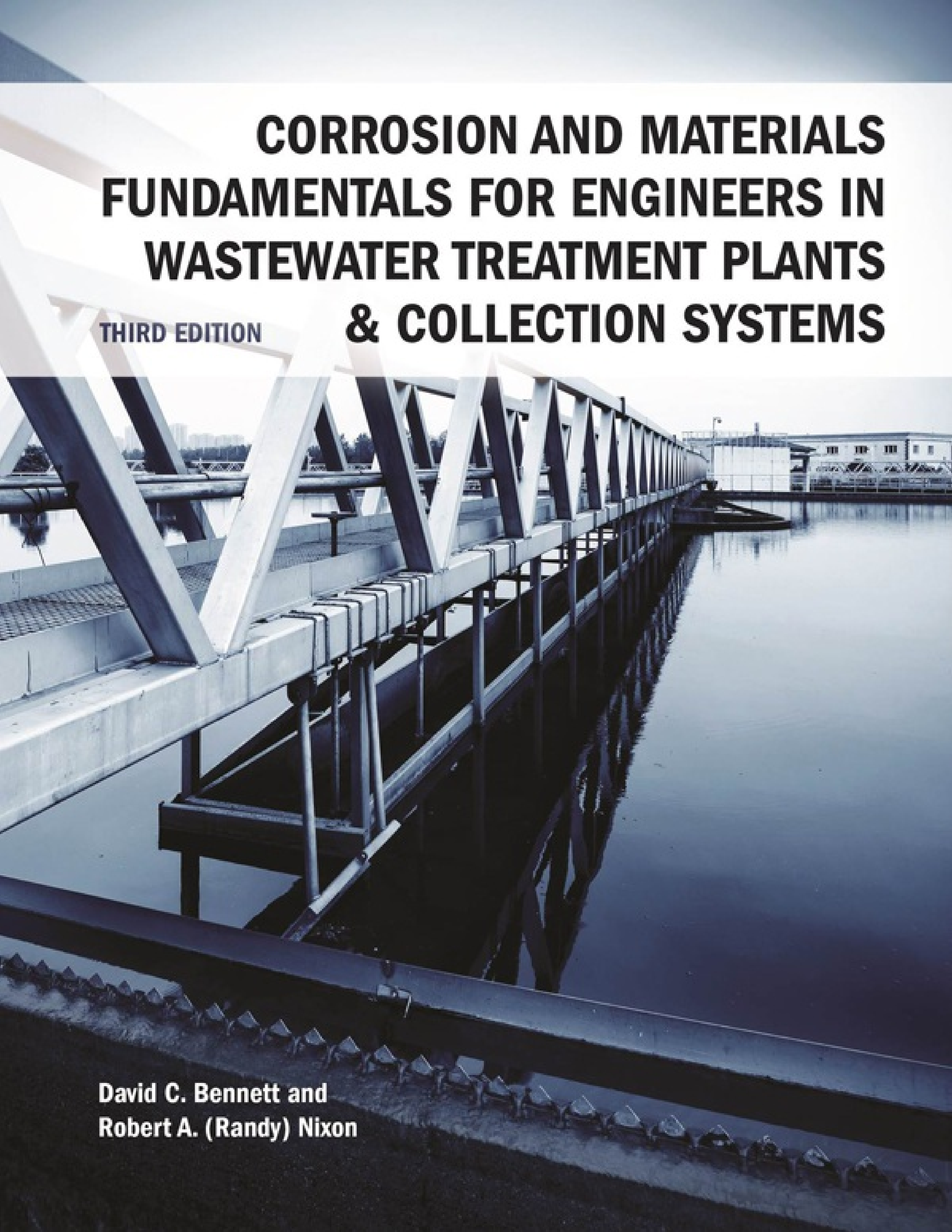

CORROSION AND MATERIALS FUNDAMENTALS FOR ENGINEERS IN WASTEWATER TREATMENT PLANTS & COLLECTION SYSTEMS

THIRD EDITION

David C. Bennett and
Robert A. (Randy) Nixon

Corrosion and Materials Fundamentals for Engineers

in Wastewater Treatment Plants & Collection Systems

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The practical recommendations, guidelines, and information in this handbook reflect the modern and generally accepted engineering practices encountered and evolved in the authors' decades of corrosion and materials engineering experience in water and wastewater treatment plants, as well as in chemical process plants and pulp and paper mills all over North America. The guidance and recommendations in this handbook should be interpreted and applied with proper engineering judgment and modified for local conditions and circumstances. The authors and their employer, Corrosion Probe, Inc., assume no liability whatsoever for any personal harm or injury, loss and damage to property, consequential loss or damage, or economic loss resulting from use of the content, recommendations, and guidance in this handbook.

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Foreword

The scale of the water purification and wastewater (sewage) treatment industries is immense. Enormous volumes of water are cleaned for safe consumption and for other purposes: approximately 35 billion gallons of water are prepared daily for domestic use in the US, and about as much is treated for industrial use. This water is distributed and resulting wastewater is collected in more than 1 million miles of pipe and sewer systems. Many urban wastewater systems are more than 60 years old. Old age is not its own problem, depending on the materials of construction, but awareness and knowledge of the corrosion mechanisms and how to mitigate them continues to expand significantly, especially over the past 30 years.

Our primary purpose with this handbook is to educate engineers and maintenance personnel who design, operate, and maintain large, multi–stage wastewater treatment plants (WWTP) in municipal and industrial service, on the basics of corrosion of metals and degradation of non–metals, including concrete, and how to mitigate them. Our aim is to provide enough knowledge about the damage mechanisms affecting construction materials for the reader to design and cost–effectively maintain the different types of fixed equipment, including tanks, pressure vessels, basins, stacks, foundations, piping, structures, etc., in the WWTP and collection systems.

