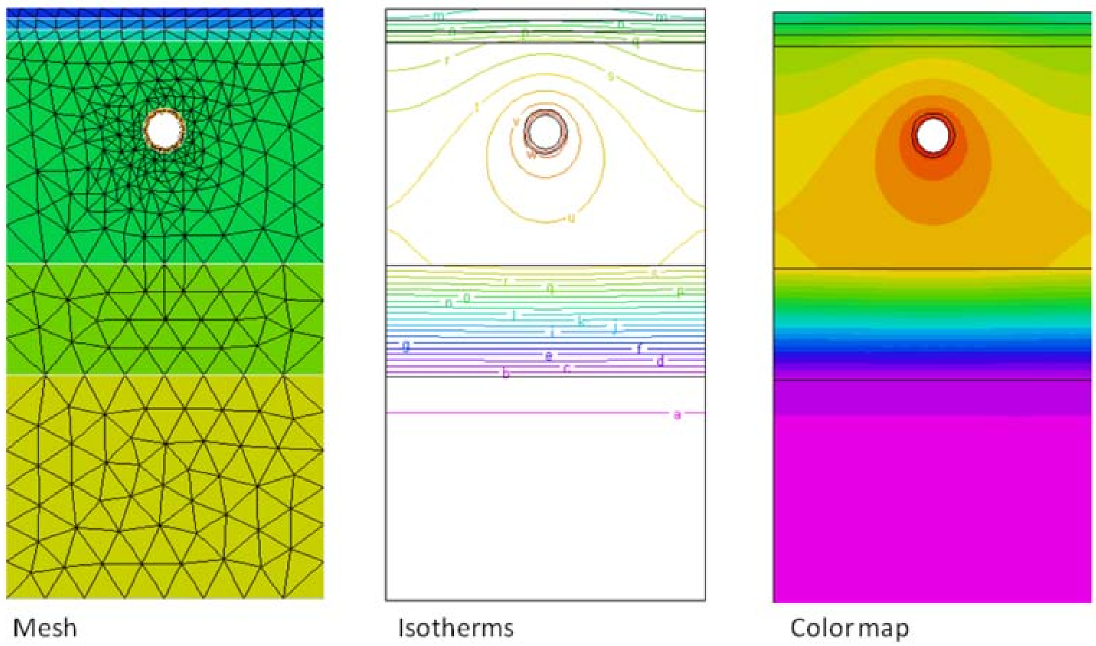
Illustrated is a simplified mechanical schematic of an underfloor heating and cooling system for thermal comfort quality with a separate air handling system for indoor air quality. In high performance residential homes of moderate size (e.g. under 3000 ft$^2$ (278 m$^2$) total conditioned floor area), this system using manufactured hydronic control appliances would take up about the same space as a three or four piece bathroom.

### *Modeling piping patterns with finite element analysis*



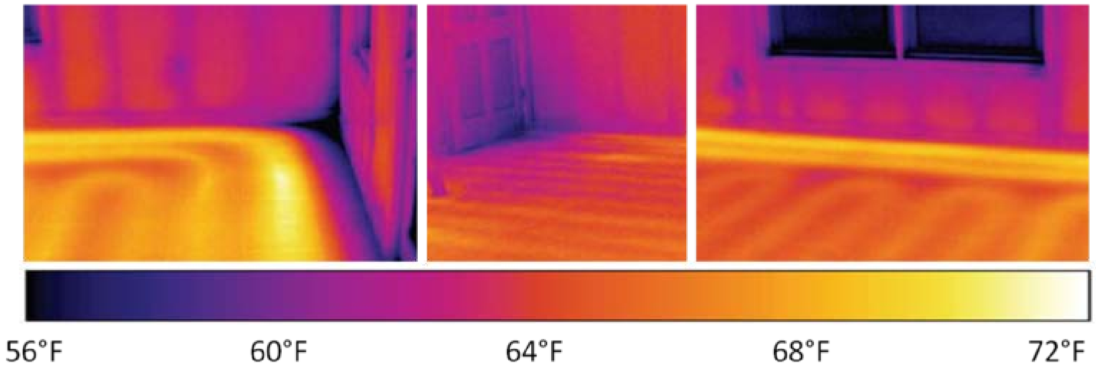

Thermal diffusions and surface temperature quality (efficacy) of various piping layouts




Typical FEA output screen shots of wire mesh, thermal isotherms and color-coded mapping

Modeling radiant piping (also tube or loop) patterns with finite element analysis(FEA) predicts the thermal diffusions and surface temperature quality or efficacy of various loop layouts. The performance of the model (left image above) and image to the right are useful to gain an understanding in relationships between flooring resistances, conductivities of surrounding mass, tube spacing's, depths and fluid temperatures. As with all FEA simulations, they depict a snap shot in time for a specific assembly and may not be representative of all floor assemblies nor for system that have been operative for considerable time in a steady state condition. The practical application of FEA for the engineer is being able to assess each design for fluid temperature, back losses and surface temperature quality. Through several iterations it is possible to optimize the design for the lowest fluid temperature in heating and the highest fluid temperature in cooling which enables combustion and compression equipment to achieve its maximum rated efficiency performance.

### *Using thermography to observe underfloor systems*






Thermographic images of a room heated with low temperature radiant heating shortly after starting up the system.

Thermography is a useful tool to see the actual thermal efficacy of an underfloor system from its start up (as shown) to its operating conditions. In a startup it is easy to identify the tube location but less so as the system moves into a steady state condition. It is important to interpret thermographic images correctly. As is the case with finite element analysis (FEA), what is seen, reflects the conditions at the time of the image and may not represent the steady conditions. For example, the surfaces viewed in the images shown, may appear 'hot', but in reality are actually below the nominal temperature of the skin and core temperatures of the human body and the ability to 'see' the pipes does not equate to 'feel' the pipes. Thermography can also point out flaws in the building enclosures (left image, corner intersection detail), thermal bridging (right image, studs) and the heat losses associated with exterior doors (center image).

### *Economics*

There is a wide range of pricing for underfloor systems based on regional differences, application and project complexity. It is widely adopted in the Nordic, Asian and European communities consequently the market is more mature and systems relatively more affordable than North America where market share for fluid based systems remains between 3% to 7% of HVAC systems (ref. Statistics Canada and U.S. Census Bureau).

In energy efficiency buildings such as Passive House, R-2000 or Net Zero Energy, simple thermostatic radiator valves can be installed along with a single compact circulator and small condensing heater controlled without or with basic hot water reset control. Economical electric resistant based systems also are useful in small zones such as bathrooms and kitchens, but also for entire buildings where heating loads are very low and preferably where photovoltaic's, wind or hydro is the generating source of electricity. Larger structures will need more sophisticated systems to deal with cooling and heating needs, and often requiring building management control systems to regulate the energy use and control the overall indoor environment.

Low temperature radiant heating and high temperature radiant cooling systems lend themselves well to district energy systems (community based systems) due to the temperature differentials between the plant and the buildings which allow small diameter insulated distribution networks and low pumping power requirements. The low return temperatures in heating and high return temperatures in cooling enable the district energy plant to achieve maximum efficiency. The principles behind district energy with underfloor systems can also be applied to stand alone multi story buildings with the same benefits. Additionally, underfloor radiant systems are ideally suited to renewable energy sources including geothermal and solar thermal systems or any system where waste heat is recoverable.

In the global drive for sustainability, long term economics supports the need to eliminate where possible, compression for cooling and combustion for heating. It will then be necessary to use low quality heat sources for which radiant underfloor heating and cooling is well suited.

## System efficiency

System efficiency and energy use analysis takes into account building enclosure performance, efficiency of the heating and cooling plant, system controls and the conductivities, surface characteristics, tube/element spacing and depth of the radiant panel, operating fluid temperatures and wire to water efficiency of the circulators. The efficiency in electric systems is analyzed by similar processes and includes the efficiency of electricity generation.

Though the efficiency of radiant systems is under constant debate with no shortage of anecdotal claims and scientific papers presenting both sides, the low return fluid temperatures in heating and high return fluid temperatures in cooling enable condensing boilers, chillers and heat pumps to operate at or near their maximum engineered performance. The greater efficiency of 'wire to water' versus 'wire to air' flow due to water's significantly greater heat capacity favors fluid based systems over air based systems. Both field application and simulation research have demonstrated significant electrical energy savings with radiant cooling and dedicated outdoor air systems based in part on the previous noted principles.

In Passive Houses, R-2000 homes or Net Zero Energy buildings the low temperatures of radiant heating and cooling systems present significant opportunities to exploit exergy.

## Efficiency considerations for flooring surface materials

System efficiency is also affected by the floor covering serving as the radiational boundary layer between the floor mass and occupants and other contents of the conditioned space. For example, carpeting has a greater resistance or lower conductance than tile. Thus carpeted floors need to operate at higher internal temperatures than tile which can create lower efficiencies for boilers and heat pumps. However, when the floor covering is known at the time the system is installed then the internal floor temperature required for a given covering can be achieved through proper tube spacing without sacrificing plant efficiency (though the higher internal floor temperatures may result in increased heat loss from the non-room surfaces of the floor).

The emissivity, reflectivity and absorptivity of a floor surface are critical determinants of its heat exchange with the occupants and room. Unpolished flooring surface materials and treatments have very high emissivity's (0.85 to 0.95) and therefore make good heat radiators.

With underfloor heating and cooling ("reversible floors") flooring surfaces with high absorbance and emissivity and low reflectivity are most desirable.

### *Global examples of large modern buildings using radiant heating and cooling*

- Manitoba Hydro Place, Canada
- California Academy of Science, United States
- Copenhagen Opera House, Denmark
- Post Tower, Germany
- Ewha Womans University, Korea
- NREL Research Support Facility, United States
- Suvarnabhumi International Airport, Bangkok
- la Defense Office, Netherlands
- Pearl River Tower, China
- 41 Cooper Square, United States
- Hearst Tower (New York City), United States
- Akron Art Museum, United States
- BMW Welt, Germany
- David Brower Center, United States

## Chapter 10

# Home Automation

**Home automation** (also called **domotics**) is the residential extension of "building automation". It is automation of the home, housework or household activity. Home automation may include centralized control of lighting, HVAC (heating, ventilation and air conditioning), appliances, and other systems, to provide improved convenience, comfort, energy efficiency and security. Home automation for the elderly and disabled can provide increased quality of life for persons who might otherwise require caregivers or institutional care.

A home automation system integrates electrical devices in a house with each other. The techniques employed in home automation include those in building automation as well as the control of domestic activities, such as home entertainment systems, houseplant and yard watering, pet feeding, changing the ambiance "scenes" for different events (such as dinners or parties), and the use of domestic robots. Devices may be connected through a computer network to allow control by a personal computer, and may allow remote access from the internet.

Typically, a new home is outfitted for home automation during construction, due to the accessibility of the walls, outlets, and storage rooms, and the ability to make design changes specifically to accommodate certain technologies. Wireless systems are commonly installed when outfitting a pre-existing house, as they reduce wiring changes. These communicate through the existing power wiring, radio, or infrared signals with a central controller. Network sockets may be installed in every room like AC power receptacles.

Although automated *homes of the future* have been staple exhibits for World's Fairs and popular backgrounds in science fiction, complexity, competition between vendors, multiple incompatible standards  and the resulting expense have limited the penetration of home automation to homes of the wealthy or ambitious hobbyists.

A typical domestic patch panel.

### *Overview and benefits*

In modern construction in industrialized nations, homes have been wired for electrical power, telephones, TV outlets (cable or antenna), and a doorbell.

Many household tasks were automated by the development of special appliances. For instance, automatic washing machines were developed to reduce the manual labor of cleaning clothes, and water heaters reduced the labor necessary for bathing.

Other traditional household tasks, like food preservation and preparation have been automated in large extent by moving them into factory settings, with the development of pre-made, pre-packaged foods, and in some countries, such as the United States, increased reliance on commercial food preparation services, such as fast food restaurants. Volume and the factory setting allows forms of automation that would be impractical or too costly in a home setting. Standardized foods enable possible further automation of handling the food within the home.

The use of gaseous or liquid fuels, and later the use of electricity enabled increased automation in heating, reducing the labor necessary to fuel heaters and stoves. Development of thermostats allowed more automated control of heating, and later cooling.

A remote control for moving vessels and vehicles was first patented by Nikola Tesla in 1898.

World's Fairs in Chicago (1934), New York (1939) and (1964–65) depicted electrified and automated homes. In 1966 Jim Sutherland, an engineer working for Westinghouse Electric, developed a home automation system called "ECHO IV"; this was a private project and never commercialized.

With the invention of the microcontroller, the cost of electronic control fell rapidly. Remote and intelligent control technologies were adopted by the building services industry and appliance manufacturers worldwide, as they offer the end user easily accessible and/or greater control of their products.

As the number of controllable appliances in the home rises, the ability of these devices to interconnect and communicate with each other digitally becomes a useful and desirable feature. The consolidation of control or monitoring signals from appliances, fittings or basic services is an aim of home automation.

In simple installations this may be as straightforward as turning on the lights when a person enters the room. In advanced installations, rooms can sense not only the presence of a person inside but know who that person is and perhaps set appropriate lighting, temperature, music levels or television channels, taking into account the day of the week, the time of day, and other factors.

Other automated tasks may include setting the air conditioning to an energy saving setting when the house is unoccupied, and restoring the normal setting when an occupant is about to return. More sophisticated systems can maintain an inventory of products, recording their usage through bar codes, or an RFID tag, and prepare a shopping list or even automatically order replacements.

Home automation can also provide a remote interface to home appliances or the automation system itself, via telephone line, wireless transmission or the internet, to provide control and monitoring via a smart phone or web browser.

An example of a remote monitoring in home automation could be when a smoke detector detects a fire or smoke condition, then all lights in the house will blink to alert any occupants of the house to the possible fire. If the house is equipped with a home theatre, a home automation system can shut down all audio and video components to avoid distractions, or make an audible announcement. The system could also call the home owner on their mobile phone to alert them, or call the fire department or alarm monitoring company.

## *System*

The elements of a domotics system are:

- hardware controllers or software controllers
- sensors
- actuators

A centralized controller can be used, or multiple intelligent devices can be distributed around the home.

### Interconnection

By wire:

1. optical fiber
2. cable (coaxial and twisted pair) , including:

   xDSL

3. powerline, including:

   X10
   Universal powerline bus (UPB)
   PLCBUS

Wireless:

1. radio frequency, including:

   Wi-Fi
   GPRS and UMTS
   Bluetooth
   DECT
   ZigBee
   Z-Wave
   X-Comfort
   ONE-NET

EnOcean

2. infrared, including:

Consumer IR

Both Wireless and Wire

1. INSTEON

## Classifications of domestic network technologies

- Device interconnection:
  - Bluetooth
  - IEEE 1394 interface (FireWire)
  - IrDA
  - Universal Serial Bus (USB)
  - ZigBee
- Control and automation nets:
  - SCS BUS with OpenWebNet
  - C-Bus (protocol)
  - CEBus
  - EnOcean
  - EHS
  - INSTEON
  - KNX (European Installation Bus)
  - LonWorks
  - ONE-NET
  - Universal Powerline Bus
  - X10
  - ZigBee
  - Z-Wave
- Data nets:
  - Ethernet
  - Homeplug
  - HomePNA
  - WiFi

There have been many attempts to standardise the forms of hardware, electronic and communication interfaces needed to construct a home automation system. Some standards use additional communication and control wiring, some embed signals in the existing power circuit of the house, some use radio frequency (RF) signals, and some use a combination of several methods. Control wiring is hardest to retrofit into an existing house. Some appliances include USB that is used to control it and connect it to a domotics network. Bridges translate information from one standard to another, *e.g.*, from X10 to European Installation Bus.

## Centralising control

Besides the upcoming standardisation of home automation hardware, there is also the issue of the control software. In older systems (and some contemporary ones), the control of each home automation system needed to be done separately, and there was thus no central control system. This sometimes led to a great amount of remote controls, one being needed to control each individual part of the system. However, with the new generation of home automation systems, central control can be foreseen. Software such as Fast Track Team Home Personality Software Greeter 1.0 (aka "Cleopatra"),, e-Home Automation, ... allows the control to happen from a single computer or television screen, and/or even from a smart phone (e.g. iPhone).

# *Tasks*

## HVAC

Heating, Ventilation and Air Conditioning (HVAC) solutions include temperature and humidity control. This is generally one of the most important aspects to a homeowner. An Internet-controlled thermostat, for example, can both save money and help the environment, by allowing the homeowner to control the building's heating and air conditioning systems remotely.

## Lighting

Lighting control systems can be used to control household electric lights.

- Extinguish all the lights of the house
- Replace manual switching with Automation of on and off signals for any or all lights
- Regulation of electric illumination levels according to the level of ambient light available
- Change the ambient colour of lighting via control of LEDs or electronic dimmers

Natural lighting control involves controlling window shades, LCD shades, draperies and awnings.

## Audio and video

This category includes audio and video switching and distribution. Multiple audio or video sources can be selected and distributed to one or more rooms.

## Security

Control and integration of security systems.

With Home Automation, the consumer can select and watch cameras live from an Internet source to their home or business. Security cameras can be controlled, allowing the user to observe activity around a house or business right from a Monitor or touch panel. Security systems can include motion sensors that will detect any kind of unauthorized movement and notify the user through the security system or via cell phone.

This category also includes control and distribution of security cameras.

- Detection of possible intrusion
    - sensors of detection of movement
    - sensors of magnetic contact of door/window
    - sensors of glass breaking
    - sensors of pressure changes
- Simulation of presence.
- Detection of fire, gas leaks, water leaks
- Medical alert. Teleassistance.
- Precise and safe closing of blinds.

