

## **West Basin Municipal Water District Ocean Water Desalination Project**

Literature Review on Long Term Corrosion and Biofouling  
Resistance of Copper Nickel Alloys and Stainless Steels for  
Marine Applications

March 2018





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## **Attachments**

Attachment A Stainless Steel Comparison Table  
Attachment B Dissolution Calculation Memo – Applied Marine Sciences



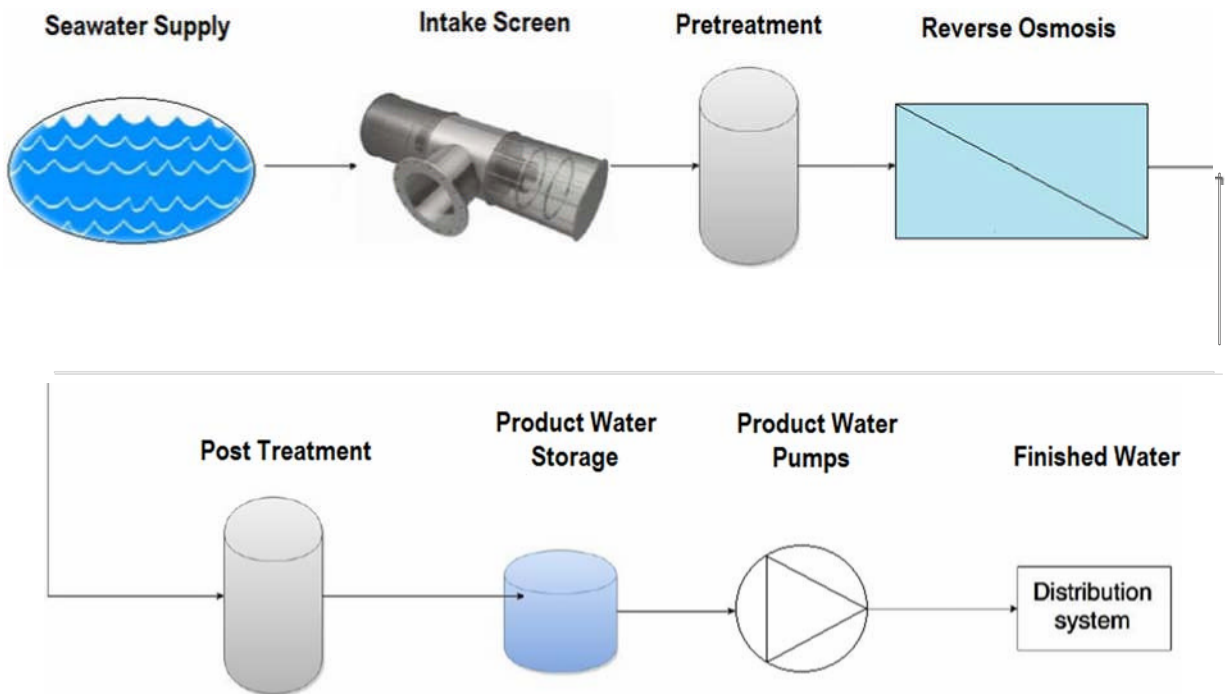


# 1. Introduction

West Basin Municipal Water District (WBMWD) has engaged GHD to undertake a comprehensive literature review on the long-term performance of the copper-nickel (Cu-Ni) alloys 90/10 (UNS No. C70600) and 70/30 (UNS No. C71 500) and duplex stainless steel grade 2205 (UNS No. S31803) as materials of construction for passive seawater intake screens. Super duplex stainless steel grade 2507 is also discussed in this memo, due to its known application for seawater intake screens in industry.

## 1.1 Background

Intake screens have been used as the first step in the seawater reverse osmosis (SWRO) desalination process (see flow diagram in Figure 1) to prevent entraining solids and marine life, and to minimize ecological impact. These screens are typically installed in the epipelagic zone (less than 200 meters, or 656 feet, below mean sea level) where dissolved oxygen, sunlight, and nutrients are relatively abundant. The primary challenges that affect long-term reliability of intake screens are susceptibility of screen materials to various corrosion processes and marine biological growth on screens (i.e. biofouling) (Missimer). Corrosion can adversely affect the structural integrity of the screens and reduces effectiveness of the screening process. Biofouling, particularly macro-biofouling, can restrict flow through the screens and may even affect the structural integrity of screens due to biofoulant weight. For these reasons, special consideration is needed when choosing the screen material to balance resistance to marine corrosion and excessive macro-biofouling with replacement costs.

