Building Automation

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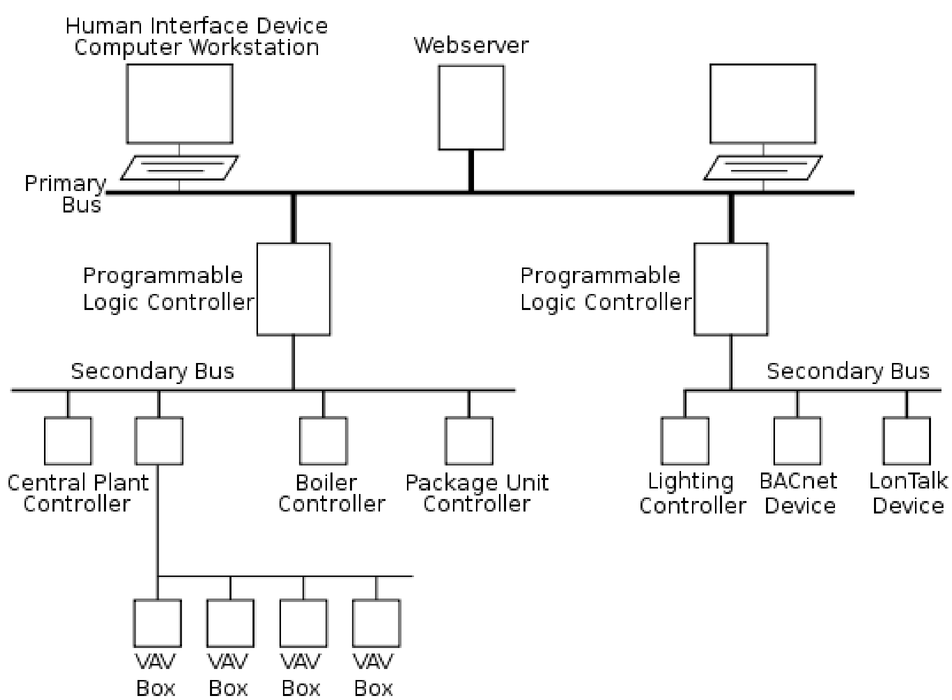
Chapter 1

Building Automation

Building automation describes the functionality provided by the control system of a building. A building automation system (BAS) is an example of a distributed control system. The control system is a computerized, intelligent network of electronic devices, designed to monitor and control the mechanical and lighting systems in a building.

BAS core functionality keeps the building climate within a specified range, provides lighting based on an occupancy schedule, and monitors system performance and device failures and provides email and/or text notifications to building engineering staff. The BAS functionality reduces building energy and maintenance costs when compared to a non-controlled building. A building controlled by a BAS is often referred to as an intelligent building system.



Topology

Most building automation networks consist of a *primary* and *secondary* bus which connect high-level controllers (generally specialized for building automation, but may be generic programmable logic controllers) with lower-level controllers, input/output devices and a user interface (also known as a human interface device).

The primary and secondary bus can be BACnet, optical fiber, ethernet, ARCNET, RS-232, RS-485 or a wireless network.

Most controllers are proprietary. Each company has its own controllers for specific applications. Some are designed with limited controls: for example, a simple Packaged Roof Top Unit. Others are designed to be flexible. Most have proprietary software that will work with ASHRAE's open protocol BACnet or the open protocol LonTalk.

Some newer building automation and lighting control solutions use wireless mesh open standards (such as ZigBee. These systems can provide interoperability, allowing users to mix-and-match devices from different manufacturers, and to provide integration with other compatible building control systems.

Inputs and outputs are either analog or digital (some companies say binary).

Analog inputs are used to read a variable measurement. Examples are temperature, humidity and pressure sensor which could be thermistor, 4-20 mA, 0-10 volt or platinum resistance thermometer (resistance temperature detector), or wireless sensors.

A digital input indicates if a device is turned on or not. Some examples of an digital input would be a 24VDC/AC signal, an air flow switch, or a volta-free relay contact (Dry Contact).

Analog outputs control the speed or position of a device, such as a variable frequency drive, a I-P (current to pneumatics) transducer, or a valve or damper actuator. An example is a hot water valve opening up 25% to maintain a setpoint.

Digital outputs are used to open and close relays and switches. An example would be to turn on the parking lot lights when a photocell indicate it is dark outside.

Infrastructure

Controller

Controllers are essentially small, purpose-built computers with input and output capabilities. These controllers come in a range of sizes and capabilities to control devices commonly found in buildings, and to control sub-networks of controllers.

Inputs allow a controller to read temperatures, humidity, pressure, current flow, air flow, and other essential factors. The outputs allow the controller to send command and control signals to slave devices, and to other parts of the system. Inputs and outputs can be either digital or analog. Digital outputs are also sometimes called discrete depending on manufacturer.

Controllers used for building automation can be grouped in 3 categories. Programmable Logic Controllers (PLCs), System/Network controllers, and Terminal Unit controllers. However an additional device can also exist in order to integrate 3rd party systems (i.e. a stand-alone AC system) into a central Building automation system).

PLC's provide the most responsiveness and processing power, but at a unit cost typically 2 to 3 times that of a System/Network controller intended for BAS applications. Terminal Unit controllers are usually the least expensive and least powerful.

PLC's may be used to automate high-end applications such as clean rooms or hospitals where the cost of the controllers is a lesser concern.

In office buildings, supermarkets, malls, and other common automated buildings the systems will use System/Network controllers rather than PLC's. Most System controllers provide general purpose feedback loops, as well as digital circuits, but lack the millisecond response time that PLC's provide.

System/Network controllers may be applied to control one or more mechanical systems such as an Air Handler Unit (AHU), boiler, chiller, etc., or they may supervise a sub-network of controllers. In the diagram above, System/Network controllers are often used in place of PLCs.

Terminal Unit controllers usually are suited for control of lighting and/or simpler devices such as a package rooftop unit, heat pump, VAV box, or fan coil, etc. The installer typically selects 1 of the available pre-programmed personalities best suited to the device to be controlled, and does not have to create new control logic.

Occupancy

Occupancy is one of 2 or more operating modes for a building automation system. Unoccupied, Morning Warmup, and Night-time Setback are other common modes.

Occupancy is usually based on time of day schedules. In Occupancy mode, the BAS aims to provides a comfortable climate and adequate lighting, often with zone-based control so that users on one side of a building have a different thermostat (or a different system, or sub system) than users on the opposite side.

A temperature sensor in the zone provides feedback to the controller, so it can deliver heating or cooling as needed.

If enabled, Morning Warmup (MWU) mode occurs prior to Occupancy. During Morning Warmup the BAS tries to bring the building to setpoint just in time for Occupancy. The BAS often factors in outdoor conditions and historical experience to optimize MWU. This is also referred to as Optimised Start.

An override is a manually-initiated command to the BAS. For example, many wall-mounted temperature sensors will have a push-button that forces the system into Occupancy mode for a set number of minutes. Where present, web interfaces allow users to remotely initiate an override on the BAS.

Some buildings rely on occupancy sensors to activate lighting and/or climate conditioning. Given the potential for long lead times before a space becomes sufficiently cool or warm, climate conditioning is not often initiated directly by an occupancy sensor.

Lighting

Lighting can be turned on, off, or dimmed with a building automation or lighting control system based on time of day, or on occupancy sensors, photosensors and timers. One typical example is to turn the lights in a space on for a half hour since the last motion was sensed. A photocell placed outside a building can sense darkness, and the time of day, and modulate lights in outer offices and the parking lot.

Lighting is also a good candidate for Demand response, with many control systems providing the ability to dim (or turn off) lights to take advantage of DR incentives and savings. if occupancy sensors are present they can also be used as burglar alarms

Air handlers

Most air handlers mix return and outside air so less temperature change is needed. This can save money by using less chilled or heated water (not all AHUs use chilled/hot water circuits). Some external air is needed to keep the building's air healthy.

Analog or digital temperature sensors may be placed in the space or room, the return and supply air ducts, and sometimes the external air. Actuators are placed on the hot and chilled water valves, the outside air and return air dampers. The supply fan (and return if applicable) is started and stopped based on either time of day, temperatures, building pressures or a combination.

Constant volume air-handling units

The less efficient type of air-handler is a "constant volume air handling unit," or CAV. The fans in CAVs do not have variable-speed controls. Instead, CAVs open and close dampers and water-supply valves to maintain temperatures in the building's spaces. They heat or cool the spaces by opening or closing chilled or hot water valves that feed their internal heat exchangers. Generally one CAV serves several spaces, but large buildings may have many CAVs.

Variable volume air-handling units

A more efficient unit is a "variable air volume (VAV) air-handling unit," or VAV. VAVs supply pressurized air to VAV boxes, usually one box per room or area. A VAV air handler can change the pressure to the VAV boxes by changing the speed of a fan or blower with a variable frequency drive or (less efficiently) by moving inlet guide vanes to a fixed-speed fan. The amount of air is determined by the needs of the spaces served by the VAV boxes.

Each VAV box supply air to a small space, like an office. Each box has a damper that is opened or closed based on how much heating or cooling is required in its space. The more boxes are open, the more air is required, and a greater amount of air is supplied by the VAV air-handling unit.

Some VAV boxes also have hot water valves and an internal heat exchanger. The valves for hot and cold water are opened or closed based on the heat demand for the spaces it is supplying. These heated VAV boxes are sometimes used on the perimeter only and the interior zones are cooling only.

A minimum and maximum CFM must be set on VAV boxes to assure adequate ventilation and proper air balance.

VAV hybrid systems

Another variation is a hybrid between VAV and CAV systems. In this system, the interior zones operate as in a VAV system. The outer zones differ in that the heating is supplied by a heating fan in a central location usually with a heating coil fed by the building boiler. The heated air is ducted to the exterior dual duct mixing boxes and dampers controlled by the zone thermostat calling for either cooled or heated air as needed.

Central plant

A central plant is needed to supply the air-handling units with water. It may supply a chilled water system, hot water system and a condenser water system, as well as transformers and auxiliary power unit for emergency power. If well managed, these can often help each other. For example, some plants generate electric power at periods with peak demand, using a gas turbine, and then use the turbine's hot exhaust to heat water or power an absorptive chiller.

Chilled water system

Chilled water is often used to cool a building's air and equipment. The chilled water system will have chiller(s) and pumps. Analog temperature sensors measure the chilled water supply and return lines. The chiller(s) are sequenced on and off to chill the chilled water supply.

Condenser water system

Cooling tower(s) and pumps are used to supply cool condenser water to the chillers. Because the condenser water supply to the chillers has to be constant, variable speed drives are commonly used on the cooling tower fans to control temperature. Proper cooling tower temperature assures the proper refrigerant head pressure in the chiller. The cooling tower set point used depends upon the refrigerant being used. Analog temperature sensors measure the condenser water supply and return lines.

Hot water system

The hot water system supplies heat to the building's air-handling unit or VAV box heating coils, along with the domestic hot water heating coils (Calorifier). The hot water system will have a boiler(s) and pumps. Analog temperature sensors are placed in the hot water supply and return lines. Some type of mixing valve is usually used to control the heating water loop temperature. The boiler(s) and pumps are sequenced on and off to maintain supply.

Alarms and security

Many building automation systems have alarm capabilities. If an alarm is detected, it can be programmed to notify someone. Notification can be through a computer, pager, cellular phone, or audible alarm.

- Common temperature alarms are: space, supply air, chilled water supply and hot water supply.
- Differential pressure switches can be placed on the filter to determine if it is dirty.
- Status alarms are common. If a mechanical device like a pump is requested to start, and the status input indicates it is off. This can indicate a mechanical failure.
- Some valve actuators have end switches to indicate if the valve has opened or not.
- Carbon monoxide and carbon dioxide sensors can be used to alarm if levels are too high.
- Refrigerant sensors can be used to indicate a possible refrigerant leak.
- Current sensors can be used to detect low current conditions caused by slipping fan belts, or clogging strainers at pumps.

At sites with several buildings, momentary power failures can cause hundreds or thousands of alarms from equipment that has shut down. Some sites are programmed so that critical alarms are automatically re-sent at varying intervals. For example, a repeating critical alarm (of an [uninterruptible power supply] in 'by pass') might resound at 10 minutes, 30 minutes, and every 2 to 4 hours there after until the alarms are resolved.

Security systems can be interlocked to a building automation system. If occupancy sensors are present, they can also be used as burglar alarms.

Fire and smoke alarm systems can be hard-wired to override building automation. For example: if the smoke alarm is activated, all the outside air dampers close to prevent air coming into the building, and an exhaust system can isolate

Room automation

Room automation is a subset of Building automation and like it, is the consolidation of one or systems under centralised control but in this case in just one room .

The most common example of *room automation* is corporate boardroom, presentation suites, and lecture halls, where the operation of the large number of devices that define the room function (such as Videoconferencing equipment, Video projectors, lighting control systems, Public address systems etc.) would make manual operation of the room very complex. It is common for room automation systems to employ a touchscreen as the primary way of controlling each operation.

Chapter 2

Active Fire Protection, BACnet and Digital Signal Interface

Active fire protection

Active fire protection (AFP) is an integral part of fire protection. AFP is characterised by items and/or systems, which require a certain amount of motion and response in order to work, contrary to passive fire protection.

Categories of Active Fire Protection

Fire suppression

Fire can be controlled or extinguished, either manually (firefighting) or automatically. Manual includes the use of a fire extinguisher or a Standpipe system. Automatic means can include a fire sprinkler system, a gaseous clean agent, or fire fighting foam system. Automatic suppression systems would usually be found in large commercial kitchens or other high-risk area.

Sprinkler systems

Fire sprinkler systems are installed in all types of buildings, commercial and residential. They are usually located at ceiling level and are connected to a reliable water source, most commonly city water. A typical sprinkler system operates when heat at the site of a fire causes a glass component in the sprinkler head to fail, thereby releasing the water from the sprinkler head. This means that only the sprinkler head at the fire location operate - not all the sprinklers on a floor or in a building. (This is a common misconception which stems from action movie scenes). Sprinkler systems help to reduce the growth of a fire, thereby increasing life safety and limiting structural damage.

Fire detection

The fire is detected either by locating the smoke, flame or heat, and an alarm is sounded to enable emergency evacuation as well as to dispatch the local fire department. An introduction to fire detection and suppression can be found here. Where a detection system is activated, it can be programmed to carry out other actions. These include de-energising magnetic hold open devices on Fire doors and opening servo-actuated vents in stairways.

Construction and maintenance

All AFP systems are required to be installed and maintained in accordance with strict guidelines in order to maintain compliance with the local building code and the fire code. An example treatise on code compliance in Miami Dade County can be seen here. Code authorities can encourage compliance through open communications, such as an invitation for code questions or an invitation to participate or an explanation of the code development process

AFP works alongside modern architectural designs and construction materials and fire safety education to prevent, retard, and suppress structural fires.