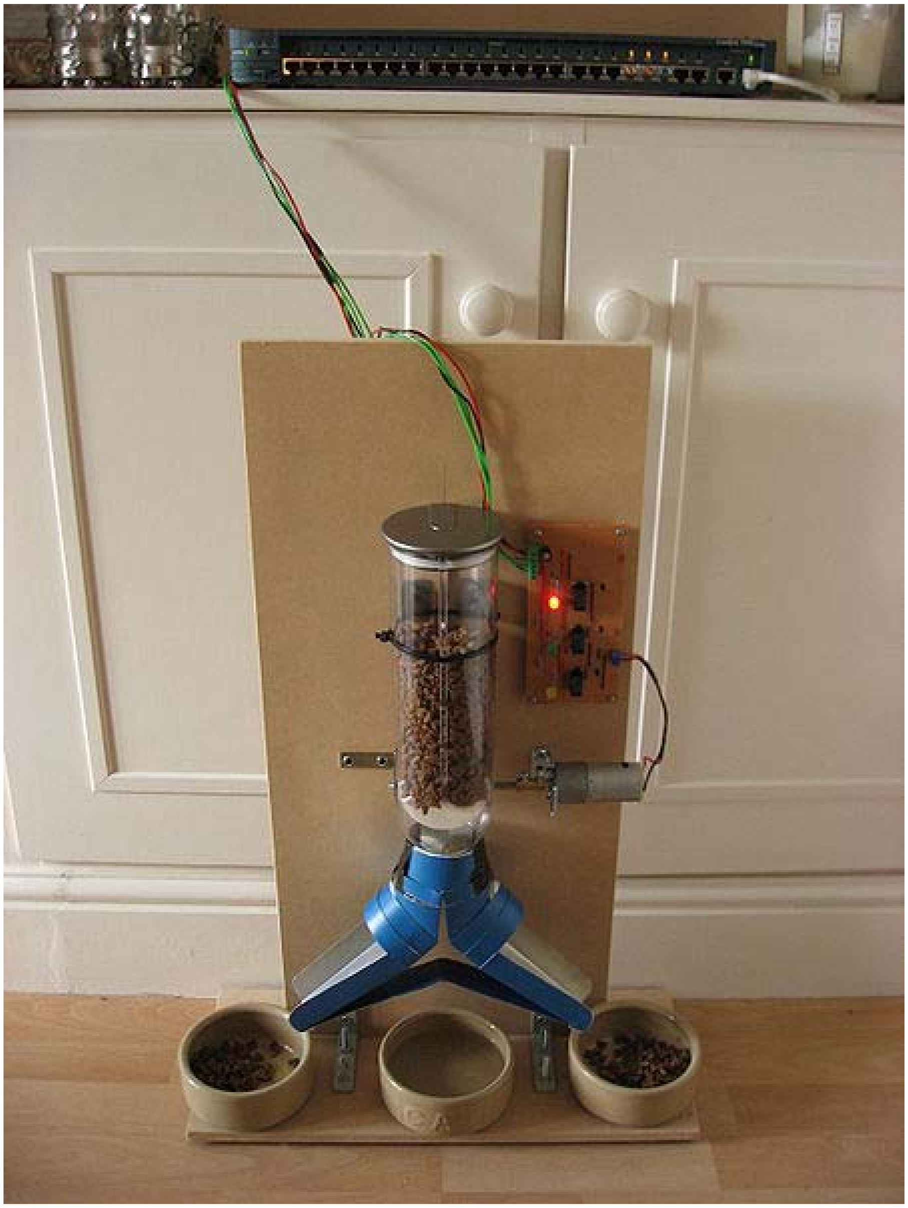
## Intercoms

An intercom system allows communication via a microphone and loud speaker between multiple rooms. Integration of the intercom to the telephone, or of the video door entry system to the television set, allowing the residents to view the door camera automatically.

## Robotics

- Control of home robots, using if necessary domotic electric beacon.
- Home robot communication (i.e. using WiFi) with the domotic network and other home robots.

## Other systems



A homemade Internet-enabled cat feeder.

Using special hardware, almost any device can be monitored and controlled automatically or remotely, including:

- Coffeemaker
- Garage door
- Pet feeding and watering
- Plant watering
- Pool pump(s) and heater, Hot tub and Spa
- Sump Pump

### Costs

An automated home can be a very simple grouping of controls, or it can be heavily automated where any appliance that is plugged into electrical power is remotely controlled. Costs mainly include equipment, components, furniture, and custom installation.

Ongoing costs include electricity to run the control systems, maintenance costs for the control and networking systems, including troubleshooting, and eventual cost of upgrading as standards change. Increased complexity may also increase maintenance costs for networked devices.

Learning to use a complex system effectively may take significant time and training.

Control system security may be difficult and costly to maintain, especially if the control system extends beyond the home, for instance by wireless or by connection to the internet or other networks.

### Smart Grid

Home automation technologies are viewed as integral additions to the Smart grid. The ability to control lighting, appliances, HVAC as well as Smart Grid applications (load shedding, demand response, real-time power usage and price reporting) will become vital as Smart Grid initiatives are rolled out. Green Automation is the term coined to describe energy management strategies in home automation when data from smart grids is combined with home automation systems to use resources either at there cheapest prices or most available. For example taking advantage of high solar panel out put in the middle of the day to run washing machines automatically.

### Organizations

- CEDIA
- Continental Automated Buildings Association
- Digital Living Network Alliance
- CENELEC
- MIT AgeLab
- SIMO TCI
- Living Tomorrow

## Chapter 11

# Programmable Logic Controller


Siemens Simatic S7-400 system at rack, left-to-right: power supply unit PS407 4A,CPU 416-3, interface module IM 460-0 and communication processor CP 443-1.

A **programmable logic controller** (**PLC**) or **programmable controller** is a digital computer used for automation of electromechanical processes, such as control of machinery on factory assembly lines, amusement rides, or lighting fixtures. PLCs are used in many industries and machines. Unlike general-purpose computers, the PLC is designed for multiple inputs and output arrangements, extended temperature ranges, immunity to electrical noise, and resistance to vibration and impact. Programs to control machine operation are typically stored in battery-backed or non-volatile memory. A PLC is an example of a *hard* real time system since output results must be produced in response to input conditions within a bounded time, otherwise unintended operation will result.

## History

The PLC was invented in response to the needs of the American automotive manufacturing industry. Programmable logic controllers were initially adopted by the automotive industry where software revision replaced the re-wiring of hard-wired control panels when production models changed.

Before the PLC, control, sequencing, and safety interlock logic for manufacturing automobiles was accomplished using hundreds or thousands of relays, cam timers, and drum sequencers and dedicated closed-loop controllers. The process for updating such facilities for the yearly model change-over was very time consuming and expensive, as electricians needed to individually rewire each and every relay.

In 1968 GM Hydramatic (the automatic transmission division of General Motors) issued a request for proposal for an electronic replacement for hard-wired relay systems. The winning proposal came from Bedford Associates of Bedford, Massachusetts. The first PLC, designated the 084 because it was Bedford Associates' eighty-fourth project, was the result. Bedford Associates started a new company dedicated to developing, manufacturing, selling, and servicing this new product: Modicon, which stood for MOdular DIgital CONtroller. One of the people who worked on that project was Dick Morley, who is considered to be the "father" of the PLC. The Modicon brand was sold in 1977 to Gould Electronics, and later acquired by German Company AEG and then by French Schneider Electric, the current owner.

One of the very first 084 models built is now on display at Modicon's headquarters in North Andover, Massachusetts. It was presented to Modicon by GM, when the unit was retired after nearly twenty years of uninterrupted service. Modicon used the 84 moniker at the end of its product range until the 984 made its appearance.

The automotive industry is still one of the largest users of PLCs.

## Development

Early PLCs were designed to replace relay logic systems. These PLCs were programmed in "ladder logic", which strongly resembles a schematic diagram of relay logic. This program notation was chosen to reduce training demands for the existing technicians. Other early PLCs used a form of instruction list programming, based on a stack-based logic solver.

Modern PLCs can be programmed in a variety of ways, from ladder logic to more traditional programming languages such as BASIC and C. Another method is State Logic, a very high-level programming language designed to program PLCs based on state transition diagrams.

Many early PLCs did not have accompanying programming terminals that were capable of graphical representation of the logic, and so the logic was instead represented as a series of logic expressions in some version of Boolean format, similar to Boolean algebra. As programming terminals evolved, it became more common for ladder logic to be used, for the aforementioned reasons. Newer formats such as State Logic and Function Block (which is similar to the way logic is depicted when using digital integrated logic circuits) exist, but they are still not as popular as ladder logic. A primary reason for this is that PLCs solve the logic in a predictable and repeating sequence, and ladder logic allows the programmer (the person writing the logic) to see any issues with the timing of the logic sequence more easily than would be possible in other formats.

### Programming

Early PLCs, up to the mid-1980s, were programmed using proprietary programming panels or special-purpose programming terminals, which often had dedicated function keys representing the various logical elements of PLC programs. Programs were stored on cassette tape cartridges. Facilities for printing and documentation were very minimal due to lack of memory capacity. The very oldest PLCs used non-volatile magnetic core memory.

More recently, PLCs are programmed using application software on personal computers. The computer is connected to the PLC through Ethernet, RS-232, RS-485 or RS-422 cabling. The programming software allows entry and editing of the ladder-style logic. Generally the software provides functions for debugging and troubleshooting the PLC software, for example, by highlighting portions of the logic to show current status during operation or via simulation. The software will upload and download the PLC program, for backup and restoration purposes. In some models of programmable controller, the program is transferred from a personal computer to the PLC though a programming board which writes the program into a removable chip such as an EEPROM or EPROM.

## *Functionality*

The functionality of the PLC has evolved over the years to include sequential relay control, motion control, process control, distributed control systems and networking. The data handling, storage, processing power and communication capabilities of some modern PLCs are approximately equivalent to desktop computers. PLC-like programming combined with remote I/O hardware, allow a general-purpose desktop computer to overlap some PLCs in certain applications. Regarding the practicality of these desktop computer based logic controllers, it is important to note that they have not been generally accepted in heavy industry because the desktop computers run on less stable operating systems than do PLCs, and because the desktop computer hardware is typically not designed to the same levels of tolerance to temperature, humidity, vibration, and longevity as the processors used in PLCs. In addition to the hardware limitations of desktop based logic, operating systems such as Windows do not lend themselves to deterministic logic execution, with the result that the logic may not always respond to changes in logic state or input status with the extreme consistency in timing as is expected from PLCs. Still, such desktop logic applications find use in less critical situations, such as laboratory automation and use in small facilities where the application is less demanding and critical, because they are generally much less expensive than PLCs.

In more recent years, small products called PLRs (programmable logic relays), and also by similar names, have become more common and accepted. These are very much like PLCs, and are used in light industry where only a few points of I/O (i.e. a few signals coming in from the real world and a few going out) are involved, and low cost is desired. These small devices are typically made in a common physical size and shape by several manufacturers, and branded by the makers of larger PLCs to fill out their low end product range. Popular names include PICO Controller, NANO PLC, and other names implying very small controllers. Most of these have between 8 and 12 digital inputs, 4 and 8 digital outputs, and up to 2 analog inputs. Size is usually about 4" wide, 3" high, and 3" deep. Most such devices include a tiny postage stamp sized LCD screen for viewing simplified ladder logic (only a very small portion of the program being visible at a given time) and status of I/O points, and typically these screens are accompanied by a 4-way rocker push-button plus four more separate push-buttons, similar to the key buttons on a VCR remote control, and used to navigate and edit the logic. Most have a small plug for connecting via RS-232 or RS-485 to a personal computer so that programmers can use simple Windows applications for programming instead of being forced to use the tiny LCD and push-button set for this purpose. Unlike regular PLCs that are usually modular and greatly expandable, the PLRs are usually not modular or expandable, but their price can be two orders of magnitude less than a PLC and they still offer robust design and deterministic execution of the logic.

## *PLC Topics*

### Features

Control panel with PLC (grey elements in the center). The unit consists of separate elements, from left to right; power supply, controller, relay units for in- and output

The main difference from other computers is that PLCs are armored for severe conditions (such as dust, moisture, heat, cold) and have the facility for extensive input/output (I/O) arrangements. These connect the PLC to sensors and actuators. PLCs read limit switches, analog process variables (such as temperature and pressure), and the positions of complex positioning systems. Some use machine vision. On the actuator side, PLCs operate electric motors, pneumatic or hydraulic cylinders, magnetic relays, solenoids, or analog outputs. The input/output arrangements may be built into a simple PLC, or the PLC may have external I/O modules attached to a computer network that plugs into the PLC.

### System scale

A small PLC will have a fixed number of connections built in for inputs and outputs. Typically, expansions are available if the base model has insufficient I/O.

Modular PLCs have a chassis (also called a rack) into which are placed modules with different functions. The processor and selection of I/O modules is customised for the particular application. Several racks can be administered by a single processor, and may have thousands of inputs and outputs. A special high speed serial I/O link is used so that racks can be distributed away from the processor, reducing the wiring costs for large plants.

### User interface

PLCs may need to interact with people for the purpose of configuration, alarm reporting or everyday control.

A Human-Machine Interface (HMI) is employed for this purpose. HMIs are also referred to as MMIs (Man Machine Interface) and GUIs (Graphical User Interface).

A simple system may use buttons and lights to interact with the user. Text displays are available as well as graphical touch screens. More complex systems use programming and monitoring software installed on a computer, with the PLC connected via a communication interface.

### Communications

PLCs have built in communications ports, usually 9-pin RS-232, but optionally EIA-485 or Ethernet. Modbus, BACnet or DF1 is usually included as one of the communications protocols. Other options include various fieldbuses such as DeviceNet or Profibus. Other communications protocols that may be used are listed in the List of automation protocols.

Most modern PLCs can communicate over a network to some other system, such as a computer running a SCADA (Supervisory Control And Data Acquisition) system or web browser.

PLCs used in larger I/O systems may have peer-to-peer (P2P) communication between processors. This allows separate parts of a complex process to have individual control while allowing the subsystems to co-ordinate over the communication link. These communication links are also often used for HMI devices such as keypads or PC-type workstations.

## Programming

PLC programs are typically written in a special application on a personal computer, then downloaded by a direct-connection cable or over a network to the PLC. The program is stored in the PLC either in battery-backed-up RAM or some other non-volatile flash memory. Often, a single PLC can be programmed to replace thousands of relays.

Under the IEC 61131-3 standard, PLCs can be programmed using standards-based programming languages. A graphical programming notation called Sequential Function Charts is available on certain programmable controllers. Initially most PLCs utilized Ladder Logic Diagram Programming, a model which emulated electromechanical control panel devices (such as the contact and coils of relays) which PLCs replaced. This model remains common today.

IEC 61131-3 currently defines five programming languages for programmable control systems: FBD (Function block diagram), LD (Ladder diagram), ST (Structured text, similar to the Pascal programming language), IL (Instruction list, similar to assembly language) and SFC (Sequential function chart). These techniques emphasize logical organization of operations.

While the fundamental concepts of PLC programming are common to all manufacturers, differences in I/O addressing, memory organization and instruction sets mean that PLC programs are never perfectly interchangeable between different makers. Even within the same product line of a single manufacturer, different models may not be directly compatible.

## *PLC compared with other control systems*


Allen-Bradley PLC installed in a control panel

PLCs are well-adapted to a range of automation tasks. These are typically industrial processes in manufacturing where the cost of developing and maintaining the automation system is high relative to the total cost of the automation, and where changes to the system would be expected during its operational life. PLCs contain input and output devices compatible with industrial pilot devices and controls; little electrical design is required, and the design problem centers on expressing the desired sequence of operations. PLC applications are typically highly customized systems so the cost of a packaged PLC is low compared to the cost of a specific custom-built controller design. On the other hand, in the case of mass-produced goods, customized control systems are economic due to the lower cost of the components, which can be optimally chosen instead of a "generic" solution, and where the non-recurring engineering charges are spread over thousands or millions of units.

For high volume or very simple fixed automation tasks, different techniques are used. For example, a consumer dishwasher would be controlled by an electromechanical cam timer costing only a few dollars in production quantities.

A microcontroller-based design would be appropriate where hundreds or thousands of units will be produced and so the development cost (design of power supplies, input/output hardware and necessary testing and certification) can be spread over many sales, and where the end-user would not need to alter the control. Automotive applications are an example; millions of units are built each year, and very few end-users alter the programming of these controllers. However, some specialty vehicles such as transit busses economically use PLCs instead of custom-designed controls, because the volumes are low and the development cost would be uneconomic.

Very complex process control, such as used in the chemical industry, may require algorithms and performance beyond the capability of even high-performance PLCs. Very high-speed or precision controls may also require customized solutions; for example, aircraft flight controls.

Programmable controllers are widely used in motion control, positioning control and torque control. Some manufacturers produce motion control units to be integrated with PLC so that G-code (involving a CNC machine) can be used to instruct machine movements.

PLCs may include logic for single-variable feedback analog control loop, a "proportional, integral, derivative" or "PID controller". A PID loop could be used to control the temperature of a manufacturing process, for example. Historically PLCs were usually configured with only a few analog control loops; where processes required hundreds or thousands of loops, a distributed control system (DCS) would instead be used. As PLCs have become more powerful, the boundary between DCS and PLC applications has become less distinct.

PLCs have similar functionality as Remote Terminal Units. An RTU, however, usually does not support control algorithms or control loops. As hardware rapidly becomes more powerful and cheaper, RTUs, PLCs and DCSs are increasingly beginning to overlap in responsibilities, and many vendors sell RTUs with PLC-like features and vice versa. The industry has standardized on the IEC 61131-3 functional block language for creating programs to run on RTUs and PLCs, although nearly all vendors also offer proprietary alternatives and associated development environments.

### *Digital and analog signals*

Digital or discrete signals behave as binary switches, yielding simply an On or Off signal (1 or 0, True or False, respectively). Push buttons, limit switches, and photoelectric sensors are examples of devices providing a discrete signal. Discrete signals are sent using either voltage or current, where a specific range is designated as *On* and another as *Off*. For example, a PLC might use 24 V DC I/O, with values above 22 V DC representing *On*, values below 2VDC representing *Off*, and intermediate values undefined. Initially, PLCs had only discrete I/O.

Analog signals are like volume controls, with a range of values between zero and full-scale. These are typically interpreted as integer values (counts) by the PLC, with various ranges of accuracy depending on the device and the number of bits available to store the data. As PLCs typically use 16-bit signed binary processors, the integer values are limited between -32,768 and +32,767. Pressure, temperature, flow, and weight are often represented by analog signals. Analog signals can use voltage or current with a magnitude proportional to the value of the process signal. For example, an analog 0 - 10 V input or 4-20 mA would be converted into an integer value of 0 - 32767.

Current inputs are less sensitive to electrical noise (i.e. from welders or electric motor starts) than voltage inputs.

## Example

As an example, say a facility needs to store water in a tank. The water is drawn from the tank by another system, as needed, and our example system must manage the water level in the tank.

Using only digital signals, the PLC has two digital inputs from float switches (Low Level and High Level). When the water level is above the switch it closes a contact and passes a signal to an input. The PLC uses a digital output to open and close the inlet valve into the tank.

