



Vital information on cooling towers, warm water systems and hot water systems

Francis Bacon, 17th century writer and science pioneer first coined the phrase "Knowledge is power" some 400 years ago. Throughout history the most dominant country has been the one with the technological edge over other countries.

The principle that underpins this adage can sometimes be forgotten. Take the field of infectious disease as an example.

Nowadays we take for granted, at least in Western societies, that epidemics of cholera, typhoid, malaria or bubonic plague will not occur. Was this improvement due to better medical treatment? No, definitely not! The decline of such fatal infections was due mostly to educated engineering solutions: cleaner air, better hygiene conditions.

The world is now so dependent upon climate control in the built environment, e.g. refrigerated food stock, pharmaceutical product manufacture and hospital air cleanliness, that heating, ventilation and air conditioning (HVAC) systems have become vital to the welfare, perhaps even the survival, of humans.

Yet the same HVAC systems that are capable of producing such immense benefits are also capable of inflicting harm. Probably the most notable example of this dark side is to be found in the epidemics of Legionnaires' disease, worldwide, that have been attributed to HVAC plant, predominantly cooling tower systems.

The solutions to this problem are conceptually straightforward but reminders are needed as pressure on the maintenance dollar increases. Training courses need to emphasise the fundamental principles involved in minimising hazards in order to equip participants for the wide range of applications found in the field.

What is a microbe?

Microbes abound in the natural environment and are normally present in low concentration levels throughout buildings. Like all human habitats, building systems are not sterile and will always contain some microbes. Health hazards (that can lead to illnesses such as Legionnaires' disease, Pontiac fever or allergic reactions such as Humidifier fever) are only created when microbes multiply to high concentrations.

The three main categories of microbes that are found in the built environment are viruses, fungi and bacteria. Viruses are the simplest form of microorganism (microbe) but they can only reproduce within other living cells. The sources for viral transmission are the building occupants rather than the building services. On the other hand, fungi and bacteria may readily colonize in building services if moisture and organic nutrients are present. Fungi (e.g. mould) attach to hard surfaces and are readily able to grow in conditions of high humidity as they thrive on air moisture. Fortunately, they are readily controlled by the normal principles of hygiene, such as keeping surfaces dry, regular

cleaning and disinfection with a mild bleaching agent. While fungi are difficult to eliminate, they will only germinate when moisture returns.

Examples of systems that may be only intermittently moist, but able to support fungal growths, are air conditioning cooling coils, condensation trays, drain lines, ducting near cooling coils, and humidifier surfaces.

Bacteria also prefer wet surfaces for growth but are mostly found where surfaces are submerged or at the interface between wet and dry areas.

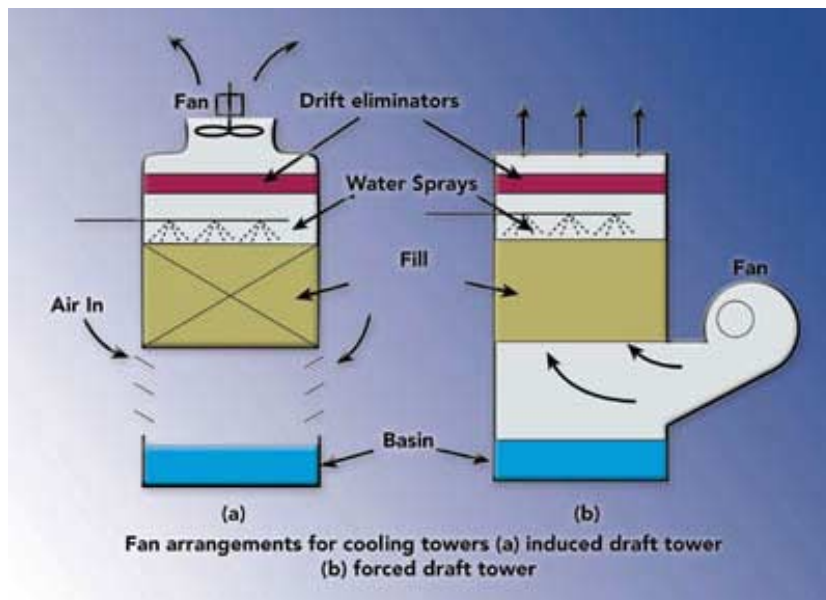
Colonization and growth of Legionella bacteria (the causative agent for Legionnaires' disease) can take place in any water-based system if the water is warm and supplied with nutrients. Examples of such systems relevant to building services are showers and baths and cooling towers (and the like) used for heat rejection for which control measures are described in the Regulations and Code of Practice.