BACnet

BACnet is a communications protocol for **b**uilding **a**utomation and **c**ontrol **net**works. It is an ASHRAE, ANSI, and ISO standard protocol.

BACnet was designed to allow communication of building automation and control systems for applications such as heating, ventilating, and air-conditioning control, lighting control, access control, and fire detection systems and their associated equipment. The BACnet protocol provides mechanisms for computerized building automation devices to exchange information, regardless of the particular building service they perform.

History

The development of the BACnet protocol began in June, 1987, in Nashville, Tennessee, at the inaugural meeting of the Standard Project Committee (SPC). The committee worked at reaching consensus using working groups to divide up the task of creating a standard. The working groups focused on specific areas and provided information and recommendations to the main committee. The first three working groups were the Data Type and Attribute Working Group, Primitive Data Format Working Group, and the Application Services Working Group.

BACnet became ASHRAE/ANSI Standard 135 in 1995, and ISO 16484-5 in 2003. The Method of Test for Conformance to BACnet was published in 2003 as BSR/ASHRAE

Standard 135.1. BACnet is under continuous maintenance by the ASHRAE Standing Standard Project Committee 135.

BACnet had an almost immediate impact on the HVAC controls industry. In 1996 Alerton announced a complete BACnet product line for HVAC controls, from the operator's workstation down to small VAV controllers. Automated Logic Corporation and Delta Controls soon followed suit. As of October 22, 2010, 476 Vendor IDs have been issued and are distributed internationally. Those vendor identifiers can be viewed at the BACnet website.

H. Michael (Mike) Newman, Manager of the Computer Section of the Utilities and Energy Management Department at Cornell University, served as the BACnet committee chairman until June, 2000, when he was succeeded by his vice-chair of 13 years, Steven (Steve) Bushby from NIST. During Steve Bushby's four-year term as committee chair the BACnet standard was republished twice, in 2001 and 2004, each time with new capabilities added to the standard. The 2001 version featured, among other things, extensions to support fire / life-safety systems. In June, 2004, 17 years after the first BACnet meeting and back in Nashville, William (Bill) Swan (a.k.a. "BACnet Bill") from Alerton began his four-year stint as committee chair. During his term the number of committee working groups grew to 11, pursuing areas such as support for lighting, access control, energy utility/building integration and wireless communications. In June 2008, in Salt Lake City, Dave Robin from Automated Logic Corporation took over the reins as the new committee chair after serving 4 years as vice chair.

In January 2006 the BACnet Manufacturers Association and the BACnet Interest Group of North America combined their operation in a new organization called BACnet International.

Protocol Overview

The BACnet protocol defines a number of services that are used to communicate between building devices. The protocol services include Who-Is, I-Am, Who-Has, I-Have, which are used for Device and Object discovery. Services such as Read-Property and Write-Property are used for data sharing.

The BACnet protocol defines a number of Objects that are acted upon by the services. The objects include Analog Input, Analog Output, Analog Value, Binary Input, Binary Output, Binary Value, Multi-State Input, Multi-State Output, Calendar, Event-Enrollment, File, Notification-Class, Group, Loop, Program, Schedule, Command, and Device.

The BACnet protocol defines a number of data link / physical layers, including ARCNET, Ethernet, BACnet/IP, Point-To-Point over RS-232, Master-Slave/Token-Passing over RS-485, and LonTalk.

BACnet Objects

The standard specifies 49 types of objects

Access Credential	Access Door	Access Point	Access Rights	Access User
Access Zone	Accumulator	Analog Input	Analog Output	Analog Value
Averaging	Binary Input	Binary Output	Binary Value	Bit String Value
Calendar	Command	Character String Value	Date Pattern Value	Date Value
Date Time Pattern Value	Date Time Value	Device	Event Enrollment	Event Log
File	Global Group	Group	Integer Value	Large Analog Value
Life Safety Point	Life Safety Zone	Load Control	Loop	Multi-state Input
Multi-state Output	Multi-state Value	Network Security	Notification Class	Octet String Value
Positive Integer Value	Program	Pulse Converter	Schedule	Structured-View
Time Pattern Value	Time Value	Trend Log	Trend Log Multiple	

- Analog Input - Sensor input
- Analog Output - Control output
- Analog Value - Setpoint or other analog control system parameter
- Binary Input - Switch input
- Binary Output - Relay output
- Binary Value - control system parameter
- Calendar - a list of dates, such as holidays or special events, for scheduling.
- Command - Writes multiple values to multiple objects in multiple devices to accomplish a specific purpose, such as day-mode to night-mode, or emergency mode.
- Device - Properties tell what objects and services the device supports, and other device-specific information such as vendor, firmware revision, etc.
- Event Enrollment - Describes an event that might be an error condition (e.g., "Input out of range") or an alarm that other devices to know about. It can directly tell one device or use a Notification Class object to tell multiple devices.
- File - Allows read and write access to data files supported by the device.
- Group - Provides access to multiple properties of multiple objects in a read single operation.
- Multi-state Input - Represents the status of a multiple-state process, such as a refrigerator's On, Off, and Defrost cycles.

- Multi-state Output - Represents the desired state of a multiple-state process (such as It's Time to Cool, It's Cold Enough and it's Time to Defrost).
- Notification Class - Contains a list of devices to be informed if an Event Enrollment object determines that a warning or alarm message needs to be sent.
- Loop - Provides standardized access to a "PID control loop".
- Program - Allows a program running in the device to be started, stopped, loaded and unloaded, and reports the present status of the program.
- Schedule - Defines a weekly schedule of operations (performed by writing to specified list of objects with exceptions such as holidays. Can use a Calendar object for the exceptions.

BACnet Testing

BACnet Testing Laboratories was established by BACnet International to test products as per BACnet standard and support compliance testing and interoperability testing activities and consists of BTL Manager and the BTL-WG. The general activities of the BTL are:

- Publish the BTL Implementation Guidelines document
- Certifying the products as per BACnet guidelines
- Support the activities of the BTL-WG,
- Maintaining the BTL test packages for technical support for use of pre-testing
- Approves Testing Laboratories for BTL Testing

The BTL also provides testing services through its managed BACnet laboratory. BACnet International and BTL have reached an agreement with SoftDEL Systems to establish and maintain a test lab for BACnet products. SoftDEL is headquartered in Pune, India where the test facility operates BTL. The BTL Manager and BTL working group of BACnet International will administer the test lab. This BACnet lab is ISO 17025 accredited

Digital Signal Interface

Digital Signal Interface (**DSI**) is a protocol for the controlling of lighting in buildings (initially electrical ballasts). It was created in 1991 by Austrian company Tridonic and is based on Manchester-coded 8-bit protocol, data rate of 1200 baud, 1 start bit, 8 data bits (dimming value), 4 stop bits, and is the basis of the more sophisticated protocol Digital Addressable Lighting Interface (DALI).

The technology uses a single byte to communicate the lighting level (0-255 or 0x00-0xFF). DSI was the start of digital communication technology and was the precursor to DALI.

Advantages

- Its simple nature makes it straightforward to understand, implement, and diagnose, while its low voltage means it typically runs along relatively thin cables.

- Because each device has its own wire to the controller (rather than being part of a network) it has no need of an address to be set, so can be replaced simply by unplugging the faulty one and plugging in the new.

- It dims to off, so does not require mains switching equipment to turn them off.

Disadvantages

- It requires one wire per control channel so a sophisticated system could have hundreds of wires, thereby making diagnoses of problems difficult.

- It is a proprietary standard initially exclusive to Tridonic and mainly brands of Tridonic's parent company Zumtobel.

Rival protocols

- DALI
- 1-10v analog

DALI

DALI is an open standard for digital control of lighting. Several companies have adopted the DALI protocol in their product offerings. Even though DALI is an open standard, there are already versions of its implementation emerging in different lighting manufacturers products as they strive to provide a point of difference. DSI is essentially the same technology as DALI in terms of messaging, however, DSI eliminates the individual addressing aspect of each light fitting found in DALI.

Chapter 3

Energy Management Software and HVAC Control System

Energy management software

Energy Management Software (**EMS**) is a general term and category referring to a variety of energy-related software applications which may provide utility bill tracking, real-time metering, building HVAC and lighting control systems, building simulation and modeling, carbon and sustainability reporting, IT equipment management, demand response, and/or energy audits.

Energy management software often provides tools for reducing energy costs and consumption for buildings or communities. EMS collects energy data and uses it for three main purposes: Reporting, Monitoring and Engagement. Reporting may include verification of energy data, benchmarking, and setting high-level energy use reduction targets. Monitoring may include trend analysis and tracking energy consumption to identify cost-saving opportunities. Engagement can mean real-time responses (automated or manual), or the initiation of a dialogue between occupants and building managers to promote energy conservation. One engagement method that has recently gained popularity is the real-time energy consumption display available in web applications or an onsite energy dashboard/display.

Data Collection

Energy Management Software collects historic and/or real-time interval data, with intervals varying from quarterly billing statements to minute-by-minute smart meter readings. The data are collected from interval meters, Building Automation Systems (BAS), directly from utilities, or other sources. Past bills can be used to provide a comparison between pre- and post-EMS energy consumption.

Electricity and Natural Gas are the most common utilities measured, though systems may monitor steam, petroleum or other energy uses, water use, and even locally generated energy.

Reporting

Reporting tools are targeted at owners and executives who want to automate energy and emissions auditing. Cost and consumption data from a number of buildings can be aggregated or compared with the software, saving time relative to manual reporting. EMS offers more detailed energy information than utility billing can provide; another advantage is that outside factors affecting energy use, such as weather or building occupancy, can be accounted for as part of the reporting process. This information can be used to prioritize energy savings initiatives and balance energy savings against energy-related capital expenditures.

Bill verification can be used to compare metered consumption against billed consumption. Bill analysis can also demonstrate the impact of different energy costs, for example by comparing electrical demand charges to consumption costs.

Greenhouse gas (GHG) accounting can calculate direct or indirect GHG emissions, which may be used for internal reporting or enterprise carbon accounting.

Monitoring

Monitoring tools track and display real-time and historical data. Often, EMS includes various benchmarking tools, such as energy consumption per square foot, weather normalization or more advanced analysis using energy modelling algorithms to identify anomalous consumption. Seeing exactly when energy is used, combined with anomaly recognition, can allow Facility or Energy Managers to identify savings opportunities.

Initiatives such as demand shaving, replacement of malfunctioning equipment, retrofits of inefficient equipment, and removal of unnecessary loads can be discovered and coordinated using the EMS. For example, an unexpected energy spike at a specific time each day may indicate an improperly set or malfunctioning timer. These tools can also be used for Energy Monitoring and Targeting. EMS uses models to correct for variable factors such as weather when performing historical comparisons to verify the effect of conservation and efficiency initiatives.

EMS may offer alerts, via text or email messages, when consumption values exceed pre-defined thresholds based on consumption or cost. These thresholds may be set at absolute levels, or use an energy model to determine when consumption is abnormally high or low.

Engagement

Engagement can refer to automated or manual responses to collected and analyzed energy data. Building control systems can respond as readily to energy fluctuation as a heating system can respond to temperature variation. Demand spikes can trigger equipment power-down processes, with or without human intervention.

Another objective of Engagement is to connect occupants' daily choices with building energy consumption. By displaying real-time consumption information, occupants see the immediate impact of their actions. The software can be used to promote energy conservation initiatives, offer advice to the occupants, or provide a forum for feedback on sustainability initiatives.

People-driven energy conservation programs, such as those sponsored by Energy Education, can be highly effective in reducing energy use and cost.

HVAC control system

A **HVAC control system** is a computerized control system for climate control in buildings. Stand alone control devices may be pneumatic or electronic. Some may have microprocessors, but to be considered a "control system" for the context here, computerized and networked are expected requirements. HVAC stands for *heating, ventilation, air-conditioning*. Often, these integrate fire, security, and lighting controls into one system. These systems typically use one or more central controllers to command and monitor the remote terminal unit controllers, and they communicate with one or more personal computers that are used as the operator interface. These control systems are typically used on large commercial and industrial buildings to allow central control of many HVAC units around the building(s). The latest systems use ethernet for communications between central controllers--allowing remote access from a web browser.

Direct digital control

Central controllers and most terminal unit controllers are programmable, meaning the direct digital control program code may be customized for the intended use. The program features include time schedules, setpoints, controllers, logic, timers, trend logs, and alarms. The unit controllers typically have analog and digital inputs that allow measurement of the variable (temperature, humidity, or pressure) and analog and digital outputs for control of the transport medium (hot/cold water and/or steam). Digital inputs are typically (dry) contacts from a control device, and analog inputs are typically a voltage or current measurement from a variable (temperature, humidity, velocity, or pressure) sensing device. Digital outputs are typically relay contacts used to start and stop equipment, and analog outputs are typically voltage or current signals to control the movement of the medium (air/water/steam) control devices such as valves, dampers, and motors.

Group of DDC controllers, networked or not, form a layer of system themselves. This "subsystem" is vital to the performance and basic operation of the overall HVAC system. The DDC system is the "brain" of the HVAC system. It dictates the position of every damper and valve in a system. It determines which fans, pumps and chiller run and at what speed or capacity. With this configurable intelligency in this "brain", we are moving to the concept of building automation.

Building Automation System

More complex HVAC systems can interface to Building Automation System (BAS), to allow the building owners to have more control over the heating or cooling units. The building owner can monitor the system and respond to alarms generated by the system from local or remote locations. The system can be scheduled for occupancy or the configuration can be changed from the BAS. Sometimes the BAS is directly controlling the HVAC components. Depending on the BAS different interfaces can be used.

History

It was only natural that the first HVAC controllers would be pneumatic, as the engineers probably understood fluid control. Thus mechanical engineers could use their experience with the properties of steam and air to control the flow of heated or cooled air. There are still pneumatic HVAC systems in operation in some buildings, such as schools and offices, which can be a century old.

After the control of air flow and temperature was standardized, the use of electromechanical relays in ladder logic to switch dampers became standardized. Eventually, the relays became electronic switches, as transistors eventually could handle greater current loads. By 1985, pneumatic control could no longer compete with this new technology.

By the year 2000, computerized controllers were common. Today, some of these controllers can even be accessed by web browsers, which need no longer be in the same building as the HVAC equipment. This allows some economies of scale, as single operations center can easily monitor thousands of buildings.

Chapter 4

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.

