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15. SUBJECT TERMS
marine corrosion, seawater, carbon steel, sulfate-reducing bacteria

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COMPARISON OF KEY WEST AND PERSIAN GULF SEAWATERS

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ABSTRACT

Experiments described in this paper demonstrated changes in the chemistries and microflora of two natural coastal seawaters collected from Key West, FL and the Persian Gulf as a result of storage and environmental conditions. Exposure to an anaerobic atmosphere containing a mixed gas of nitrogen, carbon dioxide, and hydrogen generated the highest microflora concentration, especially sulfate-reducing bacteria (SRB). Biotic dissolved sulfide levels were also highest in the mixed gas atmosphere. In contrast, sulfides were not detected in seawater maintained anaerobic with bubbled nitrogen. Separate introductions of carbon steel and agitation also affected chemistries and microflora. Key West seawater consistently had equal or greater bacterial numbers in all conditions when compared with Persian Gulf seawater. Bubbling nitrogen into natural seawater to achieve an anaerobic condition is not conducive to the growth of SRB and the resulting biotic sulfide. Laboratory experiments that mimic anaerobic conditions by bubbling nitrogen may not produce conditions found in field due to pH changes. A follow on paper is planned to address influences of chemistry and microflora on corrosivity.

Key words: marine corrosion, seawater, carbon steel, sulfate-reducing bacteria

INTRODUCTION

Natural seawater surrogates, including sodium chloride (NaCl) solutions (3.5 wt%), buffered NaCl solutions, artificial seawater and artificial seawater to which nutrients and microorganisms have been added, have been used in corrosion experiments. It is generally recognized that artificial seawater mixtures do not approximate the complexity of natural seawater, especially the organic material and the microflora. The assumption has been that laboratory prepared and commercially available NaCl solutions are free of microflora. However, over time, NaCl mixtures become contaminated with bacteria, fungi and microalgae. Yet the presence and activities of these organisms are usually not quantified or considered in corrosion experiments. Dexter[1] concluded that NaCl solutions were not free of organics. Instead, the organics in NaCl solutions were just different from those found in natural seawater. Most corrosion experiments conducted in artificial seawater do not reproduce rates and in some cases the mechanism for corrosion in natural seawater.[2] Dexter[1] carefully compared laboratory solutions and natural seawater for studying the corrosion of aluminum alloys and prepared a specific artificial medium that reproduced the short-term behavior of aluminum alloys in natural seawater. None of the laboratory solutions were able to simulate the long-term corrosion behavior of aluminum alloy in natural seawater. However, few others have considered the differences that natural seawater collected from different locations, collected at different seasons or stored under different conditions, e.g., stirred, aerated, exposed to light, collection depth might introduce to the results of corrosion experiments. Zobell and Anderson[3] and Lloyd[4] demonstrated that when seawater was stored in glass bottles, the bacterial numbers fell within the first few hours followed by an increase in the total bacterial population with a concurrent reduction in the number of species.

Experiments described in this paper were designed to evaluate the chemistries and microflora of two natural seawaters collected from Key West, FL and the Persian Gulf and to determine how both change as a function of storage. A follow-on paper will describe the influences of chemistry and microflora on corrosivity.

MATERIALS AND METHODS

Seawater Collection

On April 17, 2006 12 gallons of coastal Persian Gulf (PG) seawater collected (2 days earlier) from the U.S. Navy pier at Mina Sulman, Bahrain arrived at Naval Research Laboratory, Stennis Space Center (NRLSSC). On April 25, 2006 12 gallons of coastal seawater collected from the U.S. Naval Research Laboratory at Key West (KW), FL arrived. Seawater was shipped in 3 five-gallon plastic containers, each containing 4 gallons of seawater and a 1-gallon of headspace. Temperature of the water during transit was not measured. Exposure testing began within 24 hours of the time the water arrived at NRLSSC. Key West seawater was collected a depth of 1.2 – 1.5 meters underwater by intake pipes powered by suction pumps. Persian Gulf seawater was collected within the first meter of the seawater surface by immersing each container underwater by hand.

Exposure Conditions

Seawater samples from the two locations were maintained in the following conditions in the laboratory:

PG-A / KW-A – 450 ml stagnant seawater in hand-tightened sealed glass container exposed to air

PG-A-CS / KW-A-CS – 6 separate 450 ml stagnant seawater samples in 6 separate hand-tightened sealed glass containers with a carbon steel coupon (fully immersed) and exposed to air

PG-D / KW-D – 1500 ml stagnant seawater maintained inside an anaerobic hood within a 2000 ml glass flask sealed with a rubber stopper

PG-D-stir / KW-D-stir – 1500 ml stirred seawater maintained inside an anaerobic hood within a 2000 ml glass flask sealed with a rubber stopper

PG-D-CS / KW-D-CS – 6 separate 450 ml stagnant seawater samples in 6 separate lightly sealed glass containers with a carbon steel coupon in the seawater maintained inside an anaerobic hood

PG-B / KW-B – 1500 ml stagnant seawater contained within a 2000 ml glass flask, bubbled with house supplied nitrogen gas and sealed with a rubber stopper

PG-B-stir / KW-B-stir – 1500 ml stirred seawater contained within a 2000 ml glass flask, bubbled with house supplied nitrogen gas and sealed with a rubber stopper

The anaerobic chamber atmosphere was maintained using a gas mixture of 10% H_2, 5% CO_2, and 85% N_2. Atmospheric O_2 concentration was continuously monitored at less than 1 part-per-million (ppm). House N_2 gas specifications called for less than 100 ppm atmospheric O_2, however during the duration of the experiment the average concentration was ~10 ppm O_2. Bubbling was not vigorous with approximately 2 bubbles per second. Stirring was accomplished using a stir plate and a 2-inch magnetic stir bar rotating once per second. No nutrients or other additions were made to any of the exposure conditions.

