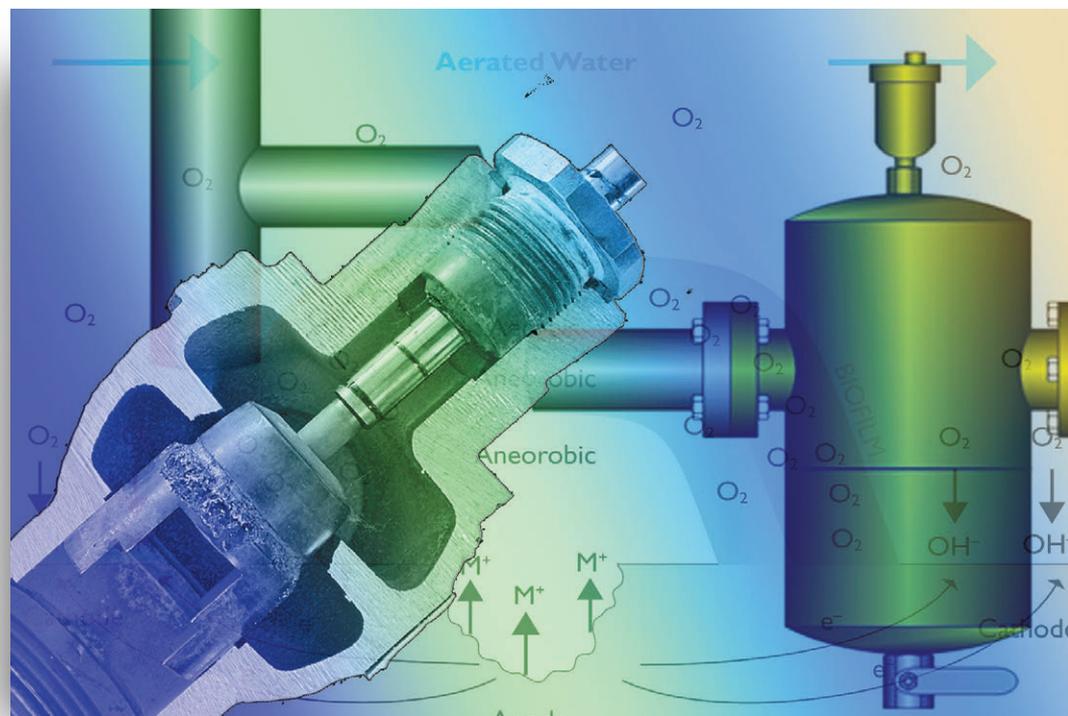


Water Treatment for Closed Heating and Cooling Systems



Edited by Reginald Brown

A joint venture with ...



BG 50/2013

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PREFACE

The treatment of water in modern closed heating and cooling systems is essential for the avoidance of microbiological fouling (biofouling), corrosion and scale. These problems can result in energy wastage, poor system performance, and the need for early replacement of plant and components. The consequences of inappropriate or non-existent water treatment can sometimes be disastrous.

This guide is intended for use by design engineers, installing contractors and the maintenance staff responsible for looking after the completed systems. It provides an introduction to current theory and practice of water treatment in closed systems including minimising the risk of corrosion through system design features and proactive monitoring.

In particular the guide will help facilities managers and others to engage in constructive discussion with water treatment professionals and choose the most appropriate water treatment programme for their systems.

The common causes of water quality and corrosion problems are explained and their implications for closed heating and cooling systems are described. Consideration is given to design, system operation, routine control, treatment and monitoring of water.

The guide partially replaces BSRIA AG 2/93 *Water treatment for building services systems* in respect of closed system applications. The guidance is consistent with BSRIA BG 29/2012 *Pre-commission cleaning of pipework systems*, BS 8552:2012 *Sampling and monitoring of water from building services closed systems. Code of practice* and the European Biocidal products Regulation (528/2012, commonly known as BPR).

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I INTRODUCTION

The scope of this guide is water treatment for the control of corrosion and maintenance of water quality in closed heating and cooling systems in buildings other than individual dwellings. This includes low temperature hot water heating systems, heat pump and chilled water systems and condenser water circuits. It is also relevant to community heating and cooling networks operating at temperatures below 110°C.

The scope does not include the specific requirements for water treatment for medium and high temperature heating systems, for which reference should be made to BS 2486^[3].

This scope does not include water treatment for open systems such as cooling towers and steam boilers or for domestic hot and cold water services.

The objectives of a water treatment programme in closed heating and cooling systems are to:

- maintain the system in a clean condition
- assist in maintaining system efficiency
- prolong system life

through the control of corrosion and fouling.

This is aided by the following elements:

1. System design
 - a. Specification of appropriate materials
 - b. Avoidance of dead legs and areas of stagnation
 - c. Operating characteristics that minimise the risk of air ingress and problems associated with low flow, such as sedimentation and biofouling

Further information on system design is provided in Section 2.

2. Installation, testing & pre-commission cleaning

Further information on these topics is provided in Section 3 and BSRIA BG 29^[1].

3. Application of a correct and appropriate water treatment programme including:
 - a. Control of corrosion by:
 - i. Application of corrosion inhibitors
 - ii. Control of scale, biofouling & other deposits
 - b. Control of scale by:
 - i. Minimising system losses & make-up
 - ii. Use of scale inhibitors
 - iii. Pre-treatment of make-up water when necessary

- c. Control of biofouling/biofilms by:
 - i. Avoidance of low flow
 - ii. Use of appropriate biocides
 - iii. Control of nutrient ingress
 - iv. Pre-treatment of make-up water when necessary
 - v. Control of scale, corrosion and sedimentation
- d. Control of sedimentation by:
 - i. Avoidance of low flow
 - ii. Use of dispersants
 - iii. Use of side-stream filtration
 - iv. Pre-treatment of make-up water when necessary
 - v. Control of scale, precipitation, biofouling & corrosion

Further information on these topics is provided in Sections 4 and 5.

- 4. Management of the programme including:
 - a. Knowledge of the system including:
 - i. Materials used
 - ii. Operational characteristics (temperature, flow rates, etc.)
 - iii. Volume
 - b. Programme design including
 - i. Product selection
 - ii. Sampling & testing regime
 - iii. Guidelines and action limits etc.
 - c. Implementation of programme
 - d. Monitoring & control
 - e. Training & competence of staff involved
 - f. Definition of reporting lines, roles & responsibilities
 - g. How to handle/report problems/areas of concern

Further information on these topics is provided in Section 6.

Section 7 briefly summarises the main legislation that is relevant to water treatment activities.

Various technical issues are discussed in detail in the appendices and there is a glossary and bibliography at the end of this guide.

2 SYSTEM DESIGN AND OPERATION

There are many factors in the design of closed heating and cooling systems that can influence corrosion. It is impossible to completely eliminate the corrosion of ordinary metals in such systems, but it is possible to control the corrosion rate to tolerable levels.

Issues that should be considered by the system designer include:

- choice of materials.
- flow rates and control strategy.
- minimising dissolved oxygen.
- filling, flushing and cleaning prior to use.
- chemical and physical water treatment.
- monitoring and maintenance.

The benefits of good design can be wasted if installation, commissioning or maintenance practices are poor or ineffective. Advice on provision of facilities for flushing and cleaning of systems prior to commissioning can be found in Section 2 of BSRIA BG 29/2012 *Pre-commission cleaning of pipework systems*^[1].

2.1 CHOICE OF MATERIALS

A wide range of well-understood materials are used in closed water systems. These include low carbon steel, stainless steel, galvanised steel, cast iron, aluminium, copper and copper alloys, elastomers and plastics.

Metals are used for distribution pipework and equipment including heat exchangers, pumps, valves, radiators and other heat emitters. Elastomers are used as seals including “O-rings” in valves and fittings. Plastics are used for pipework (PVC, ABS, HDPE etc.) and individual components of fittings and equipment (acetal, nylon, PTFE etc.).

Steel, copper alloys and aluminium are suitable for closed heating and cooling systems as the corrosion rate should be limited by the low availability of dissolved oxygen in the water and the appropriate use of corrosion inhibitors. However, there are other factors that may influence corrosion. For example:

- Mild steel, stainless steels and copper may be prone to microbially influenced corrosion (MIC).
- Heating and cooling systems contain different metals that when joined together may induce galvanic corrosion in the presence of dissolved oxygen.
- Brasses may be subject to dezincification.
- Aluminium and stainless steels are prone to pitting corrosion in high chloride environments.

Although non-metallic components such as seals, diaphragms and linings are not subject to oxygen corrosion they may be subject to chemical attack causing swelling, softening, cracking etc. This is important as degradation over time may result in leaks or restriction of flow or allow oxygen to enter the system.

All materials, be they metallic or non-metallic, should have industry approval for use in heating and cooling systems and be compatible with current water treatment chemistry. Table 1 summarises the corrosion issues of materials used in closed water systems. The corrosion processes affecting different metals in closed water systems are discussed in Section 3.1 and BS EN 14868^[10].

Table 1: Corrosion properties of frequently used materials in closed water systems

Material	Where used	Corrosion resistance	Other issues
Aluminium	Some boiler heat exchangers and radiators	Good overall corrosion resistance in oxygenated waters of neutral or slightly alkaline pH. Should not be exposed to pH greater than 8.5	Exposure to high pH causes rapid loss of metal and formation of aluminium hydroxide sludge. Susceptible to pitting corrosion at moderate chloride or sulfate concentrations
Copper and copper alloys	Copper tube, brass valves and fittings	Good overall corrosion resistance in water of neutral or moderately alkaline pH. In oxygenated water copper is subject to attack from turbulent erosion, flux residues and under-deposit corrosion.	Copper ions entering the water can result in pitting corrosion of steel and aluminium. Brass can be subject to stress corrosion cracking when exposed to ammonia.
Mild steel and cast iron	Steel pipe, boiler heat exchangers, circulating pumps	Low concentrations of dissolved oxygen result in uniform corrosion and the production of magnetite sludge. High concentrations of dissolved oxygen result in pitting attack under tubercles.	Formation of insoluble iron oxides as suspended solids increases wear in pumps and the risk of under-deposit corrosion in low flow areas where sedimentation occurs.
Galvanised steel	Some piping systems	Internally galvanised pipes and fittings should not be used in heating systems (see Section 3.1.2)	Formation of zinc hydroxide as suspended solids.
Stainless steel (SS)	Plate heat exchangers, pump casings, minor parts. Occasionally pipework.	Very good resistance to general corrosion but may be susceptible to pitting, crevice corrosion and stress corrosion cracking at high chloride or sulfate concentrations.	
Plastic	Plastic pipe including underfloor heating. Minor parts.	Resistant to corrosion but may be subject to physical degradation for example by sunlight.	Oxygen permeation through plastic pipe. Pressure resistance decreases with temperature.
Rubber	Flexible hose liners (EPDM), O-rings and seals.	Resistant to corrosion but may be subject to gradual chemical and physical degradation leading to loss of flexibility and cracking.	Amenable to the formation of biofilm.

2.2 FLOW RATES

2.2.1 Flow velocity

Flow rates (litres per second) are set by the system designer to satisfy the requirement for efficient heat transfer in heat exchangers and coils and to achieve the required distribution of heating and cooling in the building. However it is the flow velocity rather than flow rate that influences the risk of corrosion.

In oxygenated waters, the uniform corrosion rate will generally increase with flow velocity but this is less important than what happens at very low or very high flow velocity.

If the water velocity is too low then settling of solids may occur. This is mainly an issue in small bore pipework and terminal units, such as fan coils and radiators, at the extremities of the building. Accumulation of deposits increases the likelihood of under-deposit corrosion as well as biofouling and MIC.

If the velocity is too high then there is a risk of turbulent erosion. However, for this to occur there also needs to be significant oxygenation of the system water. Turbulent erosion is common in poorly balanced domestic water systems but rarely encountered in heating and cooling systems at normal design flow rates. Turbulent erosion is not the same as cavitation, which is a pressure-related phenomenon that does affect closed systems.

2.2.2 Circulation

It is essential to avoid prolonged stagnation in heating and cooling systems. Stagnation will allow the sedimentation of suspended solids and promote the formation of biofilms, increasing the risk of microbially influenced corrosion. Also, most inhibitors work more effectively under flowing rather than stagnant water conditions.

The system control strategy should therefore ensure that circulation pumps and control valves are periodically operated to reduce the risk of stagnation and ensure full distribution of all water treatment chemicals.

The minimum recommended period of circulation for heating and cooling circuits is one hour per day. Ideally this should be programmed into the building management system, where one exists. It is not necessary to operate boilers and chillers during this period.

Water sampling should not be carried out in no-flow conditions, as this could influence the results obtained.

2.3 MINIMISING DISSOLVED OXYGEN

O₂ to OH⁻) is the primary reaction that drives anodic dissolution and therefore corrosion. Control of dissolved oxygen is therefore a key aspect of controlling corrosion.

The most important way of controlling corrosion in use is to ensure that the systems are tight and do not allow ingress of oxygen, either through excessive additions of make-up water or inadequate pressurisation.

Systems should be designed with adequate numbers of air vents at high points of the system and drain valves at low points. Air pockets persisting in low flow areas of horizontal pipework and where there is inadequate venting can lead to waterline pitting of partially flooded pipes. There should also be a sufficient number of isolating valves at strategic locations to allow inspection and/or replacement of system components without having to drain large parts of the system. This reduces the exposure of the pipework to atmospheric air when drained and fresh water containing oxygen when refilled.

BS EN 14868^[10] describes the different ways that oxygen can enter a system and the effect on the likelihood of corrosion of different metals and alloys used in these systems.

In traditional closed heating systems constructed using mild steel pipe, oxygen that enters the system dissolved in the fill water is evolved as a gas during heating (and vented) or consumed by chemical reaction with the large area of steel surface. The loss of metal from general corrosion of the steel pipe due to the dissolved oxygen is not significant. If the system contains relatively little steel or other corrodible material compared to the system volume then the dissolved oxygen concentration can remain high indefinitely, resulting in rapid corrosion of the remaining steel unless adequately protected by the water treatment programme. Steel radiators are particular at risk of failure due to pitting corrosion in these circumstances.

In closed cooling systems, oxygen concentrations may remain high after filling as there is no thermal evolution of the dissolved oxygen from the fill water. However, the corrosion rate is also slower at the lower operating temperature and there may be no radiators or other thin steel components to worry about.

The risk of oxygen corrosion can be minimised by:

- good standards of design, construction and commissioning to limit air ingress and persistence.
- inclusion of physical devices to remove oxygen e.g. vacuum deaerators (see section 5.2).
- adding chemical corrosion inhibitors to passivate the metal surface or otherwise interfere with the corrosion reactions (see Section 4.1).

The key recommendations to designers are:

- Design pipework systems in accordance with the recommendations of CIBSE Code W^[2].
- Make sure that air can easily be vented from all parts of the system.
- Ensure that a positive pressure exists at all times under all operating conditions in all parts of the system.
- Ensure that there is sufficient expansion capacity.
- Ensure that plastic pipe that is prone to oxygen diffusion (such as polyethylene and polybutylene) is specified with an effective oxygen barrier.

2.3.1 Oxygen barriers in plastic pipe

One route by which oxygen can enter a closed heating or cooling system is through the use of non-barrier polyethylene (PE-X) or polybutylene (PB) plastic pipe. Oxygen can diffuse through the wall of a non-barrier plastic pipe (irrespective of the thickness and hydrostatic pressure) because the partial pressure of oxygen is much higher outside the pipe than inside.

Barrier plastic pipework (for PE-X and PB) became available in the late 1980s. This barrier is either a plastic film on the inner surface of the pipe that reduces oxygen diffusion or a concentric aluminium layer in the middle of the pipe wall (composite pipe) that prevents it. In order to maintain a continuous barrier throughout the system it is important that the pipe is used with the fittings recommended by the manufacturer.

The use of non-barrier plastic pipework for heating systems is still allowed in BS 7291^[5]. If it is used then it is crucial to maintain the correct level of a corrosion inhibitor to control corrosion.

2.3.2 Removal of air and dissolved gases

All closed systems should be designed so that displaced air can easily be removed from the system during filling.

The fill water also contains dissolved air (mostly oxygen and nitrogen) that will be evolved from solution if the water is heated. Automatic air vents allow gases evolved during the initial operation of heating systems, or created by subsequent chemical or biological processes, to be vented from high points of the system. Methods to accelerate deaeration of system water are described in Section 5.2.

2.3.3 Pressurisation of systems

Closed systems must be appropriately pressurised to operate at optimum performance and minimise the risk of corrosion. Insufficient pressurisation risks air being drawn into the system through seals, gaskets and vents. Over-pressurisation risks water loss through pressure relief valves as the system heats up.

Maintenance of adequate pressure will also reduce the risk of cavitation. If the pressure for that temperature of the water passing through a valve drops below the saturated vapour pressure for that temperature, microscopic

steam bubbles can be formed. This is known as cavitation and these bubbles can cause considerable damage particularly to brass valve seats as they implode on the metal surface.

However, increasing the pressure more than necessary could be counterproductive. Increased pressure will increase the solubility of gases such as oxygen and carbon dioxide and if these are retained in the system rather than being vented they will increase the corrosion rate.

2.3.4 Expansion vessels

Water expands by some 3% when heated from 15°C to 82°C (the design temperature for conventional LTHW systems). In closed systems this expansion is accommodated by an expansion vessel or expansion system.

The design process should:

- calculate the pressurisation unit and pressure relief valve settings to maintain a positive pressure throughout the system under all operating conditions.
- calculate the required expansion volume from the total system volume and operating temperature range.
- size the expansion vessel, calculate the bladder pressure and locate it in the system according to the methodology in BS 7074-2^[4].

These steps should ensure that the maximum design pressure of the heating system will not be exceeded during heating up and negative pressure will not develop in any part of the system during cooling down. Actual system pressure should be checked during commissioning and the pressurisation settings adjusted upwards if necessary.

2.4 DESIGN FOR WATER TREATMENT

Most closed heating and cooling systems rely on chemical water treatment for the control of corrosion. This section describes the system features necessary to implement a chemical water treatment programme. The chemicals that may be employed are discussed in Section 4.

2.4.1 Fill water pre-treatment

Closed heating and cooling systems are usually filled with mains water, though borehole water is sometimes used. Mains water complies with drinking water quality standards and should therefore be free of contamination from dirt or debris. However, there are other characteristics that may render the water undesirable for use within the system. Pre-treatment should be considered for any fill water that does not comply with the recommendations of BG 29^[1]. In particular pre-treatment may be required for:

- very hard water (particularly if the intention is to use a phosphate inhibitor programme).
- water containing a high concentration of dissolved solids (particularly chlorides and sulfates).
- water with undesirable microbiological activity, for example with high concentrations of pseudomonads or sulfate reducing bacteria (SRB).

Pre-treatment systems available can be broadly classified as:

- Water conditioning:
 - Water softening
 - Filtration
 - Automated chemical dosing (proportional to the metered volume or controlled by redox potential)
- Microbiological control:
 - Ultraviolet disinfection
 - Reverse osmosis (provides a barrier to bacteria)
 - Automated biocide dosing

Water softening

Where the available water is particularly hard, a softening plant may be temporarily installed to fill the system with reduced hardness water. It is not recommended to install a permanent softening plant solely for fill water as that will be underused and may become a source of bacterial contamination.

The fill water should not be fully soft (complete removal of calcium) as such waters are non-scale forming and, in theory, can be more corrosive than non-softened waters, particularly for copper. This risk can be offset by appropriate corrosion inhibitors e.g. azoles for copper protection.

Base-exchange softening replaces scale forming calcium and magnesium ions with sodium ions. If base-exchange softened water is used to fill the system, it is important to check that all inhibitors are suitable for use with the softened water.

Deionisation (utilising resin beds) is similar to base-exchange softening but removes both the scale forming and corrosive ions from the water and thus reduces the total dissolved solids (TDS) and conductivity. Deionisation of fill and make-up water is more expensive than base-exchange softening and generally restricted to high temperature and/or high heat-transfer heating systems. Deionised water is rarely used to fill a closed heating and cooling system but could be helpful where there is a high sulfate or chloride concentration in the raw water. Again, the water treatment package should be tailored to the use of deionised water.

Softened and deionised water have reduced buffering capacity so chemical pH buffers may need to be added as part of the water treatment package to maintain the pH at the required level.

Softening is not normally required for make-up water for closed systems as there should be minimal make-up during normal operation and the consequent addition of scale formers should be insignificant compared to the volume of the system. Some water treatment practitioners do however favour the use of blended softened water for both filling and topping up where it is already available on site (usually for hot and cold water services).

Filtration and reverse osmosis

In principle filtration of mains water should not be necessary but strainers or coarse filters are routinely used as protection against large debris and scale for pumps and control valves. Filters are discussed in Section 6.1.

Mains water is not sterile but contains a wide range of bacteria that are harmless to people but may become implicated in corrosion processes. Low pressure membrane filtration is increasingly being used to provide a physical barrier to bacteria and fungi entering the system from the water supply. This is claimed to reduce the need for biocides for subsequent microbiological control.

Certain types of high pressure reverse osmosis (RO) membrane will also reduce the concentration of scale forming ions as an alternative to softening or deionisation. This may be useful on borehole supplies of hard water. RO softened water may need the addition of pH buffers to maintain pH control as for other softened water.

Ultraviolet (UV) disinfection

Ultraviolet treatment of the fill water is also used as a precautionary measure for water supplies with high bacteria counts. Ultraviolet treatment does not provide an absolute barrier to bacteria but can significantly reduce the number of bacteria entering the system.

Conventional UV treatment cells are not recommended for treating the makeup water for closed systems as makeup should be infrequent and insignificant in volume.

Automated proportional dosing

Automated proportional dosing of water treatment chemicals and biocides may be used for the initial fill water and as part of pre-commission cleaning.

Automated proportional dosing is not recommended for treating makeup water for closed systems as the makeup should be infrequent and insignificant in volume. Maintenance additions of water treatment chemicals and biocides should be added via dosing pots or dosing pumps under manual control.

2.4.2 Solids removal and filtration

The design of pipework systems to enable flushing and cleaning and the methodology of pre-commission cleaning is discussed in Section 2.5 and BG 29^[1].

Strainers

Strainers should be fitted in accordance with design codes to protect sensitive equipment and heat exchangers. Strainers may also be fitted where secondary circuits are fed from the primary circuit. The appropriate strainer size and media must be selected according to the design flow rates and maximum allowable pressure drops. Importantly, strainers must be isolable and easily accessed for inspection and routine maintenance.

Side stream filtration

Side stream filtration can be used to help maintain a low concentration of suspended solids in the circulating water following pre-commission cleaning and reduce the risk of solids deposition and under-deposit corrosion in areas of low flow. In addition to the longer term benefits of early installation of side stream filtration, it can also help to maintain water quality during the commissioning period.

In side stream filtration a small proportion of the circulating flow is passed through the filter on a continuous basis. If however the filter becomes blocked then the risk of corrosion can be increased due to bacterial colonisation. Filters should therefore be fitted with pressure differential indicators, frequently checked and properly maintained.

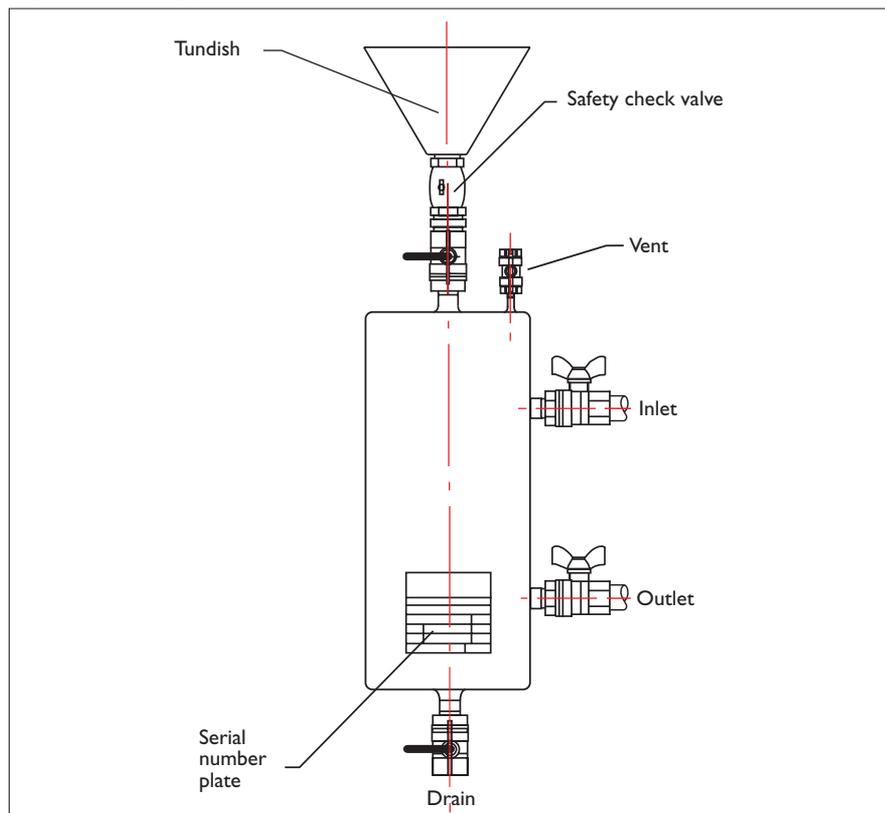
Various filtration media and bespoke filter units can remove suspended solids and some microorganisms. Particular guidance on filtration technologies can be found in Section 5.1.

2.4.3 Chemical water treatment

The chemical dosing facility should be sized relative to the system volume to allow sufficient amounts of treatment chemicals to be added efficiently.

For small systems a dosing pot is used for maintenance treatments. This is a flow-through container, plumbed in parallel with part of the circuit. It is fitted with valves so that it can be isolated, drained and filled with chemical at atmospheric pressure, then reconnected to the circuit (see Figure 1).

Figure 1: Dosing pot



It is important that the dosing pot should remain open to the system with continuous through-flow so that it does not become a dead leg and encourage the growth of bacteria. One manufacturer now combines the function of dosing pot and strainer.

Larger volumes of chemicals (for the initial dosing of small systems or maintenance dosing of larger systems) can be pumped into the system at pressure using chemical dosing pumps.

Designers should consider not only the dosing arrangement but arrangements for the safe storage of chemicals near to the dosing point.

