FINAL
INTAKE BIOFOULING AND CORROSION STUDY
(UPDATED)

West Basin Ocean Water Desalination Demonstration Facility Intake Biofouling and Corrosion Study

for the:

WEST BASIN MUNICIPAL WATER DISTRICT

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EXECUTIVE SUMMARY

West Basin Municipal Water District (WBMWD) is a wholesaler of imported water in Southern California. WBMWD serves over 1.0 million people in 17 cities. In order to diversify their water supply portfolio WBMWD plans to construct a Seawater Desalination Facility. WBMWD has completed multiple studies, pilot tests, and a demonstration project in preparation for the Seawater Desalination Facility. The initial demonstration project identified the need to further study these materials within their proposed marine environment in order to get an idea of material costs versus material usable life. The objectives of this study were to:

- Identify and quantify intake piping biofouling and rates of fouling.
- Identify and quantify intake screen biofouling and rates of fouling.
- Identify and quantify intake piping corrosion and rates of corrosion.
- Identify and quantify intake screen corrosion and rates of corrosion.

Tetra Tech, along with key subconsultants on the project, Tenera Associates and V&A Consultants, performed the following scope of work on the project:

- Literature Review
- Pipe Test Skid Design
- Construction and operations of Test Skid
- Intake Pipeline Biofouling Testing
- Intake Screen and Coupon Biofouling Testing
- Intake Screen and Coupon Corrosion Testing

Chapter 1 provides the background for the study and explains the importance of analyzing intake materials for both biofouling and corrosion properties. This chapter also provides history on the use of wedgewire screen intakes on the West Basin Demonstration Project conducted at the SEA Lab Facility in El Segundo, California.

The original Cook Legacy Screens installed at the Demonstration Project experienced both corrosion and biofouling. After a little more than a year the Cook screens experienced structural failure due to extensive build-up of macro-organisms inside the screens along with the weight of the deflection cone. The screens were made of 90-10 copper nickel material which was believed to prevent both biofouling and corrosion in a seawater environment.

A detailed literature review was performed and summarized in chapter 2. A total of 85 published research documents and technical standards were reviewed. Tetra Tech also contacted and interviewed numerous experts in the field of seawater desalination and ocean intakes.

Our literature review revealed the following:

- Copper alloys, duplex, and super duplex stainless steels are commonly used in marine installations. The 90-10 and 70-30 are two of the most common copper alloys and the duplex 2205 is the most common stainless steel alloy. During our research we found no reference to screens that were constructed with titanium. We recommend that the following materials be considered for the study.

1. 90-10 CuNi (UNS C70600)
2. Johnson Screen Z Alloy (a proprietary copper-nickel alloy)
3. 70-30 CuNi (UNS C71500)
4. 2205 Duplex stainless steel
5. 2205 Duplex stainless steel (coated with Sherwin Williams Foul Release System)

- Super duplex stainless steel was not deemed warranted as neither the duplex nor super duplex have anti-biofouling properties, and the duplex stainless steel is suitable for the offshore water temperature. The additional cost for the super duplex does not appear to be warranted for the additional anti-corrosion properties.

- The required degree of maintenance on the intake screens varied in accordance with water temperature, marine environment, and velocity. Various methods were used by Owners and operators to control biological growth including:

  1. Manual Maintenance by divers
  2. Air Bursting
  3. Chemical Treatment

- The intake pipe should be non-metallic to mitigate the corrosion issues that are present in a submerged seawater application. Additionally, the non-metallic pipes have smoother interior pipe surfaces than concrete pipes, and therefore have a lower friction coefficient.

- The required degree of maintenance on intake pipelines varied in accordance with water temperature, marine environment and velocity. Various methods were used by Owners and operators to control biological growth including:

  1. Continuous Chlorine Addition (Diablo Canyon Nuclear Plant)
  2. Heat Treatment (Encina Power Plant, Carlsbad, California)
  3. Shock Chlorination (Larnaca Desalination Plant, Cyprus)
  4. Pigging (Ashkelon Plant, Israel)

- Based on our review and interviews, chlorination was the most widely used form of chemical control strategy. Shock chlorination was used at some locations to kill the micro-organisms such as the bacterial slime layer. This is the same theory as continuous chlorination; create a hostile environment that does not promote attachment of these macro-organisms. It also may result in killing macro-organisms; however, this did not result in the attachments (e.g. shells and other encrustations) from detaching from the interior of the pipe. It has also been reported that several macro-organisms can survive several hours (more than 8 hours) of high concentrations of chlorine. The time duration was found to be dependent on type of species and site location.

- Anoxic control was found to only hinder or slows growth but does not prevent it. While the pipe is in operation, growth of micro- and macro-organisms is occurring. This method may slow or delay growth but will ultimately require maintenance in order to remove the growth that does occur.

- High velocities to control biological growth were only found to be used at one location. High velocities results in higher headloss through the intake piping and the need for higher lift at the pump station and increased energy costs.

Intake Pipe Testing Procedures, testing and results are contained in Chapter 3. A pipe test facility was constructed at the SEA lab Facility and operated for a total of 230 days. The test facility included three pipe test runs:

- Control Run (no chemical addition)
- Continuous Chloramination (dosed at 5.0 ppm)
- Shock Chlorination (dosed at 20.0 ppm for 1 hour once per week)

A summary of the results from the four test periods is contained in Table ES-1.

Table ES-1: Intake Piping Summary Analysis

	Macrofouling	Slime	Barnacles	Sand
Test 1 – 54 Days				
Control	None	Very Slight	2	None
Continuous Chlorine	None	None	None	Fine sand in bottom ½ of pipe
Shock Chlorination	None	None	75 to 80	Fine sand in bottom ½
Test 2 – 114 Days				
Control	None	Visible Slime	14	None
Continuous Chlorine	None	None	None	None
Shock Chlorination	None	None	12	None
Test 3 – 174 Days				
Control	None	Visible Slime	18	None
Continuous Chlorine	None	None	None	None
Shock Chlorination	None	None	9	None
Test 4 – 230 Days				
Control	None	None	55	None
Continuous Chlorine	None	None	None	None
Shock Chlorination	None	None	9	None

The following are recommendations for the future full-scale West Basin Facility with regard to the intake piping:

After a thorough analysis of the testing, operations and results obtained we developed the following conclusions.

- The control test pipe run had no macrofouling, some visible slime and an increasing number/size of barnacles as the test progressed.
- The continuous chlorination test pipe run had no macrofouling, no slime and no barnacles for the entire test period.
- The shock chlorination test pipe run had no macrofouling, no slime but some barnacle growth at each time period.

The lack of macrofouling in the three spools is most likely due to the cropping of macrofouling larvae from the water supply by established filter-feeder organics (mussels, barnacles, etc.) in the seawater supply line.

Low velocities may also be contributing to the lack of macrofouling.

The complete lack of fouling in the continuous chloramine treatment spools is a positive result but the low levels of macrofouling in the control spool makes any comparison difficult.

Chapter 4 provides the testing procedures and results for the biofouling and corrosion testing of the wedgewire screen materials. The intent of the test was to measure the extent of corrosion and biofouling on bare and coated metal coupons. Samples made from four different alloys were identified and installed on a testing apparatus at the West Basin Ocean Water Desalination Intake location near El Segundo, CA. Samples from each alloy were removed after 3, 6, 10, 12, and 36 months and were sent to a laboratory for analysis. The purpose of the corrosion study is the following:

A. To determine the corrosion rates and modes of anticipated corrosion that will occur on the selected materials.

B. To determine the effectiveness of several antifouling control strategies for future design, implementation and operation of intake facilities.

C. To determine the effect that a foul release protective coating will have on biological growth on the test samples.

D. To determine proper material selection, manufacturer quality control, and proper installation of screens.

E. To select materials that are readily available for manufacture of the wedgewire intake screen for use at the full-scale West Basin Ocean Water Desalination Plant.

F. To present information with material selection options.

The purpose was to provide the results of the on-site and in-situ testing of metal coupons and wedgewire screen samples after nearly 3 years of immersion in the Pacific Ocean seawater. The samples were installed on June 17, 2014 and removed on May 23, 2017. Table ES-2 summarizes the corrosion rate results for four different alloys.

Figure ES-1 summarizes the results of the testing.

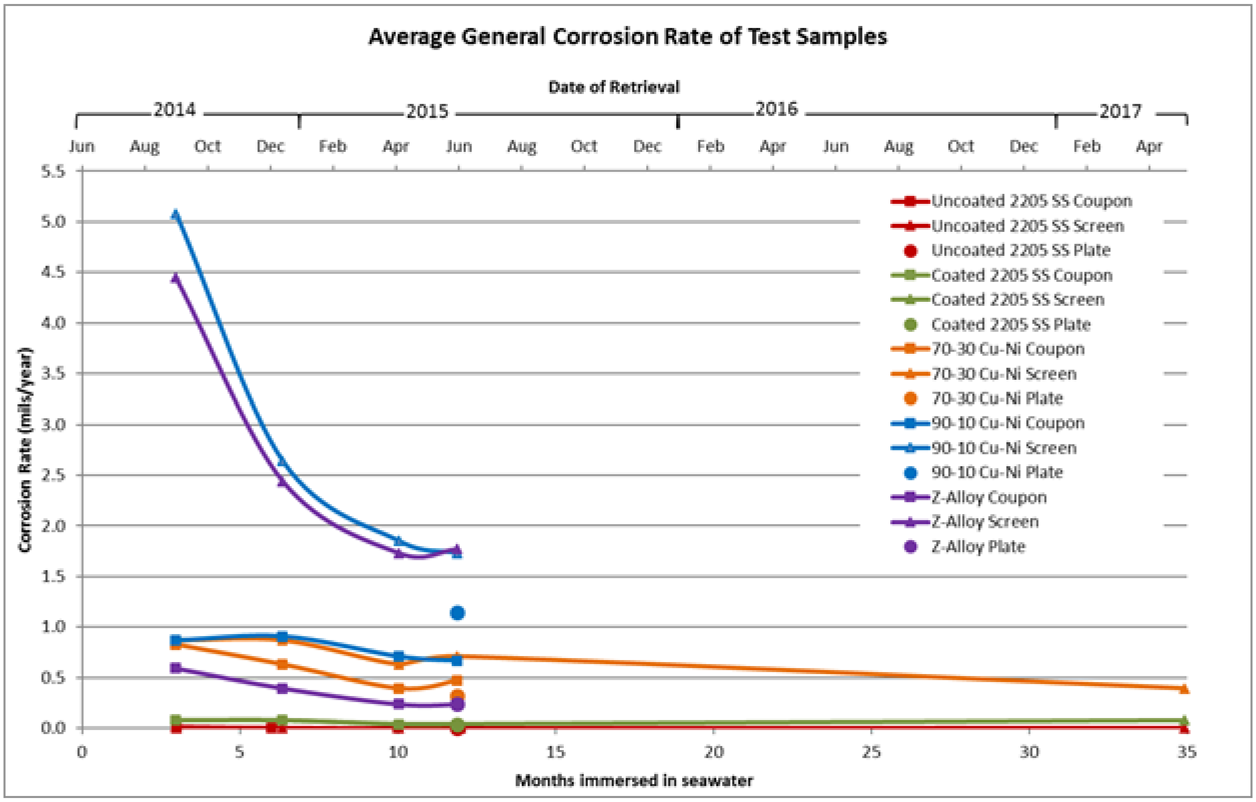


Figure ES-1: Corrosion Rates of Four Alloys after 3 years in Seawater Exposure

Figure ES-1 and Table ES-2 summarize the results of the testing. The calculated average general corrosion rate for each alloy and sample type is plotted on the graph below for each exposure time. The graphs show the trend of change in general corrosion rates by time. Please note that the average corrosion rates were calculated per the procedures outlined in ASTM G1, and the graph below was used to present those average corrosion rates; the graph was not used to calculate the average corrosion rates.

Generally, the average general corrosion rate for the samples decreased after 3 months after a protective passive film was established and the corrosion rate stabilized and became linear after 9 to 12 months as seen in the graph above. The passive film can be formed in three different ways: 1) by a metal surface reacting with an aqueous solution to form either a chemisorbed oxygen film or a multi-layered atomic layer comprised of an oxide or oxyhydroxide; 2) dissolution precipitation which produces a passive layer by the formation of an oxide, oxyhydroxide, or hydroxide film by the precipitation of dissolved metal ions and; 3) anodic oxidation of metal ions in solution which forms an oxide film containing the metal ion in a higher oxidation state than the base metal. The determination of which passive film formation process occurred in each alloy is beyond the scope of this study however the passive film is likely to have decreased the corrosion rate when it was undisturbed.

Table ES-2: Average General Corrosion Rates of Alloys in Seawater Exposure

Alloy	Sample Type	Surface Area (sq. in.)	Maximum Pitting Depth after 1 and 3 Years (mils)	1 Year Average General Corrosion Rate (mils/year)	3 Year Average General Corrosion Rate (mils/year)
2205 Duplex SS Uncoated	1-inch by 3-inch coupon	8.2	1.38	0.0004	---
	Wedgewire Screen	96.7	< 20 [A] (1yr), <20 [A] (3yr)	0.001	0.004
	4-inch by 4-inch plate	33.9	< 20 [A]	0.002	---
2205 Duplex SS with Foul Release Coating	1-inch by 3-inch coupon	8.2	1.30 [B]	0.039 [B]	---
	Wedgewire Screen	96.7	< 20 [A] (1yr), <20 [A] (3yr)	0.039 [B]	0.079
	4-inch by 4-inch plate	34.6	< 20 [A]	0.039	---
CDA 715 70-30 Cu-Ni	1-inch by 3-inch coupon	8.2	1.6	0.472	
	Wedgewire Screen	65.0	< 20 [A]	0.709	0.394
	4-inch by 4-inch plate	34.4	< 20 [A]	0.315	
CDA 706 90-10 Cu-Ni	1-inch by 3-inch coupon	8.2	11.5 (93.4 wide)	0.669	---
	Wedgewire Screen	79.1	< 20 [A]	1.732	---
	4-inch by 4-inch plate	34.1	< 20 [A]	1.142	---
Z Alloy	1-inch by 3-inch coupon	8.2	0.47	0.236	---
	Wedgewire Screen	96.3	< 20 [A]	1.772	---
	4-inch by 4-inch plate	36.6	< 20 [A]	0.232	---

A Less than detectable/measurable. The screens were metallographically mounted and optical micrographs of the surface up to 200x, resolution of several micrometers, were examined.

B Mass loss and corrosion rate includes metal and coating material.

In general, the wedgewire screens had a higher average general corrosion rate than the 1-inch by 3-inch flat coupons and the 4-inch by 4-inch flat plates of the same alloy. This could be due to the different shape, i.e., large ratio of edge area to total area, of the wedgewire screens as compared to the flat coupons and plates. It could also be due to different surface conditions and exposure conditions of test samples. The difference in the average general corrosion rates of the four alloys is likely due to a difference in the metallurgy, abrasion resistance, and corrosion resistance of the materials.

The 2205 Duplex SS uncoated and coated screens showed minimal mass loss and pitting overall after 3, 6, 10, 12, and 36 months of corrosion testing. However, the uncoated 2205 Duplex SS sample exhibited the most biofouling of all the alloys tested in this study. The average general corrosion rate is higher for the coated 2205 Duplex SS sample due to the missing anti-fouling coating that was damaged over time and does not necessarily indicated more corrosion has occurred than the uncoated sample.

The 70-30 Cu-Ni samples exhibited a moderate average general corrosion rate ranging between 0.32 mil/yr (plate sample exposed for 364 days) and 0.87 mils/yr (screen sample exposed for 91 days) during the 3-year study, with a steady decreasing trend over time. The average general corrosion rate decreases after 3 months after a protective passive film layer is established. The passivation layer acts as a shield to keep corrosive ions like chlorides away from the metal surface. The 70-30 Cu-Ni samples had less biofouling than other copper alloys after being immersed for 3 years.

The 90-10 Cu-Ni samples exhibited the highest average general corrosion rate of the 5 materials, ranging between 0.67 mil/yr (coupon sample exposed for 364 days) to 5.08 mils/yr (screen sample exposed for 91 days) during the 12-month study. The average general corrosion rate for the 90-10 Cu-Ni wedgewire screen samples quickly decreased after 3 months after a protective passive film was established, and the corrosion rate begins to stabilize after 9 to 12 months. A wedgewire sample could not be retrieved after 3 years. The sample was secured to the test rack with a plastic zip tie, which may have eroded the metal over time, and indicates that the alloy has a lower abrasion resistance than the 70-30 Cu-Ni alloy.

The Z Alloy samples’ high average general corrosion rate ranges between 0.24 mil/yr (coupon and plate samples exposed for 364 days) to 4.5 mils/yr (screen sample exposed for 91 days) during the 12-month study. The average general corrosion rate of the Z Alloy wedgewire screen samples quickly decreased after 3 months before a protective passive film was established, and the corrosion rate equalized after 9 to 12 months. A wedgewire sample could not be retrieved after 3 years. The sample was secured to the test rack with a plastic zip tie, which may have eroded the metal over time, and indicates that the alloy has a lower abrasion resistance than the 70-30 Cu-Ni alloy.

Based on the conclusions and experience with similar biofouling and corrosion studies, the following recommendations are presented for WBMWD to consider for seawater exposures:

1. Intake screens should be manufactured with 70-30 Cu-Ni as it would provide a low average general corrosion rate over a long term service life, would not require a foul release coating and will not experience heavy biofouling. The 70-30 Cu-Ni screens would provide less maintenance than the 2205 Duplex SS screens and would be recommended for long term service.
2. The foul-release-coated 2205 Duplex Stainless Steel screens would also provide a long term service based on the results of the study. The coating system provided the best protection against biofouling however the screen would have to be removed and the coating system would need to be touched up every 2 to 5 years as it is not abrasion resistant.
3. If intake screens are manufactured by 2205 Duplex Stainless Steel the following coating should be applied to the screens:
    a. 1st coat - Sherwin Williams Macropoxy 646 PW immersion grade epoxy primer at 6 mils dry film thickness (dft).
    b. 2nd coat - Sherwin Williams Seaguard Sher-Release beige silicone Tie Coat at 6 mils dft.
    c. 3rd coat - Sherwin Williams Seaguard Sher-Release white silicone Surface Coat at 6 mils dft.
4. Foul-release coated screens should be inspected every 2 to 5 years to determine if repairs are required. The foul release coating will need to be removed from immersion service and repaired while the surfaces are dry.

CHAPTER 1
BACKGROUND

INTRODUCTION

The West Basin Municipal Water District (WBMWD) is a wholesaler of imported water in Southern California. WBMWD serves over 1.0 million people in 17 cities. Their service area stretches from Malibu on the north to the Palos Verde Peninsula on the south.

WBMWD is an industry leader in water research, conservation, and recycling. In order to diversify their water supply portfolio WBMWD plans to construct a Seawater Desalination Facility. To date WBMWD has completed the following work on Seawater Desalination:

- Pilot Facility Operation
- Demonstration Facility Operation
- Performed previous studies on:
    - Intake Effects Assessment
    - High Salinity Sensitivity Study
    - Water Quality Integration Study
    - Harmful Algal Blooms
    - Program Master Plan

The Demonstration Project was constructed and operated at the SEA Lab Research Facility in Redondo Beach, California. A wedgewire screen intake was construction near the end of an existing decommissioned ocean intake serving the Redondo Beach Power Generating Facility. The wedgewire screen intakes were connected to the Demonstration Project using two (2) thirty-foot deep 6-inch HDPE pipelines installed in the existing intake tunnel, over approximately 2,000 linear feet.

Cook Legacy Screens Removed after Failure

The initial screen installed experienced signs of corrosion within months of installation. After one year of operations mussels were noticed inside the screen. Build-up of mussels, and barnacles inside the screen caused the screens to fail after approximately 15 month of service. Larvae that passed through the screens entered the 6-inch pipelines and caused extensive biofouling, barnacle, and mussel growth. This growth would foul the pipes, become loose, and then damage downstream equipment at the Demonstration Facility.

Mussels Removed from the Cook Legacy Screen after Failure

OBJECTIVES

There is not a lot known about wedgewire screen performance in the ocean. The initial demonstration project identified the need to further study these materials within their proposed habitat in order to get an idea of materials costs versus material usable life. The objectives of this study was to:

- Identify and quantify intake piping biofouling and rates of fouling.
- Identify and quantify intake screen biofouling and rates of fouling.
- Identify and quantify intake piping corrosion and rates of corrosion.
- Identify and quantify intake screen corrosion and rates of corrosion.

Tetra Tech, along with key subconsultants on the project, Tenera Associates and V&A Consultants, performed the following scope of work on the project:

- Literature Review – Tetra Tech team performed a detailed literature review to identify intake facilities used through the world on seawater desalination plants. Additionally, several engineers, operators, and owners were contacted to obtain information on chemical usage, air bursting, cleaning of screens, pigging, and cleaning of inlet lines.
- Pipe Test Skid Design – Tetra Tech designed a pipe skid and chemical feed system to test the following three conditions:
    - Control condition with no chemicals.
    - Continuous chloramination using pre-formed chloramines.
    - Weekly shock chlorination using sodium hypochlorite.

- Construction and operations of Test Skid – Tetra Tech and our subcontractor, Pascal & Ludwig, procured all material, constructed the facility, and operated the facility for the length of the study. Additional assistance from United Water, the onsite operator, was also provided.
- Intake Biofouling Testing – Pipe spools were removed at four different intervals and shipped to Tenera to analyze both micro-biofouling and macro-biofouling. The results were documented in 4 separate reports with photographs to document the biofouling.
- Intake Screen and Coupon Biofouling Testing – Sample intakes screen sections, and coupons of various materials were installed on PVC pipe racks and set in the ocean on the existing power plant intake structure. The samples were removed at approximate intervals of 3, 6, 9, and 12 months. Each sample was photographed, weighed, and analyzed for biofouling. The samples were then cleaned and shipped to V&A Consultants to perform corrosion analysis.
- Intake Screen and Coupon Testing – V&A Consultants performed a series of corrosion tests on each screen section and coupon sample after the biofouling analysis was performed to determine the amount of corrosion that occurred from both a pitting and general loss of metal. Screens were analyzed to determine if welds and/or structural support members were damaged.
- Tetra Tech prepared a quarterly report on progress, and costs to MWD for review along with monthly reports to WBMWD.

HISTORY OF WEDGEWIRE SCREENS

On October 10, 2010, the first wedgewire screen was installed at the Demonstration Project in Redondo Beach. The initial screens were manufactured by Cook Corporation. After failure of the Cook screens they were replaced with wedgewire screens manufactured by Johnson and Hendricks Companies. Table 1-1 provides a chronology of the events that occurred regarding the wedgewire screens. A description of the Cook, Johnson and Hendricks screens is contained in Table 1-2.

Table 1-1: Wedgewire Screen Chronology

Date	Event	Description
October 10, 2010	Cook Legacy Screen Installed	Initial Construction
November 30, 2010	First Corrosion Noticed	During Dive Inspection
	Screens Pulled and Re-wired	Screens were removed and Cook put new wires on the screen and reinstalled.
January 13, 2011	Flange Insulating Kits Installed	Determined screens had dissimilar metals and needed to be isolated.
April 15, 2011	Zine Anode Attached	Tenera installed to reduce corrosions, but may have had an impact on the anti-biofouling properties as well.
June 10, 2011	Zine Anode Attached	Tenera installed to reduce corrosions, but may have had an impact on the anti-biofouling properties as well.
August 10, 2011	Zine Anode Attached	Tenera installed to reduce corrosions, but may have had an impact on the anti-biofouling properties as well.

Date	Event	Description
September 23, 2011	Zine Anode Attached	Tenera installed to reduce corrosions, but may have had an impact on the anti-biofouling properties as well.
December 8, 2011	Zine Anode Attached	Tenera installed to reduce corrosions, but may have had an impact on the anti-biofouling properties as well.
January 19, 2011	Zine Anode Attached	Tenera installed to reduce corrosions, but may have had an impact on the anti-biofouling properties as well.
October 2011	Mussels First Seen in Screen	Mussels were noticed by viewing the video tape of the screens and confirmed by divers.
January 2012	Cook Screens Removed Due to Failure	Cook screen had severe build-up of macro-fouling, mussels and other marine life. Screen experienced a structural failure.
March 30, 2012	Johnson Screens Installed	Johnson screens installed on same 6-inch inlet line to Demonstration Plant where Cook screens were removed.
March 7, 2013	Hendricks Screen Installed	Hendricks screen installed by removing one of the previously installed Johnson screens.
December 31, 2014	Final Water Drawn Through Screen.	The lease agreement between WBMWD and SEA Lab ended so final pipe testing was completed.

Table 1-2: Wedgewire Screens Installed at Demolition Plant

Manufacturer	Screen Type	Metal Type	Slot Size
Cook	Cook Legacy	90-10 Copper Nickel	1 mm and 2 mm
Johnson	Z-Alloy	Proprietary	1 mm and 2 mm
Hendricks	Hendricks Tee Screen	90-10 Copper Nickel	0.5 mm

The intake pipelines were operated for one (1) year using weekly shock chlorination with no biofouling from January 2011 to January 2012. In February 2012, a chlorine leak developed due to a construction defect by the contractor and shock chlorination was stopped. In March 2012, oxic-anoxic pipe cleaning approach was used. The concept was to use one of the 6-inch pipelines while the other pipe remained full but unused. The unused pipe would become anoxic causing the micro and macro organism to die. An interval of switching the pipes from oxic to anoxic was setup at every four days. While this system worked to keep the pipelines operable, a video taken in September 2014, revealed severe mussel growth in the pipes which restricted the useable diameter from 6-inch to 3-inch.

In June 2012, West Basin hired Tetra Tech to investigate the failure of the Cook Legacy screens. A report prepared by Corrpro dated August 26, 2012, indicated minor corrosion but not significate enough to cause failure, see copy of Corrpro report in Appendix A. However, a structural review of the Cook Legacy screens indicated that the screens likely failed due to bending of the support members connected to the wedgewire. The weight of the solid deflection cone coupled with the weight of the interior biofouling caused the support members to bend and fail.

Cook Legacy Screen after Structural Failure

The Johnson and Hendricks screens experienced some biofouling but had minimal corrosion. They were in place until November 19, 2013, when they were removed. No structural damage was found on either screen. The Johnson screen did have some minor corrosion which was mostly attributed to the development of a patina on the copper but no macro-fouling. Dive videos did reveal a sea grass growing on the screens.

The Hendricks screen was found to have almost no corrosion but did have macro-fouling and mussel growth inside the screen.

While wedgewire screens are widely used for fresh water river environments they are not very common on seawater applications. On fresh water river intakes, the screens are subject to an almost constant river flow across the screens and many also use regular air bursting to remove fouling.

Little information was found on the long term fouling and corrosion of wedgewire screens which led WBMWD to perform this study.

BIOLOGICAL CONCERNS

The main biological concerns for both the pipes and screens come from both macro-fouling and micro-fouling. Macro-fouling is the accumulation of unwanted biological material on the pipe or screen. Examples of macro-fouling to be concerned with include:

- Hydroids, such as Pinauay crocea / Tubularia crocea or Tubularia;
- Acorn barnacle (Megabalanus californicus);

- Sponges;
- Tunicates;
- Mussels (Mytilus galloprovincialis);
- Bivalves (Hiatella);
- Scallops;
- Tube worms;
- Amphipods;
- Variety of other invertebrates.

Micro-fouling is the accumulation of biological settlements on the pipe or screen. Example of micro-fouling to be concerned with include:

- Red (filamentous and foliose) algae;
- Green algae;
- Bacteria;
- Biofilm/Slime;
- Various fouling organisms.

CORROSION CONCERNS

Corrosion is the degradation of the metals due to a chemical reaction with the environment. The corrosion concerns for the screens and pipes are also similar for each material. Examples of corrosion to be concerned with include:

- General corrosion;
- Pitting;
- Patina;
- Coating cracking;
- Mechanical failure.

The following chapters outline the results of the analysis performed by Tetra Tech and our subconsultants Tenera and V&A Consulting. Additional information on each portion of the analysis, along with laboratory data can be found in the attached Appendices.

CHAPTER 2
LITERATURE REVIEW

INTRODUCTION

The Tetra Tech team performed literature research and conducted interviews to assess the different materials that have been installed in marine environments and their performance. The information obtained during this phase will be used to provide recommendations for the test materials in the study moving forward to simulate the test screen material and intake piping material.

The approach to the literature research is a two-fold approach: review of published documentation and interviews. A search for published documentation was conducted for materials used for structures and/or piping at the following: desalination facilities (study, design, and operation), intake screen manufacturers, Naval/Military applications, power plants, ports, and harbors. The material obtained and reviewed as part of this research is listed on the reference summary sheet in Appendix B. Particular focus was spent on research properties of seawater that impact marine installations, type of materials, corrosion, biofouling, and maintenance. Interviews were conducted with several industry experts and operators at wedgewire screen installations. The notes from the interviews conducted are contained within Appendix B. The research conducted is a broad based focus from publications and installations both locally and international.

