10 Materials Used in the Transport of Potable Water with Special Reference to Stainless Steel and Corrosion

CONTENTS

10.1 INTRODUCTION

There are a large number of areas present in potable water systems where biofilm development can proliferate. These include pipes, valves, fire hydrants, gaskets, sealants, and lubricants. However, the emphasis in this chapter will be on the development of biofilms and the effects they have on pipe materials used in the transport of potable water.

Over the centuries there have been a large number of different materials used in the transport of potable water. Traditionally, these piping materials have included clay, wood, stone, and lead. Piping materials which are used today to carry potable water are numerous. These include ductile cast iron, cast iron lined with cement, steel, reinforced concrete, asbestos combined with portland cement, copper, and plastics, namely, polyvinyl chloride (PVC), polyethylene, polybutylene, and medium density polyethylene (MDPE).

The service life of all pipe materials is very important in potable water. This service life, however, is affected by a number of conditions including such things as water chemistry, microbial activity, climatic conditions, and corrosivity of the environment to which the pipe is exposed. In the case of cast iron and ductile iron pipe, the service life has been estimated at around 100 years; reinforced concrete, 50 years; and asbestos cement pipe; 30 years.[1] The service life of plastic pipes is uncertain because a large number of utilities is very reluctant to accept it as a replacement to the more traditional materials.

10.1.1 MATERIALS AND BIOFILM FORMATION

Materials which are exposed to potable water are the major contributor to biofilm formation. Biofilm development will form on any pipe material which is exposed to potable water. The factors known to affect this process include the length of the pipe network, the predominant pipe material, age of the pipe, number of breaks per year, corrosion, sediment accumulation, and zones of static water.

A number of piping materials have led to many consumer complaints, particularly owing to the formation of corrosion products deposited at consumers' taps as a result of microbial activity. As far back as 1916, leather washers were found to cause deterioration in the bacterial quality of water owing to the colonisation of bacteria.[2]

10.2 PIPING MATERIALS USED IN THE SUPPLY OF POTABLE WATER

Within building service lines and pipe networks, the choice of material for transporting potable water is dependant upon a number of factors including cost, durability, appearance, climate conditions, biodegradability, strength, thermal properties (with respect to hot water systems), and workability (fittings and jointing methods).[3] Traditionally, four main materials have been used in commercial and municipal buildings for the supply of potable water.[4] These have included lead, galvanised steel, copper, and black/galavanized iron. Each of these piping materials will be considered in turn.

10.2.1 LEAD

Lead is now prohibited as a new plumbing material in most European Community (EC) countries owing to the toxicity of the corrosion products formed which dissolve in the water (especially soft water) leading to concern about the public's health. Existing lead pipes are now being substituted with alternative materials. However, because of existing lead pipes which have not been replaced, the short term control measures being employed to reduce corrosion have involved the adjustments of pH in the potable water and the maintenance of central dosages of organophosphates.

10.2.2 GALVANISED STEEL

Generally, the use of zinc to coat steel pipes has provided a temporary measure in retarding corrosion and, thus, avoiding the formation of red water in stagnating plumbing systems. The good solubility of the zinc corrosion products (which are pH-dependant) and the uptake of zinc (and, possibly, lead and cadmium) into the water have led to a recommendation that galvanised steel pipes only be used in water with a pH greater than 7.3. Galvanised steels are widely used in hard water areas.

10.2.3 COPPER

Copper pipes have suffered many problems, notably from pitting corrosion, particularly in cold, hard waters, resulting in what is described as type 1 corrosion and in soft acid hot water (greater than 60°C) by type 2 corrosion which has been shown to accelerate if traces of manganese are present in the water. Copper has been shown to corrode if water velocities have exceeded 1.2 ms^{-1}. Despite this, the maximum permitted water velocities that govern the suitability for copper usage in potable water fall from 4 ms^{-1} at 10°C to 2.5 ms^{-1} at 70°C.[5] Corrosion of copper has also been shown to accelerate if water pH falls below 7.[6] Manufacturers believe that chlorine levels of 1 to 2 mg per litre pose no problems to copper. It also has been documented that copper is known to not corrode when it is exposed to mg per litre chlorine doses of 20 to 50 for 1 to 3 hours. Extreme caution, however, is necessary when using copper, particularly in the presence of high levels of carbon dioxide as this is known to increase corrosion rates. This also has been evident when copper is exposed to high temperatures.[7]

10.2.4 BLACK/GALVANIZED IRON

Black and galanized iron has been used only occasionally in potable water.[8]

10.2.5 NEW AND EMERGING MATERIALS USED IN THE TRANSPORT OF POTABLE WATER

The use of plastics, mainly PVC and MDPE, are beginning to replace traditional materials in potable water systems. However, polyvinyl plastics are known to leach chemicals and are very prone to sagging, particularly if water is left standing in them for long periods of time.[9]

As a legal requirement, materials used to transport potable water must not release chemicals at levels in excess of acceptable toxicity and health standards[10] (BS3505 and BS6920). Therefore, within hospitals and other municipal buildings, unplasticised PVC must be used in cold water systems only because they are known to leach toxic chemicals at high temperatures. The effect of chemicals leaching from plastics on human health is not known owing to a lack of documented research in this area.

In view of the continuing problem associated with piping materials,[11] particularly copper, stainless steel has been proposed as an alternative plumbing material for the supply of potable water in commercial buildings. However, there has been little documented research about its performance, effects on water quality, and susceptibility to biofilm development in potable water. One study has suggested that heavy metal ion leaching, specifically nickel, from stainless steel into potable water is evident, suggesting that this can be a temporary problem in newly plumbing piping systems.[12] However, this has since been rejected, provided that newly commissioned stainless steel piping is flushed through with potable water before any supply is made to the consumer. Any possible correlation between water quality and the different material qualities of stainless steel and the possible impact of increasing nickel allergies has not been researched at present. It is, however, unlikely that any correlation does exist as stainless steel has been found to be very stable in potable water, releasing only very low levels of metal ions into both potable water and biofilms.[13-15]

10.3 PROBLEMS ASSOCIATED WITH MATERIALS USED IN POTABLE WATER

10.3.1 CORROSION

Copper has long been the standard for many plumbing applications throughout the world,[16] with copper pipes representing 11% in Europe and 14% in the U.S. in 1989 of the total copper consumption.[17] However, problems encountered with copper piping when used for the plumbing of potable water systems in large institutional buildings (e.g., hospitals) have generated concern in various parts of the U.K.,[13,18,19] Germany,[20] Saudi Arabia,[21] and Japan. Problems noted are those of corrosion. The type of corrosion observed on copper takes the form of localised pitting or pinhole attacks evident on the inner surface of copper piping material which is generally confined to institutional buildings in soft water areas. Whilst pinhole corrosion does not result in catastrophic pipe failure, it does lead to severe shortening of a system's lifetime with disruption to the operation of municipal buildings, owing to increased incidences of repair work as a result of pipe failure and water leakage. Typical control regimes used in these systems included acid cleaning to disinfect the pipe material, filtration of the water to 0.2 μm, ultraviolet light treatment, and elevating temperatures to 60°C.[22]