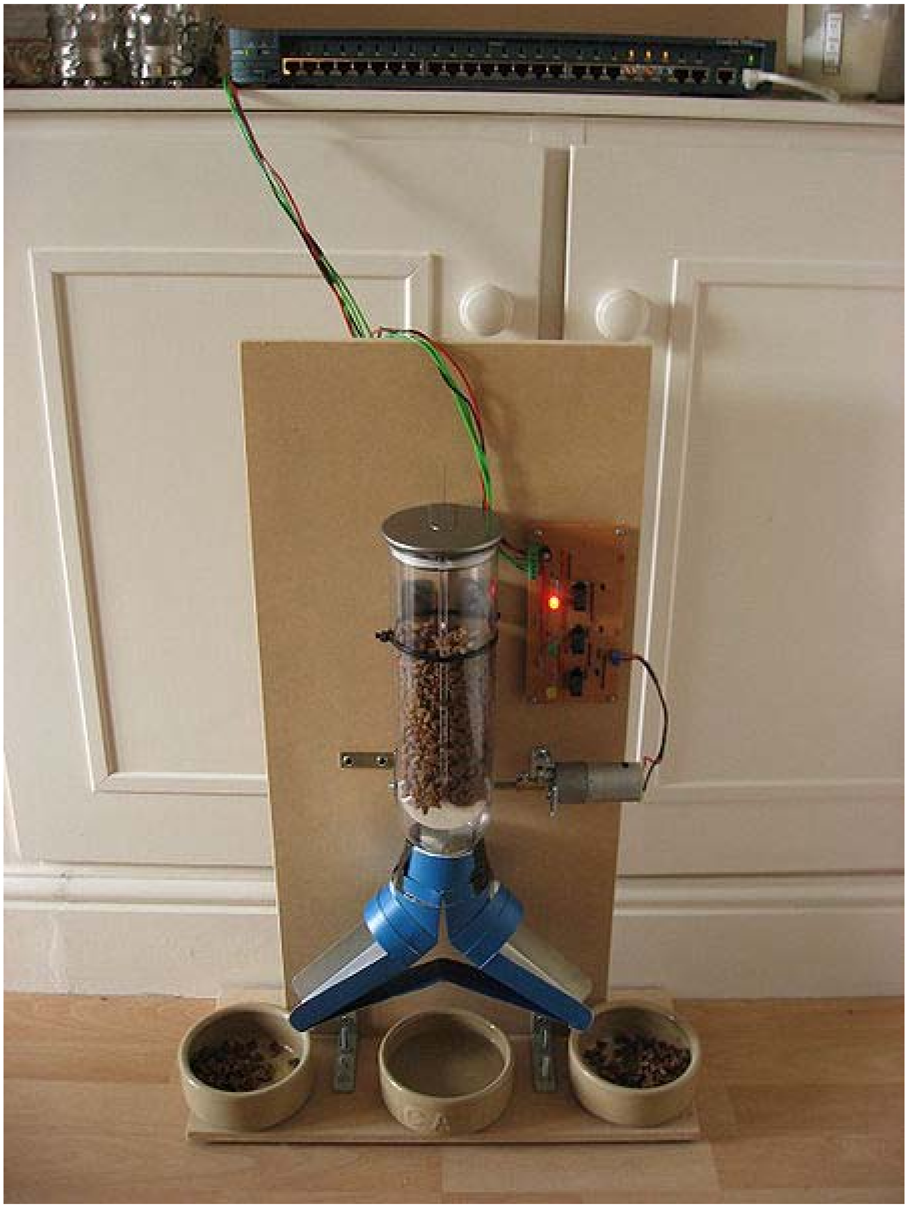
Intercoms

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 5

KNX (Standard) and oBIX

KNX (standard)

KNX is a standardised (EN 50090, ISO/IEC 14543), OSI-based network communications protocol for intelligent buildings. KNX is the successor to, and convergence of, three previous standards: the European Home Systems Protocol (EHS), BatiBUS, and the European Installation Bus (EIB or Instabus). The KNX standard is administered by the KNX Association.

KNX protocol

The standard is based on the communication stack of EIB but enlarged with the physical layers, configuration modes and application experience of BatiBUS and EHS.

KNX defines several physical communication medias:

- Twisted pair wiring (inherited from the BatiBUS and EIB Instabus standards)
- Powerline networking (inherited from EIB and EHS - similar to that used by X10)
- Radio (KNX-RF)
- Infrared
- Ethernet (also known as EIBnet/IP or KNXnet/IP)

KNX is designed to be independent of any particular hardware platform. A KNX Device Network can be controlled by anything from an 8-bit microcontroller to a PC, according to the needs of a particular implementation. The most common form of installation is over twisted pair medium.

KNX is approved as an open standard to:

- International standard (ISO/IEC 14543-3)
- Canadian standard (CSA-ISO/IEC 14543-3)
- European Standard (CENELEC EN 50090 and CEN EN 13321-1)

- China Guo Biao (GB/Z 20965)

KNX Association, as of December 2010, has nearly 220 members/manufacturers including:

- ABB
- AMX LLC
- Berker GmbH Co. KG
- Bosh Termotechnic
- Cisco Systems
- Control4 EMEA
- Creston Internacional
- Daikin Industries
- Embedded Automation
- Jung
- Legrand
- Miele & Cie KG
- ON Semiconductor
- Hager
- Schneider Electric Industries S.A.
- Somfy
- Bosch
- Russound/FMP Inc.
- Siemens
- Toshiba
- Uponor corporation

The complete list can be found here at knx.org

The KNX Association has partnership agreements with more than 30,000 installer companies in 100 countries and more than 60 technical universities as well as over 150 training centres.

Wire transmission

Twisted pair using differential signaling with a signaling speed of 9600 bit/s. Ideal wave resistance at 100 kHz is 120 Ω. Line resistance at 20 Ω/km, max 75 Ω/km. Maximum capacitance bus-to-bus line max 800 pF/m at 800 Hz. Higher capacitance requires proportionally shorter cable length. Bus power with 30 V DC and 25 mA. Devices are addressed with 8-bits.

Configuration modes

There are three categories of KNX device:

- **A-mode** or "Automatic mode" devices automatically configure themselves, and are intended to be sold to and installed by the end user.
- **E-mode** or "Easy mode" devices require basic training to install. Their behaviour is pre-programmed, but has configuration parameters that need to be tailored to the user's requirements.
- **S-mode** or "System mode" devices are used in the creation of bespoke building automation systems. S-mode devices have no default behaviour, and must be programmed and installed by specialist technicians.

KNX Products

One of the strengths of the KNX system, is that any product labeled with the KNX trademark is not a mere declaration of the manufacturer but is based on conformity testing carried out by KNX accredited third party test labs. During these tests, it is not only checked that the device supports the KNX protocol but that its useful data is coded according to the KNX standardized Data types.

This results in devices of different manufacturers and different applications that can be combined to a working installation.

The KNX Association member companies have almost 7000 KNX certified product groups in their catalogues. This wide range of products allow, for example, the integration of:

- Lighting control
- Heating/ventilation & Air Conditioning control
- Shutter/Blind & shading control
- Alarm monitoring
- Energy management & Electricity/Gas/Water metering
- Audio & video distribution

On top of that you can enable access to the system via LAN, analog or mobile phone networks for having a central or distributed control of the system via PCs, Touch screens and Smartphones.

oBIX

oBIX (for Open Building Information Exchange) is a standard for Web Services-based interfaces to building control systems. Building control systems include those electrical and mechanical systems that operate inside a building, including Heating and Cooling, Security, Power Management, and Life/Safety Alarms that are in nearly all buildings as well as the myriad of special purpose systems that may be tied to particular buildings such as A/V Event Management, Theatre Lighting, Medical Gas Distribution, Fume Hoods, and many others.

oBIX is a web services interface because it does not necessarily allow deep interactions with the underlying control systems. This interface can enable communications between enterprise applications and embedded building systems as well as between two embedded building systems. Facilities and their operations to be managed as full participants in knowledge-based businesses.

oBIX is being developed within OASIS, the Organization for the Advancement of Structured Information Standards. Version 1.0 was completed as a committee standard in December 2006.

Background

Presently most mechanical and electrical systems are provided with embedded digital controls (DDC). Most of these devices are low cost and not enabled for TCP/IP. They are installed with dedicated communications wiring. Larger DDC controllers provide network communications for these dedicated controllers. There are many well established binary protocols (BACnet, LonTalk, Modbus, DALI) that are used on these dedicated networks in addition to numerous proprietary protocols. While these binary protocols can be used over TCP/IP networks - they have challenges with routers, firewalls, security, and compatibility with other network applications. There is an added challenge in that the industry is split between several largely incompatible protocols.

Because oBIX integrates with the enterprise, it enables mechanical and electrical control systems to provide continuous visibility of operational status and performance. By exposing these operations using web services, it enables owners and tenants to use the full array of standard databases and OLAP tools to analyse their performance. oBIX enables facilities operators, owners and tenants to make decisions based on a fully integrated consideration of all life-cycle, environmental, cost, and performance factors.

Scope

oBIX provides a publicly available web services interface specification that can be used to obtain data in a simple and secure manner from HVAC, access control, utilities, and other building automation systems, and to provide data exchange between facility systems and enterprise applications. Release 1 provides a normalized representation for three of elements common to control systems:

- **Points**: representing a single scalar value and it's status – typically these map to sensors, actuators, or configuration variables like a setpoint.

- **Alarming**: modeling, routing, and acknowledgment of alarms. Alarms indicate a condition which requires notification of either a user or another application.

- **Histories**: modeling and querying of time sampled point data. Typically edge devices collect a time stamped history of point values which can be fed into higher level applications for analysis.

oBIX 1.0 provides a low level object model which can be extended during implementation. While points are directly addressable (and thereby settable), direct interaction with the points requires too much knowledge of the underlying control system for the enterprise developer. The underlyingpoints can be aggregated, the results named, alarm levels set, and histories begun using the oBIX **contract**. If oBIX exposes a low level object model for control systems, oBIX contracts create the higher level type libraries that most programmers actually want to work with.

Uses of oBIX

Tenant Interactions

To keep a public space open in the evening may require a range of calls to different organizations within a building, each initiating an interaction with a separate building control system. To schedule a public meeting tonight from 7:00 to 9:00, the organizer may have to:

- Call Security to warn the guard, and keep the (1) Access Control System working in day-time mode until 9:30. The guard may also need to disable the (2) Intrusion Detection System during that period.

- Call Maintenance to make sure the room's (3) Environmental Controls are set properly for the event. This may include over-cooling (or heating) the room in advance to make sure that the room will be comfortable when filled with the anticipated numbers of callers.

- Call the media support group to make sure the (4) A/V Event Management system is properly warmed up before the event,

In an oBIX-enabled building, these features are accomplished by instead sending an iCalendar meeting invitation to the room and/or its support systems.

Emergency Response

The Common Alerting Protocol (CAP) is a standard increasingly used for relaying information from various agencies to the public and to police and first responders. One challenge that public notification faces is that the traditional Emergency Broadcasting System for transmitting information over the radio is now much less effective, now that the public is tuned instead to personal media players such as the iPod. New versions of these protocols anticipate, for example, direct texting of all cell phones in range of a given cell tower or set of cell towers.

In a similar manner, current proposals suggest direct messaging to [Intelligent Buildings] to invoke named oBIX contracts, with effects ranging from temporary user security elevation, to initiating process shut down, to notifying in-building warning systems to read messages aloud.

The Open Geospatial Consortium anticipates Emergency Responders being able to access certain classes of geo-tagged sensor information from buildings from within their maps to improve situational awareness.

Emerging Power Markets

The GridWise Architecture Council envisions an open market or Power Providers, Transmission, Distribution, and Customer Agents negotiating freely for live power contracts based on instantaneous demand/response. The ongoing installation across the US of Electric Meters able to provide time-of-day-metering is one step to enabling this. Another is the development of Intelligent Buildings able to negotiate with the grid.

These grid negotiations are likely to be of two forms. (1) An intelligent agent residing in the building, and negotiating with the building tenants and their business processes negotiates set building system operating postures. (2) An external agent hired by the building tenants aggregates demand across multiple buildings and buys power on their behalf. Markets based on these interactions are considered to be key to creating market conditions to drive rapid innovation in on-site power storage and generation technologies.

Base Level Control Protocols

- BACnet Building Automation Control network
- KNX/EIB
- Modbus
- LonWorks
- C-Bus (protocol)
- Dynet
- Metasys
- Digital Addressable Lighting Interface DALI

Other Standards interacting with oBIX

- Open Geospatial Consortium (OGC)
- National Building Information Standard (NBIMS)
- buildingSMART

Chapter 6

Modbus

Modbus is a serial communications protocol published by Modicon in 1979 for use with its programmable logic controllers (PLCs). Simple and robust, it has since become one of the de facto standard communications protocols in the industry, and it is now amongst the most commonly available means of connecting industrial electronic devices. The main reasons for the extensive use of Modbus in the industrial environment are:

1. It has been developed with industrial applications in mind
2. It is openly published and royalty-free
3. It is easy to deploy and maintain
4. It moves raw bits or words without placing many restrictions on vendors

Modbus allows for communication between many (approximately 240) devices connected to the same network, for example a system that measures temperature and humidity and communicates the results to a computer. Modbus is often used to connect a supervisory computer with a remote terminal unit (RTU) in supervisory control and data acquisition (SCADA) systems.

The development and update of Modbus protocols are managed by the Modbus Organization, formed of independent users and suppliers of Modbus compliant devices. Some of its prominent members are Precision Digital Corporation, Motor Protection Electronics and FieldServer Technologies. Other companies, such as SoftDEL Systems and SATEC Ltd., offer Modbus devices without being formal members of Modbus Organization.

Protocol versions

Versions of the Modbus protocol exist for serial port and for Ethernet and other networks that support the Internet protocol suite. Most Modbus devices communicate over a serial EIA-485 physical layer . There are many variants of Modbus protocols

- *Modbus RTU* — This is used in serial communication & makes use of a compact, binary representation of the data for protocol communication. The RTU format follows the commands/data with a cyclic redundancy check checksum as an error check mechanism to ensure the reliability of data. Modbus RTU is the most common implementation available for Modbus. A Modbus RTU message must be transmitted continuously without inter-character hesitations. Modbus messages are framed (separated) by idle (silent) periods.

- *Modbus ASCII* — This is used in serial communication & makes use of ASCII characters for protocol communication. The ASCII format uses a longitudinal redundancy check checksum. Modbus ASCII messages are framed by leading colon (':') and trailing newline (CR/LF).

- *Modbus TCP/IP or Modbus TCP* — This is a Modbus variant used for communications over TCP/IP networks. It does not require a checksum calculation as lower layer takes care of the same.

- *Modbus over TCP/IP or Modbus over TCP or Modbus RTU/IP* — This is a modbus variant that differs from Modbus TCP in that a checksum is included in the payload as with Modbus RTU.

- *Modbus Plus (Modbus+, MB+ or MBP)* — An extended version, Modbus Plus (Modbus+ or MB+), also exists, but remains proprietary to SCHNEIDER ELECTRIC. It requires a dedicated co-processor to handle fast HDLC-like token rotation. It uses twisted pair at 1 Mbit/s and includes transformer isolation at each node, which makes it transition/edge triggered instead of voltage/level triggered. Special interfaces are required to connect Modbus Plus to a computer, typically a card made for the ISA (SA85), PCI or PCMCIA bus.

Data model and function calls are identical for the first 4 variants of protocols; only the encapsulation is different. However the variants are not interoperable as the frame formats are different.