GOAL

The goal of the literature review was to identify intake facilities used through the world on seawater desalination plants and assess the materials used in the marine environments. Additionally, several operators were contacted to obtain information on chemical usage, air bursting, cleaning of screens, pigging, and cleaning of inlet lines.

OBJECTIVES

The objectives of the Literature Review were:

- Identify and summarize typical applications of materials used in a marine environment.
- Summarize performance results of the different materials.
- Recommend materials for the study for both the intake screens and the intake pipe materials.

CHARACTERISTICS OF LOCAL SITE CONDITIONS

The installation location of the intake screen and the make-up of the sea water at that location both in terms of aquatic life and water quality are important considerations for material selection. The following site factors were identified that impact material selection:

Seawater Corrosion Factors

Based on our review of the available literature, conditions that support corrosion are site specific. We identified the parameters that, in general, were noted as impacting corrosion rate and type and provided a general summary for the corrosion tendency of seawater towards all metal alloys:

1. Concentration of chloride ion – Higher concentration of chloride ions promotes corrosion.
2. Concentration of oxygen – Conditions that result in low levels of oxygen can result in anaerobic conditions and may result in corrosion due to anaerobic micro-organisms. Environments rich in oxygen result in promoting oxidation reactions.
3. Flow velocity – Increased flow velocity leads to erosion-corrosion. Velocities depend on geometry of the structure and/or pipe. As velocities increase the potential for the protective oxide layer to be removed increases which will increase corrosion potential. The other result of high velocity is that seawater contains a high amount of total dissolved solids and suspended solids such as sand and particulates that act as an abrasive.
4. Seawater temperature – Lower temperatures slows the formation of the protective outer oxide coating while warmer temperature increases the maturation of the oxide coating.
5. Seawater pH – The specific level of sea water acidity of alkalinity can promote aqueous corrosion, an electrochemical process. Most metals form a stable oxide or other film to inhibit the corrosion process. As the environment tends to become more acidic the corrosion potential increases.
6. Microbial corrosion – Iron-oxidizing bacteria can cause a breakdown of the outer protective oxide layer of a metal or shield the oxygen from the metal resulting in pitting.

Seawater Biological Growth Factors

Similar to the corrosion factor, biological growth factors are also site specific. We have made general conclusions regarding how biological activity is affected by seawater:

1. Dissolved oxygen concentration – higher dissolved oxygen concentration supports marine life, however, lack of oxygen may also promote anaerobic bacterial growth.
2. Water temperature – warmer water temperatures promote biological growth.
3. Water salinity – a stable salinity range is critical for micro-organisms to balance osmotic pressure.
4. Flow velocity – velocities that carry nutrients provide ideal feeding grounds for macro-organisms. Conversely, stagnant conditions result in decreased nutrients and oxygen replenishment and reduces macro-organism growth rate.
5. Local biological activity (nutrients and food source availability) – a higher concentration of nutrients results in increased micro and macro biological activity.
6. Seawater pH – micro- and macro-organisms are sensitive to pH changes.
7. Pollution – micro- and macro-organisms are sensitive to pollution in the water.

Marine fouling was studied by PK Abdul Azis, et al, 2002 to address the serious implications on performance of desalination and power plants. Micro and macro-biofouling is a serious problem to utility managers that operate intake structures in seawater. The composition and community of organisms have wide variations based on location. Microfouling is caused by bacteria and diatoms attached to a surface and rapidly divide and form a slime layer. Marine animals such as barnacles, mussels, bryozoans, hydroid, tunicates, corals, etc. result in macrofouling. Attachment of biofouling results in pipelines losing their carrying capacity and corrosion of materials.

Figure 2-1: Image of Typical Macro-Biofouling

Figure 2-2: Image of Typical Micro-Biofouling

Similar marine studies at the seawater reverse osmosis plant at Al-Birk located in the southern region of the Red Sea coast of Saudi Arabia faced operational problems that were thought to stem from biofouling. The study identified that biological activity is a result of site dependent factors including: temperature, nutrient load, pollution and the depth of the intake.

Site Characterization

The OWDDF is located off the Redondo Beach coast just offshore and north of the King Harbor breakwater, at the AES Power Plant. The decommissioned north intake of the AES Power Plant was utilized by the OWDDF project with the intake piping installed through the approximately 1800 foot long, 10-foot diameter tunnel and the intake screen installed just above the outlet of the 14-foot diameter intake riser pipe at a depth of thirty feet. The AES intake tunnel pipe is no longer used to draw cooling water to the plant. As part of the Intake Barrier Structure Project performed by the District, this site was characterized per the Basis of Design Report prepared by Halcrow Inc., dated December 9, 2011. The water level, wind, currents, water temperature, salinity, and waves were analyzed. The data was derived from measurements performed by the National Oceanic and Atmospheric Administration (NOAA) at the nearby Santa Monica Pier. The site characterization from this report is summarized in Table 2-1.

The tide range is in the order of 5 to 6 feet with the Mean Sea Level (MSL) approximately 3 feet above the Mean Lower-Low Water Level. Winds in Santa Monica Bay are typically light and dominated by the northwesterly sea breeze that sets in around noon. Average wind speed is 5.6 knots and maximum wind speeds experienced during an El Nino event have been measured up to a maximum per hour average of 19.6 knots. Currents offshore of Santa Monica Bay are a combination of tidal and wave induced currents. The currents are relatively low in magnitude and the tidal current speed diminishes toward shore due to bottom friction. The water temperature seasonally varies between 57ºF and 74ºF. The average salinity is 33.5 parts per thousand (ppt). The waves are typically mild with wave heights about 3 feet for 88% of the time.

Water Chemistry

The District provided water chemistry from their monthly monitoring reports that were generated while the OWDDF was in operation. The information was provided by the District as part of their quarterly water quality sampling submittal to California Regional Water Quality Control Board dated October 31, 2011 for water samples taken at the AES Power Plant discharge pipe in July 2011, August 2011, and September 2011. These values will change throughout the course of a year and may even be different year to year. The data is a snap shop in time of the water quality and was used to gain a feel for the seawater chemistry:

pH	7.9
Temperature	70.4 F
Dissolved Oxygen	7.85 mg/l
BOD (composite)	3.52 mg/l
Ammonia (as N)	1 mg/l

General Observations of Local Conditions

The location off King Harbor is a thriving marine environment, with conditions that support marine life. Based on the published information, as well as the marine growth witnessed by the District at the OWDDF, the conditions and the nutrients are present to support aquatic organisms. In addition, the seawater is considered highly corrosive to metals.

Table 2-1: Site Characterization Table

Description	Measurement	Level
Highest Water Level Measured	Feet	8.5
Highest Astronomical Tide	Feet	7.27
Mean Higher-High Water	Feet	5.43
Mean Sea Level	Feet	2.79
North America Vertical Datum	Feet	0.19
Mean Lower-Low Water	Feet	0.00
Lowest Astronomical Tide	Feet	-1.97
Lowest Water Level Measured	Feet	-2.84
Wind	Avg Speed (knots) El Nino 1997 (knots)	5.6 19.6
Currents	Type Direction Avg Velocity (cm/sec) Max Velocity (cm/sec)	Combination tidal and wave induced. Parallel to shore in a northwestward direction on the flood tide and southeastward on an ebb tide. 40 to 70 45
Water Temperature	Ave Temp (C/(F)) Summer Temp (C/(F)) Winter Temp (C/(F))	18 (64.4F) 23 (73.4 F) 14 (57.2 F)
Salinity	Max (during 1998 El Nino) ppt Min ppt (1993 winter floods) ppt Winter to Summer Variation (%) Long Term Average ppt	34.34 31.02 10 33.5
Waves	Typical Height Wave Period Max Storm Height (1983 storm event)	Approx. 3 feet for 88% of the time 12 to 18 seconds 18.2 feet

INTAKE SCREEN MATERIAL SELECTION

Various publications and studies were reviewed relative to the performance of materials installed in a marine environment. The performance of the material is dictated by the specific installation site’s properties such as salinity, temperature, currents, and nutrient availability. Publications from international sources as well as local (west coast) publications were reviewed. In addition, interviews were conducted with several industry experts and operators. The material obtained and reviewed as part of this research is listed on the reference summary sheet in Appendix B. (The materials assessed were those that can be used to construct a wedgewire screen, such as copper alloys, steel alloys, titanium). The materials need to be commercially available as well as be made into wire, bar, and plate shapes to construct intake screens. Based on the literature research and interviews, two material groups were found overwhelmingly used; copper alloys and steel alloys.

In a seawater installation, the following challenges are present:

1. Low resistivity promoting galvanic corrosion. Dissimilar metals and alloys have different electrode potentials, and when two or more come into contact in an electrolyte, one metal acts as anode and the other as cathode. The electropotential difference between the dissimilar metals is the driving force for an accelerated attack on the anode member of the galvanic couple. The

anode metal dissolves into the electrolyte, and deposit collects on the cathodic metal. Seawater is an excellent electrolyte due to the large amount of dissolved solids.

2. Microbial growth promoting a slime layer/biofilm which forms on surfaces and has a catalytic effect on the cathodic reaction in the corrosion process (i.e. oxygen reduction).
3. Erosion corrosion – the marine environment is an abrasive environment due to the suspended solids, flowing currents, and wave action. It should also be noted that per the publication by Detlef Gille for seawater intakes for desalination plants dated February 2003, screens such as stainless steel or copper nickel that become partially blocked by fibrous debris, the velocity through the remaining free area will increase the effect of erosion-corrosion.

Any metallic material selection will be potentially affected by one or all of the above types of corrosion methods.

Copper Alloys

Information regarding the copper alloys were obtained from various sources including Copper-nickel Alloys, properties and applications published by the Copper Development Association and Uhlig’s Corrosion Handbook, 2011.

Pure copper is a very soft and malleable metal. It is alloyed with small quantities of metals to modify the properties for particular applications while retaining many of the properties of the pure metal. Additions of zinc, selenium, and nickel are made to improve the mechanical properties of the metal and to retain its corrosion resistance properties. Iron (Fe) is added to improve the resistance of some copper alloys to erosion-corrosion (about 2%). Copper and its alloys display noble potentials in regards to corrosion resistance. They also form a cuprous oxide product fill that is responsible for their protection. There are several copper alloys suitable for marine service: coppers, copper-nickels, bronzes, brasses, and copper-beryllium.

The 90% copper and 10% nickel (90-10) copper-nickel alloy is the most commonly used wrought copper alloy for marine applications such as naval and commercial shipping and offshore oil and gas production, as well as in desalination and aquaculture. Alloys with higher nickel content or highly alloyed with chromium, aluminum, and tin are used where greater resistance to flow conditions, sand abrasion, wear, and galling are required, as well as higher mechanical properties. The 70% copper and 30% nickel (70-30) copper-nickel alloy is stronger and can withstand higher flow velocities. Alloys modifying 70-30 are available when higher resistance to erosion corrosion is required due to suspended solids. Copper alloys are ductile and can be machined for shape fabrication. The 90-10 and 70-30 copper-nickel alloys can be joined by brazing and welding. While consumables are available that deposit weld metal similar in composition to the 90-10 copper-nickel alloy, welds made with them may not have adequate corrosion resistance for all applications. Consumables for the 70-30 alloy, on the other hand, offer superior deposition characteristics and the corrosion resistance of 70-30 weld metal is at least comparable to each of the base metal alloys. These consumables are therefore recommended for both types of alloy. The 90-10 copper nickel is often selected because it offers good resistance at lower costs.

Summarized herein are the properties of copper alloys used in marine service.

Table 2-2: Typical Applications for Copper-Alloys

Alloy	Typical Applications
General Engineering Alloys	
– 90-10 Cu-Ni	Naval and commercial condenser and seawater piping, boat hulls, aquaculture cages
– 70-30 Cu-Ni	Naval and commercial seawater piping, heat-exchange equipment, military submarine service, boat hulls
– Nu-Ni-Cr	Wrought condenser tubing, cast seawater pump and valve components
High Strength Copper-Nickels	
– Cu-Ni-Al	Shafts and bearing bushes, bolting, pump and valve trims, gears, fasteners
– Cu-Ni-Sn	Bearing, drill components, subsea connectors, valve actuator stems and lifting nuts, seawater pump components

Summarized herein are the copper alloys and their respective UNS reference:

Table 2-3: Metal Alloy UNS (Unified Numbering System) designations for Copper-Nickel Alloys

Alloy	UNS	ASTM
– 90-10 Cu-Ni (wrought copper alloy)	C70600 C70620 (welding rod composition) C71581 (welding filler metal)	B111, B122, B151, B171, B359, B395, B432, B466, B467, B543, B552, B608
– 70-30 Cu-Ni (wrought copper alloy)	C71500 C71520 (welding rod composition) C71581 (welding filler metal)	B111, B122, B151, B171, B359, B395, B432, B466, B467, B543, B552, B608, F467, F468

B111 – Copper and Copper-Alloy Standard Specification for Seamless Condenser Tubes and Ferrule Stock
B122 – Copper-Nickel Standard Specification for Plate, Sheet, Strip and Rolled Bar
B151 – Standard Specification for Copper-Nickel-Zinc Alloy and Copper-Nickel Rod and Bar
B171 – Standard Specification for Copper-Alloy Plate and Sheet for Pressure Vessels, Condensers and Heat Exchangers
B359 – Standard Specification for Copper and Copper-Alloy Seamless Condenser and Heat Exchanger Tubes with Integral Fins
B395 – Standard Specification for U-Bend Seamless Copper and Copper Alloy Heat Exchanger and Condenser Tubes
B432 – Standard Specification for Copper and Copper Alloy Clad Plate
B466 – Standard Specification for Seamless Copper-Nickel Pipe and Tube
B467 – Standard Specification for Welded Copper-Nickel Pipe
B543 – Standard Specification for Welded Copper and Copper-Alloy Heat Exchanger Tube
B552 – Standard Specification for Seamless and Welded Copper-Nickel Tubes for Water Desalting Plants
B608 – Standard Specification for Welded Copper-Alloy Pipe

F467 – Standard Specification for Nonferrous Nuts for General Use
F468 – Standard Specification for Nonferrous Bolts, Hex Cap Screws, Socket Head Cap Screws and Studs for General Use

Other UNS numbers for copper nickel alloys are available, however they were found to not be commonly used and their applications could not be confirmed, are no longer used but still listed or are used in the manufacturer of electrical components.

Summarized below are copper-alloys properties in seawater:

Table 2-4: Copper-Nickel Alloy Properties

Copper-Nickel Alloy Properties
Anti-biofouling properties (typically installed with no antifouling coatings but rather uncoated).
No cathodic protection of the alloy is also recommended.
Copper alloys also have a high resistance to chloride pitting and crevice corrosion.
Copper alloys are also not susceptible to: • ammonia stress corrosion cracking • suphide stress cracking • hydrogen embrittlement
The surface film (patina) is critical in corrosion resistance of the material. The surface film can take several weeks to develop and mature. During the initial exposure it is critical to establish this protective layer.
Erosion corrosion due to flow velocity or suspended material can result in the surface film to breakaway. The critical flow velocity and shear stress depend on the alloy and geometry. The maximum flow velocity for a 90-10 Cu-Ni piping greater than 4-inches is approximately 11 ft/sec. 70-30 Cu-Ni can be used at velocities around 13 ft/sec.

The anti-biofouling properties of copper-nickel alloys are attained by the formation of surface films and caused by a reaction with the seawater. In marine installations, a surface patina is developed. The eventual development of the light green patina can take years to develop. Copper alloys are intended to be allowed to corrode. The general corrosion rates for seawater vary on temperature, salinity, and pH but are expected to be between 0.02 and 0.002 mm/year, with higher rates of corrosion assumed at the initial installation and decreasing over time.

Steel Alloys

Different grades and types of steel are used in a variety of marine installations. Steel can be provided in numerous shapes and can be welded. Carbon steels can be used cost-effectively when corrosion is not an issue by providing a sufficient corrosion allowance. For this study, carbon steel is not being considered as the District is looking for a long term product.

The various types of stainless steel have differing corrosion resistance properties when in contact with seawater. Stainless steel does not have inherent anti-biofouling properties and most often needs to be coated in order to address potential biological growth. Coatings do not have a long life expectancy and vary widely due to erosion from the suspended solids in the marine environment. Certain types of stainless steel have been used in various marine applications. Grade 304 austenitic stainless steel is suitable for above the waterline applications that are frequently washed down with fresh water. Grade 316 austenitic stainless steel is suitable for above the water line installations of deck fittings and riggings. Stainless steel will corrode in seawater; however, the corrosion process is not an evenly distributed process and typically occurs through the result in pitting and crevice corrosion. Duplex stainless steel was developed to address this type of pitting and crevice corrosion. The three most common types of duplex stainless steel used in marine applications are:

1. UNS S32304 (commonly known as 2304)
2. UNS S31803 (commonly known as 2205)
3. UNS S32750 (commonly known as 2507)

In seawater applications, Duplex 2205 is the most widely used duplex stainless steel grades with good corrosion resistance and high strength. Super Duplex 2507 is used for demanding applications for increased strength and corrosion resistance properties. Super Duplex 2507 has resistance to pitting, crevice, and general corrosion. Stainless steel is also susceptible to corrosion by chlorine and sulfide attack.

Titanium

Titanium is not susceptible to a corrosive attack by seawater and it is used in various submarine valves, pumps, and ship cooling piping systems. Titanium is resistant to general corrosion and crevice corrosion in all water temperatures, polluted waters, and microbiologically influenced corrosion. Titanium is also resistant to erosion corrosion. Titanium can be machined, cut, and welded.

Anti-Biofouling Coatings

Several anti-biofouling coatings were reviewed. Anti-biofouling coatings are used on numerous submerged applications to mitigate biological growth. Coatings studied to mitigate biological growth are divided into the following categories:

1. Foul Release Coatings
2. Antifouling Coatings
3. Fluorinated Powder Coatings
4. Epoxy and Metallic Coatings

The following summarizes the results from coatings that were tested in a mussel control program published by Dr. Allen Skaja for the Bureau of reclamation, March 2012:

1. The Foul Release are silicone based. Bryozoans and algae did not foul the silicone coatings and if attached can easily be removed. Silicone foul release coatings are soft and susceptible to abrasion and/or gouging by debris. The life expectancy of this coating is about three (3) years.
2. Antifouling Coatings are copper metal filled polyester. Antifouling coatings try to mitigate biological growth by utilizing copper, an element that prohibits biological growth. The antifouling coatings perform well in mitigating mussel attachment. The life expectancy of this type of coating is about two (2) years.
3. Fluorinated Powder Coating provides a slick surface that allows easy removal of growth. These coatings do not actually inhibit growth and continual maintenance is required.
4. Epoxy and Metallic Coatings fouled within one (1) year of service.

As discussed in P.K. Abdul Azis, et al, February 2002 paper on review of control technologies for marine macrofouling; the advantages of coatings are ease of manufacture, high speed and low-cost application. The disadvantages are limited life, the lack of ways to apply coating to submerged or wetted surfaces and toxicity of control agents.

All coatings were found to require maintenance and had short life expectancies that require recoating. Some coatings are NSF 61 certified for drinking water system components.

Summary from Interviews

As part of the literature review, various interviews were conducted to assess the different materials that have been installed in marine environments and document their performance. Screens of various materials (Cu-Ni, Z-Alloy, and Stainless Steel) have been used throughout the world. In general, wedgewire screens composed of copper alloys had lower bio-growth than super duplex stainless steel. Stainless steel in general had higher corrosion resistance, especially at higher temperatures. Welds were also found susceptible to corrosion. Biogrowth and corrosion was found to occur at almost all locations and the degree of effectiveness varied widely for both copper and steel alloys. Those interviewed recommend a maintenance program. The type of maintenance varied and included manual cleaning performed by divers and utilizing compressed air to try to dislodge debris and attachments. The complete interview notes can be found in Appendix A. Below is a summary of the interviews:

Table 2-5: Summary of Interviews

Industry Expert	Discussion
Aqua Chem, Ft. Lauderdale, Florida – Director of Operation	Performance of Johnson screens in Aqua Chem RO seawater Desalination Plants.
Bilfinger Water Technologies	Suitability of material used in manufacturing of wedgewire screens for seawater applications (Bilfinger is a subsidiary of Johnson Screens).
Israeli Desalination Engineering (IDE), Israel – VP Technology	IDE has built and operates a number of large RO seawater desalination plants at various locations.
King Abdullah University of Science and Technology, Saundi Arabia – Visiting Professor	Application of wedge screens as intake inlet structure in seawater environment.
Limassol Water Co., Cyprus – General Manager	Operation of seawater intake in the RO seawater desalination plants in Cyprus.
Water Globe Consulting – President	Application of wedge screens as intake inlet structure in seawater environment.

A summary of wedge screens seawater installations was extracted from a database provided by Johnson Screens Company from their US and European office. The majority of installations listed are outside US (about 90%).

Table 2-6: Summary of Seawater Installations Provided by Johnson Screens

Period of equipment order dates	1994 - 2012
Number of seawater installations reported	78
Material of construction	316L SS – 15% Duplex steel – 32% Cu/Ni – 52%
Capacity, m3/hr (gpm)	22 – 7250 (100 – 32,000)
Slot size, mm (inch)	1 – 9 (0.04 – 0.35)

The intake screens were used for various ocean water applications including: power plants, liquefied natural gas, desalination, thalassotherapy, etc.

Conclusions for Intake Screen Material

Copper alloys, duplex, and super duplex stainless steels are commonly used in marine installations. The 90-10 and 70-30 are two of the most common copper alloys and the duplex 2205 is the most common stainless steel alloy. During our research we found no reference to screens that were constructed with titanium. We recommend that the following materials be considered for the study:

1. 90-10 CuNi (UNS C70600)
2. Johnson Screen Z Alloy (a proprietary copper-nickel alloy)
3. 70-30 CuNi (UNS C71500)
4. 2205 Duplex stainless steel
5. 2205 Duplex stainless steel (coated with Sherwin Williams Foul Release System)

Super duplex stainless steel was not deemed warranted as neither the duplex nor super duplex have anti-biofouling properties, and the duplex stainless steel is suitable for the offshore water temperature. The additional cost for the super duplex does not appear to be warranted for the addition anti-corrosion properties.

The required degree of maintenance on the intake screens varied in accordance with water temperature, marine environment, and velocity. Various methods were used by Owners and operators to control biological growth including:

1. Manual Maintenance by divers
2. Air Bursting
3. Chemical Treatment

Based on our review of different foul release coatings and our discussions with the District, we researched the coating system that has been utilized for multiple years and that also had NSF 61 certification. This Sherwin Williams Foul Release System has a well-documented product history in the United States and is NSF 61 compliant. The system consists of the following:

1. 1st coat - Sherwin Williams "Macropoxy" 646 PW immersion grade epoxy primer @ 6 mils dft
2. 2nd coat - Sherwin Williams "Macropoxy" 646 PW immersion grade epoxy primer @ 6 mils dft
3. 3rd coat - Sherwin Williams "Seaguard" Sher-Release beige silicone Tie Coat @ 6 mils dft
4. 4th coat - Sherwin Williams "Seaguard" Sher-Release white silicone Surface Coat @ 6 mils dft

It should be noted that all coatings require maintenance and recoating. The life of a coating is site specific to the conditions it must perform.

INTAKE PIPING SELECTION

Various types of piping are used in marine installations. The selection of pipe material is based on the resistance to corrosion, availability, and ease of installation. Common pipe materials used in submerged ocean water service include: concrete, duplex stainless steel, high density polyethylene (HDPE), polyvinyl chloride (PVC), and glass reinforced plastic (GRP) pipe.

Installations in Saudi Arabia, Fort Lauderdale, Cyprus, and Israel were contacted to ask about the performance and maintenance of their various intake pipelines.

Corrosion

Due to seawater's high potential for corrosion, non-metallic pipes are often the preferred option. Pipes, just like the intake screen material selection, are susceptible to same corrosion mechanisms and biological growth challenges. Metallic pipes will be subject to galvanic corrosion, microbial growth slime layer/biofilm corrosion process (i.e. oxygen reduction), and erosion corrosion. Pipe systems that utilize carbon steel, ductile iron, or 316 stainless steel are not being considered as they corrode quickly in a seawater environment and would result in a limited service life. Duplex stainless steel pipe is used commonly in desalination, naval, port, and harbor installations. Duplex stainless steel is corrosion resistant up to a point and is still susceptible to pitting and crevice corrosion in seawater with similar water temperatures. It is susceptible to chloride attack and if chlorination is being considered to mitigate biological growth, it is not a preferred material.

Concrete pipes are subject to sulfide corrosion attack due to sulfur-reducing bacteria. The bacteria produces an acid that attacks the lime in the pipe resulting in softening of the concrete. Concrete has to be coated with a protective coating to mitigate this deterioration. The coating has to be maintained as its effectiveness is diminished over time and due to erosion corrosion.

A non-metallic pipe such as HDPE, PVC and GRP are not impacted by any of the corrosion processes above.

Biological Growth and Maintenance

Concrete pipes have rougher interior surfaces and require continual maintenance due to the development of a slime layer, as well as attachment by mussels, barnacles, and other sea life. The slime layer would be a micro-fouling biofilm on the inside of the pipe, such as an algae. Concrete pipes require continual maintenance either by divers or by pigging (pulling/dragging a mandrel) to remove the attachments. Pipeline pigging is a maintenance technique that pulls or drags a mandrel through the pipeline in order to remove build-up along the interior of the pipe by scrapping it off and pushing out the debris.

All the non-metallic piping that has been placed into service has experienced attachment by biological growth at different time intervals. Based on the interviews and studies, the time interval has less to do with the material than it has to do with the marine environment and how aggressive/nutrient and animal rich it is. All non-metallic piping has to be maintained.

Maintenance strategies for intake systems to mitigate biological growth varied and are summarized herein:

1. Heat Treatment: Biofouling control methods based on temperature changes are used in power plant cooling systems (Kamala Kanta Satpathy et al., 2010). This method is routinely used at some plants in the USA, England, Italy, Netherland, and Russia. Heated effluent from the condenser of the power plant is diverted through the intake tunnel which when passed through the condenser picks up more heat. In general, heating the water to a temperature of 40º C (104º F) for approximately one hour is enough to eliminate mussel and other fouling organisms. Heat treatment was only found to be used at power plants; we did not find any desalination facilities utilizing this control strategy, and this strategy would likely be difficult and/or nearly impossible to permit now in California.

2. Scouring velocities (velocities kept at or higher than 10 fps): In Italy at Vado Ligure, the cooling water intake of a power plant (1320 MW (e), four 2.2 m diameter culverts of 1400-1500 m long) was kept free of biofouling for l4 years by maintaining a velocity of 11 ft/sec (Kamala Kanta Satpathy et al., 2010).

3. Addition of chemicals:

   a. Constant addition
   b. Shock chlorination

   Chlorination is a common method used to control biofouling on the inside of the pipe. Intermittent chlorination can be used to combat micro-fouling, such as a bacterial slime layer (Boehmer et al, 1985). Continuous chlorination is needed to address macro organisms such as mussels; mussels will close up during intermittent periods of chlorination (Boehmer et al, 1985). The reaction by addition of chlorine with sea water will result in the presence of HOCl, OCl, HOBr and OBr and will act to create the hostile environment for living organism. The fundamental objective in water chlorination is to create a hostile environment which will discourage marine organisms from establishing themselves and growing. Chlorination is effective in killing marine organisms; shells from barnacles, mussels, etc. remain in the system. (Boehmer et al, 1985).

   Continuous and shock chlorination is used Al-Jubail Power/MSF Plant. The residual chlorine target was 0.2 to 0.50 ppm.

   The seawater reverse osmosis plant at Al-Birk located in the southern region of the Red Sea coast of Saudi Arabia utilized continuous chlorination and then added sodium metabisulfite (SBS) to neutralize the chlorine residual before the reverse osmosis membranes. The free chlorine residual was a maximum of 1 mg/l. This resulted in the surviving bacteria feeding on the nutrients caused by the degradation of larger molecules and the bacteria entered into a cycle of tremendous growth. This resulted in a significant increase in biomass developing on the surfaces of the piping and RO membranes (Mohamed Saeed, January 2000).

4. Manual maintenance (typically pigging): The operators the Ashkelon Desalination Plant in Israel pig the line one to two times a year to remove macro-organism growth. The pigging is done in combination with chlorination.