When the water level drops enough so that the Low Level float switch is off (down), the PLC will open the valve to let more water in. Once the water level rises enough so that the High Level switch is on (up), the PLC will shut the inlet to stop the water from overflowing. This rung is an example of seal-in (latching) logic. The output is sealed in until some condition breaks the circuit.

```
|                                                              |
|   Low Level      High Level                 Fill Valve      |
|------[/]------|------[/]----------------------(OUT)---------|
|               |                                              |
|               |                                              |
|               |                                              |
|   Fill Valve  |                                              |
|------[ ]------|                                              |
|                                                              |
|                                                              |
```

An analog system might use a water pressure sensor or a load cell, and an adjustable (throttling) dripping out of the tank, the valve adjusts to slowly drip water back into the tank.

In this system, to avoid 'flutter' adjustments that can wear out the valve, many PLCs incorporate "hysteresis" which essentially creates a "deadband" of activity. A technician adjusts this deadband so the valve moves only for a significant change in rate. This will in turn minimize the motion of the valve, and reduce its wear.

A real system might combine both approaches, using float switches and simple valves to prevent spills, and a rate sensor and rate valve to optimize refill rates and prevent water hammer. Backup and maintenance methods can make a real system very complicated.

## Chapter 12

# Power Line Communication

**Power line communication** or **power line carrier** (**PLC**), also known as **Power line Digital Subscriber Line** (**PDSL**), **mains communication**, **power line telecom** (**PLT**), **power line networking** (**PLN**), or **Broadband over Power Lines** (**BPL**) are systems for carrying data on a conductor also used for electric power transmission.

Electrical power is transmitted over high voltage transmission lines, distributed over medium voltage, and used inside buildings at lower voltages. Powerline communications can be applied at each stage. Most PLC technologies limit themselves to one set of wires (for example, premises wiring), but some can cross between two levels (for example, both the distribution network and premises wiring). Typically the transformer prevents propagating the signal, which requires multiple PLC technologies to be used to form very large networks.

### *Basics*

All power line communications systems operate by impressing a modulated carrier signal on the wiring system. Different types of powerline communications use different frequency bands, depending on the signal transmission characteristics of the power wiring used. Since the power wiring system was originally intended for transmission of AC power, in conventional use, the power wire circuits have only a limited ability to carry higher frequencies. The propagation problem is a limiting factor for each type of power line communications. A new discovery called E-Line that allows a single power conductor on an overhead power line to operate as a waveguide to provide low attenuation propagation of RF through microwave energy lines while providing information rate of multiple Gbps is an exception to this limitation.

Data rates over a power line communication system vary widely. Low-frequency (about 100-200 kHz) carriers impressed on high-voltage transmission lines may carry one or two analog voice circuits, or telemetry and control circuits with an equivalent data rate of a few hundred bits per second; however, these circuits may be many miles long. Higher data rates generally imply shorter ranges; a local area network operating at millions of bits per second may only cover one floor of an office building, but eliminates installation of dedicated network cabling.

## *Ultra-High-frequency communication (≥100 MHz)*

The highest information rate transmissions over power line use RF through microwave frequencies transmitted via a transverse mode surface wave propagation mechanism that requires only a single conductor (U.S. Patent 7,567,154). An implementation of this technology called E-Line has been demonstrated using a single power line conductor. These systems have demonstrated symmetric and full duplex communication well in excess of 1 Gbit/s in each direction. Multiple Wi-Fi channels with simultaneous analog television in the 2.4 and 5.3 GHz unlicensed bands have been demonstrated operating over a single medium voltage line conductor. Because the underlying propagation mode is extremely broadband, it can operate anywhere in the 20 MHz - 20 GHz region. Also since it is not restricted to below 80 MHz, as is the case for high-frequency BPL, these systems can avoid the need to share spectrum with other licensed or unlicensed services and can completely avoid the interference issues associated with use of shared spectrum while offering complete flexibility for modulation and protocols of an RF-microwave system.

## *High-frequency communication (≥MHz)*

High frequency communication may (re)use large portions of the radio spectrum for communication, or may use select (narrow) band(s), depending on the technology.

### Home networking (LAN)

Power line communications can also be used in a home to interconnect home computers (and networked peripherals), as well as any home entertainment devices (including TVs, Blu-ray players, game consoles and Internet video boxes such as Apple TV, Roku, Kodak Theatre, etc.) that have an Ethernet port. Consumers can buy powerline adapter sets at most electronics retailers and use those to establish a wired connection using the existing electrical wiring in the home. The powerline adapters plug into a wall outlet (or into an extension cord or power strip, but not into any unit with surge suppression and filtering, as this may defeat the signal) and then are connected via CAT5 to the home's router. Then, a second (or third, fourth, fifth) adapter(s) can be plugged in at any other outlet to give instant networking and Internet access to an Ethernet-equipped Blu-ray player, a game console (PS3, Xbox 360, etc.) a laptop or an Internet TV  box that can access and stream video content to the TV.

The most established and widely deployed powerline networking standard for these powerline adapter products is from the HomePlug Powerline Alliance. HomePlug AV is the most current of the HomePlug specifications (HomePlug 1.0, HomePlug AV and the new HomePlug Green PHY for smart grid comprise the set of published specifications) and was adopted by the IEEE P1901 group as a baseline technology for their standard, published 30 December 2010. HomePlug estimates that over 45 million HomePlug devices have been deployed worldwide. Other companies and organizations back different specifications for power line home networking and these include the Universal Powerline Association, the HD-PLC Alliance and the ITU-T's G.hn specification.

### Internet access (broadband over powerlines)

Broadband over power lines (BPL), also known as power-line Internet or powerband, is the use of PLC technology to provide broadband Internet access through ordinary power lines. A computer (or any other device) would need only to plug a BPL "modem" into any outlet in an equipped building to have high-speed Internet access. International Broadband Electric Communications or IBEC and other companies currently offer BPL service to several electric cooperatives.

BPL may offer benefits over regular cable or DSL connections: the extensive infrastructure already available appears to allow people in remote locations to access the Internet with relatively little equipment investment by the utility. Also, such ubiquitous availability would make it much easier for other electronics, such as televisions or sound systems, to hook up. Cost of running wires such as ethernet in many buildings can be prohibitive; Relying on wireless has a number of predictable problems including security, limited maximum throughput and inability to power devices efficiently.

But variations in the physical characteristics of the electricity network and the current lack of IEEE standards mean that provisioning of the service is far from being a standard, repeatable process. And, the amount of bandwidth a BPL system can provide compared to cable and wireless is in question. The prospect of BPL could motivate DSL and cable operators to more quickly serve rural communities.

PLC modems transmit in medium and high frequency (1.6 to 80 MHz electric carrier). The asymmetric speed in the modem is generally from 256 kbit/s to 2.7 Mbit/s. In the repeater situated in the meter room the speed is up to 45 Mbit/s and can be connected to 256 PLC modems. In the medium voltage stations, the speed from the head ends to the Internet is up to 135 Mbit/s. To connect to the Internet, utilities can use optical fiber backbone or wireless link.

Deployment of BPL has illustrated a number of fundamental challenges, the primary one being that power lines are inherently a very noisy environment. Every time a device turns on or off, it introduces a pop or click into the line. Energy-saving devices often introduce noisy harmonics into the line. The system must be designed to deal with these natural signaling disruptions and work around them. For these reasons BPL can be thought of as a halfway between wireless transmission (where likewise there is little control of the medium through which signals propagate) and wired transmission (but not requiring any new cables).

Broadband over power lines has developed faster in Europe than in the United States due to a historical difference in power system design philosophies. Power distribution uses step-down transformers to reduce the voltage for use by customers. But BPL signals cannot readily pass through transformers, as their high inductance makes them act as low-pass filters, blocking high-frequency signals. So, repeaters must be attached to the transformers. In the U.S., it is common for a small transformer hung from a utility pole to service a single house or a small number of houses. In Europe, it is more common for a somewhat larger transformer to service 10 or 100 houses. For delivering power to customers, this difference in design makes little difference for power distribution. But for delivering BPL over the power grid in a typical U.S. city requires an order of magnitude more repeaters than in a comparable European city. On the other hand, since bandwidth to the transformer is limited, this can increase the speed at which each household can connect, due to fewer people sharing the same line. One possible solution is to use BPL as the backhaul for wireless communications, for instance by hanging Wi-Fi access points or cellphone base stations on utility poles, thus allowing end-users within a certain range to connect with equipment they already have.

The second major issue is signal strength and operating frequency. The system is expected to use frequencies of 10 to 30 MHz, which has been used for many decades by amateur radio operators, as well as international shortwave broadcasters and a variety of communications systems (military, aeronautical, etc.). Power lines are unshielded and will act as antennas for the signals they carry, and have the potential to interfere with shortwave radio communications. Modern BPL systems use OFDM modulation, which allows them to mitigate interference with radio services by removing specific frequencies used. A 2001 joint study by the American Radio Relay League (ARRL) and HomePlug Powerline Alliance showed that for modems using this technique "in general that with moderate separation of the antenna from the structure containing the HomePlug signal that interference was barely perceptible at the notched frequencies" and interference only happened when the "antenna was physically close to the power lines" (however other frequencies still suffer from interference).

### *Medium frequency (kHz)*

### Home control (narrowband)

Power line communications technology can use the household electrical power wiring as a transmission medium. This is a technique used in home automation for remote control of lighting and appliances without installation of additional control wiring.

Typically home-control power line communication devices operate by modulating in a carrier wave of between 20 and 200 kHz into the household wiring at the transmitter. The carrier is modulated by digital signals. Each receiver in the system has an address and can be individually commanded by the signals transmitted over the household wiring and decoded at the receiver. These devices may be either plugged into regular power outlets, or permanently wired in place. Since the carrier signal may propagate to nearby homes (or apartments) on the same distribution system, these control schemes have a "house address" that designates the owner.

Since 1999, a new power-line communication technology "universal powerline bus" has been developed, using pulse-position modulation (PPM). The physical layer method is a very different scheme than the modulated/demodulated RF techniques used by X-10. The promoters claim advantages in cost per node, and reliability.

## Low-speed narrow-band communication

Narrowband power line communications began soon after electrical power supply became widespread. Around the year 1922 the first carrier frequency systems began to operate over high-tension lines with frequencies of 15 to 500 kHz for telemetry purposes, and this continues. Consumer products such as baby alarms have been available at least since 1940.

In the 1930s, ripple carrier signalling was introduced on the medium (10-20 kV) and low voltage (240/415 V) distribution systems. For many years the search continued for a cheap bi-directional technology suitable for applications such as remote meter reading. For example, the Tokyo Electric Power Co ran experiments in the 1970s which reported successful bi-directional operation with several hundred units. Since the mid-1980s, there has been a surge of interest in using the potential of digital communications techniques and digital signal processing. The drive is to produce a reliable system which is cheap enough to be widely installed and able to compete cost effectively with wireless solutions. But the narrowband powerline communications channel presents many technical challenges, a mathematical channel model and a survey of work is available.

Applications of mains communications vary enormously, as would be expected of such a widely available medium. One natural application of narrow band power line communication is the control and telemetry of electrical equipment such as meters, switches, heaters and domestic appliances. A number of active developments are considering such applications from a systems point of view, such as demand side management. In this, domestic appliances would intelligently co-ordinate their use of resources, for example limiting peak loads.

Control and telemetry applications include both 'utility side' applications, which involves equipment belonging to the utility company (i.e. between the supply transformer substation up to the domestic meter), and 'consumer-side' applications which involves equipment in the consumer's premises. Possible utility-side applications include automatic meter reading(AMR), dynamic tariff control, load management, load profile recording, credit control, pre-payment, remote connection, fraud detection and network management, and could be extended to include gas and water.

A project of EDF, France includes demand side management, street lighting control, remote metering and billing, customer specific tariff optimisation, contract management, expense estimation and gas applications safety.

There are also many specialised niche applications which use the mains supply within the home as a convenient data link for telemetry. For example, in the UK and Europe a TV audience monitoring system uses powerline communications as a convenient data path between devices that monitor TV viewing activity in different rooms in a home and a data concentrator which is connected to a telephone modem.

### High-speed narrow-band powerline communication — distribution line carrier

DLC uses existing electrical distribution network in the medium voltage (MV) — i.e., 11 kV, Low Voltage (LV) as well as building voltages. It is very similar to the powerline carrier. DLC uses narrowband powerline communication frequency range of 9 to 500 kHz with data rate up to 576 kbit/s. DLC is suitable (even in very large networks) for multiple realtime energy management applications. It can be implemented under REMPLI System as well as SCADA, AMR and Power Quality Monitoring System. DLC complies with the following standards: EN 50065 (CENELEC), IEC 61000-3 and FCC Part 15 Subpart B.

Radio users may experience some interference to their systems when in the near proximity of overhead power lines. For two way radio systems utilizing digital schemas, such as the P25 systems, this may appear as loss of received signal caused by the radio's front end (desensitising the receiver). For analog radios the interference appears as a buzzing sound eminating from the radio's speaker. With external inductive or capacitive coupling, a distance more than 15 km can be achieved over a medium voltage network. On low voltage networks, a direct connection can be made since the DLC has a built-in capacitive coupler. This allows end-end communications from substation to the customer premises without repeaters.

The latest DLC systems significantly improve upon and differ from other powerline communication segments. DLC is mainly useful for last-mile and backhaul instrastucture that can be integrated with corporate wide area networks (WANs) via TCP/IP, serial communication or leased-line modem to cater for multi-services realtime energy management systems.

More recently, narrowband PLC communications techniques have also started to include implementations of more sophisticated communication technologies like OFDM, that were till date used in broadband domain. PRIME is one such system that operates within CENELEC A band and uses OFDM as the technology at physical layer to provide data rates of up to 128 kbit/s. The PRIME Alliance is an industrial consortium that is putting forth this open specifications of physical and MAC layers and allowing for utilities to pick solutions from different vendors.

### Transmitting radio programs

Sometimes PLC was used for transmitting radio programs over powerlines. When operated in the AM radio band, it is known as a carrier current system. Such devices were in use in Germany, where it was called *Drahtfunk*, and in Switzerland, where it was called *Telefonrundspruch*, and used telephone lines. In the Soviet Union, PLC was very common for broadcasting since the 1930s because of its low cost and accessibility. In Norway the radiation of PLC systems from powerlines was sometimes used for radio supply. These facilities were called *Linjesender*. In all cases the radio programme was fed by special transformers into the lines. To prevent uncontrolled propagation, filters for the carrier frequencies of the PLC systems were installed in substations and at line branches.

An example of the programs carried by "wire broadcasting" in Switzerland:

- 175 kHz Swiss Radio International
- 208 kHz RSR1 "la première" (French)
- 241 kHz "classical music"
- 274 kHz RSI1 "rete UNO" (Italian)
- 307 kHz DRS 1 (German)
- 340 kHz "easy music"

### Utility applications

Utility companies use special coupling capacitors to connect medium-frequency radio transmitters to the power-frequency AC conductors. Frequencies used are in the range of 24 to 500 kHz, with transmitter power levels up to hundreds of watts. These signals may be impressed on one conductor, on two conductors or on all three conductors of a high-voltage AC transmission line. Several PLC channels may be coupled onto one HV line. Filtering devices are applied at substations to prevent the carrier frequency current from being bypassed through the station apparatus and to ensure that distant faults do not affect the isolated segments of the PLC system. These circuits are used for control of switchgear, and for protection of transmission lines. For example, a protective relay can use a PLC channel to trip a line if a fault is detected between its two terminals, but to leave the line in operation if the fault is elsewhere on the system.

While utility companies use microwave and now, increasingly, fiber optic cables for their primary system communication needs, the power-line carrier apparatus may still be useful as a backup channel or for very simple low-cost installations that do not warrant installing fiber optic lines.

## *Low frequency (<kHz)*

### Utility

Power line carrier systems have long been a favorite at many utilities because it allows them to reliably move data over an infrastructure that they control. Many technologies are capable of performing multiple applications. For example, a communication system bought initially for automatic meter reading can sometimes also be used for load control or for demand response applications.

PLC is one of the technologies used in the automatic meter reading industry. Both one-way and two-way systems have been successfully used for decades. Interest in this application has grown substantially in recent history—not so much because there is an interest in automating a manual process, but because there is an interest in obtaining fresh data from all metered points in order to better control and operate the system. PLC is one of the technologies being used in Advanced Metering Infrastructure (AMI) systems.

In a one-way (inbound only) system, readings "bubble up" from end devices (i.e. meters), through the communication infrastructure, to a "master station" which publishes the readings. A one-way system might be lower-cost than a two-way system, but also is difficult to reconfigure should the operating environment change.

In a two-way system (supporting both outbound and inbound), commands can be broadcast out from the master station to end devices (meters) -- allowing for reconfiguration of the network, or to obtain readings, or to convey messages, etc. The device at the end of the network may then respond (inbound) with a message that carries the desired value. Outbound messages injected at a utility substation will propagate to all points downstream. This type of broadcast allows the communication system to simultaneously reach many thousands of devices—all of which are known to have power, and have been previously identified as candidates for load shed. PLC also may be a component of a smart power grid.

## *Broadband over power line (BPL)*

### US FCC

On 14 October 2004, the U.S. Federal Communications Commission adopted rules to facilitate the deployment of "Access BPL" -- i.e., use of BPL to deliver broadband service to homes and businesses. The technical rules are more liberal than those advanced by the US national amateur radio organization, the ARRL, and other spectrum users, but include provisions that require BPL providers to investigate and correct any interference they cause. These rules may be subject to future litigation.

On 8 August 2006 FCC adopted a memorandum opinion and an order on broadband over power lines, giving the go-ahead to promote broadband service to all Americans.The order rejects calls from aviation, business, commercial, amateur radio and other sectors of spectrum users to limit or prohibit deployment until further study is completed. FCC chief Kevin Martin said that BPL "holds great promise as a ubiquitous broadband solution that would offer a viable alternative to cable, digital subscriber line, fiber, and wireless broadband solutions", and that BPL was one of the agency's "top priorities".

### 'notching out' and dynamic adaptation to contention

New FCC rules (and the IEEE standards) require BPL systems to be capable of remotely notching out frequencies on which interference occurs, and of shutting down remotely if necessary to resolve the interference. BPL systems operating within FCC Part 15 emissions limits may still interfere with wireless radio communications and are required to resolve interference problems. A few early trials were shut down, though whether it was in response to complaints is debatable. The need to deal with signals that inevitably will propagate through thick metal wires hanging above crowded areas was always an issue in BPL standardization and the technologies to resolve it are those already used for wireless, so the issue was primarily one of thresholds and agreement on who had priority for spectrum.

In the US, simply ignoring wireless users was apparently not legal. The ARRL sued the FCC, claiming that the FCC violated the Administrative Procedure Act in creating its rules. On 25 April 2008, a US Court of Appeals agreed with the ARRL that the FCC violated the APA, especially by redacting data from the public that could have shed doubt on the FCC's decision.