2.4.4 Sampling points and monitoring equipment

There should be sufficient sample points located throughout the system to allow it to be properly monitored and managed. For most systems the drain points will provide the majority of potential sample points (see Section 2.4.5). Pressure test points (Binder points) can also be used for certain types of samples as indicated in Table 2.

Table 2: Selection of sampling points (from BS 8552^[6])

Type of sample	Sampling Point		
	Full bore drain point	Reduced bore drain point	Pressure test point
Settled solids	Yes	No	No
Suspended solids & "total" metals	Yes	Yes	No
Dissolved solids	Yes	Yes	Yes
Microbiology	Yes	Yes	Yes
Dissolved oxygen	No	See BS 8552, A.2	See BS 8552, A.2

The system designer should also consider the installation of permanent monitoring equipment such as corrosion coupon racks and on-line sensors (see Section 6.6). It is preferable to design and install monitoring equipment at the same time as pipework rather than when the system is in operation. This will also provide a full history of the corrosion environment. Electrochemical sensors may need to be temporarily removed during flushing and cleaning activities to avoid damage.

In addition to corrosion coupons, easily demountable sections of pipework can be incorporated into the system for inspection purposes e.g. flanged spool pieces in short isolable sections.

2.4.5 Maintenance & inspection

Isolation valves and drain points should be provided to enable maintenance and inspection of the following:

- Heat exchangers (boiler heat exchangers, plate heat exchangers, calorifier coils etc.)
- Terminal units (AHU heating/cooling coils, fan coils, chilled beams, radiant panels etc.)
- Control valves

- Pump sets
- Strainers and filters

The majority of samples needed to assess water quality in the system can be taken from suitable drain points (see Section 6.3.3).

Filters and plate heat exchangers should be fitted with differential pressure gauges to detect signs of blockage or fouling.

Ideally, pipework systems and equipment should not be drained for internal inspection (other than for corrosion coupon access) as this will allow wet surfaces to be exposed to oxygen and dilution of inhibitor by replacement water, both of which will increase the risk of corrosion.

2.4.6 External corrosion

Pipework is also at risk of external corrosion due to environmental factors. Leaky joints, condensation and moisture leaching through insulation materials can cause localised corrosion and eventually lead to perforation or catastrophic failure.

All steel pipework should be protected against corrosion by suitable coatings. Chilled water pipework insulation should be vapour sealed to avoid the accumulation of condensation on the pipe surface. Externally installed heating and chilled pipework must be thoroughly protected against the ingress of rainwater.

Although external corrosion is not a water treatment issue there are some failures where it may not be immediately obvious whether the problem lies inside or outside the pipe. Stress corrosion cracking (SCC) particularly affects brass fittings and valves on chilled water pipework when exposed to ammonia or other aggressive chemical species. These can be leached from certain types of fibre and rigid foam insulation when moistened by condensation on the outer surface of the pipe. Where there is any doubt as to the risk of SCC on chilled water pipework, it is recommended to terminate and seal the suspect insulation before it reaches the brass component. Neoprene insulation can then be used to individually insulate the brass component but should extend to at least 300 mm either side of it.

2.5 PRE-COMMISSION FLUSHING AND CLEANING

The installation of pipework systems results in surfaces that may be oxidised or contaminated with dirt and debris. The objective of pre-commission cleaning is to remove these contaminants and bacteria that may have colonised the system after filling and pressure testing. If this is not done then the system is at increased risk of operational problems during commissioning and corrosion problems thereafter.

The process of pre-commission cleaning, and the measures by which it is judged to be successful, are explained at length in BG 29^[1] so there is no need to do so here. Nevertheless it is useful to reiterate the guidelines for water quality at practical completion as these represent the minimum requirements for system water quality at the beginning of the routine water treatment regime.

It is important to stress that while Table 3 is applicable to many closed heating and cooling systems some of the parameters (particularly the guidelines for soluble metals) are dependent on the specific water treatment products being employed. It is the responsibility of the water treatment provider to declare the acceptable range of each parameter in relation to the correct application of their products.

Table 3: Practical completion guidelines extracted from BG 29^[1]

Parameter	Sample location	Guideline for practical completion (unless otherwise agreed by the specifier)
Suspended solids (mg/l)	Circulating pump	Less than 30 mg/l at system pump during circulation (circulate for at least one hour prior to sampling)
Settled solids (mg/l) (as defined in BG 29)	Representative points	Less than 60 mg/l in pipework at extremes of system. Less than 45 mg/l if previously sampled within 3 weeks Less than 90 mg/l at terminal units not previously sampled. Less than 45 mg/l if previously sampled (or flushed) within 3 weeks Any individual results of greater than 90 mg/l should be investigated. The point should be re-sampled after 2 weeks (or 2 weeks after remedial action) in which case the result should be less than 45 mg/l
Soluble iron (mg/l)	Representative points	Less than 3 mg/l Subject to advice from water treatment chemical supplier
Total iron (mg/l)	Representative points	Less than 15 mg/l Subject to advice from water treatment chemical supplier
Total copper (mg/l)	Representative points	Less than 1 mg/l or as recommended by the specialist
TVC at 22°C	Representative points	<100,000 cfu/ml and no increasing trend
Pseudomonads	Representative points	<10,000 cfu/100 ml at 30°C and no increasing trend
Sulfate reducing bacteria	Representative points	Absent
Nitrite/nitrate reducing bacteria	Circulating pump	For information only

Note that the guidelines for chemical parameters should be applied to individual samples whereas the guidelines for bacteria are set relative to the geometric mean result for samples taken at the same time (the numbers and location of samples being defined in BS 8552^[6]). Also, it may not be possible to achieve these guidelines for remedial flushing of an existing system.

2.6 REMEDIAL FLUSHING AND CLEANING

2.6.1 Why remedial flushing and cleaning may be necessary

If water quality is being properly managed then the system may never need to be re-flushed. However there are circumstances where the system condition and water quality have deteriorated to the extent that no amount of chemical additions will correct the evident problems.

Some scenarios that can cause the water quality to deteriorate are:

- Persistent ingress of oxygen into the systems resulting in corrosion of components
- Stagnant/low flow water conditions, resulting in microbial growth or poor surface passivation
- Reduced system operation and/or building dilapidation
- Poor management or failure of the water treatment regime
- Inappropriate water treatment chemicals
- External contamination
- High rates of leakage and makeup resulting in loss of inhibitors

Tell-tale signs that the system may need to be flushed include:

- Poor heating or cooling performance in localised areas of the building
- Blockage of terminal unit strainers
- Large amounts of solids appearing from dirt pockets and drain valves
- Unstable commissioned flows
- Excessive wear of pump seals
- Build-up of solids in radiators and terminal units
- Blockage of plate heat exchangers
- Perforation of pipework and radiators
- Heat exchanger failures
- Rapid depletion of inhibitors
- Rapid re-colonisation with high levels of bacteria after biocide treatment
- Persistently high levels of suspended solids

Dynamic flushing can be carried out using the mains water supply and back flushing small circuits and terminal devices (fan coils, AHU, etc.) to drain. In some circumstances flushing can be considerably aided by the prior use of mild dispersants and polymers to aid the suspension and hence removal of settled solids.

However, in cases where the system has suffered significant degradation it will be necessary to use chemical treatments to restore the surface of the pipe and other wetted surfaces to a condition where control of corrosion with a conventional water treatment regime can be re-established.

2.6.2 Planning remedial flushing and cleaning

Detailed guidance on flushing and cleaning, including the treatment of new additions to the existing system, can be found in BG 29^[1]. This includes the sampling and analysis procedures that should be used to verify the success of the clean. Note that the guidelines in BG 29 for water quality after the clean are appropriate to new systems and may not be achievable for remedial work in older systems.

For the avoidance of doubt, the cleaning contractor and client should review the guidelines in BG 29 and agree realistic criteria by which to assess the success of the clean prior to commencing the work. In addition to water quality guidelines modified from BG 29, those criteria may include a relative improvement against current system water quality and the physical condition of representative pipework surfaces before and after the clean.

Remedial works should be planned and executed by personnel who are experienced in pre-commission cleaning activities as the use of inappropriate chemical treatments and techniques could be further detrimental to the system.

The following issues should be considered when planning remedial flushing and cleaning works:

Planning considerations

- Condition of the installation – how bad is the problem and what is the minimum intervention that will correct it?
- Costs of cleaning compared to partial or complete replacement of the installation.
- Tenant restrictions – practical restrictions on what can be done and when
- External restrictions – are there limitations on the water supply?
- Risk to sensitive equipment – pumps, valves and sensors should be checked for compatibility with the proposed works or temporarily removed
- The pros and cons of off-line cleaning against on-line cleaning. It is not usually possible to clean a badly fouled system on-line.
- Programming of the works to minimise disruption to the occupier. It is usually possible to carry out an effective programme of sectional cleaning at night or during weekends.
- The choice of cleaning chemical(s) to be used. The efficacy of the cleaner in removing corrosion products from pipework and other components and the compatibility with the alloys to be cleaned may need to be demonstrated beforehand in a laboratory.
- Availability of drainage
- Foul drain discharge permits for flushing and cleaning activity

Considerations for the flushing contractor

- Age of the system
- System service history/water treatment log book
- Availability of up-to-date plans and schematics
- Availability of O&M manuals
- Operational history of the system including any previous remedial works
- Records of original pre-commission cleaning works (if available)
- Records of original installation and commissioning tests (if available)
- Records of installation materials
- Nature of the problem: bacteria, suspended solids, sediment, type of corrosion etc.
- Compatibility of cleaning chemicals with system materials and condition. The use of aggressive chemicals should be avoided where there is a history of leaks; alkaline cleaners should not be used in systems with aluminium boilers or radiators etc.
- Health and safety precautions for the works
- Storage of materials and equipment
- Method statement and risk assessment

Considerations for the building operator

- Programming of works to minimise disruption (usually out of normal working hours)
- Temporary provision of alternative heating/cooling where required
- Effects on normal building operation and equipment when using mains cold water for flushing should the works be of a large scale
- Protective measures for furnishings and equipment
- Re-instatement and/or re-commissioning checks on completion of the works to verify that the Landlord's and other Tenant's systems have not been affected
- Health and safety precautions for building occupiers (segregation of work areas)
- Security requirements during the works
- Interaction with the building FM/maintenance team: access, operation of controls, safety etc.
- Risk management (measures to mitigate leakage etc.)
- Insurances

2.6.3 Methodology for remedial flushing

Depending on the size of the system and scope of the remedial works, and particularly for badly fouled systems, it may be necessary to tackle the system in sections. In this case the bulk recirculating water quality needs to be improved and maintained by means of filtration while allowing sections (usually individual floors) to be temporarily isolated (possibly overnight or during a weekend), cleaned and put back into use without risk of re-contamination. Flushing out of hours reduces the risk that there will be insufficient water pressure available for the building occupier.

The contractor undertaking the works must provide a suitable and appropriate site-specific method statement. This should describe the cleaning process and the criteria for assessing its success or otherwise, to ensure that a good standard of water quality is achieved for integration back into the bulk water system.

Temporary pumps can be used for flushing and cleaning most of the isolated sections but system pumps may be used for the main plant areas. Specific provisions for the safe use of temporary pumps are discussed in Appendix A.

The cleaning specialist must be aware of the existing system chemistry and products in use. The replacement water treatment chemicals (inhibitors and biocides) must be fully compatible with those in use and be approved by the water treatment specialist as being compatible with their water treatment regime and the system materials.

Preparations for remedial flushing should include:

- Surveying the system
- Checking the locations and ratings of pressure relief valves and/or pressure reducers
- Checking the location and settings of all control and regulating valves. These may be opened or closed as required during the flushing process.
- Locating foul drains of an adequate size as close to the works as possible
- Locating a good water supply with adequate pressure and as close to the works as possible.
- Checking mains or boosted water supply pressures.
- Ensuring that the water connection and pumps can provide an adequate flow rate without losing effective pressure
- Locating or cutting in to pipework for flushing connections and drains
- Providing power supplies if temporary flushing pumps are to be utilised
- Confirming temporary pump size and power requirements if these are to be utilised
- Agreeing the site-specific methodology and water quality results required to re-integrate the cleaned pipework with the operational system
- Agreeing the risk assessment and precautionary measures to be implemented

Generally, if the building is in operation and has a good level of occupation the mains water should be of an adequate quality for flushing, though it may be prudent to sample the mains cold water prior to commencement.

Whatever cleaning methodology is implemented, ingress of air should be avoided. Installing deaerators, preferably of the vacuum type, to rapidly reduce dissolved oxygen concentrations following any form of system cleaning is recommended.

2.6.4 Cleaning on-line

As an alternative to a balanced flush, solids and colloidal matter in suspension can be removed by use of filtration over an extended time scale using the on-line method. Mild cleaning agents and polyelectrolytes will also help to dislodge and suspend loose deposits for removal by filtration. Static debris and deposits will not be removed by filtration.

Various type and grades of filter medium are used depending on particle sizes to be removed.

In side-stream filtration, a small proportion of the system flow is passed through the filter. The filter may have a dedicated pump set, which does not influence the hydraulic balance of the main system, whether operating or not. Side-stream filtration will take longer than full flow filtration to

reduce the solids concentration in the circulating water but has numerous advantages:

- the filter housing is relatively small and inexpensive
- the connecting pipework is also small and easy to retrofit
- blockage of the filter will not impact on the main system performance
- the filter can be left in situ after the flushing process for long term maintenance operation but must be regularly checked

Filter manufacturers can provide advice and recommendations for the removal of whatever contaminant is targeted. Generally, the smaller the particle size the larger the filter required to sustain the required flow rate at a reasonable pressure drop. Filtration equipment with reusable media must have an automatic or manual back flush and drain facility and precautions must be taken to ensure that the media does not become microbiologically contaminated.

Filtration equipment is discussed in more detail in Section 5.1.

2.6.5 Chemical cleaning

The application of any chemical cleaner should be in accordance with the manufacturer's guidance regarding safe working, the effective concentration range, the means to verify this, and the contact time. The use of aggressive chemical cleaners on existing systems should be avoided if possible.

Non-acidic cleaners are a blend of chelating agents, surfactants and dispersants that 'digest' the rust but leave the base metal unaffected and assist in flushing of particulate matter. They are typically applied at concentrations of 1% to 5% of the bulk water content dependant on the level of deposits to be removed. The contact time could be anything from 12 hours to three weeks, depending on the characteristics of the cleaner and state of the system.

Certain mild acid products can be utilised where there are deposits of certain compositions that cannot be removed with neutral formulations. The system water should be tested for iron and pH levels during the chemical cleaning process to determine the efficacy of the product and the exhaustion rate so as to determine the need for further chemical additions.

At the end of the cleaning process, the cleaning chemicals are usually flushed from the system which is then re-treated with inhibitors and biocides.

2.6.6 Post-works commissioning

Decommissioned equipment and control or balancing valves must be re-commissioned after the clean to ensure that the system is returned to the operational condition. Normally it is sufficient to return control valves to their original settings but since the remedial works may have affected system resistance it is advisable to carry out spot checks to assess whether a full re-commissioning may be needed.

Depending on the scope of the works it may be desirable to temporarily increase the frequency of sampling until it is demonstrated that the water quality within the system is stable. If that is not the case then the remedial flush may need to be repeated or alternative measures considered.

2.6.7 Validation of the remedial works

A full record of the remedial works carried out and results obtained (including the chemicals used, concentrations and contact times, flushing flow rates and final dosage of inhibitors and biocides) should be kept and issued to the building operator.

Sampling and analysis of water quality on completion of the remedial works should be commensurate with the objectives and scope of works and agreed prior to commencement.

Large scale works may require fully validated documentation as described in BG 29^[1] and BS 8552^[6] and confirmatory sampling with independent analysis seven days after completion of the clean. Small scale works may require only a brief description of what was done and sufficient analysis to demonstrate that it had the desired effect.

Whether the analysis and sampling is carried out by the cleaning or water treatment specialist using test kits or an independent authority using an accredited laboratory is a contractual matter, not a fundamental requirement of the process.

3 CORROSION PROCESSES

3.1 CHEMICAL CORROSION PROCESSES

BS EN ISO 8044^[11] formally defines corrosion as “physicochemical interaction between a metal and its environment that results in changes in the properties of the metal, and which may lead to significant impairment of the function of the metal, the environment, or the technical system, of which these form a part”.

In this guide corrosion is more simply defined as the loss of metal from a component due to the electrochemical reaction with its environment. In closed systems this includes loss of metal from pipes and components due to surface oxidation as well as pitting, dezincification and stress corrosion.

3.1.1 Basic theory

Corrosion of a metal in water is essentially an electrochemical process similar to that which occurs in a battery. In order for any electrochemical cell to operate all of the following are required:

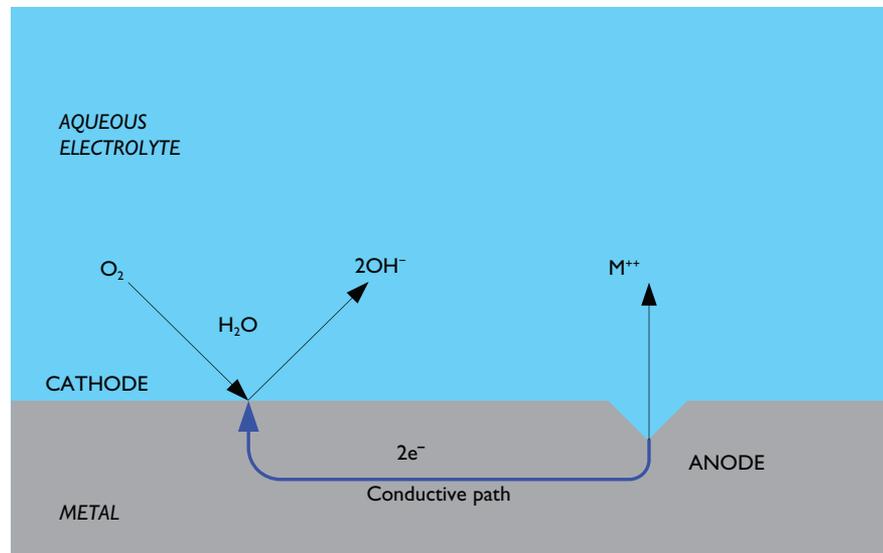
- Anode
- Cathode
- Electrolyte
- Conducting circuit

In the corrosion cell:

- the anode is the area where the oxidation of the metal takes place, releasing metal ions into solution and generating electrons – this is where the primary corrosion damage occurs
- the cathode is the area where electrons are dissipated from the metal surface, usually by the reduction of dissolved oxygen in the water to hydroxide ions
- the electrolyte is water with dissolved salts
- the conducting circuit is provided by the underlying metal

The driving force for the corrosion process is the energy released by the oxidation of the metal at the anode.

In general corrosion of a single material, anodic and cathodic areas are not fixed but evolve all over the surface of the material. In pitting corrosion of a single material, the anodic reaction becomes fixed in a particular location surrounded by cathodic sites (Figure 2). In this case M^{++} is the metal ion released by the pitting process. Metal cations may react with the hydroxyl ion formed at the cathode, ultimately to form an insoluble material, which may hinder further corrosion, for example iron oxides in the case of steel corrosion.

Figure 2: Basic mechanism of pitting corrosion

The metal oxidation at the anode(s) must be balanced by the chemical reduction taking place at the cathode(s) i.e. the rate of the anodic reaction(s) must equal the rate of the cathodic reaction(s). Therefore corrosion rates can be reduced by inhibiting either the anodic reaction (for example by coating the surface) or the cathodic reaction (for example by limiting the amount of dissolved oxygen in the water or increasing the pH).

Anodic and cathodic activity can initiate on any heterogeneous metal surface, with the possible exception of inert metals such as gold and platinum.

Factors which affect the rate of corrosion include:

- Dissolved oxygen
- Temperature
- Galvanic potential difference
- pH
- Carbon dioxide
- Total dissolved solids
- Chlorides
- Sulfates
- Bacteria
- Flow velocity
- Surface condition
- Stress

In instances where the anode is small and localised the corrosion may be locally intense resulting in pitting and eventual perforation. These factors are explained below.

Dissolved Oxygen

The concentration of dissolved oxygen is by far the most important factor controlling the rate of corrosion of metals in closed systems.

The rate of corrosion of active metals in near neutral (neither acid nor alkaline) solutions is proportional to the concentration of dissolved oxygen, and minimising this provides one method of controlling the corrosion rate. However, a reduced oxygen concentration may not necessarily be an advantage for metals protected by a passive film, e.g. stainless steel, since the ability to maintain the film will be governed by the availability of sufficient cathodic current.

Steel in contact with water containing low concentrations of dissolved oxygen and no inhibitors will corrode with the formation of black iron oxide (magnetite) sludge. At higher concentrations of dissolved oxygen red iron oxide (haematite) may be formed with pitting of the steel surface. In reality, the reaction pathways are rather complex and will result in a mixture of iron oxides in different mineral forms.

Temperature

Changes in temperature can modify the mechanism and rate of corrosion reactions.

Generally, the corrosion rate increases with increase in temperature. For example, the rate of corrosion of mild steel in dilute chloride solutions is approximately doubled by a 30°C rise in temperature, while that of admiralty brass and cupronickels doubles for a 20°C rise in temperature.

In a few cases an increase in temperature can bring about a reversal of polarity at bimetallic contacts for example in an iron/zinc couple the iron is protected by sacrificial corrosion of the zinc at ambient temperatures but begins to corrode preferentially as the temperature is raised above 60°C.

Cyclic temperature variations may encourage the onset of stress corrosion cracking in susceptible alloys.

There are also secondary temperature effects. Increasing the water temperature reduces the solubility of oxygen so temporary heating above the normal operating temperature can sometimes be used as a method of accelerating deaeration. Increasing the temperature can also result in thermal disinfection of bacteria.

Galvanic potential difference

The term “galvanic corrosion” is normally reserved for corrosion induced by the presence of two metals of different electrode potential that are electrically connected in the presence of an electrolyte. The rate of this corrosion is strongly influenced by the electrode potential difference between these areas.

The galvanic series is an arrangement of the metals in the order of their electrode potential, the most noble being at the top of the list and the most active at the bottom. An example of this is given in table 4.

The further apart the metals are on this list, the greater will be the reactivity between them and therefore the greater the speed at which the anodic site will corrode.

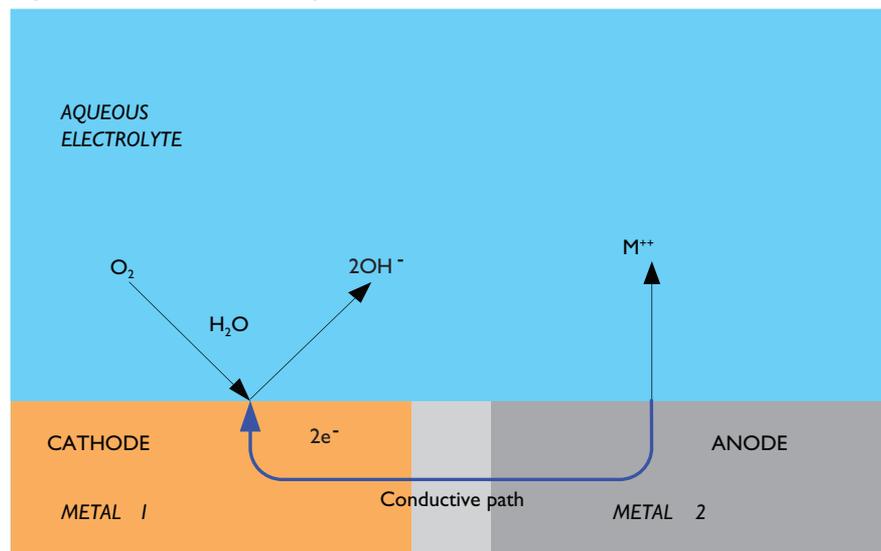
Table 4: Galvanic series of some commercial metals and alloys

The actual ordering of metals in the series may vary according to the chemical environment but the following can be taken as indicative for a closed heating or cooling system.

	More noble or cathodic (more corrosion resistant)	
Silver Solder	↑ ↓	
Stainless Steel (passive)		
Nickel-Copper Alloys		
Bronzes		
Copper		
Brasses		
Lead-Tin Alloys		
Lead		
Tin		
Soft solder		
Stainless Steel 316		
Stainless Steel 430		
Stainless Steel 410		
Cast Iron		
Low-carbon Steel		
Aluminium Alloys		
Aluminium		
Zinc		
Magnesium		More active or anodic (less corrosion resistant)

In Figure 3, “Metal 1” is the more cathodic metal and “Metal 2” is the more anodic metal. Therefore “Metal 2” will be preferentially corroded.

Figure 3: Basic mechanism of galvanic corrosion



Closed pipework systems invariably include several different metals and are potentially susceptible to galvanic corrosion. However this is rarely a serious concern where:

- The anodic area is large compared to the cathodic area
- Oxygen concentrations are low
- The correct inhibitors are deployed

The ratio of the area of anode to cathode is particularly important. The oxidation of metal at the anode must be balanced by the chemical reduction taking place at the cathode. If the anode is large relative to the cathode then the corrosion will be constrained by reaction at the cathode and any small loss of metal is spread over the relatively large area of the anode. If the cathode is large relative to the anode, corrosion will be constrained by reaction at the anode but loss of metal will be concentrated in a small area and could lead to a corrosion related failure.

In many heating and cooling systems copper is the most electropositive metal present in significant quantity and would be the cathode of most galvanic couples. However, provided the dissolved oxygen concentration is low, the cathodic reduction on copper is slow and consequently any galvanic effect should be insignificant. Nevertheless, one should always avoid the direct coupling of copper or brass to aluminium or galvanised steel as the electrochemical potential difference is much greater and pitting of the aluminium or zinc coating of the galvanised pipe is likely to occur.

Where there are undesirable combinations of materials that cannot be avoided then it may be possible to electrically disconnect the anode and cathode by using insulating materials between vulnerable parts of the system. This should only be done with expert advice.

However, in some situations the galvanic couple is not created by the design choice of materials but by the electrochemical process that causes a more noble metal to plate out from solution, particularly copper onto steel. This forms a cathodic area that can induce aggressive pitting corrosion on the surrounding steel surface.

pH

The pH (hydrogen ion concentration) of system water significantly affects the rate and degree to which metals corrode and the fate of the metal ions released into solution. Most metal will corrode more rapidly in acidic solutions (less than pH 7). Water treatment programmes for steel pipework systems are typically designed to operate between pH 8 and pH 11.