Seawater Analysis

At the onset of the experiment and continuing at 30-day intervals, 50 ml of seawater was removed from each of the eight 1500 ml exposure conditions for analysis. In addition, one 450 ml container with a carbon steel coupon was selected from each exposure condition (PG/KW-A/D-CS) every 30 days. A 50 ml sample of seawater was removed for analysis and the container was discarded. The pH was measured using a calibrated pH meter.* Dissolved sulfide concentrations were determined in triplicate using the methylene blue method 228 C.[5] Four sterile 3 ml syringes were used to remove 4 ml (1 ml in each syringe) from the 50 ml seawater sample. One ml was used to inoculate serial dilutions (10^{10}) of each the following seawater media†: phenol red dextrose broth, Postgate medium B, nutrient broth and thioglycollate medium to determine most probable numbers (MPN) of acid-producing bacteria (APB), SRB, general heterotrophic aerobes and anaerobes, respectively. Dilutions were incubated for 28 days at 25°C. Salinity, total organic carbon (TOC), and sulfate were also quantified at the onset of the experiment for both seawaters.‡

Carbon Steel Coupons

Coupons were machined from UNS G10200 carbon steel (Table 1), 5.08 cm x 10.16 cm x 0.41 cm thick with a mill finish.§ Each coupon had a gas-tungsten-arc butt-weld running down the long axis at the midline. No electrochemical or weight loss measurements were performed on the coupons in this experiment.

RESULTS

Seawater Analysis

Seawater chemistry analyses for both seawaters at the onset of the experiment are listed in Table 2. PG seawater had higher values for all parameters when compared to KW seawater. Table 3 lists the

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* Accumet Research Model AR50, Fisher Scientific

† Dixie Testing and Products, Inc., Houston, TX

‡ AccuLab Inc., Marrero, LA

§ Metals Samples®, Munford, AL

bacterial counts for the four different bacterial groups tested for both seawaters at the onset of the experiment. KW seawater had equal or greater numbers of each group of bacteria when compared to PG seawater.

The pH values were monitored over the first 160 days (experiment not completed at the time of this paper) for all experimental conditions and are shown in Figure 1. There were no differences in pH between different seawaters for the same exposure condition. However, different exposure conditions produced a range of pH vales that varied by 3 pH units. Stagnant seawaters exposed to air maintained a pH near 8.0 (PG/KW-A). Addition of carbon steel to the environment decreased pH to 7.5 (PG/KW-A-CS). Exposure to the anaerobic environment decreased pH vales to below 7.0 with KW-D having the lowest value of 6.5. Bubbling N_2 gas had the opposite effect, where an increase in pH above 9.0 was observed. (So many bacteria might be inhibited by such an alkaline pH)

Dissolved sulfide (DS) concentrations were monitored over time for all exposure conditions (Figure 2). Conditions exposing the sample to air produced sulfide levels below the resolution (<1 parts-per-billion [ppb]) of the detection method and are not shown in Figure 2. KW seawater exposed to the anaerobic stirred condition (KW-D-stir) consistently produced the highest DS concentration with a maximum of over 10^4 ppb. Anaerobic stagnant KW seawater (KW-D) produced the next highest values with over 10^2 ppb DS recorded. All other conditions produced DS concentrations less than 10^2 ppb.

Carbon Steel

Figure 3 illustrates the effect of exposure conditions on carbon steel.. After 60 days, exposure to PG seawater and air (PG-A-CS) produced large amounts of orange-red corrosion products over the entire carbon steel surface. The corrosion product was ~3 mm thick but was easily sloughed off with minimum agitation. KW seawater produced similar results but the corrosion product was not as thick (1-2 mm) and was more tenacious. Exposure to anaerobic, stagnant KW seawater (KW-D-CS) produced very different results. After 60 days, the carbon steel coupon was completely covered in a black corrosion product. The seawater itself was grayish black. Exposure to PG seawater also produced a black corrosion product but the seawater was consistently lighter in color than the KW exposure conditions (not shown). In all conditions, increased time produced thicker and more uniform corrosion products and anaerobic seawaters (with carbon steel) became darker with time. The only anaerobic condition without carbon steel to change in color was the stirred KW seawater with a light tint of dark brown floating particles and a non-uniform black coating on the stir bar.

Planktonic bacterial populations were monitored over time for all exposure conditions and the results are shown in Figure 4. Generally, KW seawater had higher total bacterial numbers in all exposure conditions when compared to PG seawater. Aerobic bacteria were the most numerous bacterial type except in KW seawater in anaerobic chamber environments. Bubbling N_2 gas through the seawaters produced the lowest concentration of bacteria in comparison to seawater left open to air and that tested in the anaerobic chamber. Bubbling N_2 gas did not promote SRB growth. Addition of carbon steel in the anaerobic chamber environment for both seawaters produced elevated levels of SRB, with KW seawater (KW-D-CS) producing the highest overall SRB concentrations. KW-D-CS condition produced orders-of-magnitude lower concentrations of the other three groups of bacteria (aerobes, anaerobes, APB) in comparison to SRB. In absence of carbon steel in the anaerobic chamber environment, stirring the KW seawater (KW-D-stir) produced similar concentrations of all four bacterial groups. In contrast, the stagnant KW seawater (KW-D) had elevated levels of anaerobic bacteria.