Other sources include spa pools, decorative fountains, nebulizers (for hospital patients), ultrasonic humidifiers (mistifiers at supermarket vegetable cabinets), cutting fluid (in industrial machine shops), dental equipment and, more recently, potting mixtures and other composted material used by home gardeners.

As Legionella are widespread in natural water sources, such as rivers, lakes, mud and soil it is not surprising that they are often present in building water systems. Absolute exclusion of these particular bacteria from water systems, although a worthy objective, may not be possible or necessary, and finding Legionella does not by itself indicate that a source presents a risk. AS/NZS 3666 Part 3 provide requirements for system decontamination should elevated Legionella counts be found.

One type of application of particular concern is the provision of warm water for bathing or showering at some hospitals and institutions for the elderly, children and the mentally ill. This water is usually supplied at a temperature of 45°C maximum which is to prevent scalding. Therefore Legionella control by elevated temperature at the point of use is not possible. Often a storage type warm water system is provided rather than a hot-cold mixing system. Cases of Legionnaires' disease amongst such susceptible people have been associated with the aerosol sprayed from showerheads or bath taps supplied by such systems. Adverse conditions may be created by the build-up of sludge in storage vessels and possible dead legs in the piping system. Regular cleaning, maintenance and disinfection of the system is required. The problem can be largely overcome by the provision of anti-scald, thermal shut-off devices which mix hot and cold water supplied to the shower outlets instead of using warm water storage tanks or calorifiers. Such outlets can be readily dismantled and disinfected periodically with chlorine. Alternatively, use cold water which is then directly heated to produce warm water.

In the case of cooling water systems which make use of cooling towers to evaporatively cool recirculating water, the risk of disease can be minimized by the following:



Cross section diagram of cooling towers showing relationship between air movements, water and drift eliminators

- Careful attention to system design and construction features.
- Use of drift eliminators.
- Siting of towers away from building air intakes, populated areas and discharges from kitchen exhaust systems.
- Maintaining the system in a clean and sound condition.
- Controlling water quality from when water is introduced into the system.
- Monitoring tower and water conditions.

Similarly, the control of all microbes able to colonize water and air-handling systems of buildings can be effected by the avoidance of growth needs, by ensuring the systems are clean, properly designed, commissioned, operated and well maintained, and by the use of appropriate water treatment techniques.

Further explanatory information regarding this subject may be found in the Standards Australia/Standards New Zealand Handbook SAA/SNZ HB32, *Control of microbial growth in air-handling and water systems of buildings* and in the monograph produced by the National Environmental Health Forum entitled, 'Guidance for the control of Legionella' [found at the website www.health.sa.gov.au/pehs (click Publications then Legionella)]. The Australian Institute of Refrigeration Air Conditioning and Heating (AIRAH) sells a series of technical manuals on cooling towers, water treatment, piping systems and maintenance. For more information call (03) 9614 8868 or go to www.airah.org.au and follow the Reference Centre prompts.

This section adapted in part from the draft Foreword to the forthcoming 2000 edition of AS/NZS 3666

What is Legionnaires' disease?

In Philadelphia in 1976, the American Legion held a bi-centennial conference to celebrate 200 years since the signing of the declaration of independence from Britain. The Legion is an organisation of ex-servicemen, similar to our RSL.