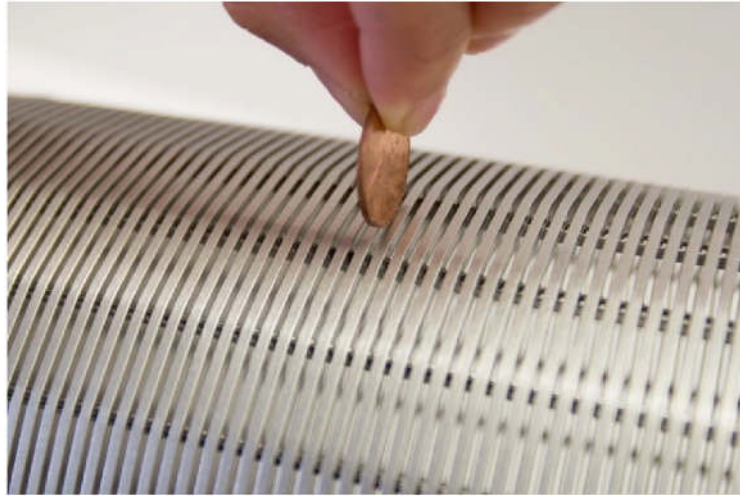


**Figure 1 SWRO Flow Diagram**





This memorandum focuses on the materials used in wedge wire type screens. Wedge wire screens are typically cylindrical metal screens with trapezoidal-shaped “wedge wire” slots with opening sizes ranging between 0.5-10 millimeters (mm, or 0.02 – 0.39 inches). Per California Ocean Plan requirements, the opening size for open ocean intake screens for ocean water desalination must be 1.0 mm (or 0.04 inches) or less (see Figure 2), approximately equivalent to the thickness of a credit card (California Ocean Plan, 2015).



**Figure 2 Wedge Wire Screen with 1-mm (0.04 inch) Openings**

*Note: The openings are smaller than the thickness of a US one cent coin. (Courtesy of West Basin Municipal Water District)*

In January of 2016, WBMWD Successfully completed their Intake Biofouling and Corrosion Study (IBCS) at their SEA Lab Facility in Redondo Beach, California. The IBCS compared several grades of copper-nickel alloy and duplex stainless steel for use in wedge wire intake screens as a first step to further our understanding of the corrosion characteristics of these materials with different geometries, for deployment in Santa Monica Bay for an ocean water desalination application. These materials have been used successfully in marine environment. The following sample geometries were tested:

- Coupons, small plates of materials tested to simulate corrosion and biofouling characteristics of the main stem and other supporting structures of a wedge wire screen; and
- Screens with openings of 2 mm to simulate corrosion and biofouling characteristics of the screened portion of a wedge wire screen.

This study was conducted over a 12-month period between 2014 and 2015, and provided important data to characterize the short-term biofouling and corrosion characteristics of the candidate materials with different geometries.





### 1.1.1 Significant Findings from the ICBS

- Pitting and general corrosion were the primary mechanisms of corrosion on the coupons
- Based on 364 days of data, coated and uncoated 2205 Duplex Stainless Steel samples had the lowest overall average corrosion rates of all of the alloys tested, however uncoated 2205 Duplex Stainless Steel samples were most heavily fouled by marine life.
- The highest pitting rate of 11.5 mils<sup>1</sup> per year (mpy) was observed on the 90/10 Cu-Ni coupons followed by 1.6 mpy pitting rate on the 70/30 Cu-Ni coupons.
- In general, the copper-nickel alloy plates indicated higher average overall corrosion rates than the 2205 Duplex Stainless Steel Plates.
- All of the copper-nickel samples appeared to be performing well at deterring the settlement of macrofouling organisms and were relatively clean of fouling.
- The uncoated 2205 Duplex Stainless Steel wedge wire sample and coupon have shown no antifouling properties and have about the same degree of fouling (species composition and growth) as the PVC racks.
- The SS samples that were painted with the foul-release coating had considerably less attached fouling than the uncoated samples, and were almost as clean as the Cu-Ni samples.
- The following recommendations were made based on the conclusions and experience with similar corrosion studies
  - Intake screens should be manufactured with 70/30 Cu-Ni as it would provide the lowest corrosion rate over a long-term service life and would not require a foul release coating.
  - Intake screens manufactured in 2205 Duplex Stainless Steel are recommended if they are coated with a foul-release coating.
  - Biofouling results also indicate that the 70/30 Cu-Ni material is superior to the other materials tested to prevent biofouling.
  - If 2205 Duplex Stainless Steel with a foul-release coating is used it will need to be inspected on a regular basis and no longer than 5 year intervals.