5. Combination of chemical and manual maintenance techniques.

Based on our research and discussion with industry experts, all piping systems will require a maintenance program whether it is chemical, manual (pigging, divers), or both. Chlorination was the chemical of choice being used to control biofouling. We did not find publications that documented the use of another disinfectant such as chloramines, ozone or any acids to control biological growth. It is our understanding that the District’s proposed full scale facility has a rated capacity of 40 mgd of seawater drawn through a 54-inch diameter pipe. This results in an average velocity through the pipe just less than 4 fps based on the District’s Ocean Water Desalination Program Master Plan. To mitigate biological growth solely through scour, velocities within the pipe will need to be about 10 feet per second or higher per the research found. Non-metallic pipes being considered are appropriate for this control strategy. Stainless steels are susceptible to corrosion attach by chlorine.

Velocity rates varied from a low of 1 fps at some of the power plant intake tunnels to a high of 7 fps. The Carlsbad Desalination Plant is being constructed with a 72-inch HDPE intake with a velocity of approximately 5.9 fps (108 mgd intake flow). The intake pump station will take suction from the outlet tunnel of the Encina Power Plant. In the future if once through cooling is eliminated the intake pump station connection will be modified to take water from the intake tunnel connected to the seawater lagoon.

In our interview with Boris Lieberman, Chief Technology Officer at IDE, he stated that using a velocity of greater than 5 fps helped to control biofouling but that other measures such as regular pigging of the intake pipe was also needed at their plants in the Mediterranean Sea.

Data shows that some marine growth can be reduced at scour velocities greater than 10 fps. The Vado Ligure power plant indicated they were able to keep intake pipes free of biofouling for 14 years by operating at 11 fps. However, these high velocities also increase energy usage and operating cost. The table below indicates the estimated annual cost increase to operate the future West Basin Seawater Desalination Plant over a velocity of 11 fps.

Table 2-7: Estimated Annual Cost Increase to Operate at High Velocities

Pipe Diameter (inch)	Flow (mgd)	Velocity (fps)	Headloss (ft)	HP	kW-h/Yr	Cost ($)
2-42	45.1	3.6	4.4	49.4	306,438	$36,773
1-34	45.1	11.0	22.4	251.3	1,560,049	$187,206
					Cost Difference	**$150,433**

Note: Assumes operations with 95% availability.

The conclusions from the interviews was that maintenance requirements are site specific; at some locations the pipe has been relatively clean requiring very little maintenance and at other locations the inlet pipe has required extensive cleaning.

Conclusions for Intake Piping Material

The intake pipe should be non-metallic to mitigate the corrosion issues that are present in a submerged seawater application. Additionally, the non-metallic pipes have smoother interior pipe surfaces than concrete pipes, and therefore have a lower friction coefficient. For the test, HDPE and/or PVC could be used. GRP type pipe does not provide the connection types to readily assemble a testing pipe rack. The interior surfaces of all three of these non-metallic materials are also very similar in how they are formed. HDPE pipe is being recommended for the following reasons:

1. It has been used at the demonstration facility and known results of its performance during and can be used as part of the study;
2. It is readily available;
3. Its interior surface is similar to that of PVC and GRP as all three are formed with a smooth interior; and
4. Cost effective.

The required degree of maintenance on intake pipelines varied in accordance with water temperature, marine environment and velocity. Various methods were used by Owners and operators to control biological growth including:

1. Continuous Chlorine Addition (see Diablo Canyon Nuclear Plant)
2. Heat Treatment (see Encina Power Plant, Carlsbad, California)
3. Shock Chlorination (see Larnaca Desalination Plant, Cyprus)
4. Pigging (see Ashkelon Plant, Israel)

Conclusions for Intake Piping Control Strategies

Based on our review and interviews, chlorination was the most widely used form of chemical control strategy. The District, as part of the OWDDF, utilized chloramination. The District preferred chloramines over free chlorine in order to protect the RO membranes from being damaged due to their sensitivity to free chlorine. The District found that utilizing chloramines it resulted in lower volume of chemicals required, it mitigated fouling of the RO membranes and resulted in lower operation and maintenance costs. Shock chlorination was used at some locations to kill the micro-organisms such as the bacterial slime layer. This is the same theory as continuous chlorination; create a hostile environment that does not promote attachment of these macro-organisms. It also may result in killing macro-organisms; however, this did not result in the attachments (e.g. shells and other encrustations) from detaching from the interior of the pipe. It has also been reported that several macro-organisms can survive several hours (more than 8 hours) of high concentrations of chlorine. The time duration was found to be dependent on type of species and site location. We also did not find publications that documented the use of other disinfectants such as chloramines, ozone or any acids to control biological growth. Another possible control strategy is creating a low oxygen (anoxic) environment. If the pipeline can be taken out of service and allowed go stagnant, resulting in depleted oxygen and nutrient levels, the macro-organism growth can be slowed. However, this will not mitigate the micro-organism slime layer growth or anaerobic bacteria. While this may result in slowed or even eventual macro-organism death, this process also may not result in detachment of the encrustations. The District employed the anaerobic approach at its demonstration facility and found similar results.

Based on our research we submit the following control strategies for this study to be considered by the District:

1. Continuous chloramination
2. Shock chlorination

The dosing and rate of the chemical will be discussed in the test plans.

Anoxic control will not be further studied as this control strategy only hinders or slows growth but does not prevent it. While the pipe is in operation, growth of micro- and macro-organisms is occurring. This method may slow or delay growth but will ultimately require maintenance in order to remove the growth that does occur. This also means that the pipeline will need to remain out of service long enough for the dissolved oxygen in the water to be depleted. This does not ultimately achieve the District’s goal of utilizing a control strategy that mitigate biological growth and minimizes future maintenance. This also results in potential long interruptions in service.

High velocities to control biological growth were only found to be used at one location. High velocities results in higher headloss through the intake piping and the need for higher lift at the pump station and increased energy costs. The increased head and energy costs will be estimated as part of the intake piping test plan. At this time, control by high velocities is not being considered a viable alternative.

Similar to the intake screens material recommendation, an anti-fouling coating is not being considered. The required maintenance and continual recoating required is not desired and almost impossible to re-coat once the piping is installed and in service.

CHAPTER 3
INTAKE PIPE TESTING

INTRODUCTION

The intake piping is a critical component of a Seawater Desalination Facility. It links the intake facility to the intake pump station and then to the pretreatment system. Intake piping is subject to both micro-biological activity (bacteria, slime, etc.) and macro-biological activity (mussels, sponges, marine organisms). Control of biological activity is critical to successful full scale operations.

A pipe test facility was build and installed at the SEA Lab Facility in Redondo Beach, California. The facility was built to simultaneously test three pipe runs subject to seawater, chloraminated seawater and shock chlorinated seawater to compare and measure micro- and macro-biological activity.

Intake Pipe Testing Facility

The Pipe Test Facility was completed, tested and placed into operation on May 7, 2014. Pipe spools were removed and inspected on the following dates:

Date Removed	Days in Operation
June 30, 2014	54
August 28, 2014	114
October 28, 2014	174
December 22, 2014	230

GOAL

The goal of the Intake Piping Test was to determine the effectiveness of anti-biofouling control strategies for intake piping in conjunction with the assessment of piping materials.

The objectives of the Intake Piping Test were:

- Design and install a piping test system that is representative of the future conditions of the full scale West Basin Desalination Project.
- Design and install a piping test system that can be used to quantify and characterize attachments of micro and macro organisms to intake piping materials.
- Obtain findings that can be used to develop appropriate measures to ensure proper future design, implementation and operation of an intake facility for West Basin's Future Desalination Project in Redondo Beach or El Segundo.

AVAILABLE FLOWS

In order to perform a representative test, the test unit was operated under similar conditions as the full scale facility. The two existing 6-inch intake pipelines are located inside the raw water feed tunnel for the Redondo Beach Power Plant. A wedgewire screen is installed at the intake of each 6-inch feed pipeline.

The influent water is pumped using two pumps installed as part of the OWDDF. Each pump is connected to a different 6-inch intake pipeline. A single pump was used to feed the Pipe Test Facility and the pumps were rotated when intake clogging occurred.

Using the 240 gpm as a guide we determined the following flow rates for the test:

	Flow (gpm)	Diameter (inch)	Velocity (fps)
IB&C Influent	240	4	2.8
Pipe Test Runs (3 each total)	80	3	3.5

The test pipe runs were sized at 3-inch to allow viewing and photographing of the inside of the pipe segments after removal. The 3.5 fps closely matches the proposed velocity shown in the PMP. Velocity on the 6-inch pipelines was be approximately 2.8 fps.

BIOFOULING CONTROL STRATEGIES

Since we were limited to three pipe runs due to flow limits at the site it was important to select the most relevant three biofouling control strategies to test. The following options were eliminated:

- High velocity to minimize biofouling was eliminated because it would not be practical to operate the future intake at 11 fps due to energy costs.
- Allowing the pipe to go anoxic for a number of days was eliminated since this method has already been used at the OWDDF with some success.
- Anti-biofouling coating on the pipe interior was eliminated since the coating was found to require reapplication every five years which would not be practical.
- Injecting chloramines once a week with a Sulfuric Acid Flush, while promising was eliminated due to lack of any literature found to confirm success. High chemical costs and difficultly obtaining permits were also concerns that led to eliminating this option.

The following three pipe test runs were determined to be the most appropriate for the study:

- Control Pipe Test consisting of 3-inch HDPE pipe with no additional biological control strategy. This was used as the baseline to compare the other pipe test runs.
- Shock chlorination as a biogrowth control method has been found to be effective at numerous installations. Liquid Sodium Hypochlorite (12.5% solution) will be used to provide a shock dosage of 20 ppm for 1 hour once a week during the study. Literature review and interviews indicated that dosages of 10 ppm or less were not effective. Data from the West Basin Demonstration Project indicate that some success was found at rates over 10 ppm. Therefore, a rate of 20 ppm was used.

  Literature review indicated various lengths of time for shock chlorination from 20 minutes to 8 hours if mussels had already begun to grow in the pipeline. Therefore, we used a shock chlorination of 1 hour once a week and evaluated every two months.
- Constant injection of chloramines was performed. Softened potable water was used to form chloramines continuously for injection into one of the pipe runs. Sodium Hypochlorite (12.5%) and Ammonium Sulfate (10%) were injected into the softened water line to form chloramines at a ratio of 4 to 1. Chloramines were formed and injected into the seawater to maintain a residual of 5 ppm.

  No literature was found on the use of chloramines in intake pipelines. Therefore, it was determined to use a dosage of 5.0 ppm which is slightly higher than is used in potable water system disinfection. This dosage was evaluated at two month intervals.

DESIGN OF TEST FACILITY

The test facility was located at the SEA Lab site in Redondo Beach, California. A 20-foot by 30-foot concrete pad area on the south side of the facility was used for the test.

West Basin and United Water provided seawater pumped to the test facility at a rate of 240 gpm at 10 psi. Seawater to the test facility was provided from a 4-inch PVC pipeline. A 4-inch PVC pipeline was also used to return the 240 gpm from the test facility to the OWDDF equalization tank outfall line. All piping on the test skid and chemical systems were rated for 125 psi maximum pressure.

Close-up of the Pipe Test Runs

Potable water at a rate of approximately 0.8 gpm was also provided at the site. Tetra Tech connected to the existing nearby potable water connection. The potable water was used, after softening, to form chloramines.

The pipe test rack consists of three 3-inch pipe test lines connected to 6-inch pipe headers. Each test run will have five removable flanged sections. The sections were constructed with an HDPE weld bead similar to the weld bead that is used to fuse the pipe in the full scale facility.

The test pipe runs each had two shutoff valves, a flowmeter, and sample taps. These were used to set flow through each pipe run and to test for chlorine residual.

In order to protect against any potential leaks or issues with intake pump failures, instrumentation has been added to the test site: a float switch has been added to sense any leakage that occurs on the test pad. Each chemical pump will be wired to shutdown remotely from a signal generated at the existing PLC. A solenoid valve has been included that can close the potable water service remotely.

The following programming was provided by United Water on the existing PLC:

- If a leak is detected from the float switch the PLC will signal the intake pumps to shutdown, chemical feed pumps to shut down and the potable water solenoid to close.
- If either intake pump shuts down the chemical feed pumps and potable water solenoid valve will be closed so that no potable water or chemicals are fed to the pipe test skid.

Chemical Feed

Table 3-1 outlines the chemical feed systems installed at the facility. All chemical storage was provided with spill prevention. Chemical feed lines were in double containment piping from the feed pump to the injection point. Sodium hypochlorite was transferred from the 55-gallon shock chlorination tank to the chloramines system as needed using a hand pump.

Table 3-1: Test Facility Chemical Feed Systems

Chemical	Concentration	Storage	Dosage	Pump Rate
Sodium Hypochlorite (Shock Chlorination)	12.5%	55 gallon drum	20 ppm (1 hour per week)	0.93 gph
Sodium Hypochlorite	12.5%	55 gallon drum	5 ppm continuous	0.23 gph
Ammonium Sulfate	10%	55 gallon drum	1.1 ppm	0.23 gph

Chloramines were continuously preformed as shown in Figure 2. Potable water was run through a water softener to produce a softened stream of water approximately 1% of the seawater flow (0.8 gpm). Ammonium sulfate will be added first and mixed with the softened water. Next sodium hypochlorite was added to preform chloramines prior to injection into the seawater stream. A rotometer will be used to control flow to the test skid. Weekly tests of total chlorine residual were taken to confirm that chloramines were properly formed.

Start-up and Testing

Prior to operation the Pipe Test Facility was subjected to testing to confirm proper operations. All valves and rotometers were opened and closed to verify tight shutoff. The test piping was filled at 50 gpm in order to purge any air from the system. The flow was increased in increments up to 240 gpm.

Valves on the pipe test runs were modulated in order to confirm that flow could be adjusted to a continuous 80 gpm per pipe run. The flow meters were calibrated to confirm flows.

After verification of stable operations, the chemical feed systems were started. Dosage rates for shock chlorination and chloramines were set and test kits were used to verify proper dosage and residuals.

The entire system was run for 2 hours to confirm stable operations then placed into service.

Early operations indicated that adjustments to the flow in each test run were needed on a daily basis due to changing feed flows and pressures. However, as the testing progressed these issues were resolved and weekly modifications were acceptable.

The original rotometer flow meters on the pipe test runs needed to be cleaned on a weekly basis. A brown slime quickly formed on the meters which eventually caused them to clog. They were replaced with paddle wheel flow meters which required less cleaning.

Operations

Tetra Tech staff provided operations support required to maintain continuous operations during the study period. One person was on site once a week to check operations. The operator was on-site on Mondays from 10:00 a.m. to approximately 2:00 p.m.

The following weekly duties were performed:

- Check all piping, chemical lines, pumps and valves for leaks.
- Check and record upstream and downstream pressures.
- Check all rotometers and confirm that flows are 80 gpm for each pipe run. Record flows prior to making any adjustments.
- Check all injection quills.
- Check total chlorine residuals for the chloramination test run.
- Check free chlorine residual for all three pipe runs.
- Check flow in solution feed line.
- Check water softener operation and call supplier if service is needed.
- Document all site conditions, flow rates, pressures, chemical drawdowns and chlorine residuals (free and total).
- Adjust chemical feed pump speed to obtain required total chlorine residual in the chloramination feed.
- Start the shock chlorine feed pump at 20 ppm.
- Check free chlorine residual on the entrance and exit of the shock chlorine pipe run. Adjust if required.
- Run shock test at 20 ppm for 1 hour then turn off chemical feed pump.
- Adjust flow if required to match 80 gpm requirement.
- Confirm all flows, pressure and residuals prior to leaving the site.

United Water operator at SEA Lab also supplied support for the project. The operator was onsite 5 days a week and performed the following duties:

- Check to make sure feed pump is operating.
- Check flow and pressure on feed pump.
- Confirm that there are no chemical or water leaks.
- Record flows and pressures on Daily Report Form.
- Check the three pipe run meters to confirm the flow is 80 gpm.
- Adjust the feed valve on the pipe run to obtain 80 gpm flow through each pipe run.
- Record all flows and pressures after any adjustments.

Removal of Pipe Test Section

In order to get a representative sampling of growth on the pipe intakes it is important to test pipe sections during each season of the year. In the spring the water will likely be at its coldest while summer and fall will have higher temperatures and correspondingly more growth. Testing at three month intervals for one year would provide a representative test inclusive of year round water temperatures. However, due to time restraints the testing needed to be completed by the end of December 2014. Therefore, pipe test sections were installed and removed as follows:

Date	Activity
May 7, 2014	Start Test
June 30, 2014	Test 1
August 26, 2014	Test 2
October 28, 2014	Test 3
December 22, 2014	Test 4

Close-up of Individual Pipe Spools

Each pipe spool was given an identifying tag, and then be bagged prior to transport to Tenera's San Luis Obispo office. The bagged spools were placed in ice chests for the trip along with sealed bags or blue-ice packs, and kept chilled until they were inspected and analyzed to ascertain their biofouling condition.

BIOFOULING ANALYSIS

Each pipe spool removed was photographed individually with photo ID tag and inspected with the following information recorded on the biofouling analysis data sheet.

1. Visual inspection of the interior of the pipe spool was performed. In order to view interior of the pipe a mirror or optic device was used.
2. The presence and thickness of a microfouling slime layer was checked. If a layer was present a sample was removed and inspected under a microscope.
3. Any major macrofouling taxa that were accessible from the pipe ends were identified. This is done prior to scraping since that procedural step may render some organisms unidentifiable.
4. Attached invertebrates, algae and slime were identified to the lowest taxonomic level possible using a number of identification guides for specific groups of invertebrate and at least the following two general identification guides: Morris, Abbott and Haderlie (1980) and Carlton (2007). Algal identifications will be based on Abbott and Hollenberg (1976).
5. The rate of microfouling growth for each technique was determined by measuring the thickness of the slime growth at each three month period.

Following the biofouling inspection and analysis, the pipe spool was cleaned, bleach washed, thoroughly rinsed, and reused as a replacement spool during the next quarterly retrieval.

RESULTS

The following is a summary of the biofouling inspection of the pipe spools. Full reports of the pipe inspections are included in Appendix C.

First Pipe Spool Inspection – July 1, 2014

Pipe Spool Description

- The pipe spools consisted of the following:
    - Each is 18-inches long with a pair of ring-flanges.
    - Each spool is constructed of three 6-inch sections; an inlet and outlet ring-flanged section and a middle pipe section.
        - The pipe material of all three sections is black high-density polyethylene (HDPE).
        - The rings for the ring-flanges are metal (galvanized steel).
        - There is some sort of double O-ring or gasket where the inlet and outlet sections connect with the middle section. These seals extend both inward into the pipe and outward above the pipe exterior. The total width of these double-seals is about 7-8 mm and they extend into the pipe interior about 3 mm. These will be referred to as "ridges", such as the first ridge or second ridge from the inlet.

    - The inlet and outlet sections surfaces are not smooth, but have small ribs around the pipe's circumference, perpendicular to the direction of flow.
        - There are about three ribs per mm and they are about 0.25 mm in height.
    - The middle section has a smooth surface, no ribs.
- The surface irregularities caused by the ribs and the ridges induce some turbulence at the pipe surface and may promote settlement by some macrofouling species, like barnacles, as has been observed in the past at pipe joints and other substrate surface anomalies (pits, bumps, scratches, old shells, etc.).

Pipe Spool A1 (Control)

- This is the first pipe spool in spool row A. No chemical injection; this is the "Control" spool row.
- First impression is that the inner surface of the spool is very clean, no macrofouling initially observed.
- Pipe surface has a very slight slime feeling to the touch. Tissue wipe made of the surface shows a brown tinge that is probably diatoms, but not enough can be collected for a microscopic inspection.
- Further inspection with a lighted-mirror tool found two small acorn barnacles (1.5 and 2.5 mm basal diameter). The smaller of the two is on the downstream side of the first ridge and the other is about 5 cm further downstream in the middle section.
- One barnacle was removed for microscopic ID and photographing. It was a Balanid barnacle, probably *Balanus glandula*, but it is too early in its development to be sure.
- No other macrofouling.
- No sand.
- Some mussel shell debris was found when the spool was remove from the pipe rack and was included in a separate bag with spool A1. This is old debris that must have originated in the seawater supply line to the test apparatus.

Pipe Spool B1 (Continuous Chloramine Injection)

- No macrofouling organisms were found.
- No slime/diatoms detected by touch or tissue wipe.
- Fine sand covers approximately the bottom ⅓ of the pipe spool.
    - Some old, empty, barnacle and mussel shell fragments mixed in with the sand.

Pipe Spool C1 (Shock Chlorination)

- No slime/diatoms detected by touch or tissue wipe.
- About 75 to 80 very small acorn barnacles (Balanidae) were observed.
    - Size (maximum basal diameter) range from about 0.5 mm to 3.0 mm.
    - Barnacles are concentrated near the two ridges with the most (45 to 50) being at or downstream of the second ridge, in the outlet section. Only two individuals were in the smooth middle section.

- Fine sand covers approximately the bottom ½ of the pipe spool.
  - Some old, empty, barnacle and mussel shell fragments mixed in with the sand.
  - Sand as deep as about 3 mm (sand depth is probably limited by the height of the ridges).

Conclusions and Questions

- Ribs and ridges probably promote settlement in comparison with the smooth middle section.
- Decreasing quantity of sand in the spools as you move upward from Row C to Row A is indicative of the decreasing flow velocity as the water moves upward in the 6-inch vertical manifold.
  - If you start with an initial flow of 150 gpm at the bottom of the manifold the average water velocity would be about 1.7 fps. After shunting ⅓ of the flow off into Row C, that would drop to about 1.1 fps. After losing another ½ of the remaining flow to Row B, the velocity would drop to about 0.6 fps.
  - It appears that the velocity at the inlet of Row A is no longer sufficient to suspend the sand grains.
- Why are there only 2 barnacles in the control spool (Row A) and 75 to 80 in the shock chlorination spool (Row C)?
  - Is this related to the loss in water velocity as the flow progresses up the vertical manifold (see above)? Is there a similar effect on the larval densities reaching Row A?
  - Is this related to the accelerated seasoning of the HDPE pipe in Row C because of the shock chlorination and abrasion by the sand?
  - Is it related to both?
- Continuous chloramine treatment appears to be effective at this time.
- Shock chlorination has not eliminated all barnacle settlement and growth.
- No slime detected by touch in Rows B & C.
  - It could be the continuous treatment in Row B, but would weekly shock chlorination be sufficient to eliminate it? (probably not).
  - Is the sand also reducing any diatoms / slime on the pipe walls- abrasion?

Second Pipe Spool Inspection – August 29, 2014

Pipe Spool A2 (Control)

- This is the second pipe spool in spool row A. No chemical injection; this is the “Control” spool row.
- First impression is that the inner surface of the spool is very clean, little macrofouling observed.
- Pipe surface has a slime feeling to the touch. Slime is visible in the photos with a brownish tinge. Samples were removed and inspected under a microscope; samples include diatoms and entrapped silt particles. Layer was not of measureable thickness or of a quantity that would allow removal for a weight determination.

- Inspection with lighted-mirror tools found a total of 14 small acorn barnacles (0.5 – 2.0 mm basal diameter). The barnacles are located near areas of surface discontinuity or turbulence, such as the inlet to the spool and the ridges that divide the spool into three section (inlet, middle, and outlet).
- Two barnacles were removed for microscopic ID. They were a Balanid barnacles, probably *Balanus glandula*, but it was too early in their development to be sure.
- No other macrofouling.
- No sand

Pipe Spool B2 (Continuous Chloramine Injection)

- No macrofouling organisms were found.
- No slime/diatoms detected by touch or tissue wipe.
- 15 small mussel shells were found in the spool (3 – 10 mm in length). All of the shells were empty and none of them were attached to the pipe surface (no byssal threads). All of the shells are new in appearance with clean dark outer surfaces and a shiny inner nacreous layer (mother of pearl).
    - These shells did not originate in the spool and there is no evidence of mussel attachment in any of the three spools (no remnants of byssal threads or signs of past byssus attachment on the pipe surfaces). Shells are probably from the seawater supply line.
- No sand

Pipe Spool C2 (Shock Chlorination)

- No slime/diatoms detected by touch or tissue wipe.
- 12 small acorn barnacles (Balanidae) were observed.
    - Size (maximum basal diameter) range from about 0.5 mm to 3.0 mm.
    - Only one barnacle each found in the inlet and middle sections of the spool, the other ten were in the outlet section.
- Three of the larger (2 to 3 mm) barnacles were identified as *Megabalanus californicus*, the others appear to be *Balanus glandula*.
- No sand

Conclusions

- Little or no macrofouling in any of the three spools.
- Although there is a complete lack of fouling in the Continuous Chloramine treatment spool (spool B2), the paucity of fouling in the Control spool (spool A2) provides little comparison against which to evaluate the efficacy of any of the treatments.
- The lack of macrofouling in the Control spool is most likely due to the cropping of macrofouling larvae from the water supply by established filter-feeding organisms (mussels, barnacles, etc.) in the seawater supply line. There may be other contributing factors including the low flow velocities in portions of the system, and cropping of food items from the seawater flow as it passes through the supply line (reducing survival and growth of any organisms settling in the pipe spools).

Third Pipe Spool Inspection – October 28, 2014

Pipe Spool A3 (Control)

- This is the third pipe spool in spool row A. No chemical injection; this is the “Control” spool row.
- First impression is that the inner surface of the spool is very clean, little macrofouling observed.
- Photos were taken from inlet and outlet ends **(Figure 3-1).**
- Pipe surface has a slimy feeling to the touch. Slime layer is visible in the photos with a brownish appearance. Samples were removed and inspected under a dissecting microscope. The samples appeared to be comprised of filamentous material (probably algal filaments) with entrapped detritus (silt, etc.). The layer was not of measureable thickness (less than 0.5 mm) or of a quantity that would allow its removal for a weight determination. Following photographs and inspection, this layer was easily removed from the pipe surface by either a gentle swipe with a finger or soft instrument, or by flushing with water from a hose.
- Inspection with lighted-mirror tools found a total of 18 small acorn barnacles (2 mm to 4 mm basal diameter). The barnacles are located near areas of surface discontinuity or turbulence, such as the inlet to the spool and the ridges that divide the spool into three sections (inlet, middle, and outlet). Barnacles that were large enough to be identified were *Megabalanus californicus*, the others were Balanid barnacles, possibly *Balanus glandula* or *M. californicus*, but it was too early in their development to be sure.
- Six small acorn barnacles (1 mm) were found on the face of the outlet flange – not within the pipe spool **(Figure 3-1).**
- No other macrofouling was found.
- No sand

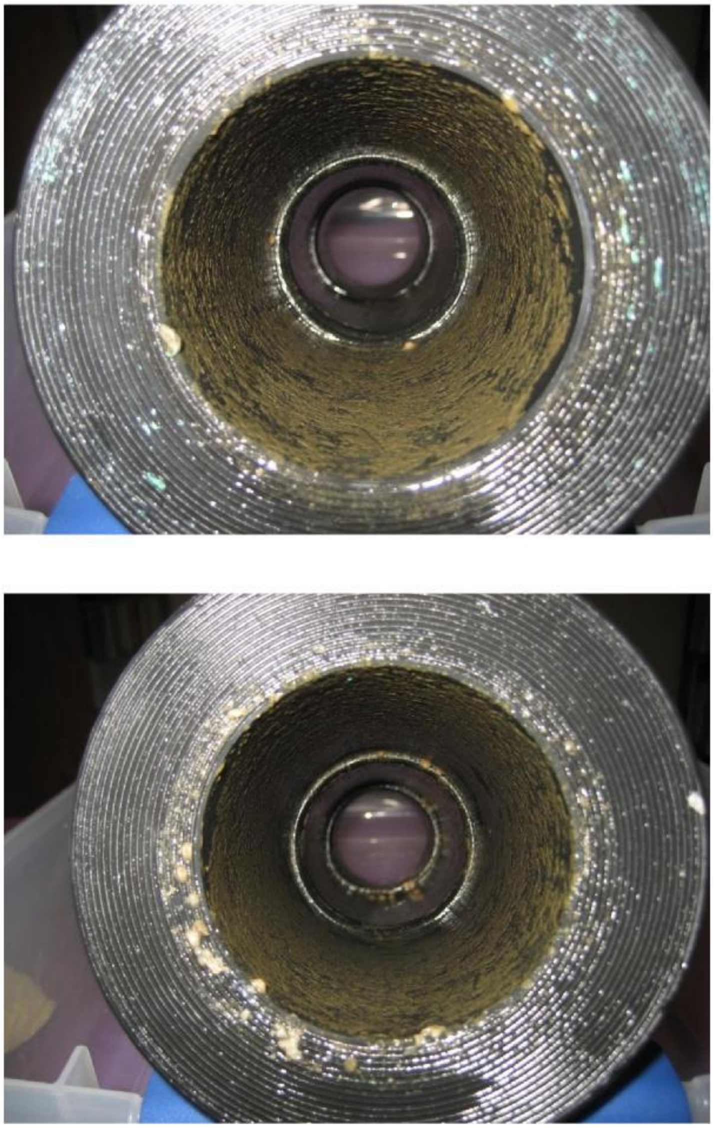


Figure 3-1. Pipe spool A3 (Control) October 28, 2014. Inlet (top) and Outlet (bottom).