Communication and devices

Each device intended to communicate using Modbus is given a unique address. In serial and MB+ networks only the node assigned as the Master may initiate a command, but on Ethernet, any device can send out a Modbus command, although usually only one master device does so. A Modbus command contains the Modbus address of the device it is intended for. Only the intended device will act on the command, even though other devices might receive it (an exception is specific broadcastable commands sent to node 0 which are acted on but not acknowledged). All Modbus commands contain checking information, ensuring that a command arrives undamaged. The basic Modbus commands can instruct an RTU to change a value in one of its registers, control or read an I/O port, as well as commanding the device to send back one or more values contained in its registers.

There are many modems and gateways that support Modbus, as it is a very simple protocol and often copied. Some of them were specifically designed for this protocol. Different implementations use wireline, wireless communication, such as in the ISM band, and even SMS or GPRS. One of the more common designs of wireless networks makes use of the mesh topology. Typical problems the designers have to overcome include high latency and timing problems.

Frame Format

All modbus variants choose different frame formats.

Modbus RTU Frame Format

Name	Length	Function
Start	3.5c idle	*at least 3-1/2 character times of silence (MARK condition)*
Address	8 bits	*Station Address*
Function	8 bits	*Indicates the function codes like read coils / inputs*
Data	n * 8 bits	*Data + length will be filled depending on the message type*
CRC Check	16 bits	*Error checks*
End	3.5c idle	*at least 3-1/2 character times of silence between frames*

Modbus ASCII Frame Format

Name	Length	Function
Start	1 char	*starts with colon (:) (ASCII value is 3A hex)*
Address	2 chars	*Station Address*
Function	2 chars	*Indicates the function codes like read coils / inputs*
Data	n chars	*Data +length will be filled depending on the message type*
LRC Check	2 chars	*Error checks*

End	2 chars	*carriage return – line feed(CRLF) pair (ASCII values of 0D & 0A hex)*

Modbus TCP Frame Format

Name	Length	Function
Transaction Identifier	2 bytes	*For synchronization between messages of server* & client
Protocol Identifier	2 bytes	*Zero for MODBUS/TCP*
Length Field	2 bytes	*Number of remaining bytes in this frame*
Unit Identifier	1 byte	*Slave Address (255 if not used)*
Function code	1 byte	*Function codes as in other variants*
Data bytes	n bytes	*Data as response or commands*

Unit identifier is used with MODBUS/TCP devices that are composites of several MODBUS devices, e.g. on MODBUS/TCP to MODBUS RTU gateways. In such case, the unit identifier tells the Slave Address of the device behind the gateway. Natively MODBUS/TCP-capable devices usually ignore the Unit Identifier.

Supported Function Codes

Modbus function codes / data types includes the following types. Most commonly used are given in *italics*.

- *01 Read Coil Status*
- *02 Read Input Status*
- *03 Read Holding Registers*
- *04 Read Input Registers*
- *05 Force Single Coil*
- *06 Preset Single Register*
- 07 Read Exception Status
- 08 Diagnostics
- 09 Program 484
- 10 Poll 484
- 11 Fetch Communication Event Counter
- 12 Fetch Communication Event Log
- 13 Program Controller
- 14 Poll Controller
- *15 Force Multiple Coils*
- *16 Preset Multiple Registers*
- 17 Report Slave ID

- 18 Program 884/M84
- 19 Reset Comm. Link
- 20 Read General Reference
- 21 Write General Reference
- 22 Mask Write 4X Register
- 23 Read/Write 4X Registers
- 24 Read FIFO Queue

Implementations

Almost all implementations have variations from the official standard. Different varieties might not communicate correctly between equipment of different suppliers. Some of the most common variations are:

- Data types
    - Floating point IEEE
    - 32-bit integer
    - 8-bit data
    - Mixed data types
    - Bit fields in integers
    - Multipliers to change data to/from integer. 10, 100, 1000, 256 ...

- Protocol extensions
    - 16-bit slave addresses
    - 32-bit data size (1 address = 32 bits of data returned.)
    - Word swapped data

Limitations

- Since Modbus was designed in the late 1970s to communicate to programmable logic controllers, the number of data types is limited to those understood by PLCs at the time. Large binary objects are not supported.

- No standard way exists for a node to find the description of a data object, for example, to determine if a register value represents a temperature between 30 and 175 degrees.

- Since Modbus is a master/slave protocol, there is no way for a field device to "report by exception" (except over Ethernet TCP/IP, called open-mbus)- the master node must routinely poll each field device, and look for changes in the data. This consumes bandwidth and network time in applications where bandwidth may be expensive, such as over a low-bit-rate radio link.

- Modbus is restricted to addressing 247 devices on one data link, which limits the number of field devices that may be connected to a master station (once again Ethernet TCP/IP proving the exception).

- Modbus transmissions must be contiguous which limits the types of remote communications devices to those that can buffer data to avoid gaps in the transmission.

- Modbus protocol provides no security against unauthorized commands or interception of data.

Trade group

The *Modbus organization* is a trade association for the promotion and development of Modbus protocol.

Chapter 7

Energy Monitoring and Targeting

Energy monitoring and targeting (M & T) is an energy efficiency technique based on the standard management axiom stating that “you cannot manage what you cannot measure”. M&T techniques provide Energy Managers with feedback on operating practices, results of energy management projects, and guidance on the level of energy use that is expected in a certain period.

The goal of using M&T to determine the relationship of energy use to key performance indicators (production, weather, etc.) is to help business managers:

- Identify and explain increase or decrease in energy use
- Draw energy consumption trends (weekly, seasonal, operational…)
- Determine future energy use when planning changes in the business
- Diagnose specific areas of wasted energy
- Observe how the business reacted to changes in the past
- Develop performance targets for energy management programs
- Manage their energy consumption, rather than accept it as a fixed cost that they have no control over.

The ultimate goal is to reduce energy costs through improved energy efficiency and energy management control. Other benefits generally include increased resource efficiency, improved production budgeting and reduction of greenhouse gas (GHG) emissions.

History

M&T is an established technique that has proved its worth. First launched as a national program in the UK in 1980, it then spread throughout Europe and its reputation is now slowly growing in America.

Goals and benefits

Throughout the numerous M&T projects implemented since the 1980s, a certain number of benefits have proved to be recurrent:

- Energy cost savings: generally 5% of the original energy expenses, according to The Carbon Trust. Carbon Trust has conducted a study over 1000 SMES and has concluded that on average an organisation could save 5%.
- Reduction in GHG emissions: lower energy consumption helps reduce emissions
- Financing: measured energy reductions help obtain grants for energy efficiency projects
- Improved product and service costing: sub-metering allows the division of the energy bill between the different processes of an industry, and can be calculated as a production cost
- Improved budgeting: M&T techniques can help forecast energy expenses in the case of changes in the business, for example
- Waste avoidance: helps diagnose energy waste in any process.

The technique

Key principles

Monitoring and Targeting techniques rely on three main principles, which form a constant feedback cycle, therefore improving control of energy use.

Monitoring

Monitoring is the regular collection of information on energy use, in order to establish a basis for energy management and explain deviations from an established pattern. Its primary goal is to maintain said pattern, by providing all the necessary data on energy consumption, as well as certain key variables, as identified during preliminary investigation (production, weather, etc.).

Target setting

Targeting consists in defining the levels of energy consumption desirable for the management. Targets are based on the previous knowledge acquired during the monitoring phase as well as intimate knowledge of the business. These are objectives to work towards: therefore, they must constitute a challenge, yet remain achievable.

Reporting

The final principle is the one which enables ongoing control of energy use, achievement of targets and verification of savings: reports must be issued to the appropriate managers. This in turn allows decision-making and actions to be taken in order to achieve the targets, as well as confirmation or denial that the targets have been reached.

Procedures

Before the M&T measures themselves are implemented, a few preparatory steps are necessary. First of all, key energy consumers on the site must be identified. Generally, most of the energy consumption is concentrated in a small number of processes, like heating, or certain machinery. This normally requires a certain survey of the building and the equipment to estimate their energy consumption level.

It is also necessary to assess what other measurements will be required to analyze the consumption appropriately. This data will be used to chart against the energy consumption: these are underlying factors which influence the consumption, often production (for industry processes) or exterior temperature (for heating processes), but may include many other variables.

Once all variables to be measured have been established, and the necessary meters installed, it is possible to initiate the M&T procedures.

Measure

The first step is to compile the data from the different meters. Low-cost energy feedback displays have become available. The frequency at which the data is compiled varies according to the desired reporting interval, but can go once every 30 seconds to once every 15 minutes. Some measurements can be taken directly from the meters, others must be calculated. These different measurements are often called streams or channels.

Driving factors such as production or degree days also constitute streams and must be collected at intervals to match.

Define the base-line

The data compiled must then be plotted on a graph in order to define the general consumption base-line. Consumption rates are plotted in a scatter plot against production or any other variable previously identified, and the best fit line is identified. This graph is the image of the business' average energy performance, and conveys a lot of information:

- The y-intercept gives the minimal consumption in the absence of the variable (no production, zero degree-day...). This is the base load of the system, the minimal consumption when it is not operating.
- The slope represents the relationship between the consumption and the previously identified variable. This represents the efficiency of the process.
- The scatter is the degree of variability of the consumption with operational factors.

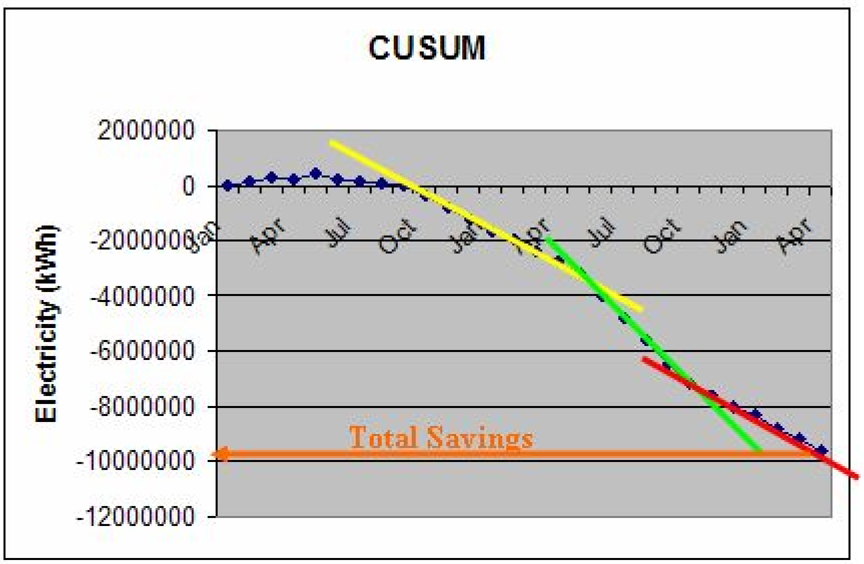
The slope is not used quite as often for M&T purposes. However, a high y-intercept can mean that there is a fault in the process, causing it to use too much energy with no performance, unless there are specific distinctive features which lead to high base loads.

Very scattered points, on the other hand, may reflect other significant factors playing in the variation of the energy consumption, other than the one plotted in the first place, but it can also be the illustration of a lack of control over the process.

Monitor variations

The next step is to monitor the difference between the expected consumption and the actual measured consumption. One of the tools most commonly used for this is the CUSUM, which is the CUmulative SUM of differences. This consists in first calculating the difference between the expected and actual performances (the best fit line previously identified and the points themselves).

The CUSUM can then be plotted against time on a new graph, which then yields more information for the energy efficiency specialist. Variances scattered around zero usually mean that the process is operating normally. Marked variations, increasing or decreasing steadily usually reflect a modification in the conditions of the process.



In the case of the CUSUM graph, the slope becomes very important, as it is the main indicator of the savings achieved. A slope going steadily down indicates steady savings. Any variation in the slope indicates a change in the process. For example, in the graph on the right, the first section indicated no savings. However, in September (beginning of the yellow line), an energy efficiency measure must have been implemented, as savings start to occur. The green line indicates an increase in the savings (as the slope is becoming steeper), whereas the red line must reflect a modification in the process having occurred in November, as savings have decreased slightly.

Identify causes

Energy efficiency specialists, in collaboration with building managers, will decipher the CUSUM graph and identify the causes leading to variations in the consumption. This can be a change in behaviour, a modification to the process, different exterior conditions, etc. These changes must be monitored and the causes identified in order to promote and enhance good behaviour, and discourage bad ones.

Set targets

Once the base line has been established, and causes for variations in energy consumption have been identified, it is time to set targets for the future. Now with all this information in hand, the targets are more realistic, as they are based on the building's actual consumption. Targeting consists in two main parts: the measure to which the consumption can be reduced, and the timeframe during which the compression will be achieved.

A good initial target is the best fit line identified during step 2. This line represents the average historical performance. Therefore, keeping all consumption below or equal to the historical average is an achievable target , yet remains a challenge as it involves eliminating high consumption peaks.

Some companies, as they improve their energy consumption, might even decide to bring their average performance down to their historical best. This is considered a much more challenging target.

Monitor results

This brings us back to step 1: measure consumption. One of the specificities of M&T is that it is an ongoing process, requiring constant feedback in order to consistently improve performance. Once the targets are set and the desired measures are implemented, repeating the procedure from the start ensures that the managers are aware of the success or failure of the measures, and can then decide on further action.

Chapter 8

Automatic Fire Suppression

Automatic fire suppression systems control and extinguish fires without human intervention.

According to the National Fire Protection Association, there were 1,602,000 fires reported in the United States in 2005. There were 3,675 civilian deaths, 17,925 civilian injuries, and $9.2 billion in property damage. A fire department responded to a fire every 20 seconds and a structure fire was reported every 62 seconds.

Although man has fought fire for centuries, it was not until Feb. 10, 1863 that the first fire extinguisher patent was issued to Alanson Crane of Virginia. The first fire sprinkler system was patented by H.W. Pratt in 1872. But the first practical automatic sprinkler system was invented in 1874 by Henry S. Parmalee of New Haven, CT. He installed the system in a piano factory he owned.

Types of automatic systems

Automatic system in a computer room

Today there are numerous types of Automatic Fire Suppression Systems. Systems are as diverse as the many applications. In general, however, Automatic Fire Suppression Systems fall into two categories: *engineered* and *pre-engineered* systems.

Engineered Fire Suppression Systems are design specific. Engineered systems are usually for larger installations where the system is designed for the particular application. Examples include marine and land vehicle applications, computer clean rooms, public and private buildings, industrial paint lines, dip tanks and electrical switch rooms. Engineered systems use a number of gaseous or solid agents. Many are specifically formulated. Some, such as 3M Novec 1230 Fire Protection Fluid, are stored as a liquid and discharged as a gas.

Pre-Engineered Fire Suppression Systems use pre-designed elements to eliminate the need for engineering work beyond the original product design. Typical industrial solutions use a simple wet or dry chemical agent, such as potassium carbonate or monoammonium phosphate (MAP), to protect spaces such as paint rooms and booths, storage areas and commercial kitchens. In Europe, a small number of residential designs have also emerged. These units often employ water mist with or without a surfactant additive, and target retrofit applications where the risk of fire or fire injury is high but where a conventional fire sprinkler system would be unacceptably expensive.