## 1.2 Purpose

This memorandum supplements the findings of the ICBS with a literature review and summary focusing on the suitability of copper-nickel alloys 90/10 and 70/30, and stainless steel grades duplex 2205 and super duplex 2507 as construction materials for intake screens given long-term deployment in the marine environment. Several typical corrosion and fouling mechanisms are discussed for metals in seawater and a comparison of each material based on these mechanisms is provided.

<sup>1</sup> 1 mil = 0.001 inch or 0.0254 millimeter



## 13 Methodology

A wide variety of references including texts and published articles on the performance and behavior of these alloys in the seawater environment have been reviewed. The goal is to provide a guide for the project team in the evaluation and use of these alloys in marine environments for a long-term exposure period. The following sources were consulted:

- Corrosion reference handbooks;
- Scientific magazines i.e. NACE, IDA and relevant Elsevier journals;
- Relevant technical articles from international/national conference proceedings;
- Publications published by reputable organizations, e.g. US Department of Defense and other international associations; and
- National and international standards.

This memorandum is fully referenced to allow quick access to the relevant literature. It is understood that the documents referenced have been peer reviewed and are therefore considered accurate.

# 2. Discussion

## 2.1 Corrosion Mechanisms

The open ocean tends to be a particularly corrosive environment (for common metallic components) having high concentrations of dissolved chloride and other corrosive dissolved solids, and high oxygen concentrations. A number of factors can influence corrosion rates in metallic materials that are being considered for the intake screens, including the chemical composition of materials, fabrication techniques, surface condition, and design. Major mechanisms of corrosion that might affect intake screens are discussed below. There is some overlap between the categories of local corrosion as will be evident in the paragraphs below. Therefore, it is less important to categorize the local corrosion than it is to understand the mechanisms involved to prevent failure due to corrosion.

### 2.1.1 General Corrosion

General corrosion is defined as a type of corrosion attack that is more or less uniformly distributed over the entire exposed surface of a metal. All of the materials discussed in this review form protective coatings<sup>2</sup> when exposed to dissolved oxygen in seawater and, thus, are resistant to general corrosion (Sch tze, Roche, & Bender, 2016).

<sup>2</sup> Chromium in stainless steels develops a passive protective chromium oxide layer when it is exposed to oxygen. Copper in copper-nickel alloys also develops a passive protective copper oxide layer when exposed to oxygen.



## **2.1.2 Local Corrosion**

### ***Dissimilar Metals/Galvanic Corrosion***

Galvanic corrosion is generally defined as the preferential corrosion of one metal in electrical contact with another, with the aid of an electrolyte. With due care taken at installation this is not anticipated to be an issue, as the screens will not be in contact with dissimilar metals.

### ***Crevice Corrosion***

Crevice corrosion (sometimes considered a subset of under deposit corrosion) results when local differences in oxygen concentration occur at a metal surface, typically associated with small pockets of stagnant water in voids. These voids can exist with deposits on the metal surface, such as foulants or with small pockets around welding irregularities on the wedge wire screens (i.e. coarse ripples, grooves, overlaps, abrupt ridges, undercuts and valleys). A differential aeration cell is established between the oxygenated seawater at the external surface and the oxygen deficient water in the crevice. This causes the metal surface within the crevice to become anodic, promoting corrosion. Hydrolysis of metal ions in the crevice causes an acidic environment further contributing to corrosion. It is necessary that the crevice is large enough to allow the entry of the corrosive solution (i.e. salt water) and narrow enough to form a stagnant state where diffusion of oxygen into the crevice is restricted. The opening of the crevice is generally of the order of 50–200  $\mu\text{m}$ . The narrow space present between two metals is a favorable site for crevice corrosion (Sastri, 2015).