"It is one thing for the Commission to give notice and make available for comment the studies on which it relied in formulating the rule while explaining its non-reliance on certain parts", D.C. Circuit Judge Judith Rogers wrote. "It is quite another thing to provide notice and an opportunity for comment on only those parts of the studies that the Commission likes best."

US power and telecommunications companies had meanwhile started tests of the BPL technology, over the protests of the radio groups. After claims of interference by these groups, many of the trials were ended early and proclaimed successes, though the ARRL and other groups claimed otherwise.

Some of the same providers conducting those trials later began commercial roll-outs in limited neighborhoods in selected cities, with some level of user acceptance but also many documented cases of interference reported to the FCC by Amateur Radio users. Some wireless users filed a petition for reconsideration with the FCC in February 2005.

Austria, Australia, New Zealand and other locations have also experienced early BPL's so-called "spectrum pollution" and raised concerns within their governing bodies. In the UK, the BBC has published the results of a number of tests (The effects of PLT on broadcast reception,PLT and Broadcasting, Co-existence of PLT and Radio Services) to detect interference from BPL installations. It has also made a video (Real Media format), showing broadcast of data and interference from in-home BPL devices.

In June 2007, NATO Research and Technology Organisation released a report titled HF Interference, Procedures and Tools (RTO-TR-IST-050) which concluded that widespread deployment of BPL may have a "possible detrimental effect upon military HF radio communications and COMINT systems."

## Interference issue remains a challenge to PLC systems

These concerns remain a challenge to widespread PLC adoption, predating the IEEE standards and G.hn for in-home use. All new powerline modems are supposed to detect the existence of SW-Radio services at the location and time of operation by monitoring the ground noise at the socket where the modem is connected but in reality this is not being implemented.

Questions remain how effectively an interference-avoidance system will meet the requirements of SW-Radio services where reception is the first concern. Frequency avoidance schemes cannot adapt to the very low signal levels necessary for a radio receiver to operate reliably. By far, most SW-Radio services are receiving sites and not transmitting sites, so the interference issue remains significant. Current detection schemes are dependent upon transmitted signal levels as the triggering event to force equipment into a frequency avoidance scheme.

In April 2009 the Wireless Institute of Australia reported that radio amateurs in Australia appear to be safe from the rollout of a nationwide Broadband over Powerline or BPL system. Australia's government announced that it will be building a system based on fibre optic technology for its backbone - though it would likely still rely on BPL on high-voltage lines in remote areas. This decision would appear to remove the possibility of widespread interference to radio communications from any network-wide adoption of BPL technology, but still leaves as a concern the possibility of interference from in-home use of G.hn over AC.

The British communications regulator Ofcom has investigated a number of PLT-related complaints but nearly 20% of these remain unresolved. Ofcom maintains that "there does not at present appear to be significant public harm arising from this situation." Since publishing this statement, Ofcom was presented with evidence by the RSGB (Radio Society of Great Britain) that PLT is causing significant disruption to Amateur Radio and Shortwave broadcast resulting in Ofcom commissioning a report into the interference being caused by the technology.

The Electromagnetic Compatibility Industry Association (EMCIA), formed in March 2002 for the benefit of companies involved in the supply, design, test or manufacture of EMC products, or the provision of EMC Services and is a UKTI Accredited Trade Organisation, submitted a stern report to the Parliamentary Committee overseeing broadband, stating that they "..very strongly recommend that the Committee specifically excludes the use of PowerLine Telecommunication (PLT*)..."

It is reported, that these "In Home" Power Line Networking systems, can cause widespread disruption to nearby radio services that use the Shortwave radio spectrum (3 to 30 MHz); and now the VHF radio spectrum (30 to 300MHz). Though some systems when quiescent and not transferring data appear relatively quiet, others continue to send considerable RF energy into the mains wiring when no data is being transferred. All of them can create huge amounts of interference to nearby services (including it has been observed, ADSL2+ via overhead telco cable) when they transfer data. It does appear the problem is worse in some places than others; the local domestic mains wiring practices in different countries appear to have a marked effect on the level of the resulting local radio interference created.

The Radio Society of Great Britain is extremely concerned over PLT and has established a Spectrum Defence Fund.

There are now in-home PLT devices on the market that use both the HF radio spectrum and the VHF radio spectrum (with harmonics observed at 1GHz). This new breed of PLT still use the mains cabling for something it was never designed for. Mains cabling in all countries was only ever intended to carry 50 or 60Hz power. The result is disruption to local FM and DAB broadcast reception, with possible adverse effects to nearby emergency services who may use the VHF spectrum for their own communications.

## *Automotive uses*

Power-line technology enables in-vehicle network communication of data, voice, music and video signals by digital means over direct current (DC) battery power-line. Advanced digital communication techniques tailored to overcome hostile and noisy environment are implemented in a small size silicon device. One power line can be used for multiple independent networks. The benefits would be lower cost and weight (compared to separate power and control wiring), flexible modification, and ease of installation. Potential problems in vehicle applications would include the higher cost of end devices, which must be equipped with active controls and communication, and the possibility of intereference with other radio frequency devices in the vehicle or other places.

Prototypes are successfully operational in vehicles, using automotive compatible protocols such as CAN-bus, LIN-bus over power line (DC-LIN) and [DC-bus].

LonWorks power line based control has been used for an HVAC system in a production model bus.

## *Failure Scenarios*

There are many ways in which the communication signal may have error introduced into it. Interference, cross chatter, some active devices, and some passive devices all introduce noise or attenuation into the signal. When error becomes significant the devices controlled by the unreliable signal may fail, become inoperative, or operate in an undesirable fashion.

1. **Interference:** Interference from nearby systems can cause signal degradation as the modem may not be able to determine a specific frequency among many signals in the same bandwidth.
2. **Signal Attenuation by Active Devices**: Devices such as relays, transistors, and rectifiers create noise in their respective systems, increasing the likelihood of signal degradation. Arc-fault circuit interrupter (AFCI) devices, required by some recent electrical codes for living spaces, may also attenuate the signals.
3. **Signal Attenuation by Passive Devices**: Transformers and DC-DC converters attenuate the input frequency signal almost completely. "Bypass" devices become necessary for the signal to be passed on to the receiving node. A bypass device

may consist of three stages, a filter in series with a protection stage and coupler, placed in parallel with the passive device.

## *Standards*

Two distinctly different sets of standards apply to powerline networking as of early 2010.

### IEEE P1901, ITU G.hn home grids

Within homes, the HomePlug AV and IEEE P1901 standards specify how, globally, existing AC wires should be employed for data purposes. The IEEE 1901 includes HomePlug AV as a baseline technology, so any future IEEE 1901 products will be fully interoperable with HomePlug AV, HomePlug Green PHY or the forthcoming HomePlug AV2 specification (under development now and expected to be approved in Q1 2011).

### Smart grids and use of BPL for telemetry and data provision by powercos

Power providers are also standardizing their internal and external communications including use of BPL technologies to provide direct links to power system components like transformers. In North America another IEEE standard group is supervising these activities.

Unlike home users, power providers are more able to consider widespread deployment of fiber optic cables immune to electromagnetic interference (and which do not generate any) and for which mature devices (switches, repeaters) are available. Accordingly there is no one single compelling reason to carry data on the existing power lines themselves as there is in homes, except in remote regions where fibre optic networks would not normally be deployed at all. Power network architectures with many transformers are more likely to be served using fibre.

Even if a home is using BPL it may not necessarily connect to the Internet using a BPL-based gateway (typically a smart meter), although this would have major advantages to both the consumer and provider. NIST and IEEE have considered whether requiring smart meters to all be fully functioning BPL gateways would not accelerate demand side management and create a uniform market into which security, home control and other providers can sell.

### Standards organizations

Several competing organizations have developed specifications, including the HomePlug Powerline Alliance, Universal Powerline Association and HD-PLC Alliance. On December 2008, the ITU-T adopted Recommendation G.hn/G.9960 as a standard for high-speed powerline, coax and phoneline communications. The National Energy Marketers Association was also involved in advocating for standards. IEEE P1901 is an IEEE working group developing the global standard for high speed powerline communications. In July 2009, the working group approved its "IEEE 1901 Draft Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications" as an IEEE draft standard for broadband over power lines defining medium access control and physical layer specifications. The IEEE 1901 Draft Standard was published by the IEEE in January 2010 and the final standard is expected to be published and ratified in September or October of 2010.

NIST has included IEEE 1901, HomePlug AV and ITU-T G.hn as "Additional Standards Identified by NIST Subject to Further Review" for the Smart grid in the United States.

# Chapter 13

# Universal Powerline Bus and PLCBUS

## Universal powerline bus

**Universal powerline bus** (or **UPB**) is a protocol for communication among devices used for home automation. It uses power line wiring for signaling and control.

UPB was developed by PCS Powerline Systems of Northridge, California and released in 1999. Based on the concept of the ubiquitous X10 standard, UPB has an improved transmission rate and higher reliability. While X10 without specialty firewalls has a reported reliability of 70-80%, UPB reportedly has a reliability of more than 99%.

### *Power-line carrier control overview*

Household electrical wiring such as Romex or BX is used to send digital data between UPB devices.

While in the X10 protocol this digital data is encoded onto a 120 kHz carrier which is transmitted as bursts during the relatively quiet zero crossings of the 50 or 60 Hz AC alternating current waveform, the UPB protocol works differently.

The UPB communication method consists of a series of precisely timed electrical pulses (called UPB Pulses) that are superimposed on top of the normal AC power waveform (sine wave). Receiving UPB devices can easily detect and analyze these UPB Pulses and pull out the encoded digital information from them.

UPB Pulses are generated by charging a capacitor to a high voltage and then discharging that capacitor's voltage into the powerline at a precise time. This quick discharging of the capacitor creates a large "spike" (or pulse) on the powerline that is easily detectable by receiving UPB devices wired large distances away on the same powerline.

### *UPB protocol*

While transmitting, one UPB Pulse is generated each half-cycle of the 60Hz AC electrical power cycle. The generation of each UPB Pulse is precisely timed to occur in one of four predefined positions in the half-cycle of the AC powerline. The position of each UPB Pulse determines its value as either 0, 1, 2, or 3. This method of encoding data as a relative position of a pulse is a well-known and used method in digital communications known as Pulse Position Modulation (PPM). Since each UPB Pulse can encode two bits of digital information and there are 120 AC half-cycles per second (at 60Hz), UPB communication has a raw speed of 240 bits per second. Although this speed isn't fast enough for doing high bandwidth applications it is perfectly adequate for doing command and control communication.

UPB Pulses are transmitted in a special region toward the end of the AC half-cycle known as the UPB Frame. This region was selected due to its relatively low noise characteristics and for other attributes that make it an optimum position for powerline communications. UPB Frames are synchronized to the low-to-high transition of the AC waveform (known as the AC zero-crossing point) such that one Frame starts T/Frame milliseconds after the zero crossing and the other Frame starts 8,333 milliseconds (one half-cycle at 60Hz) after the first one.

### *Controllers*

UPB controllers range from extremely simple plug-in modules to very sophisticated whole house home automation controllers.

The simplest controllers are plug-in controllers that are recommended for a moderate amount of switches and devices as it becomes cumbersome to control a wide range of devices.

More sophisticated controllers can control more units and/or incorporate timers that perform pre-programmed functions at specific times each day. Units are also available that use passive infrared motion detectors or photocells to turn lights on and off based on external conditions.

Finally, whole house home automation controllers can be fully programmed. These systems can execute many different timed events, respond to external sensors, and execute, with the press of a single button, an entire *scene*, turning lights on, establishing brightness levels, and so on.

### *Things to consider*

UPB is a powerline carrier technology which can be affected by devices on the powerline. However with the advance of the technology to Generation II there are only a few items that can affect the UPB Signal. The engineering team created specific devices to isolate these items.

# PLCBUS

**PLCBUS (Communication Protocol)** or PLC-BUS is a power-line communication protocol for communication between electronic devices used for home automation. It primarily uses power line wiring for signaling and control.

PLCBUS is similar to the X10 (industry standard) power line communication protocol. Though PLCBUS uses the same addressing scheme it is not compatible with X10. PLCBUS and X10 can coexist in the same power-line network and can interact with the use of bridges (like the PLCBUS 4808 device).

## *History and adoptation*

PLCBUS was developed in 2002 by ATS Ltd. in Amsterdam the Netherlands. Companies like Philips, Magma  and KPN  have agreements with ATS Ltd. regarding PLCBUS products. Also Microsoft, IBM, KPN, Nokia, Motorola, Hewlett Packard, Dell, Siemens and Intel have are said to have agreements with ATS Ltd.. Philips, Nokia, Siemens and the French power company Électricité de France are member of the PLC-BUS Union Commission.

In 2005 the Chinese company Shanghai Super Smart Electronics bought the PLCBUS Technology for their home automation products . Currently the use of PLCBUS, however, is not as widespread as the X10 protocol and there is no vibrant community of PLCBUS users.

## *Advantages*

Advantages of are:

- Reliable two way communication: an ACK is being send back to the sender module to acknowledge command
- Possibility to query the status of a module (for example to determine if a device is switched on or what the dim level of a light is)
- Possibility to monitor the noise and signal levels per module
- Fast: the time between the sending of a command and the retuning of an ACK is ~500ms
- Scalability: up to 64000 module can be addressed. An address consists of a user code, house code and unit code to uniquely identify a module. The large number of addressable modules greatly decreases the chance of unwanted interactions with PLCBUS modules of neighbors, eliminating the need of filters.

## *Disadvantages*

- The normal PLCBUS switches can only switch local appliances. Special scene controller switches are needed to switch appliances remotely.

- Modules no not report when operated locally, the module status has to be polled actively.

## *Typical devices*

An **applicance switch** is used to both locally switch a device on/off andremote (from a scene controller or computer interface for example). Special micro modules are available that can be installed behind switches. Existing on/off switches or momentary (normal-open) switches can be used in conjunction with those micro modules. Also available are plugin appliance switches which don't have to be built-in and which can also be operated locally or remote.

A **light dimmer** is used to set a lights' lightlevel both locally and remote (from a scene controller or computer interface for example). Special micro modules are available that can be installed behind switches or in the ceiling above the light. Existing on/off switches or momentary (normal-open) switches can be used in conjunction with those micro modules. Also available are plugin light dimmers which don't have to be built-in and which can also be operated locally or remote.

A **scene controller** or scene switch is a switch which can operate appliances and lights remote but not locally. It can send macros to set light levels and switch appliances on or off. Scene controllers are typically used to perform activities. For example for watching TV lights are dimmed, the window blinds are closed and the TV is turned on.

A **computer interface** like the PLCBUS 1141, conntected to a serial RS-232 or USB port, can be used to operate appliances and lights and to read module status. Windows software is available and also Linux drivers do exist.

A **bridge** can be used to mix PLCBUS technology with other power-line communication technology. For example the PLCBUS 4808 device can be used to let PLCBUS devices interoperate with X10 devices.

A **phase coupler** can be used to couple up to three different electrical phases. In a normal house, typically only one phase is available.

# Chapter 14

# Insteon

**Insteon** (commonly written **INSTEON**) is a system for connecting lighting switches and loads without extra wiring, similar to the X10 standard, designed specifically to address the inherent limitations in the X10 standard but also to incorporate backward compatibility with X10.

Insteon is designed to enable simple devices - such as light switches - to be networked together using the powerline, radio frequency (RF), or both. All Insteon devices are peers, meaning each device can transmit, receive, and repeat any message of the Insteon protocol, without requiring a master controller or routing software.

The system is a dual-band mesh topology employing AC-power lines and a radio-frequency (RF) protocol to communicate with devices. It is a home automation networking technology designed by SmartLabs, Inc.

All Insteon powered devices act as repeaters, meaning that they repeat each message they hear. This is in contrast to other mesh networking topologies where only "advanced nodes" repeat. Automatic error detection and correction are included in all Insteon compatible products. The powerline protocol uses phase-shift keying and is designed so that the repetition is synchronized: all repeaters repeat the same message during precisely-defined time slots, so while the repetitions collide, they do so in harmony in a manner that preserves the message. The power line AC frequency is used as the synchronization source.

## *Network Topology*

Insteon is an integrated dual-mesh network that combines wireless radio frequency (RF) with the home's existing electrical wiring. This is intended to improve reliability by providing a backup system in case of wireless interference. As a peer-to-peer network, devices do not require network supervision, thus dispensing with the need for controllers and routing tables.

Each transmission contains a two-bit "hops" field that starts at 3 and is decremented each time a node in the network repeats a message. The repetition scheme is designed so that all of the nodes repeat the messages in precise sync with one another, so the repetitions collide by design and strengthen one another in harmony.

### *Notable limitations*

- Although the network is dual-mesh, many of the core Insteon compatible products on the market (such as the relay-based light switch for installation in junction boxes) can only communicate on one medium or the other (RF or powerline), rather than both. This negates the benefit of dual mesh for a significant portion of any given installation.
- As with X10, powerline communication is not always dependable, and messages can be lost, even with an acknowledgment and retry scheme. Powerline communication reliability can be hampered by household appliances that generate electrical noise on frequencies near those used by Insteon communication (131.65 kHz). This makes it necessary to purchase additional products to repeat signals and filter noise.
- No network troubleshooting tools exist for Insteon, as there are for X10. The only method for troubleshooting an installation is trial and error with filtering and repeater devices.
- Insteon is designed around 60 Hz power often called "two phase" where all circuits cross zero volts at the same time, as is the standard in North American homes. Almost all compatible products support only 110 volts AC. Three-phase power is not supported by the protocol. 220 volt power is only supported on a few products, but this is mainly a limitation of Insteon-compatible devices themselves, not the protocol.

### *Installation*

Insteon devices are set up using a *Plug and Tap* method. Each device has its own unique ID. The procedure to link two Insteon devices can be done manually at the devices. Though a basic system can be deployed without a controller or PC, such a device may be added for advanced home management. Some such devices are able to save and restore the configuration of individual devices on the network.

### *Transmission*

Insteon uses digital signal processing to encode and transmit messages, enabling rapid transmission of control data between Insteon devices. Individual Insteon messages can also carry up to 14 bytes of arbitrary user data to support home-control applications from developers.

### *X10 Compatibility*

Insteon allows manufacturers to develop products that are both Insteon-compatible and X10-ready. Homeowners with existing X10 networks can migrate to an Insteon network without having to discard all their existing X10 devices. Insteon devices repeat Insteon signals and not X10.