Aluminium is corroded at high pH so water treatment programmes for systems containing aluminium are limited to a pH of 8.5 or less, subject to advice from the aluminium component manufacturers.

Carbon dioxide

Dissolved carbon dioxide contributes to corrosion by reducing the pH of the water and increasing its capacity to corrode metals.

Total dissolved solids

A high concentration of total dissolved solids in water increases its conductivity and therefore the risk of certain corrosion processes. However, it is the composition of the TDS in terms of the concentrations of individual ions that may be of more concern.

Chlorides

Chlorides are potentially aggressive as they interfere with the development of protective films and also allow passive films to be broken down more readily. The danger of having partial passivation is that the corrosive attack is concentrated at active sites leading to pitting corrosion.

Chloride at the typical levels found in natural waters should not be an issue for copper and brass in closed systems, since oxygen levels are very low. If however chloride levels are unusually high (>100 mg/l) the dose rate and concentration of passivating inhibitors, particularly nitrite, may need to be increased (see Section 4.1.2).

For other materials, including those that have a naturally formed protective oxide film such as aluminium and stainless steel alloys, certain grades may have reduced susceptibility to chloride attack and should be chosen where this is potentially an issue (see Section 3.1.2).

Sulfates

High concentrations of sulfates may also increase corrosion rates but are not as aggressive as chlorides at the same concentration. However, sulfate ions can be metabolised by various sulfate reducing bacteria (SRBs) causing pitting corrosion in anaerobic conditions under biofilm and deposits (see Section 3.2).

Bacteria

There are many other bacteria (aerobic and anaerobic) that can result in corrosion, either directly or indirectly, as discussed in Section 3.2.

Flow velocity

The general corrosion rate in a pipe gradually increases with flow velocity. At a high flow velocity, particularly in the presence of entrained gases or solids, turbulent erosion may occur. This causes uneven attack on pipework surfaces after flow discontinuities. Turbulent erosion mainly affects the softer metals such as copper and brass, particularly in domestic water systems, but is relatively uncommon in closed systems.

In closed systems it is a low flow velocity or stagnation that is more of a problem. Under these conditions suspended solids can settle out on pipework, increasing the likelihood of under deposit attack and MIC leading to rapid pitting corrosion.

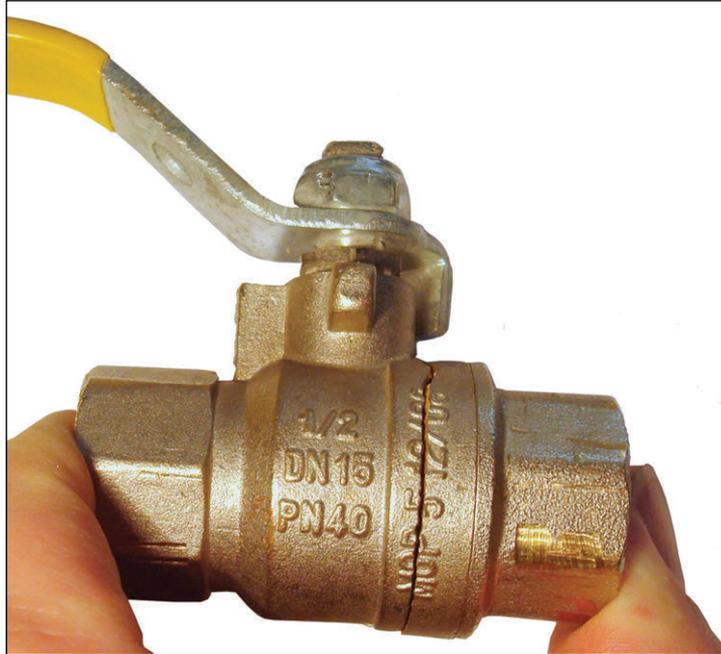
Surface condition

Dirty surfaces, such as those contaminated with grease or scale are more susceptible to localised corrosion than clean surfaces. One explanation is that isolated areas of contamination on an otherwise clean surface can initiate differential oxygen corrosion. Dirty surfaces also encourage the growth of biofilm and MIC.

Stress

Stresses in certain metals and alloys can cause stress-corrosion cracking (SCC) when they are exposed to specific corrosive environments. The factors required to produce this effect are a susceptible alloy/environment combination, tensile stress (either applied or residual from the metal forming processes) and exposure to an aggressive species. For example ammonia causes SCC of brass and chloride causes SCC of stainless steel. A valve that has suffered from SCC is shown in figure 4.

Figure 4: SCC of ball valve



Other factors

Other factors that increase heterogeneity and therefore encourage the initiation of corrosion cells and should be avoided where possible include:

- Discontinuities in the natural or applied protective surface coating (including inhibitor films)
- Local differences in oxygen concentration caused by accumulation of deposits on surfaces and in crevices
- Differences in metallurgy due to welding
- The proximity of dissimilar metals

3.1.2 Corrosion effects on various metals

Aluminium and aluminium alloys

Cast aluminium alloys are used extensively in boiler heat exchangers while wrought aluminium alloys are sometimes used for radiators. Although aluminium is a very reactive metal, it has a high resistance to corrosion because of the tenacious and inert oxide film which forms on the surface. This oxide layer is generally stable in the pH range of 6.5 to 8.5 but starts to break down or dissolve in more acid or alkaline conditions. In any water treatment programme, it is important that account must be made of any aluminium in the system, so that the pH does not exceed 8.5. This is lower than that typically used for steel systems without aluminium.

The behaviour of aluminium in water systems depends on carbonate hardness and concentrations of chlorides and copper. Higher chloride (and sulfate) content encourages general corrosion and pitting whilst higher carbonate hardness reduces the number of pits formed. If oxygen is present, dissolved copper in the water may have a profound effect on pitting corrosion; the amount of copper necessary to initiate pitting varies with hardness and chloride content, but can be as low as 0.02 ppm.

Contact with copper and copper alloys, and to a lesser extent, iron and iron alloys, will induce galvanic corrosion in all environments where dissolved oxygen is present. Aluminium is intentionally used a sacrificial anode in some situations to protect more vulnerable materials.

Cast iron

Typical applications of cast iron include boiler sections (heat exchangers), pump housings, large valves and pipe fittings (malleable iron). Corrosion rates for cast iron in closed heating and cooling systems are similar to those for mild steel and the same programmes of water treatment apply.

Copper and copper alloys

Copper and its alloys comprise a versatile range of materials which are used in a wide variety of building services applications. Copper is used extensively for pipework, hot water cylinders and heat exchanger coils due to its excellent ductility and thermal conductivity. A wide range of copper alloys including brasses and bronzes are available and mainly used for valves, pipe fittings and pump components.

Copper metal – Copper tube is widely used in closed heating and cooling systems and acute failures due to internal corrosion are rare. Where general surface corrosion occurs due to oxygen ingress, the release of copper ions into the water may increase the rate of corrosion and pitting on other more active metals in the system such as mild steel. The risks are greatest in the early life of the system when oxygen concentrations are high and metal surfaces not yet fully protected by the water treatment programme.

Brasses – The common brasses consist of a range of copper alloys containing from 10% to 50% zinc with other minor alloying elements. Brasses can suffer from two particular forms of corrosion leading to

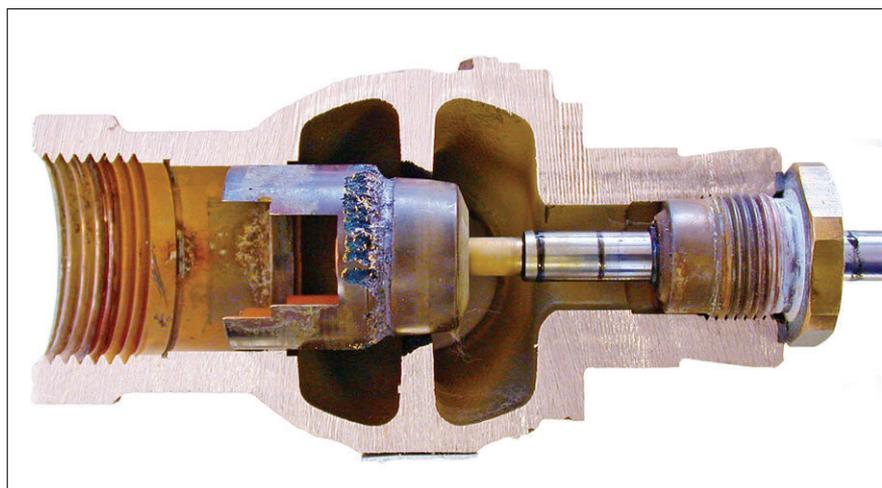
catastrophic failure of components. These are dezincification and stress corrosion cracking.

Dezincification is where zinc is preferentially removed from the alloy leaving a porous mass of copper having little strength. Where leakage or breakage of a brass fitting has occurred, dezincification may be suspected if the defective area has a dull, coppery appearance. Dezincification is well known in domestic water systems but rarely encountered in closed systems as it requires a high oxygen environment. The risk can be reduced by specifying components manufactured from dezincification resistant (DZR) brasses.

Stress corrosion cracking (SCC) occurs where brass components are exposed to both mechanical stress and certain corrosive chemical species, particularly ammonia and related compounds. The stress can be residual from the manufacturing process or imposed during installation for example brass nuts of compression fittings are inevitably subject to high hoop stresses as a result of tightening. SCC is a particular problem in chilled water systems where corrosive species can be leached from insulation materials as condensate forms on the outer surface of the pipe and fitting. SCC is rarely initiated from inside the fitting as the aggressive chemical species are unlikely to be present in sufficient concentration in the system water to cause SCC. However, there are examples, including the failure of valves, where the crack appears to originate from a surface in contact with system water. The risk of SCC (and dezincification) can be eliminated by specifying bronze components but these are more expensive than brass.

In common with copper, brasses are relatively soft and can suffer attack by erosion, impingement or cavitation. Cavitation in heating and cooling systems is most frequently encountered on valve seats where the valve has been operated in an almost closed position. This risk is exacerbated in water with high suspended solids or debris. An example is shown in figure 5.

Figure 5: Control valve damaged by cavitation



Bronzes (gun metals, phosphor bronzes, and tin bronzes) - The term 'bronze' should refer to copper-tin alloys, but in practice a variety of copper alloys are termed bronzes irrespective of whether they contain tin. This wide variation in composition makes corrosion behaviour of a component difficult to predict unless the specific composition is known. Gun metals are probably the best all round choice for general valves and fittings in water-based heating systems.

Aluminium bronzes - These materials generally have a high resistance to corrosion, impingement attack and cavitation erosion. They are however surprisingly prone to pitting corrosion in natural waters and can suffer selective corrosion analogous to dezincification. They are used for tube plates, back boilers and pump impellers.

Cupro-nickel alloys - Alloys containing copper and nickel have excellent resistance to corrosion in many environments, including those containing chlorides. They are more stable than bronzes under flow conditions, less susceptible to stress corrosion and are used in shell and tube heat exchanger applications.

Stainless steel

The term "stainless steel" covers a wide of alloys incorporating iron, chromium and nickel. These can be grouped by metallurgical characteristics as martensitic, ferritic and austenitic. Austenitic grades have the highest corrosion resistance and ductility and are most frequently used in closed systems. Examples of the use of stainless steel in closed systems include valve stems, pump shafts and impellers, strainers, parts of fittings, expansion joints, plate heat exchangers and buffer vessels. Stainless steel is occasionally used for pipe sections and associated fittings but less so in closed systems than domestic water systems.

Stainless steels are potentially subject to pitting, corrosion and stress corrosion, particularly in the presence of high concentrations of chlorides. The stainless steel grades used in components used for closed systems are unlikely to be adversely affected at the concentrations normally encountered in closed systems filled from mains water. Stainless steel pipework can however be affected by external corrosion if protective coatings fail, particularly on buried pipe.

Steel (low carbon and low alloy)

Low carbon and low alloy steel, generically known as mild steel, is used in a wide variety of applications due to its ease of fabrication and mechanical properties. Applications include pipework, boiler heat exchangers and radiators. Mild steel will readily corrode when exposed to water containing dissolved oxygen unless protected in some way.

At dissolved oxygen concentrations above 1 mg/l in untreated water, the corrosion products may form bulky mounds on the surface called tubercles. These overlie areas where localised attack is occurring and can lead to pipe wall perforation or reduce the carrying capacity of pipes due to the reduction in cross sectional area. At lower concentrations of dissolved oxygen, iron oxide corrosion products can form a magnetite

sludge that restricts flow and may lead to blockages or increased risk of MIC. This is commonly found in the base of steel radiators and the cast iron heat exchangers of older boilers.

Steel corrosion can occur even in the absence of oxygen, if the water contains sulfate reducing bacteria (see Section 3.2.1).

Zinc

Zinc is used as a protective coating on some steel pipes and fittings, mainly for cold water services. Internally coated pipes and fittings are NOT suitable for hot water or heating systems as the corrosion rate in oxygenated water increases dramatically above 55°C and a reversal of potential occurs above 60°C. The zinc then becomes cathodic to steel, stimulating attack which can result in localised corrosion (pitting) and subsequent perforation.

3.2 MICROBIALLY INFLUENCED CORROSION (MIC)

Bacteria are single celled microorganisms that often aggregate into colonies. The typical cell size is 1 µm to 10 µm. The population of microorganisms can be diverse and variable depending on the degree of sensitivity to the oxidation–reduction potential of their environment. Bacteria can be classed into the following categories depending on how much oxygen they require for respiration:

- Aerobes (grow in the presence of oxygen), e.g. Pseudomonas, Aeromonas, Flavobacter.
- Facultative anaerobes (able to grow with or without oxygen) e.g. Klebsiella, E.coli.
- Anaerobes (grow in the absence of oxygen) e.g. Sulfate reducing bacteria (SRB).

Each type of bacteria therefore requires different conditions for survival and growth. If conditions are right for growth they can multiply rapidly, with numbers doubling in as little as 20 minutes. One bacterial cell can potentially become 200 million in less than 10 hours!

All natural sources of water (including tap water) contain many different types of bacteria, some of which may multiply and lead to problems within a pipework system if they encounter suitable conditions for growth. Bacteria can circulate freely in the system water as “planktonic” bacteria or adhere to the pipe walls as “sessile” bacteria.

Closed systems, if left filled and untreated, can quickly develop a biofilm layer on pipe surfaces. A biofilm is a microbial mass of aquatic bacteria and other microorganisms together with trapped particles and dead bacteria cells, bound together by an exopolymer. This is an extracellular polysaccharide exudate produced by slime forming bacteria such as pseudomonads, constituting up to 90% of the biofilm. It protects the sessile bacteria from hostile conditions including exposure to biocides. A consortium of bacteria is therefore able to develop within the biofilm on the pipe wall where both aerobic and anaerobic species can flourish. This is the starting point for microbially influenced corrosion.

During the late 1990s, some bacteria (particularly *Pseudomonas*) were linked to a series of damaging contamination problems within closed heating and cooling systems. The symptoms included blockages at valves and strainers, sludge formation, and severe gassing affecting flow measurements and commissioning results. There is no evidence to confirm that *Pseudomonas* was directly responsible for these problems – other bacteria may have been to blame. However, it has been found that where concentrations of *Pseudomonas*-like bacteria (pseudomonads) in system water are high, the risk of these problems is increased. *Pseudomonad* concentrations are therefore increasingly used as one indicator of the biological quality of system water.

Other bacteria of concern are nitrate/nitrite reducing bacteria (NRB) and nitrite oxidising bacteria. These bacteria can cause rapid loss of nitrite-based inhibitor from the system and so increase the risk of electrolytic corrosion. In addition, some of these bacteria can produce ammonia that can increase corrosion of copper and brass.

There is a natural order in which bacteria develop within closed heating and cooling systems. First the aerobic bacteria colonise surfaces and multiply in oxygenated sections of the system. In stagnant areas of the system these species quickly reduce the available oxygen allowing growth of anaerobic bacteria such as SRB and NRB.

There are three ways in which bacteria are able to cause or influence corrosion:

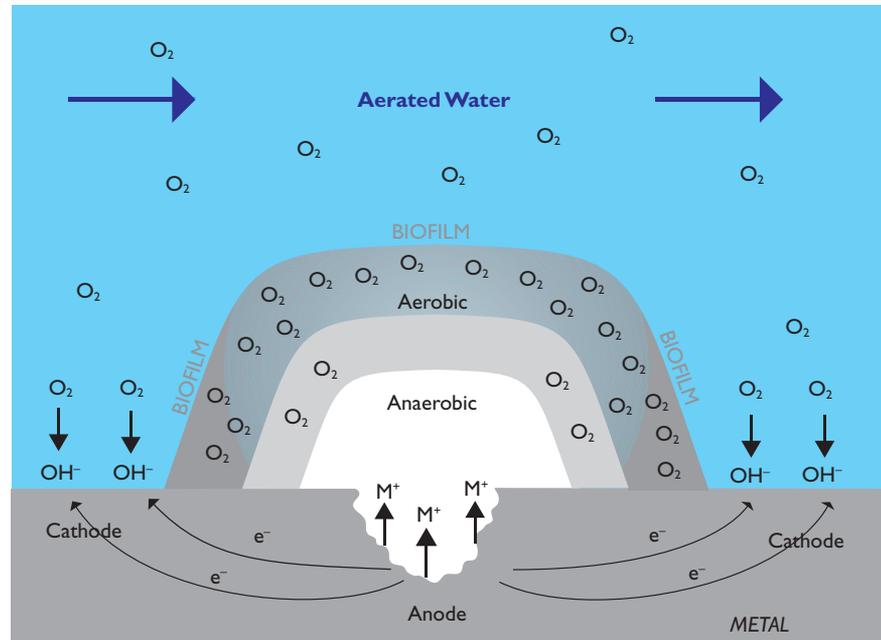
- a. directly, by obscuring the surface, resulting in a differential aeration cell
- b. directly, by producing metabolic by-products which are in themselves aggressive towards metal surfaces
- c. indirectly, by acting on the treatment chemicals in a way that renders them less effective

These are described in more detail in the following sections.

3.2.1 Direct MIC

Direct MIC occurs when sessile bacteria are in direct contact with the metal surface, usually under the biofilm. Different bacteria can be implicated in various forms of corrosion in different systems but specific examples for closed heating and cooling systems include:

Oxygen depletion corrosion: If there is a substantial biofilm, a zone of oxygen depletion can occur at the interface between the biofilm and the metallic surface. The different oxygen potentials between the inside and outside of the biofilm cause the inside to become the anode and the outside to become the cathode. This then allows electrolytic corrosion to take place. This is illustrated in figure 6.

Figure 6: Differential oxygen cell formed under biofilm

Corrosion of stainless steel: Stainless steel is corrosion resistant due to the presence of a film of a stable oxide on the surface. However in the low oxygen conditions under a biofilm, this oxide layer breaks down thus removing that protection and allowing corrosion to occur.

Corrosion due to SRB: The absence of oxygen under the biofilm allows the growth of anaerobic organisms such as SRB which are one of the most frequent causes of MIC. SRB reduce sulfate from the fill water to hydrogen sulfide which reacts with the metal to produce metal sulfides as corrosion products. The involvement of SRB in corrosion failures is inferred from the evolution of hydrogen sulfide when the corrosion deposit is acidified. Figure 7 shows two examples of SRB attack on pipe surfaces under the microscope (at low magnification).

Figure 7: Examples of SRB pitting corrosion

It is possible to reduce the risk of SRB activity by limiting essential bacterial nutrients such as phosphorus, nitrogen, and sulfate. Reverse osmosis or deionised fill water will have fewer problems with SRB. Also, any practices that minimise biofilm such as flushing, disinfection and the removal of dead legs, will reduce the growth of SRB.

3.2.2 Indirect microbial influence

Examples of the indirect influence of bacteria include:

Nitrate/nitrite reducing bacteria: Nitrite can be metabolised by certain bacteria (for example *Pseudomonas denitrificans* and *Bacillus*) and rapidly depleted from a closed system. As the concentration of the nitrite falls it becomes less effective and may actually increase the rate of corrosion. The degradation products may also be detrimental for example nitrate/nitrite reducing bacteria (NRB) may reduce nitrates, nitrites and organic nitrogen compounds to ammonia, which is aggressive to copper and copper alloys.

Interference with the action of treatment chemicals: In general terms chemical corrosion inhibitors are able to reduce corrosion by coating the exposed metal surfaces. Biofilm prevents the inhibitor from reaching the metal surface and therefore allows corrosion to take place as discussed in section 3.2.1.

Degradation of glycols: Bacteria can survive in water containing up to 20% glycol and are able to use the glycol as a nutrient (a source of organic carbon). It is important to maintain the glycol concentration above 20% to prevent proliferation of those bacteria unless there are additional biocides present. The glycol concentration should be checked and corrected after any water replacement that could have resulted in dilution. The physical characteristics of glycols and measurement of concentration are discussed in Appendix E.

4 CHEMICAL WATER TREATMENT

4.1 CORROSION INHIBITION

The purpose of water treatment in a closed heating or cooling system is to ensure that the system maintains its efficiency and achieves or even extends its life expectancy. In practice the focus tends to be on protecting the metal components of the system from corrosion processes that may lead to the formation of suspended solids and pitting, though the adverse effects of poor water quality on other materials should not be ignored.

4.1.1 Corrosion inhibitor treatment programme

The inhibitor programme/products should tolerate and be effective under the following conditions:

- Make-up water characteristics within the ranges specified by the programme/product provider
- Dissolved oxygen concentrations within the range specified by the programme/product provider
- Total dissolved solids and suspended solids within the range specified by the programme/product provider
- pH appropriate to the materials of construction
- System operating temperature specified by the designer

The inhibitor programme/products should:

- exhibit good wetting properties. They should not support or promote foaming conditions in areas of high turbulence.
- provide a protective layer on clean metal surfaces that is effective both in flowing water during system operation and stagnation during extended plant shut-downs.
- ideally provide both cathodic as well as anodic inhibition, thereby giving some protection to metal surfaces under debris.
- provide protection to all vulnerable metals in the system.

Inhibitors work by a number of different mechanisms, but those used in closed systems all result in microscopically thin molecular films that are invisible to the naked eye.

The inhibitor programme should be effective under conditions of slight dilution or over-concentration and protect all the metals present in the system. The intended application (systems and materials) and effective concentration of each inhibitor should be documented by the programme/product provider.

The addition of each inhibitor required to reach a target concentration should be calculated using an accurate estimate of the system volume. The actual concentration of inhibitor should always be checked after addition and circulation of the inhibitor.

Note that some inhibitors, such as nitrite, can promote pitting corrosion when present below a critical concentration. It is very important to

maintain inhibitor concentrations above the manufacturer's recommended "safe" concentration when using these.

The water treatment programme should specify sufficient reserves of inhibitors so that precise remedial additions are not required for minor losses of system water and inhibitors should only require occasional topping up. Such reserves should allow for any degradation or adsorption of inhibitor on system surfaces and debris.

The water treatment chemicals should not be aggressive to any materials found in the system including solders, jointing compounds, rubber and plastic components. Where necessary, the treatment programme should be compatible with antifreeze components such as glycols.

The water treatment programme should have sufficient buffering capacity to maintain the system pH within the specified range in the presence of cleaning residues, antifreeze, degradation products of the water treatment chemicals and bacteria metabolites.

Chemical spot tests and performance tests should be available so that the efficiency of the water treatment can be measured in the field.

The water treatment programme should not promote the establishment or growth of fungi or bacteria. Refer to Section 4.2 for the application of biocides.

Where appropriate, the water treatment programme should inhibit scaling or precipitation of hardness salts or other impurities. Refer to Section 4.3 for the application of scale inhibition.

4.1.2 Properties of corrosion inhibitors

Inhibition may result from:

- the inhibitor molecule being chemisorbed on the metal surface so forming a protective film either by itself or in combination with metallic ions.
- the formation of passive oxide films.
- the inhibitor reacting with corrosion promoting species present in the system water.

Corrosion inhibitors can be generally classified into anodic, cathodic or organic film-forming.

Anodic inhibitors build a very thin and generally invisible protective film initially at the anode which may eventually spread all over the metal surface. Whilst the degree of protection offered by many anodic inhibitors is high, care must be taken to ensure that they do not fall below their critical concentration as this can cause pitting attack on the metal surface.

Cathodic inhibitors are generally less effective than the anodic type and may form visible films on the cathode surface. Whilst there is no critical lower concentration, excessively high concentrations could cause precipitation, increasing the risk of under-deposit corrosion.

Cath-anodic corrosion inhibitors have properties of both anodic and cathodic inhibitors, though there are few examples in common use. More usually the correct balance of protection is achieved by blending different anodic and cathodic inhibitors to achieve the required performance.

Organic film forming inhibitors usually have a mixed mode of action - they inhibit both anodic and cathodic reactions. However, they are generally used to prevent corrosion under acidic conditions rather than in neutral oxygenated waters.

In general terms, if the mean corrosion rate is reduced to an acceptable rate for all the metals present and there is no sign of pitting attack then effective corrosion protection has been achieved.

The common corrosion and scale inhibitors used in closed systems are listed in Table 5 and the subsequent text. The dose rates and target concentrations should be specified by the programme/product provider and documented by the water treatment specialist in the system water treatment log book.

Table 5: Common corrosion and scale inhibitors

Component	Inhibitor function
Nitrite	Corrosion inhibitor for ferrous metals
Nitrate	Corrosion inhibitor for aluminium
Molybdate	Corrosion inhibitor
Azoles	Corrosion inhibitors for copper and copper alloys
Phosphate	Corrosion inhibitor for steel
Polyphosphate	Scale and corrosion inhibitor (reverts to orthophosphate)
Phosphonates	Scale and corrosion inhibitor
Silicates	Corrosion inhibitor for steel, copper alloys and aluminium
Tannins	Film forming corrosion inhibitor and oxygen scavenger
Benzoate	Anodic inhibitor
Triethanolamine, monoethanolamine, alkylcarboxylates and substituted triazines	Organic film formers and corrosion inhibitors
Phosphono- and phosphino- carboxylic acids	Cathodic inhibitor and scale dispersant
Diethylhydroxylamine	Oxygen scavenger
Borate	pH buffer, biocide, corrosion inhibitor

Nitrite – The nitrite anion (NO_2^-) is an oxidizing anodic inhibitor for mild steel that has been in use for many years. Unlike molybdate, nitrite does not require dissolved oxygen to function as a passivating inhibitor. The optimum dose depends on the concentration of aggressive ions such as chloride and sulfate and system temperature. As with other anodic inhibitors, if the concentration falls below a critical level then severe

pitting can ensue. Too little nitrite can be worse than none at all. Table 6 suggests the critical concentrations of chloride and sulfate for pitting of steel in nitrite inhibitor based on information from *Corrosion and Corrosion Control*^[18].