Components

By definition, an automatic fire suppression system can operate without human intervention. To do so it must possess a means of detection, actuation and delivery.

In many systems, detection is accomplished by mechanical or electrical means. Mechanical detection uses fusible-link or thermo-bulb detectors. These detectors are designed to separate at a specific temperature and release tension on a release mechanism. Electrical detection uses heat detectors equipped with self-restoring, normally-open contacts which close when a predetermined temperature is reached. Remote and local manual operation is also possible.

Actuation usually involves either a pressurised fluid and a release valve, or in some cases an electric pump.

Delivery is accomplished by means of piping and nozzles. Nozzle design is specific to the agent used and coverage desired.

Extinguishing agents

In the early days, water was the exclusive fire suppression agent. Although still used today, water has limitations. Most notably, its liquid and conductive properties can cause as much property damage as fire itself.

Agent	Primary Ingredient	Applications
FM-200	Heptafluoropropane	Electronics, medical equipment, production equipment, libraries, data centers, medical record rooms, server rooms, oil pumping stations, engine compartments, telecommunications rooms, switch rooms, engine and machinery spaces, pump rooms, control rooms
3M Novec 1230 Fire Protection Fluid	Fluorinated ketone	Electronics, medical equipment, production equipment, libraries, data centers, medical record rooms, server rooms, oil pumping stations, engine compartments, telecommunications rooms, switch rooms, engine and machinery spaces, pump rooms, control rooms
Argonite	Argon and nitrogen	Same applications and FM-200 and Novec 1230 fluid; less Class B style hazards
FE-13	Fluoroform	Police evidence freezers, inerting natural gas pumping stations or trains/trucks/cranes operating in cold weather, electronics, medical equipment,

		production equipment, libraries, data centers, medical record rooms, server rooms, oil pumping stations, engine compartments, telecommunications rooms, switch rooms, engine and machinery spaces, pump rooms, control rooms
Wet Chemical	Potassium carbonate	Commercial kitchens
ABC Dry Chemical	Monoammonium phosphate	Paint booths, dip tanks, coating operations, flammable liquid storage areas, paint mixing areas, exhaust ducts
Regular Dry Chemical	Sodium bicarbonate	Gasoline, propane and solvents, live electrical equipment, flammable liquids
Carbon Dioxide	Carbon Dioxide	Non-occupied control rooms, coating operations, paint lines, dust collectors, transformer vaults, live electrical equipment, flammable liquids, commercial fryers
Foam	Synthetic detergent, polysaccharide, fluoroakyl suffaccant	Flammable liquids
Purple K Dry Chemical	Potassium bicarbonate	High hazard commercial and industrial applications, especially with flammable liquids
Halotron 1	2,2-dichloro-1,1,1-trifluoroethane	Live electrical equipment, flammable liquids
Water Mist	Water	Ordinary flammables (Paper, wood, cloth)
Water	Water	Ordinary flammables (Paper, wood, cloth)

Health and environmental concerns

Despite their effectiveness, chemical fire extinguishing agents are not without disadvantages. In the early 20th century, carbon tetrachloride was extensively used as a dry cleaning solvent, a refrigerant and as a fire extinguishing agent. In time, it was found carbon tetrachloride could lead to severe health effects.

From the mid 1960s Halon 1301 was the industry standard for protecting high value assets from the threat of fire. Halon 1301 had many benefits as a fire suppression agent; it is fast acting, safe for assets and required minimal storage space. Halon 1301s major drawbacks are that it depletes atmospheric ozone and is potentially harmful to humans.

Since 1987, some 191 nations have signed The Montreal Protocol on Substances That Deplete the Ozone Layer. The Protocol is an international treaty designed to protect the ozone layer by phasing out the production of a number of substances believed to be responsible for ozone depletion. Among these were halogenated hydrocarbons often used in fire suppression. As a result manufacturers have focused on alternatives to Halon 1301 and Halon 1211 (halogenated hydrocarbons).

A number of countries have also taken steps to mandate the removal of installed Halon systems. Most notably these include Germany and Australia, the first two countries in the world to require this action. In both of these countries complete removal of installed Halon systems has been completed except for a very few essential use applications. The European Union is currently undergoing a similar mandated removal of installed Halon systems.

Modern systems

Since the early 1990s manufacturers have successfully developed safe and effective Halon alternatives. These include DuPont FM-200, American Pacific's Halotron and 3M Novec 1230 Fire Protection Fluid. Generally, the Halon replacement agents available today fall into two broad categories, in-kind (gaseous extinguishing agents) or not in-kind (alternative technologies). In-kind **gaseous agents generally fall into two further categories, Halocarbons and Inert Gases. Not in-kind alternatives include such options as water mist or the use of early warning smoke detection systems.**

Chapter 9

Fire Extinguisher

A stored-pressure fire extinguisher

A **fire extinguisher** is an active fire protection device used to extinguish or control small fires, often in emergency situations. It is not intended for use on an out-of-control fire, such as one which has reached the ceiling, endangers the user (i.e. no escape route, smoke, explosion hazard, etc.), or otherwise requires the expertise of a fire department. Typically, a fire extinguisher consists of a hand-held cylindrical pressure vessel containing an agent which can be discharged to extinguish a fire.

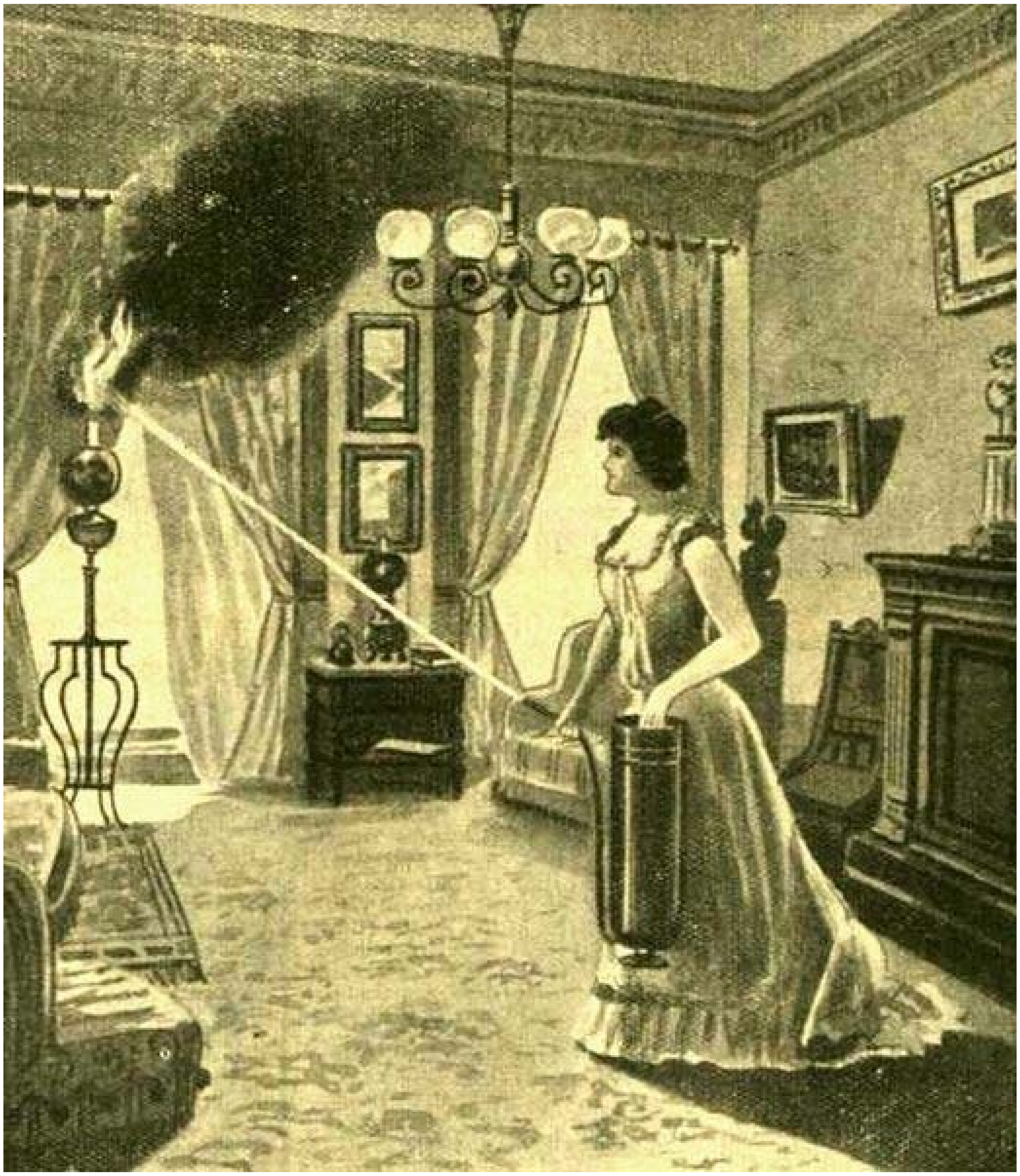
In the United States, fire extinguishers, in all buildings other than houses, are generally required to be serviced and inspected by a Fire Protection service company at least annually. Some jurisdictions require more frequent service for fire extinguishers. At the time of service, a fire extinguisher tag is placed on the extinguisher to indicate the type of service perform (annual inspection, recharge, new fire extinguisher) and date of service.

There are two main types of fire extinguishers: stored pressure and cartridge-operated. In stored pressure units, the expellant is stored in the same chamber as the firefighting agent itself. Depending on the agent used, different propellants are used. With dry chemical extinguishers, nitrogen is typically used; water and foam extinguishers typically use air. Stored pressure fire extinguishers are the most common type. Cartridge-operated extinguishers contain the expellant gas in a separate cartridge that is punctured prior to discharge, exposing the propellant to the extinguishing agent. This type is not as common, used primarily in areas such as industrial facilities, where they receive higher-than-average use. They have the advantage of simple and prompt recharge, allowing an operator to discharge the extinguisher, recharge it, and return to the fire in a reasonable amount of time. Unlike stored pressure types, these extinguishers utilize compressed carbon dioxide instead of nitrogen, although nitrogen cartridges are used on low temperature (-60 rated) models. Cartridge operated extinguishers are available in dry chemical and dry powder types in the US and in water, wetting agent, foam, dry chemical (classes ABC and BC), and dry powder (class D) types in the rest of the world.

A fire extinguisher located in a middle school.

Fire extinguishers are further divided into handheld and cart-mounted, also called wheeled extinguishers. Handheld extinguishers weigh from 0.5 to 14 kilograms (1 to 30 pounds), and are hence, easily portable by hand. Cart-mounted units typically weigh 23+ kilograms (50+ pounds). These wheeled models are most commonly found at construction sites, airport runways, heliports, as well as docks and marinas.

History



A 1905 illustration marketing extinguishers.

The first fire extinguisher of which there is any record was patented in England in 1723 by Ambrose Godfrey, a celebrated chemist. It consisted of a cask of fire-extinguishing liquid containing a pewter chamber of gunpowder. This was connected with a system of fuses which were ignited, exploding the gunpowder and scattering the solution. This device was probably used to a limited extent, as Bradley's Weekly Messenger for November 7, 1729, refers to its efficiency in stopping a fire in London.

The modern fire extinguisher was invented by British Captain George William Manby in 1818; it consisted of a copper vessel of 3 gallons (13.6 litres) of pearl ash (potassium carbonate) solution contained within compressed air.

A classic copper building type soda-acid extinguisher

The soda-acid extinguisher was first patented in 1866 by Francois Carlier of France, which mixed a solution of water and sodium bicarbonate with tartaric acid, producing the propellant CO_2 gas. A soda-acid extinguisher was patented in the U.S. in 1881 by Almon M. Granger. His extinguisher used the reaction between sodium bicarbonate solution and sulfuric acid to expel pressurized water onto a fire. A vial was suspended in the cylinder containing concentrated sulfuric acid. Depending on the type of extinguisher, the vial of acid could be broken in one of two ways. One used a plunger to break the acid vial, while the second released a lead stopple that held the vial closed. Once the acid was mixed with the bicarbonate solution, carbon dioxide gas was expelled and thereby pressurized the water. The pressurized water was forced from the canister through a nozzle or short length of hose.

The cartridge-operated extinguisher was invented by Read & Campbell of England in 1881, which used water or water-based solutions. They later invented a carbon tetrachloride model called the "Petrolex" which was marketed toward automotive use.

A glass "grenade" style extinguisher, to be thrown into a fire.

The chemical foam extinguisher was invented in 1904 by Aleksandr Loran in Russia, based on his previous invention of fire fighting foam. Loran first used it to extinguish a pan of burning naphtha. It worked and looked similar to the soda-acid type, but the inner parts were slightly different. The main tank contained a solution of sodium bicarbonate in water, whilst the inner container (somewhat larger than the equivalent in a Soda-Acid unit) contained a solution of Aluminium Sulphate. When the solutions were mixed, usually by inverting the unit, the two liquids reacted to create a frothy foam, and carbon dioxide gas. The gas expelled the foam in the form of a jet. Although liquorice-root extracts and similar compounds were used as additives (stablilsing the foam by reinforcing the bubble-walls), there was no "foam compound" in these units. The foam was a combination of the products of the chemical reactions: Sodium and Aluminium salt-gels inflated by the carbon-dioxide. Because of this, the foam was discharged directly from the unit, with no need for an aspirating branchpipe (as in newer foam-compound types).

A Pyrene, brass, carbon-tetrachloride extinguisher

In 1910, The Pyrene Manufacturing Company of Delaware filed a patent for a using carbon tetrachloride (CTC) to extinguish fires. The liquid vaporized and extinguished the flames by inhibiting the chemical chain reaction of the combustion process (it was an early 20th century presupposition that the fire suppression ability of carbon tetrachloride relied on oxygen removal.) In 1911, they patented a small, portable extinguisher that used the chemical. This consisted of a brass or chrome container with an integrated handpump, which was used to expel a jet of liquid towards the fire. It was usually of 1 imperial quart (1.1 L) or 1 imperial pint (0.6 L) capacity but was also available in up to 2 imperial gallon (9 L) size. As the container was unpressurized, it could be refilled after use through a filling plug with a fresh supply of CTC.

Another type of carbon-tetrachloride extinguisher was the **Fire grenade**. This consisted of a glass sphere filled with CTC, that was intended to be hurled at the base of a fire (early ones used salt-water, but CTC was more effective). Carbon tetrachloride was suitable for liquid and electrical fires and the extinguisers were fitted to motor vehicles. Carbon-tetrachloride extinguishers were withdrawn in the 1950s because of the chemical's toxicity–exposure to high concentrations damages the nervous system and internal organs. Additionally, when used on a fire, the heat can convert CTC to Phosgene gas , formerly used as a chemical weapon.