Wagner, Fischer, and Paradies[23] have also described serious problems of copper corrosion in a county hospital in Germany, evident in cold and warm water systems, shortly after the hospital was opened. From this work, they established this so-called new type of corrosion characterised as

1. A biofilm consisting of polysaccharides.
2. Perforation of copper tubes in a short period of time.
3. Significant dissolution of copper into the potable water.[20]

Materials which were investigated as an alternative to copper as a result of premature corrosion in this German hospital, included stainless steel, cross-linked polyethylene (VPE), and polypropylene. It was found after 1 year that stainless steel piping used to carry potable water showed no evidence of general attack or pitting corrosion. A similar result was found in a hospital study conducted in Scotland even after 4 years exposure to potable water.[13]

Despite evidence of copper pipe corrosion in German hospitals, the exact cause has not been fully ascertained. Chamberlain et al.[24] have, however, shown that by using model polysaccharides, some of the copper corrosion events observed *in situ* could be studied and observed *in vitro*. They described similar results using exopolymeric substances produced from microorganisms isolated from perforated copper pipes. It has also been suggested that owing to the formation of an unequally distributed biofilm evident in potable water, local anodes form leading in some cases to the perforation of copper tubes. Therefore, the presence of copious amounts of exopolymeric substances and biofilm formation play a very crucial role in corrosion of copper in potable water environments.[24]

Cast iron pipes are also subjected to corrosion, often as a result of microbially induced corrosion owing to biofilm development. Corrosion of this nature often leads to coloured water and taste and odour problems which become an aesthetic problem to the consumer. However, on the public health side, corrosion of pipes is known to lead to a loss of chlorine residual, a depletion in oxygen levels, a reduction of sulphate to hydrogen sulfide, and a build up of iron precipitates in biofilms.[25,26] This, ultimately, generates an extensive ecosystem, protective haven, and niche for pathogens, but, in particular, faecal and total coliforms.

It is well documented that with the aging of a piping system comes accumulation of heavy scale corrosion products which leads to the restriction in the passage of water. This ultimately leads to pipeline breaks which causes bacterial colonisation and biofilm formation. Also, taste and odour problems may be generated and experienced by the consumer.

It has been extensively published that the major cited problems consumers experience include[25]

- Taste and odour—owing to algae,[27] bacteria (actinomycetes), iron/sulphate-reducing bacteria (*Desulfovibrio*),[28] and fungi.
- Red and cloudy water—owing to iron-oxidizing (*Gallionella* and *Leptothrix*) bacteria.[29]
- Black water—due to *Pseudomonas*, *Corynebacterium*, *Pedomicrobium*, and *Actinomycetes* as well as *Mycelia sterilia* (fungi imperfectants).[30]

10.3.2 THE MECHANISM OF MICROBIALLY INDUCED CORROSION (MIC) IN POTABLE WATER

Corrosion is viewed as a series of electrochemical reactions at a metal surface when exposed to an aqueous phase-containing electrolyte. It was not until recently that biological processes were implicated in corrosion. Microbially induced corrosion (MIC) has generally been considered as occurring in anaerobic environments where sulphide-producing bacteria are active, but now aerobes have also been implicated in this corrosion process.[31]

Corrosion may occur on submerged metal surfaces owing to uneven colonisation of microorganisms.[32] As the microorganisms at the metal surface replicate forming microcolonies, an uneven distribution of developing microcolonies may occur resulting in areas of heavy and light colonisation. In areas of bulk fluids which are aerated, the oxygen consumption by the surface-attached bacteria can create an oxygen gradient near the metal surface. Therefore, the higher concentrations of oxygen occurs where the biofilm is in contact with the bulk aqueous phase and the lowest concentrations develop at the bottom of the biofilm which is in contact with the metal surface (Figure 10.1).[33] This type of oxygen concentration cell is likely to develop where an uncolonised area of the surface is in contact with the oxygenated bulk phase and meets an area covered by colonies of oxygen respiring bacteria. This would result in the area under the microcolony being anodic to the area exposed to the bulk aqueous phase (Figure 10.2).[33]

Microorganisms may also facilitate the formation of differential aeration cells on metal surfaces where an uneven distribution of corrosion products develop, induced by abiotic factors. A short period of time after initial colonisation of bacteria, other microcolonies of different species develop next to one another and merge to form a biofilm. As these biofilms contain a diverse range of microorganisms, a range of microbial activity will take place. The biofilm will restrict the diffusion of products

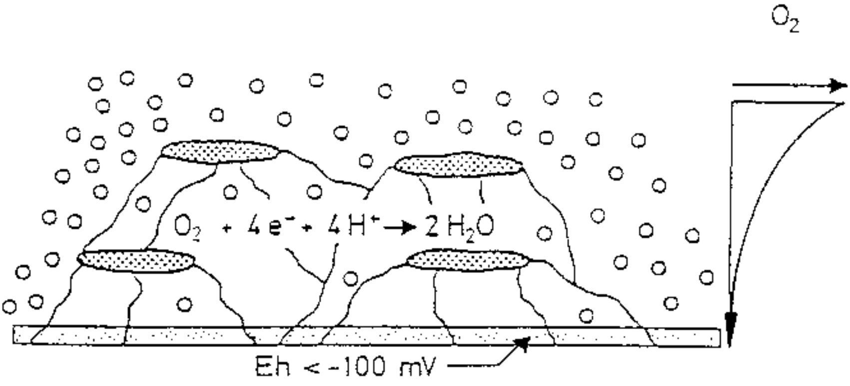

FIGURE 10.1 Oxygen concentration gradient in a biofilm caused by respiratory activity of microorganisms. From *Biofouling and Biocorrosion in Industrial Water Systems,* What is biocorrosion?, Flemming, H.C. and Geesey, G.G., Eds., 156, Copyright 1990, with permission from Springer-Verlag.