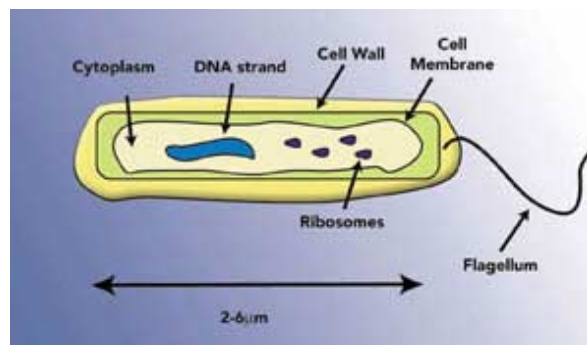
More than 180 delegates, all staying at the same hotel, developed an acute, severe illness and 29 of them died. The final toll was 34 deaths, some of them simply passers by in the street.

Initially the cause of their illness was unknown, with food poisoning a major suspect. We now know that what they had was Legionnaires' disease, a form of pneumonia, or infection of the lung.

Of course, the American Legion is not happy with the name. Had this illness first occurred in Australia, under similar circumstances, our ex-servicemen and women would probably not appreciate it being known as "RSL disease"!

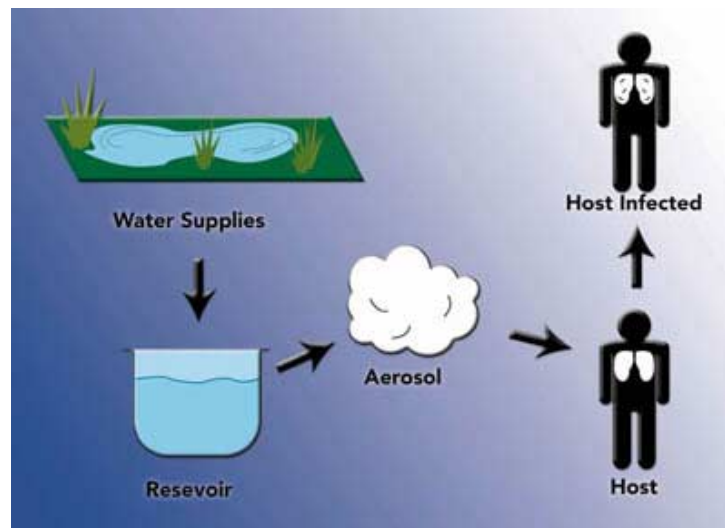
The cause of Legionnaires' disease is a family of bacteria and as such, it is a micro organism, not a virus. This distinction is important when it comes to treatment because few viral diseases respond to antibiotics, whereas most bacterial diseases do.

Legionella pneumophila is the name scientists gave to the bacterium but there are at least 50 other species, all closely related. The microorganism is relatively hard to grow and detect in laboratory cultures, compared with other types of bacteria, but modern culture techniques have improved analysis. Growth on laboratory culture media is very slow, typically 7 days. Incubation in the lung is similarly slow and may not be detected until a few days after infection. Growth in cooling towers can also be relatively slow and is readily prevented by the biocidal effect of appropriate disinfectants.



The Legionella bacterium

Legionella bacteria can be disseminated in fine water droplet suspensions called aerosols, which may be inhaled. It is important to note that the number of actual cases of Legionnaires' disease in Australia is very low compared with other afflictions such as Hepatitis, Salmonellosis or Tuberculosis. This is partly due to the fact that unlike many bacterial infections, Legionella is not spread from person to person.



The cycle of Legionnaires' disease

Outbreaks of Legionnaires' disease tend to occur in the summer and autumn, peak time for cooling tower operations. However, a species called *Legionella longbeachae*, not found in cooling towers, is associated with potting mixtures and composts and can cause the same disease. People tend to contract the disease from this species while gardening, i.e. predominantly in the spring. Sporadic cases of Legionnaires' disease may occur throughout the year.

What are the symptoms?

The disease usually starts as a mild respiratory infection, similar to influenza, but within 48 hours the condition worsens, the temperature rises considerably, a dry cough develops and there may be confusion if the brain is affected. Many other organs in the body are also involved.

The diagnosis is usually difficult to make although a new test, the Urinary Antigen Test, is able to detect antibodies to *Legionella pneumophila* relatively quickly. Legionella does not respond to penicillin nor a range of other antibiotics. Those based on erythromycin are the first choice.