Pipe Spool B3 (Continuous Chloramine Injection)

- This is the third pipe spool in spool row B and was treated with continuous injection of a chloramine solution.
- Photos taken from inlet and outlet ends **(Figure 3-2).**
- No macrofouling organisms were found.
- No slime/diatoms detected by touch or tissue wipe.
- No sand

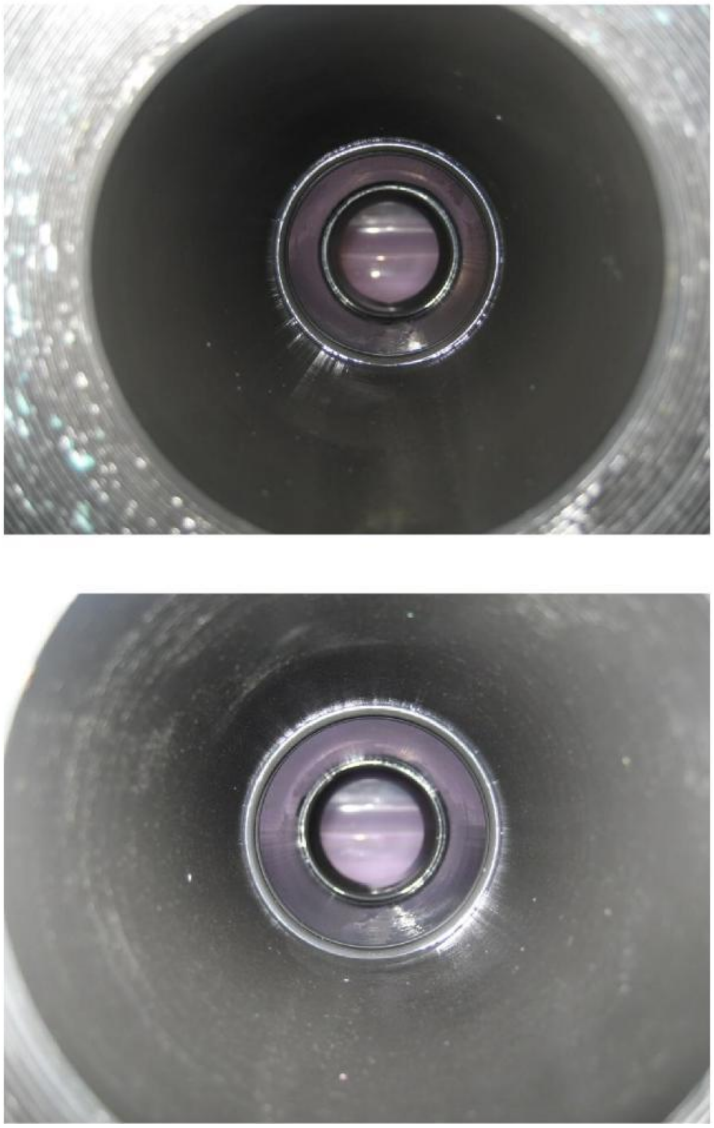


Figure 3-2. Pipe spool B3 (Continuous Chloramine Injection) October 28, 2014. Inlet (top) and Outlet (bottom).

Pipe Spool C3 (Shock Chlorination)

- This is the third pipe spool in spool row C and received a weekly shock treatment with sodium hypochlorite.
- Photos taken from inlet and outlet ends **(Figure 3-3).**
- The pipe walls have a slight brown tinge, but do not feel slimy to the touch. The material can be easily removed with a tissue wipe. This could be fine silt trapped in a bacteria layer, or a thin layer of diatoms.
- 9 small acorn barnacles (Balanidae) were observed; 3 in the inlet section and 6 in the outlet section.
    - Size (basal diameter) ranged from about 1 mm to 3 mm.
    - No barnacles found in the middle section of the spool.
- A small ball of plastic shavings were found at the ring between the middle and outlet section.
- No sand

Conclusions

- Little or no macrofouling in any of the three spools.
- Although there is a complete lack of fouling in the Continuous Chloramine treatment spool (spool B3), the paucity of fouling in the Control spool (spool A3) provides little comparison against which to evaluate the efficacy of any of the treatments.
- The lack of macrofouling in the Control spool is most likely due to the cropping of macrofouling larvae from the water supply by established filter-feeding organisms (mussels, barnacles, etc.) in the seawater supply line. There may be other contributing factors including the low flow velocities in portions of the system, and cropping of food items from the seawater flow as it passes through the supply line (reducing survival and growth of any organisms settling in the pipe spools).

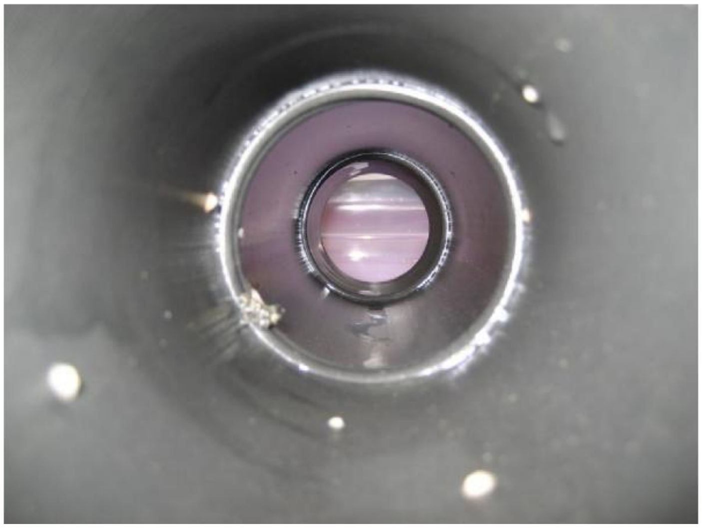


Figure 3-3. Pipe spool C3 (Shock Chlorination) October 28, 2014. Inlet (top) and Outlet (bottom).

Fourth Pipe Spool Inspection – December 23, 2014

Pipe Spool A4 (Control)

- This is the fourth pipe spool in spool row A. No chemical injection; this is the "Control" spool row.
- First impression is that the inner surface of the spool is very clean, little macrofouling observed.
- Photos were taken from inlet and outlet ends **(Figure 3-4)**.
- The pipe surface had a dull brown appearance, but no slimy feeling to the touch as had been detected at the end of October when the last set of spools were inspected. Following photographs and inspection, an attempt was made to remove some of the brown discoloration with a tissue wipe, but no material came off the surface of the pipe.
- Inspection with lighted-mirror tools found a total of 11 small acorn barnacles in the inlet section of the pipe spool, 19 barnacles in the middle section and 25 in the outlet section. The barnacles ranged in size from <1 mm to 4 mm. The barnacles were located near areas of surface discontinuity or turbulence, such as the inlet to the spool and the ridges that divide the spool into three sections (inlet, middle, and outlet). Barnacles that were large enough to be identified were *Megabalanus californicus*, the others were Balanid barnacles, possibly *Balanus glandula* or *M. californicus,* but it was too early in their development to be sure.
- No other macrofouling was found.
- No sand or debris was observed in the spool.

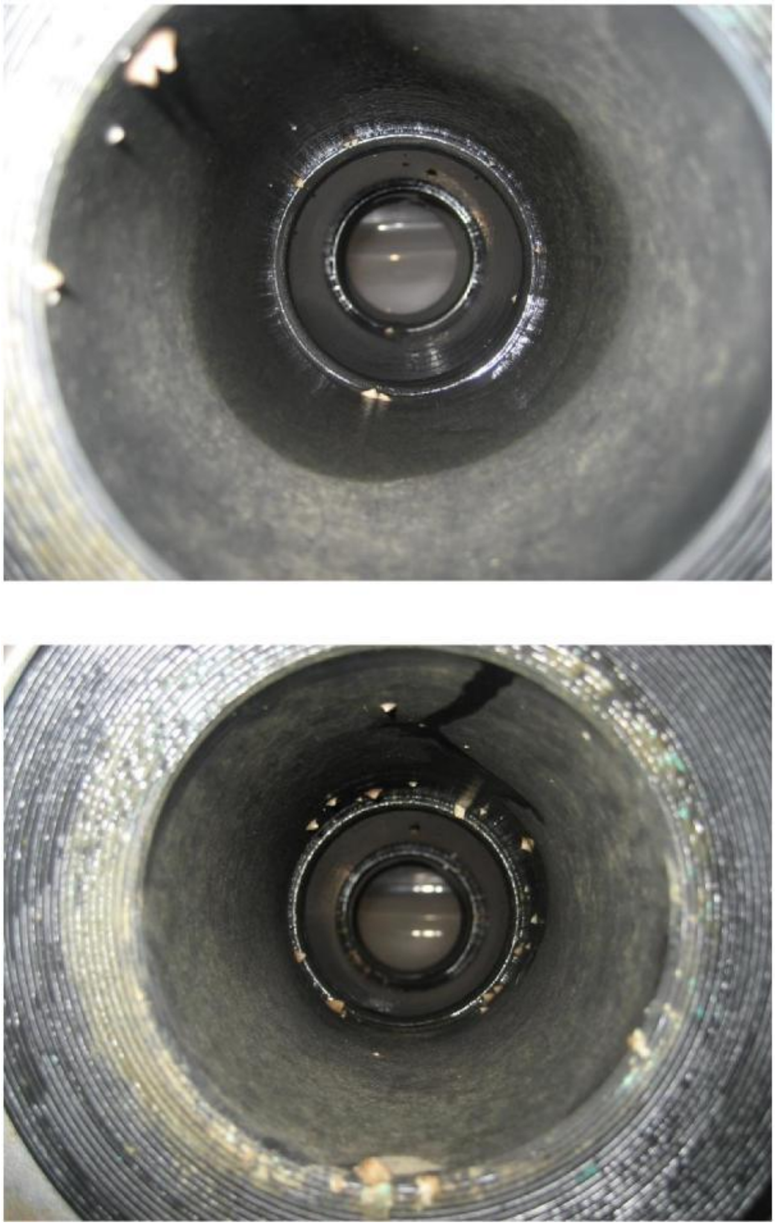


Figure 3-4. Pipe spool A4 (Control) December 23, 2014. Inlet (top) and Outlet (bottom).

Pipe Spool B4 (Continuous Chloramine Injection)

- This is the fourth pipe spool in spool row B and was treated with continuous injection of a chloramine solution.
- Photos taken from inlet and outlet ends **(Figure 3-5).**
- No macrofouling organisms were found.
- No slime/diatoms detected by touch or tissue wipe.
- No sand or debris, although a rust stain was observed in the inlet section **(Figure 3-5).**

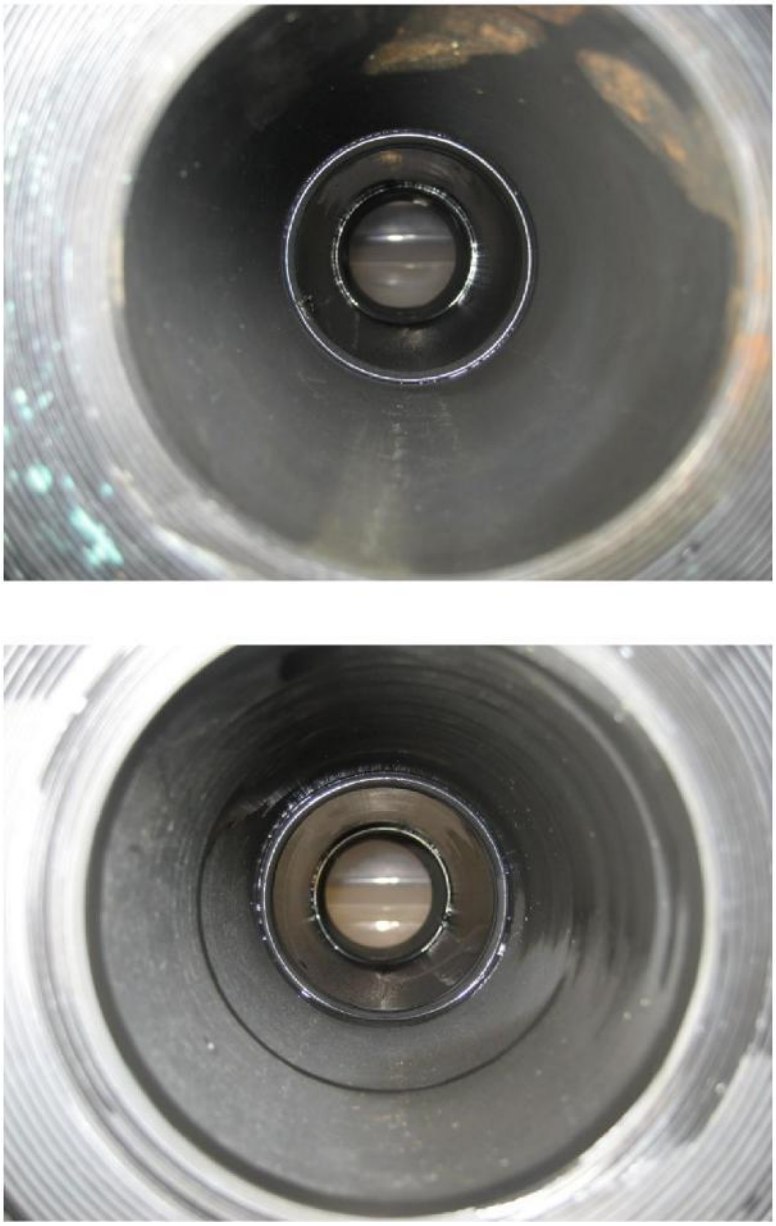


Figure 3-5. Pipe spool B4 (Continuous Chloramine Injection) December 23, 2014. Inlet (top) and Outlet (bottom).

Pipe Spool C4 (Shock Chlorination)

- This is the fourth pipe spool in spool row C and received a weekly shock treatment with sodium hypochlorite.
- Photos taken from inlet and outlet ends **(Figure 3-6).**
- No slime/diatoms detected by touch or tissue wipe.
- 9 small acorn barnacles (Balanidae) were observed; 5 in the inlet section, 2 in the middle section, and 2 in the outlet section.
    - Size (basal diameter) ranged from about <1 mm to 3 mm.
- No sand or other debris was observed.

Conclusions

- Little or no macrofouling in any of the three spools.
- Although there is a complete lack of fouling in the Continuous Chloramine treatment spool (spool B3), the paucity of fouling in the Control spool (spool A4) provides little comparison against which to evaluate the efficacy of any of the treatments.
- The lack of macrofouling in the Control spool is most likely due to the cropping of macrofouling larvae from the water supply by established filter-feeding organisms (mussels, barnacles, etc.) in the seawater supply line. There may be other contributing factors including the low flow velocities in portions of the system, and cropping of food items from the seawater flow as it passes through the supply line (reducing survival and growth of any organisms settling in the pipe spools).

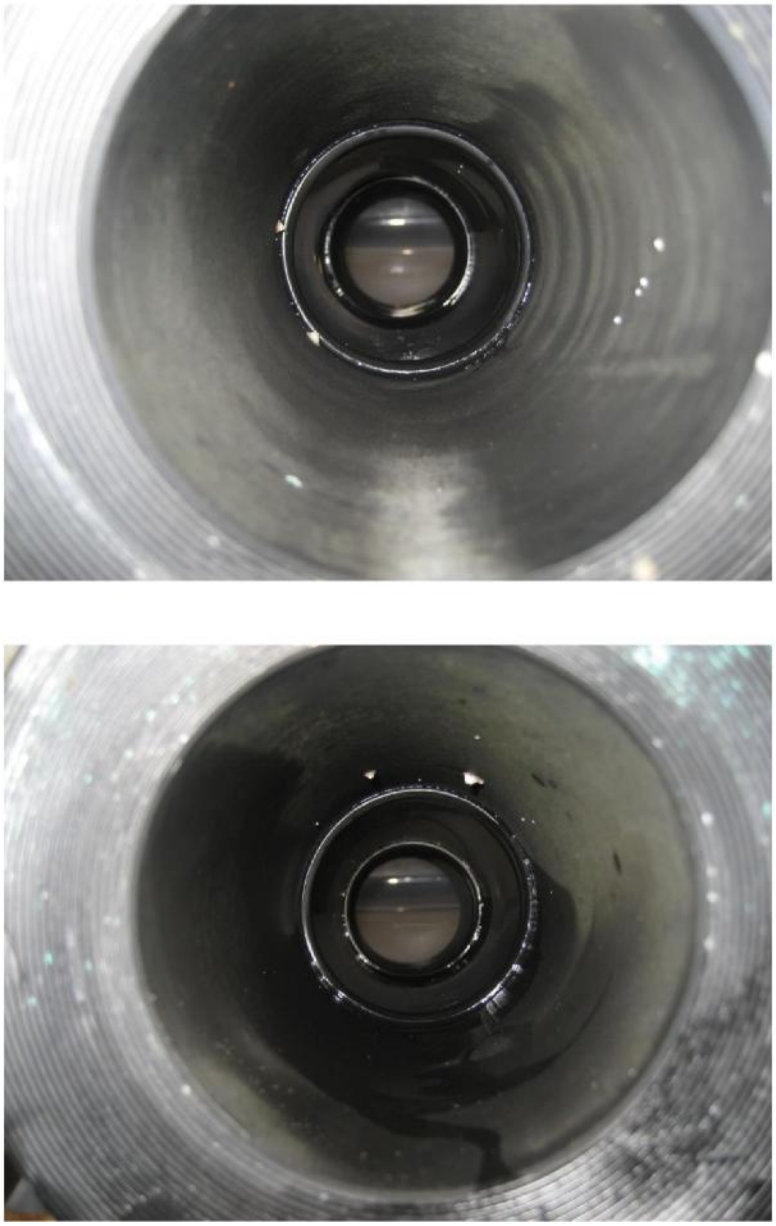


Figure 3-6. Pipe spool C4 (Shock Chlorination) December 23, 2014. Inlet (top) and Outlet (bottom).

CONCLUSIONS

A summary of the results from the four test periods is contained in Table 3-2.

After a thorough analysis of the testing, operations and results obtained we developed the following conclusions.

- The control test pipe run had no macrofouling, some visible slime and an increasing number/size of barnacles as the test progressed.
- The continuous chlorination test pipe run had no macrofouling, no slime and no barnacles for the entire test period.
- The shock chlorination test pipe run had no macrofouling, no slime but some barnacle growth at each time period.

The lack of macrofouling in the three spools is most likely due to the cropping of macrofouling larvae from the water supply by established filter-feeder organics (mussels, barnacles, etc.) in the seawater supply line.

Low velocities may also be contributing to the lack of macrofouling.

The complete lack of fouling in the continuous chloramine treatment spools is a positive result but the low levels of macrofouling in the control spool makes any comparison difficult.

Table 3-2: Summary Analysis

	Macrofouling	Slime	Barnacles	Sand
Test 1 – 54 Days				
Control	None	Very Slight	2	None
Continuous Chlorine	None	None	None	Fine sand in bottom ½ of pipe
Shock Chlorination	None	None	75 to 80	Fine sand in bottom ½
Test 2 – 114 Days				
Control	None	Visible Slime	14	None
Continuous Chlorine	None	None	None	None
Shock Chlorination	None	None	12	None
Test 3 – 174 Days				
Control	None	Visible Slime	18	None
Continuous Chlorine	None	None	None	None
Shock Chlorination	None	None	9	None
Test 4 – 230 Days				
Control	None	None	55	None
Continuous Chlorine	None	None	None	None
Shock Chlorination	None	None	9	None

RECOMMENDATIONS

The following are recommendations for the future full scale West Basin Facility:

- Continuous chloramination is viable and should be considered for future use in the intake system.
- Results for shock chloramination were not as positive as continuous chlorination but due to the overall lack of macrofouling shock chlorination should not be eliminated from consideration.

Future testing if desired should take into account that using an existing intake which already has a significant build-up of macrofouling can significantly affect results.

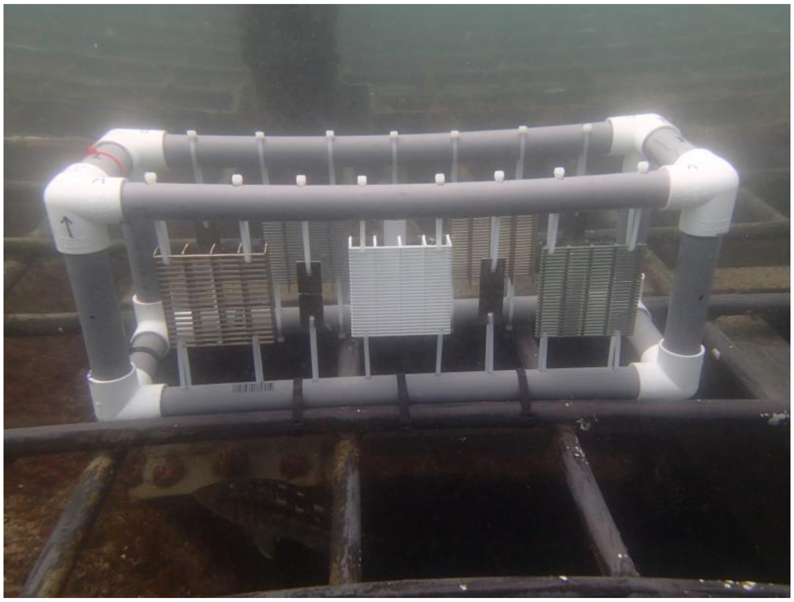
As described in other sections of this report the seawater at the Redondo Beach site has significant macro- and micro-biological effects. The long water supply feed line to the pipe test facility have skewed the test results somewhat.

CHAPTER 4
INTAKE SCREEN BIOFOULING AND CORROSION TESTING

INTRODUCTION

West Basin Municipal Water District's (District) Ocean Water Desalination Demonstration Facility located at the SEA Lab in Redondo Beach included an evaluation of passive screening and subsurface intake systems. The small-scale temporary facility allowed the District to research and test the impacts on marine organisms. The selection of the wedgewire screen was aimed to reduce the number of organisms that are entrained or drawn into the intake and the number of organisms that are impinged on the screen surface. As part of this study, corrosion and biofouling of different wedgewire screen materials that could be used to manufacture the intake screen were evaluated.

Test coupon racks consisted of metal alloy coupons, wedgewire (WW) mesh samples, and metal alloy plates which were attached to non-conductive frames made of PVC. The frames were secured to the metal grating covering the inlet to the intake (non-operational) for the Redondo Beach Generating Station. Four test coupon racks were installed on June 17, 2014. The racks were removed and inspected on the following dates:



Coupon and Screen Test Rack

Date Removed	Months in Operation
September 16, 2014	3
December 29, 2014	6
April 21, 2015	10
June 16, 2015	12
May 23, 2017	36

GOAL

The goal of the Intake Screen Biofouling and Corrosion Test was to determine the material selection for the wedgewire intake screen.

OBJECTIVES

The objectives of the Intake Screen Biofouling and Corrosion Test were:

- Select materials that are readily available for manufacture of the wedgewire intake screen for use at the full scale West Basin Desalination Plant.
- Test different material types to quantify and characterize attachment of micro and macro organisms to the test coupons.
- Test different material types submerged in a marine environment to characterize the type of corrosion and determine the rate of corrosion.
- Obtain findings that can be used to specify the materials of construction for the future wedgewire screen intake to be used at the District's Future Desalination Project in Redondo Beach or El Segundo.
- Estimate the frequency of replacement and/or frequency of cleaning/maintenance based on the findings.

INTAKE SCREEN TESTING

The testing samples consisted of metal coupons, wedgewire screens (coated and uncoated) and metal alloy plates for installation on the in-situ testing apparatus. Twenty metal coupons (1 inch wide by 3 inches long by 1/6 inch thick) were deployed and removed at 3, 6, 10, and 12 months. Twenty-five wedgewire screens (4 inches by 4 inches with 2 mm spacing) were deployed and removed at 3, 6, 10, 12 and 36 months. Five metal plates (4 inch by 4 inch by 1/8 inch thick) were deployed and removed at 12 months. The following materials were tested:

1. CuNi 90/10 (UNS 70600)
2. Johnson Screen Z-Alloy
3. 70Cu-30Ni (UNS 71500)
4. 2205 duplex stainless steel (uncoated)
5. 2205 duplex stainless steel (coated Sherwin Williams Foul Release System)

Initial Testing

Cleaning of alloy coupons and WW mesh were performed per ASTM G-1 *Preparing, Cleaning, and Evaluating Corrosion Test Specimens*. The procedures in ASTM G-1 are designed to remove corrosion products without significant removal of base metal. This allows an accurate determination of the mass loss of the metal or alloy that occurred during exposure to the corrosive environment. This ASTM covers procedures for preparing bare, solid metal specimens for tests, for removing corrosion products after the test has been completed, and for evaluating the corrosion damage that has occurred. Emphasis is placed on procedures related to the evaluation of corrosion by mass loss and pitting measurements. The coupons and WW mesh were attached to the PVC racks prior to shipping to the site to maximize cleanliness.

Weighing and pitting identification of the coupons were performed per ASTM D2688 *Standard Test Method for Corrosivity of Water in the Absence of Heat Transfer (Weight Loss Method)*. This ASTM includes procedures in Sections 14.10 through 14.14 that involve weighing and classifying the types of pits. This test method covers the determination of the corrosivity of water by evaluating pitting and by measuring the weight loss of metal specimens. Pitting is a form of localized corrosion: weight loss is a measure of the average corrosion rate. The rate of corrosion of a metal immersed in water is a function of the tendency for the metal to corrode and is also a function of the tendency for water and the chemical constituents it contains to promote (or inhibit) corrosion.

A metallographic examination of the coupons was performed per ASTM E3 *Standard Guide for Preparation of Metallographic Specimens*. The primary objective of metallographic examinations is to reveal the constituents and structure of metals and their alloys by means of a light optical or scanning electron microscope.

The initial metal coupon testing included the baseline parameters:

1. Weigh all samples
2. Examine samples visually to 40X
3. Color photograph, one of each material type
4. Photomicrograph @ 10X, one of each material type
5. Photomicrograph @ 50X, one of each material type
6. Scanning Electron Micrograph (SEM) @ 100X, one of each material type
7. Energy Dispersive Spectroscopy (EDS), one of each material type

The initial wedgewire mesh testing included the baseline parameters:

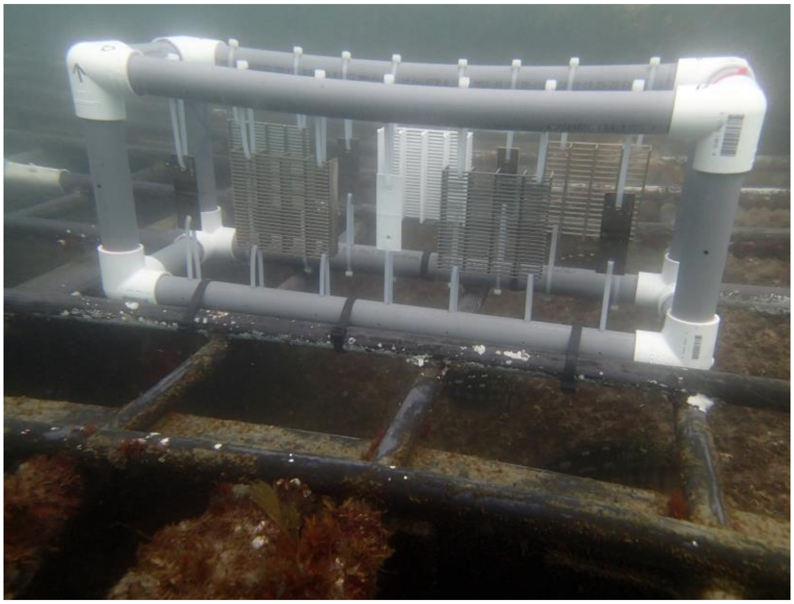
1. Weigh all samples
2. Examine samples visually to 40X
3. Color photograph, one of each material type

All testing was performed on the coupons. The wedgewire mesh was only weighed, photographed and visually examined. The rate of corrosion and pitting on the coupons was evaluated per the ASTM protocols. The wire mesh was weighed and the change in weight was evaluated against the weight change on the coupons. If the weight change observed was appreciably different (more than 20%), then additional testing will be recommended to the District. It is not practical, nor is there a standard to try to measure pitting on the small wire that the wedgewire mesh is constructed of. A visual examination was performed to ascertain where, if any, corrosion is occurring (e.g. wire, bare plate, round bar, welds, etc).