Compared to typical process environments in chemical, petrochemical, and pulp and paper plants, process environments in water and wastewater treatment plants are benign from a corrosion standpoint. Predictable properties of WWTP environments makes the corrosion mechanisms and rates for common construction materials predictable. We believe it is precisely because corrosion of fixed equipment is slow and predictable that corrosion and material problems in wastewater treatment plants often go unattended until the failure or advanced deterioration threatens the equipment's and the plant's reliability.

Luckily for the people responsible for controlling corrosion in a WWTP, the metal and non–metal corrosion mechanisms have been extensively studied. Good understanding of the damage mechanisms obtained from reading this book will help the plant engineers control the costs of corrosion and increase the durability and reliability of facilities and equipment. The management goal should be No surprises at lowest cost! As shown in the Table of Contents, we describe the water and wastewater environments; list the corrosion and physical damage mechanisms that affect common materials of construction, including concrete, cast iron, carbon steel, stainless steel, and aluminum alloys; and provide practical guidance for mitigating the damage mechanisms and solving many corrosion problems, often by using modern alloys and materials and proven corrosion mitigation technologies.

We welcome suggestions and comments on how we can improve this handbook to more effectively meet our goal of educating our readers—please contact us at the address below.

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Figure 1. Aerial view of large wastewater treatment plant, showing circular clarifiers and digesters

and rectangular tanks for grit removal and aeration. (This New Jersey plant sells dried sludge waste as a soil–enhancing material). Photo retrieved from Google Earth.

1 Corroding Environments

1.1 Corrosiveness of wastewaters

“Wastewater” in a municipal utility consists of solutions of mildly aggressive contaminants and suspended solids in water that was “used” for domestic, recreational, and light industrial sanitation purposes. Contaminants in raw wastewater or sewage from domestic sources typically include fats, oils, greases, soaps, detergents, as well as other organic materials, dirt, plastics, human waste, and food waste. Wastewater streams are typically very dilute. Typical dissolved solids concentration is under 0.5%, or 5,000 mg/l (ppm) and suspended solids level also is low. Wastewater flowing into some treatment plants may be augmented by stormwater runoff, with all of its contaminants.