Although Legionnaires' disease is one that readily catches the headlines it is important to keep it in perspective. There are certainly worse diseases in Australia carrying considerably more risk and we accept them without panic. Nonetheless it is a disease whose source is collections of warm water, such as cooling towers. As such, it is readily preventable.

Requirements of the Australian Standard

The Australian Standard covering microbial control in building air handling and water systems is AS/NZS 3666. This Standard is in three parts.

Part 1 covers design, installation and commissioning issues. These include filters in air handling systems, ductwork and equipment items such as evaporative coolers and humidifiers.

Most of the public health implications of the Standard are contained in the sections on cooling water systems (cooling towers) and warm water systems. Cooling towers must be fitted with high performance drift eliminators, they must be located at least 8 metres from kitchen exhausts and must be properly commissioned at startup after installation.

Requirements for warm water systems (called heated water systems in the standard so as to include hot water systems) are generally set out in AS 3500, the plumbing code.

Part 2 of the Standard covers ongoing operation and maintenance issues such as inspection and servicing frequencies, accessibility, safety matters, use of automatic water treatment plant and the proper storage of chemicals. The need for maintenance manuals and site log books are highlighted.

In relation to cooling towers, Part 2 provides prescriptive requirements for periodic shutdown and cleaning. In order to cater for non-prescriptive approaches, Part 3 was introduced. This is a performance-based standard that is the basis for much of the new legislation applying in Australia, including Victoria.

Part 3 emphasises not only the assessment of risk factors that apply to cooling towers but also the need for monitoring of physical, chemical and microbiological parameters. Appendix A to Part 3 sets out the required procedures for collecting water samples from cooling water systems. Usually the sample container is provided by the laboratory that is to do the testing. Purpose-made sampling points are usually provided so the sample can be taken safely, i.e. without accessing the operating cooling tower; if access is needed then a respirator should be worn.

The three parts to this Standard are practical documents. They set out what is required but give little information about why. This is to be found in handbooks and codes of practice such as those produced by the Department of Human Services and by the Australian Institute of Refrigeration Airconditioning and Heating.

All three parts to the Standard are prescribed in the Plumbing (Cooling Towers) Regulations 2001 in Victoria. Plumbing work carried out on cooling water systems must comply with the Standard. However, evaporative air coolers are specifically excluded from the Plumbing Regulations.



Regular and appropriate maintenance is important under AS/NZS 3666

What is the difference between cooling towers and dry air-cooled plant?

The wet-type cooling tower is the most efficient heat sink available for most air conditioning and process-cooling applications while the air-cooled option best suits outdoor compressor-condenser packages. Cooling towers occupy less space (typically only one third that necessary for dry air cooled plant), consume less energy, can be located remotely from the refrigeration plant, are quieter and will continue often be the best option available. One disadvantage of air-cooled units is that they require greater through-air flow than cooling towers. In addition, when used with refrigeration systems, the compressors must be larger because the system coefficient of performance is lower due to the rejection of heat to ambient air at the dry bulb air temperature (say 35°C) compared with heat rejection at a temperature approaching the wet bulb air temperature (say 20°C). Condenser heat is typically rejected at 15°C above the heat sink, i.e. at 35°C (or less) for cooling towers but 50°C (or more depending on the size of unit selected) condensing temperature for dry air-cooled plant. The saving in compressor power requirement for cooling towers may typically be 20 to 30% compared with dry air-cooled plant.

The issue of noise pollution should not be overlooked either. Communities are becoming more conscious of noise as an unacceptable environmental pollutant, particularly if it exceeds the level of being merely a nuisance and destroys the natural quality of living in both urban and rural areas. Cooling towers typically require about 25% of the airflow of dry air cooling units and fan noise is consequently much reduced. Cooling towers can often be supplied with belt-driven slow speed fans for quiet operation at night if needed.

At small sizes, typically under 500 kW_r heat rejection, air cooled plants tend to be more cost effective as the capital, operating and maintenance costs are lower and there is a wide range of makes and types to choose from. The conclusion often reached is: small sizes – air-cooled; large sizes – water-cooled plant.

What is the difference between plume and drift?

The air being discharged from a cooling tower is usually saturated with water vapour and has a high dew point temperature.