Test Coupon Rack Design

Metal alloy coupons and wedgewire (WW) mesh samples were attached to non-conductive frames made of PVC and the frames were secured to the metal grating that covers the inlet to the intake (non-operational) for the Redondo Beach Generating Station. It was anticipated that there would be four replicates (racks), each holding the different alloy coupons and WW mesh samples. Each of the four racks had a full complement of the alloy coupons and WW mesh samples. At the start of the study the four racks were secured to the intake grating using multiple heavy-duty plastic cable ties. Each test rack was a 9” x 9” x 18” box frame constructed out of 1-inch diameter schedule 80 PVC pipe. WW mesh coupons were attached to the two (vertical) 9” x 18” sides and the alloy coupons on each of the two vertical

9" x 9" sides. The frame was drilled with holes to allow it to fill with water. The holes were used to thread the securing plastic cable ties. Four racks, one each for the 3, 6, 10, and 12 month retrievals. A fifth rack with wire mesh screen samples were installed at the beginning of the study and removed after 36 months.



View of Coupon and Screen Test Rack in Place

Every three months of submersion, one of the racks was retrieved and returned to shore for biofouling analysis. All of the coupons and WW mesh samples were photographed. The WW mesh samples were inspected to identify and quantify the macrofouling that had colonized on the sample coupons. Following the biofouling analysis, the coupons were delivered to the corrosion engineer to assess the type and rate of corrosion that has occurred during the deployment period. This process was repeated after 3, 6, 10, 12, and 36 months; each time another rack was retrieved and given a biofouling and corrosion assessment.

Equipment List (per Two-Person Team)

Boat-based deployment and retrieval

- 14' whaler boat with engine and all equipment in working order
- One set paddles (for shallow water/emergency)
- Life jackets/work vests
- SCUBA gear
- GPS device for locating the RBGS intake
- Cell phone with fully charged battery

- Underwater digital camera and UW video camera
- Hand tools for deployment and retrieval of coupon racks
- Heavy-duty plastic cable ties

Shore-based biofouling analysis

- Digital camera with extra battery packs and memory cards
- Photo tags for the coupons being retrieved
- Biofouling Analysis data sheets
- Whirl-paks with pre-cut waterproof labels, to store specimens
- 250 ml 95% ethanol in tightly-capped nalgene container

Retrieval Procedures

The following procedure was used by the dive team retrieving coupon test racks from the Redondo Beach offshore test site. After anchoring the boat and entering the water, the dive team proceeded as described below:

Initial Field Inspection

The dive team initially inspected the coupon racks to ascertain their condition and recorded the following on a waterproof datasheet:

1. The presence of all the racks that are currently deployed – are any racks or coupons missing?
2. The physical condition of the racks – have any of the racks or coupons been damaged?
3. Compare the biofouling condition of the racks and coupons – do any of the racks look overtly different than the other racks?
4. The team will replace cable ties as needed to insure that the racks remain secured in place.

Photo Documentation

Conditions permitting, the dive team used an underwater still camera and/or a video camera to make a photographic record of the racks and coupons prior to removing the rack that was to be retrieved. Care was taken not to remove or disturb any of the biofouling on the coupons. Any sort of manipulations were noted on the datasheet and photographically documented (before and after shots).

Test Rack Retrieval

Upon completion of the photo documentation, one of the racks was retrieved and placed in the boat. While diving, the organisms attached to the racks that was left in place was scraped off to lessen the potential that they might grow onto the coupons. The rack was then transported back to King Harbor for further inspection and photo documentation on shore.

On Shore Inspection

Prior to the coupons being removed from the rack, the rack was photographed in such a way that both sides of the coupons are documented in place.

Each alloy coupon and wedgewire mesh coupon was then removed from the rack and photographed individually (both sides with a photo ID tag). Only the wedgewire mesh will be inspected with the following information recorded on the biofouling analysis data sheet:

1. A visual estimate of the percent cover of each taxon on both sides (front and back) of the WW mesh was recorded on the datasheet. If the WW mesh coupons have cross support pieces (ribs) that have substantial surface area, a record was also made of the percent cover of each taxon on a combination of this entire surface area. Besides the percent cover of attached taxa, the percent bare surface and diatom film if present was also recorded. When estimating the percent cover on the WW screen material, the observer made their estimate on the entire size of the coupon and not try to factor out the open space between the metal. Based on Tenera's previous field studies, the growth pattern of sponges, tunicates, and other fouling organisms is such that they would successfully span across the open areas of the screen.
2. Attached invertebrates and algae were identified to the lowest taxonomic level possible using a number of identification guides for specific groups of invertebrate and at least the following two general identification guides: Morris, Abbott and Haderlie (1980) and Carlton (2007). Algal identifications were based on Abbott and Hollenberg (1976). It is anticipated that most taxa were not to be identified to the species level, but if for instance there was an attached sponge, it did not matter what species was attached but it is important that a sponge did attach and is surviving on the metal. Tenera has conducted studies along the California coast on marine algae and invertebrates over the last 35 years and their staff members are familiar with the majority of the algae and invertebrates that are anticipated to attach to the surfaces of the test apparatus during this study. Samples of those organisms that could not immediately be identified were preserved in the field and taken to Tenera's San Luis Obispo, CA laboratory for identification. If possible, the samples were removed from the PVC rack and not the coupons.
3. The number of motile individuals of the major taxa on the removed rack assembly were determined and recorded.
4. The size range of attached taxa (i.e. barnacles and mussels) was recorded on the datasheet for each WW mesh. The size of colonial organism like sponges and tunicates will be estimated only by the percent cover estimates. Organisms were not removed from the WW mesh or coupons in order to prevent any damage to the coupons prior to corrosion analyses.
5. Upon completion of the inspection each coupon and WW mesh sample was placed inside a bag along with an identification tag and will be sent to the lab to perform the corrosion analyses.

It order to evaluate biofouling, our approach is to evaluate the organisms growing on the sample with the largest surface area and one that is more representative of what will be used in the final installation. We intend to utilize the wedgewire mesh samples for the biofouling evaluation. We do not have any reason to believe that micro- or macro- organisms would grow/attach to one coupon over the other.

Laboratory Testing Post Submersion

The following summarizes the protocols that were followed for the analysis of the coupons. These were recommended by the study's corrosion engineer. Sample cleaning was performed per ASTM G-1 *Preparing, Cleaning, and Evaluating Corrosion Test Specimens* and ASTM D2688 *Standard Test Method for Corrosivity of Water in the Absence of Heat Transfer (Weight Loss Method)*. A metallographic examination was performed per ASTM E3 *Standard Guide for Preparation of Metallographic Specimens*.

Pitting examination was performed per ASTM G46 *Standard Guide for Examination and Evaluation of Pitting Corrosion* and ASTM D2688. ASTM D2688 provides a visual comparison standard; ASTM G46 covers the procedures used in a more detailed identification and examination of pits and in the evaluation of pitting.

Coupons (3, 6, 10, and 12 months of exposure) were sent to the lab for the following tests:

1. Examine visually to 40X, as determined by biofouling buildup
2. Color photograph
3. Sample cleaning and weighing per ASTM G1 & D2688
4. Pitting examination per ASTM G46
5. Dimensional inspection (micrometers or NOGO gauge)
6. Photomicrograph @ 10X, one of each material type after cleaning
7. Photomicrograph @ 50X, one of each material type after cleaning
8. Scanning Electron Micrograph @ 100X, one of each material type after cleaning
9. Elemental analysis with EDS, one of each material type after cleaning
10. Metallographic examination per ASTM E3, one of each material type

The wedgewire mesh testing included the following parameters:

1. Weigh all samples
2. Examine samples visually to 40X
3. Color photograph, one of each material type

Corrosion Analysis

From the information obtained from the above testing the following information was obtained:

1. Change in weight
    a. Reduction of overall weight resulting is metal loss
    b. Increase in overall weight due to the formation of oxides
    c. Leaching rate
    d. Comparison between coupon and wedgewire mesh weight change
2. Type of corrosion
3. Rate of corrosion

BIOFOULING RESULTS

The following is a summary of the biofouling inspection of the test racks. Full reports of the Biofouling inspections are included in Appendix D.

Table 4-1: Biofouling Summary of Notes- First Test Rack Inspection – September 16, 2014

Test Material	Biofouling Notes	
PVC test rack	Heavily fouled to the point where almost none of the PVC was visible.	
CDA 706 (90 – 10 Copper Nickel)	Wedgewire sample: Quite clean, with some attached hydroids covering less than 1 percent of the surface. Some loose silt. A green patina covered much of the surface. About 50 percent of the surface had a very light covering of diatoms and entrapped silt. All of the fouling was removed with just a light brushing using a soft nylon brush.	Coupon: Quite clean, with hydroids attached to about 1 percent of the surface. About 70 to 80 percent of the surface had a light covering of diatoms and entrapped silt. All of the fouling was removed with just a light brushing using a soft nylon brush.
Z-Alloy	Wedgewire sample: Quite clean, with some attached hydroids covering less than 1 percent of the surface. Some loose silt. The surface had a green patina. About 50 percent of the surface had a very light covering of diatoms and entrapped silt.	Coupon: Had two acorn barnacles attached to it. A light layer of diatoms and silt covered about 50 percent of the surface.
2205 SS (stainless steel) with antifouling coating	Wedgewire sample: About 30 percent of the samples surface had hydroids attached to it About 2 percent of the surface was covered with an encrusting bryozoans and another 5 percent had a filamentous red alga attached to it. The foul-release coating was in very good shape and all of the fouling was removed with just a light brushing using a soft nylon brush.	Coupon: Quite clean with about 1 percent of the surface with attached hydroids, about 5 percent covered by an encrusting bryozoans, and about 7 percent with a light film of diatoms and silt. The foul-release coating was in very good shape and all of the fouling was removed with just a light brushing using a soft nylon brush.
2205 SS (stainless steel) uncoated	Wedgewire sample: Very heavily fouled with hydroids covering most of the surface. The fouling was firmly attached and was not removed.	Coupon: Very heavily fouled with hydroids and red algae covering most of its surface. The fouling was firmly attached and was not removed.
CDA 715 (70 – 30 Copper Nickel)	Wedgewire sample: The CDA 715 WW sample was similar to the CDA 706 and Z-Alloy samples, but with more hydroids (about 30 percent coverage), more of a diatom and silt film/layer, and only a few small patches of green patina on the metal's surface.	Coupon: The CDA 715 WW coupon was similar to the CDA 706 and Z-Alloy coupons. Hydroids were attached to about 2 percent of the coupon surface. Diatoms and entrapped silt covered about 80 percent of the surface.

Table 4-2: Biofouling Summary of Notes- Second Test Rack Inspection – December 29, 2014

Test Material	Biofouling Notes	
PVC test rack	The PVC test rack was heavily fouled to the point where almost none of the PVC was visible.	
CDA 706 (90 – 10 Copper Nickel)	Wedgewire sample: Quite clean, with some attached hydroids covering less than 1 percent of the surface.	Coupon: Quite clean, with hydroids attached to about 1 percent of the surface.

Test Material	Biofouling Notes	
	Some loose silt. A green patina covered much of the surface. About 50 percent of the surface had a very light covering of diatoms and entrapped silt.	About 70 to 80 percent of the surface had a light covering of diatoms and entrapped silt.
Z-Alloy	Wedgewire sample: Quite clean, with some attached hydroids covering less than 1 percent of the surface. Some loose silt. The surface had a green patina. About 60 percent of the surface had a very light covering of diatoms and entrapped silt.	Coupon: Had two acorn barnacles attached to it. A light layer of diatoms and silt covered about 50 percent of the surface.
2205 SS (stainless steel) with antifouling coating	Wedgewire sample: About 40 percent of the samples surface had hydroids attached to it About 2 percent of the surface was covered with an encrusting bryozoans and another 5 percent had a filamentous red alga attached to it. The foul-release coating was in very good shape and all of the fouling was removed with just a light brushing using a soft nylon brush.	Coupon: Quite clean with about 5 percent of the surface covered with filamentous red algae, a light film of diatoms and a little silt. There was a patch of encrusting bryozoan. The foul-release coating was in very good shape and all of the fouling was removed with just a light brushing using a soft nylon brush.
2205 SS (stainless steel) uncoated	Wedgewire sample: Very heavily fouled with hydroids covering most of the surface. The fouling was firmly attached and was not removed.	Coupon: Very heavily fouled with hydroids and red algae covering most of its surface. The fouling was firmly attached and was not removed.
CDA 715 (70 – 30 Copper Nickel)	Wedgewire sample: Similar to the CDA 706 and Z-Alloy samples, but with more hydroids (about 30 percent coverage), more of a diatom and silt film/layer, and only a few small patches of green patina on the metal's surface.	Coupon: Similar to the CDA 706 and Z-Alloy coupons. Hydroids were attached to about 5 percent of the coupon surface. Diatoms and entrapped silt covered about 80 percent of the surface.

Table 4-3: Biofouling Summary of Notes- Third Test Rack Inspection – April 21, 2015

Test Material	Biofouling Notesf	
PVC test rack	The PVC test rack was heavily fouled to the point where almost none of the PVC was visible.	
CDA 706 (90 – 10 Copper Nickel)	Wedgewire sample: Relatively clean, with a few hydroids covering about 10 to 20 percent of the surface. The hydroids were densest near the locations of the plastic cable ties used to secure the sample to the PVC rack and were easily detached. A green patina covered most of the surface. About 80 percent of the surface had a very light covering of diatoms, short filamentous algae and entrapped silt. All fouling and debris was easily removed with a soft nylon brush after photographing and inspection.	Coupon: Quite clean, with only three hydroids, no barnacles or other attached macrofouling. About 80 percent of the surface had a light covering of diatoms, some filamentous red algae and entrapped silt. There was a green/brown patina on most of the surfaces. All silt and fouling was easily removed with a soft nylon brush after photographing and inspection.
Z-Alloy	Wedgewire sample: The sample was quite clean, similar to the CDA 706 with a few hydroids covering less than 10 percent of the surface. About 80	Coupon: The coupon had a few hydroids attached to it near one of the mounting holes. There was a light

Test Material	Biofouling Notesf	
	percent of the surface had a very light covering of diatoms, filamentous red algae, and entrapped silt. All fouling and debris was easily removed with a soft nylon brush.	layer of diatoms, filamentous red algae, and entrapped silt that covered about 60 percent of the surface. No green patina.
2205 SS (stainless steel) with antifouling coating	Wedgewire sample: About 20 percent of the sample's outer surface had filamentous red algae, some hydroids, some encrusting bryozoans. About 50 percent of the underside ribs were clean of fouling. The other 50 percent was covered with encrusting bryozoans, filamentous red algae, hydroids, 9 half-slipper shells, mussels, and some solitary tunicates. The foul-release coating was in very good shape and all of the fouling was removed with just a light brushing using a soft nylon brush.	Coupon: The coupon was quite clean with about 10 percent of the surface covered with filamentous red algae, a light film of diatoms and a little silt. There was a patch of encrusting bryozoan. The foul-release coating was in very good shape and all of the fouling was removed with just a light brushing using a soft nylon brush.
2205 SS (stainless steel) uncoated	Wedgewire sample: Very heavily fouled with hydroids covering most of the surface. The fouling was firmly attached and was not removed.	Coupon: Very heavily fouled with hydroids and red algae covering most of its surface. The fouling was firmly attached and was not removed.
CDA 715 (70 – 30 Copper Nickel)	Wedgewire sample: Similar to the CDA 706 and Z-Alloy samples, but with more filamentous red algae (about 10 percent coverage), more of a diatom and silt film/layer, and only a little green patina on the metal's surface. There were a few hydroids and a few erect bryozoans. All fouling and debris was easily removed with a soft nylon brush after photographing and inspection.	Coupon: Similar to the CDA 706 and Z-Alloy coupons. A few hydroids were attached near the holes in the coupon. Diatoms and entrapped silt covered about 80 percent of the surface. The coupon had more green patina than the CDA 715 Wedgewire sample, especially on the test welds. All fouling and debris was easily removed with a soft nylon brush after photographing and inspection.

Table 4-4: Biofouling Summary of Notes- Fourth Test Rack Inspection – June 16, 2015

Test Material	Biofouling Notes	
PVC test rack	The PVC test rack was heavily fouled to the point where almost none of the PVC was visible.	
CDA 706 (90 – 10 Copper Nickel)	Wedgewire sample: Relatively clean, with only a few hydroids, mostly concentrated by the sites of the plastic cable ties used to secure the sample to the rack. A green patina covered most of the surface. About 80 percent of the surface had a very light covering of diatoms and short filamentous algae along with entrapped silt. All fouling and debris was easily removed with a soft nylon brush after photographing and inspection. (**See Figure 4-1**)	Coupon: Quite clean, with no hydroids, no barnacles or any other attached macrofouling. About 90 percent of the surface had a light covering of diatoms, some filamentous red algae and entrapped silt. There was a green/brown patina on most of the surfaces. All silt and fouling was easily removed with a soft nylon brush after photographing and inspection. (**See Figure 4-2**)

Test Material	Biofouling Notes	
Z-Alloy	Wedgewire sample: Quite clean, similar to the CDA 706 (IVA1) with only three individual hydroids covering less than 1 percent of the surface. The surface had a green patina. About 60 percent of the Wedgewire (outer) surface had a very light covering of diatoms, filamentous red algae, and entrapped silt. All fouling and debris was easily removed with a soft nylon brush after photographing and inspection. Some of the patina was removed by the brushing, exposing fresh metal. (**See Figure 4-3**)	Coupon: No hydroids or other macrofouling invertebrates. There was a layer of diatoms, filamentous red algae, and entrapped silt that covered about 65 percent of the surface. No green patina. All fouling was easily removed with soft nylon brush. (**See Figure 4-4**)
2205 SS (stainless steel) with antifouling coating	Wedgewire sample: About 50 percent of the sample's outer surface had a light covering of diatoms and filamentous red algae. About 50 percent of the inner ribs were cover with what appears to be gastropod eggs. Another 25 percent of the inner ribs was covered with a combination of a few individual hydroids, 12 half-slipper shells, or slipper limpets, 10 mussels (4-20 mm), 6-8 barnacles (*M. californicus*), 4 worm tubes, 4 small white bivalves (3 mm), and a crab. The foul-release coating was in very good shape even at the cable tie sites. All of the fouling was removed with light brushing using a soft nylon brush or, in the case of the limpets, with light finger pressure. (**See Figure 4-5**)	Coupon: Very clean. About 50 percent of the surface had a very light film of diatoms and a little silt. The foul-release coating was in very good shape and all of the fouling was removed with just a light brushing using a soft nylon brush. (**See Figure 4-6**)
2205 SS (stainless steel) uncoated	Wedgewire sample: Very heavily fouled with little of the metal visible. The fouling was firmly attached and was not removed. (**See Figure 4-7**)	Coupon: Very heavily fouled with hydroids and red algae covering most of its surface. The fouling was firmly attached and was not removed. (**See Figure 4-8**)
CDA 715 (70 – 30 Copper Nickel)	Wedgewire sample: Similar to the CDA 706 and Z-Alloy samples, but with more of the surface, about 60 percent, covered by amphipod tubes and filamentous red algae. There was also more of a diatom and silt film/layer, and only a little green patina on the metal's surface. Eight very small mussels. There were no barnacles or other macrofouling aside from the hydroids and mussels. All fouling and debris was easily removed with a soft nylon brush after photographing and inspection. (**See Figure 4-9**)	Coupon: Similar to the CDA 706 and Z-Alloy coupons. A few hydroids, without polyps, were attached near the holes in the coupon. Amphipod tubes, diatoms and entrapped silt covered about 80 percent of the surface. The coupon had more green patina than the CDA 715 Wedgewire sample, especially on the test welds. All fouling and debris was easily removed with a soft nylon brush after photographing and inspection. (**See Figure 4-10**)

Table 4-5: Biofouling Summary of Notes- Fifth Test Rack Inspection – May 23, 2017

Test Material	**Biofouling Notes**	
PVC test rack	The PVC test rack was heavily fouled to the point where almost none of the PVC was visible. The encrusting biofouling layer exceeded 25mm (1 inch) in thickness on some portions of the rack (**See Figure 4-11**).	
CDA 706 (90 – 10 Copper Nickel)	Wedgewire sample: Missing from the rack.	Coupon: N/A
Z-Alloy	Wedgewire sample: Missing from the rack.	Coupon: N/A
2205 SS (stainless steel) with antifouling coating	Wedgewire sample: About 80 percent of the sample's outer surface had a light covering of diatoms and filamentous or encrusting red algae. There were 45 – 50 acorn barnacles (*Megabalanus californicus*) that ranged in size from 5 – 24 mm. The majority of the barnacles were on the underside of the sample attached to the flat metal sides and reinforcing ribs. About 85% of the outer wedgewire face was not occluded by the barnacles or other fouling. Most of the barnacles were firmly attached, usually at locations where some damage or imperfection in the foul-release coating allowed the barnacle to get a foothold on the bare metal or the primer coat under the foul-release coating. Barnacles that had settled on undamaged portions of the coating could be easily removed with gentle pressure. There were also some hydroids and amphipod tubes on the underside of the sample and attached to the barnacle shells. (**See Figure 4-12**)	Coupon: N/A
2205 SS (stainless steel) uncoated	Wedgewire sample: This sample was very heavily fouled with none of the metal visible prior to the removal of the sample from the rack. Most of the surface was covered by a layer of tan-colored sponge, hydroids, bryozoans, filamentous algae, and amphipod tubes. Beneath and intermixed with the sponge/hydroid layer were hundreds of acorn barnacles (*M. californicus*) ranging in size from about 4 – 25 mm. Also intermixed with the hydroids were about 10 small mussels (*M. galloprovincialis*) up to 8 mm in length, scallops, white bivalves, tube worms, amphipods, crabs, erect and encrusting bryozoans, red algae (filamentous and foliose), oysters (to 30 mm), encrusting sponge, c/s tunicate, and probably other small invertebrates. The original weight of the sample was about 312 g and the fouling added another 433 g. The fouling was very firmly	Coupon: N/A

Test Material	**Biofouling Notes**	
	attached and some of the material could not be removed prior to sending the sample to V&A Consulting Engineering due to the potential of damaging the sample prior to metal analyses. (**See Figure 4-13**)	
CDA 715 (70 – 30 Copper Nickel)	Wedgewire sample: The CDA 715 WW samples from Racks I – IV, were similar to the CDA 706 and Z-Alloy samples, but with more of the surface covered by amphipod tubes and filamentous red algae. There were also more of a diatom and silt film/layer, but less of the green patina than on the other two samples. The sample from Rack V could not be compared with the 90-10 Cu-Ni or the Z-Alloy because those samples were missing. Overall this sample looked very good after being submerged for almost three years. About 70 percent of the outer surface had a light covering of filamentous algae, diatoms, hydroids, and entrapped silt and debris (soft material). The underside had some amphipod tubes, five small (2 – 5 mm diameter) acorn barnacles (M. californicus), and three small white bivalves (2 – 3 mm length). All fouling and debris was easily removed with a soft nylon brush after the sample was photographed and inspected. There was accelerated corrosion/erosion on the wedgewire at the sites of the plastic cable ties, but it was not severe enough to result in the loss of the sample. (**See Figures 4-14 and 4-15**)	Coupon: N/A

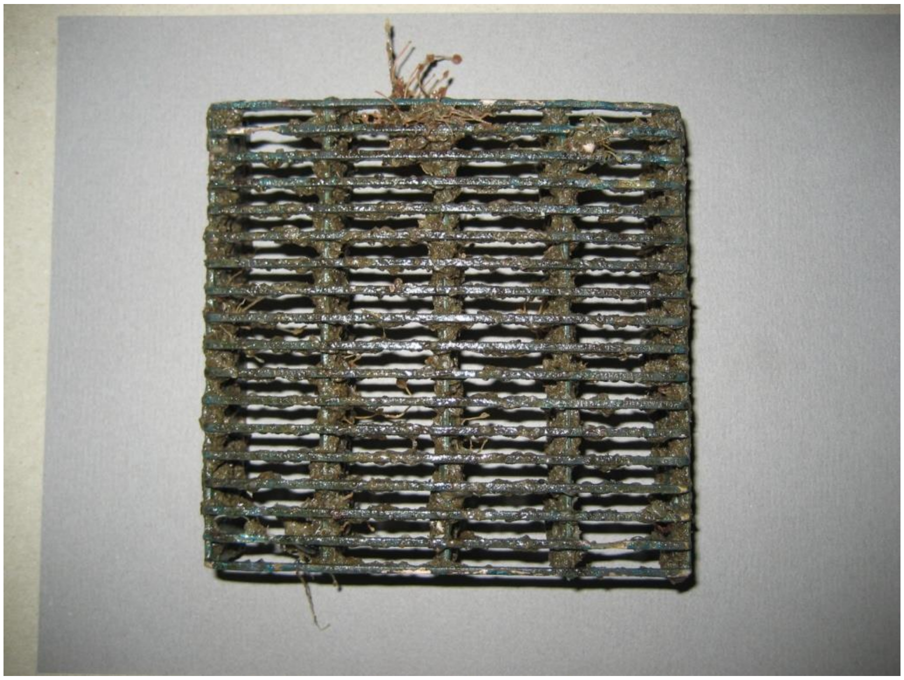


Figure 4-1: 90/10 Cu-Ni (CDA706) Wedgewire sample, photographed 06/17/15.

Figure 4-2: 90/10 Cu-Ni (CDA706) coupon, photographed 06/17/15.

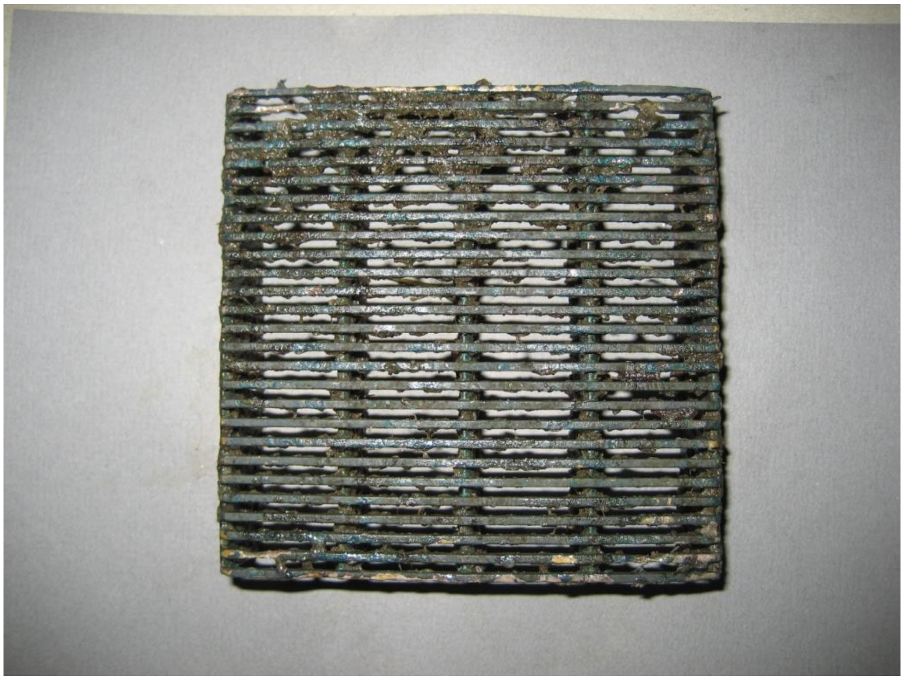


Figure 4-3: Z-alloy Wedgewire sample, photographed 06/17/15.

Figure 4-4: Z-alloy coupon, photographed 06/17/15.

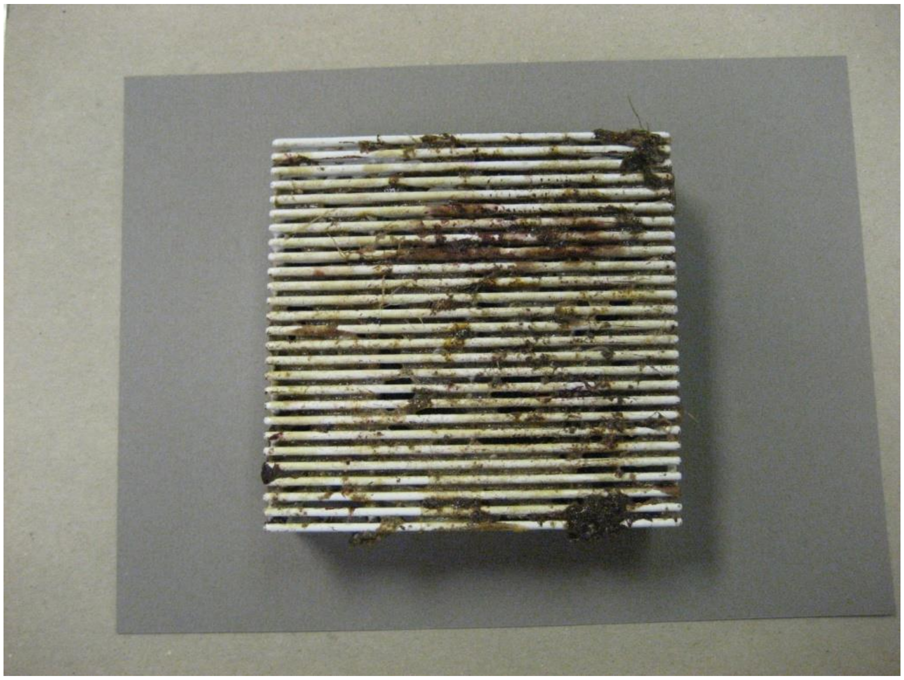


Figure 4-5: 2205 stainless steel Wedgewire sample with foul release coating, photographed 06/17/15.