DISCUSSION

Open ocean seawater has been well characterized.[6] The major ions in seawater are those that make a significant contribution to measured salinity. Major ions include elements present in concentrations greater than 1 ppm in oceanic water. The chemical and physicochemical properties of seawater can be attributed to 13 major ions that make up over 99.9% of the material dissolved in seawater. Seawater contains 3.5% NaCl (Table 4). These major ions exist primarily as free ions, but small amounts form ion pairs due to the electrostatic interaction between the highly charged ions in solution. Ion pairing becomes significant for sulfate ions, which can form ion pairs with magnesium, calcium, and strontium. Only half of the sulfate in seawater exists as a free ion. The primary source of major ions to the ocean is riverine input. Once these ions enter the ocean, their residence time is very long compared to the mixing time for the oceans. The total salt content (or salinity) of a seawater sample may change with depth or location in the ocean, due to precipitation, evaporation or mixing. However, the ratio of the major ions varies only slightly in the open ocean. This concept, known as constancy of composition, or Marcet's principle, results from the fact that the oceans are well mixed in relation to the major constituents. Because of this consistency, most descriptions of seawater are limited to location, temperature, oxygen and salinity.

Those elements found in seawater at levels below 1 ppm are considered trace elements. Table 4 lists the remaining trace elements in seawater, along with their residence times. These elements exhibit an enormous range of chemical reactions and enter widely into the biochemical and geochemical cycles of the ocean. While the concentrations and residence times reported in Table 5 are accepted averages for trace elements, the values have limited meaning because of large variations both geographically and with depth, and the limited, reliable oceanic profiles for many of these elements.

Like the major ions, riverine input is the primary source of trace elements to the ocean, accounting for over 90% of the total. Other significant inputs come from ice transport (mainly from Antarctica) and atmospheric dust. Removal of trace elements from the ocean results from a combination of adsorption onto particulate material, biological uptake, and perhaps precipitation for a few elements (e.g., Sr, Ba). Such processes result in short residence times for trace elements and make their concentrations low in seawater.

Many inorganic chemical constituents of seawater are involved in the oceanic life processes. These compounds include water, oxygen, nitrogen, phosphorus, silicon, carbon (carbonate), and to a lesser extent such trace elements as iron, manganese, molybdenum, zinc, cobalt, copper, and vanadium. Except for water, oxygen, and carbon, these elements are classified as micronutrient elements. They are defined as materials essential to the growth of plants and animals that are present in such small concentrations that they may become depleted in the water column, thereby limiting additional growth. Nitrogen, phosphorus, silicon, and inorganic carbon are generally considered the most important-and most often measured-nutrient elements. Average concentrations of these elements in seawater are given in Table 6. Nitrogen, phosphorus, and silicon exist in the ocean primarily as the metabolizable compounds of nitrate (NO_3), phosphate (PO_4^{3-}), and silicate ($Si(OH)_4$). The concentration of these nutrient compounds varies with both depth and location in the ocean, and also changes seasonally in response to increased biological uptake or release. Vertical distributions of phosphate, nitrate, and silicates occur in the oceans. These vertical distributions are characterized by four different layers: (1) a surface layer in which the concentration is uniformly low as the result of biological uptake, (2) a layer in which the concentration increases rapidly with depth, (3) a layer of maximum concentration that is usually located between 500 and 1,500 m, which results from re-mineralization of organic

phosphorus and nitrogen, and (4) a thick bottom layer with relatively little change with depth. These distributions are controlled by a combination of biological removal and release and vertical and horizontal mixing of deep-water masses with high nutrient levels.

Dissolved and colloidal organic compounds have been detected in seawater in concentrations of up to 2ppm. Concentrations tend to be highest in the near-shore and near-surface waters. Deep-water organic material concentrations are nearly constant, with dissolved organic carbon levels between 200-300 μgCL^{-1} and particulate organic carbon levels less than 10 μgCL^{-1}. Surface values vary seasonally in cycles that are related to the biological cycles. There appear to be two types of dissolved organic material (DOM): young, labile DOM, which is released by lysis of cells and older, refractory DOM. In the water column, the combined effects of condensation reactions, metal complexation, microbial degradation and oxidation result in the elimination of the more labile constituents with depth. About 10% by weight of the DOM in seawater has been identified as common components of living organisms such as free and combined amino acids, carbohydrates, fatty acids, hydrocarbons, steroids, urea and glycolic acid. The bulk of the remainder consists of humic and fulvic acids and other refractory heteropolycondensates, commonly referred to as Gelbstoff, or yellow substances.

The concentration of dissolved gases (O_2 and CO_2) in surface waters is determined by their solubilities, which are functions of salinity and temperature. Air-sea exchange of O_2 is rapid and the O_2 concentration is within a few percent of air saturation for a specific temperature and salinity. Exchange of CO_2 is less rapid because of the carbonate/bicarbonate ions that are formed when CO_2 dissolves in seawater.[1] The pH of natural seawater is controlled by CO_2. As more CO_2 is dissolved the pH decreases. If CO_2 is removed from solution, pH increases. In the experiments described in this paper, bubbling N_2 into natural seawater produced a pH shift from 8.0 to above 9.0. Maintenance of seawater in an anaerobic hood with an anaerobic mixture of gases produced a pH shift of 8.0 to below 7.0. Dissolved O_2 concentration is coupled to pH through CO_2. When photosynthesis consumes CO_2 and produces oxygen, the water tends to have a high O_2 and high pH (8.2). When the reverse happens waters have a low pH and oxygen.

Coastal seawater is more variable than open-ocean seawater, since coastal seawater is subject to natural and made-made influences. PG coastal seawater has a higher salinity that open ocean PG seawater.[7] Dexter[1] concluded that natural coastal seawater from a variety of locations gave results that were internally consistent within a single batch of water, but were inconsistent from batch to batch at the same site and between sites.