Although both can be sent over the same powerline, Insteon commands are not similar to or compatible with X10, and X10 commands are not Insteon. Rather, Insteon driver chipsets simply include the capability of transmitting, receiving, and responding to X10 powerline messages in addition to Insteon messages. X10 compatibility is implemented in the Insteon-compatible chipsets made by SmartLabs which are offered for sale to other product vendors wishing to implement Insteon in their products. Other than requiring detection of X10 signals and taking steps to prevent collisions with X10 messages in transit, X10 compatibility is not part of the Insteon protocol itself.

### *Specifications*

Data Rate

- Instantaneous 13,165 bit/s
- Sustained 2,880 bit/s

Message Types

- Standard 10 B
- Extended 24 B

Message Format/Structure

- Source Address 3 B
- Destination Address 3 B
- Flags 1 B
- Command 2 B
- User Data 14 B
- Message Integrity 1 B

Devices Supported

- Unique IDs 16,777,216
- Device Types 65,536
- Commands 65,536
- Group Members 256

Insteon Engine Memory Requirements

- RAM 80 B

- ROM 3 kB

Typical Application (Light Switch, Lamp Dimmer) Memory Requirements

- RAM 256 B
- EEPROM 256 B
- Flash 7 kB

Powerline Physical Layer

- Frequency 131.65 kHz
- Modulation BPSK
- Min Transmit Level 3.16 Vpp into 5 ohms
- Min Receive Level 10 mV
- Phase Bridging Insteon RF or hardware

RF Physical Layer

- Frequency 902 to 924 MHz
- Modulation FSK
- Sensitivity -103 dBm
- Range 150 ft unobstructed line-of-sight

# Chapter 15

# Bus SCS and C-Bus (Protocol)

## Bus SCS

**SCS** is an acronym for "*Sistema Cablaggio Semplificato*" ("Simplified Wiring System"). It uses a fieldbus network protocol and has applications in the field of home automation and building automation.

### General Features

An SCS bus is based on a sheathed twisted pair formed of two flexible conductors; these are braided and unshielded with isolation 300/500V – according to the rules adopted by CEI (Italian Electrotechnical Committee).

### Communication

Across the Scs bus four different types of signals are transmitted in frequency modulation

- Electricity Supply
- Data
- Sound
- Video

The transmission protocol is the CSMA/CA.

### Functions

Through the SCS bus you have the following functions:

- Automation
- Sound diffusion
- Energy management

- Thermoregulation
- Video intercom
- Alarm system

All the listed functions share the same technology and the same procedures for configuration / installation.

### *Certifications*

Devices connected to the SCS bus are IMQ-certified and comply with these product standards (International Electrotechnical Commission (IEC) EN 50428 - IEC EN 60669-1/A1 - IEC EN 60669-2-1 - IEC EN 50090-2-2 - IEC EN 50090-2-3 ).

### *Integration*

You can interact with the SCS bus through a gateway and an open high-level protocol called OpenWebNet.
These gateways are bidirectional; they translate SCS frames into OpenWebNet frames, and the other way round.

# C-Bus (protocol)

**C-Bus** is a proprietary communications protocol for home and building automation that can handle cable lengths up to 1000 meter using Cat.5 cable. It is used in Australia, New Zealand, Asia, the Middle East, Russia, USA, South Africa, the UK and other parts of Europe including Greece and Romania. C-Bus was created by Clipsal's *Clipsal Integrated Systems* division for use with its brand of home automation and building lighting control system. C-Bus has recently become available in the USA under the 'SquareD Clipsal' brand name.

C-Bus is used in the control of domotics, or home automation systems, as well as commercial building lighting control systems. Unlike the more common X10 protocol which uses a signal imposed upon the AC power line, C-Bus uses a dedicated low-voltage cable or two-way wireless network to carry command and control signals. This improves the reliability of command transmission and makes C-Bus far more suitable for large, commercial applications than X10.

### *C-Bus System*

The C-Bus System can be used to control lighting and other electrical systems and products via remote control and can also be interfaced to a home security system, AV products or other electrical items. The C-Bus system is available in a wired version and a wireless version, with a gateway available to allow messages to be sent between wired and wireless networks.

The wired C-Bus system uses a standard category 5 UTP (Unshielded Twisted Pair) cable as its network communications cable. Clipsal manufacture a specific category 5 cable for use within electrical distribution panels. This cable has a pink outer sheath which is rated to ensure adequate electrical isolation between the mains voltages found in distribution panels and the extra low voltage C-Bus. Outside of distribution panels standard category 5 UTP cable can be used.

The category 5 C-Bus network wiring uses a free topology architecture. The maximum length of cable used on a C-Bus network is 1000 metres; however this is easily extended using C-Bus Network Bridges. Up to 100 units can be installed on a C-Bus network and this can also be extended using Network Bridges.

The maximum number of C-Bus networks in one installation is 255 (note that this limitation does not apply if a C-Bus Ethernet Interface is utilised, the system size is then limited to IP Addressing only). The maximum number of networks connected in series to the local network via Network Bridges is seven (i.e. using six network bridges).

Each standard C-Bus unit requires 18mA @ 15-36Vdc to operate. However some C-Bus units require up to 40mA.

More than one C-Bus power supply can be connected to a C-Bus network to provide sufficient power to the C-Bus units, the C-Bus power supplies will share the load evenly.

Each C-Bus network requires a network burden. This network burden can be enabled on C-Bus output units through software or a hardware burden can be connected to the network.

Each C-Bus network requires at least one system clock generating unit for data synchronisation.

The isolation between the mains supply circuitry and the 36V dc C-Bus circuitry is greater than 3.5kV. This is achieved using double wound transformers and opto isolators. This means the C-Bus wiring, connections and circuitry can be considered Extra Low Voltage.

## *Wiring Design of C-Bus Systems*

In C-Bus systems, the connections between the DB and (for example) the ceiling lights, and between the DB and the junction box (wall switch) are completely separate. In addition, there are no connections between the Junction Box and the respective ceiling lights. The Intelligence of a C-BUS system lies in a “Channel Dimmer” or “Channel Actuator” which is installed in the DB and would replace the traditional standard relay installed in existing homes today. This “Channel Dimmer” would have a 120/220V Line interconnection directly to the ceiling light and a neutral connection back from the ceiling light to the “Channel Dimmer”. The “Channel Dimmer” will control the light directly and will receive its commands either from a rail mounted controller that is connected to its communication port or bus port, or manually from a wall mounted light switch/keypad. This wall mounted light switch would not be connected to any load whatsoever, it would be directly connected with the “Channel Dimmer” by means of a control/signaling cable. The “Channel Dimmers” normally come as 4-channel or 8-channel, this means that they can be connected to 4 or 8 separate lighting circuits at the same time and this din-rail mounted device is also a single point of failure for all these 4 or 8 lighting circuits.

## *C-Bus Interoperability*

As of 9th December 2008 Clipsal opened its C-Bus protocols to anyone who wants to interact with it programatically.

Using one of Clipsal C-Bus PC Modules: Serial (Comport rs232) or Ethernet (tcp/ip) modules, you can interact with other home automation systems, or interact with Andriod apps, and iPad/iPhone apps. All you do is plug a network cable from your Home ADSL WiFi router to the Clipsal C-Bus Ethernet module, and then any Android or iPad can control your home automation system. You can also use this same method to integrate C-bus with HomeSeer using MCSxAP. And in theory you can also do this to integrate C-Bus via a X10 module for the PC.

If you a .Net/Java/c++ software developer, you can find the C-Bus protocol information here to interact from your PC:

Even though C-Bus or Clipsal Bus is a closed protocol. The C-Bus was developed using the ISO 7 layer reference model. C-Bus supports a number of interfaces such as RS232 and TCP/IP and makes these protocols available to third party companies. Clipsal has also developed a server application called C-Gate, to facilitate software integration. The C-Bus interface specifications are available at no-cost through the C-Bus Enabled Program, however it is necessary to agree to a license agreement. It is also possible to become a C-Bus enabled partner; This requires payment but provides a greater level of support for product development and certification.

## *The future of C-Bus*

C-Bus as a home automation and building lighting control system is used primarily in Australia (Sydney Opera House etc.). C-Bus is currently available in Asia, the United Kingdom (installed in Wembley Stadium and Manchester City Football Club), Russia, USA (named SquareD) and a number of other countries are now using this system. One major obstacle to widespread use of wired C-Bus is that it will not work with a standard mains wire installation, a completely new wiring system must be installed for a wired C-Bus system which means that it is normally only used for new builds. The C-Bus wireless (RF) system can however be retrofitted using the existing mains wiring.

C-Bus is compatible with BACnet, TCP/IP, Crestron, AMX, LonWorks, ModBus, Charmed Quark Controller, the Comfort Intelligent Home System and some other protocols through interfaces.

## Chapter 16

# X10 (Industry Standard)


X10 modules (clockwise from upper left): An original BSR lamp module, a "chime module", a recent lamp module, an outlet module

**X10** is an international and open industry standard for communication among electronic devices used for home automation, also known as *domotics*. It primarily uses power line wiring for signaling and control, where the signals involve brief radio frequency bursts representing digital information. A wireless radio based protocol transport is also defined.

X10 was developed in 1975 by Pico Electronics of Glenrothes, Scotland, in order to allow remote control of home devices and appliances. It was the first general purpose domotic network technology and remains the most widely available.

Although a number of higher bandwidth alternatives exist, X10 remains popular in the home environment with millions of units in use worldwide, and inexpensive availability of new components.

## History

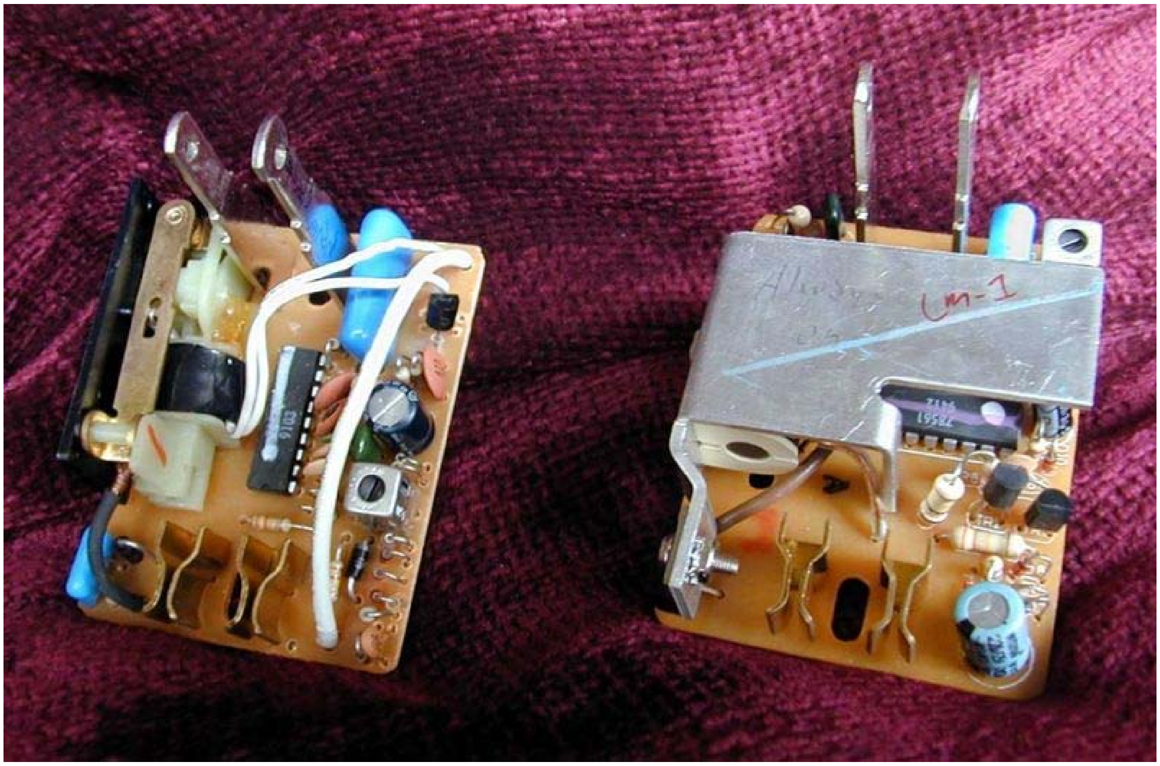
In 1970, a group of engineers started a company in Glenrothes, Scotland called Pico Electronics. The company revolutionized the calculator industry by developing the first single chip calculator.  When the calculator IC prices started to fall. Pico refocused on commercial products rather than plain ICs.

In 1974, the Pico engineers jointly developed a vinyl LP changer with BSR, at the time the largest manufacturer of record changers in the world. It could be operated by a remote control using ultrasound signals. Which gave the idea of remote control for lights and appliances. By 1975, the X10 project was conceived, named so because it was the tenth project. In 1978, X10 products started to appear in Radio Shack and Sears stores. Together with BSR a partnership was formed, with the name X10 Ltd. At that time the system consisted of a 16 channel command console, a lamp module, and an appliance module. Soon after came the wall switch module and the first X10 timer.

In the 1980s the CP-290 computer interface was released. Software for the interface run on the Apple II, Macintosh, MS-DOS, and MS-Windows.

In 1984, BSR went out of business, and X10 (USA) Inc was formed. In the early 1990s, the consumer market was divided into two main categories, the ultra-high-end with a budget at > 100 000 USD and the mass market with budgets at 2000 - 35 000 USD. CEBus (1984) and LonWorks (1991) were attempts to improve reliability and replace X10, but have yet to succeed with market ubiquity.

## *Power line carrier control overview*



X10 modules: The interior of an appliance module (note the impulse relay on the left) and a lamp module (note the TRIAC and heat sink)

Household electrical wiring (the same which powers lights and appliances) is used to send digital data between X10 devices. This digital data is encoded onto a 120 kHz carrier which is transmitted as bursts during the relatively quiet zero crossings of the 50 or 60 Hz AC alternating current waveform. One bit is transmitted at each zero crossing.

The digital data consists of an address and a command sent from a controller to a controlled device. More advanced controllers can also query equally advanced devices to respond with their status. This status may be as simple as "off" or "on", or the current dimming level, or even the temperature or other sensor reading. Devices usually plug into the wall where a lamp, television, or other household appliance plugs in; however some built-in controllers are also available for wall switches and ceiling fixtures.

The relatively high-frequency carrier frequency carrying the signal cannot pass through a power transformer or across the phases of a multiphase system. For split phase systems, the signal can be passively coupled from phase-to-phase using a passive capacitor, but for three phase systems or where the capacitor provides insufficient coupling, an active X10 repeater can be used. To allow signals to be coupled across phases and still match each phase's zero crossing point, each bit is transmitted three times in each half cycle, offset by 1/6th cycle.

It may also be desirable to block X10 signals from leaving the local area so, for example, the X10 controls in one house do not interfere with the X10 controls in a neighboring house. In this situation, inductive filters can be used to attenuate the X10 signals coming into or going out of the local area.

## X10 protocol

Whether using power line or radio communications, packets transmitted using the X10 control protocol consist of a four bit *house code* followed by one or more four bit *unit code*, finally followed by a four bit command. For the convenience of users configuring a system, the four bit house code is selected as a letter from A through P while the four bit unit code is a number 1 through 16.

When the system is installed, each controlled device is configured to respond to one of the 256 possible addresses (16 house codes × 16 unit codes); each device reacts to commands specifically addressed to it, or possibly to several broadcast commands.

The protocol may transmit a message that says "select code A3", followed by "turn on", which commands unit "A3" to turn on its device. Several units can be addressed before giving the command, allowing a command to affect several units simultaneously. For example, "select A3", "select A15", "select A4", and finally, "turn on", causes units A3, A4, and A15 to all turn on.

Note that there is no restriction (except possibly consideration of the neighbors) that prevents using more than one house code within a single house. The "all lights on" command and "all units off" commands will only affect a single house code, so an installation using multiple house codes effectively has the devices divided into separate zones.

List of X10 commands:

| Code | Function | Description |
|---|---|---|
| 0 0 0 0 | All units off | Switch off all devices with the house code indicated in the message |
| 0 0 0 1 | All lights on | Switches on all lighting devices (with the ability to control brightness) |
| 0 0 1 0 | On | Switches on a device |
| 0 0 1 1 | Off | Switches off a device |
| 0 1 0 0 | Dim | Reduces the light intensity |
| 0 1 0 1 | Bright | Increases the light intensity |

| | | |
|---|---|---|
| 0 1 1 1 | Extended code | Extension code |
| 1 0 0 0 | Hail request | Requests a response from the device(s) with the house code indicated in the message |
| 1 0 0 1 | Hail acknowledge | Response to the previous command |
| 1 0 1 x | Pre-set dim | Allows the selection of two predefined levels of light intensity |
| 1 1 0 1 | Status is on | Response to the Status Request indicating that the device is switched on |
| 1 1 1 0 | Status is off | Response indicating that the device is switched off |
| 1 1 1 1 | Status request | Request requiring the status of a device |

### *Power line protocol physical layer details*

In the 60 Hz AC current flow, a bit value of one is represented by a 1 millisecond burst of 120 kHz at the zero crossing point (nominally 0°, but within 200 microseconds of the zero crossing point), immediately followed by the absence of a pulse. A zero value is represented by the absence of 120 kHz at the zero crossing point (pulse), immediately followed by the presence of a pulse. All messages are sent twice to reduce false signaling. After allowing for retransmission, line control, etc., data rates are around 20 bit/s, making X10 data transmission so slow that the technology is confined to turning devices on and off or other very simple operations.

In order to provide a predictable start point, every data frame transmitted always begin with a *start code* of 1110. Immediately after the start code, a *house code* (A–P) appears, and after the letter code comes a *function code*. Function codes may specify a unit number code (1–16) or a command code, the selection between the two modes being determined by the last bit where 0=unit number and 1=command. One start code, one letter code, and one function code is known as an X10 **frame** and represent the minimum components of a valid X10 data packet.

Each frame is sent twice in succession to make sure the receivers understand it over any power line noise for purposes of redundancy, reliability, and to accommodate line repeaters.

Whenever the data changes from one address to another address, from an address to a command, or from one command to another command, the data frames must be separated by at least 6 clear zero crossings (or "000000"). The sequence of six zeros resets the device decoder hardware.

Later developments (1997) of hardware are improvements of the native X10 hardware. This is called "Advanced X10" or A10. These devices contain improved hardware with a receiver and transmitter allowing two-way communication between the devices. In Europe (2001) for the 230 VAC 50 Hz market, this improvement is called Xanura. All improved products use the same X10 protocol.