Figure 4-6: 2205 stainless steel coupon with foul release coating, photographed 06/17/15.

Figure 4-7: 2205 stainless steel Wedgewire sample, photographed 06/17/15.

Figure 4-8: 2205 stainless steel coupon, photographed 06/17/15.

Figure 4-9: 70/30 Cu-Ni (CDA715) Wedgewire sample, photographed 06/17/15.

Figure 4-10: 70/30 Cu-Ni (CDA715) coupon, photographed 06/17/15.

Figure 4-11: Rack V with three remaining wedgewire samples still attached, photographed 05/23/17.

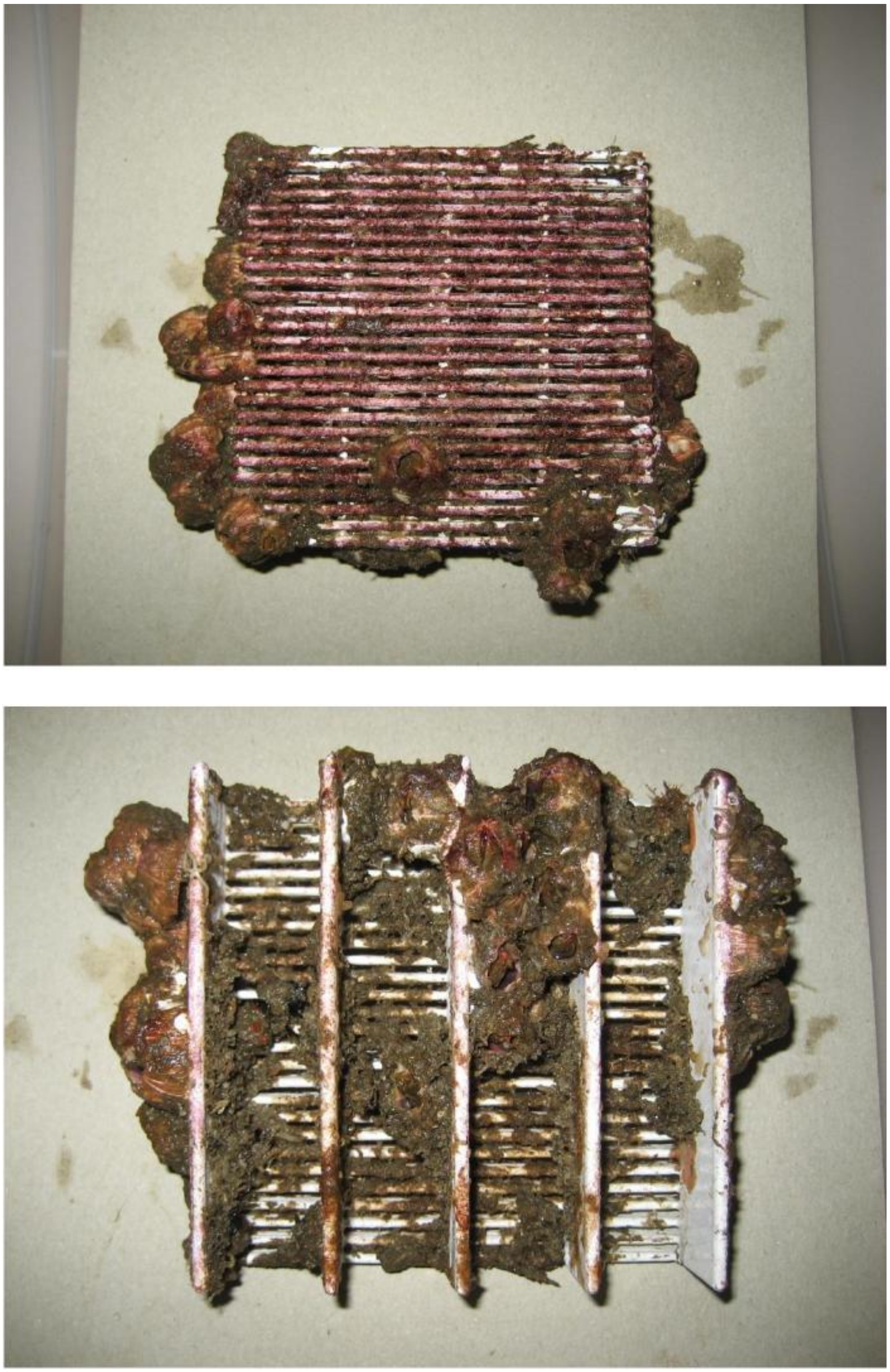


Figure 4-12: 2205 stainless steel wedgewire sample with foul release coating, photographed 05/24/17.

Figure 4-13: 2205 stainless steel wedgewire sample, photographed 05/24/17.

Figure 4-14: 70-30 Cu-Ni (CDA715) wedgewire sample, photographed 05/24/17.

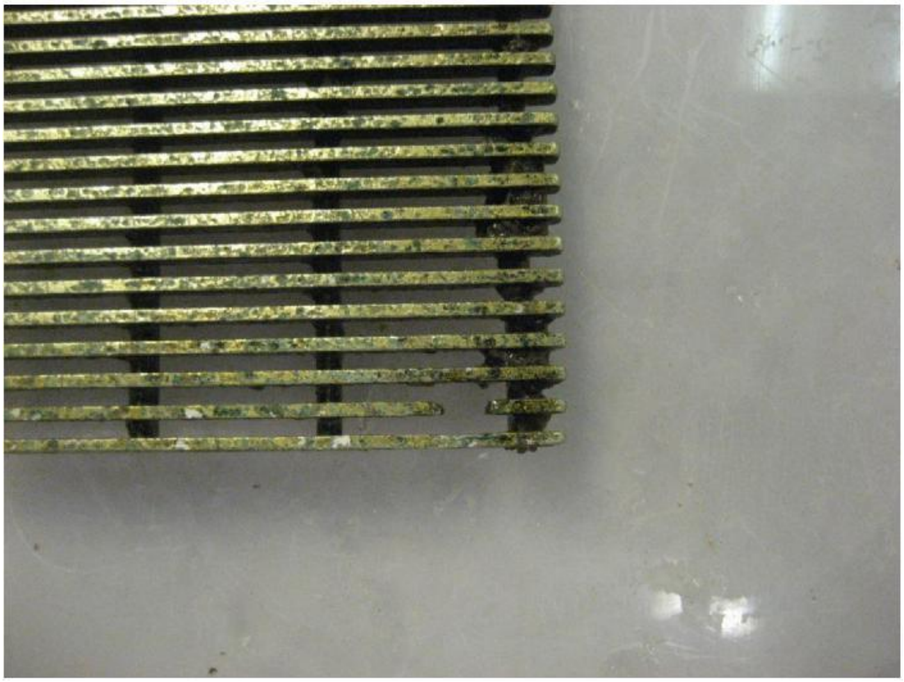


Figure 4-15: 70-30 Cu-Ni (CDA715) wedgewire sample, photographed 05/25/17, showing erosion/corrosion at one of the four attachment points.

<u>Alloy Test Plates</u>

Five 4-inch square alloy test plates, one each of the same materials as the Wedgewire samples and the alloy coupons, were attached to frames made of ¾ inch PVC pipe, enclosed in plastic mesh bags (¼ inch Vexar), and suspended about 12 inches below the intake structure grating. The test was designed to approximate the conditions that might be found in the interior of a Wedgewire intake module (relatively low water velocity and screening that excludes large predatory organisms such as fish, crabs, and sea stars). The plates were deployed along with the Wedgewire/coupon test racks on June 17, 2014. On September 16, 2014, after 92 days of exposure, the original mesh bags were removed and replaced with new bags. No photos were taken at that time. December 29, 2014, after 196 days of exposure, the bags were again replaced with new bags; this time the plates were photographed, in situ, prior to being enclosed in the new bags. The plates were then returned to their original positions beneath the grating. On April 21, 2015, after 309 days of exposure, the bags were again replaced and the plates photographed. One of the frames and its plate (Plate 5, 2205 stainless steel with the foul release coating) had fallen into the intake structure and had to be retrieved by the divers. The reason for the failure of the cords suspending that plate is unknown. The cords suspending all five of the frames/plates were replaced.

On June 16, 2015, after 365 days of exposure, the bags were removed, the plates were again photographed in situ and then retrieved. The plates were returned to Tenera's San Luis Obispo, CA. laboratory where they were weighed, photographed, and inspected on June 18, 2015, to assess any biofouling present on each plate. The plates were then shipped to V&A Consulting Engineers in Oakland, Calif. for metallurgical analyses.

The following biofouling assessment is based on the biofouling inspections conducted on June 18, 2015, at Tenera's laboratory in San Luis Obispo, CA. In situ and laboratory photographs of each plate are also included.

- **CDA 706 (90/10 Copper/Nickel), Plate 1,** (**Figure 4-16**)
  - The plate is almost entirely covered with a dark blue-green patina. This tends to flake off when the plate is handled.
  - No attached macrofouling.
  - No slime detectable.
  - No algae, diatoms, or silt.

Figure 4-16: 90/10 Cu-Ni (CDA706) test plate (Test Plate 1), photographed 06/18/15 prior to biofouling inspection.

- **CDA 715 (70/30 Copper/Nickel), Plate 2,** (**Figure 4-17**)
  - The plate is very clean with almost no discoloration or oxidation visible (a very slight, light-green discoloration). The plate looks almost new.
  - No attached macrofouling.
  - No algae.
  - A little debris near the cable tie holes.
  - Motile species: one small polychaete and six small amphipods.
  - A little silt and perhaps some diatoms.

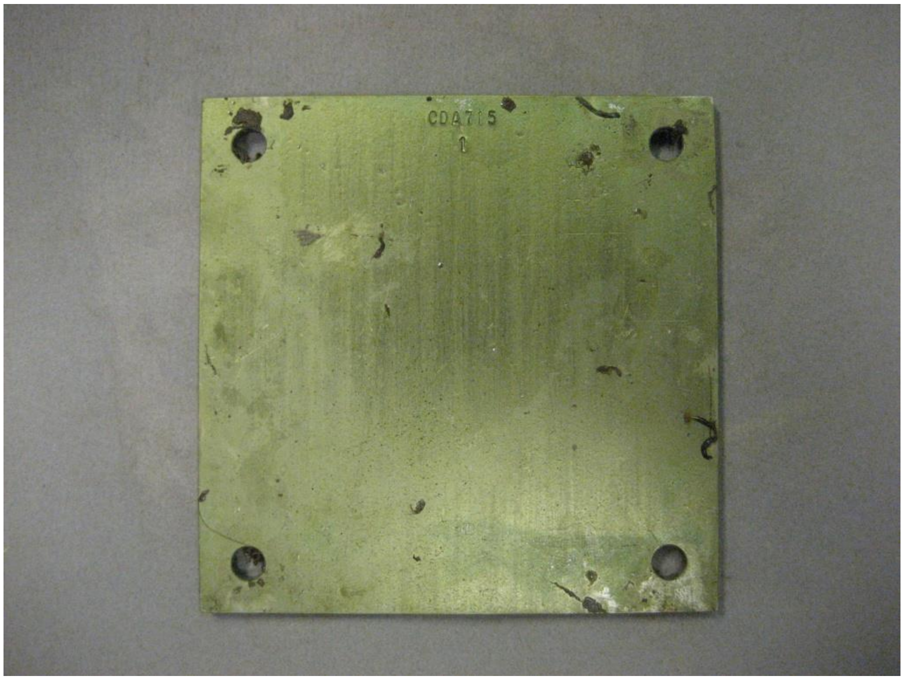


Figure 4-17: 70/30 Cu-Ni (CDA715) test plate (Test Plate 2), photographed 06/18/15 prior to biofouling inspection.

- **Z-alloy, Plate 3, (Figure 4-18)**
  - The plate is very clean, except for a single 19 mm mussel that had been attached to one of the cable ties. When the cable tie was removed, the mussel remained loosely attached to the plate by three byssal threads.
  - No attached macrofouling.
  - The plate has a light brown/gold patina. This is a duller finish than the CDA 715 plate, but does not have the patina of the CDA 706 plate.
  - Motile species: 8 small (3 mm) amphipods stranded on the plate.

Figure 4-18: Z-alloy test plate (Test Plate 3), photographed 06/18/15 prior to biofouling inspection.

- **2205 Stainless Steel (uncoated), Plate 4, (Figure 4-19)**
  - This plate is very heavily fouled; almost completely covered with macrofouling, primarily a large, expansive encrusting sponge. Very little metal visible. Other species include:
    - Parchment worm tubes (10+ cm long).
    - Sipunculid worms (about 3 cm long).
    - 8 slipper limpets (10 to 20 mm).
    - 10 mussels (*M. galloprovincialis*), 2 to 20 mm long. There could be more mussels in the sponge.
    - 7 Oysters (probably *Ostrea lurida*), 24 to 44 mm).
    - Hundreds of barnacles (*M. californicus*), 2 to 14 mm, diameter.
    - White bivalves (probably *Hiatella sp*.), up to 18 mm.
    - Erect and encrusting bryozoans.
    - Calcareous worm tubes.
    - C/S tunicate.
    - Hydroids.
  - As with the other plates, a variety of encrusting invertebrates were attached to the PVC frame and the plastic cable ties that secure the plate to the frame. In this case, there is little to differentiate between the stainless steel plate and the plastic components.

Figure 4-19: 2205 stainless steel test plate (Test Plate 4), photographed 06/18/15 prior to biofouling inspection.

- **2205 Stainless Steel with foul release coating, Plate 5, (Figure 4-20)**
  - As stated earlier, this plate and its frame and bag were missing when the divers arrived at the WB intake in April 2015. The cords that suspended the frame may have failed, but remained intact on the other four plates. The plate was found lying in the soft sediment and was retrieved from inside the intake by the divers and returned to its original position. The cords were replaced on all five of the plate frames.
  - The fouling that was observed growing on the plate and on the PVC frame in December 2014 was gone with the exception of some empty barnacle shells on the frame. The soft sediment at the bottom of the intake was probably anaerobic and the fouling probably suffocated, died, and decayed. The black coloration on the PVC frame supports the assumption that the sediment had gone anaerobic.
  - This plate is of the same material as Plate 4, but has been coated with a silicone elastomer foul release coating.
  - On June 18, 2015:
    - The coating was intact and in good shape.
    - The plate was very clean with the exception of some small patches of encrusting bryozoans and a few small patches of erect bryozoans.
    - All of the fouling slid off the plate/coating with just a slight finger pressure.
    - The PVC frame was still much cleaner (less fouling) than the other four frames that had not dropped into the sediment within the intake structure.

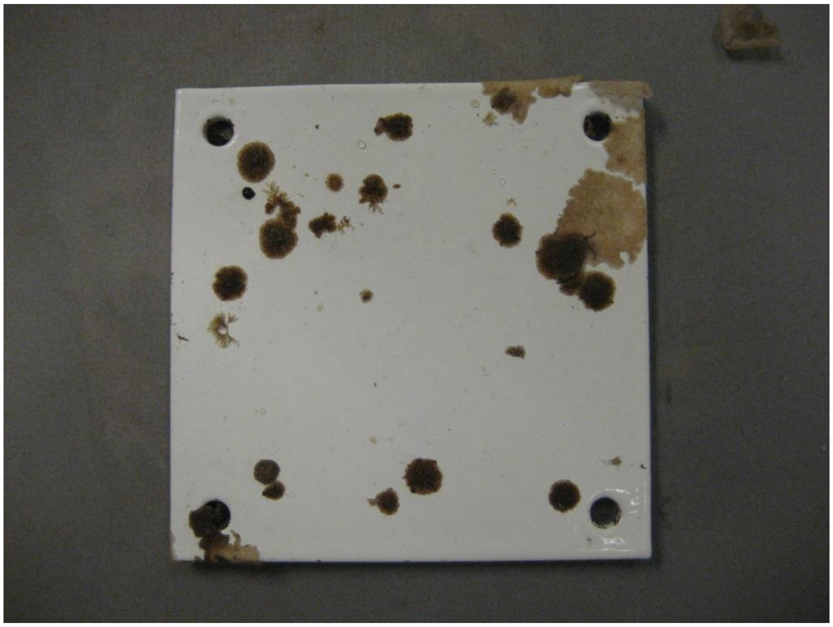


Figure 4-20: 2205 stainless steel test plate with foul release coating (Test Plate 5), photographed 06/18/15 prior to biofouling inspection.

Weight Change

Prior to the biofouling inspections and assessments, each Wedgewire sample, alloy coupon, and alloy plate was blotted to remove any excess water and then weighed along with any accumulated fouling. The resulting weight was then compared with the dry weight that was recorded prior to deployment of the test racks. Presented below in Tables 4-6 and 4-7 are the percentage change in weight for each of the Wedgewire samples, alloy coupons and test plates retrieved.

Table 4-6: Summary of Weight Change Percentages of Wedgewire Samples

Wedgewire Samples	Test Rack I	Test Rack II	Test Rack III	Test Rack IV	Test Rack V
CDA 706 (90/10 Cu-Ni)	-2.8%	-2.5%	0.3%	2.8%	Missing
CDA 715 (70/30 Cu-Ni)	3.5%	2.8%	7.2%	4.7%	10.9%
Z-alloy	-2.1%	-2.2%	-1.4%	-0.6%	Missing
2205 Stainless Steel (uncoated)	64.9%	73.0%	88.5%	78.5%	138.7%
2205 Stainless Steel (coated)	4.5%	12.5%	10.9%	15.8%	37.8%

Table 4-7: Summary of Weight Change Percentages of Alloy Coupons

Wedgewire Samples	Test Rack I	Test Rack II	Test Rack III	Test Rack IV	After 365 Days of Exposure
CDA 706 (90/10 Cu-Ni)	0.7%	-0.3%	0.5%	1.8%	-1.1%
CDA 715 (70/30 Cu-Ni)	1.1%	0.0%	2.5%	4.3%	-0.3%
Z-alloy	0.7%	0.1%	6.8%	10.5%	-0.1%
2205 Stainless Steel (uncoated)	121.3%	148.5%	183.0%	139.7%	92.5%
2205 Stainless Steel (coated)	0.5%	1.3%	0.8%	1.3%	1.2%

Biofouling Conclusions

- In comparison with the macrofouling observed on the PVC racks and the uncoated stainless steel samples, the 70-30 Cu-Ni sample performed very well at deterring the settlement of macrofouling organisms.
- The uncoated (bare metal) stainless steel wedgewire sample showed no antifouling properties and had about the same degree of biofouling (species composition and growth) as the PVC racks.
- The SS sample that was painted with the foul-release coating had considerably less attached fouling that the uncoated SS samples, and was almost as clean as the Cu-Ni sample. The barnacles that were present appear to have initially attached themselves at locations where the coating had detached from the sample or some surface irregularity existed. The foul-release coating is fairly soft and can easily be damaged.
- Two of the samples, the 90-10 Cu-Ni and the Z-Alloy were missing from Rack V. During past inspections of these materials from Racks I - IV it was noted that they were quite resistant to biofouling, even after 365 days of submergence at the intake. However, it was also noted that the wedgewire at the sites of the four securing cable ties were quite worn; possibly as a result of accelerated corrosion beneath the cable tie and erosion due to rubbing of the cable tie against the metal. This may have eventually caused the metal to wear through at the points of attachment and resulted in the loss of the samples. The plastic cable ties that had secured these samples to Rack V remained intact and were still looped through the rack when it was retrieved. This indicates that the cable ties were neither cut nor worn through resulting in the loss of the samples. This was most unfortunate since these two materials were the most resistant to biofouling.

CORROSION STUDY

The following is a summary of the corrosion inspection of the test racks performed by V&A Consultants. Full reports of the corrosion inspections are included in Appendix E. The corrosion sample testing dates of the four alloys were:

- First Sample Removal – September 16, 2014
- Second Sample Removal – December 29, 2014
- Third Sample Removal – April 21, 2015
- Fourth Sample Removal – June 16, 2015
- Fifth Sample Removal – May 23, 2017

Procurement of Materials

There were 45 samples that were exposed within one year: 20 coupons (5 sample types; 4 exposure durations), 20 screens (5 sample types; 4 exposure durations), and 5 plates (5 sample types; 1 exposure duration). Also, there were 5 additional coupon samples (1 sample of each material type) that were not exposed and were procured for baseline EDS measurements. There were 5 additional screen samples (5 sample types; 1 exposure duration) allocated for the 3-year exposure.

V&A coordinated with the coupon vendors and screen manufacturers for the procurement of the testing samples. Metal Samples Company of Munford, Alabama, provided the 1-inch by 3-inch long by 1/16-inch thick coupons in 90-10 Copper-Nickel (Cu-Ni), 70-30 Cu-Ni, and the 2205 Duplex Stainless Steel. Metal Samples also provided the 4-inch by 4-inch by 1/8-inch thick flat plate in the same metal alloys. Holes were made on each 1-inch by 3-inch and 4-inch by 4-inch metal sample in order to secure it to the testing rack with plastic zip ties.

Johnson Screens/Bilfinger Water Technologies of New Brighton, Minnesota provided the 4-inch by 4-inch wedgewire screens in the 90-10 Cu-Ni, 2205 Duplex Stainless Steel, and Z alloys. They also provided the 1-inch by 3-inch by 1/16-inch thick coupons and the 4-inch by 4-inch flat plate in the Z alloy.

Hendrick Screen Company of Owensboro, Kentucky, provided the 4-inch by 4-inch wedgewire screens in 70-30 Cu-Ni.

Coating for Stainless Steel Screens and Coupons

V&A searched for a coating that would provide an NSF Standard 61-approved coating for drinking water contact and was known to prevent the attachment of marine life on hydraulic structures. V&A identified the following foul release coating system for the stainless steel samples from the literature review and discussions with manufacturers:

1. 1st coat - Sherwin Williams Macropoxy 646 PW immersion grade epoxy primer at 6 mils dry film thickness (dft).
2. 2nd coat - Sherwin Williams Seaguard Sher-Release beige silicone Tie Coat at 6 mils dft.
3. 3rd coat - Sherwin Williams Seaguard Sher-Release white silicone Surface Coat at 6 mils dft.

The coating was applied by Fuji Hunt Smart Surfaces in Davidsonville, Maryland.

Lab Analysis

Chemical Analysis by EDS

Anamet, Inc. of Hayward, California, performed a quantitative chemical analysis by Energy Dispersive x-ray Spectra (EDS) on a baseline control sample and on the samples after they were immersed in seawater. Anamet's report contains images of the spectra and is included as Appendix A.

Scanning Electron Microscopy

Anamet, Inc. of Hayward, California, performed Scanning Electron Microscopy (SEM) on the samples. The SEM uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. The signals that derive from electron-sample interactions reveal information about the sample including texture, chemical composition, and crystalline structure.

Metallography

Optical macrographs of the samples were also recorded by Anamet, Inc. before and after cleaning of the samples and are attached in Anamet's reports. A metallographic examination of a cross section of each sample was recorded.

Corrosion Rate Analysis

Samples were weighed by Anamet, Inc. Laboratories in Hayward, CA before they were installed. The samples were analyzed by the lab after they were exposed to the seawater environment per ASTM G1 *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens* and ASTM D2688 *Standard Test Method for Corrosivity of Water in the Absence of Heat Transfer (Weight Loss Method)*. The samples were cleaned with either nitric acid or hydrochloric acid. Plots of mass loss versus cleaning cycles for each sample are attached in Anamet's report. Pitting examination was performed per ASTM G46 *Standard Guide for Examination and Evaluation of Pitting Corrosion*.

Procedures

After the initial baseline parameters were obtained, the samples were shipped to Tenera Environmental for installation at the project site. Tenera Environmental assembled the testing rack and affixed the coupons and wedgewire screens prior to immersion in the ocean source water. The wedgewire screens were secured to the testing rack with plastic zip ties. There was one test rack for each set of samples to be removed at each specified interval.

The testing samples consisted of metal coupons, wedgewire screens and flat plates (coated and uncoated) for installation on the in-situ testing apparatus installed by Tenera Environmental divers. Samples and cleaning were performed per ASTM G-1 *Preparing, Cleaning, and Evaluating Corrosion Test Specimens* and ASTM D2688 *Standard Test Method for Corrosivity of Water in the Absence of Heat Transfer (Weight Loss Method)*. ASTM G-1 includes procedures in Sections 14.10 through 14.14 that involve weighing and classifying the types of pits. This test method covers the determination of the corrosivity of water by evaluating pitting and by measuring the weight loss of metal specimens. Pitting is a form of localized corrosion: weight loss is a measure of the average corrosion rate.

A metallographic examination was performed per ASTM E3 *Standard Guide for Preparation of Metallographic Specimens*. The primary objective of metallographic examinations is to reveal the constituents and structure of metals and their alloys by means of a light optical or scanning electron microscope.

Before installation the samples were examined for the following baseline parameters:

1. Weigh all samples per ASTM G1. Samples to be coated will be weighed before and after coating application.
2. Examine samples visually to 40X
3. Color photograph, one of each material type
4. Photomicrograph @ 10X, one of each material type
5. Photomicrograph @ 50X, one of each material type
6. Scanning Electron Micrograph (SEM) @ 100X, one of each material type
7. Energy Dispersive Spectroscopy (EDS), one of each material type

Samples removed after 3, 6, 10, 12, and 36 months of exposure were examined for the following:

1. Sample cleaning and weighing per ASTM G1 and ASTM D2688
2. Pitting examination per ASTM G46
3. Dimensional inspection (micrometers or NOGO gauge): Wedgewire and gap dimensions
4. Photomicrograph @ 10X, one of each material type After Cleaning (AC)
5. Photomicrograph @ 50X, one of each material type AC
6. Scanning Electron Micrograph @ 100X, one of each material type AC
7. Elemental analysis with EDS, one of each material type AC
8. Metallographic examination per ASTM E3, one of each material type

Corrosion Mechanisms

Corrosion is an electrochemical phenomenon that takes place at the interface of the metal and electrolyte, which in this case is seawater. When the metal is in contact with the electrolyte, a difference in potential develops at the electrolyte/metal interface. When corrosion reactions take place, they generate a current between two points on the metal surface with current flow through the electrolyte. Factors that may impact the corrosion rate include the following:

- Presence of inclusions in the metal or a Heat Affected Zone due to welding.
- Mechanical stresses caused by welding, forming or temperature.
- Water velocity and tidal fluctuations at the surface of the coupon (not possible to simulate in a lab).
- Alloy resistance to corrosion due to high chloride concentrations in seawater.
- Water temperature, dissolved oxygen, sulfates, and chlorides. Water temperature data was collected at the intake to better understand and account for how temperature may impact the corrosion rate.

The following sections explain some possible corrosion mechanisms for the metals based on V&A's research.

Uniform Corrosion

If all metal surfaces are attacked via corrosion at an equal rate, the corrosion is termed uniform. As far as failure rate, the uniform corrosion rate is expressed in terms of pipe penetrating rates (rate of pipe wall loss) in thousandths of inches (mils) per year (mpy).

Localized and Pitting Corrosion

When corrosion of the metal surface is localized, the surface under the most aggressive attack becomes recessed with respect to the rest of the pipe surface and visible pits are formed. In such instances, the attack is said to be non-uniform, localized, or pitting corrosion. Theoretically, corrosion pitting in metals is divided into two phases: pit initiation and propagation.

Stress Corrosion Cracking

The occurrence of stress corrosion cracking (SCC) depends on the simultaneous achievement of three requirements: 1) a susceptible material; 2) a chemical environment that causes SCC for that material and 3) sufficient tensile (mechanical) stress within the material. The mechanical stresses may be caused by welding, forming, applied loads, and temperature.

Figure 4-21 and Figure 4-22 show samples of the cracking that might occur for copper alloys and duplex stainless steel under mechanical and chemical stresses. These photos are not of the metal samples that are part of this study and are presented for demonstrative purposes only.