Crevice corrosion can be largely avoided with proper component design and proper installation, (e.g. surface preparation, welding, etc.).

### ***Pitting Corrosion***

Pitting corrosion commonly occurs when the protective passivating film breaks down in small isolated spots on a metals surface. Pitting corrosion is typically associated with high chloride concentration as found in seawater. Similar to crevice corrosion, a contributing factor is the spot becoming anodic. Pitting is a form of extremely localized corrosion that leads to the creation of pinpoint holes in the metal. The corrosion penetrates the metal, with limited diffusion of ions, further amplifying the localized lack of oxygen. Pits can grow in size from those that are difficult to detect with the naked eye to those with a diameter and depth that can be measured in millimeters. Alloys resistant to pitting corrosion are typically resistant to other types of local corrosion attack as well, due to the similar mechanism of corrosion (Féron, 2007).

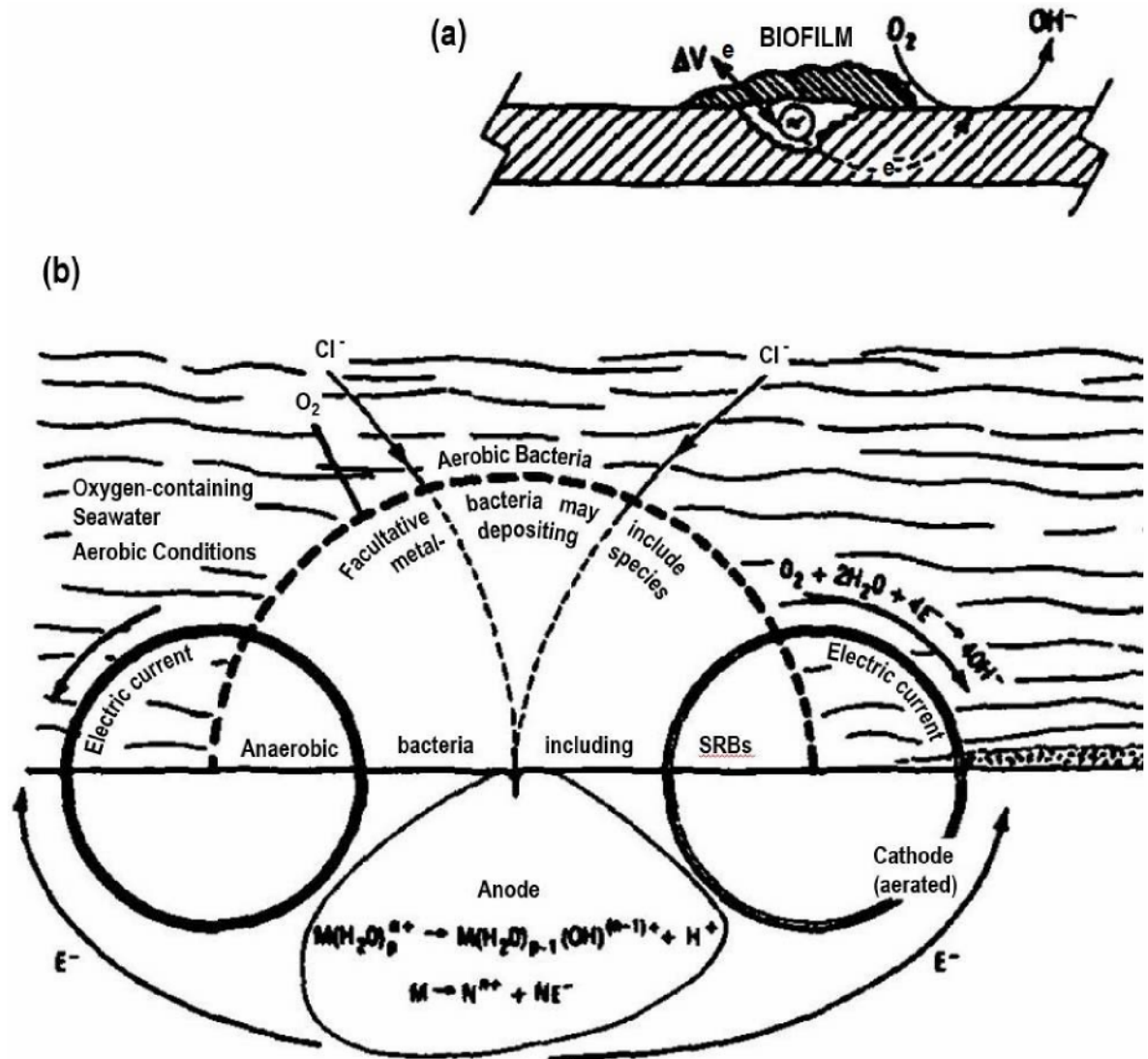
### ***Under Deposit Corrosion***

Deposits of material on wedge wire screens provide electrochemical conditions that favor corrosion and possibly additional deposition. The material that forms these deposits can be inert/non-reactive, microbiological, or larger biological species, such as barnacles or mussels. The deposit leads to the formation of differential aeration cells on the metal surface as a result of a patchy distribution of hard deposits. In the worst cases, under-deposit corrosion causes deep pitting (Desalination of Seawater, Manual of Water Supply Practices).

### ***Microbially Induced Corrosion (MIC)***

A great variety of microorganisms are present in natural aqueous environments such as bays, harbors, coastal seawaters, and open ocean, which have an affinity to attach to hard solid surfaces

and develop biofilms (Sastri, 2015). Biofilms deplete localized oxygen under the film and can cause differential aeration, selective leaching, under-deposit corrosion, and cathodic depolarization. Figure 3 below provides an illustrative example of microbially induced under-deposit corrosion and oxygen concentration cells (Little, Wagner, Ray, & McNeil, 1990).



**Figure 3 Example of a Microbially Induced Differential Aeration Cell**

(a) Differential aeration cell formed by microbial colonies. (b) Detailed reactions resulting from the formation of a differential aeration cell.