### *The radio protocol*


A four-channel radio switch and radio-to-power-line transponder

To allow the operation of wireless keypads, remote switches, and the like, a radio protocol is also defined. Operating at a frequency of 310 MHz in the U.S. and 433 MHz in European systems, the wireless devices send data packets that are very similar to ordinary X10 power line control packets. A radio receiver then provides a bridge which translates these radio packets to ordinary X10 power line control packets.

The devices available using the radio protocol include:

- Keypad controllers ("clickers")
- Keychain controllers that can control one to four X10 devices
- Burglar alarm modules that can transmit sensor data
- Passive infrared switches to control lighting and X-10 chimes
- Non-passive information bursts

### *Device modules*

X10 modules: A lamp socket module

Depending on the load that is to be controlled, different modules must be used. For incandescent lamp loads, a *lamp module* or *wall switch* module can be used. These modules switch the power using a TRIAC solid state switch and are also capable of dimming the lamp load. Lamp modules are almost silent in operation, and generally rated to control loads ranging from approximately 40 to 500 watts.

For loads other than incandescent lamps, such as fluorescent lamps, high-intensity discharge lamps, and electrical home appliances, the triac-based electronic switching in the lamp module is unsuitable and an *appliance module* must be used instead. These modules switch the power using an impulse relay. In the U.S., these modules are generally rated to control loads up to 15 amperes (1800 watts at 120V).

Many device modules offer a feature called *local control*. If the module is switched off, operating the power switch on the lamp or appliance will cause the module to turn on. In this way, a lamp can still be lit or a coffee pot turned on without the need to use an X10 controller. Wall switch modules may not offer this feature.

Some wall switch modules offer a feature called *local dimming*. Ordinarily, the local push button of a wall switch module simply offers on/off control with no possibility of locally dimming the controlled lamp. If local dimming is offered, holding down the push button will cause the lamp to cycle through its brightness range.

Higher end modules have more advanced features such as programmable on levels, customizable fade rates, the ability to transmit commands when used (referred to as 2-way devices), and *scene* support.

There are sensor modules that sense and report temperature, light, infra-red, motion, or contact openings and closures. Device modules include thermostats, audible alarms and controllers for low voltage switches.

### *Controllers*


X10 controllers: A simple controller, a radio controller, and an original controller usable with an ultrasonic remote control

X10 controllers range from extremely simple to very sophisticated.

The simplest controllers are arranged to control four X10 devices at four sequential addresses (1–4 or 5–8). The controllers typically contain the following buttons:

- Unit 1 on/off
- Unit 2 on/off
- Unit 3 on/off
- Unit 4 on/off
- Brighten/dim (last selected unit)
- All lights on/all units off

More sophisticated controllers can control more units and/or incorporate timers that perform preprogrammed functions at specific times each day. Units are also available that use passive infrared motion detectors or photocells to turn lights on and off based on external conditions.

Finally, very sophisticated units are available that can be fully programmed or, like the X10 Firecracker, use a program running in an external computer. These systems can execute many different timed events, respond to external sensors, and execute, with the press of a single button, an entire *scene*, turning lights on, establishing brightness levels, and so on. Control programs are available for computers running Microsoft Windows, Apple's Macintosh, Linux and FreeBSD operating systems.

Burglar alarm systems are also available. These systems contain door/window sensors as well as motion sensors that use a coded RF signal to identify when they are tripped or just to routinely check-in and give a heart-beat signal to show that the system is still active. Users can arm and disarm their system via several different remote controls which also use a coded RF signal to ensure security. When an alarm is triggered the console will make an outbound phone call with a recorded message. The console will also use X10 protocols to flash lights when an alarm has been triggered while the security console sounds an external siren. Using X10 protocols signals will also be sent to remote sirens for additional security.

## *Weak points and limitations*

### Compatibility with installed wiring and appliances

One problem with X10 is excessive attenuation of signals between the two live conductors in the 3-wire 120/240 volt system used in typical North American residential construction. Signals from a transmitter on one live conductor may not propagate through the high impedance of the distribution transformer winding to the other live conductor. Often, there's simply no reliable path to allow the X10 signals to propagate from one transformer leg wire to the other; this failure may come and go as large 240 volt devices such as stoves or dryers are turned on and off. (When turned on, such devices provide a low-impedance bridge for the X10 signals between the two leg wires.) This problem can be permanently overcome by installing a capacitor between the leg wires as a path for the X10 signals; manufacturers commonly sell signal couplers that plug into 240 volt sockets that perform this function. More sophisticated installations install an active repeater device between the legs, while others combine signal amplifiers with a coupling device. A repeater is also needed for inter-phase communication in homes with three-phase electric power. In many countries outside North America, entire houses are typically wired from a single 240 volt single-phase wire, so this problem does not occur.

An RCD/GFCI can attenuate X10 signals passing through the device. This means that X10 signals passing through an RCD may not be strong enough to provide reliable communication.

Television receivers or household wireless devices may cause spurious "off" or "on" signals. Noise filtering (as installed on computers as well as many modern appliances) may help keep external noise out of X10 signals, but noise filters not designed for X10 may also attenuate X10 signals traveling on the branch circuit to which the appliance is connected.

Certain types of power supplies used in modern electronic equipment, such as computers, television receivers and satellite receivers, attenuate passing X10 signals by providing a low impedance path to high frequency signals. Typically, the capacitors used on the inputs to these power supplies short the X10 signal from line to neutral, suppressing any hope of X10 control on the circuit near that device. Filters are available that will block the X10 signals from ever reaching such devices; plugging offending devices into such filters can cure mysterious X10 intermittent failures.

Some X10 controllers may not work well or at all with low power devices (below 50 watts) or devices like fluorescent bulbs that do not present resistive loads. Use of an appliance module rather than a lamp module may resolve this problem.

## Commands getting lost

X10 signals can only be transmitted one command at a time, first by addressing the device to control, and then sending an operation for that device to perform. If two X10 signals are transmitted at the same time they may collide or interleave, leading to commands that either cannot be decoded or that trigger incorrect operations. The CM15A and RR501 Transceiver can avoid these signal collisions that can sometimes occur with other models.

## Relatively slow

The X10 protocol is slow. It takes roughly three quarters of a second to transmit a device address and a command. While generally not noticeable when using a tabletop controller, it becomes a noticeable problem when using 2-way switches or when utilizing some sort of computerized controller. The apparent delay can be lessened somewhat by using slower device dim rates. With more advanced modules another option is to use group control (lighting scene) extended commands. These allow to adjust several modules at once by a single command.

### Limited functionality

X10 protocol does support more advanced control over the dimming speed, direct dim level setting and group control (scene settings). This is done via extended message set, which is an official part of X10 standard . However support for all extended messages is not mandatory, and a lot of cheaper modules implement only the basic message set. These require adjusting each lighting circuit one after the other, which can be visually unappealing and also very slow.

### Interference and lack of encryption

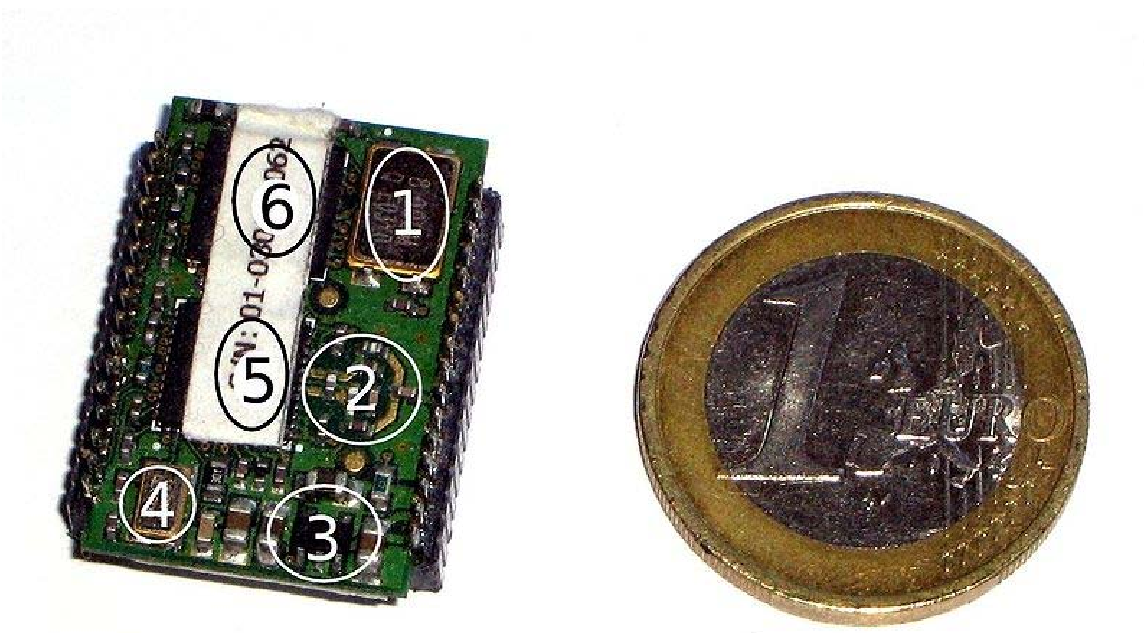
The standard X10 power line and RF protocols lack support for encryption, and can only address 256 devices. Unfiltered power line signals from close neighbors using the same X10 device addresses may interfere with each other. Interfering RF wireless signals may similarly be received, with it being easy for anyone nearby with an X10 RF remote to wittingly or unwittingly cause mayhem if an RF to power line device is being used on a premises.

## *Bridges*

There are bridges to translate X10 to other domotic standards (e.g., KNX). ioBridge translates the X10 protocol to a web service API via the X10 PSC04 Powerline Interface Module.

## Chapter 17

# ZigBee




ZigBee module. The €1 coin, shown for size reference, is about 23 mm (0.9 inch) in diameter.

**ZigBee** is a specification for a suite of high level communication protocols using small, low-power digital radios based on the IEEE 802.15.4-2003 standard for Low-Rate Wireless Personal Area Networks (LR-WPANs), such as wireless light switches with lamps, electrical meters with in-home-displays, consumer electronics equipment via short-range radio needing low rates of data transfer. The technology defined by the ZigBee specification is intended to be simpler and less expensive than other WPANs, such as Bluetooth. ZigBee is targeted at radio-frequency (RF) applications that require a low data rate, long battery life, and secure networking.

### *Technical overview*

ZigBee is a low-cost, low-power, wireless mesh networking standard. First, the low cost allows the technology to be widely deployed in wireless control and monitoring applications. Second, the low power-usage allows longer life with smaller batteries. Third, the mesh networking provides high reliability and more extensive range.

It is not capable of powerline networking though other elements of the OpenHAN standards suite promoted by openAMI and UtilityAMI deal with communications co-extant with AC power outlets. In other words, ZigBee is intended not to support powerline networking but to interface with it at least for smart metering and smart appliance purposes. Utilities, e.g. Penn Energy, have declared the intent to require them to interoperate again via the openHAN standards.

### *Trademark and Alliance*

The ZigBee Alliance is an association of companies working together to enable reliable, cost-effective, and low-power wirelessly networked monitoring and control products based on an open global standard.

The ZigBee Alliance is a group of companies that maintain and publish the ZigBee standard. The term **ZigBee** is a registered trademark of this group, not a single technical standard.

As per its main role, it standardizes the body that defines ZigBee, and also publishes application profiles that allow multiple OEM vendors to create interoperable products. The current list of application profiles either published, or in the works are:

### *Released specifications*

- ZigBee Home Automation
- ZigBee Smart Energy 1.0
- ZigBee Telecommunication Services
- ZigBee Health Care
- ZigBee Remote Control

### *Specifications under development*

- ZigBee Smart Energy 2.0
- ZigBee Building Automation
- ZigBee Retail Services

The relationship between IEEE 802.15.4 and ZigBee is similar to that between IEEE 802.11 and the Wi-Fi Alliance. The ZigBee 1.0 specification was ratified on 14 December 2004 and is available to members of the ZigBee Alliance. Most recently, the ZigBee 2007 specification was posted on 30 October 2007. The first ZigBee Application Profile, Home Automation, was announced 2 November 2007. As amended by NIST, the Smart Energy Profile 2.0 specification will remove the dependency on IEEE 802.15.4. Device manufacturers will be able to implement any MAC/PHY, such as IEEE 802.15.4(x) and IEEE P1901, under an IP layer based on 6LoWPAN.

ZigBee operates in the industrial, scientific and medical (ISM) radio bands; 868 MHz in Europe, 915 MHz in the USA and Australia, and 2.4 GHz in most jurisdictions worldwide. The technology is intended to be simpler and less expensive than other WPANs such as Bluetooth. ZigBee chip vendors typically sell integrated radios and microcontrollers with between 60 KB and 256 KB flash memory.

## *Chip vendors/devices include*

- Atmel ATmega128RFA1
- Digi International XBee XB24CZ7PIS-004
- Freescale MC13213
- Ember EM250
- Jennic JN5148
- Renesas uPD78F8056/57/58, M16C/6B3 and R8C/3MQ
- STMicroelectronics STM32W
- Samsung Electro-Mechanics ZBS240
- Texas Instruments CC2530 and CC2520

Radios are also available as stand-alone components to be used with any processor or microcontroller. Generally, the chip vendors also offer the ZigBee software stack, although independent ones are also available.

Because ZigBee can activate (go from sleep to active mode) in 30 msec or less, the latency can be very low and devices can be very responsive — particularly compared to Bluetooth wake-up delays, which are typically around three seconds. Because ZigBees can sleep most of the time, average power consumption can be very low, resulting in long battery life.

The first stack release is now called *ZigBee 2004*. The second stack release is called *ZigBee 2006*, and mainly replaces the MSG/KVP structure used in 2004 with a "cluster library". The 2004 stack is now more or less obsolete.

*ZigBee 2007*, now the current stack release, contains two stack profiles, stack profile 1 (simply called ZigBee), for home and light commercial use, and stack profile 2 (called ZigBee Pro). ZigBee Pro offers more features, such as multi-casting, many-to-one routing and high security with Symmetric-Key Key Exchange (SKKE), while ZigBee (stack profile 1) offers a smaller footprint in RAM and flash. Both offer full mesh networking and work with all ZigBee application profiles.

ZigBee 2007 is fully backward compatible with ZigBee 2006 devices: A ZigBee 2007 device may join and operate on a ZigBee 2006 network and vice versa. Due to differences in routing options, ZigBee Pro devices must become non-routing ZigBee End-Devices (ZEDs) on a ZigBee 2006 network, the same as for ZigBee 2006 devices on a ZigBee 2007 network must become ZEDs on a ZigBee Pro network. The applications running on those devices work the same, regardless of the stack profile beneath them.

## *Licensing*

For non-commercial purposes, the ZigBee specification is available free to the general public. An entry level membership in the ZigBee Alliance, called Adopter, provides access to the as-yet unpublished specifications and permission to create products for market using the specifications.

The click through license on the ZigBee specification requires a commercial developer to join the ZigBee Alliance. "No part of this specification may be used in development of a product for sale without becoming a member of ZigBee Alliance." This causes problems for open-source developers because the annual fee conflicts with the GNU General Public License. From the GPL v2, "b) You must cause any work that you distribute or publish, that in whole or in part contains or is derived from the Program or any part thereof, to be licensed as a whole at no charge to all third parties under the terms of this License." Since the GPL makes no distinction between commercial and non-commercial use it is impossible to implement a GPL licensed ZigBee stack or combine a ZigBee implementation with GPL licensed code. The requirement for the developer to join the ZigBee Alliance similarly conflicts with most other Free software licenses.

## *Uses*

ZigBee protocols are intended for use in embedded applications requiring low data rates and low power consumption. ZigBee's current focus is to define a general-purpose, inexpensive, self-organizing mesh network that can be used for industrial control, embedded sensing, medical data collection, smoke and intruder warning, building automation, home automation, etc. The resulting network will use very small amounts of power — individual devices must have a battery life of at least two years to pass ZigBee certification.

Typical application areas include

- **Home Entertainment and Control** — Smart lighting, advanced temperature control, safety and security, movies and music

- ***Wireless Sensor Networks'*** — Starting with individual sensors like Telosb/Tmote and Iris from Memsic.

## *Device types*

There are three different types of ZigBee devices:

- *ZigBee coordinator (ZC)*: The most capable device, the coordinator forms the root of the network tree and might bridge to other networks. There is exactly one ZigBee coordinator in each network since it is the device that started the network originally. It is able to store information about the network, including acting as the Trust Center & repository for security keys.
- *ZigBee Router (ZR)*: As well as running an application function, a router can act as an intermediate router, passing on data from other devices.
- *ZigBee End Device (ZED)*: Contains just enough functionality to talk to the parent node (either the coordinator or a router); it cannot relay data from other devices. This relationship allows the node to be asleep a significant amount of the time thereby giving long battery life. A ZED requires the least amount of memory, and therefore can be less expensive to manufacture than a ZR or ZC.

## *Protocols*

The protocols build on recent algorithmic research (Ad-hoc On-demand Distance Vector, neuRFon) to automatically construct a low-speed ad-hoc network of nodes. In most large network instances, the network will be a cluster of clusters. It can also form a mesh or a single cluster. The current profiles derived from the ZigBee protocols support beacon and non-beacon enabled networks.

In non-beacon-enabled networks (those whose beacon order is 15), an unslotted CSMA/CA channel access mechanism is used. In this type of network, ZigBee Routers typically have their receivers continuously active, requiring a more robust power supply. However, this allows for heterogeneous networks in which some devices receive continuously, while others only transmit when an external stimulus is detected. The typical example of a heterogeneous network is a wireless light switch: The ZigBee node at the lamp may receive constantly, since it is connected to the mains supply, while a battery-powered light switch would remain asleep until the switch is thrown. The switch then wakes up, sends a command to the lamp, receives an acknowledgment, and returns to sleep. In such a network the lamp node will be at least a ZigBee Router, if not the ZigBee Coordinator; the switch node is typically a ZigBee End Device.

In beacon-enabled networks, the special network nodes called ZigBee Routers transmit periodic beacons to confirm their presence to other network nodes. Nodes may sleep between beacons, thus lowering their duty cycle and extending their battery life. Beacon intervals may range from 15.36 milliseconds to 15.36 ms * $2^{14}$ = 251.65824 seconds at 250 kbit/s, from 24 milliseconds to 24 ms * $2^{14}$ = 393.216 seconds at 40 kbit/s and from 48 milliseconds to 48 ms * $2^{14}$ = 786.432 seconds at 20 kbit/s. However, low duty cycle operation with long beacon intervals requires precise timing, which can conflict with the need for low product cost.

In general, the ZigBee protocols minimize the time the radio is on so as to reduce power use. In beaconing networks, nodes only need to be active while a beacon is being transmitted. In non-beacon-enabled networks, power consumption is decidedly asymmetrical: some devices are always active, while others spend most of their time sleeping.