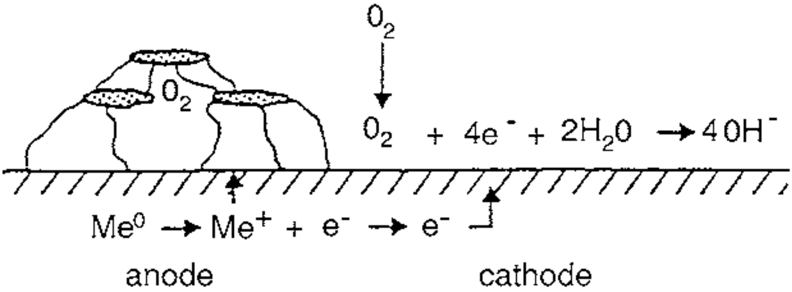

FIGURE 10.2 Differential aeration cell resulting from the heterogeneous distribution of biofilms. From *Biofouling and Biocorrosion in Industrial Water Systems,* What is biocorrosion?, Flemming, H.C. and Geesey, G.G., Eds., 156, Copyright 1990, with permission from Springer-Verlag.

of microbial metabolites excreted from cells in each microcolony. This will lead to very high concentrations of metabolic by-products at or near the underlying surface.[34] Where the surface is not compatible with the metabolites, corrosion may result.[35]

10.3.3 CHARACTERISTICS OF MATERIALS IN POTABLE WATER

Before any material can be worthy of usage within potable water systems, it must show a high tolerance to the effect of microbial adhesion, biofouling, and biofilm development.[36,37] The physico-chemical and energy characteristics of many materials depend on its surface finish and surface roughness.[38] Surface roughness can be measured by the use of stylus type surface tracing which gives average peak to valley height (Ra). Today, aided by computers a three-dimensional surface profile can be obtained. Atomic force microscopy should make it possible to visualise microorganisms adhering to surfaces with varying degrees of surface roughness.[39-42]

When a material comes in contact with potable water, microbes adhere, grow, and produce extracellular material eventually forming a biofilm (Figure 10.3) of a complex microbial community. Eventually, the polymers produced by the microbes become immobilised within a three-dimensional matrix of microbes and organic ions. The chemical composition of this matrix is heterogeneous, often containing polysaccharides, proteins, and nucleic acids which help govern the properties and functions of the biofilm and, ultimately, its effects on corrosion.

Biofilms which form within potable water depend upon the hydrodynamic conditions of the system. Within static conditions, biofilms form as a result of bacterial sedimentation with nutrients regularly replenished within this type of system (dead legs). With a dynamic flowing system, biofilms are often thicker. However, the thickness of this biofilm will depend on the flow velocity of the liquid.[43-45] Therefore, as well as considering a material for its suitability for usage in potable water, the effects of biofilm development on its long term performance must be determined before it can be commissoned ultimately for use.

After several days of being immersed into potable water, it is possible to rank different materials according to the number of attached cells in potable water: cast

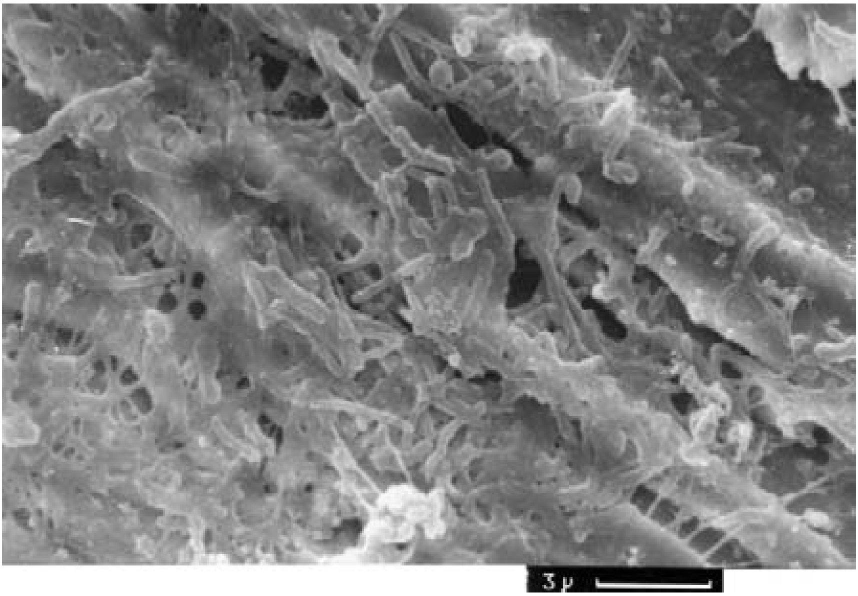

FIGURE 10.3 Biofilm in stainless steel potable water.

iron has a greater number of attached cells than does cement lined cast iron, which has a greater number of attached cells than does stainless steel.[46] Work completed recently has established that there are also significant differences between cast iron, medium density polyethylene (MDPE), and unplasticised polyvinyl chloride (uPVC) in drinking water.[47] Other research has found no significant differences in the accumulation of cells on copper, PVC, or iron surfaces,[48] but other work has contradicted this.[49]

Heat tint presence on the heat affected zone (HAZ) on some metal, but in particular stainless steel, has long been known to increase metal ion leaching and degradation of materials in high purity water.[50] Research work on MIC has also shown clearly that the removal of heat tint, by pickling or electropolishing, enhances resistance to both crevice corrosion and MIC. It now seems that the full inherent corrosion resistance of particular metals such as stainless steel is restored by preventing or removing heat tint.

10.4 NUISANCE ORGANISMS AND POTABLE WATER PROBLEMS

An important problem which is sometimes overlooked in piping materials is the fact that corrosion, as mentioned previously, can be induced by a number of microorganisms leading to the formation of MIC. The groups of microorganisms which bring about this effect can be classified as[51]

- Aerobic and facultative anaerobic heterotrophs.
- Autotrophic nitrifiers.
- Denitrifiers.
- Nitrogen fixers.

- Iron precipitating bacteria.
- Sulphate reducers.
- Sulphur oxidising.

It is acknowledged generally that in potable water there are a lot of microbes which constitute a nuisance rather than generating any public health concern. Therefore, problems associated with potable water must be found to be associated with biofilms rather than with free floating cells. A large variety of microorganisms have been found in biofilms attached to metal surfaces. The diversity of these microorganisms found within a biofilm which play a role in corrosion on these metal surfaces are shown in Table 10.1.[52]

The microbial composition of water samples and pipe corrosion deposits can be seen in Table 10.2.[51] The organisms in these biofilms range from viruses to complex multicellular organisms and can be divided into three main groups: algae, bacteria, and fungi.