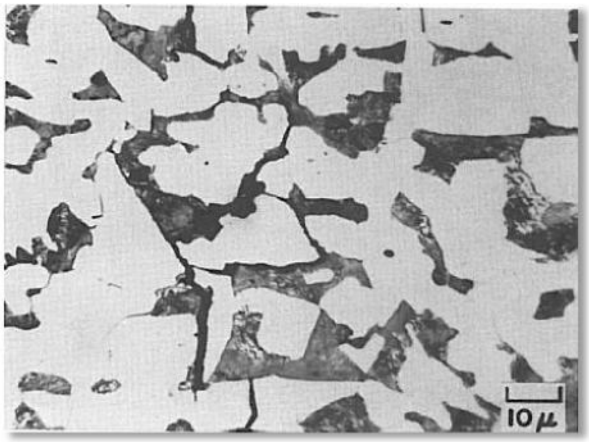


Figure 4-21: Intergranular Stress Corrosion Cracking in a Steel Pipe.

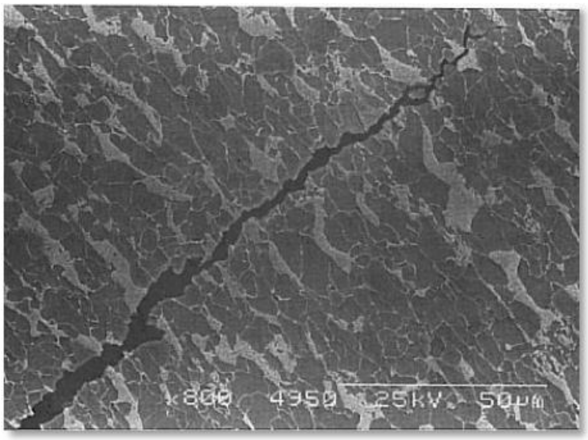


Figure 4-22: Transgranular Stress Corrosion Cracking in a Steel Pipe.

Reference Corrosion Rates from Studies Performed by Others

V&A researched seawater corrosion rates for the alloys in this study to compare the corrosion rate of the alloys with the results of this study. Table 4-8 summarizes the information found in corrosion control literature.

Table 4-8: Average Corrosion Rates from Literature Review for Alloys in Seawater

Material	UNS	1-year Average General Corrosion Rate (mil/yr)	3-year Average General Corrosion Rate (mil/yr.)	Reference
2205 duplex stainless steel	S32205	0.03		McGuire, Stainless Steels for Design Engineers, p. 101, 2008
70-30 Cu-Ni	C71500	Flowing: 1.06 Quiet: 0.22	Flowing: 1.41 Quiet: 0.66	Efird & Anderson, Mater. Perform., Vol. 14 (No. 11), 1975
90-10 Cu-Ni	C70600	Flowing: 0.79 Quiet: 0.22	Flowing: 1.32 Quiet: 0.48	Efird & Anderson, Mater. Perform., Vol. 14 (No. 11), 1975

Figure 4-23 shows a graph of the average corrosion rates for several metal alloys in seawater. As seen in the graph, 70-30 Cu-Ni and 90-10 Cu-Ni have a corrosion rate of 0.15 to 0.5 mils per year.

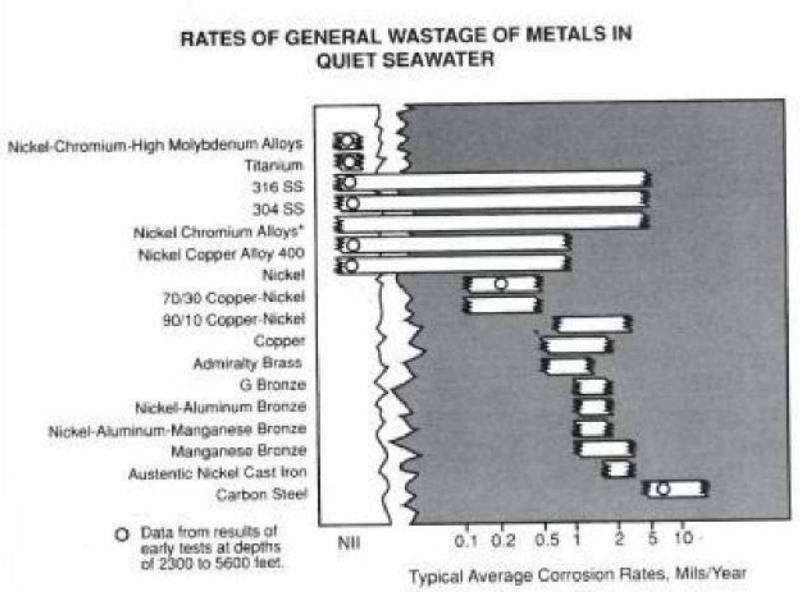


Figure 4-23: Graph of Average Corrosion Rates of Different Alloys in Seawater[1]

CORROSION RESULTS

The fourth set of 15 3-inch by 1-inch coupons, 4-inch by 4-inch flat plates and screens was installed on Tuesday, June 17, 2014, and retrieved after 364 days on Tuesday, June 16, 2015. Photographic documentation and lab results and analysis are presented below.

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[1] NACE Corrosion Engineer's Reference Book, 2nd Ed. (1991) R.S. Treseder (editor)

Photos of Samples after 12 Months of Exposure

Figures 4-24 through 4-43 show photos of the samples before they were cleaned or analyzed.

Figures 4-31, 4-34, 4-36, 4-40, and 4-41 show some further oxidation and discoloration of the copper alloy sample surfaces after being exposed to the atmosphere for up to 7 days.

Figures 4-33, 4-38, and 4-43 show some typical mechanical damage to the screen wires that was observed on the 70-30 Cu-Ni, 90-10 Cu-Ni, and Z Alloy screens. The damage was observed at each corner of the screen where the screens were secured to the test rack. The mechanical damage may have been caused by the turbulence in the water and the abrasion by the zip ties that prevented the passivation of the metal at those locations. The exposed metal was corroded and metal loss occurred.

Figure 4-24: Marine life attached to uncoated 2205 Duplex stainless steel coupon with a weld.

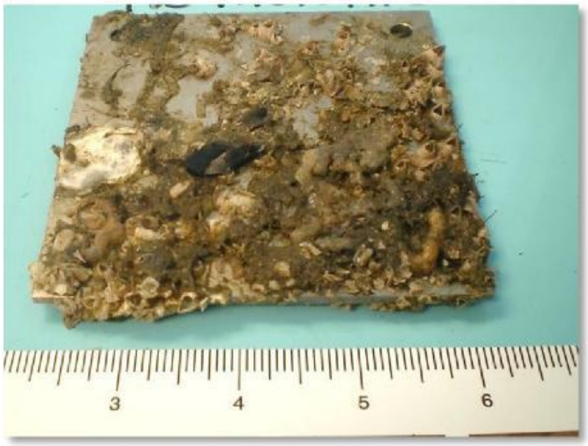

Figure 4-25: Marine life attached to uncoated 2205 Duplex stainless steel flat plate.

Figure 4-26: Marine life attached to uncoated 2205 Duplex stainless steel wedgewire screen.

Figure 4-27: Slight damage to coating on edge and initiation of biofouling on corner of coated 2205 Duplex stainless steel coupon.

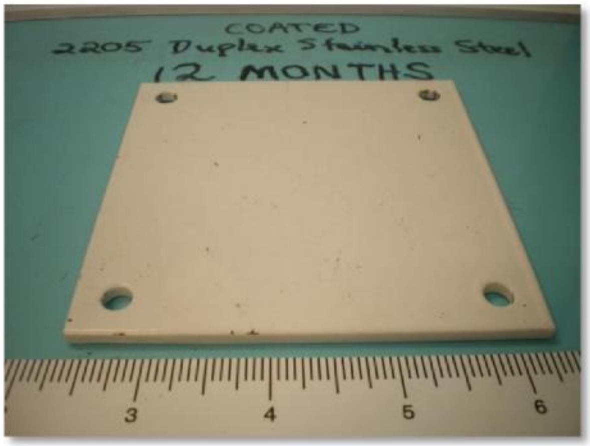

Figure 4-28: Coated 2205 Duplex stainless steel flat plate in good condition.

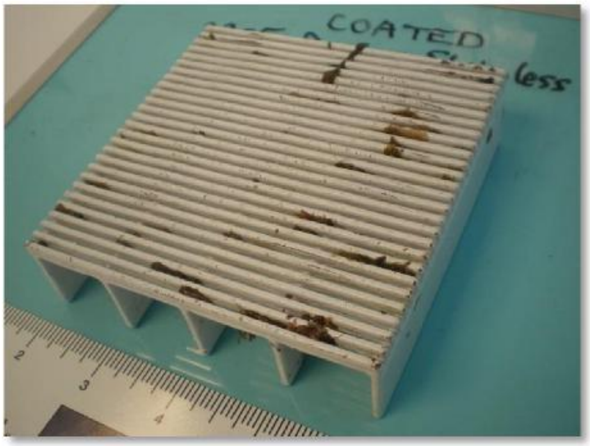

Figure 4-29: Coating damage to coated 2205 Duplex stainless steel wedgewire sample.

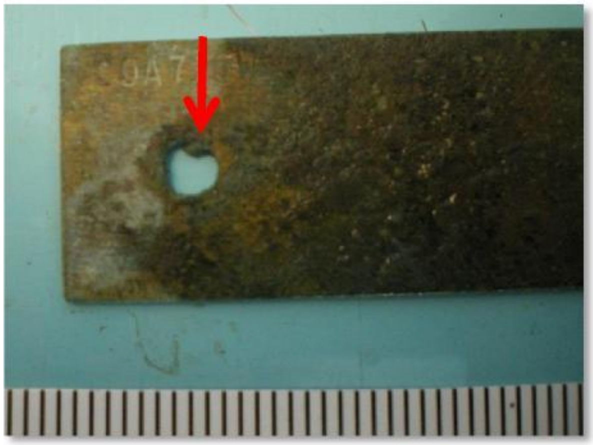

Figure 4-30: Detail view of hole and surface of 70-30 Cu-Ni coupon.

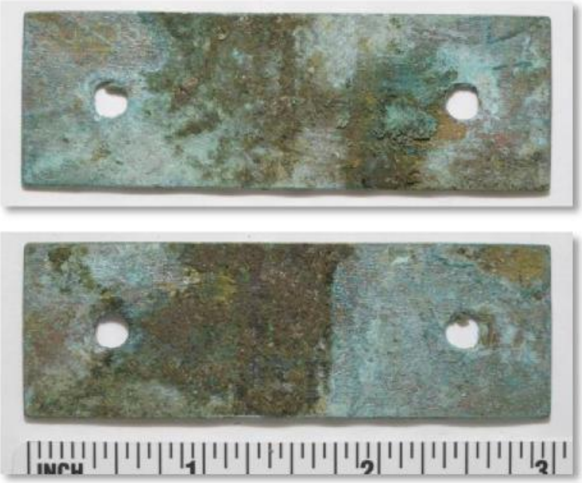

Figure 4-31: Development of copper patina on 70-30 Cu-Ni coupon, front (top), back (bottom).

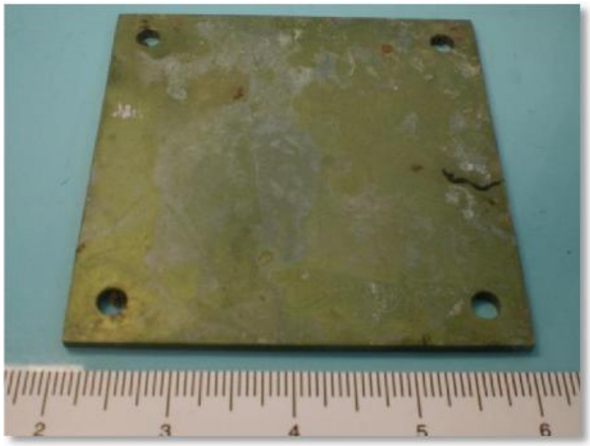

Figure 4-32: Surface discoloration of 70-30 Cu-Ni flat plate.

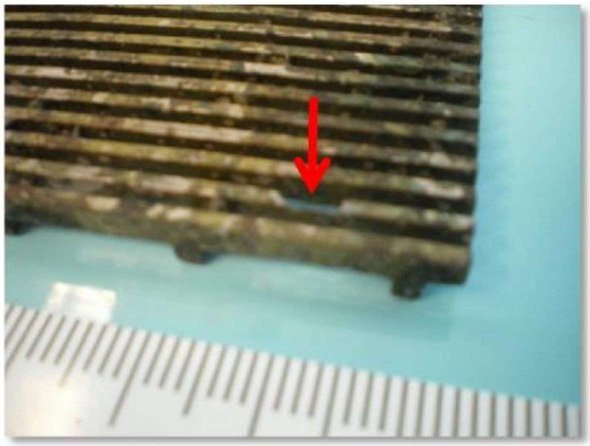

Figure 4-33: Mechanical damage to 70-30 Cu-Ni wedgewire screen.

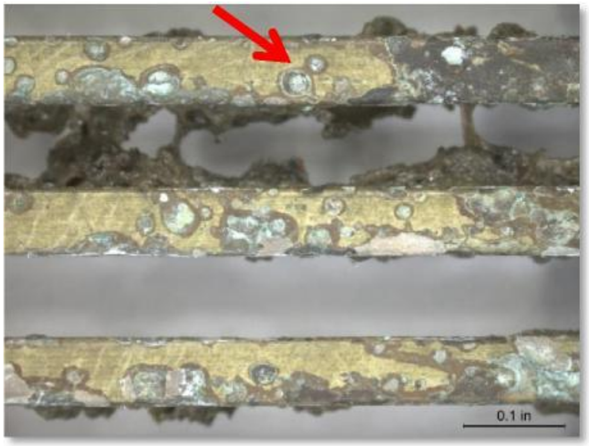

Figure 4-34: 70-30 Cu-Ni wire screen at 10X magnification, pitting and discoloration.

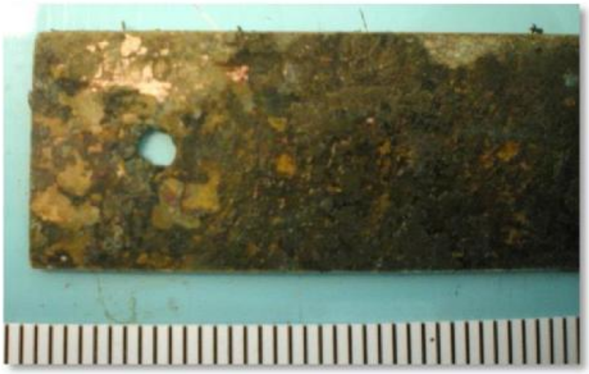

Figure 4-35: Detail view of 90-10 Cu-Ni 1-inch by 3-inch coupon with weld.

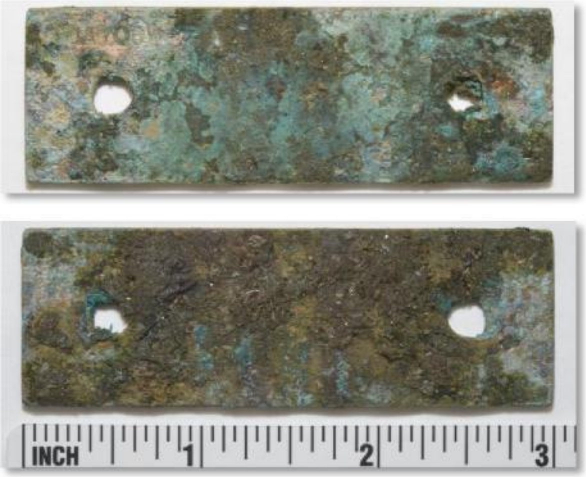

Figure 4-36: Development of patina on 90-10 Cu-Ni coupon, front (top), back (bottom).

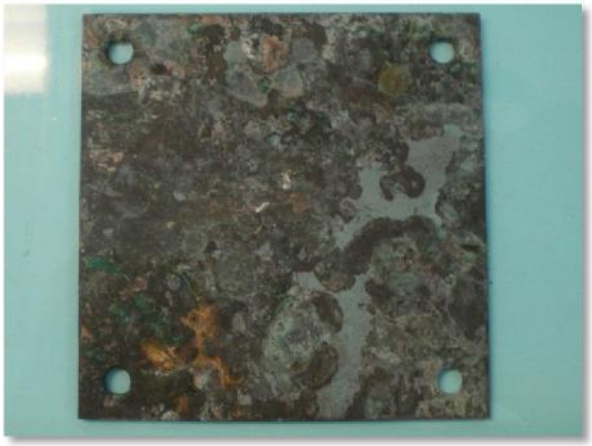

Figure 4-37: 90-10 Cu-Ni plate.

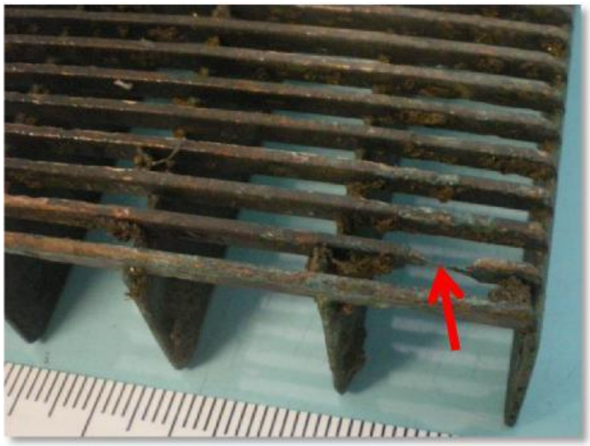

Figure 4-38: Mechanical damage to 90-10 Cu-Ni wedgewire screen.

Figure 4-39: Z alloy 1-inch by 3-inch coupon with weld front.

Figure 4-40: Surface discoloration of Z alloy coupon, front (top), back (bottom).

Figure 4-41: Surface discoloration of Z alloy coupon, shown at 50X magnification.

Figure 4-42: Minimal corrosion was observed on the Z alloy flat plate.

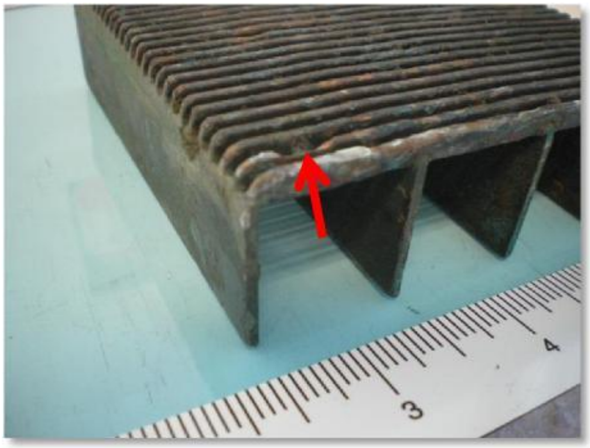

Figure 4-43: Mechanical damage to Z alloy wedgewire screen.

Photos of Samples after 3 years of Exposure

The fifth set of wire screen samples was installed on Tuesday, June 17, 2014, and retrieved after nearly 3 years on Tuesday, May 23, 2017. Photographic documentation and lab results and analysis are presented below.

Two of the wire screen samples could not be retrieved since they detached from the test rack. It is suspected that the samples suffered a severe loss of material at the cable tie attachment points and fell. The bottom of the intake riser is filled with very fine silt which reduces visibility to zero when disturbed making retrieval very difficult. The material loss may have been caused by the turbulence in the water and the abrasion by the zip ties that prevented the passivation of the metal at those locations. The 70-30 Cu-Ni wire screen (see Photo 4-11 to Photo 4-14) and the immersed 1-year wire screens (see previous report) show signs of wear at the cable tie attachment points. This was identified in the previous report and Tenera Environmental wove the cable ties through the second slot at each point as a precautionary measure. Inspection of the PVC rack found that the cable ties from the missing samples (that could be seen through the biofouling) were still fully intact with closed loops.

Photo 4-1 through Photo 4-14 show the samples after 3 years of exposure. These photos are courtesy of Anamet, Inc. and are included in the reports in Appendix A.

Photo 4-1: Uncoated 2205 Duplex SS wedgewire screen, before cleaning.

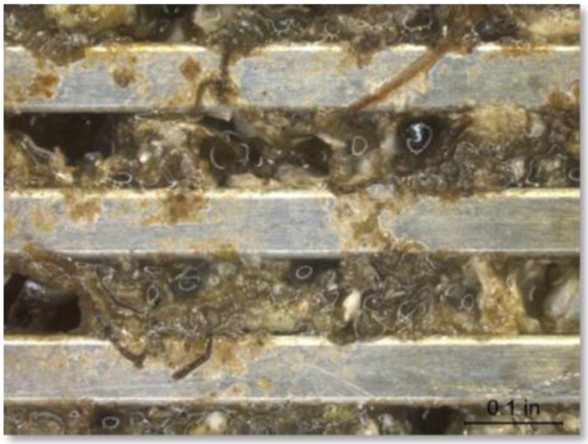

Photo 4-2: Detail view (10x) of uncoated 2205 Duplex stainless steel before cleaning.

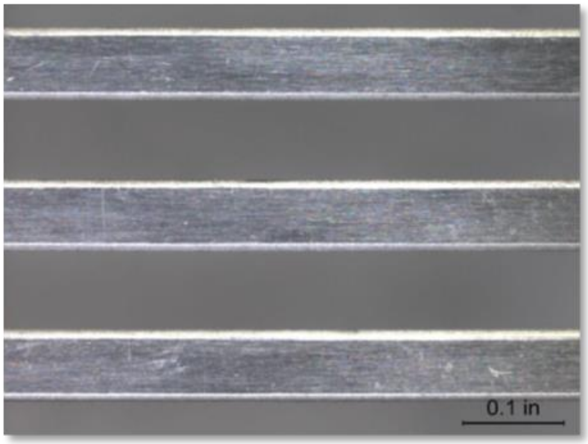

Photo 4-3: 2205 Duplex stainless steel wire screen, after cleaning (10x).

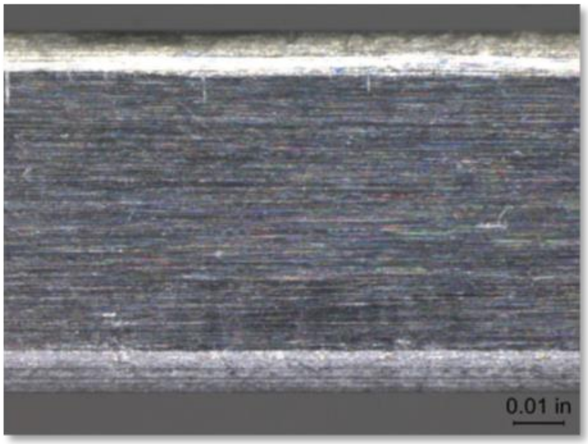

Photo 4-4: Detail view (50x) of uncoated 2205 Duplex stainless steel, after cleaning.

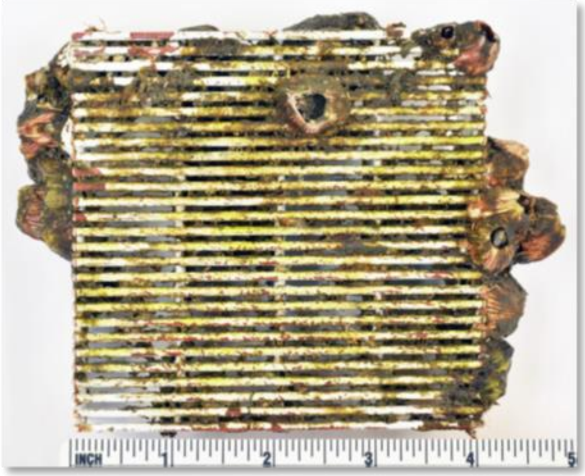

Photo 4-5: Coated 2205 Duplex SS wire screen, before cleaning.

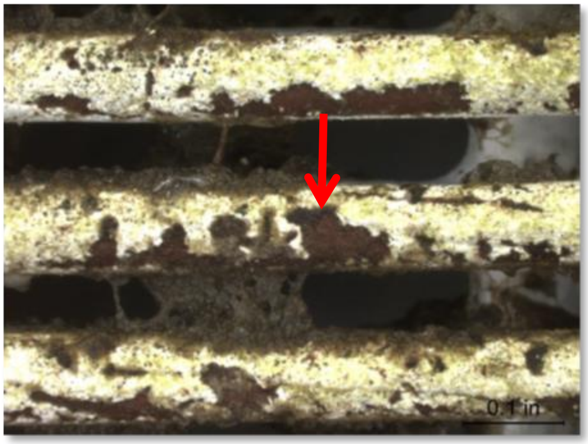

Photo 4-6: Detail view (10x) of coating damage on 2205 Duplex SS, before cleaning.

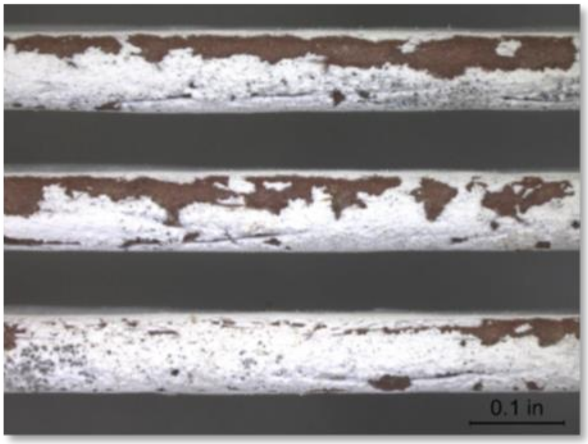

Photo 4-7: Coated 2205 Duplex stainless steel wire screen, after cleaning (10x).

Photo 4-8: Detail view (50x) of coating damage, after cleaning.

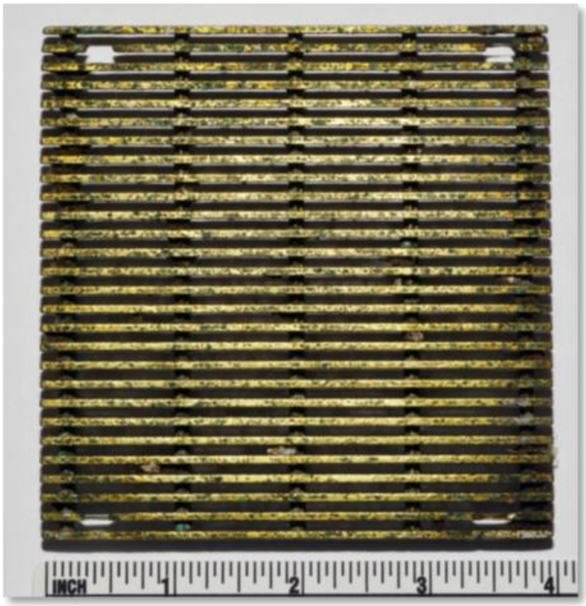

Photo 4-9: 70-30 Cu-Ni wedgewire screen, before cleaning.

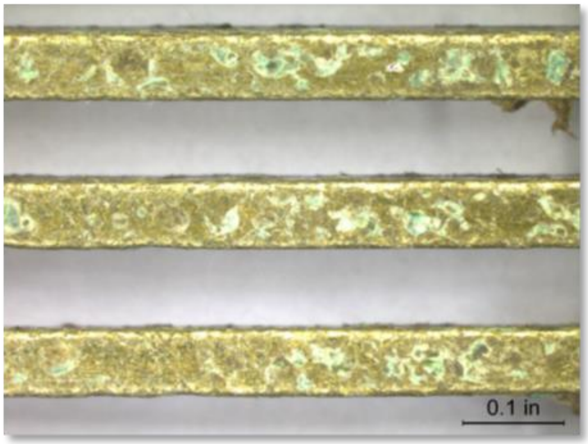

Photo 4-10: Detail view (10x) of 70-30 Cu-Ni wedgewire screen.

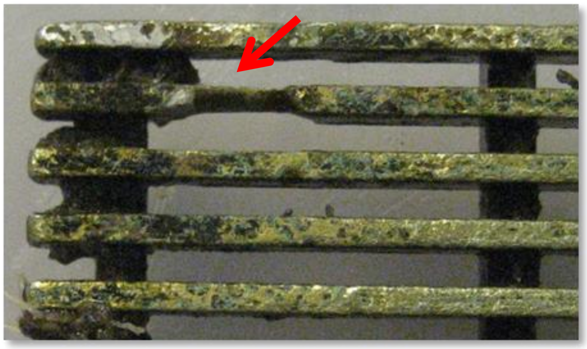

Photo 4-11: Mechanical damage to 70-30 Cu-Ni wedgewire screen at top left corner.

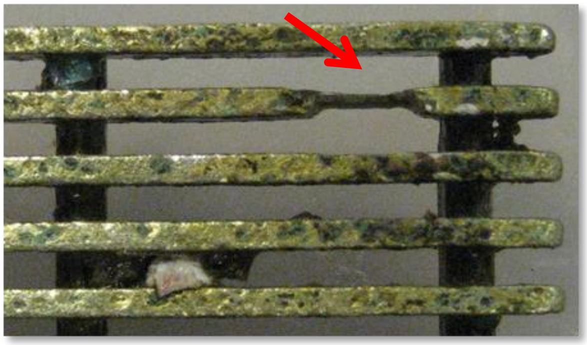

Photo 4-12: Mechanical damage to 70-30 Cu-Ni wedgewire screen top right corner.