Except for the Smart Energy Profile 2.0, which will be MAC/PHY agnostic, ZigBee devices are required to conform to the IEEE 802.15.4-2003 Low-Rate Wireless Personal Area Network (WPAN) standard. The standard specifies the lower protocol layers—the physical layer (PHY), and the media access control (MAC) portion of the data link layer (DLL). This standard specifies operation in the unlicensed 2.4 GHz (worldwide), 915 MHz (Americas) and 868 MHz (Europe) ISM bands. In the 2.4 GHz band there are 16 ZigBee channels, with each channel requiring 5 MHz of bandwidth. The center frequency for each channel can be calculated as, $F_C = (2405 + 5 * (ch - 11))$ MHz, where ch = 11, 12, ..., 26.

The radios use direct-sequence spread spectrum coding, which is managed by the digital stream into the modulator. BPSK is used in the 868 and 915 MHz bands, and OQPSK that transmits four bits per symbol is used in the 2.4 GHz band. The raw, over-the-air data rate is 250 kbit/s per channel in the 2.4 GHz band, 40 kbit/s per channel in the 915 MHz band, and 20 kbit/s in the 868 MHz band. Transmission range is between 10 and 75 meters (33 and 246 feet) and up to 1500 meters for zigbee pro, although it is heavily dependent on the particular environment. The output power of the radios is generally 0 dBm (1 mW).

The basic channel access mode is "carrier sense, multiple access/collision avoidance" (CSMA/CA). That is, the nodes talk in the same way that people converse; they briefly check to see that no one is talking before they start. There are three notable exceptions to the use of CSMA. Beacons are sent on a fixed timing schedule, and do not use CSMA. Message acknowledgments also do not use CSMA. Finally, devices in Beacon Oriented networks that have low latency real-time requirements may also use Guaranteed Time Slots (GTS), which by definition do not use CSMA.

## ZigBee RF4CE

On March 3, 2009 the RF4CE (Radio Frequency for Consumer Electronics) Consortium agreed to work with the ZigBee Alliance to jointly deliver a standardized specification for radio frequency-based remote controls. ZigBee RF4CE is designed to be deployed in a wide range of remotely-controlled audio/visual consumer electronics products, such as TVs and set-top boxes. It promises many advantages over existing remote control solutions, including richer communication and increased reliability, enhanced features and flexibility, interoperability, and no line-of-sight barrier.

## *Software and hardware*

The software is designed to be easy to develop on small, inexpensive microprocessors. The radio design used by ZigBee has been carefully optimized for low cost in large scale production. It has few analog stages and uses digital circuits wherever possible.

Even though the radios themselves are inexpensive, the ZigBee Qualification Process involves a full validation of the requirements of the physical layer. This amount of concern about the Physical Layer has multiple benefits, since all radios derived from that semiconductor mask set would enjoy the same RF characteristics. On the other hand, an uncertified physical layer that malfunctions could cripple the battery lifespan of other devices on a ZigBee network. Where other protocols can mask poor sensitivity or other esoteric problems in a fade compensation response, ZigBee radios have very tight engineering constraints: they are both power and bandwidth constrained. Thus, radios are tested to the ISO 17025 standard with guidance given by Clause 6 of the 802.15.4-2006 Standard. Most vendors plan to integrate the radio and microcontroller onto a single chip getting smaller devices .

## *History*

- ZigBee-style networks began to be conceived around 1998, when many installers realized that both Wi-Fi and Bluetooth were going to be unsuitable for many applications. In particular, many engineers saw a need for self-organizing ad-hoc digital radio networks.
- The IEEE 802.15.4-2003 standard was completed in May 2003 and has been superseded by the publication of IEEE 802.15.4-2006.
- In the summer of 2003, Philips Semiconductors, a major mesh network supporter, ceased the investment. Philips Lighting has, however, continued Philips' participation, and Philips remains a promoter member on the ZigBee Alliance Board of Directors.
- The ZigBee Alliance announced in October 2004 that the membership had more than doubled in the preceding year and had grown to more than 100 member companies, in 22 countries. By April 2005 membership had grown to more than 150 companies, and by December 2005 membership had passed 200 companies.
- The ZigBee specifications were ratified on 14 December 2004.
- The ZigBee Alliance announces public availability of Specification 1.0 on 13 June 2005, known as ZigBee 2004 Specification.
- The ZigBee Alliance announces the completion and immediate member availability of the enhanced version of the ZigBee Standard in September 2006, known as ZigBee 2006 Specification.
- During the last quarter of 2007, ZigBee PRO, the enhanced ZigBee specification was finalized.

### Origin of the ZigBee name

The name of the brand is originated with reference to the behaviour of honey bees after their return to the beehive.

# Chapter 18

# Z-Wave

**Z-Wave** is a proprietary wireless communications protocol designed for home automation, specifically to remote control applications in residential and light commercial environments. The technology uses a low-power RF radio embedded or retrofitted into home electronics devices and systems, such as lighting, home access control, entertainment systems and household appliances.

The Z-Wave Alliance is an international consortium of manufacturers that provide interoperable Z-Wave enabled devices.

## *Overview*

Z-Wave is a low-power wireless technology designed specifically for remote control applications. Unlike Wi-Fi and other IEEE 802.11-based wireless LAN systems that are designed primarily for high-bandwidth data flow, the Z-Wave RF system operates in the sub gigahertz frequency range and is optimized for low-overhead commands such as on-off (as in a light switch or an appliance) and raise-lower (as in a thermostat or volume control), with the ability to include device metadata in the communications.

Because Z-Wave operates apart from the crowded 2.4 GHz frequency, it is largely unaffected by interference from common household wireless electronics that operate in this range. Z-Wave does share a range (900 MHz) used by some cell-phones and would be susceptible to interference from such devices. However, this freedom from normal household interference allows for a standardized low-bandwidth control medium that can be reliable alongside common wireless devices.

As a result of its low power consumption and low cost of manufacture, Z-Wave is easily embedded in consumer electronics products, including battery operated devices such as remote controls, smoke alarms and security sensors. Z-Wave is currently supported by over 200 manufacturers worldwide and appears in a broad range of consumer products in the U.S. and Europe.

The standard itself is not open and is available only to Zensys customers under non-disclosure agreement. Some Z-Wave product vendors have embraced the open source and hobbyist communities.

## Applications

Z-Wave is a mesh networking technology where each node or device on the network is capable of sending and receiving control commands through walls or floors and use intermediate nodes to route around household obstacles or radio dead spots that might occur in the home. Z-Wave devices can work individually or in groups, and can be programmed into scenes or events that trigger multiple devices, either automatically or via remote control. Some common applications for Z-Wave include:

**Remote home control and management**

By adding Z-Wave to home electronics such as lighting, climate and security systems, it is possible to control and monitor these household functions via remote control, based on manual or automated decisions. The control can be applied to a single device or group of devices, in a single room or zone or throughout the entire home. One of the benefits of Z-Wave over power line communication technologies is the ability to function in older houses lacking a neutral wire. Z-Wave devices can also be monitored and controlled from outside of the home by way of a gateway that combines Z-Wave with broadband Internet access.

**Energy Conservation**

Z-Wave is envisioned as a key enabling technology for energy management in the green home. As an example, Z-Wave-enabled thermostats are able to raise or lower automatically, based on commands from Z-Wave enabled daylight sensors. Grouped scene controls can ensure that unnecessary energy consumption is minimized by various all-off states for systems throughout the home, such as lighting, appliances and home entertainment systems.

**Home safety and security systems**

Because Z-Wave can transceive commands based on real time conditions, and is able to control devices in intelligent groupings, it allows novel extensions of traditional home security concepts. As an example, the opening of a Z-Wave enabled door lock can de-activate a security system and turn on lights when children arrive home from school, and send a notification to a parent's PC or cell phone via the Internet. Opening a Z-Wave enabled garage door can trigger exterior and interior home lights, while a Z-Wave motion detector can trigger an outdoor security light and a webcam, which would allow the end user to monitor the home while away.

**Home entertainment**

Z-Wave's ability to command multiple devices as a unified event makes it well suited for home audio and video applications. For example, a simple "Play DVD" command on the remote control could turn on the needed components, set them to the correct inputs and even lower motorized shades and dim the room lights. Z-Wave's RF technology is also well suited as an evolution of conventional infrared (IR) based remote controls for home electronics, as it is not constrained by IR's line of sight and distance limitations. In January of 2008, Zensys announced a single-chip solution that pairs Z-Wave with IR control, positioning the technology as an all encompassing solution for home remote controls.

## *Setting up a Z-Wave network*

Z-Wave mesh networks can begin with a single controllable device and a controller. Additional devices can be added at any time, as can multiple controllers, including traditional hand-held controllers, key-fob controllers, wall-switch controllers and PC applications designed for management and control of a Z-Wave network.

A device must be "included" to the Z-Wave network before it can be controlled via Z-Wave. This process (also known as "pairing" and "adding") is usually achieved by pressing a sequence of buttons on the controller and the device being added to the network. This sequence only needs to be performed once, after which the device is always recognized by the controller. Devices can be removed from the Z-Wave network by a similar process of button strokes.

This inclusion process is repeated for each device in the system. Because the controller is learning the signal strength between the devices during the inclusion process, the devices themselves should be in their intended final location before they are added to the system.

However, once a device has been introduced into a network, it can become troublesome to remove the unit without actually having the functional unit present. A number of Z-Wave users have complained that a Z-Wave controller can be functionally destroyed by the bulb that it controls blowing and any controlling units then report errors every time a command that would affect that unit is sent, *i.e.*, group commands / scene commands / all-on / all-off, etc. The only way to restore the service to a non-error reporting state is to factory reset all controllers and then relearn all Z-Wave devices.

## *Z-Wave Alliance*

The Z-Wave Alliance is a consortium of over 160 independent manufacturers who have agreed to build wireless home control products based on the Z-Wave standard. Principal members include Cooper Wiring Devices, Danfoss, Fakro, Ingersoll-Rand, Intermatic, Leviton, Universal Electronics, Wayne-Dalton, Z-Wave and Zensys.

Products and applications from the Z-Wave Alliance fall into all major market sectors for residential and light commercial control applications. These include lighting, HVAC and security control, as well as home theaters, automated window treatments, pool and spa controls, garage and access controls and more.

### Radio specifications

Bandwidth: 9,600 bit/s or 40 kbit/s, fully interoperable

Modulation: GFSK

Range: Approximately 100 feet (or 30 meters) assuming "open air" conditions, with reduced range indoors depending on building materials, etc.

Frequency band: The Z-Wave Radio uses the 900 MHz ISM band: 908.42 MHz (United States); 868.42 MHz (Europe); 919.82 MHz (Hong Kong); 921.42 MHz (Australia/New Zealand).

### Radio specifics

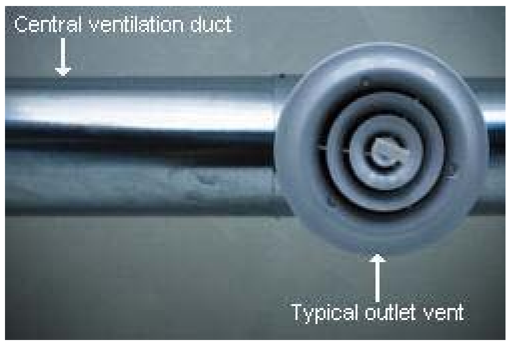
In Europe, the 868 MHz band has a 1% duty cycle limitation, meaning that a Z-Wave unit can only transmit 1% of the time. This limitation is not present in the U.S. 908 MHz band, but U.S. legislation imposes a 1 mW transmission power limit, as opposed to 25 mW in Europe. Z-Wave units can be in power-save mode and only be active 0.1% of the time, thus reducing power consumption dramatically.

### Topology and routing

Z-Wave uses a source-routed mesh network topology and has one or more master controllers that control routing and security. Devices can communicate to another by using intermediate nodes to actively route around household obstacles or radio dead spots that might occur. A message from node A to node C can be successfully delivered even if the two nodes are not within range, providing that a third node B can communicate with nodes A and C. If the preferred route is unavailable, the message originator will attempt other routes until a path is found to the "C" node. Therefore a Z-Wave network can span much farther than the radio range of a single unit; however with several of these hops a delay may be introduced between the control command and the desired result. In order for Z-Wave units to be able to route unsolicited messages, they cannot be in sleep mode. Therefore, most battery-operated devices are not designed as repeater units. A Z-Wave network can consist of up to 232 devices with the option of bridging networks if more devices are required.

# Chapter 19

# HVAC

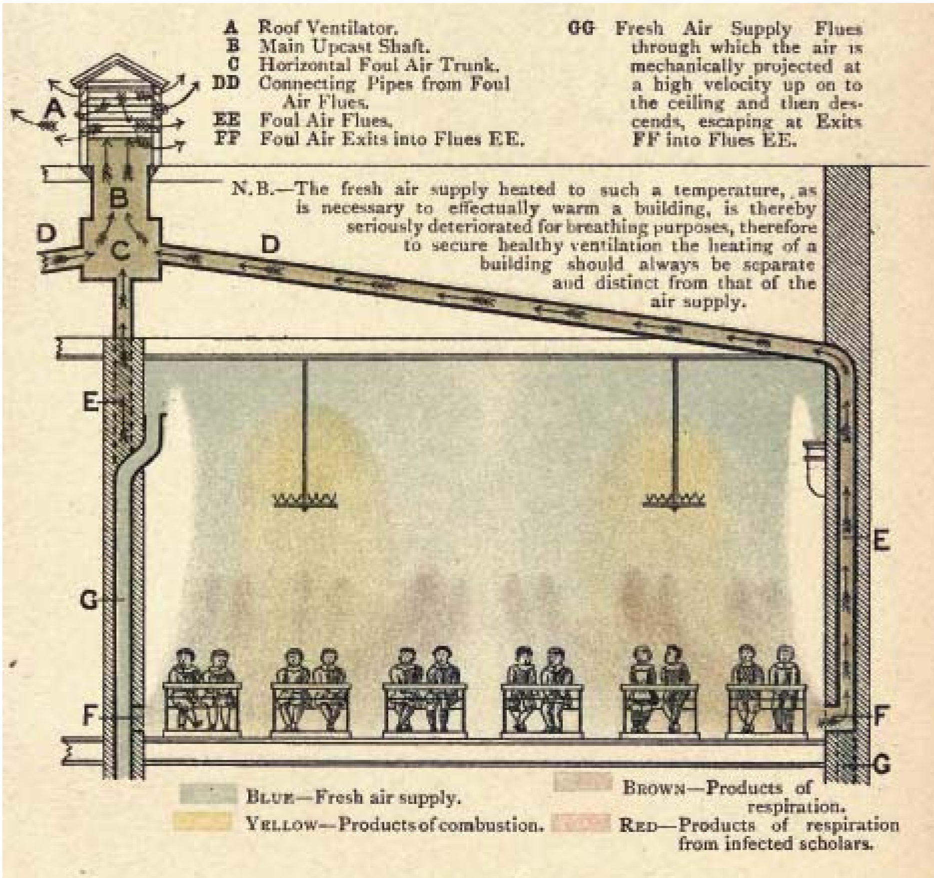



HVAC systems use ventilation air ducts installed throughout a building that supply conditioned air to a room through rectangular or round outlet vents, called diffusers; and ducts that remove air through return-air grilles

**HVAC** (Heating, Ventilating, and Air Conditioning) refers to technology of indoor or automotive environmental comfort. HVAC system design is a major subdiscipline of mechanical engineering, based on the principles of thermodynamics, fluid mechanics, and heat transfer. Refrigeration is sometimes added to the field's abbreviation as HVAC&R or HVACR, or ventilating is dropped as in HACR (such as the designation of HACR-rated circuit breakers).

HVAC is important in the design of medium to large industrial and office buildings such as skyscrapers and in marine environments such as aquariums, where safe and healthy building conditions are regulated with temperature and humidity, as well as "fresh air" from outdoors.

### *Background*




Ventilation (architecture) on the downdraught system, by impulsion, or the 'plenum' principle, applied to schoolrooms (1899)

Heating, ventilating, and air conditioning is based on inventions and discoveries made by Nikolay Lvov, Michael Faraday, Willis Carrier, Reuben Trane, James Joule, William Rankine, Sadi Carnot, and many others.

The invention of the components of HVAC systems went hand-in-hand with the industrial revolution, and new methods of modernization, higher efficiency, and system control are constantly introduced by companies and inventors all over the world. The three central functions of heating, ventilating, and air-conditioning are interrelated, providing thermal comfort, acceptable indoor air quality, within reasonable installation, operation, and maintenance costs. HVAC systems can provide ventilation, reduce air infiltration, and maintain pressure relationships between spaces. How air is delivered to, and removed from spaces is known as room air distribution.

In modern buildings the design, installation, and control systems of these functions are integrated into one or more HVAC systems. For very small buildings, contractors normally "size" and select HVAC systems and equipment. For larger buildings, building services designers and engineers, such as mechanical, architectural, or building services engineers analyze, design, and specify the HVAC systems, and specialty mechanical contractors build and commission them. Building permits and code-compliance inspections of the installations are normally required for all sizes of buildings.

The HVAC industry is a worldwide enterprise, with career opportunities including operation and maintenance, system design and construction, equipment manufacturing and sales, and in education and research. The HVAC industry had been historically regulated by the manufacturers of HVAC equipment, but Regulating and Standards organizations such as HARDI, ASHRAE, SMACNA, ACCA, Uniform Mechanical Code, International Mechanical Code, and AMCA have been established to support the industry and encourage high standards and achievement.

Design of the HVAC system.

The starting point in carrying out a heat estimate both for cooling and heating will depends on the ambient and inside conditions specified. However before taking up the heat load calculation, it is necessary to work out the fresh air requirement for each area in details, as pressurization is an important requirement.

## *Heating*


Central heating unit

There are many different types of standard heating systems. Central heating is often used in cold climates to heat private houses and public buildings. Such a system contains a boiler, furnace, or heat pump to heat water, steam, or air, all in a central location such as a furnace room in a home or a mechanical room in a large building. The use of water as the heat transfer medium is known as hydronics. The system also contains either ductwork, for forced air systems, or piping to distribute a heated fluid and radiators to transfer this heat to the air. The term *radiator* in this context is misleading since most heat transfer from the heat exchanger is by convection, not radiation. The radiators may be mounted on walls or buried in the floor to give under-floor heat.

In boiler fed or radiant heating systems, all but the simplest systems have a pump to circulate the water and ensure an equal supply of heat to all the radiators. The heated water can also be fed through another (secondary) heat exchanger inside a storage cylinder to provide hot running water.