TABLE 10.1
Microorganisms Associated with Corrosion

Microorganism	Growth Requirement	Corrosion and Related Problems
General aerobic microorganisms, e.g., *Aerobacter*, yeasts, moulds	Water carbon source, nitrogen and phosphorous, trace elements	Differential aeration cells
General anaerobic microorganisms	Water, carbon source, nitrogen and phosphorous, trace elements	Produces organic acids that preferentially chelate specific alloying elements
Iron-oxidizing bacteria	Water CO_2, oxygen, ferrous materials, nitrogen and phosphorus, trace elements	Oxidize ferrous (+2) to ferric (+3), cause blockage of pipes, create anaerobic conditions
Nitrite-oxidizing bacteria	Water, nitrate, carbon sources, phosphorus, trace elements, ammonia, and aeration	Consume nitrite corrosion inhibitors, differential aeration cell
Nitrate-reducing bacteria	Water, carbon source, nitrogen and phosphorus, sulphate, trace elements	Reduce nitrate, produce large quantities of organic acids
Pseudomonas sp.	Water, hydrocarbons, nitrogen and phosphorus, trace elements, manganese and iron, aeration	Skin infections, provide material for anaerobic organisms, differential aeration cell
Sulfur-oxidising bacteria	Water, sulphides or sulphur, CO_2, nitrogen and phosphorus, trace elements, oxygen	Produces up to 10% H_2SO_4, concrete attack
SRB	Water, carbon source, nitrogen and phosphorus, trace elements	Produce large quantities of sulfide, sever localized corrosion

Source: Adapted from Videla, H.E., *Manual of Biocorrosion*, ©1996, CRC Press, with permission. Reproduced with permission of Stein, A.A., MIC treatment and prevention, in *Practical Manual on Microbiologically Influenced Corrosion*, Kobrin, G., Ed., NACE International, Houston, TX, 1993, 101. NACE International is the copyright holder of this table.

TABLE 10.2
Microbial Composition of Water Samples and Pipe Corrosion Deposits

	Untreated Water (August (1989)		Untreated Water (March 1990)		Treated Water (March 1990)		Corrosion Tubercles	
Microorganisms	**20°C**	**8°C**	**20°C**	**8°C**	**20°C**	**8°C**	**20°C**	**8°C**
Aerobic SPC[a]	2.2 ¥ 10^6	1.5 ¥ 10^5	3.2 ¥ 10^4	9 ¥ 10^3	20	ND	2.9 ¥ 10^7	2.0 ¥ 10^6
Anaerobic SPC[a]	2.0 ¥ 10^1	ND	1.0 ¥ 10^1	ND	<1	ND	3.0 ¥ 10^6	ND
Total coliforms[b]	570	350	200	75	<1	ND	5.0 ¥ 10^4	ND
Fungal SPC[c]	4.8 ¥ 10^4	2.1 ¥ 10^2	3.5 ¥ 10^3	2.0¥10^2	3	ND	3.0 ¥ 10^5	7.8 ¥ 10^2
Iron reducers[d]	540	240	70	49	<0.3	<0.3	>24,000	430
Sulfate reducers[e]	280	130	<3	<3	<0.3	<0.3	280	110
Sulfite reducers[e]	120	93	4	4	<0.3	<0.3	460	210
Thiosulfate reducers[e]	540	170	240	79	9.3	1.5	920	540
Iron oxidizers[f]	54	24	7.9	7	<0.3	<0.3	75	64

[a] Cfu/ml (water) or cfu/g (corrosion tubercle), 7-day incubation at 20°C, 10-day incubation at 8°C.

[b] Cfu/ml (water) or cfu/g (corrosion tubercle), 48-day incubation at 35°C, 10-day incubation at 8°C.

[c] Cfu/ml (water) or cfu/g (corrosion tubercle), 7-day incubation at 20°C, 10-day incubation at 8°C.

[d] Organisms/ml (water) or cfu/g (corrosion tubercle), by 5-tube MPN, using dilutions of 1.0–0.0001 ml in B_{10} broth, 14-day incubation.

[e] Organisms/ml (water) or cfu/g (corrosion tubercle), by 5-tube MPN, using dilutions of 1.0–0.0001 ml in Butlin's broth and either 1% (v/v) Na_2SO_4, Na_2SO_3, or $Na_2S_2O_3$,14-day incubation.

[f] Organisms/ml (water) or cfu/g (corrosion tubercle), by 5-tube MPN, using dilutions of 1.0–0.0001 ml in modified Winogradsky's broth,14-day incubation.

Source: From Geldreich.[51]

10.4.1 ALGAE AND DIATOMS

Algae are mainly microscopic organisms, but some algae such as seaweeds are macroscopic. Algae are important fouling organisms in biofilms exposed to light because algae contain chloroplasts and are capable of photosynthesis. They are classified into seven divisions based on their morphology. The main groups of algae are green algae, red algae, brown algae, and diatoms. They play an important part in MIC owing to their ability to produce molecular oxygen, corrosive organic acids, slime, and nutrients for other microorganisms involved in MIC.[35] It is highly unlikely that these will be present in potable water in a viable state (owing to a lack of sunlight in the closed system).

Microalgae have been reported to affect electrochemical reactions directly. The diatom species, *Nitzchia*, has been shown to bring about a reduction in corrosion by causing cathodic polarisation.[35] Conversely, *Achnantles* was found to induce cathodic depolarisation. Of cyanobacterium, two species have been implicated in the corrosion of stainless steel.[32] As with macroscopic algae, diatoms are known not to proliferate in potable water owing to the restriction of a light source. However, diatoms are known to become entrapped in biofilms present in potable water. The number of different species present in these biofilm is quite large [Figures 10.4(a)–(e)]. Whether diatoms have any significance in potable water is presently an area which has not been investigated.

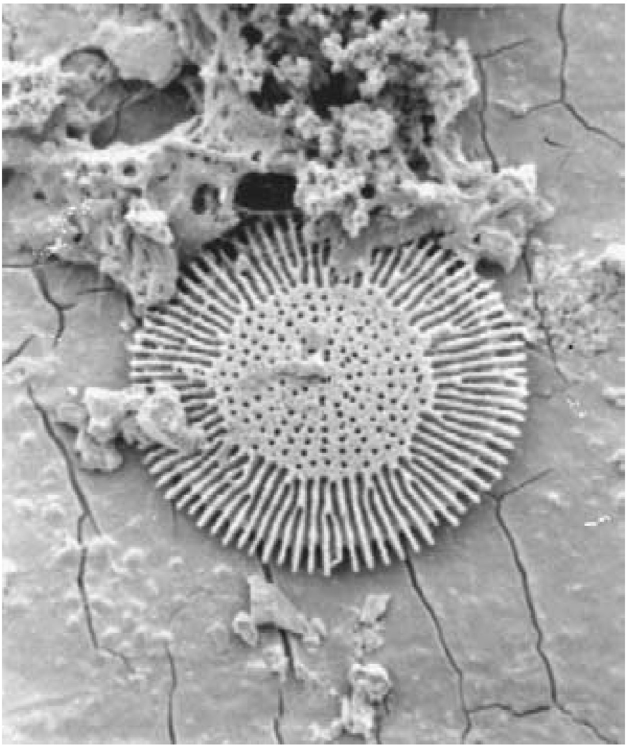

FIGURE 10.4a Diatom associated with surfaces in potable water.