In the 1940s, Germany invented the liquid chlorobromomethane (CBM) for use in aircraft. It was more effective and slightly less toxic than carbon tetrachloride and was used until 1969. Methyl bromide was discovered as an extinguishing agent in the 1920s and was used extensively in Europe. It is a low-pressure gas that works by inhibiting the chain reaction of the fire and is the most toxic of the vaporizing liquids, used until the 1960s. The vapor and combustion by-products of all vaporizing liquids were highly toxic, and could cause death in confined spaces.

A chemical foam extinguisher with contents.

The carbon dioxide (CO_2) extinguisher was invented (at least in the US) by the Walter Kidde Company in 1924 in response to Bell Telephone's request for an electrically non-conductive chemical for extinguishing the previously difficult to extinguish fires in telephone switchboards. It consisted of a tall metal cylinder containing 7.5 lbs. of CO_2 with a wheel valve and a woven brass, cotton covered hose, with a composite funnel-like horn as a nozzle. CO_2 is still popular today as it is an ozone-friendly clean agent and is used heavily in film and television production to extinguish burning stuntmen. Carbon dioxide extinguishes fire mainly by displacing oxygen. It was once thought that it worked by cooling, although this effect on most fires is negligible. This characteristic is well known and has led to the widespread misuse of carbon dioxide extinguishers to rapidly cool beverages, especially beer.

An early dry chemical extinguisher, the first ones had copper cylinders, this one is steel.

In 1928, DuGas (later bought by ANSUL) came out with a cartridge-operated dry chemical extinguisher, which used sodium bicarbonate specially treated with chemicals to render it free-flowing and moisture-resistant. It consisted of a copper cylinder with an internal CO_2cartridge. The operator turned a wheel valve on top to puncture the cartridge and squeezed a lever on the valve at the end of the hose to discharge the chemical. This was the first agent available for large scale three-dimensional liquid and pressurized gas fires, and was but remained largely a specialty type until the 1950s, when small dry chemical units were marketed for home use. ABC dry chemical came over from Europe in the 1950s, with Super-K being invented in the early 60s and Purple-K being developed by the US Navy in the late 1960s.

In the 1970s, Halon 1211 came over to the US from Europe, where it had been used since the late 40s or early 50s. Halon 1301 had been developed by DuPont and the US Army in 1954. Both 1211 and 1301 work by inhibiting the chain reaction of the fire, and in the case of Halon 1211, cooling class A fuels as well. Halon is still in use today, but is falling out of favor for many uses due to its environmental impact. Europe, and Australia have severely restricted its use, since the Montreal Protocol of 1987. It is however still in use in the United States, the Middle East, and Asia.

Classification

Internationally there are several accepted classification methods for hand-held fire extinguisher. Each classification is useful in fighting fires with a particular group of fuel.

Australia

Type	Pre-1997	Current	Suitable for use on Fire Classes (brackets denote sometimes applicable)					
Water	Solid red	Solid red	A					
Foam	Solid blue	Red with a blue band	A	B				
Dry chemical (powder)	Red with a white band	Red with a white band	A	B	C		E	
Carbon dioxide	Red with a black band	Red with a black band	(A)	B		D		F
Vaporising liquid (non-halon clean agents)	Not yet in use	Red with a yellow band	A	B	C		E	
Halon	Solid yellow	No longer produced	A	B			E	
Wet chemical	Solid oatmeal	Red with an oatmeal band	A					F

In Australia, yellow (Halon) fire extinguishers are illegal to own or use on a fire, unless an essential use exemption has been granted.

United Kingdom

Typical United Kingdom CO_2 and water fire extinguishers

According to the standard BS EN 3, fire extinguishers in the United Kingdom as all throughout Europe are red RAL 3000, and a band or circle of a second colour covering between 5–10% of the surface area of the extinguisher indicates the contents. Before 1997, the entire body of the fire extinguisher was colour coded according to the type of extinguishing agent.

The UK recognises six fire classes:

- Class A fires involve organic solids such as paper and wood.

- Class B fires involve flammable or combustible liquids. Petrol, grease and oil fires are included in this class.
- Class C fires involve flammable gases
- Class D fires involve combustible metals.
- Class E fires involving electrical appliances (no longer used as when the power supply is turned off an electrical fire can fall into any category)
- Class F fires involve cooking fat and oil.

Type	Old code	BS EN 3 colour code	Suitable for use on fire classes (brackets denote sometimes applicable)					
Water	Signal red	Signal red	A					
Foam	Cream	Red with a cream panel above the operating instructions	A	B				
Dry powder	French blue	Red with a blue panel above the operating instructions	(A)	B	C		E	
Carbon dioxide CO_2	Black	Red with a black panel above the operating instructions		B			E	
Wet chemical	Not yet in use	Red with a canary yellow panel above the operating instructions	A	(B)				F
Class D powder	French blue	Red with a blue panel above the operating instructions				D		
Halon 1211/BCF	Emerald Green	No longer in general use	A	B			E	

In the UK the use of Halon gas is now prohibited except under certain situations such as on aircraft and in the military and police.

Fire extinguishing performance per fire class is displayed using numbers and letters such as 13A, 55B.

EN3 does not recognise a separate electrical class - however there is an additional feature requiring special testing (35 kV dielectric test per EN 3-7:2004). A powder or CO_2 extinguisher will bear an electrical pictogramme as standard signifying that it can be used on live electrical fires (given the symbol E in the table). If a water-based extinguisher has passed the 35 kV test it will also bear the same electrical pictogramme - however, any water-based extinguisher is only recommended for inadvertent use on electrical fires.

United States

There is no official standard in the United States for the color of fire extinguishers, though they are typically red, except for Class D extinguishers, which are usually yellow, and water, which are usually silver, or white if water mist. Extinguishers are marked with pictograms depicting the types of fires that the extinguisher is approved to fight. In the past, extinguishers were marked with colored geometric symbols, and some extinguishers still use both symbols. The types of fires and additional standards are described in NFPA 10: Standard for Portable Fire Extinguishers, 2010 edition.

Fire Class	Geometric Symbol	Pictogram	Intended Use
A	Green Triangle	Garbage can and wood pile burning	Ordinary solid combustibles
B	Red Square	Fuel container and burning puddle	Flammable liquids and gases
C	Blue Circle	Electric plug and burning outlet	Energized electrical equipment
D	Yellow Decagon (Star)	Burning Gear and Bearing	Combustible metals
K	Black Hexagon	Pan burning	Cooking oils and fats

The Underwriters Laboratories rate fire extinguishing capacity in accordance with UL/ANSI 711: Rating and Fire Testing of Fire Extinguishers. The ratings are described using numbers preceding the class letter, such as 1-A:10-B:C. The number preceding the A multiplied by 1.25 gives the equivalent extinguishing capability in gallons of water. The number preceding the B indicates the size of fire in square feet that an ordinary user should be able to extinguish. There is no additional rating for class C, as it only indicates that the extinguishing agent will not conduct electricity, and an extinguisher will never have a rating of just C.

Installation

A fire extinguisher fitted to the passenger seat of a car.

Fire extinguishers are typically fitted in buildings at an easily-accessible location, such as against a wall in a high-traffic area. They are also often fitted to motor vehicles, watercraft, and aircraft - this is required by law in many jurisdictions, for identified classes of vehicles. Under NFPA 10 all commercial vehicles must carry at least one fire extinguisher, with size/UL rating depending on type of vehicle and cargo (i.e. fuel tankers typically must have a 9.1 kg (20 lb), when most others can carry a 2.3 kg (5 lb)). The revised NFPA 10 created criteria on the placement of "Fast Flow Extinguishers" in locations such as those storing and transporting pressurized flammable liquids and pressurized flammable gas or areas with possibility of three dimensional class B hazards are required to have "fast flow" extinguishers as required by NFPA 5.5.1.1. Varying classes of competition vehicles require fire extinguishing systems, the simplest requirements being a 1A:10BC hand-held portable extinguisher mounted to the interior of the vehicle.

Types of extinguishing agents

Dry chemical

A small, disposable sodium bicarbonate dry chemical unit intended for home kitchen use.

A typical dry chemical extinguisher containing 5 lbs. of ammonium phosphate dry chemical.

A 20lb.U.S.Navy cartridge-operated purple-K dry chemical (potassium bicarbonate) extinguisher.

Two Super-K (potassium chloride) extinguishers.

Powder based agent that extinguishes by separating the four parts of the fire tetrahedron. It prevents the chemical reaction between heat, fuel and oxygen and halts the production of fire sustaining "free-radicals", thus extinguishing the fire.

- Monoammonium phosphate, also known as "tri-class", "multipurpose" or "ABC" dry chemical, used on class A, B, and C fires. It receives its class A rating from the agent's ability to melt and flow at 177 °C (350 °F) to smother the fire. More corrosive than other dry chemical agents. Pale yellow in color.
- Sodium bicarbonate, "regular" or "ordinary" used on class B and C fires, was the first of the dry chemical agents developed. It interrupts the fire's chemical reaction, and was very common in commercial kitchens before the advent of wet

chemical agents, but now is falling out of favor, as it is much less effective than wet chemical agents for class K fires, less effective than Purple-K for class B fires, and is ineffective on class A fires. White or blue in color.

- Potassium bicarbonate (aka Purple-K), used on class B and C fires. About two times as effective on class B fires as sodium bicarbonate, it is the preferred dry chemical agent of the oil and gas industry. The only dry chemical agent certified for use in ARFF by the NFPA. Violet in color.
- Potassium bicarbonate & Urea Complex (aka Monnex/Powerex), used on Class B and C fires. More effective than all other powders due to its ability to decrepitate (where the powder breaks up into smaller particles) in the flame zone creating a larger surface area for free radical inhibition. Grey in color.
- Potassium Chloride, or Super-K dry chemical was developed in an effort to create a high efficiency, protein-foam compatible dry chemical. Developed in the 60s, prior to Purple-K, it was never as popular as other agents since, being a salt, it was quite corrosive. For B and C fires, white in color.
- Foam-Compatible, which is a sodium bicarbonate (BC) based dry chemical, was developed for use with protein foams for fighting class B fires. Most dry chemicals contain metal stearates to waterproof them, but these will tend to destroy the foam blanket created by protein (animal) based foams. Foam compatible type uses silicone as a waterproofing agent, which does not harm foam. Effectiveness is identical to regular dry chemical, and it is light green in color (some ANSUL brand formulations are blue). This agent is generally no longer used since most modern dry chemicals are considered compatible with synthetic foams such as AFFF.
- MET-L-KYL / PYROKYL is a specialty variation of sodium bicarbonate for fighting pyrophoric liquid fires (ignite on contact with air). In addition to sodium bicarbonate, it also contains silica gel particles. The sodium bicarbonate interrupts the chain reaction of the fuel and the silica soaks up any unburned fuel, preventing contact with air. It is effective on other class B fuels as well. Blue/Red in color.

Foams

A 2½ gallon AFFF foam fire extinguisher

Applied to fuel fires as either an aspirated (mixed & expanded with air in a branch pipe) or non aspirated form to form a frothy blanket or seal over the fuel, preventing oxygen reaching it. Unlike powder, foam can be used to progressively extinguish fires without flashback.

- AFFF (aqueous film forming foam), used on A and B fires and for vapor suppression. The most common type in portable foam extinguishers. It contains fluoro tensides which can be accumulated in human body. The long-term effects of this on the human body and environment are unclear at this time.

- AR-AFFF (Alcohol-resistant aqueous film forming foams), used on fuel fires containing alcohol. Forms a membrane between the fuel and the foam preventing the alcohol from breaking down the foam blanket.
- FFFP (film forming fluoroprotein) contains naturally occurring proteins from animal by-products and synthetic film-forming agents to create a foam blanket that is more heat resistant than the strictly synthetic AFFF foams. FFFP works well on alcohol-based liquids and is used widely in motorsports.
- CAFS (compressed air foam system) Any APW style extinguisher that is charged with a foam solution and pressurized with compressed air. Generally used to extend a water supply in wildland operations. Used on class A fires and with very dry foam on class B for vapor suppression.
- Arctic Fire is a liquid fire extinguishing agent that emulsifies and cools heated materials more quickly than water or ordinary foam. It is used extensively in the steel industry. Effective on classes A, B, and D.
- FireAde, a foaming agent that emulsifies burning liquids and renders them non-flammable. It is able to cool heated material and surfaces similar to CAFS. Used on A and B (said to be effective on some class D hazards, although not recommended due to the fact that fireade still contains amounts of water which will react with some metal fires).

An American water extinguisher

Water

Cools burning material.

- APW (Air pressurized water) cools burning material by absorbing heat from burning material. Effective on Class A fires, it has the advantage of being inexpensive, harmless, and relatively easy to clean up. In the United States, APW units contain 2.5 gallons (9 litres) of water in a tall, stainless steel cylinder. In Europe, they are typically mild steel lined with polyethylene, painted red, containing 6–9 litres (1.75–2.5 gallons) of water.

- Water Mist uses a fine misting nozzle to break up a stream of deionized water to the point of not conducting electricity back to the operator. Class A and C rated. It is used widely in hospitals for the reason that, unlike other clean-agent suppressants, it is harmless and non-contaminant. These extinguishers come in 1.75 and 2.5 gallon units, painted white in the United States and red in Europe.

Wet chemical and water additives

- Wet Chemical (potassium acetate, carbonate, or citrate) extinguishes the fire by forming a soapy foam blanket over the burning oil and by cooling the oil below its ignition temperature. Generally class A and K (F in Europe) only, although newer models are outfitted with misting nozzles as those used on water mist units to give these extinguishers class B and C firefighting capability.
- Wetting Agents Detergent based additives used to break the surface tension of water and improve penetration of Class A fires.
- Antifreeze Chemicals added to water to lower its freezing point to about −40 °F. Has no appreciable effect on extinguishing performance.

Clean agents and carbon dioxide

A 5 lb. CO_2 fire extinguisher

Agent displaces oxygen (CO_2 or inert gases), removes heat from the combustion zone (Halotron, FE-36) or inhibits chemical chain reaction (Halons). They are labelled clean agents because they do not leave any residue after discharge which is ideal for sensitive electronics and documents.

- Halon (including Halon 1211 and Halon 1301), a gaseous agent that inhibits the chemical reaction of the fire. Classes B:C for lower weight fire extinguishers (2.3 kg; under 9 lbs) and A:B:C for heavier weights (4.1–7.7 kg; 9–17 lbs). Banned from new production, except for military use, as of January 1, 1994 as its properties contribute to ozone depletion and long atmospheric lifetime, usually

400 years. Halon was completely banned in Europe resulting in stockpiles being sent to the United States for reuse. Although production has been banned, the reuse is still permitted. Halon 1301 and 1211 are being replaced with new halocarbon agents which have no ozone depletion properties and low atmospheric lifetimes, but are less effective. Currently Halotron I, Halotron II, FE-36 Cleanguard and FM-200 are meant to be replacements with significantly reduced ozone depletion potential.