Table 6: Critical concentrations for pitting of steel in nitrite inhibitor

Nitrite inhibitor NO ₂ ⁻ mg/l	Chloride Cl ⁻ mg/l	Sulfate SO ₄ ²⁻ mg/l
33	127	14
67	278	37
333	1207	304

Given that nitrite concentrations will normally be held above 300 mg/l and mains water chloride and sulfate concentrations should be well below 100 mg/l this issue is unlikely to be a major concern in most systems filled from the mains. However chloride and sulfate can be much higher in borehole water. Table 8 of BG 29^[1] suggests that water containing up to 250 mg/l sulfate or chloride should be acceptable for filling the system. Also bear mind that chloride and sulfate can accumulate in the system in the longer term as the breakdown product of some biocides.

Nitrite may be used alone or synergised with alkaline buffering agents and other inhibitors such as molybdate. Azoles are added when protection of copper or copper alloys is required. If aluminium is present, a specific aluminium inhibitor such as silicate or nitrate will also be needed.

Nitrite is compatible with glycol antifreeze and commonly used non-oxidizing biocides. Nitrite should not be mixed with organic amines, amides or other organic inhibitors that dissociate under heat transfer or catalysed conditions to form nitrosamines or other suspected carcinogens.

Nitrite is readily degraded by various microorganisms, generally described as nitrite reducing (denitrifying) or nitrite oxidising (nitrifying) bacteria. Nitrifying bacteria oxidize nitrite to nitrate, while denitrifying bacteria reduce nitrite to nitrogen gas or ammonia. In addition to the loss of protection resulting from the reduction in nitrite concentration, the degradation products may also be detrimental. For example nitrate is also a nutrient for other bacteria (though it also has an inhibitor function), whereas ammonia is aggressive to copper and copper alloys. Diligent use of a non-oxidizing biocide regime is imperative when using a nitrite program. Oxidizing biocides should not be used with nitrite treatments, since they will oxidize nitrite ions to nitrate ions.

Nitrate – The nitrate anion (NO₃⁻) may be included with other inhibitors for the protection of aluminium components and solder. In particular the addition of nitrate can overcome the detrimental effect of nitrite on aluminium.

Nitrate functions by controlling the growth of the aluminium hydroxide film and also as a pitting inhibitor by the preferential reaction of nitrate with the active aluminium surface.

If copper or copper alloys are present, an azole is recommended, since neither nitrite nor nitrate provides protection against corrosion of these materials.

Whilst nitrate is not as problematical as nitrite in terms of critical concentration, care must be taken with the biocide regime.

Molybdate – The molybdate anion (MoO_4^{2-}) is widely used as an anodic inhibitor. Molybdate (added to the system as sodium molybdate) requires some dissolved oxygen to function effectively though the concentrations typically found in closed heating and cooling systems are usually sufficient for this. If there is insufficient oxygen for molybdate inhibition the system is unlikely to be at immediate risk of oxygen corrosion.

Molybdate is most often synergised with other inhibitors such as nitrite. In this combination, nitrite takes the place of oxygen in forming the protective oxide film. The molybdate also helps to retard the growth of pits should the concentration of nitrite fall. The benefits of molybdate/nitrite programmes include enhanced corrosion control, a reduced propensity for pitting relative to nitrite alone, and both low carbon steel and aluminium corrosion control. Molybdate/nitrite programmes are compatible with commonly used non-oxidizing biocides as well as ethylene and propylene glycols.

The absorbance of molybdate onto the outer hydrated iron oxide layer means that when molybdate is fed to a poorly maintained system containing old corrosion products, molybdate will be consumed. Therefore, prior to using a molybdate based treatment in a fouled system, the system should be cleaned to remove existing corrosion products.

Azoles – Aromatic azoles such as tolyltriazole (TT), benzotriazole (BT), mercaptobenzotriazole (MBT) and other substituted azoles are used in closed systems for controlling copper or copper alloy corrosion. Substituted azoles have also been utilised for controlling aluminium corrosion. The azole requirement increases with increasing concentration of chloride and sulfate ions.

In addition to controlling copper or copper alloy corrosion, azoles react with cuprous ions in solution to prevent them from plating out as metallic copper on low carbon steel or aluminium surfaces which can lead to aggressive local pitting.

Orthophosphates – Orthophosphates (PO_4^{3-}) are used as either the mono, di or tri metal salts depending upon the pH of the system. They are anodic inhibitors for low carbon steels but are rarely used alone as they form insoluble precipitates with water hardness salts, and do not function in the absence of oxygen. Orthophosphates should be used with care especially with aluminium heat exchangers as they can induce pitting attack under high heat flux conditions. Several European countries prohibit the discharge of phosphates or orthophosphates into the sewerage system.

Polyphosphates - Polyphosphates are complex linear condensed or polymerised phosphates with variable chain length. They are used as the metal salts of hexametaphosphate, tripolyphosphate and pyrophosphate, all of which act as cathodic inhibitors for steel when combined with calcium. Threshold concentrations of these chemicals will not only provide corrosion protection to the system but in the range pH 7.0 to 8.0 will also precipitate scale formers. Polyphosphates hydrolyse to orthophosphate under strongly acid or alkaline conditions or under the influence of high heat flux.

Phosphonates - Phosphonates are organic compounds that are structurally related to orthophosphates. They are chelating agents and bind strongly to metal surfaces. Several are now being used as cathodic corrosion inhibitors for low carbon steels and as deposit (calcium carbonate) control agents.

Phosphonates work in a similar manner to polyphosphates but are more resistant to hydrolysis and thermal breakdown under high heat transfer conditions. They usefully synergise with other inhibitors and can stabilise formulation concentrates. Overdosing of phosphonate formulations, especially in soft water areas, can induce cupro-solvency. Failure to control this can cause problems when attempting to protect mixed metal systems especially where aluminium is present.

Phosphonates degrade to orthophosphate and organic acids in the presence of oxidising species. As these are potential nutrients for bacteria the implication of changing an existing programme to or from one with phosphonates and interaction with other chemicals that may be present should be carefully considered.

Silicates - Silicates are considered to be anodic filming inhibitors. They have a variable composition of $n\text{Na}_2\text{O} : m\text{SiO}_2$. Generally, a ratio of m/n between 2.5 and 3.0 is effective. With silicate treatments the protective film develops slowly and may take weeks to form. The film is believed to consist of silica gel along with ferric hydroxide precipitates. Silicates provide protection for low carbon steel, copper, copper alloys and aluminium.

Silicates are not used as stand-alone corrosion inhibitors for low carbon steel protection but may be added to the water treatment programme for control of aluminium corrosion and/or to augment the performance of other inhibitors.

An advantage of silicates is that they do not act as a nutrient for microbes and are an option where microbiological control is difficult. A disadvantage is the tendency for silica deposition to occur if the product is over-dosed, used with hard water at high temperature or where pH is not properly controlled. For example, if silica is used for aluminium corrosion control and the pH is elevated then aluminium silicate deposition may occur, which can plug nozzles and other small orifices.

The efficiency of silicate anodic protection is less than that for polyphosphates. Concentrations of the order of 100 ppm are required for silicate to be effective. The silicates are stable only at relatively high pH and readily form insoluble salts with hardness formers (calcium and magnesium salts). These precipitates can be highly abrasive and can also form thermally insulating layers particularly in boiler heat exchangers. Silicates are, however, useful in neutralising the effects of acidic soft waters to minimise the dezincification of brass and cupro-solvency.

Tannins – Tannins (and lignins) are mixtures of materials derived from wood bark and have been widely used for many years as oxygen scavengers, crystal modifiers, sludge dispersants and cathodic film formers. They are not generally used in isolation but synergised with other additives.

Careful control of pH may be necessary to avoid precipitation of tannins leading to rapid depletion of the active reserve. Unlike many inorganic anions, tannins do not promote localised attack when present at below critical concentrations. Excessive concentrations of tannins have however been observed to form thick films on heat exchanger surfaces under conditions of high heat flux and these films can become detached as large platelets (suspended solids) which can settle in areas of low flow and cause pump and valve problems.

Benzoate – The benzoate anion may be loosely described as an anodic inhibitor but is rarely used in isolation. In heating and cooling systems benzoate (as the sodium salt of benzoic acid) is usually combined with nitrite. Benzoate does not promote localised corrosion when used below critical concentration. Benzoate is readily biodegradable and requires regular top-up and close control of biocides to maintain the required concentration.

Organic film formers – These are organic molecules that react with metal surfaces in contact with the water in which they are dissolved to form a protective barrier.

Triethanolamine and monoethanolamine form barrier films that prevent oxygen from reaching the metal surface, thus inhibiting the reaction at the cathode. They act as anodic inhibitors for aluminium by blocking pores in the surface oxide film.

Alkylcarboxylates are absorbed onto metal/metal oxide surfaces, possibly through hydrogen bonding. The hydrophobic hydrocarbon tail provides a barrier that prevents water and hence dissolved oxygen from reaching the metal surface.

Substituted triazines form a film over anodic sites. There is a wide range of possible compounds with different organic substitution groups. Substituted triazines do not provide protection for aluminium, copper or copper alloys so other inhibitors are added for systems containing these e.g. silicates for aluminium.

Combinations of organic film formers and vapour corrosion inhibitors (VCIs) are now being used in closed heating and cooling systems particularly for low conductivity systems. There is however concern that the addition of organic carbon to the system could promote microbiological growth.

Phosphono- and phosphino- carboxylic acids – Both of these copolymers act as cathodic inhibitors and scale inhibitor/dispersants.

Oxygen scavengers – Sodium sulfite and other oxygen scavengers including diethylhydroxylamine (DEHA) have historically been used in high temperature heating systems with steel pipework on the basis that removal of dissolved oxygen will prevent oxygen corrosion.

Sulfites are still used for steam boiler plant and high temperature heating systems but rarely in low temperature systems as they could promote the growth of SRB by providing a source of oxidised sulfur and anaerobic conditions. This is not an issue in high temperature systems as the bacteria are eliminated by thermal disinfection.

DEHA is used for controlling ferrous metal corrosion in both high and low temperature systems, particularly those that require the water to maintain a low conductivity. In addition to being an oxygen scavenger and pH buffer, DEHA acts as a passivator, converting haematite to magnetite.

Systems relying on oxygen scavengers require frequent (even daily) monitoring, especially where there is oxygen ingress either directly or via makeup water.

Borate – Sodium borate is a pH buffer, biocide and corrosion inhibitor. It is compatible with both molybdate and nitrite in high pH water treatment programmes. Its use is likely to be curtailed as a consequence of the Biocidal Products Regulation (see Appendix C).

4.1.3 Practical considerations in choosing a water treatment programme

There is no one treatment programme that eliminates corrosion and deposition in every application, and there is usually more than one possible option available for each application. A practical water treatment programme is likely to combine several chemicals with different functions, often as proprietary formulations, to provide overall protection for the system.

It is up to the provider to:

1. Obtain relevant information on the closed system to be treated
2. Evaluate which treatment options will achieve the corrosion control and water quality objectives, taking account of customer concerns and references, regulatory issues and product selection constraints
3. Follow up the treatment programme with proper monitoring of chemical, microbiological and physical parameters, ideally including monitoring of corrosion rates.

Where multi-component formulations are used, the scope of analysis should be sufficient to detect whether the treatment programme is becoming unbalanced and to allow remedial dosing to restore the balance. If depletion of threshold components goes unnoticed the system could be vulnerable to rapid localised attack.

For example, when using nitrite/molybdate inhibitor package it is usual to test the nitrite first, as this is the component more likely to disappear. If the nitrite concentration is low then the molybdate should also be tested so that the remedial dosing can be adjusted to bring both components up to the recommended concentration. In some situations it will only be necessary to add nitrite.

Water treatment chemicals that will be exposed to metal surfaces with high rates of heat transfer should have been tested for possible effects of thermal degradation and catalytic oxidation.

Some water treatment chemicals encourage microbiological growth, either directly or indirectly through their degradation products. In such cases a complementary biocide should normally be used.

All biocides (see Section 4.2.2) must be compatible with the components of the corrosion inhibition programme so that neither reduces the effectiveness of the other.

Finally it is essential that the treatment formulation concentrate has a long shelf life. Liquid formulation concentrates should not re-crystallise or undergo phase separation on freeze-thaw testing. The activity of the ingredients should not be depleted with time and the concentrate should not be susceptible to biodegradation in storage.

The water treatment specialist should be aware of the possibility of feedwater pre-treatment to control dissolved gas concentrations, water hardness, dissolved solids and pH.

4.2 BACTERIA AND BIOFOULING INHIBITION

In closed systems the primary concern is biofouling, though fungal growth can sometimes be significant. The bacteria that cause most problems in closed heating and cooling systems are:

- Sulfate reducing bacteria (SRB)
- Nitrite reducing bacteria
- Pseudomonads

It is likely that over 90% of the microorganisms present in a badly fouled closed system exist in biofilms attached to surfaces within that system.

Bacteria in the biofilm may be up to 3000 times more resistant to biocides than bacteria present within system water. This illustrates how difficult it is to eliminate microorganisms when they are present in established biofilms.

Biofilms cause a number of operating problems including:

- microbially influenced corrosion (MIC).
- reduced efficacy of corrosion inhibitors due to their inability to access pipework surfaces.
- reduction of heat transfer in heat exchangers.
- in extreme cases, reduced water flow due to partial or complete blockage of valves, strainers etc.

Biofouling and corrosion of metal pipe surfaces occurs in several stages. Firstly one or more slime forming bacteria attach to the pipe surface and begin to multiply and exude exopolymer allowing other bacteria to attach to the surface and multiply. The accumulation of bacteria and exopolymer quickly forms a complex three dimensional structure. This interferes with the action of inhibitors and allows the formation of an anoxic zone adjacent to the metal surface. This results in a differential aeration cell where areas under the biofilm are anodic relative to areas beyond the biofilm with greater oxygen availability, and the potential for localised corrosion. Partial lifting of a biofilm can also result in differential aeration.

The anoxic conditions under the biofilm also provide ideal conditions for the growth of anaerobic bacteria, such as the SRB that accelerate corrosion and pit formation. SRB accelerate corrosion by reducing sulfate to hydrogen sulfide that reacts to form insoluble sulfides and cathodic depolarisation (removal of hydrogen from the cathode). Other bacteria can also create acidic environments (with sulfuric acid, hydrochloric acid etc.) under the biofilm, resulting in corrosion.

Biofilms can propagate through detachment of clumps of cells, or by a type of “seeding dispersal” that releases individual cells. Either type of detachment allows bacteria to attach to a surface or to a biofilm downstream of the original community.

The ability of biofilm to trap particulate matter increases operational problems and cleaning challenges. Overall the presence of a biofilm increases the risk of damaging corrosion and equipment failures.

4.2.1 Factors promoting growth of bacteria and MIC

pH: Most microorganisms grow best at pH 6.5 to 7.5. Few thrive below pH 4 or above pH 9 though there are reported cases of microbes surviving at less than pH 1 or above pH 11. In general, bacteria tend to predominate above pH 6 or above whereas fungi and yeasts can flourish in acidic conditions, below pH 6.

Temperature: Most spoilage microorganisms tend to grow best at temperatures of 15 - 40°C. Although the usual design temperatures for heating and chilled water systems may not appear to favour bacteria growth, some areas within the system may provide ideal temperatures for bacteria growth, particularly under part load operating conditions or when the system is inactive.

Nutrients: It is unfortunate that some of the chemicals that are added to the system as corrosion inhibitors, or their degradation products, also provide essential nutrients for certain bacteria. Even biocides may become nutrients as they degrade. While this situation cannot be avoided, the water treatment specialist should be aware of the issue and where necessary take additional steps to counteract the problem.

Biofilms: Biofilms protect bacteria from the action of biocides and provide a range of environmental conditions suitable for the growth of different bacteria as well as being directly implicated in corrosion processes.

Stagnation: Closed water systems should be designed to minimise the risk of biofouling. In practice this means avoiding areas of stagnation including dead-legs. Dead-legs are lengths of pipework that are nominally more than three times the pipework diameter in length and have no flow. These should be eliminated or modified to provide water circulation. Dead-legs allow undisturbed microbial proliferation and biofilms that can affect water quality throughout the system. All closed water systems should be designed to provide routine circulation through all wetted areas.

Dirt and debris: Dirt and debris will absorb and reduce the effectiveness of biocides and other water treatment chemicals and provide areas of local stagnation. Dirt and debris particles may also become incorporated in the biofilm and may become a source of nutrients for bacteria.

Materials: The selection and installation of pipes, fittings and equipment should avoid use of materials or design features that support microbiological growth. Once colonised, an unsuitable material may continue to seed the system with bacteria even after shock dosing with biocide.

Table 7 suggests an assessment of microbial control applicable to a typical system based on TVC results. The numerical levels should however be adjusted by the water treatment specialist to take account of the specific requirements of the system and also the incubation temperature used for TVC determination. Also, an assessment of microbial control should not be based on a solely on single result or set of results but on the trend of those results.

Table 7: Assessment of microbial control

TVC in circulating water (cfu/ml)	Microbial control
>10 ⁶	Biocide failing to provide protection
10 ⁴ - 10 ⁶	Unsatisfactory biocide control
10 ² - 10 ⁴	Biocide control satisfactory
<10 ²	Excellent biocide control

4.2.2 Selection of biocides

It is much easier and more cost effective to maintain microbiological control within a closed heating and cooling system than to clean up a badly fouled system containing a heavy build-up of biofilm.

Microbiological control of a system is achieved by:

- ensuring that the system remains free of debris and settled solids
- including an appropriate biocide in the pre-commission cleaning process for new systems (or system flush for older systems)
- ensuring that an appropriate biocide is present in the system at the correct concentration following pre-commission cleaning. This can be classed as a maintenance biocide.
- on-going microbiological monitoring of the system.
- shock dosing of an appropriate biocide if levels of bacteria or biofilm become unacceptable.

It is difficult if not impossible to clean up a microbiologically fouled system with only one dose of biocide, as biocides are never 100% effective at killing or dispersing slimes. Where shock dosing of a particular biocide has not proved effective it may be necessary to carry out a laboratory biocide evaluation in order to select an alternative biocide for use in the system.

When selecting a biocide for use in a system, whether as a biocidal flush, maintenance dose biocide or a shock dose biocide, a number of factors need to be considered:

- **Contact time:** This is only appropriate for biocides used during a biocidal flushing procedure. A biocide must be selected that works optimally within the timescale of the actual biocidal flushing process.
- **Concentration:** The biocide supplier will provide recommended dose rates for their products. The system volume needs to be known to ensure accurate dosing of the correct amount of biocide.

- Temperature: Most biocides have an optimum temperature range for use, above which rapid degradation will occur.
- pH: Biocides have an optimum pH range for their use, with an upper limit. More alkaline conditions may cause rapid degradation of the biocide.
- Compatibility with the other chemicals present within the system, particularly the corrosion inhibitors and glycols.
- Broad spectrum of activity against different bacteria or particular effectiveness against target organisms.
- Implications of discharges to the environment
- Cost effectiveness

Although a broad spectrum biocide is ideal for flushing and maintenance dosing, certain biocides are more effective against certain bacteria. If there are specific problems with particular bacteria it is important to choose a biocide and dosing regimen that has been shown to be effective against these. This information can generally be obtained from the company supplying the biocide.

Different dose rates are required for a maintenance dose biocide (to prevent microbiological growth and therefore produce a biostatic effect) and a shock dose biocide (to kill high microbiological numbers present and bring the system under control and therefore produce a biocidal effect). The activity of antimicrobial agents is often quantified as a minimum concentration that is required to inhibit the growth of the target organisms (minimum inhibitory concentration) or as a concentration that leaves no detectable survivors after a specified contact time (minimum bactericidal concentration, generally taken as the minimum concentration required to achieve 99.9 percent reduction in bacteria).

The volume and frequency of biocide applications are dependent on system volume, temperature, pH and biocide half-life under those conditions and will be specific for each site. These parameters need to be considered prior to the implementation of any biocide treatment regime.

The water treatment specialist must be aware of the possibility of the build-up of immunity of organisms to biocides. This may require control agents to be periodically changed even when they might still appear to be effective (see Section 4.2.3).

Low temperature hot water (LTHW) heating systems that run continuously with flow temperatures greater than 60°C should have greatly reduced susceptibility to microbiological growth though all systems have cooler sections and dead legs. Also, many heating systems are switched off during the summer months and provide ideal temperatures for bacteria to grow during these 'down times'. It is recommended that these are dosed with biocides prior to seasonal shut downs in order to prevent growth of bacteria during this time. It is strongly recommended that both heating and cooling systems continue to be circulated (for at least an hour a day) during their off-season to avoid stagnation and provide continuing protection from biocides and inhibitors (see Section 2.2.2).

Biocides can be divided into two main groups: oxidising biocides and non-oxidising biocides.

Oxidising biocides

Commonly used oxidising biocides include chlorine, bromine, chlorine dioxide and hydrogen peroxide. Oxidising biocides kill bacteria but will also react with any organic matter present in the system. Also, at the concentration required for effective antimicrobial activity most oxidising biocides will be corrosive. The use of oxidising biocides in closed heating and cooling systems is therefore not recommended.

Non-oxidising biocides

The following non-oxidising biocides are currently still permitted under the Biocidal Products Regulation (BPR) for use in closed systems:

- Isothiazolinones
- DBNPA
- Bronopol
- Gluteraldehyde
- THPS
- Triazines

Details of the properties and application of these biocides are given in Appendix C.

4.2.3 Microbial resistance

Bacteria can become resistant to biocides. However it is important to note that the term “resistance” is often used loosely and somewhat inaccurately in the context of closed systems. Unlike antibiotic resistance, an increase in the minimum inhibitory concentrations of a biocide does not necessarily mean that a biocide will have no effect. It may simply be that an increased concentration of the biocide is required to achieve a sustained improvement as most of the bacteria in the system are present within the biofilm.

It is also possible that a particular biocide has limited impact in the system due to degradation by high pH or temperature. After the initial dosing and significant kill of bacteria, the biocide will be rapidly depleted to below its effective concentration. Bacteria will then be released into the water from the biofilm resulting in a sharp increase in the measured numbers. In this case a biocide which has better pH and/or temperature stability should be selected.

However, genuine resistance does occur. When a biocide is no longer controlling bacteria at the recommended dose, alternating the treatment with different biocide might help to rid of the system of any resistant or harder to kill strains. The second biocide could be applied as shot dose.

The system dynamics need to be fully understood to decide on the most effective treatment. Options might include a quick acting biocide followed by a more persistent maintenance biocide, a change of biocide or a shorter time between dosing the existing biocide. Generally it is recommended

to carry out a biocide screening test to determine the most effective combination and concentration of biocides.

4.3 SCALE INHIBITION

Calcium scale (limescale) is not usually considered an acute problem in heating and cooling systems with minimal fresh water additions. However, over the lifetime of a system, repeated draining and refilling of a system can result in scale deposition that will significantly reduce heat transfer efficiency, particularly in boilers. Most commercially available corrosion inhibitors therefore contain chemicals for scale control.

In hard water areas, base-exchange softening of the fill water can be beneficial. If this is carried out it is important that the water is not over-softened and the chemical corrosion inhibitors are compatible with softened water. Water softeners should not be left in-situ after filling. This is discussed in Section 2.4.1.

5 NON-CHEMICAL WATER TREATMENT

5.1 FILTRATION

5.1.1 Strainers

All systems are fitted with strainers to protect pumps and control elements. Strainers are intended to capture large debris that might cause blockage or damage for example foreign objects, metal fragments, jointing tape and large corrosion flakes. None of these should be present in a previously cleaned system. Strainers do not retain fine particles of metal oxides, scale and precipitates that contribute to the suspended solids result in a normal system.

The element in an in-line “Y” pattern strainer will be either:

- a perforated screen (available hole sizes 0.8 – 3.2 mm)
- a mesh screen (available hole sizes down to 0.08 mm)

The typical strainer is supplied with a 0.8 mm stainless steel mesh though different sizes can be specified. It is counterproductive to specify a smaller mesh than is actually needed as this will increase the pressure drop and the risk of blockage of the strainer itself if not regularly inspected. A Y pattern strainer is shown in figure 9.

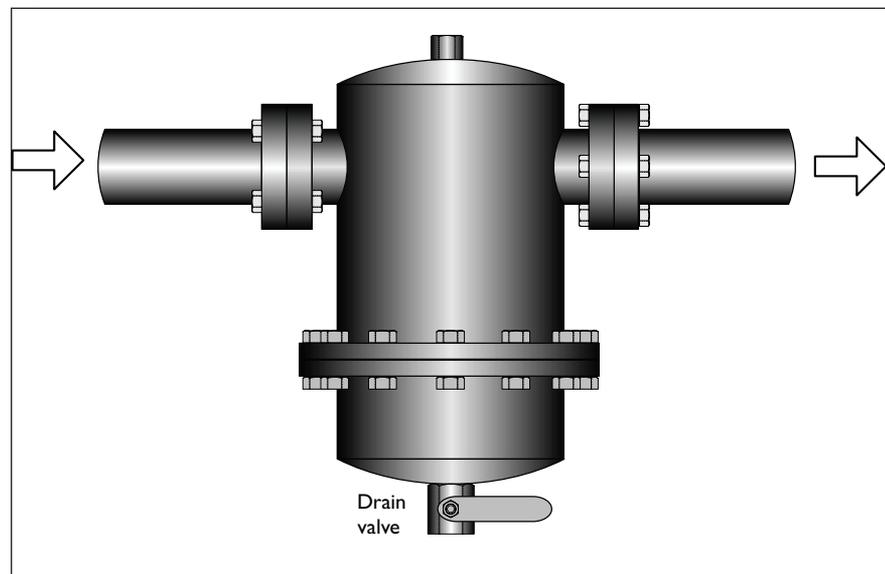
Figure 9: Y pattern strainer



On large pipework systems or where the concentration of large solids is such that frequent cleaning of the filter may be required (e.g. open condenser water systems), duplex basket filters are used. These would not usually be required for routine operation of closed systems but may be employed during flushing activities.