Common dissolved contaminants in domestic wastewater are chloride, sulfate and phosphate ions, nitrogen compounds, and a wide variety of organic solvents and compounds. The pH of domestically generated wastewater is normally between 6 and 9. Higher levels of soaps and kitchen and laundry products, most of which are alkaline for better degreasing effectiveness, moves the pH level to the higher end of that range.

Wastewater streams from industrial facilities often contain more contaminants than domestic wastewater. However, most industrial waste streams today are treated at the source to meet discharge permit limits set by the receiving WWTP. They test for pH, organics, dissolved salts, and heavy metal ions.

Wastewater is aerated (contains dissolved oxygen) in most parts of the wastewater system, except where microbiological (septic) activity consumes the dissolved oxygen, often creating sulfide gas in the water and above it. Because domestic wastewater rarely is hotter than 40 °C (105 °F) and has neutral pH, it is not much more corrosive than the fresh municipal water from which it starts. Immersed carbon steel in wastewaters in the treatment plant typically corrodes < 10 mils per year (0.010 inch/year). Regular stainless steels and some aluminum alloys resist corrosion in wastewater environments. More details, including the effects of chloride ions on corrosion, are given in Chapter 3.

Where wastewater is not aerated, e.g., under deposits and in stagnant conditions favoring septicization, more acidic conditions can arise—often containing sulfide ions. Further discussed below, anaerobic microbiological reactions can create local environments that accelerate the corrosion of iron, carbon steel, and concrete, and may be acidic enough to corrode aluminum and cause localized corrosion of stainless steel.

Sanitary and industrial wastewater, often combined with stormwater in the sewer, is collected in buried piping systems that range from 6-inch diameter pipes at point sources, including houses and buildings, through mid–trunk lines from 12 to 24 inches in diameter, to larger diameter pipes—sized to handle the wastewater capacity predominantly with gravity flow. Industrial wastewater may have dedicated sewers. Stormwater runoff could be combined with sanitary sewage or separated.

Standard design is for pipes to be buried well below the frost line, with manholes regularly spaced for inspection and maintenance purposes. Longer collection distances increase the likelihood that wastewater on its way to the treatment plant will lose its aeration and becomes septic and anaerobic, which in turn increases the amount of hydrogen sulfide gas in the space above the water level.

Old sanitary sewers were made from cast iron (gray or ductile) or vitrified clay pipe with gasketed, bell and spigot joints. Modern sanitary sewers up to 24” diameter are made from PVC with gasket joints. Larger pipes are made from reinforced concrete (RCP), typically with a steel cylinder supporting a concrete lining inside the pipe and a concrete sleeve around the steel pipe. Larger pipes can be made with or without helically wound wire in tension to prestress the internal and external concrete layers in compression.

1.2 Microbiological considerations

Domestic sewage and industrial wastewaters normally contain many microorganisms, including active bacteria, in incoming wastewater streams and nutrients to sustain microbiological activity. Some bacteria metabolize sulfate ions and other sulfur compounds to produce corrosive compounds such as hydrogen sulfide, which dissolves in water to produce hydrosulfuric acid and other acid species that accelerate metal corrosion and attack of concrete and protective coatings.

Genus *Thiobacillus* aerobic bacteria in wastewater streams oxidize sulfide ions, sulfur, thiosulfate, and polythionite ions and flourishes at 24–35 °C (75–95 °F). One group, *Thiobacillus intermedius*, is active in pH range 4–7, oxidizing sulfide ions to thiosulfate ions ($S_2O_3^{2-}$). A second group, *Acidithiobacillus thiooxidans*, flourishes at lower pH levels, oxidizing bisulfide ions (HS^-) to SO_3 which creates sulfurousacid, and oxidizes ferrous ions (Fe^{2+}) to ferric (Fe^{3+}) ions, which increase the corrosion–driving (oxidizing) power of the water.