- CO_2, a clean gaseous agent which displaces oxygen. Highest rating for 7.7 kg (20 pound) portable CO_2 extinguishers is 10B:C. Not intended for Class A fires, as the high-pressure cloud of gas can scatter burning materials. CO_2 is not suitable for use on fires containing their own oxygen source, metals or cooking media. Although it can be rather successful on a person on fire, its use should be avoided where possible as it can cause frostbite and is dangerous to use as it may displace the oxygen needed for breathing, causing suffocation.
- Mixtures of inert gases, including Inergen and Argonite.
- compressed CO2 sprinkler is another design used to fight the electric fires with cubic cylinder of 7 cubic meter starting from 1 meter above the sprinkler level.
- Novec 1230 fluid (aka "dry water" or Saffire fluid), a fluoronated ketone that works by removing massive amounts of heat. Available in fixed systems in the US and in portables in Australia. Unlike other clean agents, this one has the advantage of being a liquid at atmospheric pressure, and can be discharged as a stream or a rapidly vaporizing mist, depending on application.

Class D

A class D fire extinguisher for various metals

There are several Class D fire extinguisher agents available, some will handle multiple types of metals, others will not.

- Sodium Chloride (Super-D, Met-L-X or METAL.FIRE.XTNGSHR) contains sodium chloride salt and thermoplastic additive. Plastic melts to form an oxygen-excluding crust over the metal, and the salt dissipates heat. Useful on most alkali metals including sodium and potassium, and other metals including magnesium, titanium, aluminum, and zirconium.

- Copper based (Copper Powder Navy125S) developed by the U.S. Navy in the 70s for hard-to-control lithium and lithium-alloy fires. Powder smothers and acts as a heat sink to dissipate heat, but also forms a copper-lithium alloy on the surface which is non-combustible and cuts off the oxygen supply. Will cling to a vertical surface-lithium only.

- Graphite based (G-Plus, G-1, Lith-X, Pyromet or METAL.FIRE.XTNGSHR) contains dry graphite that smothers burning metals. First type developed, designed for magnesium, works on other metals as well. Unlike sodium chloride powder extinguishers, the graphite powder fire extinguishers can be used on very hot burning metal fires such as lithium, but unlike copper powder extinguishers will not stick to and extinguish flowing or vertical lithium fires. Like copper extinguishers, the graphite powder acts as a heat sink as well as smothering the metal fire.

- Sodium carbonate based (Na-X) used where stainless steel piping and equipment could be damaged by sodium chloride based agents to control sodium, potassium, and sodium-potassium alloy fires. Limited use on other metals. Smothers and forms a crust.

- Some water based suppressants may be used on certain class D fires, such as burning titanium and magnesium. Examples include the Fire Blockade and FireAde brands of suppressant. Some metals, such as elemental Lithium, will react explosively with water, therefore water-based chemicals should never be used on such fires due to the possibility of a violent reaction.

Most Class D extinguishers will have a special low velocity nozzle or discharge wand to gently apply the agent in large volumes to avoid disrupting any finely divided burning materials. Agents are also available in bulk and can be applied with a scoop or shovel.

Fire Extinguishing Ball

Several modern ball or "grenade" style extinguishers are on the market. They are manually operated by rolling or throwing into a fire. The modern version of the ball will self destruct once in contact with flame, dispersing a cloud of ABC dry chemical powder over the fire which extinguishes the flame. The coverage area is about 5 square meters. One benefit of this type is that it may be used for passive suppression. The ball can be placed in a fire prone area and will deploy automatically if a fire develops, being triggered by heat. Most modern extinguishers of this type are designed to make a loud noise upon deployment.

This technology is not new, however. In the 1800s, glass fire grenades filled with suppressant liquids were popular. These glass fire grenade bottles are sought by collectors. Some later brands, such as Red Comet, were designed for passive operation, and included a special holder with a spring loaded trigger that would break the glass ball when a fusible link melted. As was typical of this era, some glass extinguishers contained the toxic carbon tetrachloride.

Maintenance

An empty fire extinguisher which was not replaced for years.

Most countries in the world require regular fire extinguisher maintenance by a competent person to operate safely and effectively, as part of fire safety legislation. Lack of maintenance can lead to an extinguisher not discharging when required, or rupturing when pressurized. Deaths have occurred, even in recent times, from corroded extinguishers exploding.

There is no all-encompassing fire code in the United States. Generally, most municipalities (by adoption of the International Fire Code) require inspections every 30 days to ensure the unit is pressurized and unobstructed (done by an employee of the facility) and an annual inspection by a qualified technician. Hydrostatic pressure testing for all types of extinguishers is also required, generally every five years for water and CO_2 models up to every 12 years for dry chemical models.

Recently the National Fire Protection Association and ICC voted to allow for the elimination of the 30 day inspection requirement so long as the fire extinguisher is monitored electronically. According to NFPA, the system must provide record keeping in the form of an electronic event log at the control panel. The system must also constantly monitor an extinguisher's physical presence, internal pressure and whether an obstruction exists that could prevent ready access. In the event that any of the above conditions are found, the system must send an alert to officials so they can immediately rectify the situation. Electronic monitoring can be wired or wireless.

In the UK, three types of maintenance are required:

- Basic Service: All types of extinguisher require a basic inspection annually to check weight, correct pressure (using a special tool, not just looking at the gauge) and for signs of damage or corrosion, cartridge extinguishers are opened up for internal inspection & check weighing of the cartridge, labels are checked for legibility, where possible dip tubes, hoses and mechanisms checked for clear free operation.

- Extended Service: Water, Wet Chemical, Foam & Powder extinguishers require every five years a more detailed examination including a test discharge of the extinguisher and recharging; on stored pressure extinguishers this is the only opportunity to internally inspect for damage/corrosion. By recharging fresh agent is used as they all have a shelf life, even water goes foul inside an extinguisher; Note: extinguishers should be percentage tested according to total number of units in any given area. Some extinguishers contain pressure in excess of 1.38 MPa (200 psi) and this internal pressure over periods of time affects each brand & make differently depending on their placement & location.

- Overhaul: CO_2 extinguishers, due to their high operating pressure, are subject to pressure vessel safety legislation and must be hydraulic pressure tested, inspected internally & externally and date stamped every 10 years. As it cannot be pressure tested a new valve is also fitted. If replacing any part of the extinguisher (valve, horn, etc.) with a part from another manufacturer then the extinguisher will lose its fire rating. This may invalidate insurance, as would incorrect or inadequate servicing if it were to be found.

In the United States there are 3 types of service as well:

- Maintenance Inspection: All types of extinguishers should be inspected at least once a year. The extinguisher is checked to make sure it has proper pressure (gauge in green or proper cartridge weight), has the correct volume of extinguishing agent (tech weighs it), is within the required hydrotest and internal maintenance intervals, is in good condition and all external parts are serviceable. Often, dry chemical and dry powder types are hit on the bottom with a rubber mallet to make sure the powder is free-flowing, which is called "fluffing" the powder. The tech will then attach a new tamper seal around the pin and a yearly service tag.

- Internal Maintenance:

Water - every 5 years Foam - every 5 years Wet chemical & CO2 - every 5 years Dry chemical - every 6 years Halon and clean agents - every 5 years.

The extinguisher is emptied of its chemical and pressure to check for proper operation. All components are disassembled, inspected, cleaned, lubricated, or replaced if defective. Liquid agents are replaced at this time, dry agents may be re-used if in good condition, halon is recovered and re-used, but CO_2 is discharged into the atmosphere. The extinguisher is then re-filled and recharged, after a "verification of service" collar is placed around the cylinder neck. It is impossible to properly install or remove a collar without depressurizing the extinguisher. Note: Cartridge-operated extinguishers should be visually examined, but do not require a verification of service collar.

- Hydrostatic testing: Water, Foam, Wet chemical, and CO_2, every 5 years. Dry chemical, dry powder, halon, and clean agents, every 12 years.

Note: these are the required intervals for normal service conditions, if the extinguisher has been exposed to excessive heat, vibration, or mechanical damage it may need to be tested sooner.

The agent is emptied and depressurized and the valve is removed. After a thorough internal and external visual inspection, the cylinder is filled with water, placed inside a safety cage, and pressurized to the specified test pressure (varies with the type, age, and cylinder material) for the specified time period. If no failure, bulges, or leaks are detected, the cylinder passes. The cylinder is then emptied of water and thoroughly dried. CO_2 types have the test date, company's ID, etc. stamped on the cylinder, all other types get a sticker on the back of the cylinder. Once dry, the units are recharged. Unlike the UK, the US does not rebuild extinguishers and replace valves at specific intervals unless parts are found to be defective, with the exception of halon. Halon types are often given new o-rings and valve stems at every internal maintenance to minimize any leakage potential.

OEM equipment must be used for replacement parts for the extinguisher to maintain its UL rating. If parts are unavailable, replacement is recommended, keep in mind extinguishers have a projected service life of about 25–35 years, although many are of such quality that they can outlast this, but realize that science is ever-changing, and something that was the best available 30 years ago may not be acceptable for modern fire protection needs.

Vandalism and extinguisher protection

A fire extinguisher stored inside a cabinet mounted to a wall

Fire extinguishers can be a target of vandalism in schools and other open spaces. Extinguishers can be partially or fully discharged by a vandal, impairing the extinguisher's actual firefighting abilities.

In open public spaces, extinguishers are ideally kept inside cabinets that have glass that must be broken to access the extinguisher, or which emit an alarm siren that cannot be shut off without a key, to alert people the extinguisher has been handled by an unauthorized person when a fire is not present.

Fire extinguisher signs

Heavy-duty CO_2-powered fire extinguisher on standby at a temporary helicopter landing site

Fire extinguisher identification signs are small signs designed to be mounted near a fire extinguisher, in order to draw attention to the extinguisher's location (e.g. if the Extinguisher is on a large pole, the sign would generally be at the top of the pole so it can be seen from a distance). Such signs may be manufactured from a variety of materials, commonly self-adhesive vinyl, rigid PVC and aluminum.

In addition to words and pictographs indicating the presence of a fire extinguisher, some modern extinguisher ID signs also describe the extinguishing agent in the unit, and summarize the types of fire on which it may safely be used.

Some public and government buildings are often required, by local legal codes, to provide an ID sign for each extinguisher on the site.

Similar signs are available for other fire equipment (including fire blankets and fire hose reels/racks), and for other emergency equipment (such as first aid kits).

Placement of fire extinguisher signs

Most licensing authorities have regulations describing the standard appearance of these signs (e.g. text height, pictographs used and so on).

Photo-luminescent fire extinguisher signs

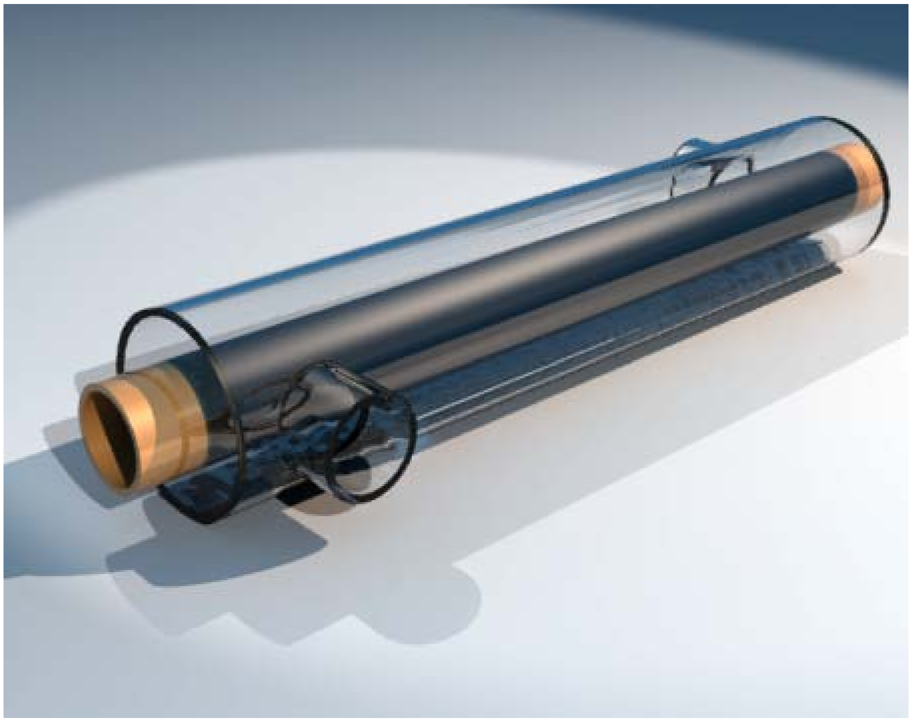
Photo-luminescent fire extinguisher signs are made with a photoluminescent phosphor that absorbs ambient light and releases it slowly in dark conditions — the sign "glows in the dark". Such signs are independent of an external power supply, and so offer a low-cost, reliable means of indicating the position of emergency equipment in dark or smoky conditions.

Photo-luminescent signs are sometimes wrongfully described as being reflective. A reflective material will only return ambient light for as long as the light source is supplied, rather than storing energy and releasing it over a period of time. However, many fire extinguishers and extinguisher mounting posts have strips of retroreflective adhesive tape placed on them to facilitate their location in situations where only emergency lighting or flashlights are available.