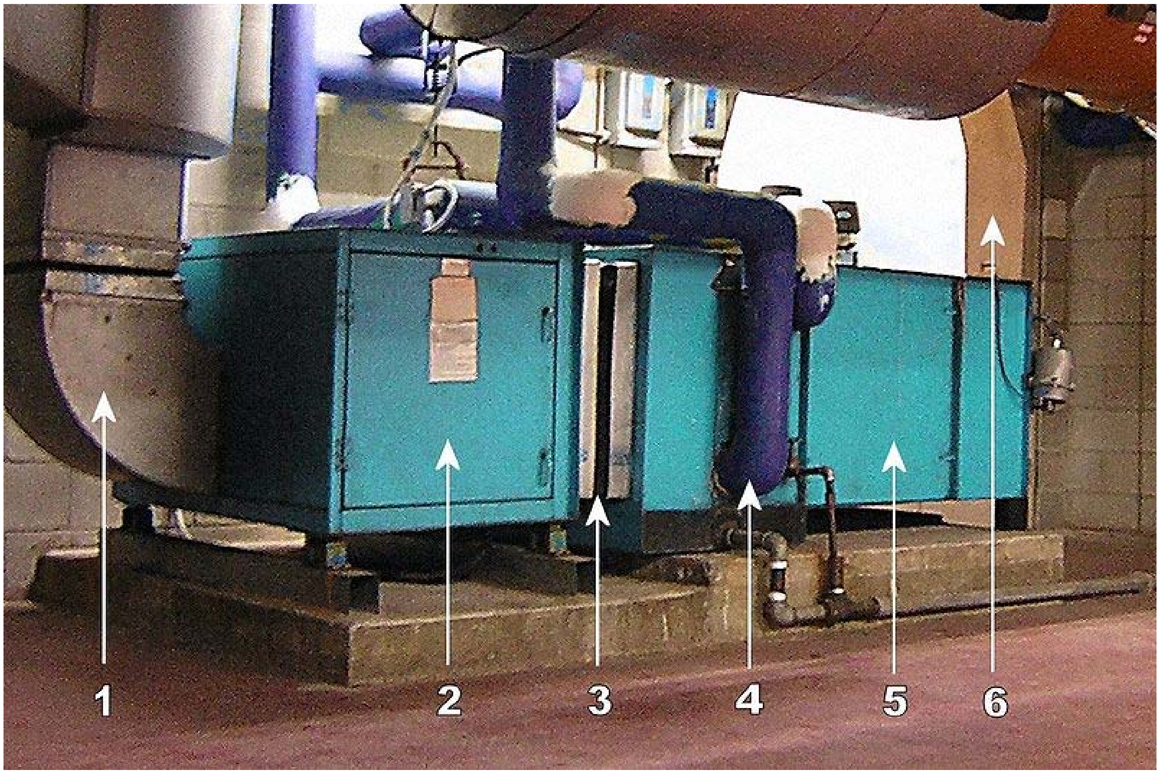
Forced air systems send heated air through ductwork. During warm weather the same ductwork can be used for air conditioning. The forced air can also be filtered or put through air cleaners.

Heating can also be provided from electric, or resistance heating using a filament that becomes hot when electric current is caused to pass through it. This type of heat can be found in electric baseboard heaters, portable electric heaters, and as backup or supplemental heating for heat pump (or reverse heating) system.

The heating elements (radiators or vents) should be located in the coldest part of the room, typically next to the windows to minimize condensation and offset the convective air current formed in the room due to the air next to the window becoming negatively buoyant due to the cold glass. Devices that direct vents away from windows to prevent "wasted" heat defeat this design intent. Cold air drafts can contribute significantly to subjectively feeling colder than the average room temperature. Therefore, it is important to control the air leaks from outside in addition to proper design of the **heating system**.

The invention of central heating is often credited to the ancient Romans, who installed a system of air ducts called a hypocaust in the walls and floors of public baths and private villas.

## *Ventilating*




An air handling unit is used for the heating and cooling of air in a central location

Ventilating is the process of "changing" or replacing air in any space to control temperature or remove moisture, odors, smoke, heat, dust, airborne bacteria, carbon dioxide, and to replenish oxygen. Ventilation includes both the exchange of air to the outside as well as circulation of air within the building. It is one of the most important factors for maintaining acceptable indoor air quality in buildings. Methods for ventilating a building may be divided into *mechanical/forced* and *natural* types. Ventilation is used to remove unpleasant smells and excessive moisture, introduce outside air, to keep interior building air circulating, and to prevent stagnation of the interior air.

### Mechanical or forced ventilation

"Mechanical" or "forced" ventilation is provided by an air handler and used to control indoor air quality. Excess humidity, odors, and contaminants can often be controlled via dilution or replacement with outside air. However, in humid climates much energy is required to remove excess moisture from ventilation air.

Kitchens and bathrooms typically have mechanical exhaust to control odors and sometimes humidity. Factors in the design of such systems include the flow rate (which is a function of the fan speed and exhaust vent size) and noise level. If ducting for the fans traverse unheated space (e.g., an attic), the ducting should be insulated as well to prevent condensation on the ducting. Direct drive fans are available for many applications, and can reduce maintenance needs.

Ceiling fans and table/floor fans circulate air within a room for the purpose of reducing the perceived temperature because of evaporation of perspiration on the skin of the occupants. Because hot air rises, ceiling fans may be used to keep a room warmer in the winter by circulating the warm stratified air from the ceiling to the floor. Ceiling fans do not provide ventilation as defined as the introduction of outside air.

### Natural ventilation

Natural ventilation is the ventilation of a building with outside air without the use of a fan or other mechanical system. It can be achieved with openable windows or trickle vents when the spaces to ventilate are small and the architecture permits. In more complex systems warm air in the building can be allowed to rise and flow out upper openings to the outside (stack effect) thus forcing cool outside air to be drawn into the building naturally through openings in the lower areas. These systems use very little energy but care must be taken to ensure the occupants' comfort. In warm or humid months, in many climates, maintaining thermal comfort solely via natural ventilation may not be possible so conventional air conditioning systems are used as backups. Air-side economizers perform the same function as natural ventilation, but use mechanical systems' fans, ducts, dampers, and control systems to introduce and distribute cool outdoor air when appropriate.

## *Air conditioning*

Air conditioning and refrigeration are provided through the removal of heat. The definition of cold is the absence of heat and all air conditioning systems work on this basic principle. Heat can be removed through the process of radiation, convection, and Heat cooling through a process called the refrigeration cycle. The conduction mediums such as water, air, ice, and chemicals are referred to as refrigerants.

An air conditioning system, or a standalone air conditioner, provides cooling, ventilation, and humidity control for all or part of a house or building.

The refrigerant cycle consists of four essential elements to create a cooling effect. The system refrigerant starts its cycle in a gaseous state. The compressor pumps the refrigerant gas up to a high pressure and temperature. From there it enters a heat exchanger (sometimes called a "condensing coil") where it loses energy (heat) to the outside. In the process the refrigerant condenses into a liquid. The liquid refrigerant is returned indoors to another heat exchanger ("evaporating coil"). A metering device allows the liquid to flow in at a low pressure at the proper rate. As the liquid refrigerant evaporates it aborbs energy (heat) from the inside air, returns to the compressor, and the cycle repeats. In the process, heat is absorbed from indoors, and transferred outdoors, resulting in cooling of the building.

Central, 'all-air' air conditioning systems are often installed in modern residences, offices, and public buildings, but are difficult to retrofit (install in a building that was not designed to receive it) because of the bulky air ducts required. A duct system must be carefully maintained to prevent the growth of pathogenic bacteria in the ducts. An alternative to large ducts to carry the needed air to heat or cool an area is the use of remote fan coils or split systems. These systems, although most often seen in residential applications, are gaining popularity in small commercial buildings. The evaporator coil is connected to a remote condenser unit using piping instead of ducts.

Dehumidification in an air conditioning system is provided by the evaporator. Since the evaporator operates at a temperature below dew point, moisture in the air condenses on the evaporator coil tubes. This moisture is collected at the bottom of the evaporator in a condensate pan and is removed by piping it to a central drain or onto the ground outside. A dehumidifier is an air-conditioner-like device that controls the humidity of a room or building. It is often employed in basements which have a higher relative humidity because of their lower temperature (and propensity for damp floors and walls). In food retailing establishments, large open chiller cabinets are highly effective at dehumidifying the internal air. Conversely, a humidifier increases the humidity of a building.

Air-conditioned buildings often have sealed windows, because open windows would disrupt the attempts of the HVAC system to maintain constant indoor air conditions.

All modern air conditioning systems, down to small "window" units, are equipped with internal air filters. These are generally of a light weight gauze-type element, and must be replaced as conditions warrant (some models may be washable). For example, a building in a high-dust environment, or a home with furry pets, will need to have the filters changed more often than buildings without these dirt loads. Failure to replace these filters as needed will contribute to a lower heat-exchange rate, resulting in wasted energy, shortened equipment life, and higher energy bills; also low air flow can result in "iced-up" or "iced-over" evaporator coils, and then there is no air flow at all. Additionally, very dirty or plugged filters can cause overheating during a heating cycle, and can possibly result in damage to the furnace unit or even fire.

It is important to keep in mind that because an air conditioner moves heat from the indoor (evaporator) coil to the outdoor (condenser) coil, the latter must be kept just as clean as the former. This means that, in addition to replacing the air filter at the evaporator coil, it is also necessary to regularly clean the condenser coil. Failure to keep the condenser clean will eventually result in harm to the compressor, because the condenser coil is responsible for discharging both the indoor heat (as picked up by the evaporator) plus the heat generated by the electric motor driving the compressor.

Outside, "fresh" air is generally drawn into the system by a vent into the evaporator section. Adjustment of the percentage of return air made up of fresh air can usually be adjusted by manipulating the opening of this vent.

## *Energy efficiency*

For the last 20 to 30 years, manufacturers of HVAC equipment have been making an effort to make the systems they manufacture more efficient. This was originally driven by rising energy costs, and has more recently been driven by increased awareness of environmental issues. In the USA, the EPA has also imposed tighter restrictions. There are several methods for making HVAC systems more efficient.

### Heating energy

Water heating is more efficient for heating buildings and was the standard many years ago. Today forced air systems can double for air conditioning and are more popular.

A couple of benefits of forced air systems, which are now widely applied in churches, schools and high-end residences,are 1) better air conditioned effect 2) up to 15-20% energy saving, and 3) evenly conditioned effect. A drawback is the installation cost, which might be slightly higher than traditional HVAC system.

Energy efficiency can be improved even more in central heating systems by introducing zoned heating. This allows a more granular application of heat, similar to non-central heating systems. Zones are controlled by multiple thermostats. In water heating systems the thermostats control zone valves, and in forced air systems they control zone dampers inside the vents which selectively block the flow of air. In this case, the control system is very critical to maintain a proper temperature.

### Geothermal Heat Pump

Geothermal heat pumps are similar to ordinary heat pumps, but instead of using heat found in outside air, they rely on the stable, even heat of the earth to provide heating, air conditioning and, in most cases, hot water. From Montana's −70 °F (−57 °C) temperature, to the highest temperature ever recorded in the U.S.—134 °F (56.7 °C) in Death Valley, California, in 1913—many parts of the country experience seasonal temperature extremes. A few feet below the earth's surface, however, the ground remains at a relatively constant temperature. Although the temperatures vary according to latitude, at 6 feet (1.83 m) underground, temperatures range from 45 to 75 °F (7.2 to 23.9 °C).

While they may be more costly to install initially than regular heat pumps, they can produce markedly lower energy bills—30 percent to 40 percent lower, according to estimates from the U.S. Environmental Protection Agency.

### Ventilation energy recovery

Energy recovery systems sometimes utilize heat recovery ventilation or energy recovery ventilation systems that employ heat exchangers or enthalpy wheels to recover sensible or latent heat from exhausted air. This is done by transfer of energy to the incoming outside fresh air.

## Air conditioning energy

The performance of vapor compression refrigeration cycles is limited by thermodynamics. These air conditioning and heat pump devices *move* heat rather than convert it from one form to another, so *thermal efficiencies* do not appropriately describe the performance of these devices. The **Coefficient-of-Performance** (COP) measures performance, but this dimensionless measure has not been adopted, but rather the **Energy Efficiency Ratio** (*EER*). EER is the Energy Efficiency Ratio based on a 35 °C (95 °F) outdoor temperature. To more accurately describe the performance of air conditioning equipment over a typical cooling season a modified version of the EER is used, and is the **Seasonal Energy Efficiency Ratio** (*SEER*). SEER ratings are based on seasonal temperature averages instead of a constant 35 °C outdoor temperature. The current industry minimum SEER rating is 13 SEER. The SEER article describes it further, and presents some economic comparisons using this useful performance measure.

Engineers have pointed out some areas where efficiency of the existing hardware could be improved. For example, the fan blades used to move the air are usually stamped from sheet metal, an economical method of manufacture, but as a result they are not aerodynamically efficient. A well-designed blade could reduce electrical power required to move the air by a third.

- Chilled beam
- Circulator pump
- Cooling tower
- Damper (flow)
- Dedicated outdoor air system
- Diffuser
- Displacement Ventilation
- Duct
- Economizer
- Evaporative cooler
- Fan coil unit
- Fan (mechanical)
- Heater
- Heat exchanger, including 'coils'
- Heat Pump
- Heat recovery ventilator
- Humidifier / Dehumidifier
- HVAC control system
- Piping
- Valve
- Variable air volume
- Variable-frequency drive, for fine control of pumps
- Underfloor air distribution

# *HVAC industry and standards*

## North America

### USA

In the United States, HVAC engineers generally are members of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). ASHRAE is an international technical society for all individuals and organizations interested in HVAC. The Society, organized into Regions, Chapters, and Student Branches, allows exchange of HVAC knowledge and experiences for the benefit of the field's practitioners and the public. ASHRAE provides many opportunities to participate in the development of new knowledge via, for example, research and its many Technical Committees. These committees meet typically twice per year at the ASHRAE Annual and Winter Meetings. A popular product show, the AHR Expo, is held in conjunction with each Winter Meeting. The Society has approximately 50,000 members and has headquarters at Atlanta, Georgia, USA.

The most recognized standards for HVAC design is based on ASHRAE data. ASHRAE is the American Society of Heating, Refrigerating and Air-Conditioning Engineers. The ASHRAE Handbook's most general volume, of four, is Fundamentals; it includes heating and cooling calculations. Each volume of the ASHRAE Handbook is updated every four years. The design professional must consult ASHRAE data for the standards of design and care as the typical building codes provides little to no information on HVAC design practices; such codes, such as the UMC and IMC, do include much details on installation requirements, however. Other useful reference materials include items from SMACNA, ACCA, and technical trade journals.

American design standards are legislated in the Uniform Mechanical Code or International Mechanical Code. In certain states, counties, or cities, either of these codes may be adopted and amended via various legislative processes. These codes are updated and published by the International Association of Plumbing and Mechanical Officials (IAPMO) or the International Code Council (ICC) respectively, on a 3-year code development cycle. Typically, local Building Permit Departments are charged with enforcement of these standards on private and certain public properties.

In the United States, as well as throughout the world, HVAC contractors and companies are members of NADCA, the National Air Duct Cleaners Association. NADCA was formed in 1989 as a non-profit association of companies engaged in the cleaning of HVAC systems. Its mission was to promote source removal as the only acceptable method of cleaning and to establish industry standards for the association. NADCA has expanded its mission to include the representation of qualified companies engaged in the assessment, cleaning, and restoration of HVAC systems, and to assist its members in providing high quality service to their customers. The goal of the association is to be the number one source for the HVAC cleaning and restoration services: first time, every time. NADCA has experienced phenomenal membership growth and has been extremely successful with the training and certification of air systems cleaning specialists, mold remediators, and HVAC inspectors. The association has also published important standards and guidelines, educational materials, and other useful information for the consumer and members of NADCA. Their headquarters are located in Washington, D.C.

## Europe

## United Kingdom

The Chartered Institute of Building Services Engineers is a body that covers the essential Service (systems architecture) that allow buildings to operate. It includes the electrotechnical, heating, ventilating, air conditioning, refrigeration and plumbing industries. To train as a building services engineer, the academic requirement are GCSEs (A-C) / Standard Grades (1-3) in Maths and Science, which are important in measurements, planning and theory. Employers will often want a degree in a branch of engineering, such as building environment engineering, electrical engineering or mechanical engineering. To become a full member of CIBSE, and so also to be registered by the Engineering Council UK as a chartered engineer, one must also attain an Honours Degree and a Masters Degree in a relevent engineering subject.

CIBSE publishes several guides to HVAC design relevent to the UK market, and also the Republic of Ireland, Australia, New Zealand and Hong Kong. These guides include for various recommended design criteria and standards, some of which are cited within the UK building regulations, and therefore form a legislative requirment for major building services works. The main guides are:

- Guide A: Environmental Design
- Guide B: Heating, Ventilating, Air Conditioning and Refrigeration
- Guide C: Reference Data
- Guide D: Transportation systems in Buildings
- Guide E: Fire Safety Engineering
- Guide F: Energy Efficiency in Buildings
- Guide G: Public Health Engineering
- Guide H: Building Control Systems
- Guide J: Weather, Solar and Illuminance Data
- Guide K: Electricity in Buildings
- Guide L: Sustainability
- Guide M: Maintenance ENgineering and Management

Within the construction sector, it is the job of the building services engineer to design and oversee the installation and maintenance of the essential services such as gas, electricity, water, heating and lighting, as well as many others. These all help to make buildings comfortable and healthy places to live and work in. Building Services is part of a sector that has over 51,000 businesses and employs represents 2%-3% of the GDP.

## Australia

Air Conditioning and Mechanical Contractors Association of Australia (AMCA)
Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH),
CIBSE

## Asia

### India

The Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE) was established to promote the HVAC industry in India. ISHRAE is an associate of

ASHRAE. ISHRAE was started at Delhi in 1981 and a chapter was started in Bangalore in 1989. Between 1989 & 1993, ISHRAE chapters were formed in all major cities in India and also in the Middle East.

## Pakistan

Air-conditioning technology has been in use in Pakistan since 1947, the time of its independence. At that point local expertise was dependent on the supply and installation of imported equipment in accordance with the system designs from abroad. Once Pakistani engineers recognized the importance of the field they became active in developing expertise in design, manufacture, installation, operation, and maintenance. In 1995 the Pakistan HVACR Society was formed. Since then, the Society started organizing various disciplines of the field under its umbrella.