FIGURE 10.4b Diatom associated with surfaces in potable water.

10.4.2 Bacteria

10.4.2.1 Sulphate Reducing Bacteria

Bacteria are the primary organisms in most biofilms. Perhaps the most important biofilm bacteria associated with MIC are sulphate reducing bacteria (SRBs). The biochemistry and physiology of SRBs have been described by Postgate.[53] SRBs are anaerobic chemoheterotrophs that are physiologically and ecologically homogeneous. They derive their carbon and energy from organic nutrients and use sulphate as a terminal electron acceptor with the production of sulphide.[31] The production of hydrogen sulphide at the end of its metabolic pathway is generally found to be corrosive toward metal surfaces. SRBs are located deep in biofilms where anaerobic conditions prevail. They are known to utilise short chain organic acids released by other organisms present in a biofilm.[54] As these bacteria utilise the available organic nutrients, hydrogen sulphide is produced leading to the development of a foul odour.

SRBs constitute a very diverse range of organisms. The most commonly encountered organisms are *Desulfovibrio*, *Thiobacillus*, *Beggiatoa*, *Thiodendran*, and *Thiothrix*. However, sulphur oxidising bacteria, that is, *Thiobacillus* have been reported to have an important role in the association with microbiological fouling. Sulphur

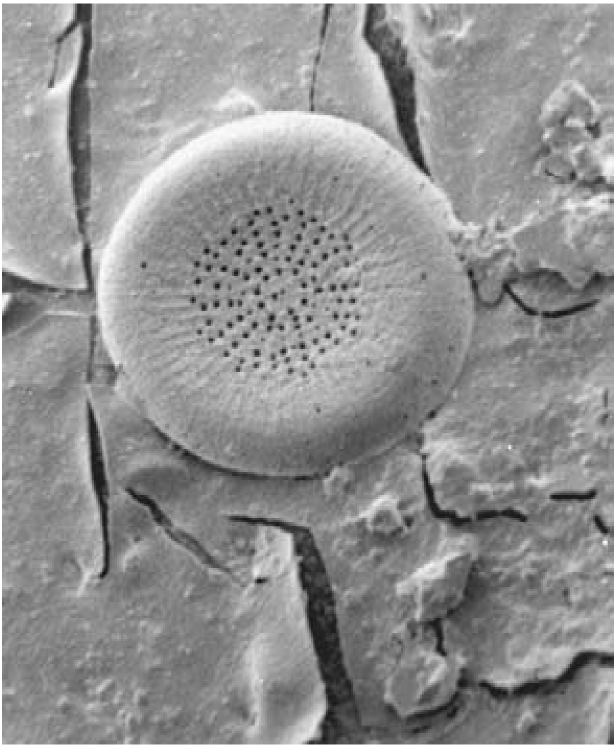

FIGURE 10.4c Diatom associated with surfaces in potable water.

oxidising bacteria are often found in the association with SRBs, forming a consortium known as a sulphuretum, where oxidised and reduced sulphur environments will alternate.

10.4.2.2 Iron Bacteria

Iron precipitating bacteria are generally located in biofilms which produce tubercles in iron pipes leading to a reduction in water flow. Examples of these organisms include *Crenothrix polyspora* and *Sphaerotilus natans*. Others include *Gallionella*, *Hyphomicrobium*, and *Caulobacter.*

Iron oxidising bacteria obtain energy by oxidising ferrous ions (Fe^{2+}) to ferric ions (Fe^{3+}). They have been associated with the corrosion of water systems.[32] The main group of iron oxidising bacteria include the filamentous genus *Sphaerotilus*, its related forms, *Crenothrix* and *Leptothrix* species, and the unicellular stalked bacterium *Gallionella*. These bacteria are often found in association with sulphate reducing and oxidising bacteria.[55] *Pedomicrobium manganicum* has also been shown to be able to oxidise ferrous iron on stainless steel.[32] It also has been known to oxidise manganese in potable water systems and bind MnO_2 in its extracellular polysaccharides.[56]

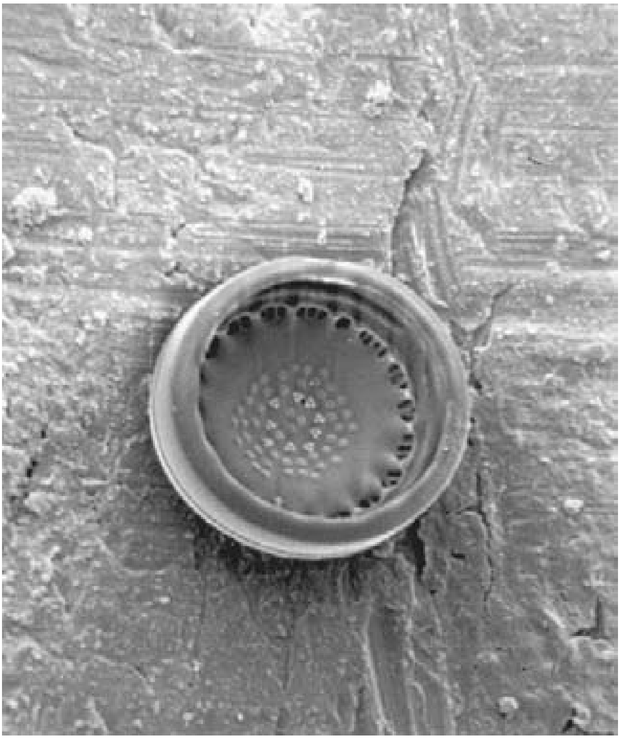

FIGURE 10.4d Diatom associated with surfaces in potable water.

Iron reducing bacteria include *Pseudomonas* sp. which have been implicated in the reduction of Ferric (Fe^{3+}) to ferrous iron (Fe^{2+}). Bacteria capable of reducing Fe^{3+} anoxically include *Bacillus*, *Pseudomonas*, *Micrococcus*, *Corynebacterium*, *Alcaligenes*, and *Vibrio*, to name but a few.[57] Particularly, *Pseudomonas* and *Bacillus* sp. are the most common iron oxidising bacteria found in water distribution systems.[37]

10.4.2.3 Nitrogen Bacteria

Nitrogen utilising bacteria are involved in the recycling of nitrogen compounds. Aerobic species, such as *Nitrosomonas*, will oxidise ammonia to nitrite which in turn is oxidised to nitrate by *Nitrobacter* spp. These organisms rarely exist in isolation and are usually part of a complex consortial biofilm.