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Microorganisms influence corrosion in wastewater streams when bacterial colonies grow in biofilms, slimes, and organic deposits that form on immersed surfaces and in vapor space surfaces above the wastewater. Local environments produced by microbiological activity differ from the bulk environment. Occluded microenvironments can become acidic enough to attack concrete and corrode iron, steel, and aluminum. A common phenomenon typically blamed on *Acidithiobacillus ferrooxidans* bacteria is the formation of large, hard mounds of iron-hydroxide corrosion product in steel or iron pipes. Microbiologically influenced corrosion (MIC) can affect aluminum alloys and lead to unexpected localized corrosion of stainless steels when chlorides are present.

1.2.1 Biogeneration of sulfides

Domestic sewage typically contains substantial amounts of sulfate ions (SO_4^{2-}). Where sulfate–reducing bacteria (SRB) exist within biofilms and slime layers formed in sewer piping and on other sewage–contacted surfaces, the SRB use local *anaerobic* conditions, which typically arise in 1 to 2 weeks, depending on local conditions, to reduce sulfate ions to sulfide ions (S^{2-}).

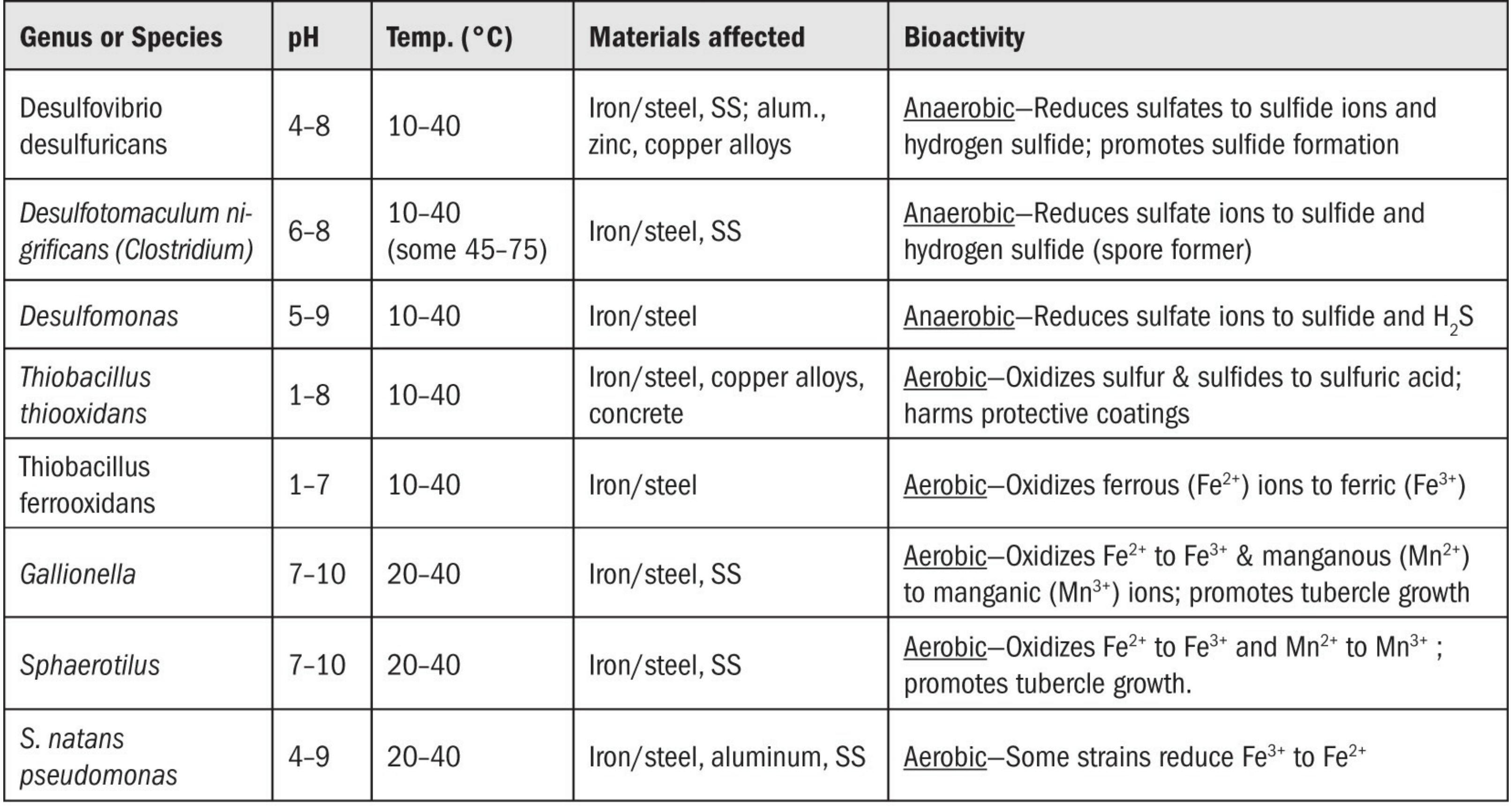
Sulfide ions react with water and hydrogen ions to form hydrosulfide (bisulfide) ions (HS^-), which produce dissolved hydrogen sulfide (H_2S) gas, with its characteristic "rotten egg" odor. The solubility of H_2S gas in water decreases rapidly when the water is agitated and turbulent.