5.1.2 Dirt separators

Dirt separators are essentially in-line pots containing a mesh to create a stagnation region that encourages sedimentation of particles from the system water (Figure 10). The sedimented particles can be periodically drained from the base of the dirt separator, which may be removed for cleaning or mesh replacement.

Figure 10: Dirt separator

Some manufacturers produce devices that combine dirt removal with deaeration (see Section 5.2.1).

5.1.3 Magnetic filtration

Magnetic filters are similar to dirt separators but incorporate permanent magnets to trap ferromagnetic material. They are widely fitted when replacing boilers in domestic heating systems, mainly to protect the new boiler heat exchanger and pump seals from magnetite that has been previously formed in the old boiler and radiators. In principle, magnetic filtration should not be advantageous on a properly maintained system with low suspended solids.

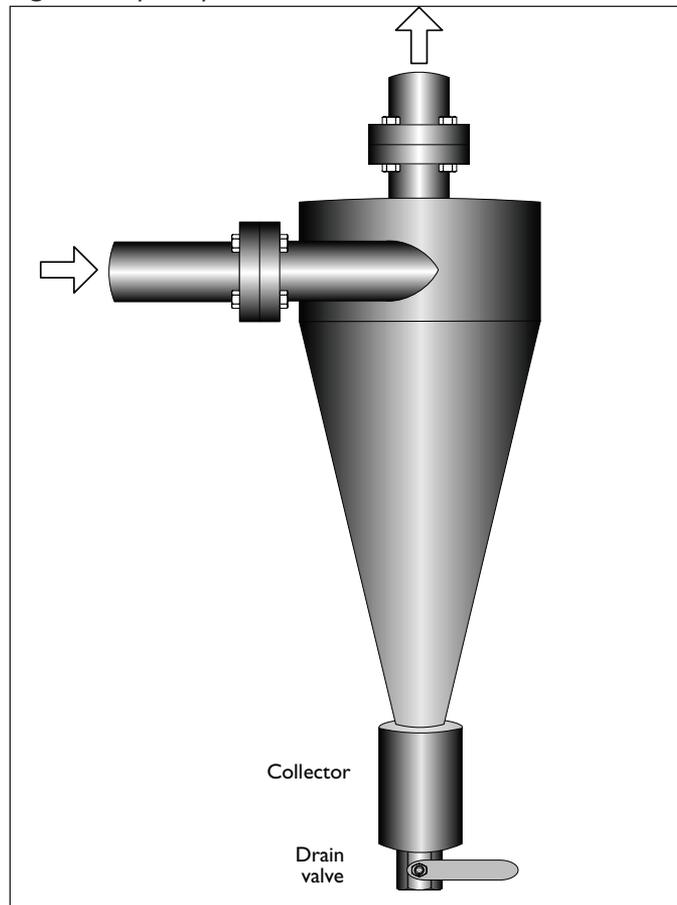
5.1.4 Hydro-cyclones

The principle of the hydro-cyclone is that the centripetal forces generated in a rapidly spinning water column cause particles to move to a region where they can be separated from the main water flow, collected and drained off. The typical form is an inverted cone where the water enters tangentially at the top. Clean water is discharged on the vortex axis at the top, and particles collected via a drain at the bottom (figure 11).

The size range of particles removed by the hydro-cyclone depends on the rotational velocity of the water column and the dimensions of the cyclone. Increasing the efficiency and reducing the minimum size of particles collected will increase the pressure drop and hence the pumping energy absorbed by the cyclone.

Although cyclones could be sized for the total system flow (particularly in flushing applications), they are most often installed as side stream devices, usually with a separate pump. Although not as effective as media filters, there is no cost of consumables apart from the energy requirement associated with the pumping.

Figure 11: hydro-cyclone



5.1.5 Disposable media filters

These are typically cartridge or bag filters, usually installed as a side stream across the system circulating pump, accepting flow from the line on the pressure (downstream) side of the pump and returning to the suction (upstream) side of the pump. These filters remove mobile particles down to 5 μm or less.

Side stream units are normally sized such that the whole water system volume passes through the filter at least once over a 24 hour period. As they are on a side-stream, clogging up the filter does not cause back-pressure problems on the main system. Cartridge filters are periodically removed and replaced with a new cartridge, the need for replacement being determined by pressure drop or visual inspection.

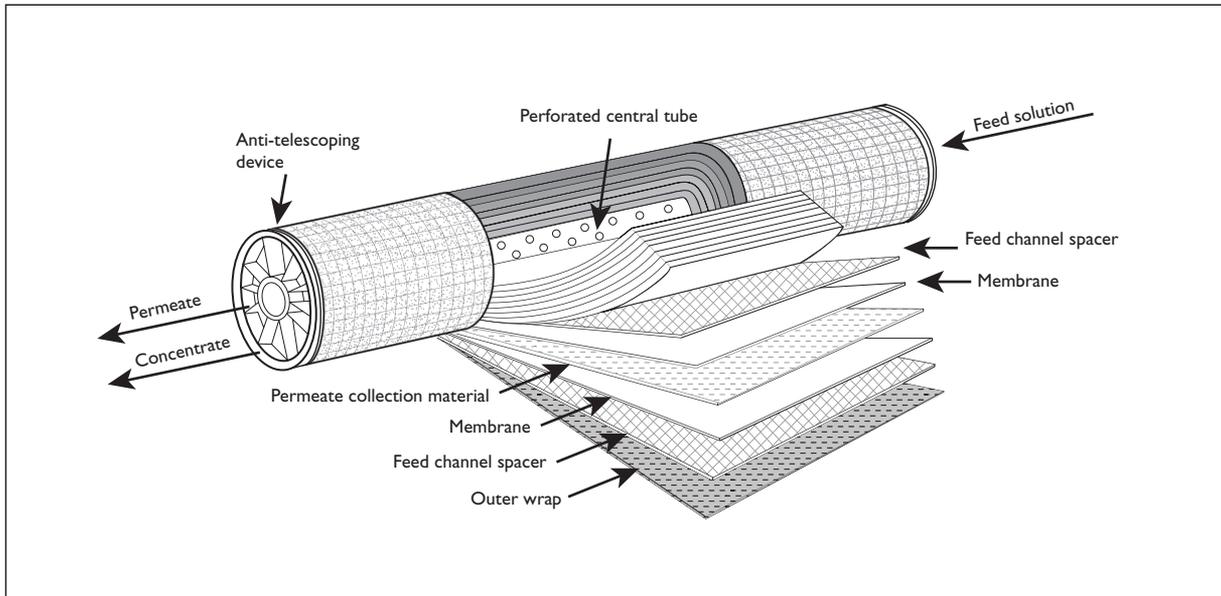
The pore size of the filter media can be varied and reduced over time to “polish” the system water.

5.1.6 Reverse osmosis

Reverse osmosis is a form of pressure driven filtration through micro-porous membranes. It can be used to improve the quality of mains water and borehole water supplies. It is not applicable to water already within the heating or cooling system. Different types of membrane can be used for the rejection of microscopic dirt particles and bacteria or for softening i.e. the rejection of scale forming species (see figure 12).

One difference between reverse osmosis and conventional filtration is that the rejected species are continuously carried away to waste, the wastewater flow being up to 20% of the input flow. Therefore the systems are relatively low maintenance, though the removal of chlorine and addition of small amounts of chemicals to reduce scale formation may be required to prolong the life of the membrane.

Figure 12: Reverse osmosis spiral-wound membrane element



The sole application of reverse osmosis for closed systems is the pre-treatment of fill water, particularly to provide a physical barrier against the ingress of bacteria.

5.2 DEAERATION

Cold tap water used to fill systems is often more than 95% saturated with dissolved gases including oxygen. The equilibrium concentration of oxygen depends on temperature, pressure and other dissolved components in the water but could be as high as 10 mg/l. In order to manage the corrosion risk, the oxygen concentration should ideally be reduced to less than 1 mg/l, and as quickly as possible.

The solubility of oxygen in water decreases with increasing temperature so normal operation of a heating system will start to reduce the oxygen concentration compared to the fill water. Passive deaerators speed up the process of reaching an equilibrium concentration of oxygen at the maximum temperature to which the water is heated. Note that the maximum temperature reached at the surface of a boiler heat exchanger will generally be higher than the system flow temperature.

Once the system has achieved an equilibrium concentration of oxygen by thermal evolution of dissolved air then further reduction in the oxygen concentration is achieved mainly through chemical reaction with metal surfaces i.e. corrosion processes.

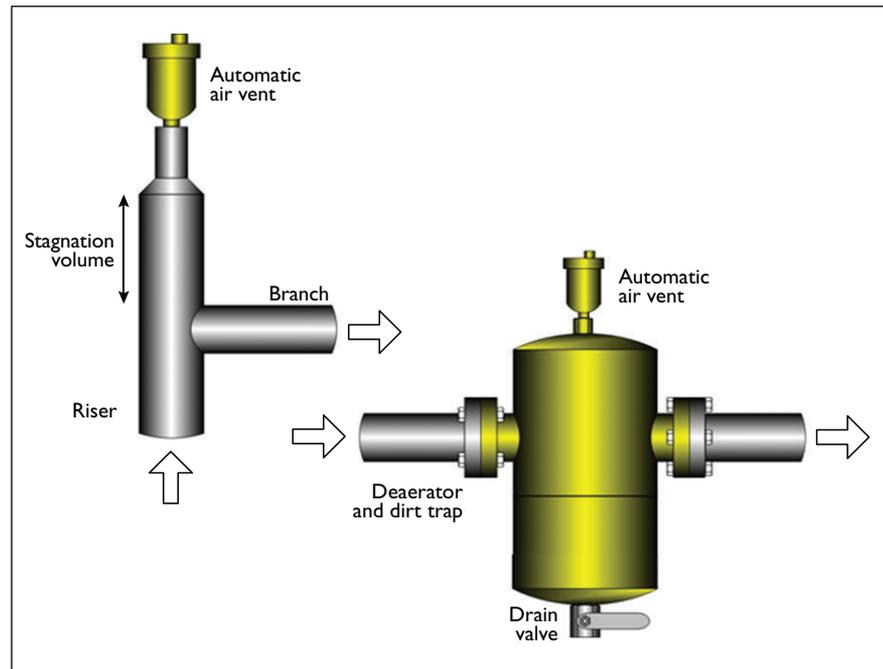
Chilled water systems may never see a temperature higher than the ambient in the building, so the dissolved oxygen can only be removed by corrosion, microbiological processes, chemical oxygen scavengers (rarely used) or the application of technologies such as vacuum deaeration. Vacuum deaeration can also be used for heating system water. This and other possibilities are described below.

5.2.1 Passive deaeration

All systems should be fitted with manual and/or automatic air vents at the top of risers and at high points where air (and other gases generated in the system) will naturally collect when released from solution.

Passive deaerators encourage the release of air from solution by providing a matrix that stimulates the formation of small bubbles, particularly after a temperature or pressure change. Those bubbles then coalesce and can be vented. Unlike normal vents, the system flow goes through the deaerator. The deaerator can also include a dirt collection (sedimentation) function. This is illustrated in figure 13.

Figure 13: Air vent and combined deaerator with dirt trap



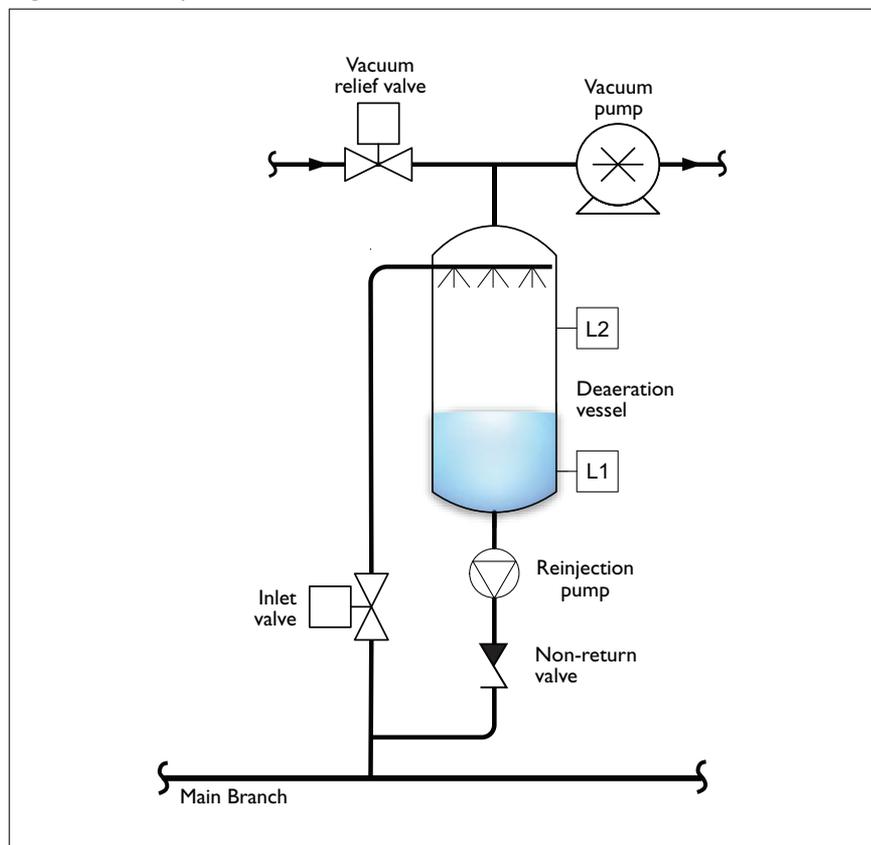
5.2.2 Vacuum deaeration

Vacuum deaeration (also known as vacuum degassing) is the process of exposing the system water (usually automatically in batches) to greatly reduced pressure to encourage deaeration. Figure 14 shows the principle of a batch deaerator where water is sprayed into a deaeration cylinder under partial vacuum. This causes dissolved gases to be released from the water and expelled through the vacuum pump. When the deaerated water reaches level L2, the vacuum is then released and the deaerated water pumped back into the system to complete the cycle. Since the pressure reduction is created by the deaerator vacuum pump rather than system water flow, the unit can be located at any convenient point in the system. An additional expansion vessel may be installed to compensate

for the volume of water temporarily removed from the system during the deaeration cycle.

Vacuum deaeration is sometimes integrated with the system pressurisation set so that fill water goes through the deaeration cycle before it enters the system and a single pump can be used for pressurisation and reinjection. However, many vacuum deaerators are installed on a temporary standalone basis, to provide rapid reduction of the oxygen concentration during construction and commissioning of the system, and then removed.

Figure I4: Principle of vacuum deaerator



5.2.3 Anodic oxygen removal

In passive anodic oxygen removal, system water is circulated at low velocity through a vessel containing a highly reactive anode material (such as magnesium or zinc) so that dissolved oxygen can be consumed by electrolytic action between this and a cathodic material.

In active anodic oxygen removal, otherwise known as the ‘impressed current method’, oxygen is removed by imposing a direct current on the anode. The current, and hence the rate of oxygen removal, is controlled in proportion to the concentration of dissolved oxygen measured by a suitable detector located downstream of the reaction vessel.

In both these methods, the oxygen reacts with the anode, initially to form hydroxyl ions which tend to elevate the pH of the system water. Also, subsequent reactions of the metal ions may result in increased suspended solids and scale.

5.3 SACRIFICIAL ANODES

The use of sacrificial anodes is an extension of cathodic protection measures, whereby a vulnerable structure is coupled with a more active metal, such as zinc or magnesium and occasionally aluminium. A galvanic cell is produced in which the active metal becomes the anode and provides a flux of electrons to this structure. The structure then becomes the cathode, and is protected, while the anode is gradually destroyed, hence the term sacrificial anode.

The most common applications of sacrificial anodes in building services are tap water storage tanks, direct fired water heaters and stainless steel hot water cylinders, particularly in areas of extremely hard water where the oxygen and conductivity levels are high.

Sacrificial anodes are rarely used within closed systems. The principle can however be adopted where lengths of pipework are to be protected from external corrosion. Due to the low open circuit potential differences between steel and for example a magnesium strip, one anode can only protect a limited length of pipe line. However, this low potential difference (voltage) can be preferable to a higher impressed voltage as the danger of over-protecting some portions of the installation is less.

Sacrificial anodes require regular replacement and must be included in the planned maintenance regime. It should also be borne in mind that excessive or inappropriate cathodic protection can in fact accelerate corrosion processes.

5.4 OTHER NON-CHEMICAL TREATMENTS

Closed heating and cooling systems are predominantly treated with chemical inhibitors and biocides. However, in recent years a number of well-authenticated non-chemical methods of scale inhibition, corrosion inhibition and bacterial inhibition have been reported, mainly in cooling towers, but also occasionally in closed systems.

The authors of this text would strongly advise the owner/operator of any system considering using a non-chemical system to seek the following evidence before relying on innovative solutions:

- Proof of current usage:
 - Is there authentic case study data relevant to closed systems?
 - Are there references from users, independent of the supplier?
 - Are site visits to existing installations possible?
 - Is the supplier open about installations that may not have performed to expectations and the reasons why?
- Effect of installation of the proposed unit on the existing treatment:
 - If the unit purports only to control bacteria is it compatible with the current corrosion inhibitor programme?
- Measures that will need to be put in place before installation for comparative performance evaluations including:
 - Corrosion rate (various metals)
 - Total bacterial counts
 - Biofilm monitoring

The following text describes some approaches that have been tried:

Magnetic water treatment: Magnetic water treatment has been promoted since the 1930's. The main application is to inhibit scale deposition in domestic water systems. This is not relevant to closed systems. Magnetic filters may be relevant to closed systems as discussed in Section 5.1.3.

Electrostatic water treatment: These units generate a strong electric field in a flow-through cell. This is claimed to disrupt bacteria growth as well as reducing scale formation. The units are principally marketed for cooling tower applications.

pH management units: These consist of vessels packed with reactive mineral media, usually a blend of calcite and dolomite (calcium and magnesium carbonates). The circulating water is passed through the unit on a side stream basis. These units are claimed to be 'self-regulating' in that while the initially-produced effluent from the bed is increased in hardness, alkalinity and pH, this 'surplus' hardness is precipitated in the form of a fine suspension which is then filtered out by re-passage through the media. The claimed result is to produce water that is "naturally balanced" having low hardness and high pH, which is non-scaling and non-corrosive.

Hydrodynamic cavitation: This is a heavily engineered system that circulates a proportion of the system water through a 'cavitation chamber'. This imposes stresses on the water such that when it is super-saturated with calcium bicarbonate, partial decomposition occurs and calcium carbonate is precipitated (in the form of amorphous 'aragonite') with the liberation of carbon dioxide. The precipitated calcium carbonate is continuously removed via a downstream filtration system.

In addition to the shock-precipitation of calcium carbonate, the stresses in the cavitation chamber also destroy bacteria (including legionellae). A number of these systems are in use in the USA and Europe (including the UK). Most are in evaporative cooling tower systems, although there are reports of successful usage for bacterial control in closed systems.

Ultraviolet irradiation: Ultraviolet (UV) irradiation is undoubtedly effective in disinfecting tap water and therefore useful in removing bacteria from fill water. It is seldom used for treating water already inside closed systems due to attenuation by suspended solids and other constituents of the water including dissolved iron and inhibitors. Also, UV only kills bacteria at the point of exposure. There is no residual effect in the water so the biofilm in the rest of the system is unaffected.

Catalysed UV: A relatively recent entry to the water-treatment market (for bacterial inhibition) has been the combination of UV with titanium dioxide. Irradiation of a titanium dioxide coated surface by UV light of a specific wavelength stimulates the production of hydroxyl radicals which are effective against a range of bacteria, fungi etc. This is more effective than UV alone and is claimed to prevent the build-up of biofilms in circulating systems. The technology is currently confined to the treatment

of fill-waters and cooling towers but may have a future role in closed systems.

Ultrasonic cavitation: These units generate high frequency ultrasonic waves in a side stream treatment chamber, creating shear stresses that are lethal to bacteria. The units are principally marketed for cooling tower applications but may be used in other recirculating water applications. Although ultrasonic treatment operates principally within the treatment chamber, it is claimed that the interference with microbial populations has an indirect effect on biofilm.

Pulsed power units: These units consist of a solenoid coil around a reaction chamber through which this system water is passed on a side-stream basis. The water passing through the chamber receives a series of high frequency electric pulses and a varying DC field. The units are claimed to control scale formation by the controlled precipitation of calcium carbonate in the amorphous (aragonite) form. They are also claimed to inhibit bacteria by a process termed 'electroporation' where the high frequency pulsing action damages the membranes of planktonic bacteria. The units are principally marketed for cooling tower applications.

6 MANAGEMENT OF THE WATER TREATMENT PROGRAMME

6.1 OVERVIEW

6.1.1 Roles and responsibilities

It is essential that any water treatment programme is implemented within a clear and documented framework of roles and responsibilities. In many cases, corrosion failures in the early life of a closed heating or cooling system have been traced back to management failures, particularly in the period between pre-commission cleaning and handover. This period is now addressed by specific guidance in BG 29^[1]. However, loss of control at any stage in the life of the system can rapidly lead to failures.

There are four main actors associated with the water treatment programme:

- Client: the organisation that commissions the cleaning or water treatment activity
- Cleaning specialist: a person or organisation appointed to carry out pre-commission cleaning or remedial cleaning of a pipework system and related activities
- Water treatment specialist: a person or organisation appointed to maintain the water quality and manage the corrosion, scaling, sedimentation & biofouling risk within a pipework system; and to supply the water treatment products.
- System operators: Staff who control the system on a daily basis and who may be responsible for interim monitoring tasks and in some cases interim dosing of chemicals.

6.1.2 Objectives of monitoring

It is essential that regular monitoring is carried out to evaluate the effectiveness of the water treatment programme. That may include sampling and analysis of system water, direct monitoring of corrosion rates and inspection of corrosion coupons. It should not be assumed that because a treatment programme has performed satisfactorily in one application it will be equally successful in another. All systems are different both in design and operational history.

The objective of monitoring a closed heating or cooling system is to provide information about the current condition of that system and/or the water within it.

Monitoring should be carried out using appropriate methodologies and equipment to ensure that the results obtained are accurate, meaningful and comparable. Samples should be taken at a sufficient number of representative locations to provide an overall view of the system condition and to allow for assessment of the significance of the results.

Water analysis alone cannot give the full picture of the condition of the system and, since it is only done periodically, rarely picks up sudden changes in the system condition e.g. the loss of inhibitor due to unscheduled drain-down or leakage. However, there are opportunities for the continuous monitoring of certain system parameters as explained in Section 6.6.4.

6.1.3 Frequency of sampling

Sampling and analysis of system water is an essential part of a treatment regime and should include both the circulating water and fill/make up water supplied to the system. Sampling and analysis may be carried out, at various times, by the cleaning specialist, water treatment specialist or system operators, provided they have been trained to do so.

The programme of monitoring appropriate to each system should be defined, documented and implemented by the water treatment specialist. The frequency and extent of this routine monitoring will depend on the operating characteristics, susceptibility to disturbance, and operational importance of the system and may vary through the life of the building.

The typical frequency of routine monitoring for heating and cooling systems in non-domestic buildings in mid-life is one to three months. More frequent monitoring may be desirable during the first 6 months of operation of a new system and immediately after any significant system changes such as replacement or addition of plant or terminal units.

Detailed guidance is provided in BS 8552^[6].

6.2 WATER SAMPLING AND ANALYSIS

Sampling and analysis of the water circulating through the main plant is the primary method of assessing the efficacy of the water treatment programme i.e. control of scale, suspended solids, corrosion and biofouling. Other methods such as corrosion and biofouling coupons may be used in a supporting role. Sampling, analysis, interpretation of results and the recommendation of corrective actions should be carried out by persons with suitable training, competence and experience.

BS 8552^[6] recommends that additional samples are taken from remote locations in the building to help demonstrate that the water treatment regime is effective throughout the system. The number of such samples depends on the volume and complexity of the system.

If these remote location samples are taken from low flow areas including terminal units then they may contain higher concentrations of solids and bacteria than at the main plant. This effect should be considered in the interpretation of results. Where the results are deemed unacceptable then further investigation and specific remedial actions may be required for example remedial flushing or operational changes.

Routine monitoring can be carried out utilising site test kits. These are available for determination of most chemical and microbiological parameters of importance to water treatment. The benefit of test kits for routine monitoring of chemical parameters is that they provide rapid on the spot results that can be acted upon without the delays associated with analysis by external laboratories. However it is essential that the selected test kit provides a suitable range and accuracy for the analysis and the operator is aware of the limitations of the test method including possible interferences.

6.3 SAMPLING FOR WATER CHEMISTRY

If the cleaning or water treatment specialist employed is not the product supplier they should consult with the product supplier as to which analyses are to be used to quantify the levels of active inhibitors in the system and control limits to be maintained. These should be clearly documented in the site/system water treatment logbook.

All results should be recorded in the site/system water treatment log book. Where results exceed action limits then predefined remedial actions should be carried out and recorded or the matter reported to the responsible person for action.

The detailed scope of sampling and analysis should be defined and documented by the water treatment specialist in the sampling and analysis plan. This scope should include key components of the water treatment programme and various indicators of water quality (see Section 6.5).

Detailed guidance on sampling, sample handling and reference analytical methods is given in BS 8552^[6], but an overview is given below.

6.3.1 Sample bottles

Where the sample is destined for laboratory analysis it is preferable to use single use sample bottles provided by the laboratory. This will ensure that the correct bottle is used and sufficient volume is available for the proposed analysis.

Where the sample is destined for immediate on-site analysis then a clean high density polyethylene bottle with a wide neck is suitable for collecting the sample prior to chemical analyses.

6.3.2 Sample labelling and paperwork

All sample bottles should be suitably labelled using an adhesive label or permanent marker. The information provided should, as a minimum, allow the sample to be clearly identified, state the analysis required and allow the sample to be referenced to the sampling worksheet (sometimes referred to as the chain of custody form).

Where the sample is destined for laboratory analysis, pre-numbered labels and a corresponding chain of custody form can be supplied by the laboratory. The level of information provided with the sample should, as a minimum, unambiguously identify the precise origin of the sample, the condition of the sample when taken and the required analysis.

The information required on the chain of custody form should include:

- Date and time of sampling
- Client/site address
- Origin of the sample (system and sample point)
- Type of water being sampled (chilled, heating, condenser water etc.)
- Identity (name & organisation) of the sampler
- Analysis required

When the sample arrives at the laboratory the chain of custody form should be signed by the person receiving the sample, with time and date. The laboratory will allocate a unique reference number to the sample (if not already printed on the label) that will allow it to be tracked during analysis and reporting.