10.4.2.4 Manganese Utilising Bacteria

Manganese utilising bacteria generally lead to the creation of black water. Organisms which have been located in a biofilm that ultilises manganese (greater than 0.01 to 0.5 mg per litre) include *Pseudomonas*, *Arthrobacter*, *Hyphomicrobium*, and *Sphaerotilus discophorus*.[58]

FIGURE 10.4e Diatom associated with surfaces in potable water.

10.4.2.5 Fungi

Microfungi grow saprophytically on nonliving organic material deriving energy from fermentation or oxidation. Organic acids, produced as an end product in fungal biochemical reactions, are generally corrosive to metal surfaces particularly when associated with biofilms.

10.5 CHARACTERISTICS OF MATERIALS WHICH HAVE EFFECTS ON BIOFILM FORMATION

The welded joints of metal pipes found in potable water have enormous potential for bacterial adhesion and, ultimately, biofouling, owing the large surface area available for attachment (Figure 10.5).

Recent research into the factors influencing microbiological corrosion of stainless steel indicates that welding reduces the resistance of stainless steel against MIC. Punter[50] found no cases of stainless steel corrosion on stainless steel samples without a weld. The usage and performance of stainless steel in potable water may be largely determined by the way in which the pipe surfaces are cleaned and disinfected. Optimisation of the cleaning and disinfecting procedures appears to be a way to achieve control over MIC of stainless steel.[38]

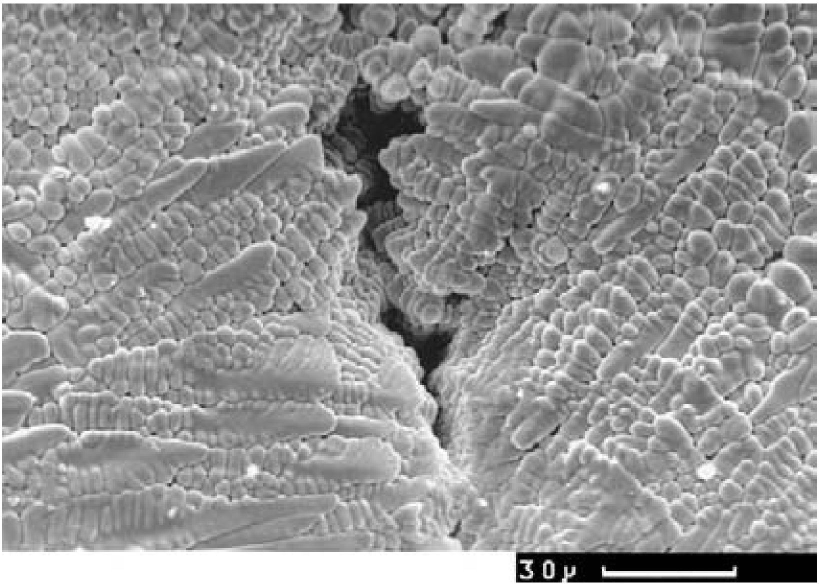

FIGURE 10.5 Weld showing the presence of large pores which aid in bacterial attachment.

When materials are used in potable water environments for the first time, MIC must be viewed as a possibility. However, provided that specific guidelines and certain measures are undertaken, metallic materials used in potable water have been known to have very long service lives.

10.6 THE USE OF STAINLESS STEEL IN POTABLE WATER

Domestic potable water installations are part of the distribution system which ends at the consumer's tap. Many decades ago, concerns were mainly owing to the technical quality of the materials and the plumbing system with regard to failures by water hydraulics, whereas water quality supplied to the consumer was not a major concern. However, priorities have changed in Europe within the last decade owing to the EC directive on Potable Water and the National Potable Water Regulations. Although stainless steel is not a standard material for distribution systems, it has acted as a materials solution in several problem areas. These have included pipe attachments to bridge spans, trenchless piping, New York City risers, and laterals. Other examples are those in Japan, Sweden, and Italy where PVC and ductile mains water pipes are being replaced by grade 316 stainless steel following 10 years of testing.

During the 1960s, new homes in numerous counties of England were plumbed with type 302 (UNS S30200) light gauge stainless steel tubing in lieu of copper (which was more expensive at the time). These installations were made with the approval of the British Water Works Association. The principal producer of stainless steel pipe in England estimated that approximately 16.4 million feet of pipe used to transport potable water was placed in service during the 1966 to 1982 period. Tuthill,[59] through extensive surveys, found that 5 counties that had stainless steel pipe in service for 20 years or more had no problems with stainless steel pipe failure and corrosion. This study established that stainless steel could be used as a long term viable piping system for transporting potable water. However, owing to high stainless steel prices at the time, it was never fully commisioned as a cost-effective alternative to copper for transporting potable water.

Today, areas in Tokyo, New York, and the Middle East have used stainless steel for certain areas of their potable water distribution systems, reestablishing evidence on the long term performance and sustainability of stainless steel. In Tokyo, after a period of 10 years of evaluating candidate materials, the Water Works Bureau of Tokyo (WBT) in 1980 began replacing leaking connectors, joining the street submains to the dwellings outside meters, with 1 inch (internal diameter) type 316 piping.[60] After 11 years of use, there have been no reported internal or external corrosion of any of the stainless steel connectors. System leakage had also been dramatically reduced.[61]

In the U.S., the Bureau of Water Supply in New York, after extensively evaluating materials for use in the Rondout Reservoir, selected 304 stainless steel pipes for valves in piping systems.[61] After a period of 6 years, only 1 instance of corrosion had been reported with these valves, which was owed to water being left stagnant in the pipeline for several months.

In the Middle East, purified water from desalination plants is blended with local groundwater for potable use. The piping used to transport this water is welded, large diameter stainless steel, typically 24 inch, and usually grade 316L. Some leakage problems were recorded in three of these plants, owing to an uncontrolled usage of hypochlorite which had been left standing in the piping system. These failures, as in New York, were attributed to overchlorination.[59]

Stainless steel piping has been used instead of ductile iron in more than 30 potable water treatment plants in the U.S., largely because of the financial savings.[61] Savings from the use of stainless steel over ductile iron were estimated at $50,000 for the Tauton potable water plant in Massachusetts.[62]

Therefore, the performance of stainless steel in potable water has led to an increase in consumer confidence for usage. With a good understanding of fabrication and post fabrication of stainless steel, combined with a knowledge of the effects of chloride levels, oxidants, and conditions which may lead to both crevice and MIC, it is feasible that stainless steel has a service life of 100 years.[63]

10.6.1 COMPOSITION AND PHYSICAL CHARACTERISTICS OF STAINLESS STEEL

There are a number of grades of stainless steel with different compositions and properties and, consequently, different uses. Stainless steels are alloy steels which in addition to iron, contain chromium, nickel, molybdenum (grade 316), and small amounts of other elements. This can be seen in Table 10.3. Types 304 and 304L are the most widely used basic grades of chromium-nickel stainless steels which are

TABLE 10.3
Chemical Composition (%/wt) of Stainless Steel 304 and 316 Pipe Sections (Avesta Sheffield Ltd.)