Several investigators have demonstrated that manipulation of electron acceptors in seawater can have a profound influence on the microflora. Rizk et al.[8] used nanofiltration to reduce sulfate in seawater from 2.6 g/l to 50 mg/l. In laboratory studies they were able to demonstrate that decreased sulfate concentration in injected seawater significantly restricted the activity of SRB and the amount of hydrogen sulfide decreased as a direct function of the amount of sulfate in the water. In contrast, Jhobalia et al.[9] demonstrated that high sulfate concentration in the medium (increases from 1.93 g/l to 6.5 g/l) could inhibit growth of SRB and the corrosion rate of mild steel.

Laboratory and field experiments have demonstrated that nitrate treatment can be an effective alternative to biocide treatment to reduce the numbers of SRB and their activity, a process known as biocompetitive exclusion. The addition of nitrate can induce a shift in the dominant population from SRB to nitrate-reducing bacteria (NRB). Nitrate treatment was implemented on an oil platform in the North Sea (Veslefrikk).[10] The change from glutaraldehyde treatment to nitrate resulted in a dramatic change in the bacterial community. The SRB population decreased and the NRB increased. After four

months of nitrate addition the activity of SRB in the biofilm was markedly reduced as measured with respiratory methods and an enrichment of NRB was measured. After 32 months of nitrate treatment, SRB numbers were reduced twenty-thousand fold and SRB activity was reduced fifty fold. Corrosion measurements decreased from 0.7 mm/year to 0.2 mm/year. Gullfaks platforms[11] have been treated with nitrate to reduce H_2S production. A one-thousand fold reduction in SRB numbers and a ten to twenty fold reduction in sulfate respiration activity and a 50% reduction in corrosion as measured by weight loss. Reservoir characteristics and nutrient availability have a significant impact on the effectiveness of nitrate injection.

Hubert et al.[12] demonstrated that both nitrate and nitrite are effective treatments for decreasing sulfide concentrations. The required dose depends on the concentration of oil organics used as the energy source by the microbial community. Because of its higher oxidative power, nitrate can remove more oxidizable oil organics than nitrite. However, nitrite is a stronger inhibitor of SRB growth.

Both the addition and removal of oxygen have been proposed as corrosion control measures. Khanal and Huang[13] demonstrated that oxygenation was effective in controlling sulfides during anaerobic treatment of high-sulfate wastewater. However, SRB in biofilms depend on other organisms to remove oxygen and produce nutrients, so they can survive in aerated systems. Furthermore, oxygen exacerbates the problem of corrosion. Hamilton[14] proposed a model for MIC in which he concluded that several MIC mechanisms involved a process of electron transfers from base metal to oxygen as the ultimate electron acceptor through a series of coupled reactions. The specific coupled reactions varied with mechanism and causative organism. In the case of SRB, sulfate, an intermediate electron acceptor, is reduced to sulfide that reacts with a metal to form a corrosion product that ultimately transfers electrons to oxygen. Consistent with that model, most reported cases of SRB induced corrosion are in environments with some dissolved oxygen in the bulk medium.[15, 16]

Removing oxygen from seawater has been proposed as a corrosion control measure for unprotected carbon steel ballast tanks. Matsuda et al.[17] conducted shipboard trials by sealing a ballast tank at the deck and installing vertical pipes into the headspace. They reported that pumping pure nitrogen gas into the headspace for 1.5 hr reduced oxygen levels in the seawater to approximately 0.2 mg/l and decreased the rate of uniform corrosion of carbon steel by 90% as determined by weight loss. However, in laboratory experiments, Lee et al.[18] compared corrosion resulting from stagnant aerobic natural seawater with corrosion resulting from stagnant anaerobic natural seawater over a one-year period. They demonstrated the following: (1) corrosion was more aggressive under totally anaerobic conditions as measured by instantaneous corrosion rates ($1/R_p$) and weight loss, (2) under aerobic conditions corrosion was uniform and the surface was covered with iron oxides (lepidocrocite and goethite) and (3) under anaerobic conditions the corrosion was localized pitting and the corrosion products were mackinawite and pyrrothite. Lee et al.[19] designed field experiments to evaluate deoxygenation of natural seawater as a corrosion control measure for unprotected carbon steel seawater ballast tanks. They demonstrated the difficulty of maintaining hypoxic seawater. Using a gas mixture it was possible to displace dissolved oxygen. However, aerobic respiration and corrosion reactions consumed oxygen and produced totally anaerobic conditions within the first days of hypoxia. When gaskets and seals failed, oxygen was inadvertently introduced. The impact of oxygen ingress on corrosion depends on the amount of oxygen in the system at the time oxygen is introduced. Carbon steel exposed to cycles of hypoxic seawater and oxygenated atmosphere had higher corrosion rates than coupons exposed to cycles of either consistently aerobic or deoxygenated conditions.

It was demonstrated that the microbial population that one is able to detect is determined by the way the water is maintained. The microbial populations were followed using liquid culture techniques

that are recognized as capable of growing only a small percentage of the natural populations. These techniques can be used to make comparison, but not to make determinations about population diversity – requiring genetic identification methods. In addition, techniques employed in molecular biology could be used in further work to determine which microbiological populations are metabolically active/inactive in each environment. The authors also recognize that the planktonic populations described in this paper cannot be used to draw conclusion about the sessile populations that would be involved in microbiologically influenced corrosion.