BS 8552^[6] suggests additional information to be recorded including:

- Nominal water treatment package (nominal concentrations of inhibitors, biocide, anti-freeze etc.)
- Temperature
- Visual appearance (clarity, colour, presence of settled solids)
- Odour (ammoniacal, sulfide etc.)
- Storage conditions (whether refrigerated)
- Other observations (anything unusual about the sample or the way it was collected)

The same information should be recorded for samples analysed on site.

6.3.3 Sample collection

Not all potential sampling points are suitable for all analyses, particularly for settled or suspended solids.

Table 8 summarises which sample points are suitable for different samples.

Table 8: Selection of sampling points (from BS 8552^[6])

Type of sample	Sampling Point		
	Full bore drain point	Reduced bore drain point	Pressure test point
Settled solids	Yes	No	No
Suspended solids & "total" metals	Yes	Yes	No
Dissolved solids	Yes	Yes	Yes
Microbiology	Yes	Yes	Yes
Dissolved oxygen	No	See BS 8552, A.2	See BS 8552, A.2

6.3.4 Storage and transportation

Samples should be stored and transported generally in accordance with BS EN ISO 5667-3^[13].

Samples should be analysed as soon as possible. Samples for laboratory analysis should arrive such that analysis can be commenced within 24 hours of the sample being taken. The impact of the time between sampling and analysis should be minimised by:

- filling sample containers to the brim;
- storing samples in the dark; and
- refrigerating samples to between 2°C and 8°C, except where otherwise indicated in the analytical method.

It is sometimes argued that samples for chemical analysis do not need to be refrigerated and there are pros and cons to doing so. Refrigeration will reduce the activity of certain bacteria that might influence the chemistry (particularly nitrite concentrations) but it may also increase the rate of precipitation of dissolved solids from solution.

6.4 SAMPLING FOR MICROBIOLOGY

Sampling is an important part of the analytical process and the manner in which the sample is collected and subsequently stored and transported prior to analysis can greatly affect the final results. Results from poorly handled samples can then be misleading and result in inappropriate actions or treatments being undertaken.

A sample should be representative of the water within a system. Ideally the water will be exactly the same when it is tested in the laboratory as when it was in the system. In reality the sample will start to change as soon as it is put in a sample bottle. In order to minimise these changes the sample should be collected, stored and transported in an appropriate manner. Detailed guidance on sampling, sample handling and reference analytical methods is given in BS 8552^[6], but an overview is given below.

6.4.1 Sample bottles

Sample bottles for microbiological analysis should be made of plastic or glass, pre-sterilised and free from any toxic substances. Where the sample is destined for laboratory analysis it is preferable to use single-use sample bottles provided by the laboratory. This will ensure that the correct bottle is used, the required preservative is present and sufficient volume is available for the proposed analysis

Sample bottles provided by laboratories are usually pre-loaded with a small quantity of sodium thiosulfate solution, equivalent to a final concentration of approximately 18 mg/l in the full bottle. Sodium thiosulfate neutralises any residual oxidising biocide that may be present in the sample as that could change the result. Pre-loaded bottles should only be used for the microbiological sampling. If the bottle is damaged in any way, or the seal is broken, the bottle should not be used.

Ideally a separate bottle (which should be clean but not necessarily sterile) should be used for chemical analysis (see Section 6.3). If there is no sodium thiosulfate in the microbiological sample bottle and there is sufficient sample, both the microbiological and chemical analysis may be undertaken from that bottle. However in this situation, the microbiological analysis must be undertaken first in order to minimise the risk of contaminating the sample. Conversely microbiological analysis should NOT be undertaken from a chemical sample bottle as it may not have been sterile before use.

6.4.2 Sample labelling and paperwork

Refer to section 6.3.2.

6.4.3 Sample collection

Samples of system water for microbiological analysis can be taken from dedicated sampling points, drain valves or binder points. BS 8552^[6] provides guidance on the selection of sampling points for other samples (refer to Table 8).

The following procedure should be used for drain valves:

1. Disinfect the sampling point prior to taking the microbiological sample by spraying with propan-2-ol (minimum 70% solution). This should be allowed to evaporate before the sample is taken. If a binder point is used, the binder probe should be sterilised internally and externally before use. Samples should not be taken through a hose or non-sterile conduit.
2. Fully open the sample valve, discharge sufficient volume of water to flush the dead leg into a waste container (for disposal) and close the sample valve.
3. Re-open the sample valve and discharge the required volume of water slowly into the sample bottle. The sample bottle should be held in one hand and the cap removed and held in the other – do not put the cap down and take care not to touch the neck of the bottle with fingers. The bottle should be inserted into a steady flow of water from the outlet, without touching the neck of the bottle sample point. The bottle should be filled but not overflowed.

If using a binder point and tube, the needle and tube should be disinfected before use by flushing the inside, and swabbing the outside, with propan-2-ol solution. There is not usually any system dead leg but the binder probe should be inserted and the sample tube briefly flushed to remove any residual disinfectant before collecting the sample as described above in step 3.

Note: It has been common practice when taking water samples for microbiological analysis from open systems to leave a small airspace in the sample bottle. However, given that the sample is being extracted from a low oxygen environment in a closed system, BS 8558^[7] states that the sample bottle should be filled to the brim. This is to avoid increasing the dissolved oxygen concentration during handling and is consistent with BS EN ISO 5667-3^[13].

The chemical samples bottles should be filled in the same way.

When taking both chemical and microbiological samples from the same sample point, the microbiological sample should be taken first.

6.4.4 Storage and transportation

Samples should be stored and transported generally in accordance with BS EN ISO 5667-3^[13].

Samples should be analysed as soon as possible. Samples for laboratory analysis should arrive such that the analysis can be commenced within

24 hours of the sample being taken. The impact of the time between sampling and analysis should be minimized by:

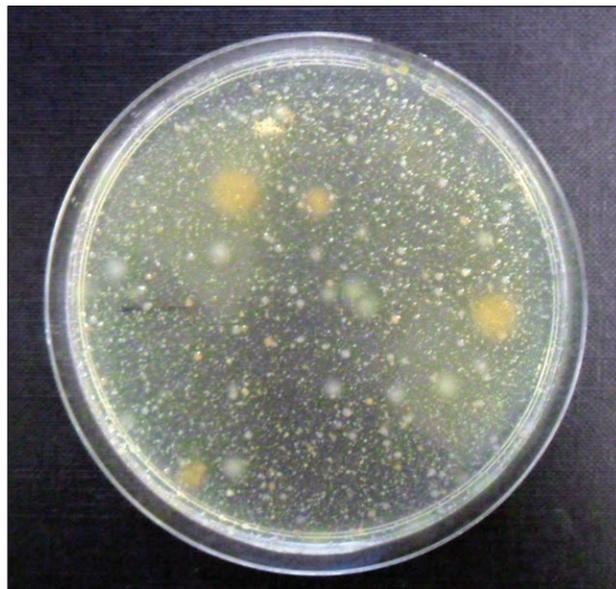
1. Filling sample containers to the brim (as described in Section 6.4.3)
2. Refrigerating samples to between 2°C and 8°C (except where otherwise indicated in the analytical method). Cool boxes with ice packs can be used for transportation.
3. Storing samples in the dark

6.4.5 Laboratory analysis

The majority of methods used for the analysis of water from closed systems are based on, but not necessarily identical to, those used for the analysis of bacteria in drinking waters. These include quantitative methods that give an estimate of bacteria numbers and semi – quantitative methods that give an indication of bacteria numbers. The analysis may be designed to encourage growth of the general population of bacteria (e.g. total viable count) or to highlight specific bacteria, either by using a selective growth media or by causing the bacteria of interest to stand out from the other bacteria in some way (e.g. colour changes).

In order to obtain a bacterial plate count the organisms are grown on a suitable medium until the colonies formed reach a size that can be counted (see figure 15).

Figure 15: Plate count



There are several reasons why the final result will always be an estimate:

1. The sample may not be representative of the number of planktonic bacteria in the system. Occasionally a fragment of biofilm containing hundreds of bacteria will end up in the sample and may distort the result.
2. The number of bacteria in the sample could increase or decrease during transportation and while waiting for the analysis to begin, depending on how the sample is handled.

3. Growth media do not provide 100% recovery of bacteria in the sample – it could be as low as 60%. However, this effect should be consistent between samples.
4. It is assumed that one colony comes from one bacterium but because bacteria sometimes clump together, a single visible colony may in fact be derived from a number of individual bacteria. The result is therefore expressed as a colony forming unit per standard volume rather than a definitive number of bacteria.

Table 9 lists the main microbiological tests and the time required to obtain a result. These tests are further explained in the following sections.

Table 9: Comparison of the main microbiological tests

Test	Time to result	Results
Pseudomonads	2 days (plus 2 further days if identification is required)	cfu/100ml
Total viable count	3 days	cfu/ml
Nitrite reducing bacteria	5 days	Presence/absence
Semi-quantitative sulfate reducing bacteria	6 days (or 21 day reference method)	Presence/absence
Quantitative SRB	1 day	cfu/ml

6.4.6 Pseudomonads

Pseudomonads are “pseudomonas-like” bacteria. At present there is no standard method specifically for the analysis of pseudomonads in closed systems. BS 8552^[6] states that a suitable reference method is BS EN ISO 13720^[14], using a pseudomonas selective agar base with CFC selective supplement for “pseudomonas species”. The incubation period is 48 hours at a temperature of 30°C.

In practice most laboratories will use an adapted drinking water method with a proprietary selective agar. The principle of this method is for 1 ml of sample to be filtered through a membrane filter with a pore size of 0.45 µm. The pore size of the filter membrane is small enough to trap all the bacteria from the sample on its surface. The drinking water method requires 100 ml to be filtered but closed systems often have much higher numbers of pseudomonads so there may be too many bacteria to count if 100 ml is used.

The membrane and attached bacteria is then transferred to a selective media designed to encourage the growth of the pseudomonads and inhibit the growth of other bacteria that are not of interest. The membrane and media are then incubated at 30°C for 48 hours

After incubation the membrane is examined for blue-green, greenish-brown, yellow-green or colourless colonies, or colonies which exhibit fluorescence under exposure to ultraviolet light. Any such colonies are counted and recorded. These colonies are considered to be “pseudomonas

species” or pseudomonads. On occasion the analysis may be taken a step further to allow for the identification of the predominant bacteria types.

Note that the results are usually expressed as cfu per 100 ml for consistency with guidelines in BG 29^[1]. Results provided “per ml” should therefore be multiplied by 100 for comparison with guidelines.

6.4.7 Total viable count (TVC)

This analysis is considered to provide an indication of overall water quality with respect to bacteria. However it is recognised that this method will measure only a proportion of the bacteria present as only aerobic bacteria that grow on the nutrient media and at the incubation temperature of the method will be recorded. The TVC result is nevertheless useful for monitoring the trend in water quality, particularly to identify loss of control of bacteria.

BS 8552^[6] states that a suitable reference method is BS EN ISO 6222^[12] (see also BS EN ISO 19458^[15]).

For the laboratory analysis, 1 ml of sample is spread on the surface of a nutrient rich media. Alternatively a 1 ml volume of sample is added to a Petri dish and mixed with molten nutrient rich media and the media allowed to set.

The next step is to incubate the plate for the specified incubation temperature and time: 22°C for 72 hours, 30°C for 72 hours or 37°C for 48 hours depending on the application and objectives of the analysis. Following incubation, the plates are counted and the result expressed as cfu/ml.

Note that since the result of the TVC test is sensitive to the incubation temperature, results obtained at different incubation temperatures cannot be directly compared or included in the same trend analysis.

TVC results can also be obtained using test kits, in which case the manufacturer’s instructions should be followed. Note that the results from laboratory analysis and test kits are likely to differ (though they should be self-consistent) and should not be combined for the purpose of assessing trends.

6.4.8 Nitrate/Nitrite reducing bacteria (NRB)

The usual method for determination of NRB is a semi-quantitative proprietary test kit. For one such test, 2 ml of sample is added to a tube of indicator media. This is then incubated at 30°C for five days, with the tube being examined every day and any changes recorded.

If NRB are present the media turns pink and bubbles of ammonia gas are produced. The time it takes for these reactions to take place gives an indication of the number of bacteria present. A positive reaction after 1 day of incubation indicates heavy contamination ($> 10^6$ cfu/ml) and a positive reaction after 5 days indicates low level contamination (10 – 100 cfu/ml). However, for practical purposes this should probably be considered as a presence/absence test.

The shortcoming of this method is that the generation of the pink colour is due to an increase in the alkalinity of the media due to the production of ammonia by the NRB. If the sample is alkaline in the first place, the media will change to pink regardless of the presence of NRB. Conversely if the sample is acidic the media will turn yellow, and even if NRB are present they may not be able to generate enough ammonia to change the colour of the indicator and therefore a false negative result may be reported.

There are also dip slide versions of this test.

6.4.9 Sulfate reducing bacteria (SRB)

BS 8552^[6] recommends the 21 day SRB test for reference purposes but shorter tests may provide sufficient confidence for routine management of the water system provided sufficient numbers of samples are collected and analysed (see BS 8552^[6] Annex C).

Test kit methods rely on the fact that SRB reduce sulfates to produce hydrogen sulfide gas, which in turn results in a blackening of the culture media.

In the first method, 2 ml of sample is added to the surface of the indicator gel in a tube. The tube is then incubated at 30°C for five days and checked daily for a blackening of the media. If a black line appears on the surface it indicates a positive reaction. The number of bacteria present is then estimated by how quickly the blackening moves down the tube. For example if 100% of the tube is black within 2 days there are >100,000 cfu/ml, but if there is only 20% blackening after 6 days there are approximately 100 cfu/ml.

The second method is a quantitative method based on that developed for drinking water analysis. A volume of the sample (100 ml) is filtered through a membrane filter with a pore size of 0.45 µm. The pore size of the membrane is small enough to trap all the bacteria from the sample on its surface. The membrane is then transferred, face-upwards to a selective nutrient medium and incubated for 24 hours at 37°C under anaerobic (without oxygen) conditions. Each viable organism responsive to the media should multiply to give a visible colony.

Colonies of sulfate reducing clostridia are recognised by specific growth characteristics and interaction with the selective media. Black colonies are counted and recorded as sulfate reducing bacteria.

Caution needs to be applied to the interpretation of results because of the specificity of growth media to SRB species. For example, in many affected systems the predominant SRB is *Desulfovibrio desulfuricans* rather than *Clostridium* and this may respond differently in different tests. A study of SRB methods and confidence limits based on experimental data is discussed in BS 8552^[6] Annex C.

6.4.10 Other microorganisms

Usually only the organisms mentioned in Table 10 are included the routine analysis of closed systems. However, there are numerous other species of bacteria and fungi that can be found within closed heating and cooling systems. Where a system has a particular problem or routine control measures appear not to be working, additional analysis may be required, especially a check for the presence of fungi in cooling systems. Under certain conditions fungi can proliferate and severely affect the efficiency of the system.

6.5 WATER QUALITY ANALYSIS AND GUIDELINES

The possible range of analysis likely to be carried out on site on samples from closed systems together with guideline control limits, where applicable, are detailed in Table 10 below. Notes are provided below the table. The essential analysis and specific control limits for the system and water treatment programme in use must be specified by the water treatment specialist.

Table 10: Comparison of the main microbiological tests

Group	Parameter	Guideline	Note
Physical condition	Visual appearance (suspended/settled solids)	Clear with no visible suspended solids or gassing	1
	Odour	No strong sulphurous or ammoniacal smell	2
	pH	Within specified range	3
	Conductivity and total dissolved solids (TDS)	Within specified range	4
	Suspended solids	Limit as specified for the circulating water. No increasing trend	5
	Settled solids (as defined in BG 29 ^[1] & BS 8552 ^[6])	Limits as specified for pipework at the extremes of the systems and for terminal units	6
Water treatment status	Nitrite (where used)	Within specified range	7
	Nitrate	Within specified range	8
	Molybdate (where used)	Within specified range	9
	Boron	Within specified range	10
	Phosphonate	Within specified range	11
	Organic inhibitors	See note	12
	Silicate	Within specified range	13
	Orthophosphate	Within specified range	14
Hardness	Total alkalinity	For information	15
	Calcium hardness	For information	16
	Total hardness	For information	17

Cont...

Table 10 cont: Comparison of the main microbiological tests

Group	Parameter	Guideline	Note
Corrosion products	Total iron	Limit as specified	18
	Dissolved iron	Limit as specified	19
	Copper	Limit as specified No increasing trend	20
	Zinc	Limit as specified No increasing trend	21
	Aluminium	Limit as specified No increasing trend	22
Other	Sulfate	>90% of fill water sulfate No decreasing trend	23
	Chloride	Limit as specified	24
	Ammonia	Limit as specified	25
	Dissolved oxygen	For information	26
Microbiology	Total viable count (TVC)	Limit as specified No increasing trend	27
	Pseudomonads	Limit as specified No increasing trend	28
	Sulfate reducing bacteria (SRB)	Not detected	29
	Nitrite reducing bacteria (NRB)	For information	30

Notes to Table 10:

- Visual appearance. This is the simplest test but also the most subjective and difficult to report consistently. Some practitioners recommend that the sample should be photographed routinely or if there is anything at all unusual. It is also possible that the sample can significantly change between sampling and arrival at the laboratory e.g. due to precipitation of dissolved iron on exposure to atmospheric oxygen. Cloudiness that clears quickly on standing is probably due to dissolved gases such as air, nitrogen or carbon dioxide released when the sample is depressurised and the reasons for this should be investigated.*
- Odour. A strong foul or sulfide smell is suggestive of stagnant anaerobic conditions and significant SRB activity. This should not be present in a normal system. A strong ammoniacal smell is suggestive of NRB activity though a slight ammoniacal odour can also be associated with some water treatment chemicals. The microbiological status can be checked with the relevant bacteria test.*
- pH. All closed system water treatment is intended to produce neutral to alkaline conditions i.e. above pH 7. The maximum allowable pH is dependent on the materials present e.g. up to pH 8.5 for systems containing aluminium but up to pH 11 for all steel systems. The pH will usually decline if there is a loss of water treatment. An increase in pH over the upper*

limit of the range may indicate that the wrong water treatment chemical or wrong dosage has been added to the system.

4. *Conductivity and TDS. The relationship between conductivity and TDS varies according to the chemistry of the system so any estimate of TDS based on conductivity reading should be treated with caution. Ideally the specified range should be expressed as conductivity as this will be the easiest to measure on site. A sudden drop in conductivity could be indicative of water loss from the system. For TDS determination the sample should be evaporated at 105°C. The laboratory should be made aware of the presence of glycol as this can interfere with the results.*
5. *Suspended solids. This is the key indicator of water quality. Suspended solids should normally be less than 30 mg/l in the circulating water and a well-controlled system may consistently achieve less than 10 mg/l. A high suspended solids result may indicate poor control of corrosion rates and should be considered together with the results for corrodible metals.*
6. *Settled solids (as defined in BG 29^[1] and BS 8552^[6]). The result will indicate the degree of sedimentation of suspended solids at the sample location since the last discharge of water from that sample point (for sampling or maintenance). BG 29 suggests that the limit for settled solids in pipework at the extremes of the system should be no more than double the suspended solids limit (i.e. 60 mg/l) and less than three times for terminal units (i.e. 90 mg/l). If the sample point has been used within the last 3 weeks and the system is well controlled there should be no significant increase over the suspended solids result. In that case the limit for either should be less than 150% of the suspended solids limit (i.e. 45 mg/l).*
7. *Nitrite is the principal corrosion inhibitor in many water treatment packages and it is essential to maintain the concentration in the range recommended by the water treatment specialist. A low concentration of nitrite could actually increase the corrosion rate. A rapid loss of nitrite may indicate the presence of nitrite reducing bacteria. This should be confirmed with the NRB test.*
8. *Nitrate may be included as a component of the water treatment package (to synergise with nitrite) but can also be formed by oxidation of the nitrite.*
9. *Molybdate is a common inhibitor in many water treatment packages. Molybdate will gradually be lost through precipitation and over-dosing can result in an increase in suspended solids.*
10. *Boron can be present in the water treatment package as borate.*
11. *Phosphonate may be included in the water treatment package as a scale inhibitor. Loss of concentration is not critical.*
12. *Organic corrosion and scale inhibitors can be difficult and/or expensive to monitor. The water treatment specialist will provide advice on what is feasible and the associated guidelines.*
13. *Silicate may be present at trace levels in the water supply and as a film forming inhibitor in the water treatment package for high pH water treatment programmes.*
14. *Orthophosphate may be included in the water treatment package as a corrosion inhibitor.*

15. Total alkalinity (also known as methyl orange alkalinity from the use of methyl orange indicator in the analytical titration) is used together with pH to calculate the carbonate concentration in the sample.
16. Calcium hardness is a measure of the scale forming potential of the water.
17. Total hardness is the sum calcium and magnesium hardness of the water expressed as mg/l CaCO₃.
18. Total iron. The result is used to comment on the source of suspended and settled solids.
19. Dissolved iron is used as a primary indicator of corrosion control in systems containing steel. A limit of 3 mg/l or less may be set for typical nitrite/molybdate regimes (see BG 29^[1]) but may be much higher for some proprietary products. Care must be taken in the interpretation of dissolved iron results in high pH systems, and where there is only a small amount of steel, as a low result may not mean that the system is safe.
20. Copper (dissolved or total). New systems with fresh copper surfaces are vulnerable to cupro-solvency and high concentrations of dissolved copper could result in pitting corrosion of steel and aluminium.
21. Zinc (dissolved or total). Zinc plated surfaces should not be used in heating systems as the plating will be rapidly corroded. If zinc is found in other circumstances it could be indicative of dezincification.
22. Aluminium (dissolved or total) is an indicator of corrosion control in systems with aluminium components.
23. Sulfate is present in the fill/make-up water. The concentration of sulfate in the system water should remain above 90% of that for the fill water. A downward trend in sulfate could indicate the presence of active SRB.
24. Chloride is present from the fill water and the degradation of biocides. A high concentration of chloride will increase the risk of pitting and stress corrosion. There is no generally accepted "safe" level of chloride.
25. Ammonia can be produced by the action of bacteria on nitrite, nitrate and organic water treatment components. High concentrations of ammonia are detrimental to copper and copper alloys. Some practitioners recommend remedial action if ammonia concentrations exceed 30 to 40 mg/l. However, there is no published evidence to justify this recommendation in terms of an increased risk of SCC.
26. Dissolved oxygen is required for most of the metallic corrosion processes in closed systems. Cold tap water is often nearly saturated with dissolved oxygen. Since corrosion processes will tend to reduce the concentration of dissolved oxygen in the system water, the trend of results should be decreasing. A persistently high concentration (>2 mg/l) in circulating water may be indicative of oxygen continuing to enter the system e.g. through inadequate system pressurisation (see section 2.3) or through plastic pipe. Very low concentrations of oxygen relative to the circulating water in samples taken from terminal units may indicate stagnation and/or local corrosion.
27. Total viable count (TVC) is a measure of the concentration of aerobic bacteria in the water. These bacteria may not be implicated in corrosion but high levels

of TVC are indicative of poor microbiological control. The typical control range is 1,000 to 10,000 cfu/ml (see Section 4.2.1 and Table 7) and no increasing trend. This is based on the geometric mean of the samples as explained in BS 8558^[7].

28. *Pseudomonads* are slime forming bacteria that promote the formation of biofilms. They are obligate anaerobes which means they can act as either aerobic or anaerobic depending on conditions within the system. When anaerobic they act as nitrate/nitrite reducers

There is no defined relationship between the concentration of *pseudomonads* in the water and the much higher concentration in the biofilm where they do the damage (see Section 3.2). High concentrations of *pseudomonads* in system water are however taken as indicative of poor microbiological control.

BG 29^[1] states that the limit for *pseudomonads* in system water at handover should be less than 10,000 cfu/100ml (100 cfu/ml) and no increasing trend. This is based on the geometric mean of the samples as explained in BS 8558^[7]. Opinions vary about the significance of high *pseudomonad* counts in older systems with some practitioners arguing that the limits should be the same as for TVC at 30°C and that 100 cfu/ml would certainly be no cause for concern. Various data from actual sites suggest that *pseudomonas* counts are typically around 10% of TVC counts in a “dirty” system (one operating around the TVC limit) but only 1% of TVC in a clean system, hence the criteria in BG 29. The water treatment specialist should decide on a suitable control limit for *pseudomonads* based on his knowledge of the system and operational requirements.

29. *Sulfate reducing bacteria (SRB)* are anaerobic bacteria that are a significant cause of under-deposit pitting corrosion in pipework systems. As with other bacteria, there is no relationship between the concentration of bacteria in the water and in the biofilm. There are also difficulties in the sampling and analysis as SRB may become dormant when exposed to oxygen in the sample bottle and there are at least three different methods of analysis that may respond differently to different SRB (see Section 6.4.9). A positive result should be treated as an indication of the presence of SRB but a “non-detectable” result does not mean the absence of SRB.
30. *Nitrite reducing bacteria (NRB)* reduce nitrite (or nitrate) inhibitor to ammonia or nitrogen gas. NRB analysis is generally carried out to investigate the reasons for rapid loss of nitrite. In most situations the major concern is the loss of inhibitor, though a high concentration of ammonia is corrosive to copper alloys. NRB include some *pseudomonads* when exposed to anaerobic conditions.

Conclusions about the state of the system and any decisions about remedial work should take account of all the available evidence. Often the first step in dealing with water that falls outside the acceptable range for a particular parameter should be to repeat the sampling to confirm the result.

6.6 CORROSION MONITORING

Analysis of system water quality provides useful information about the concentration and performance of corrosion inhibitors and biocides but only gives a partial picture of the overall condition of the system and the extent to which corrosion is taking place. Several additional techniques and methods of corrosion monitoring can be applied to provide a more complete picture of the health of the system.

The key ingredients of a corrosion monitoring programme are:

1. System knowledge
2. Site testing of critical performance criteria
3. Documentation of observations and recommendations

System knowledge: Before taking on responsibility for monitoring and treating a system, the water treatment specialist should review the operational and design characteristics of the system. They should be aware of:

- Materials present
- Working temperature and pressure
- Operating volume (from previous testing)
- History of the system (including any pre-commission cleaning activity, any known corrosion problems and remedial works)
- History of the water treatment (programmes and products used)

Although some of this information may be available in the operation and maintenance (O&M) manuals for the building it should be copied to the water treatment logbook for easy reference.