1.2.2 Biogeneration of sulfuric and other sulfur acids

Sulfur-oxidizing bacteria (SOB) on wet, aerated (aerobic) surfaces with $pH > 8$ are especially active in nutrient–rich biofilms and scum layers generally found at the waterline where oxygen abounds. SOB convert H_2S and other sulfides into sulfurous and sulfuric acids, in some cases producing acid solutions with $pH < 2$. Various *Thiobacillus* SOB species thrive under different conditions so if conditions are too acidic for one bacterial species, another takes over.

H_2S gas acidifies water to produce hydrosulfuric acid: the pH depends on the partial pressure (concentration) of the H_2S gas. Because 50% H_2S concentration has a pH around 3.9–4.0, condensed moisture in headspaces of enclosed wastewater treatment plant structures can be acidic enough to corrode carbon steel and zinc and attack concrete. When conditions become aerobic, oxygen combines with H_2S gas and water and to produce polythionic acid, $H_2S_x0_6$ ($x = 3, 4$, or 5.2), a weak sulfuric acid that corrodes carbon steel, zinc, and concrete.

TABLE 1. Microorganisms Involved in Microbiologically Influenced Corrosion (MIC)



Genus or Species	pH	Temp. (°C)	Materials affected	Bioactivity
Desulfovibrio desulfuricans	4–8	10–40	Iron/steel, SS; alum., zinc, copper alloys	Anaerobic—Reduces sulfates to sulfide ions and hydrogen sulfide; promotes sulfide formation
Desulfotomaculum nigrificans (Clostridium)	6–8	10–40 (some 45–75)	Iron/steel, SS	Anaerobic—Reduces sulfate ions to sulfide and hydrogen sulfide (spore former)
Desulfomonas	5–9	10–40	Iron/steel	Anaerobic—Reduces sulfate ions to sulfide and H_2S
Thiobacillus thiooxidans	1–8	10–40	Iron/steel, copper alloys, concrete	Aerobic—Oxidizes sulfur & sulfides to sulfuric acid; harms protective coatings
Thiobacillus ferrooxidans	1–7	10–40	Iron/steel	Aerobic—Oxidizes ferrous (Fe^{2+}) ions to ferric (Fe^{3+})
Gallionella	7–10	20–40	Iron/steel, SS	Aerobic—Oxidizes Fe^{2+} to Fe^{3+} & manganous (Mn^{2+}) to manganic (Mn^{3+}) ions; promotes tubercle growth
Sphaerotilus	7–10	20–40	Iron/steel, SS	Aerobic—Oxidizes Fe^{2+} to Fe^{3+} and Mn^{2+} to Mn^{3+} ; promotes tubercle growth.
S. natans pseudomonas	4–9	20–40	Iron/steel, aluminum, SS	Aerobic—Some strains reduce Fe^{3+} to Fe^{2+}

Source: Metals Handbook, 9th ed., vol. 13. Materials Park, OH, USA: American Society of Metals, 1987, p. 118.