If the ambient air is at a lower temperature, then moisture will condense forming a cloud of extremely fine particles of pure water. This cloud is called a plume which, while harmless to life, may still seriously damage adjacent walls, windows and structures due to these surfaces being kept wet for long periods.

At sites where cooling tower plume causes the growth of moulds and structural damage to buildings, discharge ducts to direct the cooling tower exhaust away from the building should be considered.

Drift differs from plume in that it comprises water particles that have not been evaporated before leaving the tower. These particles therefore contain a proportion of chemicals and biological contamination similar to that in the tower water circulating system.

Cooling tower design should ensure that drift is negligible by preventing the entrainment of such droplets and their escape through the discharge of the tower.

Drift eliminators can be used to catch unevaporated water droplets before they are discharged.

Manufacturers of cooling towers in Australia and elsewhere have greatly improved the performance of drift eliminators in recent years with the development of components vacuum – moulded to precise geometric patterns. Water lost as drift may now be much lower than in earlier styles. Such eliminator modules may also be retrofitted to older towers. Care should be taken with any eliminator installation to ensure that there is no opportunity for air to bypass the eliminators and so defeat their purpose.

Cooling towers and trade wastes

Water is intentionally lost to sewer from cooling water systems by:

- bleed-off or blowdown;
- flushing.

Bleed-off is used to control the amount of dissolved solids in the circulating water which would otherwise accumulate due to the continuous loss of pure water in evaporation. Usually bleed-off is carried out on a continuous basis by a small branch line discharging to sewer; discharge rate is regulated by one of a number of methods. Depending on the installation, anywhere from 0.25% to as much as 2% of the circulating water rate is discharged to sewer in this way.

Blowdown is another way of achieving the same result. Automatic controls at a pre-set level of dissolved solids open the blowdown valve to discharge basin water to sewer.

Flushing is an activity that may be carried out at the time of system cleaning; generally twice a year. Flushing is sometimes performed for the complete system but may be only for the heat rejection device (e.g. cooling tower) itself.

There is increasing concern about the air-side (drift loss from air exhaust) and waterside environmental burden resulting from such discharges. Uncontrolled losses should therefore be kept to a minimum.

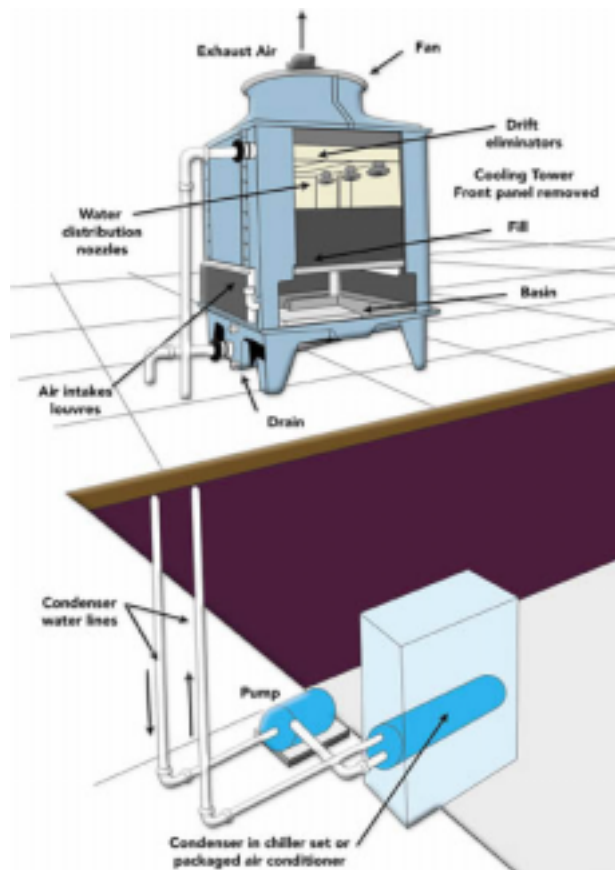


Legionella in cooling towers

Cooling towers

Cooling towers are devices designed to cool water and dissipate heat to the environment and are often associated with air conditioning, refrigeration systems, and a wide range of other plant. The towers may have a variety of materials in their construction including fibreglass, P.V.C., galvanised and stainless steel, brass, wood and concrete.