Documentation: The water treatment specialist should document the system parameters, site testing results, and any observations and recommendations provided. Verbal communication of critical observations and recommendations must be confirmed in writing. It is also a good practice to document (as explicitly as possible) the consequences of not heeding these observations and recommendations.

Site testing techniques are described in the following sections.

6.6.1 Corrosion coupons

Corrosion coupons are used to assess the rate of corrosion of metals in cooling and heating systems. Standard coupons of most common metals and alloys are commercially available, usually with a bead-blast finish. These come in vapour phase inhibitor impregnated bags to prevent any corrosion before use. They may be supplied pre-weighed but, if weight loss determinations are to be performed by a laboratory other than the coupon supplier, they should be weighed immediately before use to a resolution of 0.1 mg.

The coupon materials should correspond to the at-risk materials in the system for example mild steel, copper, brass or aluminium. Note however that extruded aluminium coupons may behave differently to the cast Al-Si

alloys typically used to make heat exchangers. At least two coupons from each metal of interest should be used to obtain mean corrosion rates. Coupons can be assembled into bundles and placed in coupon chambers or attached to coupon racks for insertion in the system.

In making coupon bundles, the coupons are normally electrically insulated from each other by the use of PTFE spacers, with PTFE sleeves over the brass bolts used to hold the bundle together. However, coupons of different metals (e.g. steel and copper) may be bolted together to produce a galvanic couple if required. It is important that clean gloves are used when handling the coupons at any time to prevent grease and other contaminants affecting the results.

In order to obtain accurate corrosion rates, coupons should be left in the system for at least one month. To obtain trends in corrosion rates, coupons need to be placed in the system and taken out at different intervals. The mean corrosion rates for each metal averaged over the exposure period can then be determined.

On removal of coupons from the system, they should be immediately rinsed in demineralised water, followed by methanol and then dried in warm air. Coupons should then be stored in a desiccator or bags containing silica gel for transport to the laboratory for inspection and weighing.

Exposed coupons should be assessed for any pitting corrosion by visual inspection under a low power microscope. The general condition and any salient features should be photographed for record purposes. Note that it is not unusual for some crevice corrosion to be observed at the mounting points but this is not of concern.

Corrosion rates are estimated by carrying out weight loss determinations on each coupon in turn. Several cleaning stages are carried out on each coupon using inhibited acids in order to obtain a corrected weight loss, as specified in ASTM G-1^[16].

6.6.2 Corrosion probes

Corrosion probes allow continuous monitoring of corrosion rates. The most common probes for closed systems are based on the principle of linear polarisation resistance (LPR). Two or three electrode versions are available and whilst mild steel electrodes are the most common, other probe materials can be obtained.

The LPR method is based on the fact that polarising electrodes by less than 20 mV produces a linear current response. The slope of the graph of the polarisation voltage plotted against polarisation current is the polarisation resistance, which is inversely proportional to corrosion rate. A more accurate determination of corrosion rates can be obtained by the instrument, using default “Tafel” slopes in the Stern-Geary equation. A combination of the LPR technique and corrosion coupons will provide a fairly accurate assessment of the corrosion rates of various metals in the system and trends in corrosion rates over time.

If pitting corrosion is taking place, this will result in an imbalance between the two electrodes and give rise to a fluctuating potential difference between them. Some devices (e.g. Corrat[®]) can exploit this effect to give an indication of pitting in addition to the general corrosion rate.

LPR meters and probes can be installed on site to give intermittent readings of corrosion rates. However, they can also be used with data loggers to store information, which makes on-line monitoring possible. This enables alarms to be set if corrosion rates exceed pre-set values due to sudden changes in water quality.

The user of LPR probes needs to be aware of a number of things:

- Low conductivity water samples can cause corrosion rates to be underestimated, as the solution resistance is added to the polarisation resistance. However, in typical heating and cooling systems the conductivity is usually more than high enough for these errors to be insignificant.
- LPR probes should be aligned perpendicular to the flow so that one electrode is not shielding the other, which could affect the readings.
- LPR probes located in stagnant areas will give results that are unrepresentative of system conditions. This point is common to all methods of measuring corrosion.

Electrical resistance corrosion probes are not recommended for use in closed systems as they only provide useful information at much higher rates of corrosion than would normally be encountered.

6.6.3 Biofilm monitoring

There are a number of possible approaches to biofilm monitoring in closed system but unlike corrosion monitoring, there are no standard or widely used methods. Qualitative judgements on the presence of biofilm are often made on the surface condition of corrosion coupon racks.

Quantitative methods rely on inserting a surface into the system for a period of weeks or months, then removing that surface and recovering the bacteria for analysis. Alternatively the surface may be assessed directly with microscopy or a bioluminescence technique.

A method for biofilm monitoring in closed systems using glass beads is described in Appendix D.

6.6.4 Continuous monitoring of key system parameters

Corrosion in closed heating and cooling systems is governed primarily by the concentration of dissolved oxygen, the presence of microorganisms and how these factors are mediated by the use of water treatment, i.e. corrosion inhibitors and biocides.

Periodic water analysis can measure the concentration of inhibitors and pick up signs of metal corrosion. LPR probes and corrosion coupons can give an accurate assessment of corrosion rates. However, to understand how the whole system is performing and pre-empt damage due to loss of control, continuous monitoring can be useful.

For instance, it is no use adding more chemicals to the system to tackle a leak. Many inhibitors cannot cope with gross aeration of system waters due to fresh make-up water, or negative pressures at the top of the system pulling in air. Water treatment should not be used to address problems that could and should be remedied by simple engineering changes.

There are a number of robust sensors available that can be used for in-line monitoring of heating and cooling systems (Table 11). They will need to be calibrated before use but once installed they should not drift or give noisy signals.

Table 11: Sensors for in-line monitoring of closed heating and cooling systems

Parameter	Comment
Temperature	The temperature difference between flow and return sensors can be used to verify that heating or cooling water is circulating as required. Sufficient temperature sensors may already be installed as part of the building management system
Pressure	A pressure sensor should be installed at the top of the system, at the minimum pressure point, to verify that positive pressure is maintained under all operating conditions to prevent air entering the system through vents etc.
Pressurisation system water meter	Persistent make-up may be indicative of a leak in the system and adds dissolved oxygen. Planned events such as partial drain down/refill for maintenance reasons should be followed by water sampling and analysis to check inhibitor concentration.
Conductivity	A sudden change in conductivity indicates that something has happened to the system and, if the reasons are not obvious, should trigger further identification to identify the cause.
LPR probe	LPR technology (e.g. Corrat [®]) can be used for monitoring general corrosion rates and as a pitting indicator for steel and other metals (see section 6.6.2).
Galvanic current	The galvanic current flowing between steel and copper gives a good indication of the level of corrosion protection in system. Without inhibitors present, this responds quickly to changes in dissolved oxygen.
Dissolved oxygen	Oxygen sensors are relatively expensive and therefore permanently installed sensors are not widely used but may be justified for large systems. Both optical and electrolytic sensors are available. In-line sensors need to have a stainless steel body.

Unfortunately this list of robust in-line sensors does not include pH and ion selective electrodes as these need frequent calibration and cannot withstand high temperatures. pH and ion selective electrodes can be incorporated in automated sampling and analysis systems but these are generally too expensive for most closed heating and cooling systems.

Continuous monitoring of the available sensors via the building management system allows alarms to be set and the water treatment specialist to be automatically informed of loss of control. In addition, the logged data should be available to help the water treatment specialist diagnose the cause of the problem.

7 REGULATIONS

7.1 HEALTH AND SAFETY

The UK approach to health and safety is generally implemented through the Health and Safety etc. Act 1974 (as amended) and the regulations made under the act. Further information on these regulations and practical guidance on safe working practice can be found at www.hse.gov.uk. The following regulations (as amended) are particularly relevant to water treatment operatives:

Management of Health and Safety at Work Regulations 1999

The Regulations require employers to assess risks to health and safety and record findings. Having done so they must implement measures to control risks, appoint competent people, set up emergency procedures and provide information and training for employees and anyone else who needs to know.

Employees have to use equipment in accordance with training and have the duty to report dangerous situations to their employers. A particular issue for water treatment personnel is that they often work alone and out of sight of other building occupants and therefore need to be particularly conscious of the safe working practice when it comes to handling potentially hazardous materials.

Personal Protective Equipment at Work Regulations 1992

Personal protective equipment (PPE) is defined as all equipment designed to be worn or held to protect against a hazard at work. PPE should be relied on as a last resort but PPE should be suitable for both the risk and the user. The employer has a duty to provide and maintain PPE and ensure it is properly used. Virtually all PPE should carry the CE mark.

These regulations do not apply to processes covered by other regulations, which means they do not cover hearing protection or respiratory protective equipment.

Control of Substances Hazardous To Health Regulations 2002

The aim of the COSHH Regulations is to protect workers' health from hazardous substances used at work. The employer has to assess the risks from such substances, and for certain substances he has to monitor the employee's exposure to them. The regulations define what constitutes suitable personal protective equipment.

Hazardous substances include both chemical and biological agents.

Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995

RIDDOR covers the notification and reporting of injuries and dangerous occurrences. The specific injuries and incidents which legally must be reported are specified in the Regulations. However, any injuries sustained by a water treatment operative, however minor, must be reported both to their employer and the person responsible for health and safety on the site.

Confined Spaces Regulations 1997

These regulations require employers to avoid entry to confined spaces by finding alternative methods of work, but if entry to a confined space is unavoidable, a safe method of work must be in place together with adequate emergency arrangements which will also safeguard rescuers.

Although people tend to think of confined spaces as tunnels and tanks, some plant rooms can be classed as confined spaces within the meaning of the regulations.

Work at Height Regulations 2005

These regulations impose health and safety requirements with respect to work at height. They cover organising and planning work at height, competency and supervision, risk avoidance, selection of work equipment and inspection regimes. Duties are placed on employers, the self-employed and contractors.

Step ladders are often used when taking samples in site. The safe use of step ladders for sampling in ceiling voids always requires two persons.

Electricity at Work Regulations 1989

These regulations impose health and safety requirements with respect to electricity at work. They impose duties on employers, and requirements as to systems, work activities and protective equipment.

It is a well-known saying that electricity and water do not mix. Work involving temporary pumps needs to be properly checked and safety tested by competent persons before use.

The Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2009

The regulations governing what chemicals may be carried in what quantities, the type of packaging and how the vehicle must be marked are very complex. Suffice to say that the best source of guidance on the practical requirements will normally be the manufacturer or supplier of the chemical. Under no circumstances should water treatment chemicals that are marked as hazardous be transported in unmarked vehicles.

7.2 OTHER REGULATIONS

Various regulations apply to water systems in general including the installation and operation of closed heating and cooling systems. The applicable legislation for England is shown below. Different legislation may apply in other parts of the UK but the practical requirements are similar.

Water Supply (Water Fittings) Regulations 1999

The Water Regulations impose requirements for backflow prevention that are applicable when filling or flushing a heating or cooling system.

Water Industry Act 1991

The Water Industry Act provides for discharges of “trade effluent” to the sewer to require a permit from the sewerage undertaker. Although this principally affects the permitting of pre-commission cleaning activity, any drain down of a heating or cooling system at any stage in the life of the building could require a permit. There is no minimum volume. The application for the permit will require details of the volume and constituents of the discharge and may take several weeks to obtain. Each sewerage undertaker has different requirements for information and it is advisable to consult them as early as possible if a discharge is planned.

APPENDIX A USE OF TEMPORARY PUMPS

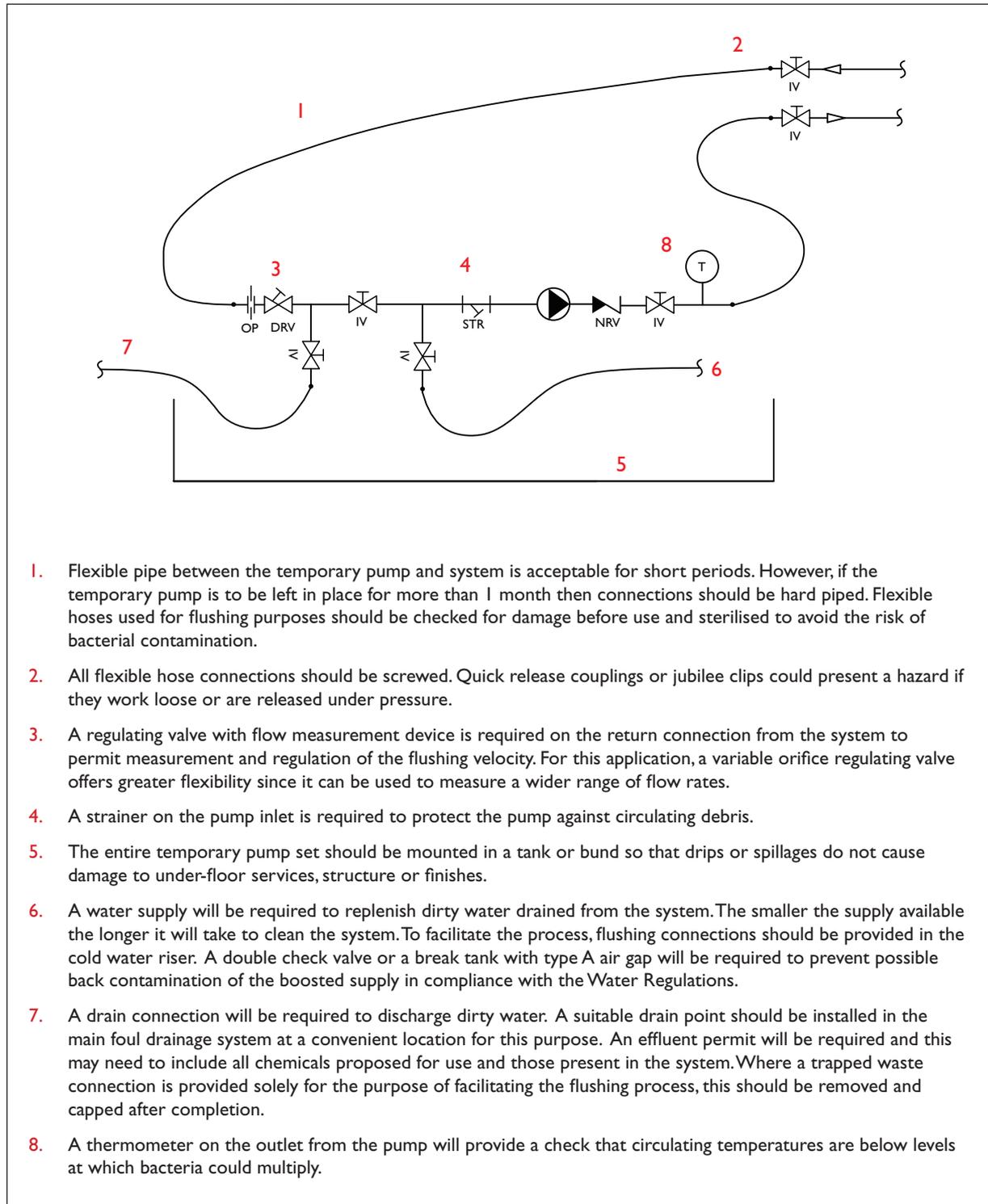
All temporary pumps should be:

- fitted with pressure control.
- located in bunds to retain water in the event of a leak.
- connected to the building system with hoses and components that are tested and rated to at least 1.5 times the maximum pump pressure.

Figure 16 (from BG 29^[1], with commentary) illustrates the main features of a temporary pump installation. In addition:

- Sampling and dosing connections should be available (not shown in Figure 16).
- The water inlet and outlet connections to the system should be of adequate size (ideally line size).
- Hoses should be of sufficiently large diameter to achieve the required flow rates given the available pressure at the pumps.
- Hoses should be checked for damage and sterilised before use.
- The pump should be connected to a suitably rated electrical supply via an isolator and appropriate protective devices.
- A safety barrier should be erected around the work area.
- A notice board detailing chemical COSHH information should be displayed.

Figure 16: Temporary pump arrangement (from BG 29^[1])



APPENDIX B CASE STUDIES

Case study I – MIC in radiators

Building: Large government office building.

Manifestation: Blocking of radiators with sludge and pinhole leaks at the bottom of radiators under sludge within a few years of construction.

Figure 17 shows a transverse section through the partially blocked lower waterway of a radiator with severe pitting corrosion.

Figure 17: Sludge and pitting corrosion in lower waterway of radiator



Cause: The LTHW system contained a large amount of non-barrier plastic pipework which allowed oxygenation of system water. Iron oxide corrosion debris had accumulated in the bottom of radiators and growth of sulfate reducing bacteria (SRB) under sludge led to microbially influenced corrosion (MIC) and localised pitting.

Solution: The system was too badly affected for any on-line remediation to be effective and the radiators were all replaced.

Case study 2 – Sporadic pitting in new radiators and towel rails

Building: Residential apartments on a community heating scheme

Manifestation: Pinhole leaks in radiators and towel rails within 6-12 months of completion.

Figure 18: Pinhole corrosion of radiator (outside surface)

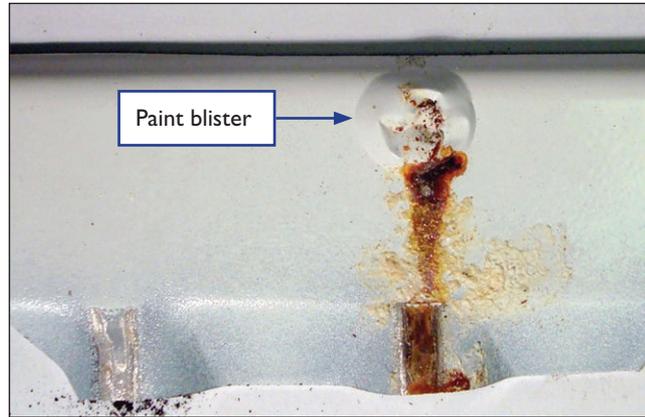
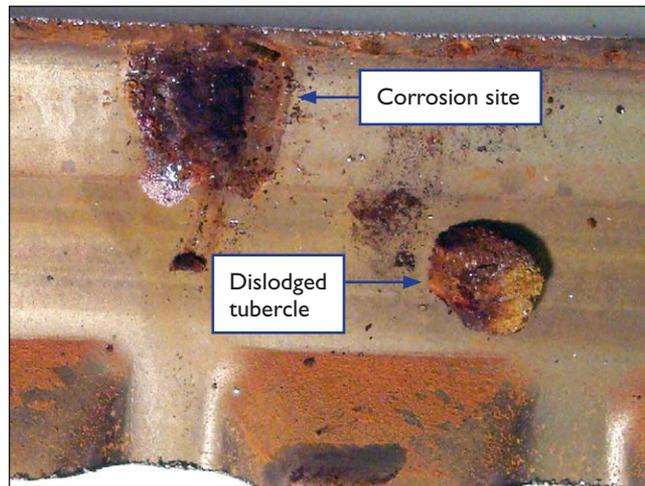
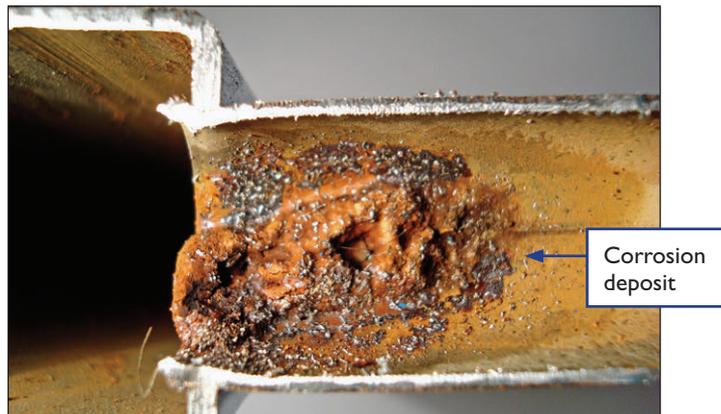


Figure 19: Inside surface of radiator



Note: the corrosion tubercle has been dislodged during the cutting of the sample

Figure 20: Inside surface of towel rail



Note: The corrosion deposit is contaminated with swarf from cutting the sample. The perforation occurs through the tube under the corrosion deposit, near to the junction between the tube and header.

Cause: Progressive commissioning and occupancy together with a plastic pipe distribution system led to persistently high oxygen levels. This rapid pitting is a form of differential oxygen corrosion that can occur in isolated locations anywhere on the inner surface but usually adjacent to a seam or crevice between the opposing faces of the radiator. Note that the surrounding surface has no corrosion as the pitting area becomes anodic. This is different to longer term radiator corrosion that is associated with the build-up of sludge and debris in the lower waterway.

Solution: In this case the developer changed from plastic to steel pipe to reduce oxygen ingress. Other similar projects use heat interface units with plate heat exchangers so that any problems with water quality in the distribution system do not spread into the completed apartments.

Case study 3 – Pinhole leaks in thin wall carbon steel tube

Building: Refurbished office building

Manifestation: Pinhole leaks in several areas of the new chilled water distribution system became evident within a few weeks of occupation.

Figure 21: Pinhole in thin wall carbon steel tube

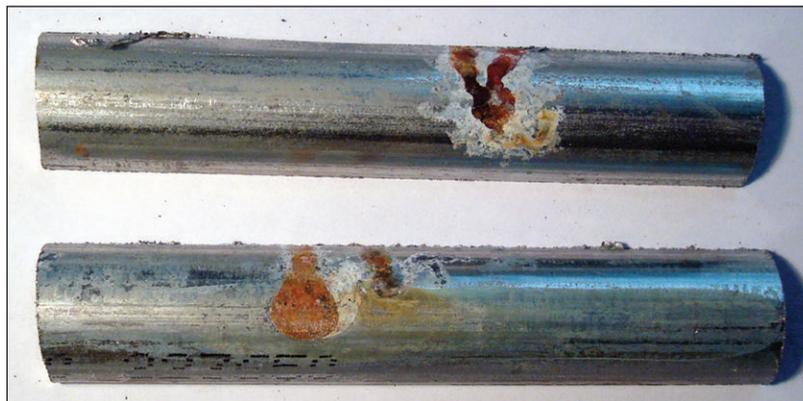


Figure 22: Internal corrosion deposits obscuring the leak site

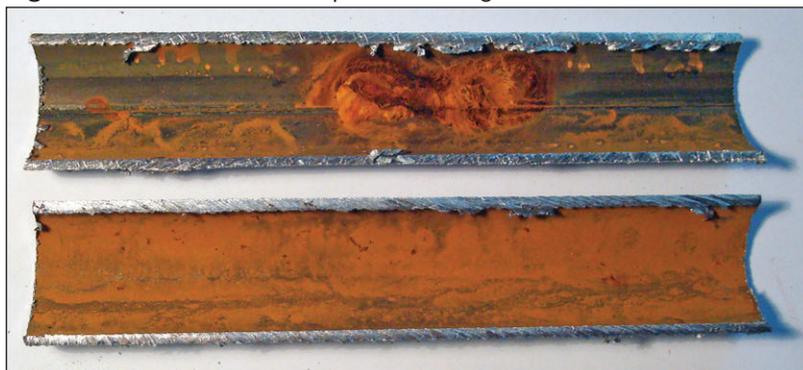


Figure 23: Corrosion and pitting in heat affected zone (cleaned sample)



Cause: Examination of the affected pipe revealed pitting corrosion in the heat affected zone of the seam weld. There were known problems in achieving effective pre-commission cleaning and subsequent water treatment due to high levels of suspended solids in the pre-existing systems but also a suspicion of copper deposition around the perforation sites. Unfortunately no detailed surface analysis was undertaken in this case.

Solution: The affected areas were re-cleaned and pipe replaced as necessary.

Case study 4 – Rapid pitting corrosion of thin wall carbon steel tube

Building: New educational building

Manifestation: Pinhole leaks, poor water quality and sludge in the heating systems soon after pre-commission cleaning.

Figure 24: Severe pitting on thin wall carbon steel tube (cleaned sample)



Cause: Examination of the pipe samples taken from a number of different areas of the building found some instances of severe pitting under a thick layer of brown/black corrosion deposit. The causes of the problem included deficiencies in pre-commission cleaning, ingress of oxygen and poor management of water quality immediately after commissioning.

Solution: Large parts of the system were recommended for replacement and the remainder for re-cleaning.

Case study 5 - Widespread corrosion in heating and chilled water systems

Building: Large business park

Manifestation: Blockage of pipework together with failure of boilers and condenser coils

Cause: Insufficient expansion vessel capacity and poor maintenance of system pressures leading to large water losses, loss of inhibitors and gross aeration.

Figure 25 shows the tube bundle of a large shell and tube condenser. Several tubes had failed due to corrosion and there was considerable corrosion debris collected in the bottom of the shell. Figure 26 shows sections of 20 mm steel pipe with oxygen pitting corrosion.

Figure 25: Heat exchanger shell and tubes

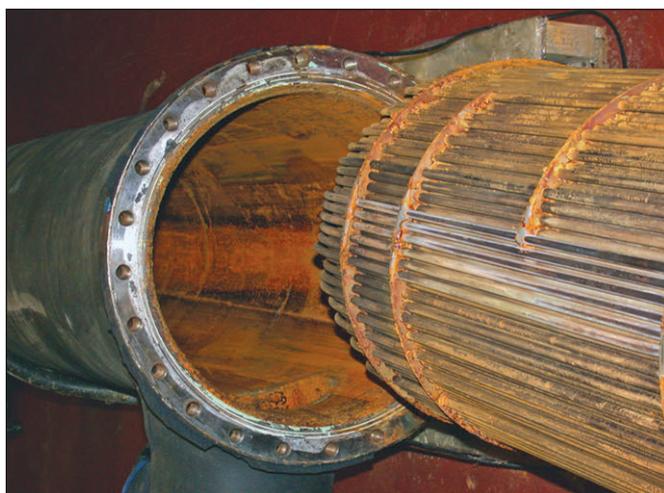


Figure 26: Oxygen corrosion in steel pipe



Solution: Remedial flushing of pipework was possible in some areas but extensive replacement of pipework and system components was necessary. Larger expansion vessels were installed to avoid water losses and the system pressure increased. A proper maintenance regime was introduced to monitor system conditions and water quality.