CONCLUSIONS

Experiments described in this paper demonstrate that methods for handling and storage of natural coastal seawater can dramatically influence the chemistry and microflora, particularly over time. Key West seawater consistently had equal or greater bacterial numbers in all conditions when compared with Persian Gulf seawater. Bubbling nitrogen into natural seawater to achieve an anaerobic condition was not found to be conducive to the growth of SRB. Despite the higher initial dissolved sulfate concentration in PG water, the highest DS concentrations were measured in KW seawater, both stirred and stagnant, maintained in an anaerobic hood. Sulfides were not detected in KW seawater maintained with bubbled nitrogen. Laboratory experiments that mimic anaerobic conditions by bubbling nitrogen may not produce conditions found in field due to pH changes. Therefore, removal of oxygen is not the only consideration when attempting to reproduce anaerobic conditions.

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TABLE 1

CHEMICAL COMPOSITION OF UNS G10200

AISI-SAE designation	C	Mn	P max	S max	Fe
1020	0.17-0.23	0.3-0.6	0.04	0.05	balance

TABLE 2

SEAWATER CHEMISTRY

Seawaters	**pH**	**Salinity (g/L)(ppt)**	**Total Organic Carbon (mg/L)(ppm)**	**Sulfate (mg/L)(ppm)**
Key West	7.82	38	1.79	3864
Persian Gulf	7.98	44	1.94	4696

TABLE 3

BACTERIAL CONCENTRATIONS AT ONSET OF EXPERIMENT

Seawaters	**Aerobes 10^X**	**Anaerobes 10^X**	**APB 10^X**	**SRB 10^X**
Key West	6	4	3	2
Persian Gulf	6	2	2	1

TABLE 4

THE MAJOR IONS OF SEAWATER[6]

Ion	Symbol	g kg^{-1} at S = 35	% as free ion	% by weight of the total major constituents
Sodium	Na^+	10.78	99	30.66
Magnesium	Mg^{2+}	1.283	87	3.65
Calcium	Ca^{2+}	0.4119	91	1.17
Potassium	K^+	0.399	99	1.13
Strontium	Sr^{2+}	0.0079	90	0.02
Chloride	Cl^-	19.344	100	55.03
Sulfate	SO_4^{2-}	2.711	50	7.71
Bicarbonate	HCO_3^-	0.1135	67	0.32
Bromide	Br^-	0.0672	100	0.19
Borate	$B(OH)_3$	0.0203		0.06
Carbonate	CO_3^{2-}	0.0116		0.03
Borate	$B(OH)_4^-$	0.0066	10	0.02
Fluoride	F^-	0.0012	100	0.01
				100.00

TABLE 5

MEAN CONCENTRATION OF TRACE ELEMENTS IN SEAWATER EXCLUSIVE OF NUTRIENTS AND DISSOLVED GASES[6]

Element	Symbol	Concentration (μmol kg^{-1})	Residence time (years)
Lithium	Li	2.5×10^{1}	5.7×10^{5}
Rubidium	Rb	1.4	3.0×10^{6}
Iodine	I	4.4×10^{-1}	3.4×10^{5}
Barium	Ba	1.0×10^{1}	8.8×10^{3}
Indium	In	(1.0×10^{-6})*	—
Zinc	Zn	6.0×10^{-3}	5.1×10^{2}
Iron	Fe	(1.0×10^{-3})	5.4×10^{1}
Aluminum	Al	(3.0×10^{-2})	6.2×10^{2}
Molybdenum	Mo	1.1×10^{-1}	8.2×10^{5}
Selenium	Se	1.7×10^{-3}	2.6×10^{4}
Tin	Sn	(4.0×10^{-6})	—
Copper	Cu	4.0×10^{-3}	9.7×10^{2}
Arsenic	As	2.3×10^{-2}	3.9×10^{4}
Uranium	U	1.3×10^{-2}	$\sim 5 \times 10^{5}$
Nickel	Ni	8.0×10^{-3}	8.2×10^{3}
Vanadium	V	2.3×10^{-2}	4.5×10^{4}
Manganese	Mn	5.0×10^{-3}	1.3×10^{3}
Titanium	Ti	$(<2.0 \times 10^{-2})$	3.7×10^{3}
Antimony	Sb	1.2×10^{-3}	5.7×10^{3}
Cobalt	Co	(3.0×10^{-5})	3.4×10^{2}
Cesium	Cs	2.2×10^{-3}	3.3×10^{5}
Cerium	Ce	2.0×10^{-5}	1.4×10^{3}
Yttrium	Y	1.5×10^{-4}	7.4×10^{2}
Silver	Ag	(2.5×10^{-5})	3.5×10^{2}
Lanthanum	La	3.0×10^{-5}	3.2×10^{2}
Cadmium	Cd	7.0×10^{-4}	—
Tungsten	W	6.0×10^{-4}	—
Germanium	Ge	7.0×10^{-5}	—
Chromium	Cr	4.0×10^{-3}	8.2×10^{3}
Thorium	Th	$(<3 \times 10^{-6})$	—
Scandium	Sc	(1.5×10^{-5})	—
Lead	Pb	1.0×10^{-5}	8.1×10^{1}
Mercury	Hg	(5.0×10^{-6})	5.6×10^{2}
Gallium	Ga	(3.0×10^{-4})	9.0×10^{3}
Bismuth	Bi	(1.0×10^{-4})	—
Niobium	Nb	$(<5 \times 10^{-5})$	—
Thallium	Tl	6.0×10^{-9}	—
Gold	Au	(2.5×10^{-5})	9.7×10^{4}
Praseodymium	Pr	4.0×10^{-6}	3.1×10^{3}

*The values in parentheses are speculative.