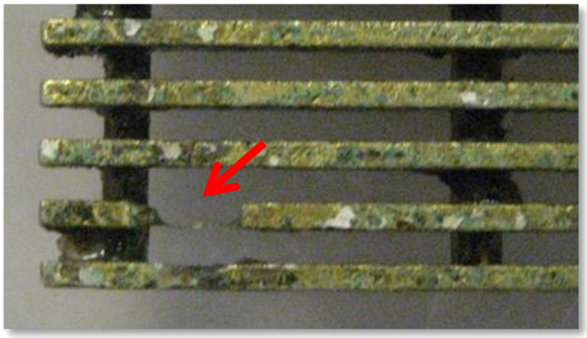

Photo 4-13: Mechanical damage to 70-30 Cu-Ni wedgewire screen at bottom left corner.

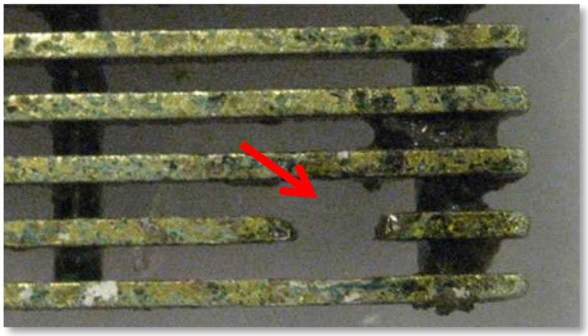

Photo 4-14: Mechanical damage to 70-30 Cu-Ni wedgewire screen at bottom right corner.

Photo 4-15: 70-30 Cu-Ni wire screen, after cleaning.

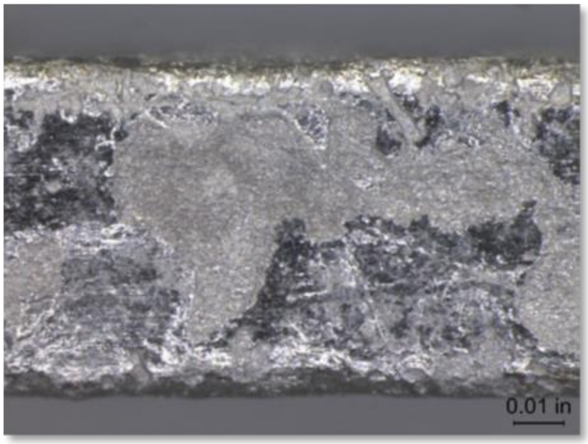

Photo 4-16: Detail view (50x) of 70-30 Cu-Ni wire screen, after cleaning.

Table 4-9 summarizes the results of the average general corrosion rate analysis conducted by Anamet, Inc. after the samples were exposed to seawater for nearly 3 years starting on June 17, 2014.

Pitting depths were not previously performed on the wedgewire screens due to the difficulty of mounting a pit depth gauge on the surface and were estimated to be less than 20 mils. Instead, pit depths were measured on the flat plate samples of the same alloy. In this report, the pit depths were estimated by metallographically mounting the screen and measuring the pits visually. After the 3 years of exposure, the foul release-coated 2205 Duplex SS screen pitting depth of 0.9 mils is less than the depth that was measured after 1 year of exposure (1.38 mils) on an uncoated 2205 Duplex SS sample. The smaller pitting depth on the foul-release-coated sample is likely due to the shorter time of exposure of the metal since it was protected by the coating. The 70-30 Cu-Ni screen pitting depth of 2.8 mils is greater than the depth measured after 1 year of exposure (1.57 mils).

Table 4-9
Average General Corrosion Rates of Alloys in Seawater Exposure

Alloy	Sample Type	Surface Area (sq. in.)	Maximum Pitting Depth after 1 and 3 Years (mils)	1 Year Average General Corrosion Rate (mils/year)	3 Year Average General Corrosion Rate (mils/year)
2205 Duplex SS Uncoated	1-inch by 3-inch coupon	8.2	1.38	0.0004	-
	Wedgewire Screen	96.7	< 20 [A] (1 yr), <20 [A] (3 yr)	0.001	0.004
	4-inch by 4-inch plate	33.9	< 20 [A]	0.002	-
2205 Duplex SS with Foul Release Coating	1-inch by 3-inch coupon	8.2	1.30 [B]	0.039 [B]	-
	Wedgewire Screen	96.7	< 20 [A] (1 yr), 0.9 (3 yr)	0.039 [B]	0.079
	4-inch by 4-inch plate	34.6	< 20 [A]	0.039	-
CDA 715 70-30 Cu-Ni	1-inch by 3-inch coupon	8.2	1.6	0.472	-
	Wedgewire Screen	65.0	< 20 [A] (1 yr), 2.8 (3 yr)	0.709	0.394
	4-inch by 4-inch plate	34.4	< 20 [A]	0.315	-
CDA 706 90-10 Cu-Ni	1-inch by 3-inch coupon	8.2	11.5	0.669	-
	Wedgewire Screen	79.1	< 20 [A]	1.732	-
	4-inch by 4-inch plate	34.1	< 20 [A]	1.142	-
Z Alloy	1-inch by 3-inch coupon	8.2	0.47	0.236	-
	Wedgewire Screen	96.3	< 20 [A]	1.772	-
	4-inch by 4-inch plate	36.6	< 20 [A]	0.232	-

[A] Less than detectable/measurable. The screens were metallographically mounted and optical micrographs of the surface up to 200x, resolution of several micrometers, were examined.

[B] Mass loss and corrosion rate includes metal and coating material.

Corrosion Rate over Time

The calculated average general corrosion rate value for each alloy and sample type is plotted on the graph below for each exposure time. Figure 4-44 visually summarizes the results of the corrosion rate analysis over nearly 3 years of testing. Please note that the corrosion rates were calculated per the procedures outlined in ASTM G1 and the graph below was not used to calculate the corrosion rate.

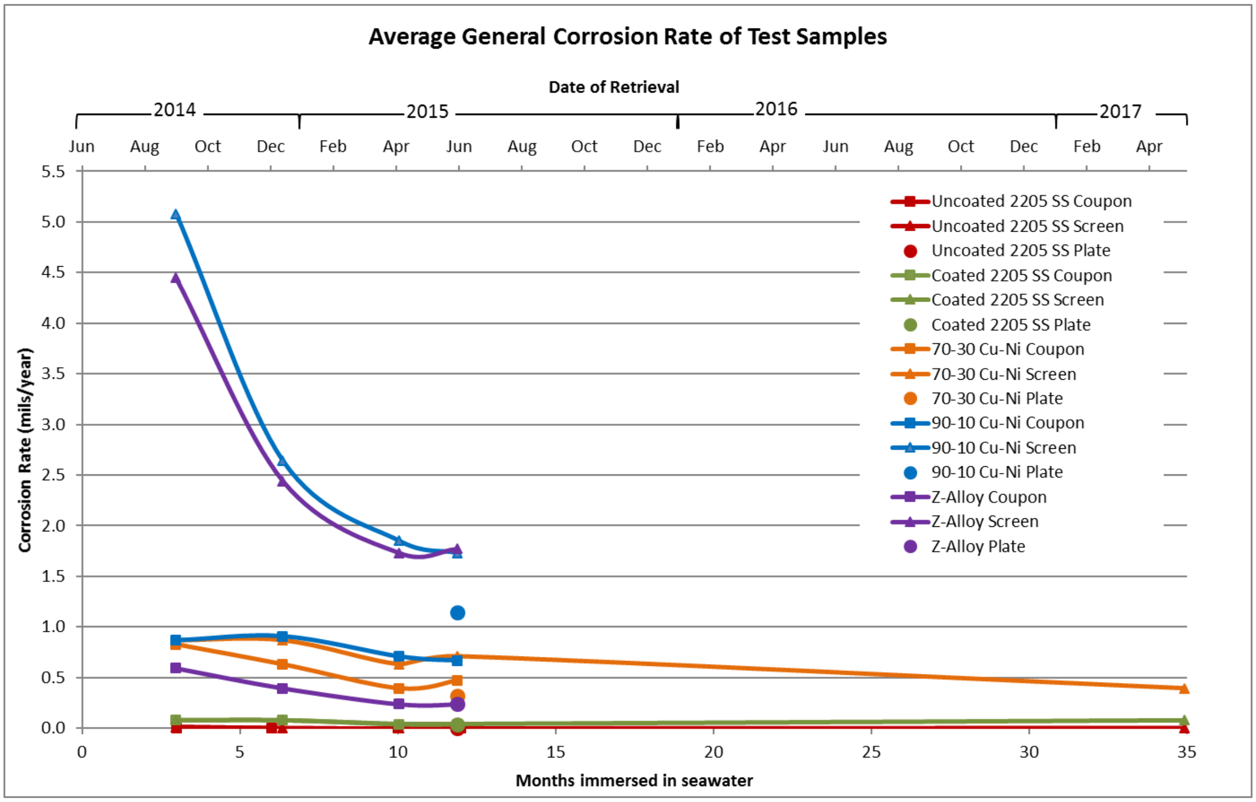

Figure 4-44: Corrosion Rates of Four Alloys over nearly 3 years in Seawater Exposure

The 2205 Duplex SS uncoated and coated screens showed minimal mass loss and pitting overall after 3, 6, 10, 12, and 36 months of corrosion testing. The average general corrosion rates of the 3-year stainless steel samples did increase slightly from the 12-month samples and were most similar to their respective materials' 6-month samples; however, the difference is minimal. The average general corrosion rate is higher for the coated 2205 Duplex SS sample due to the missing anti-fouling coating that was damaged over time and does not necessarily indicated more corrosion has occurred than the uncoated sample.

The 70-30 Cu-Ni wire screen showed a non-linear decrease in the average general corrosion rate from the 3-month to the 3-year samples. This is consistent with previous studies completed by others. The average general corrosion rate decreases after 3 months after a protective passive film layer is established. The passivation layer acts as a shield to keep corrosive ions like chlorides away from the metal surface. The trend of decreasing average general corrosion rate over time is similar over the 3-year study at an approximate loss of 0.176 mils/yr. The average general corrosion rate has likely reached a steady state and has built up a protective layer on the surface. It should be noted that the 70-30 Cu-NI wire screens had a lot less marine growth than the uncoated stainless steel screens.

Notably, the two wire screens that were not retrieved after 3 years previously had the highest corrosion rates. The average general corrosion rate for the 90-10 Cu-Ni and Z Alloy wedgewire screen samples quickly decreases after 3 months before a protective passive film is established and the corrosion rate equalizes after 9 to 12 months. At 12 months, the 90-10 Cu-Ni and Z Alloy wire screens had an average general corrosion rate of approximately 1.75 mils/yr and seemed to be reaching a steady state corrosion rate. Additionally, at 12 months, the 90-10 Cu-Ni and Z Alloy wire screens were showing surface discoloration and development of blue-green patina. The difference in the average general corrosion rates of the alloys is likely due to a difference in the metallurgy, abrasion resistance, and corrosion resistance of the materials.

In general, the wedgewire screens had a higher average general corrosion rate than the 1-inch by 3-inch flat coupons the 4-inch by 4-inch flat plates of the same alloy. This is likely due to the larger surface area of the wedgewire screens as compared to the flat coupons and plates.

Water Temperature

The corrosion rates may have also been affected by the seasonal water temperature changes. Graph the water temperature data collected at the intake throughout the course of the study. The temperature logger was able to log data until February 8, 2017 when the memory was filled or power was lost.

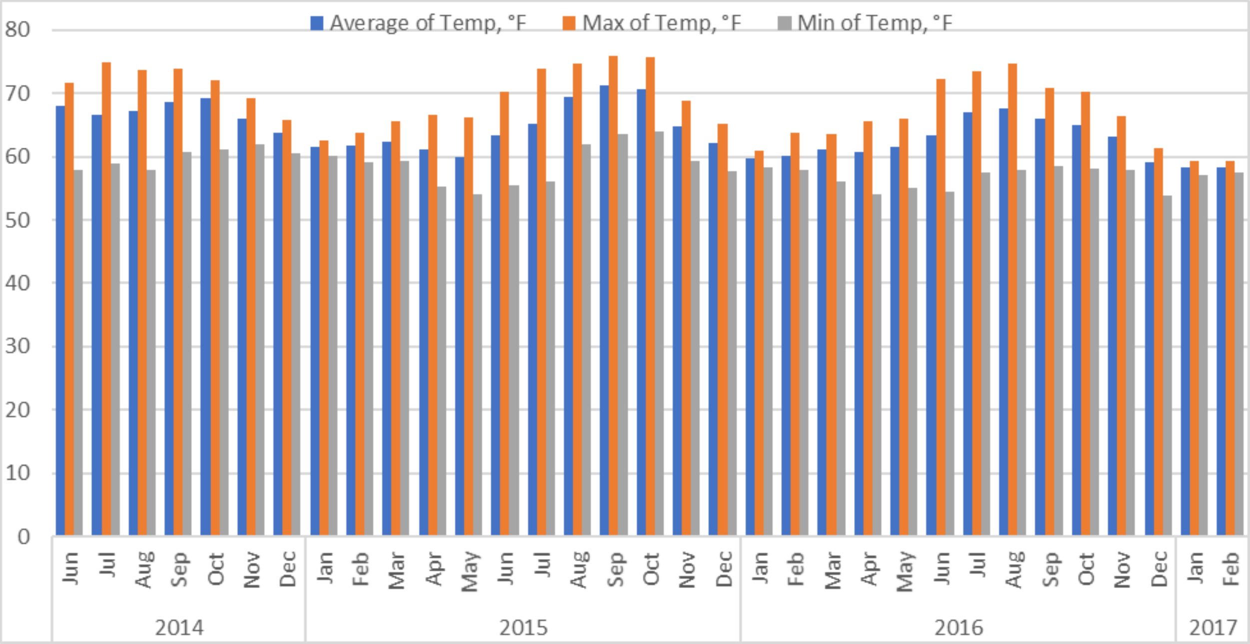

Figure 4-45: Summary of Temperature Data Per Month

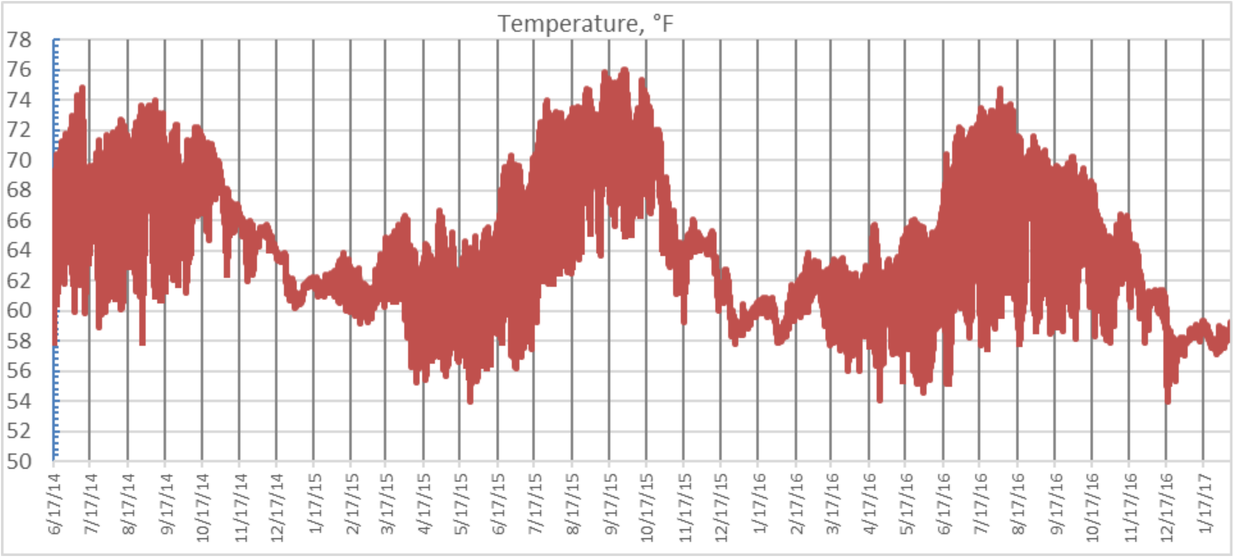

Figure 4-46: Raw Temperature Data Over Time at Intake Structure

The water temperature for all of the months was an average of 64 degrees Fahrenheit, minimum 54 degrees Fahrenheit and maximum 76 degrees Fahrenheit.

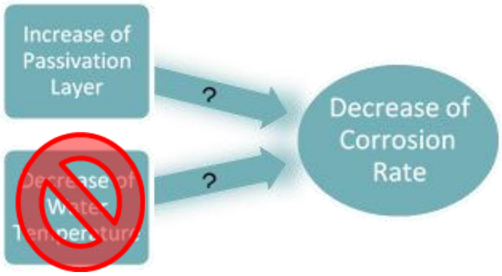

Figure 4-47: Potential Corrosion Rate Factors

The lower average corrosion rates of 10, 12 and 36 months appear to coincide with lower water temperatures, averaged over time. However, the lower average general corrosion rate also coincided with a more developed passivation layer. The causal influence of each factor cannot be separated in this study, but the decrease in temperature was minimal compared to the amount of passivation layer visible and the temperature effect should average out for the 3-years study. Therefore, the increase of passivation layer probably had a larger effect than the temperature change.

Comparison between the Different Material Types

Based on the data over 3 years, coated and uncoated 2205 Duplex Stainless Steel has the lowest average corrosion rates of the four metal alloy screens tested in this study. However, the uncoated 2205 Duplex Stainless Steel samples were the most heavily fouled by marine life.

Of the copper alloy wire screens, the 70-30 Cu-Ni sample exhibited only slight green marine life fouling; probably of the amount that may help reduce the corrosion rate by limiting the exposure of the metal to the seawater. After 3 years of immersion in seawater, the 70-30 Cu-Ni average general corrosion rate was 44% less than the average general corrosion rate after 1 year of the same alloy. This indicates that the corrosion rate has decreased over time and is likely due to the formation of the protective passivation layer over time that has shielded the metal from the corrosive seawater environment.

Of the three samples retrieved after 3-years, the highest pitting rate was observed on the 70-30 Cu-Ni wire screen. However, these were still shallow pits of less than or equal to 2.8 mils.

SEM and Energy X-ray Spectra Results

Baseline SEM and EDS scans were performed on the samples at the start of the study prior to deploying the samples into the seawater and can be viewed in V&A’s November 2014 report. A summary of the EDS results and chemical composition requirements for 2205 Duplex SS and 70-30 Cu-Ni samples are presented in Table 4-10.

The SEM scan (Anamet report Figure 5) of the 2205 Duplex SS indicated long narrow pits which was likely caused by corrosion. The EDS spectra after the cleaning of the sample indicated mostly chromium and iron at higher concentrations than minimum UNS standards; however, it is just estimated.

The SEM scan (Anamet report Figure 5) of the anti-fouling coated 2205 Duplex SS sample indicated degradation of the coating which was likely caused by erosion or abrasion. The EDS spectra (Anamet report Figure 6) of the coating after the cleaning of the sample indicated mostly carbon, oxygen, and silicon which fits the general description of Sherwin Williams Sher-Release Seaguard data sheet.

The SEM scan (Anamet report Figures 5 and 6) of the 70-30 Cu-Ni metal indicated pits which was likely caused by corrosion. The EDS spectra after the cleaning of the sample indicated mostly copper and nickel at lower concentrations than minimum UNS standards. This is likely because more carbon was on the samples during the EDS measurements, which caused the percentage of the other elements to appear lower than they likely are away from carbon contamination. The concentration of chlorides of 1.3% by weight (13,000 ppm) high due to the seawater exposure. For reference, the material certificates from the sample material manufacturers are included in the Appendix E.

Table 4-10: EDS Results for Baseline and 3-Year Exposure Samples

Element	Chemical Composition (Percent by Weight)							
	2205 Duplex SS (UNS S32205)				CDA 715 70-30 Cu-Ni			
	Spec	Cert	Baseline	3 Years	Spec	Cert	Baseline	3 Years
Carbon, C	≤ 0.30	0.019	5.35	4.11	≤ 0.050	0.004	19.58	6.46
Oxygen, O	-	-	1.70	-	-	-	1.24	-
Aluminum, Al	-	-	0.71	-	-	-	-	-
Silicon, Si	≤ 1.00	0.430	0.32	0.38	-	-	0.12	0.23
Chromium, Cr	22.0-23.0	22.500	21.48	22.71	-	-	-	-
Titanium, Ti	-	-	-	-	-	-	-	0.28
Manganese, Mn	≤ 2.00	1.390	1.16	-	≤ 1.0	0.68	0.53	0.74
Iron, Fe	Remainder	Remainder	61.16	64.46	0.40-1.00	0.50	0.47	0.67
Nickel, Ni	4.50-6.50	5.600	4.84	4.98	29-33	29.7	23.69	29.47
Zirconium, Zr	-	-	0.49	-	-	-	-	-
Molybdenum, Mo	3.00-3.50	3.100	2.80	3.36	-	-	-	-
Copper, Cu	-	-	-	-	≥ 65	69.16	54.37	62.13
Nitrogen, N	0.14-0.20	0.180	-	-	-	-	-	-
Phosphorus, P	≤ 0.030	0.023	-	-	≤ 0.003	< 0.01	-	-
Sulfur, S	≤ 0.020	0.001	-	-	≤ 0.020	0.001	-	-
Lead, Pb	-	-	-	-	≤ 0.020	< 0.01	-	-
Zinc, Zn	-	-	-	-	≤ 0.010	< 0.01	-	-

Sources of Variation

Corrosion rate variation for duplicate samples may be attributed to numerous factors, including differences in chemistry, surface condition, condition of exposure, location of test samples, and geometry and resultant biofouling. Also, environmental conditions may influence the degree of biofouling and integrity of the passive film, such as turbulence or mechanical damage. The thin passive oxide film is sensitive to the environment in which it is formed. The corrosion rate is directly influenced by the passive film because it acts as a barrier to the corrosion reaction on the metal surface.

CORROSION CONCLUSIONS

Coupons

1. The average general corrosion rates of the 12-month samples were similar to the 10-month samples. The passivation layer that was building up during the first 10 months was no longer increasing. The 3 year average general corrosion rate decreased for the 70-30 Cu-Ni screen.
2. The average general corrosion rate of the uncoated and coated 2205 Duplex Stainless Steel coupons was the lowest of the four alloys that were included in this study.
3. The greatest amount of biofouling was observed on the uncoated 2205 Duplex Stainless Steel coupons.
4. The average general corrosion rate of the 90-10 Cu-Ni coupons was the highest of the four alloys that were included in this study.
5. The lowest coupon pitting depth was measured on the Z Alloy coupons after 364 days of exposure in seawater.
6. The highest pitting depth was measured on the 90-10 Cu-Ni coupon after 364 days of exposure in seawater.
7. Pitting and general corrosion were the primary modes of corrosion on the coupons.
8. There is a large difference in the overall corrosion rate between the coupons and screens for the 90-10 Cu-Ni and Z Alloy samples. This could be due to different chemistry, surface conditions, conditions of exposure and location of test samples.
9. The overall average general corrosion rates of the 90-10 Cu-Ni and Z Alloy screens were 3 to 8 times higher than the coupons of the same alloy. This could be due to different chemistry, surface conditions, conditions of exposure and location of test samples.
10. The overall average general corrosion rates were higher than the data found in the literature summarized as outline in Appendix B.

Screens

1. The 2205 Duplex Stainless Steel Uncoated: lowest and steady average general corrosion rate of less than 0.004 mils/yr after the first 3 months (initially 0.013 mils/yr rate). The average general corrosion rate is 7.5 times less than the data found in the literature (0.03 mils/yr). Minimal to non-detectable pitting was observed. However, this alloy had the most marine life attached to the surfaces of all the samples. The SEM scan (Anamet report Figure 5) of the sample indicated long narrow pits which was likely caused by corrosion. The EDS spectra after the cleaning of the sample indicated mostly chromium and iron at higher concentrations than minimum UNS standards.
2. The 2205 Duplex Stainless Steel with 18 mils of Foul-Release Coating: steady and minimal average general corrosion rate of 0.04 to 0.08 mils/yr. Minimal to non-detectable pitting was observed. Note that the total mass loss and corrosion rate includes coating material and does not necessarily represent the metal loss only. Marine life/ bio-fouling mostly occurred after 12 months in concentrated locations; probably at areas of coating failure. The SEM scan (Anamet report Figure 5) of the sample indicated degradation of the coating which was likely caused by erosion or abrasion. The EDS spectra of the coating after the cleaning of the sample indicated mostly carbon, oxygen, and silicon which fits the general description of the Sherwin-Williams Sher-Release Seaguard data sheet.

3. The CDA715 (70-30 Cu-Ni): moderate average general corrosion rate ranging between 0.32 mil/yr (plate sample exposed for 364 days) and 0.87 mils/yr (screen sample exposed for 91 days) during the 3-year study, with a steady decreasing trend over time. This study had a lower average general corrosion rate than found in the literature (1.06 mils/yr after 1 year and 1.41 mil/yr after 3 years). Shallow pitting of up to 2.8 mils in 3 years. The 70-30 Cu-Ni samples had less biofouling than other copper alloys after being immersed for 3 years. The biofouling on the surface is more prominent than surface discoloration. The SEM scan (Anamet report Figure 5 and 6) of the metal indicated pits which was likely caused by corrosion. The EDS spectra after the cleaning of the sample indicated mostly copper and nickel at lower concentrations than industry standards which may be due to deposits on the surface. The concentration of chlorides were high due to the seawater exposure.
4. The CDA 706 (90-10 Cu-Ni): highest average general corrosion rate of the 5 materials, ranging between 0.67 mil/yr (coupon sample exposed for 364 days) to 5.08 mils/yr (screen sample exposed for 91 days) during the 12-month study. The sample was secured to the test rack with a plastic zip tie which may have eroded the metal over time and indicates that the alloy has a lower abrasion resistance than the 70-30 Cu-Ni alloy. The material loss especially at the attachment points is probably why this sample was not able to be retrieved after 3 years of immersion.
5. The Z Alloy: high average general corrosion rate ranging between 0.24 mil/yr (coupon and plate samples exposed for 364 days) to 4.5 mils/yr (screen sample exposed for 91 days) during the 12-month study. A sample could not be retrieved after 3 years. The sample was secured to the test rack with a plastic zip tie which may have eroded the metal over time and indicates that the alloy has a lower abrasion resistance than the 70-30 Cu-Ni alloy. The material loss especially at the attachment points is probably why this sample was not able to be retrieved after 3 years immersion.

Flat Plates

1. The average general corrosion rate of the uncoated 2205 Duplex Stainless Steel 4-inch by 4-inch flat plates was the lowest of the four alloys after 364 days of exposure.
2. The greatest amount of biofouling was observed on the uncoated 2205 Duplex Stainless Steel wedgewire screens.
3. The overall average corrosion rate of the 90-10 Cu-Ni flat plates was the highest of the four alloys that were included in this study.
4. The lowest average corrosion rate was measured on the 2205 Duplex Stainless Steel after 364 days of exposure in seawater.
5. In general, the copper alloy plates (70-30 Cu-Ni, 90-10 Cu-Ni, and Z Alloy) indicated higher average overall corrosion rates than the coated and uncoated 2205 Duplex Stainless Steel plates. For example, the average overall corrosion rate of the 90-10 Cu-Ni flat plate is over 100 times greater than the average overall corrosion rate of the uncoated 2205 Duplex Stainless Steel.

RECOMMENDATIONS

Based on the conclusions and experience with similar biofouling and corrosion studies, the following recommendations are presented for WBMWD to consider for seawater exposures:

1. Intake screens should be manufactured with 70-30 Cu-Ni as it would provide a low average general corrosion rate over a long term service life, would not require a foul release coating and will not experience heavy biofouling. The 70-30 Cu-Ni screens would provide less maintenance than the 2205 Duplex SS screens and would be recommended for long term service.
2. The foul-release-coated 2205 Duplex Stainless Steel screens would also provide a long term service based on the results of the study. The coating system provided the best protection against biofouling however the screen would have to be removed and the coating system would need to be touched up every 2 to 5 years as it is not abrasion resistant.
3. If intake screens are manufactured by 2205 Duplex Stainless Steel the following coating should be applied to the screens:
   a. 1st coat - Sherwin Williams Macropoxy 646 PW immersion grade epoxy primer at 6 mils dry film thickness (dft).
   b. 2nd coat - Sherwin Williams Seaguard Sher-Release beige silicone Tie Coat at 6 mils dft.
   c. 3rd coat - Sherwin Williams Seaguard Sher-Release white silicone Surface Coat at 6 mils dft.
4. Foul-release coated screens should be inspected every 2 to 5 years to determine if repairs are required. The foul release coating will need to be removed from immersion service and repaired while the surfaces are dry.