Case study 6 - Inappropriate water treatment

Building: College

Manifestation: Blockage of radiators due to large amounts of alumina debris.

Cause: A strongly alkaline corrosion inhibitor which resulted in corrosion of the aluminium boilers and circulation and deposition of alumina corrosion products as shown in Figure 27 and Figure 28.

Figure 27: Oxygen corrosion in steel pipe



Figure 28: Debris viewed under microscope (x8)



Solution: Remedial flushing of the radiators and system pipework. The system was re-treated with a more appropriate inhibitor and biocide and carefully monitored.

Case study 7 – SCC of brass fitting under insulation

Building: Office chilled water system

Manifestation: Leakage of brass valves under thermal insulation. Figure 29 shows longitudinal stress corrosion cracks running through a brass fitting and nut.

Figure 29: SCC in brass nuts



Cause: Poorly fitted phenolic foam insulation allowing condensation on pipe. High hoop stresses on fittings coupled with exposure to ammonia leached from the insulation resulted in stress corrosion cracking of fitting from outside.

Solution: The affected valves were replaced and the insulation improved to prevent condensation on the pipework and leaching of aggressive species.

Case study 8 - SCC in a stainless steel water jacket

Building: Food Factory

Manifestation: Leaks in the stainless steel hot water jacket surrounding a pipe delivering liquid chocolate. The leaks were due to stress corrosion cracks initiating from pits in stainless steel. Figure 30 shows a crack at approximately 20 times magnification.

Figure 30: Stress corrosion cracking in stainless steel (x20)



Cause: Incorrect grade of austenitic stainless steel (304 instead of 316) susceptible to pitting and stress corrosion in high chloride water. Note that although this is not a conventional building heating and cooling application the same problem could occur in any closed system with stainless steel heat exchangers or pipework.

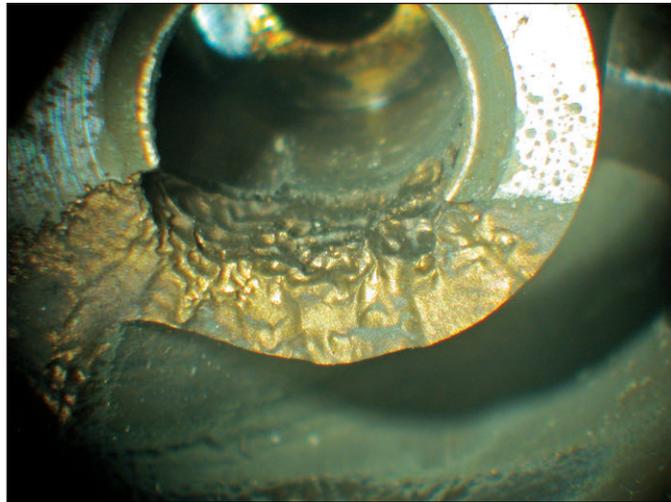
Solution: RO water installed to eliminate chloride from water. The RO water was then passed through a dolomitic limestone filter to reintroduce some hardness.

Case study 9 - Erosion corrosion of brass valve seat

Building: Large four story office block

Manifestation: Brass control valves to fan coil units 'letting by' and therefore giving poor temperature control and wasting of energy for the air conditioning system. Figure 31 shows an example at 8 times magnification.

Figure 31: Erosion of brass valve seat (x8)



Cause: Erosion corrosion with possible cavitation due to low static pressures at top of building. Also high concentrations of ammonia in the system as a result of microbial degradation of the nitrite/nitrate inhibitor.

Solution: The affected valves were replaced. The system was flushed out and inhibited with non-nitrite inhibitor to avoid ammonia formation. The system static pressure was increased to reduce the risk of cavitation at the top of the building. In these situations the control strategy and pump settings should also be reviewed with the aim of reducing the differential pressure across the control valve.

Case study 10 - Poor water quality leading to blockages

Building: LTHW system in large office block.

Manifestation: Loss of flow due to fan coil unit strainers repeatedly becoming blocked.

Figure 32: Blocked fan coil strainer



Cause: Loss of control of water quality and corrosion leading to high levels of circulating solids and pseudomonad bacteria.

Solution: The main plant and risers were cleaned using system pumps, followed by side stream filtration to maintain physical cleanliness of recirculating water. Each floor was then individually cleaned, off-line, using a temporary pump (one floor per weekend). Full building and system operation was maintained through all working hours.

Case study 11 – Copper sulfide scale

Building: Large office building with fan coil heating and cooling

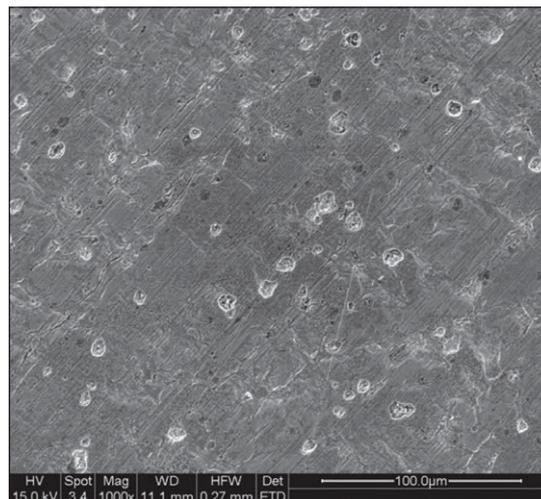
Manifestation: Persistent suspended solids in the form of black flakes following pre-commission cleaning.

Figure 33: Copper sulfide scale



Cause: Examination of copper tube from the system found a uniform layer of black scale that was friable when dried. Analysis of the scale using x-ray diffraction found this to be almost pure copper (I) sulfide (Cu_2S). Some pitting was found underneath the scale layers but this was considered unlikely to result in perforation. The origin of the sulphide was never fully explained but believed to be due to microbiological action in the system prior to pre-commission cleaning.

Figure 34: Copper sulfide scale



Solution: A pilot scale cleaning rig was set up to assess cleaning strategies for the distribution pipework as the scale was resistant to normal cleaning chemicals. The system was eventually cleaned using ammonium citrate followed by hydrogen peroxide to dissolve the scale. The fan coils were replaced as a precautionary measure as the tube in these is much thinner (0.3 mm) than distribution pipework.

APPENDIX C BIOCIDES

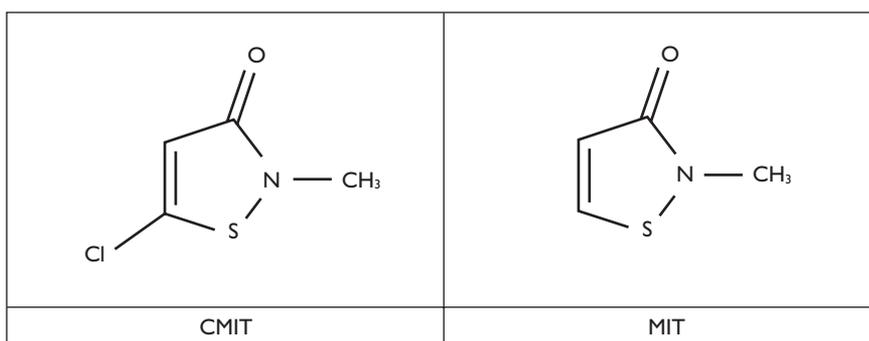
One of the main driving forces behind the current and future availability of biocides in the water treatment industry is the European Biocidal Products Regulation (528/2012, commonly known as BPR) which came into force on the 1st September 2013, repealing the European Biocidal Products Directive (98/8/EC, commonly known as BPD).

For a summary of the implementation of the BPR in the UK see www.hse.gov.uk/biocides/

The characteristics of some of the non-oxidising biocides that are currently still permitted for use in closed heating and cooling systems are summarised below.

Isothiazolinones

These biocidal products consist of a 3:1 ratio mixture of 5-chloro-2-methyl-2H-isothiazol-3-one plus 2-methyl-2H-isothiazol-3-one (CMIT/MIT) (abbreviated name).

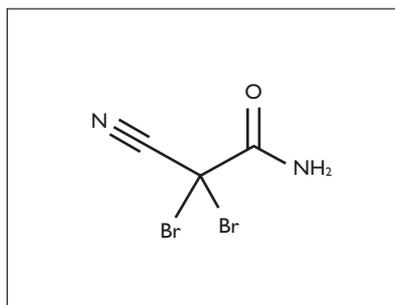


The characteristics of isothiazolinones are:

- Broad-spectrum bactericide. Effective against the majority of bacteria likely to be found in closed heating and cooling systems.
- Effective over the range pH 6.5 to 8.5.
- The dose rate of 1.5% active isothiazolinone is typically 200 ppm for maintenance dose rate and 400 ppm for shock dose.
- The contact time for a shock dose is typically 5 to 6 hours.
- Stable up to 50°C

DBNPA

2-2-Dibromo-3-nitrilopropionamide. Biocide with an active halogen group.

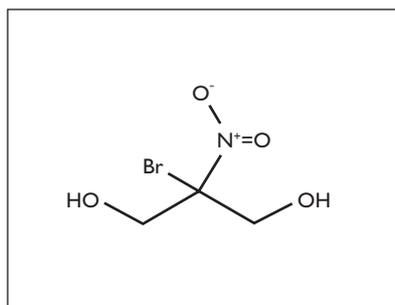


The characteristics of DBNPA are:

- Broad spectrum bactericide.
- Effective over the range pH 6.0 to 8.0. DBNPA hydrolyses rapidly above pH 8.0.
- Fast acting. The contact time for a shock dose may be less than 1 hour.
- The dose rate of a 20% active solution is typically 100 ppm for a maintenance dose and 200 ppm for a shock dose.
- Stable up to 50°C.

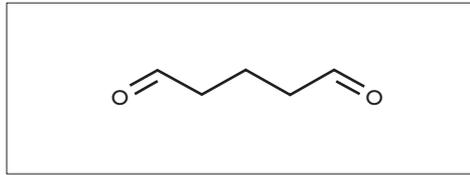
Bronopol

2-Bromo-2-nitropropane-1,3-diol.



The characteristics of bronopol are

- Broad spectrum micro-biocide, slimicide and aerobic/anaerobic bactericide.
- Effective over the range of pH 6.0 to 8.0 although the breakdown products are also micro-biocidal under alkaline conditions
- The dose rate for 20% active material is typically 100 ppm for maintenance dose and 200 ppm for a shock dose.
- Stable up to 40°C.

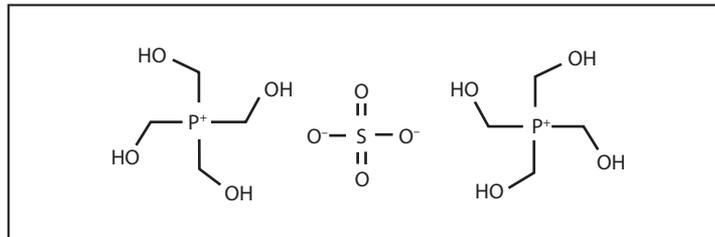
Gluteraldehyde

The characteristics of glutaraldehyde are:

- Broad spectrum bactericide.
- Good for difficult and persistent organisms including SRB and biofilms
- Effective over a wide pH range (typically pH 6.5 to 9.0)
- Fast-acting. Usually 3 to 4 hours contact time but perhaps 4 to 6 hours with difficult slimes.
- The dose rate for a 45% active material is typically 100 to 125 mg/l though a heavily slimed cooling system may need 200 - 300 mg/l as a shock dose for the initial clean-up.
- Stable up to 60°C

THPS

Tetrakis (hydroxymethyl) phosphonium sulfate

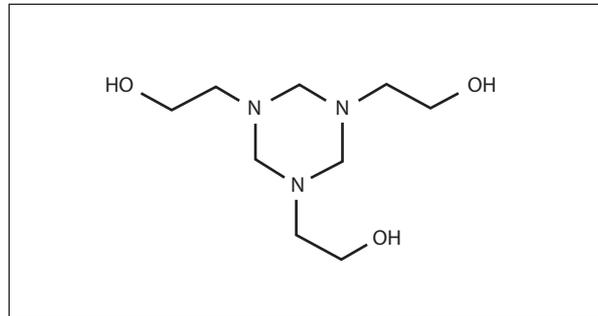


The characteristics of THPS are:

- Broad spectrum bactericide. Very effective against SRB.
- Acts by disrupting the structure of bacterial cell membranes leading to cell lysis.
- Fast-acting. 3 to 4 hours contact time for optimum activity.
- Effective over a very wide pH range (typically pH 3 to 10).
- The dose rate for 25% active material is typically 60 to 80 mg/l.
- Note: Overdosing with THPS has been linked to the formation of copper sulfide scale in copper tube.
- Stable up to 60°C.

Triazines

A number of triazine based biocides can be used within closed heating and cooling systems, the predominant one being 1,3,5-tris(hydroxy-ethyl)-s-hexahydrotriazine (HHT).



The characteristics of HHT are:

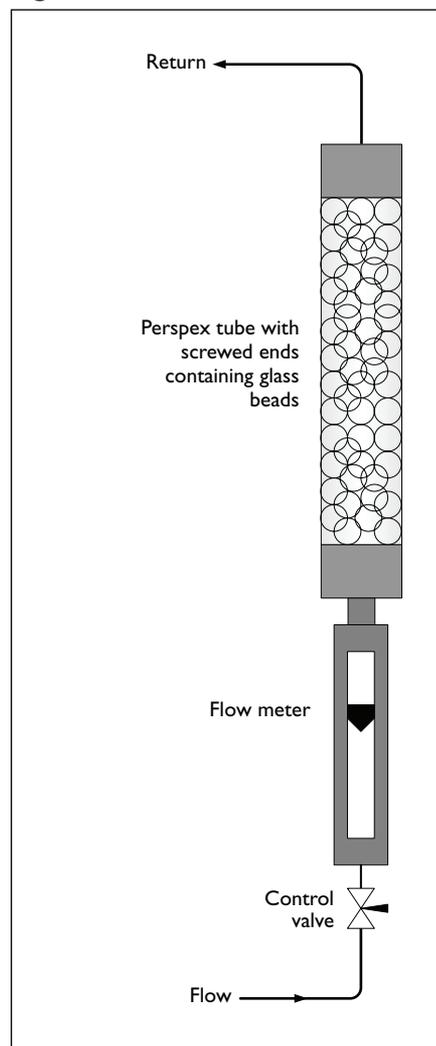
- Broad spectrum bactericide. Effective against SRB and biofilms
- Relatively slow acting with optimal biocidal activity after 24 hours contact.
- Effective over a wide pH range (optimum pH 8.0 to 11.0).
- Stable up to 80°C.

APPENDIX D QUANTITATIVE MEASUREMENT OF BIOFILM

The principle of this method is the insertion of a small canister of glass beads of known surface area into the system water flow, possibly at the same location as the corrosion monitoring coupon. Biofilm forms on the surface of the beads. At the end of the monitoring period the canister is removed and a number of the glass beads are agitated in a known volume of water to release the biofilm. A sample of this water is then analysed for TVC in the normal way.

In the version developed by the General Electric Company for cooling towers (Figure 35) a 100 mm diameter transparent Perspex® tube is installed vertically and connected between a flow and return branch. The flow through the tube is controlled to 10-15 litres per minute. The idea of the transparent tube is to allow a visible indication of the accumulation of gross biofilm or debris but it must be protected from sunlight. 20 of the 3 mm diameter beads are removed for each biofilm determination.

Figure 35: Biofilm monitor



APPENDIX E ANTI-FREEZE

The most common anti-freeze components for building services chilled water applications are ethylene glycol and propylene glycol. Propylene glycol is nowadays preferred to ethylene glycol as it is less hazardous and the impact of discharges to the environment and on sewage treatment processes is less.

Glycol solutions are more corrosive than pure water and must be used in combination with corrosion inhibitors. Also, the breakdown products are acidic so pH should be monitored.

Glycols also provide a carbon source for bacteria growth and can be broken down by bacteria, though high concentrations (>15% by volume) are biocidal.

The basic characteristics of glycol solutions are shown in Table 12 and figures 36 and 37. Note that the freezing points will be influenced by other water treatment components. Also, unlike pure water, glycol solutions become slushy and more difficult to pump before they reach their freezing point.

Glycol concentration can be verified by density measurements or by optical properties. There are simple low-cost devices available for both these approaches.

Glycols interfere with gravimetric suspended solids determination so the presence of glycols in water samples should be notified to the laboratory prior to their analysis.

Table 12: Characteristics of glycols

Ethylene glycol				Propylene glycol			
% by mass	% by volume	Freezing point °C	Density @ 20°C kg/m ³	% by mass	% by volume	Freezing point °C	Density @ 20°C kg/m ³
0	0	0	998.2	0	0	0	998.2
5	4.4	-1.4	1005.9	5	4.8	-1.6	1003.3
10	8.9	-3.2	1013.3	10	9.6	-3.3	1008.1
15	13.6	-5.4	1021.6	15	14.5	-5.1	1013.4
20	18.1	-7.8	1029.7	20	19.4	-7.1	1019.0
21	19.2	-8.4	1031.1	21	20.4	-7.6	1019.5
22	20.1	-8.9	1032.7	22	21.4	-8	1020.5
23	21	-9.5	1034.2	23	22.4	-8.6	1021.5
24	22	-10.2	1035.8	24	23.4	-9.1	1022.5
25	22.9	-10.7	1037.4	25	24.4	-9.6	1023.6
26	23.9	-11.4	1039.0	26	25.3	-10.2	1024.6
27	24.8	-12	1040.5	27	26.4	-10.8	1025.6
28	25.8	-12.7	1042.1	28	27.4	-11.4	1026.6
29	26.7	-13.3	1043.7	29	28.4	-12	1027.6
30	27.7	-14.1	1045.3	30	29.4	-12.7	1028.4

Source data: ASHRAE Handbook. Fundamentals^[17]

Figure 36: Freezing point of ethylene glycol solutions

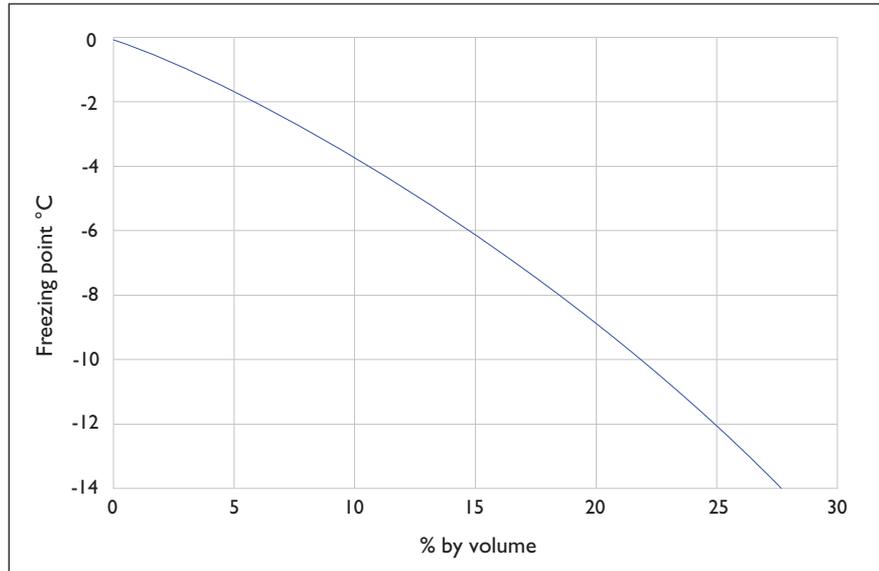
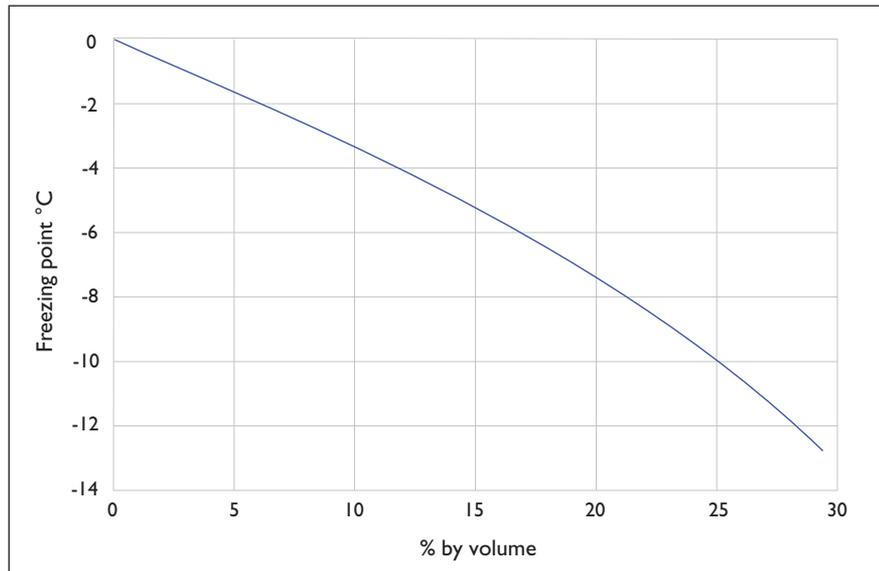


Figure 37: Freezing point of propylene glycol solutions



GLOSSARY

ABS	Acrylonitrile Butadiene Styrene – a thermoplastic
Aerobic	Requires oxygen to support life
Alkalinity	A measure of the concentration of carbonate and bicarbonate ions in solution.
Anaerobic	Does not require oxygen to support life.
Anion	Ion possessing a positive charge.
Anode	The positive pole in a chemical reaction cell e.g. in a battery. Metals always corrode at the anodes
Bactericide	A biocide effective against bacteria
Bacterium	Microscopic usually unicellular organism
Back flushing	The process of removing debris from a terminal unit by discharging system water from a convenient drain point such that the direction of flow through the terminal unit is opposite to the normal operating flow
Base exchange softener	An ion exchange system that replaces calcium and magnesium ions with sodium ions to reduce the hardness of the water
Binder point	Self-sealing pressure test point from which fluid can be discharged by insertion of a matching needle probe
Biocide	Chemical agent which either kills or prevents the multiplication of organisms in water systems
Biofilm	A mass of bacteria and other microorganisms and particles embedded in an exopolymer attached to a surface.
Biofouling	Fouling of surfaces caused by bacteria and biofilms.
Cathode	The negative pole in a chemical reaction cell e.g. in a battery. Metals tend to be passive at the cathode.
Cation	Ion possessing negative charge
Cfu	Colony forming unit
Cavitation	Formation and sudden collapse of vapour bubbles in a liquid. Cavitation can occur in pumps causing erosion of the pump impeller.
Chelating agent	Organic compound causing a substance that would normally be insoluble to be held in solution or to pass into solution
Closed system	System where the water is circulated without loss or addition
Conductivity	Measure of the ability of a solution to carry an electric current. Usually expressed in microsiemens per centimetre ($\mu\text{S}/\text{cm}$)
Corrosion	Loss of metal from a component due to the electrochemical reaction with its environment. The term is also used to describe the chemical degradation of non-metallic materials.
Corrosion coupons	Small strips of metal placed in a water system to enable the rate of corrosion in that system to be assessed.
Corrosion inhibitor	Compound that suppresses corrosion. Inhibitors may work by coating the corrodible surface or interfering with the chemical reaction that leads to corrosion.
Crevice corrosion	Localised corrosion occurring in a crevice or crack in a metal surface.
Deaerator	A means of removing dissolved gases including oxygen from system water.
Dead leg	A length of pipe normally closed at one end
Dezincification	Corrosion of brass (an alloy of copper and zinc) where the zinc is preferentially removed to leave a weak porous matrix of copper
Dip slide	Disposable plastic slide coated with microbiological nutrients for the assessment of bacteria concentrations in water

Erosion	Loss of metal by physical removal through impingement with water alone or gases and particles suspended within it
Hardness	A measure of the calcium and magnesium content of the water
Heterogeneous metal surface	A surface that is not completely homogeneous i.e. there are variations in surface condition
HDPE	High Density Polyethylene – a thermoplastic
LTHW	Low Temperature Hot Water in the context of heating systems
Method statement	Detailed description of the on-site work activity, including preparatory works and access provisions
MIC	Microbially Influenced Corrosion - corrosion that is initiated or accelerated by microbial activity, particularly the formation of biofilms
Microorganism	Microscopic life forms that can thrive in water system including algae, fungi and bacteria
NRB	Nitrate/Nitrite Reducing Bacteria
pH	A measure of the whether the water is alkaline or acidic based on the logarithm of the hydrogen ion concentration. Water at pH 7 is neutral. Water at greater than pH 7 is alkaline and water at less than pH7 is acidic. For most metals corrosion rates will increase as the pH falls below 7.
Pitting	Locally severe corrosion forming deep pits in the metal surface. This can lead to perforation of pipes and radiators.
Practical completion	The point of issuing a certificate of practical completion of construction works for the relevant system by the responsible person appointed by or on behalf of the client, after which responsibility for that system passes to the client
Pseudomonads	Pseudomonas – like bacteria. Prior to the advent of DNA classification methods, many bacteria were classified as Pseudomonas species on the basis of appearance and growth characteristics. These are now recognised as distinct species but are still relevant to pipework corrosion.
PTFE	Polytetrafluoroethylene – a thermoplastic
PVC	Polyvinyl Chloride – a fluoropolymer plastic
Sampling and analysis plan	A detailed description of the objectives of sampling, numbers and locations of samples, the analyses to be carried out for each sample and guidelines for interpretation of the results
Scale	A dense, adherent deposition of mineral particles usually composed of insoluble salts of calcium, magnesium and iron. Scale is formed when the water is heated or when the pH or alkalinity of the water is changed. The risk of scale forming is greatest with hard water and smallest with soft water.
SCC	Stress Corrosion Cracking - a specific form of corrosion that leads to cracking and mechanical failure of stressed brass and stainless steel components when exposed to certain chemical species
SRB	Sulfate Reducing Bacteria
Suspended solids	Insoluble dispersed solids that may be separated from the water by filtration. The concentration of suspended solids is determined by passing a measured quantity of water through a pre-weighed filter and re-weighing the filter after drying.
TDS	Total Dissolved Solids - solids that are dissolved in the water but may be measured by weighing the residue remaining after the water is evaporated
TVC	Total Viable Count - a measure of the number of aerobic bacteria present in the sample. The result is expressed as cfu/ml.
Tubercle	A wart-like mound of corrosion deposit on the surface of a pipe. Pitting corrosion may be occurring under the tubercle potentially leading to perforation of the pipe.

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