1.2.3 Modern water environment trends

The hydrosulfuric acid generated by hydrogen sulfide (H_2S) gas formed in municipal wastewaters causes acid attack of portland cement concrete, generally observed as the accelerated loss of cement paste. Thirty years ago, H_2S concentrations up to 15 ppm were commonplace in vapor spaces in sewage collection systems and in primary stage tanks in wastewater treatment plants.

In recent decades, as collection systems pipe sewage longer distances, concentrations of biogenerated gases, including H_2S, methane, carbon dioxide (CO_2), and ammonia found in vapor spaces has increased, probably due to a higher likelihood of anaerobic conditions, due to the sewage spending longer time in the collection system.

An alternative explanation for increased H_2S concentrations in wastewater in the last 30 years is that the Clean Water Act of 1980 decreased levels of heavy metal ions that curtail the activity of SRB. High concentrations of sulfide gas, especially at warmer ambient temperatures in southern states, causes surprisingly rapid attack of regular concrete, especially if it has no corrosion mitigation measures such as low permeability and an organic lining or coating.

Another regulatory trend potentially causing higher levels of H_2S to accumulate in wastewater treatment plant tanks and equipment is the adoption of environmental rules requiring plants to “control H_2S odor emissions at the source.” With odor control systems on wastewater treatment tanks, clarifiers, etc., localized H_2S concentrations up to 500 ppm have been reported in poorly ventilated spaces at hot times of the year.

Measures for mitigating corrosion by acids resulting from high H_2S levels include use of:

- ○ Chemical–resistant plastics, including FRP made with polyester and vinyl ester thermosetting resins, and thermoplastics PVC, CPVC, polypropylene (PP) and high–density polyethylene (HDPE).
- ○ Stainless steels, especially Type 316L, ferritic and duplex grades with acceptable resistance to localized corrosion, and aluminum alloys.
- ○ Dense concrete made with extra–low water:cement (w-c) ratios and modern mix designs to minimize permeability and maximize resistance to chemical attack.
- ○ Chemical–resistant coatings and linings formulated with either organic resins or inorganic cements to resist the acidic and sulfide gas conditions and microbiological attack.

These corrosion mitigation measures are discussed in more detail in the next chapters.

1.3 Wastewater treatment stages

Collected wastewater reaching the WWTP is typically subjected first to screening in the “headworks” to remove trash and floating and suspended materials larger than the screen spacing. Next the water slows down so grit, sand, and insoluble material can settle out or float off. In the secondary treatment stages, undesirable microorganisms in the water are microbiologically converted to form a sludge sediment and the water is clarified and decanted as reasonably clean, “gray” water. Finally, the gray water may be purified/disinfected in tertiary treatment to obtain potable water or water that meets the WWTP’s water discharge permit.

Methods and equipment for each step of the process vary broadly depending who designed the treatment stage and when, as well as the size/scale of the treatment plant (see **Figure 1**). **Figure 2** illustrates primary, secondary, and tertiary treatment stages. Many wastewater treatment plants do not have tertiary treatment.

1.3.1 Primary (mechanical) treatment

Raw wastewater is usually pretreated by coarse screening with a traveling screen to remove large suspended material, plastics, and other floating trash and debris before the wastewater enters a series of “grit basins” or tanks, in which suspended materials that passed through the screens settles out. Sediments and debris are continuously moved with a chain conveyor across the bottom of the grit basin to a sump for removal and disposal.

Basic chemical treatment is initiated after screening and grit removal by aerating the wastewater on