During operation, warm water from a heat exchanger is sprayed into the top of a large chamber over packing (the fill). This packing may be plastic or metal in a honeycomb or close packed arrangement or in a series of wooden slats. As water droplets fall through the tower they coalesce and so increase in size; the fill is employed to make the water fall in a thin layer of very large surface area to maximise evaporation. Water droplets partially evaporate and also lose heat to the surrounding air by conduction and convection as they fall through the tower. This results in the cooling of the remainder of the droplet. The water finally collects in the “sump” or “tower basin”. This cooled water can then be recirculated to the heat exchanger.



Typical cooling water system comprising cooling tower and condenser water circuit

Water quality

The quality of water circulating through a cooling water system has a significant effect on the overall system efficiency, the degree of maintenance required, and the useful life of system components. Since the water in these systems is cooled primarily by

evaporation of a portion of the circulating water, the concentration of dissolved solids and other impurities in the water can increase rapidly. Also, appreciable quantities of airborne impurities, such as dust and gases, may be introduced into the system during operation. If no water is bled from the system, the ultimate concentration of impurities, such as dust and gases, may be introduced into the system during operation.

Water treatment objectives

The objectives of a water treatment regime are:

- to inhibit the formation of scale
- to minimise general fouling;
- to inhibit corrosion of the system metals
- to control the growth of microbiological organisms.

These problems can cause energy wastage, poor system performance and possible need for early replacement of plant components.

Scaling is a type of deposit on the surfaces in the system. Scaling is related to water hardness which is determined by the amount of salts dissolved as rainwater filters through the ground. Water from limestone and chalky regions will contain a higher proportion of calcium and magnesium compounds.

When deposition of these salts is heavy, heat transfer and water flow may be severely restricted. The resulting rise in condensing temperature will cause a reduction in refrigeration capacity and more power will be needed.

During normal cooling tower operation, large quantities of airborne dirt can be introduced into the system, which subsequently settle out as silt deposits. Such deposits can promote corrosion, harbour microorganisms detrimental to the system, and foul fluid flow. Silt is normally controlled by adding polymers to the system, which keep the particulates in suspension while flowing through the system. Eventually, particulates settle in the tower basin where deposits can be more easily removed during periodic maintenance.

Corrosion control is often accomplished by adding chemical compounds to form a protective, insoluble film on metal surfaces throughout the system. Water systems are often operated at elevated pH (typically 8 to 8.6) to protect against corrosion while not imposing an excessive burden on the scale inhibitor (scaling tends to increase as pH increases).

Biofilms

The cooling water system creates a number of ecological niches for colonisation by microorganisms. Entry into the system by microorganisms may be via the water supply, the air-intake or during tower construction. The constant fall of water through the tower acts as a very efficient air scrubber. This introduces large amounts of organic and inorganic particles into the system.

Biofouling is the buildup of biological slimes together with some concentration and deposition of salts and debris on surfaces so reducing the overall efficiency of the cooling tower and cooling water circuit.

Microbial control principles

A general principle in water treatment is that the attempt to control microbes needs to be done well; otherwise the microbes will win!

Algae, fungi, bacteria and other microorganisms grow readily in evaporative cooling tower systems and can:

- form an insulating coating on heat-transfer surfaces
- restrict fluid flow
- promote corrosion
- attack organic components within the system (such as wood).

The common method of control is to treat the system on a periodic basis with a biocide such as chlorine. Normally, two different biocides are added on an alternating basis to ensure that microorganisms do not select a type that has a resistance to any one compound. Often a combination of methods is used aimed at improving cleanability and at achieving effective and economic control e.g. filtration plus a biocide.

Legionella can be readily found in warmed water in buildings as well as natural waters such as lakes and rivers. The interdependence of Legionella with other microbes for survival and food sources has led to the recommendation to maintain cooling tower systems (and other vulnerable systems) free of attached microbial matter, sediment, debris and the like, as the best way to minimise the risk of Legionella infection. The conventional practice is one of regular cleaning plus use of penetrating biocides to disperse or control (limit growth) of organisms on wetted surfaces of piping, the tower and the condenser tubes.