In addition to creating a biofilm on the metal surface, microorganism's metabolic processes often accelerate corrosion by generating corrosive by-products. This results in corrosion of the metal, forming a pit or crevice beneath the biofilm area. All proposed intake screen materials have been reported to undergo MIC to some extent, but research indicates copper-nickel fouls at a rate slower than stainless steel, and there is less biological diversity on copper-nickel surfaces in identical conditions (Little, Wagner, Ray, & McNeil, 1990). Not all MIC that can occur in oxygen saturated



seawater is aerobic. Although the open ocean is oxygen saturated in normal conditions anaerobic microorganisms can survive in anaerobic microniches until suitable conditions become available, such as within a biofilm, where oxygen quickly depletes (Little, Wagner, Ray, & McNeil, 1990).

### ***Biofouling Mechanisms***

Biofouling can be separated into two categories, micro-biofouling and macro-biofouling. Micro-biofouling in seawater generally consists of adhesion of marine bacteria, microalgae, protozoa, and their cellular exudates, and the formation of a slime layer, or biofilm, which can be accompanied by MIC (see previous section) (Little, Wagner, Ray, & McNeil, 1990). Macro-biofouling is caused by the growth and colonization of large organisms, such as sessile organisms (e.g. barnacles, bivalve mollusks, tunicates, and calcareous red or green algae), on metal surfaces. Seawater flowing through the intake screen slots promotes attachment and rapid growth of these sessile organisms, which can result in under deposit corrosion. Metabolites secreted by these organisms may also contribute to the corrosion process. Biofouling on intake screens and support structures has serious implications in the performance of intake screens and can impede flow, contribute to corrosion, and may cause permanent structural damage due to the load (Missimer).

## **2.2 Intake Screen Materials**

Copper-nickel alloy and duplex stainless steel are the most common materials used for seawater contact applications, with titanium alloys and super duplex stainless steels being more expensive alternatives applied in specialized cases (Voutchkov, 2017). This review focuses on copper-nickel alloys and 2205 duplex stainless steel, with consideration of super duplex 2507, building on the findings of the ICBS.