TABLE 6

AVERAGE CONCENTRATION OF NUTRIENT IONS DISSOLVED IN SEAWATER[6]

Dissolved Species	Concentration (μmol kg^{-1})
Nitrate-Nitrogen	30
Phosphate-Phosphorus	2
Silicate-Silicon	110
Total Carbon Dioxide	Extremely variable 2350

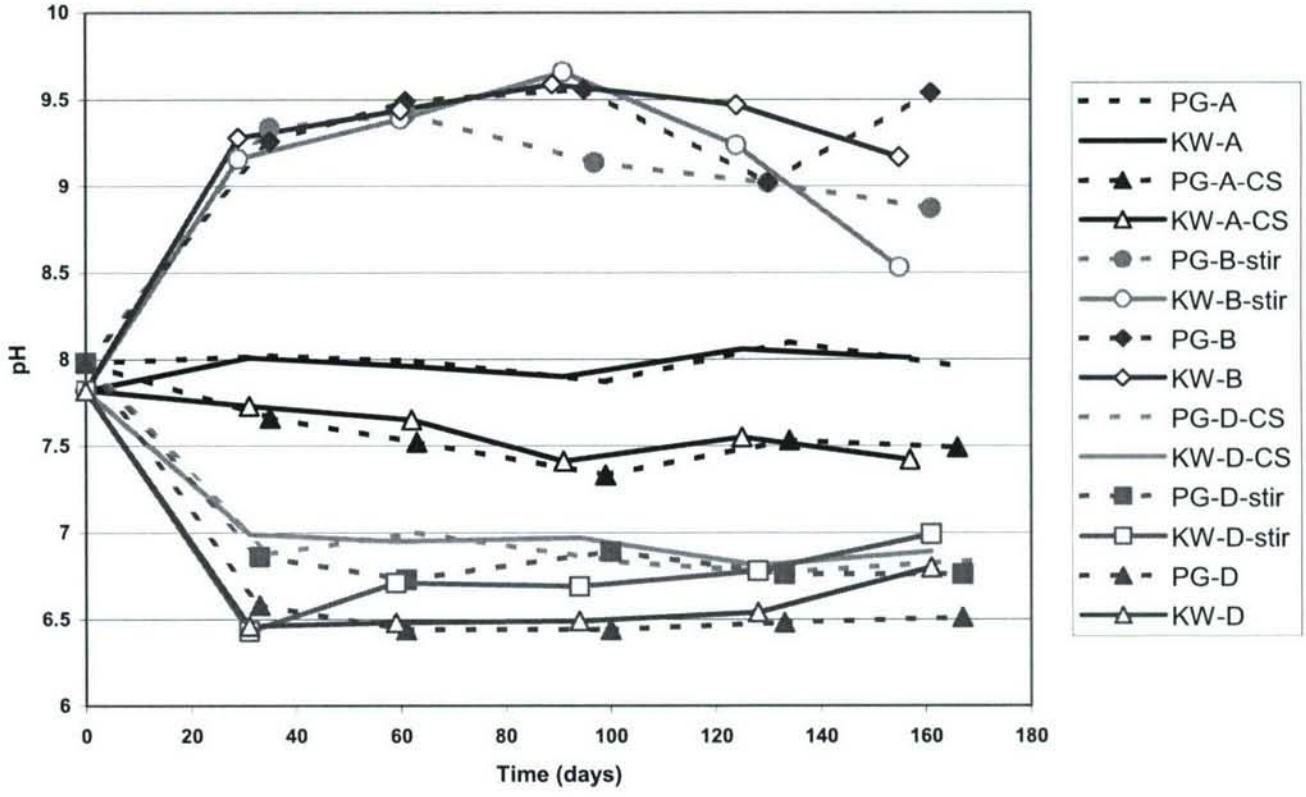

FIGURE 1 - pH values over time (days).