Ultra Violet Light Disinfection

As previously mentioned, to control microbial in cooling towers, chemical dosing is generally used. An alternative to chemical dosing is the use of Ultra Violet Light Disinfection of the water. The ultra violet light is not visible and falls in the range 200 to 295nm (nano metres (10^{-9} m)) and is known as short-wave ultra violet light (UV-C). To produce UV-C, a low-pressure mercury lamp is used, the bluish glow given off by the lamp is the starter gas and UV-C is not visible to the naked eye. The lamp requires a special quartz tube, which allows for the transmittance of the UV-C.

The water passes through the UV-C filter and the microbial is destroyed by the UV light. Factors that need to be considered with respect to performance are as follows:

Suspended solids can hide or shield microbial as it passes through the light beam
Staining of the transparent column that the water flows through will reduce the UV effect

As there are no anti-bacterial chemicals present in the water system, any microbial that has not been destroyed by the UV will be able to multiply in the basin
If the water system is not recirculating then there is no effective water treatment. In this situation a high level of microbial culture could be present at start up, potentially increasing the risk of a Legionella outbreak

The lamp has a finite life and the manufacturers instruction on lamp replacement must be followed

There are several methods of controlling microbial within cooling water systems. A combination of methods may be required, with a consistent approach to water testing and reviewing controlling techniques to minimize microbial growth within the system.

The cooling tower life cycle

It is now well recognised that control of microorganisms, including Legionella, must be considered at all stages of the cooling tower life cycle. Life cycle requirements can be summarised as:

a. Planning

Great care is needed when siting cooling towers and planning should take into account the following factors:

- height of adjacent structures,
- direction of prevailing winds and any localised wind patterns,
- location of building air inlets, including openable windows,
- proximity to other thermal or polluted discharges.

If not properly considered, some of these factors may seriously affect the thermal performance of cooling towers. They may also increase the possibility of tower exhaust air entering habitable spaces.

b. Design Features

Towers should be selected not only for functional capability but also for operability, maintainability, accessibility, drainability, cleanability, reliability and, for packaged towers, routine component removability (especially the fill where scrubbing of microbial nutrients from the air primarily takes place).

Good performance drift eliminators are important for secondary control in the chain of Legionella transmission.

c. Commissioning

The commissioning stage is of vital importance. There is often pressure to achieve early completion and handover of facilities. A number of outbreaks of Legionnaires' disease around the world have been associated with the startup of cooling tower systems. Proper commissioning includes taking precautions to control risk at startup as well as ensuring the system operates correctly and within design parameters. Commissioning and startup procedures should include detailed precautions necessary to control risk.

d. Inspections

The dynamic operational nature of cooling towers necessitates regular inspection to ensure all items continue to perform as designed. Cooling towers should be inspected at monthly intervals for slime and algal growths, deterioration of materials, damage to components (e.g. drift eliminators), blockages, corrosion effects and for correct

operation of fans, motors and pumps. Weekly inspections are recommended for sensitive sites such as hospitals.

e. Maintenance

It is unreasonable to expect any item of mechanical plant to operate efficiently and reliably without maintenance.

Maintenance activities should include:

- periodic disinfection, flushing and physical cleaning of the cooling tower to remove accumulations of sediment and organic matter (which provide surface area and microbial food, both necessary for bacterial growth)
- attention to the items identified by inspections, e.g. corrosion protection and replacement of broken components.



The importance of maintenance – cooling towers are not plant nurseries!

f. Operation

Operational activities should include:

- good records, to ensure that adequate precautions continue to be carried out and that detailed results and log books of repairs are available for monitoring
- a water treatment program which contains:
 - proven biocides which provide a residual effect to prevent the multiplication of bacteria and other microbes in the total system
 - scale and corrosion inhibitors which reduce the quantity of scale and rust that might otherwise shield microbes, and
 - dispersants which disperse sediments and allow other water treatment chemicals to work more effectively (some chemical suppliers have developed biocides which incorporate dispersant properties)

Bacteria living in such sediments should be controlled not only for reasons of public health but also for functional reasons. If not controlled, they can form slimes, which foul heat exchange surfaces and are capable of producing hydrogen sulphide, which is highly corrosive to metals. It is important that the water treatment program addresses not only the cooling tower but also the heat exchanger and pipework

around the system as microbial growths may occur at all these surfaces forming "biofilms" which may lead to ongoing seeding of the circulating water.