Elements	Pipe 304	Pipe 316
C	0.054	0.022
Si	0.420	0.410
Mn	1.860	1.500
P	0.023	0.024
S	0.0120	0.002
Cr	18.20	16.730
Mo	0.170	2.040
Ni	10.190	10.980
Nb	0.010	0.010
Co	0.110	0.160
Cu	0.150	0.190
Sn	0.010	0.012
W	0.040	0.130
N	0.079	0.049
V	0.050	0.050

used for potable water applications. Types 316 and 316L are the more corrosion-resistant grades which, in addition to chromium and nickel, contain molybdenum and are shown to be a better performer in potable waters than the 304 grades.[64]

Stainless steels have an oxide film on the surface, composed of oxy-hydroxide of chromium and iron,[65] and are referred to as a passive film. This makes the steel resistant to corrosion in aggressive, acid, or neutral-chlorinated solutions. The composition of the passive layer depends on the metal substratum, the surface finishing treatment (annealing or pickling), and the medium in which it is immersed.[66] Whilst the passive film present is a tough durable oxide layer, it occasionally may contain defects. It is at such defects that stainless steel may corrode when environmental conditions become aggressive enough to take advantage of any weakness in the film. Stainless steel grades 304 and 316, with a 2B finish, have been found to exhibit a surface oxide layer containing mainly chromium, oxygen, iron, and carbon. Energy dispersive X-ray analysis and electron spectroscopy for chemical analysis of the surfaces of stainless steel grades 304 and 316 have confirmed the presence of chromium, manganese, iron, and nickel in the oxide layer with molybdenum identified only on the surface of stainless steel grade 316.[64]

In the continued effort to enhance corrosion resistance, elements such as nickel, molybdenum, and titanium have been added to stainless steel. The result is alloys with strength and corrosion resistance best demonstrated by the 300 series.[67] Molybdenum greatly enhances resistance to localised corrosion which gives grade 316 steel an advantage over grade 304. The low levels of carbon present in grades 304

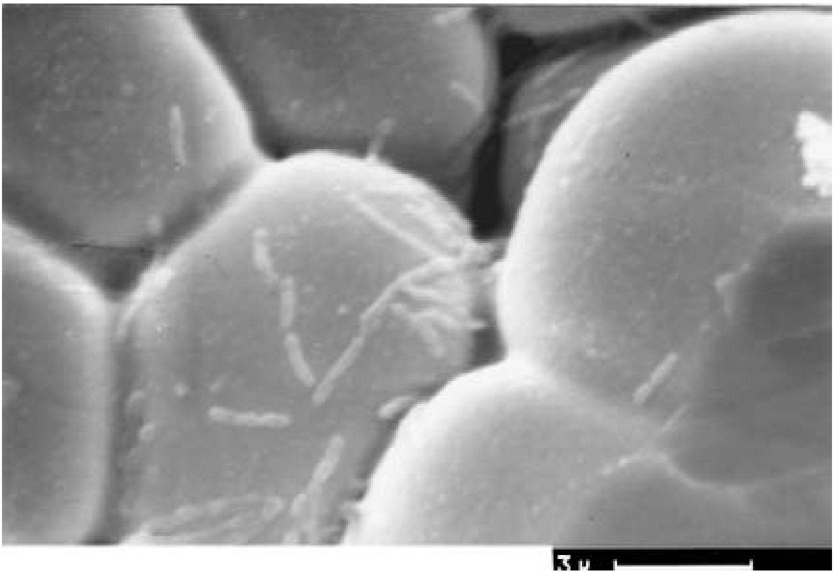

FIGURE 10.6 Small colonies of bacteria observed on stainless steel after exposure to potable water.

and 316 stainless steel should not give rise to significant problems associated with welding of these alloys. However, special low carbon (less than 0.03%) grades, 304L and 316L, are available for certain welding applications and provide greater resistance to corrosion in potable water.

On stainless steel, two surface finishes, available commercially, are generally used in the transport of potable water. These include the 2B pickled finish and the 2R bright annealed finish. However, a 2D surface finish may also be used (Table 10.4). Stainless steel is obtained industrially by direct continous casting of slabs, which are hot-rolled. Following this process, the stainless steel sheets are subsequently annealed and then cold-rolled into a tube. A final annealing follows and, in some cases, the sheet is pickled if the annealing has been done in an oxidising atmosphere (the surface quality is then designated 2D finish). To avoid the final pickling process, the steel is annealed in a protective atmosphere, giving a bright

TABLE 10.4
Surface Finishes Available on Stainless Steel (from BS 1449: Part 2)

Finishes	Description	Comments
2D	Cold rolled, softened, and descaled	A matt finish for general applications
2B	Cold rolled, softened, descaled, and lightly rolled on polished rolls	A smooth finish for general applications, brighter than 2D finish
2A	Bright annealed	A cold-rolled reflective finish retained through annealing

finish designated 2R in France and BA in the U.S. With the 2D finish, a skin-pass operation is carried out to enhance the final brightness, the surface quality so obtained being designated 2B or pickling finish. To achieve finish 4, 2D, or 2R pipe surfaces sheets are polished with fine-grained polishing belts. For stainless steel, both basic surface composition and roughness differ according to the type of finish required with roughness increasing with the thickness of the metal sheet and tube.[68] The surface finish determines the energy characteristics of stainless steel which will have very important implications on the adhesion rate of potable water bacteria and pathogens. However, the role of surface finish with respect to bacterial adhesion has not yet been determined clearly, but it may be assumed that stainless steel with the smoothest finish would have the lower initial bacterial adhesion rate in potable water.[14]

10.6.2 A Comparison of Biofilm Development on Stainless Steel Grades 304 and 316 and Other Materials in Potable Water

Recent work on the use of stainless steel in potable water supplies has established some very interesting results suggesting differences between stainless steel grades 304 and 316 commissioned for use in potable water.[13,14,42,64] It is well known that metallic surfaces play an important role in the early stages of biofilm development, influencing both the rate of microbial adhesion and the distribution of these cells.[69] An area of particular importance is surface roughness where increasing surface roughness generally increases microbial colonisation.[70–72] It has also been found that porous welds, an observed characteristic of stainless steel 304 pipe weld, may provide increased sites for colonisation and ultimately biofilm formation.[13,73,64]

Scanning electron micrographs taken of the surface of stainless steel following exposure to potable water have confirmed that microorganisms accumulate at discontinuities on the submerged stainless steel surfaces.[64,72,74] The effect of surface roughness on surface conditioning (organic) and on subsequent adhesion and biofilm formation on stainless steel in potable water is of interest. Because all surfaces immersed in potable water environments are rapidly coated with a biological layer (conditioning film), it is presumed that both smooth and roughened surfaces will be coated. However, the hydrophobicity of the surface, the nature of the environment, and the degree and type of surface rugosity may well determine the nature and amount of conditioning film. The surface might be coated with a thin conditioning film which mirrors surface irregularities or the coating might be uneven, related to flow in a moving system. These features may well influence the speed of microbial deposition and the type of organisms colonising surfaces and, therefore, may have an effect on the corrosion rates of these two stainless steel grades particularly in potable water.