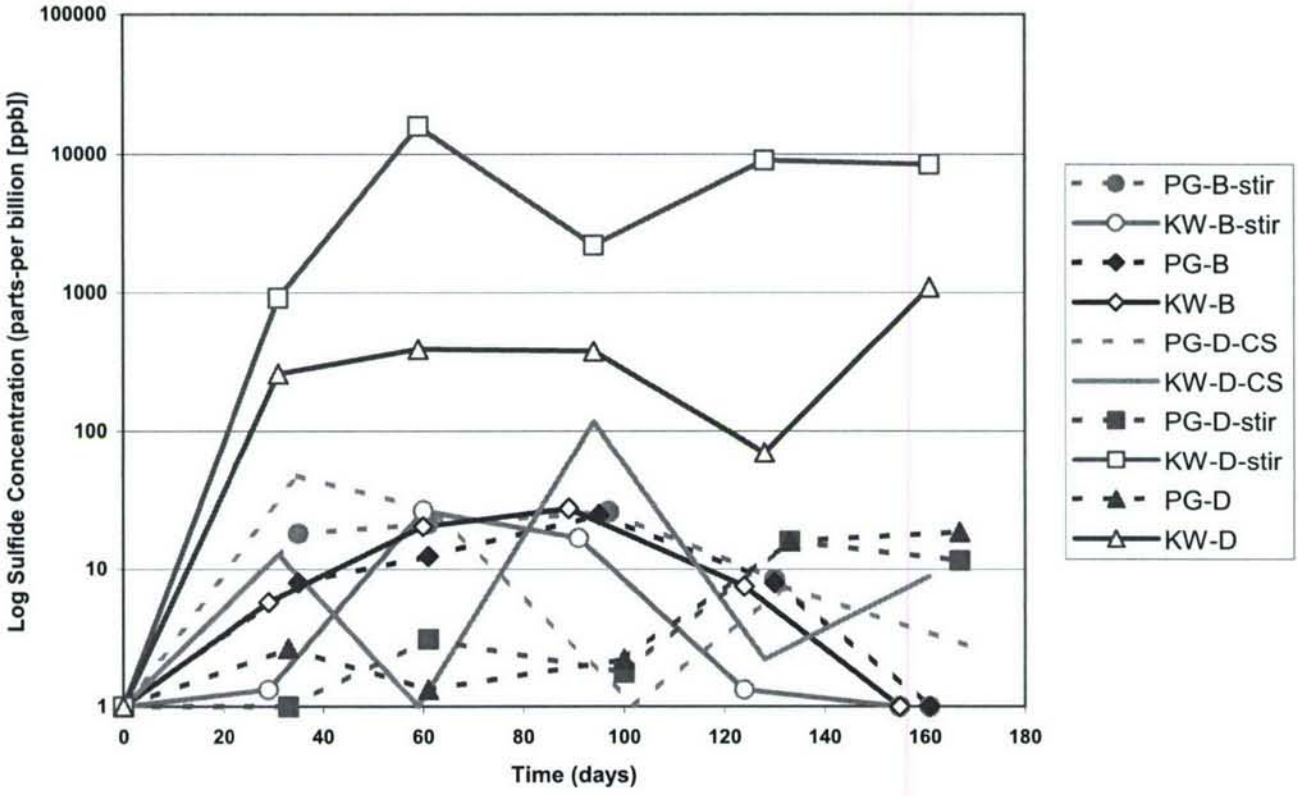

FIGURE 2 - Log sulfide concentration (ppb) over time (days).

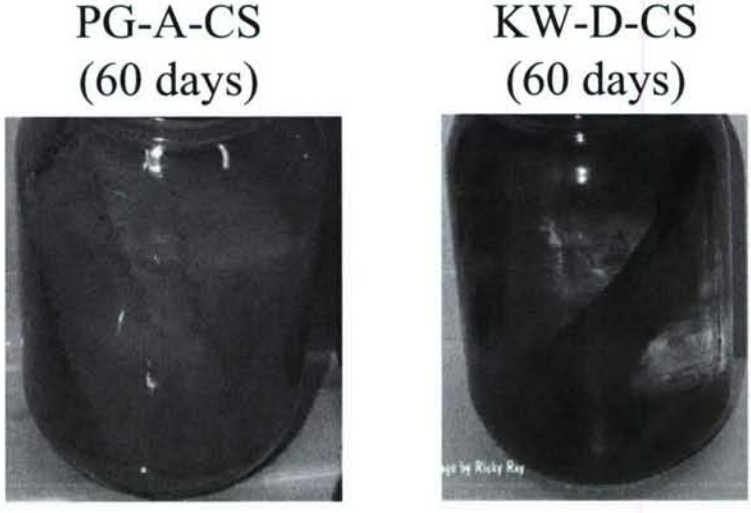

FIGURE 3 - Carbon steel exposed to seawaters in two different conditions.