Legionnaires disease – frequently asked questions

What is the cause?

A group of bacteria called Legionella. The bacteria are found in moist environments, e.g. lakes, rivers, soils, cooling water systems and warm water systems generally in low counts.

How is it spread?

The disease is transmitted when a susceptible person inhales high counts of airborne Legionella contained in an aerosol (fine airborne particles) produced by warm water equipment such as cooling towers, spa baths and the like.

Legionnaires' disease cannot be acquired from drinking contaminated water nor is it contagious i.e. it cannot be spread from one person to another. An individual has to be susceptible and inhale a sufficient dose.

When is there a hazard?

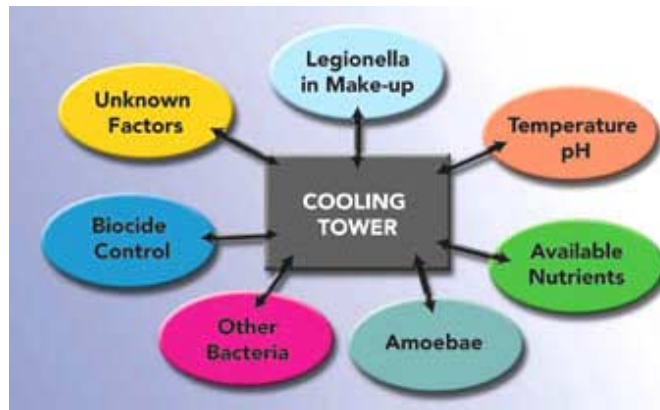
If a body of water is contaminated with Legionella it would still require multiplication before it is considered a risk. Counts must be high and the environment must encourage the formation of fine droplets in a humid ambient environment (which prevents drying of the droplets) before it is considered a risk.

Who is susceptible?

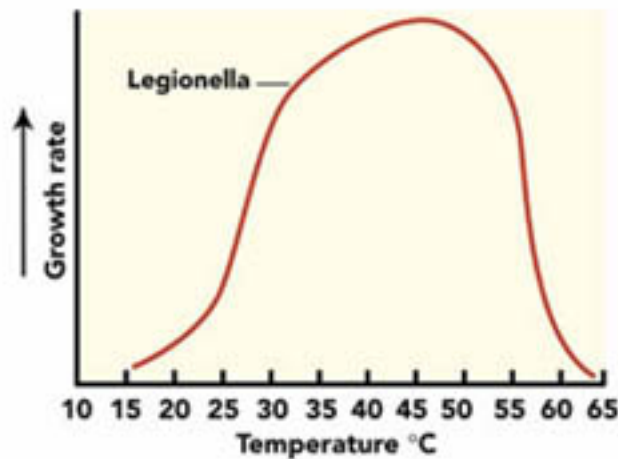
Those most at risk of developing Legionnaires' disease are the elderly, the ill, heavy drinkers and/or smokers or those with respiratory complaints.

What factors are important in the prevention of Legionella growth?

- careful design and maintenance of building water systems
- keeping the water system as cool as possible (preferably under 25°C)
- for hot water systems, regular use of the water, and keeping the temperature above 50°C so that *Legionella* will die over time
- a planned water treatment program for spas, cooling water systems and the like, such as the use of chlorine or bromine chemicals to reduce levels of the bacteria to counts that will not cause a risk to health
- regular inspection of all water systems, flushing and cleaning as appropriate to ensure the biological activity is low
- worker protection by wearing suitable respirators where there may be doubts about a particular water system
- adequate space should be provided around equipment to ensure that good maintenance and easy cleaning are possible.



A number of factors influence the growth of legionella



Legionella growth rates increase dramatically between 25°C and 50°C

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