Chapter 10

Heat Exchanger

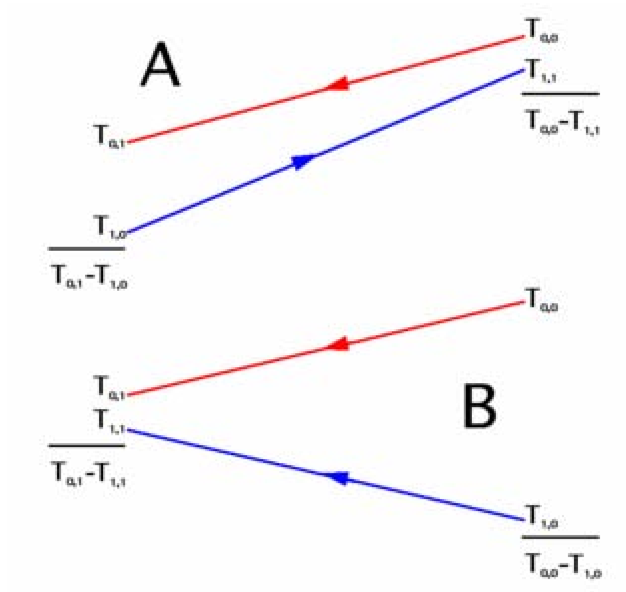
An interchangeable plate heat exchanger



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

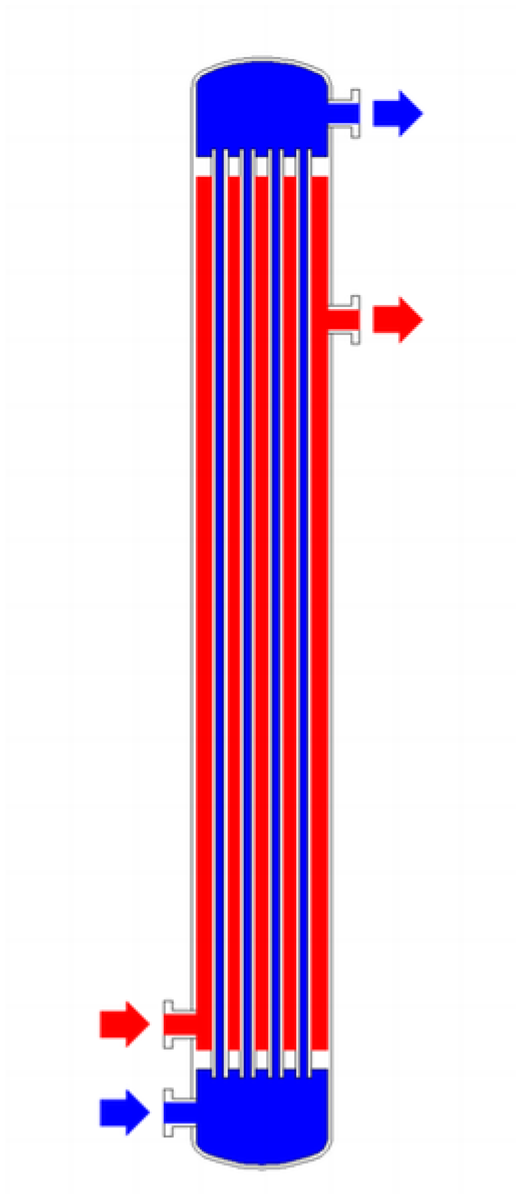


Fig. 1: Shell and tube heat exchanger, single pass (1-1 parallel flow)

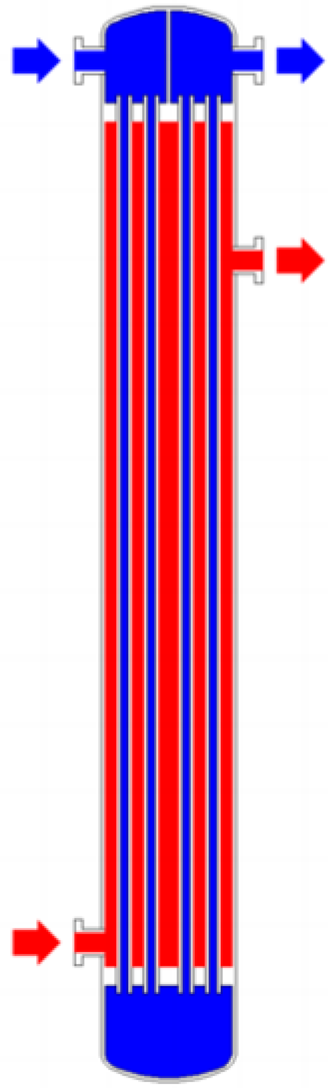


Fig. 2: Shell and tube heat exchanger, 2-pass tube side (1-2 crossflow)

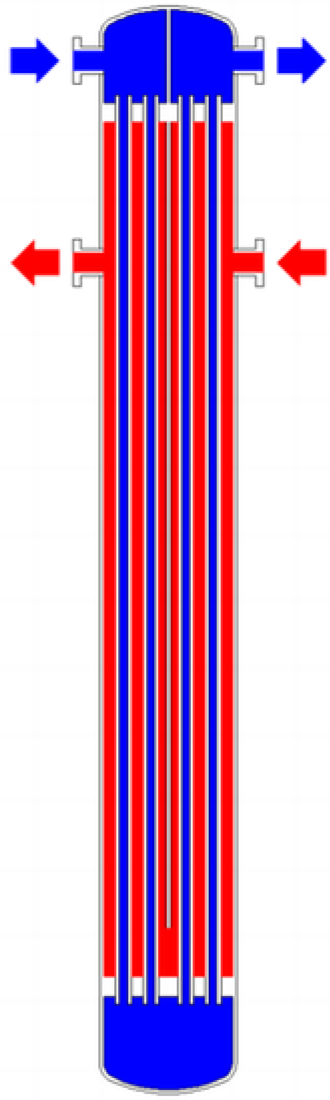


Fig. 3: Shell and tube heat exchanger, 2-pass shell side, 2-pass tube side (2-2 countercurrent)

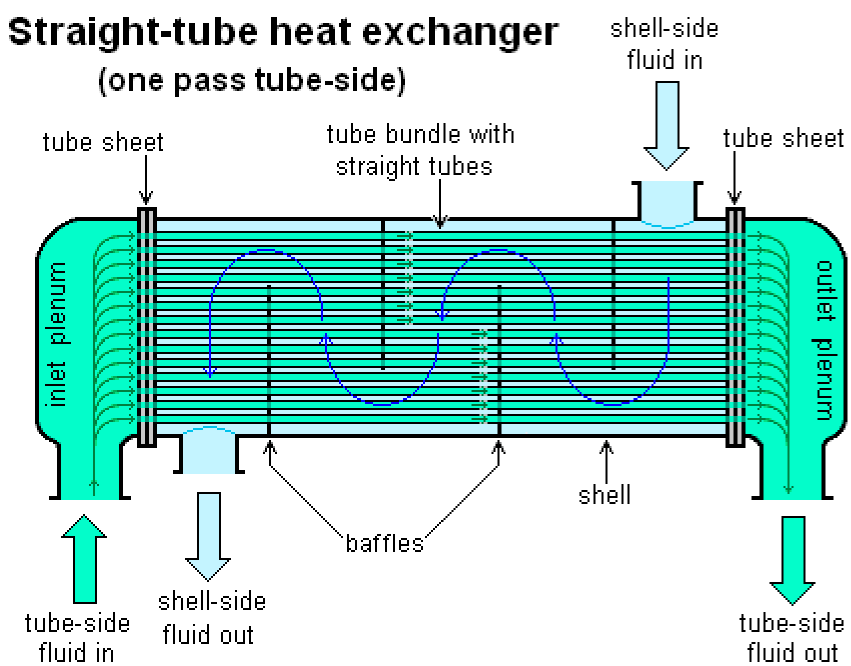
There are two primary classifications of heat exchangers according to their flow arrangement. In *parallel-flow* heat exchangers, the two fluids enter the exchanger at the same end, and travel in parallel to one another to the other side. In *counter-flow* heat exchangers the fluids enter the exchanger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

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



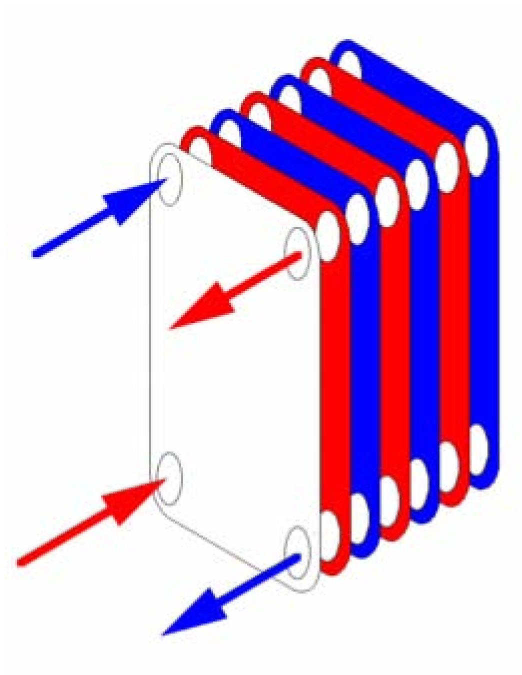
A Shell and Tube heat exchanger

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

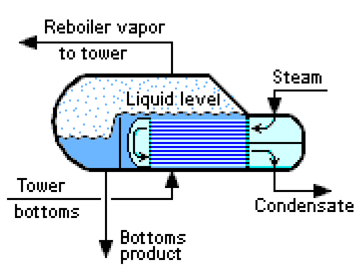
A Waste Heat Recovery Unit (WHRU) is a heat exchanger that recovers heat from a hot gas stream while transferring it to a working medium, typically water or oils. The hot gas stream can be the exhaust gas from a gas turbine or a diesel engine or a waste gas from industry or refinery.

Dynamic scraped surface heat exchanger

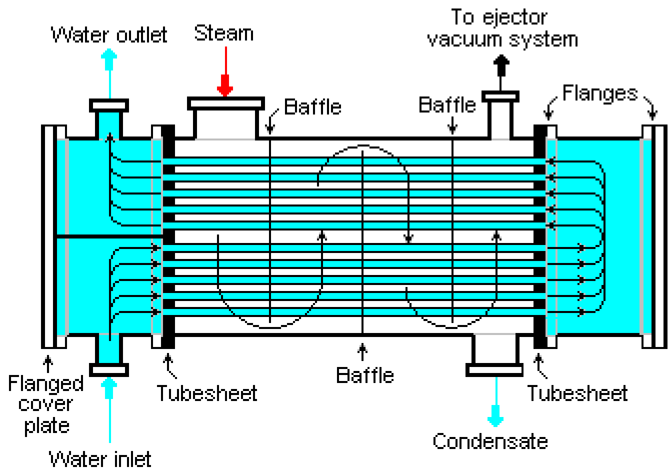
Another type of heat exchanger is called "(dynamic) scraped surface heat exchanger". This is mainly used for heating or cooling with high-viscosity products, crystallization processes, evaporation and high-fouling applications. Long running times are achieved due to the continuous scraping of the surface,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

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*.

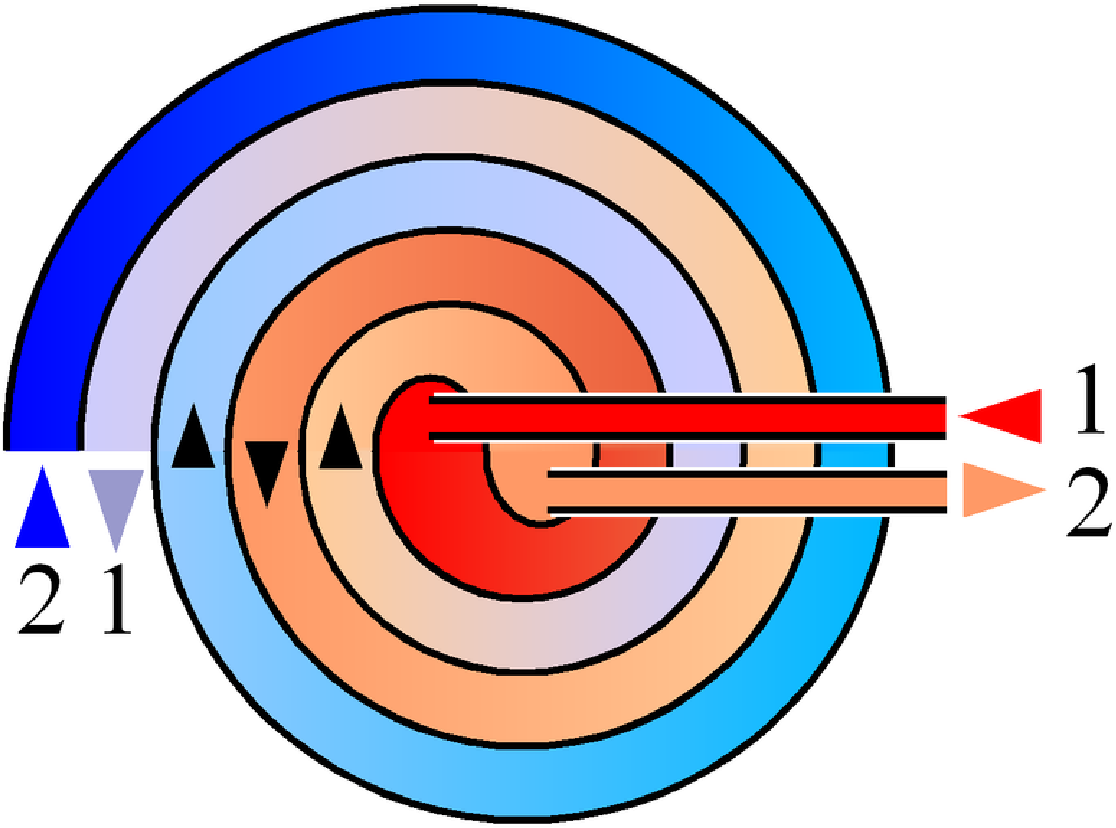
On the air side of HVAC coils a significant difference exists between those used for heating, and those for cooling. Due to psychrometrics, air that is cooled often has moisture condensing out of it, except with extremely dry air flows. Heating some air increases that airflow's capacity to hold water. 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

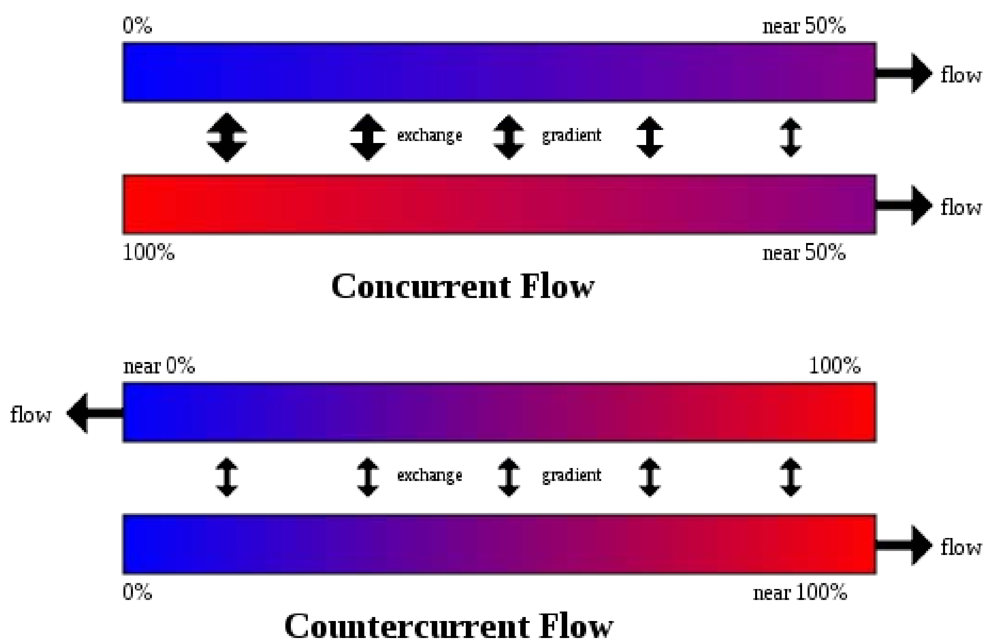
The distance between the sheets in the spiral channels are maintained by using spacer studs that were welded prior to rolling. Once the main spiral pack has been rolled, alternate top and bottom edges are welded and each end closed by a gasketed flat or conical cover bolted to the body. This ensures 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 γ 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:

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

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.