Previous research on biofilm formation on stainless steel in potable water has shown that matt stainless steel (of unknown grade, which was characterised as rough) accumulated 1.44 times more microbes than electropolished stainless steel.[44,69] This would suggest that stainless steel with a smooth surface finish decreases the adhesion of microorganisms.

FIGURE 10.7 Evidence of small and single colonies in potable water.

In all potable water-based studies colonisation of bacteria on the stainless steel surfaces observed using epifluorescence and scanning electron microscopy has been found to be patchy, consisting of small colonies (Figure 10.6) and single cells (Figure 10.7). There seems to be no uniform microbial colonisation of either stainless steel grades in potable water. Scanning electron microscopy has revealed several types of sessile microorganisms including rod-shaped bacteria, coccoid bacteria, spiral bacteria, filamentous bacteria, curved rods, yeast cells, many different species of diatoms, and fungal hyphae attached to stainless steel in potable water. These microbial colonies are generally found to be present in crevices and fissures on the stainless steel surfaces, particularly at high velocities.

From studies looking at stainless steel in potable water, it is generally found that grade 304 is colonised by bacteria at a higher rate than grade 316. Studies have also found that molybdenum, present in the passive layer of grade 316, has an effect on bacterial growth in potable water by reducing the viability and biofilm development of heterotrophic and sulphate reducing bacteria.[75-77]

10.7 EFFECTS OF DISINFECTANTS ON STAINLESS STEEL AND OTHER MATERIALS IN POTABLE WATER

Chlorination of potable water is standard practice, providing excellent protection against bacterial strains that cause either public health problems or microbiologically induced corrosion. Also, the material chosen to distribute potable water must not have effects on demand for chlorine because this will have effects on the disinfection process and, ultimately, reduce chlorine availability to treat water. Within iron pipes, chlorine doses as high as 4 mg per litre have been shown to have little impact on biofilm reduction because iron corrosion products interfere with free chlorine disinfection. It is often found that the chlorine demand is 10 times higher in iron pipes than other pipes of other composition.[78,79]

Other considerations that need to be taken into account for the use of materials used in potable water is the effect chlorine may have on increasing the potential to cause corrosion on certain metals. For example, it is often documented that chlorine has to be administered with care when using stainless steel so as not to leave too high a chorine residual known to have effects on its corrosion potential. There are situations in which corrosion (MIC) appears to have occurred on stainless steel, owing to high levels of residual chlorine. These have been identified in water treatment plants on the welds on 304L stainless steel piping. This seems to be owing to hydro-test water being left standing in the stainless steel piping for a month or more, allowing bacteria to induce microbiologically induced corrosion.[59] Type 304 stainless steel is generally acceptable for chloride levels up to 200 mg per litre chloride and 316 for levels up to 1000 mg per litre.

Sedimentation water found within crevices (such as those that originate from incomplete fusion of the circumferential weld) of stainless steel under some conditions can lead to localised pitting-type attacks on stainless steel if chlorides are present in sufficient concentrations. Crevice corrosion of type 304 stainless steel is rare at below 1000 mg per litre chlorides.[80] However, crevice corrosion can occur in water of lower chloride content, particularly if a mechanism of chlorine concentration is present. With respect to copper, the highest corrosion probability is observed for intensively branched, horizontally installed pipework with prolonged periods of stagnation.[20]

Research has shown that low carbon grades of stainless steel—types 304L and 316L avoid corrosion in the heat affected zone (HAZ) of welds at the 1 to 2 mg per litre residual chlorine concentrations normally encountered in potable water. Type 316/316L is resistant up to 5 mg per litre residual chlorine. Studies indicate that type 316L would be a safer choice than type 304L when higher residual chlorine is encountered.[59]

When chlorine is added to manganese-bearing waters with oxidising bacteria such as *Gallionella*, a self-sustaining corrosion reaction is initiated, resulting in severe pitting of stainless steel.[81] Although corrosion of this type has not been reported in potable water plants, it is possible and should be considered when raw waters contain appreciable manganese.

10.8 CONCLUSION

Pipe materials are the most extensive part of any potable water system. The characteristics of a piping material are fundamental to the development of a biofilm. Other factors which need to be taken into account when evaluating materials for the transport of potable water are the length of the pipe needed, the predominant pipe material, the age of the pipe, corrosion, and zones of static water. Whilst cast iron has been in use for over 280 years, the choice of materials used to transport potable water are immense. The choice of material used to transport potable water lies with respect to its application. For example, copper would never be used in a water distribution system. However that was often said of stainless steel, but now it is being used as a piping material in water distribution particularly in Turin, Italy. However as a general understanding, the choice of material for long runs of distribution pipe include ductile iron, cast iron lined with cement, steel, reinforced concrete, and PVC. Within service lines and building pipe networks, the most predominately used materials are plastics and copper. However, stainless steel is beginning to replace traditional materials such as these.

Overall, stainless steel is a very worthy candidate for the replacement of copper as a domestic and industrial potable water supply pipe system, particularly in areas where corrosion is proliferate. They have extremely low corrosion rates in potable water and are 100% recyclable. Stainless steel can handle turbulent high velocity waters and provide a long service life providing proper operational repair is applied. However, research on the usage and overall performance of stainless steel in potable systems is very limited, suggesting this is a very important area for future investigations.[13] More research is necessary on metal ion leaching from stainless steel into potable waters, particularly owing to changes in the EC standards for metal ions within potable water, and the effects of residual chlorine on the corrosion potential of stainless steel. Also, all aspects of biofilm development, particularly consortial development, paying particular attention to pathogenic and coliform inhibition, is a necessity if this metal's overall performance is going to be fully accepted for use in potable water.

Stainless steel is a very cost effective material of construction when compared with the more traditional construction materials which are used in potable water.

Guidelines are available for the installation and usage of stainless steel within institutional buildings' plumbing systems, particularly hospitals.[9] This suggests that the use of stainless steel within municipal buildings' plumbing systems is becoming more widespread and dependable, confirming stainless steel as a reliable alternative to the normal traditional materials such as copper.

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