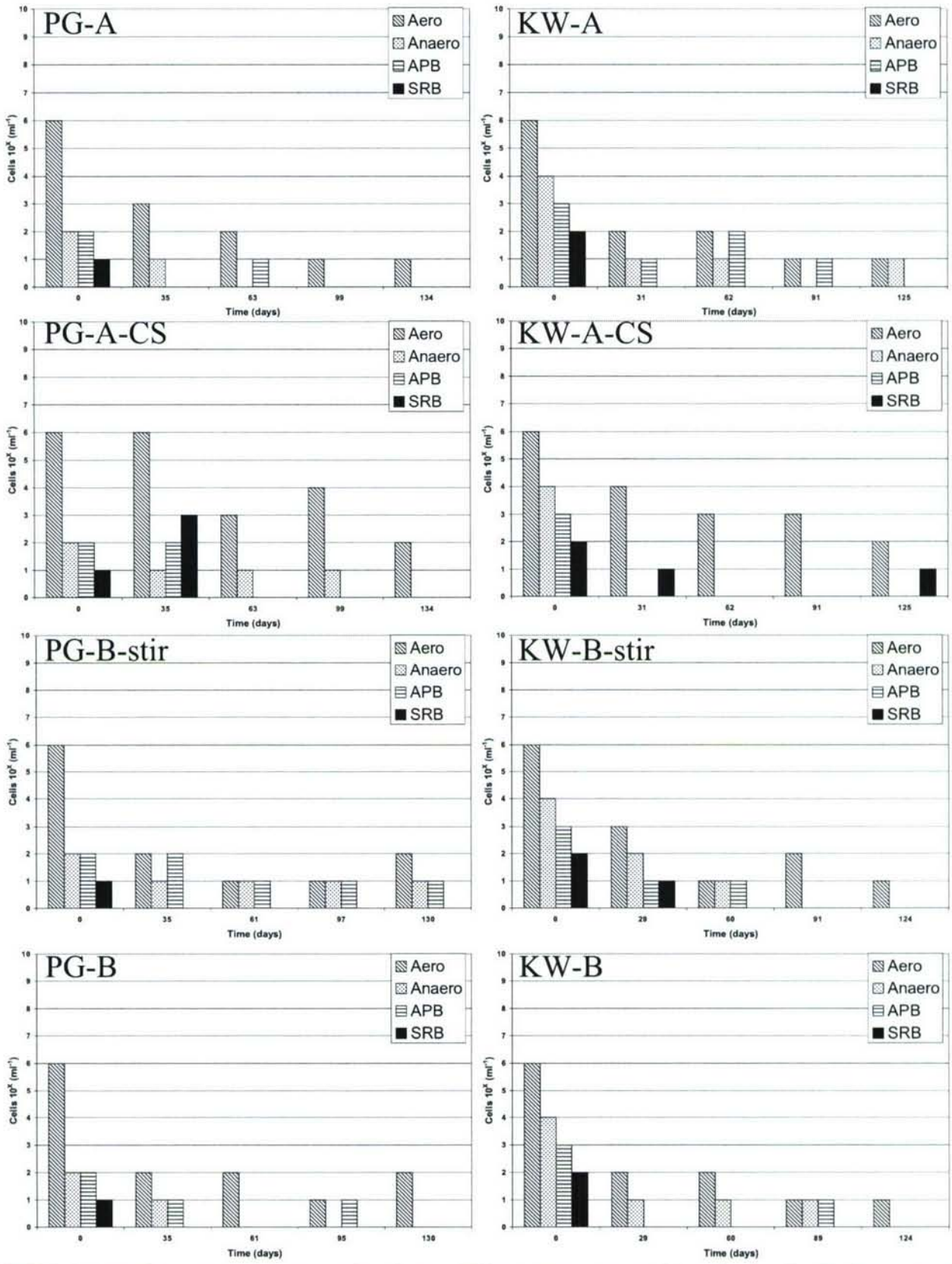

FIGURE 4 - Bacterial concentrations over time for the different exposure conditions for Persian Gulf seawater (left side) and the corresponding Key West seawater condition (right side).

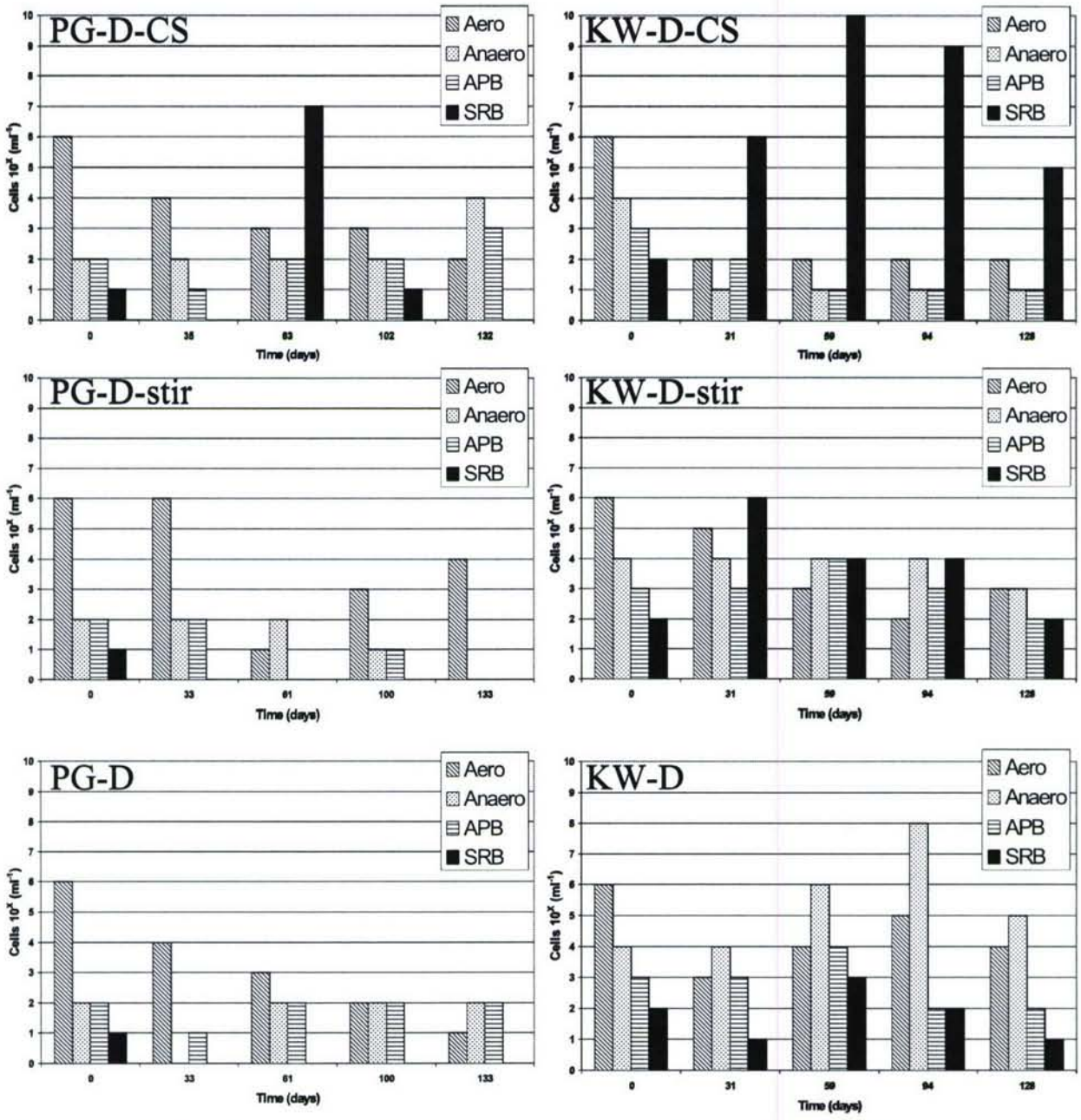

FIGURE 4 (continued) - Bacterial concentrations over time for the different exposure conditions for Persian Gulf seawater (left side) and the corresponding Key West seawater condition (right side).