### **2.2.1 Copper-Nickel Alloys**

Copper-nickel alloys have been used in seawater service with success since around 1940. These alloys are less susceptible to fouling in seawater than stainless steels (Schumacher, 1979). As early as 1962, it was determined from observations gained during service on ships that both 90/10 and 70/30 alloys have a service life of greater than 20 years (Lague & Tuthill, 1962).

Copper-nickel alloys are composed primarily of copper with nickel and small amounts of strengthening elements, including iron and manganese, making up the remainder. Copper-nickel alloys 90/10 (10% nickel) and 70/30 (30% nickel) are widely used for seawater applications (Féron, 2007). Cu-Ni 70/30 is stronger with greater resistance to flow erosion, but 90/10 is suitable for most applications and is more widely adopted due to lower cost. The proposed alloys compositions are shown in Table 1.

**Table 1 Copper-Nickel Alloys Composition (Weight %)**

	Copper-Nickel 70/30	Copper-Nickel 90/10
Ni	29.0 - 32.0	9.0 - 11.0
Fe	0.5 - 1.5	1.0 - 2.0
Mn	0.4 - 1.0	0.3 - 1.0
Cu	remaining	remaining



Copper and nickel are closely related and have similar atomic radii and lattice parameters. They are wholly miscible in both liquid and solid state. . At all temperatures and concentrations, copper–nickel alloys crystallize in a single-phase face-centred cubic structure, which provides very good ductility and impact strength even at low temperatures. The absence of phase transformation during thermal cycles reduces the effect of welding on mechanical characteristics and increases the localized corrosion resistance of the alloy (Féron, 2007).

Increasing the nickel content of the alloy provides increased strength and corrosion resistance, which needs to be balanced with decreasing thermal and electrical conductivity. Additionally, the solubility of iron, which further improves corrosion resistance, increases with nickel content before falling off at nickel weight percent exceeding 30%. The addition of manganese improves casting characteristics and increases strength by immobilizing sulfur as manganese sulfide. Sulfur impurities, common in refined copper, can cause major issues with hot forging<sup>3</sup> (Copper-Nickel Alloys: Properties, Processing, Applications).

One of the main issues causing failure of copper-nickel is incorrect chemical composition of the alloy. During the alloying process, nickel diffuses slowly into copper leading to concentration gradients in the melt. Hot or cold forging followed by a re-crystallization anneal homogenizes the structure allowing more uniform development of the oxide layer leading to higher local corrosion resistance (Féron, 2007).

Incorrect fabrication is another major contributing factor to premature failure of copper-nickel alloys. Copper-nickels are readily welded by most conventional processes. Gas-shielded Tungsten Arc (TIG or GTAW) welding and Manual Metal Arc (MMA, SMAW) welding are common methods used by manufacturers for wedge wire intake screens using copper-nickel. The key requirement is correct preparation. Particular attention needs to be given to cleanliness and the use of fuels with low sulfur content, during welding or any heat treatment (Copper-Nickel Alloys: Properties, Processing, Applications).

### ***Significance of the Cuprous Oxide Layer***

The seawater corrosion resistance offered by copper-nickel is the result of a complex thin protective surface film that quickly and organically forms when exposed to clean oxygen saturated seawater. It is well established that the film is primarily composed of cuprous oxide ( $\text{Cu}_2\text{O}$ ), often containing nickel and iron oxide, cuprous hydroxyl-chloride and cupric oxide (North & Pryor, 1970) (Milosev & Metikos-Hukovic, 1992) (Shibad, Singh, & Gadiyar, 1989). Initial exposure to clean oxygen saturated seawater is crucial to the long-term performance of copper-nickel alloys.

The behavior and protection mechanism of the copper-nickel in marine environments have been the subject of many detailed studies under various conditions, i.e. differing flow velocities, temperatures, pH values, compositions of seawater, and many other factors. Compounds in seawater react with the products of copper-nickel corrosion to build a multi-layered structure of copper containing molecules (Kievits & Ijsseling, 1972). Iron in copper-nickel alloys increases the electronic resistance of  $\text{Cu}_2\text{O}$ , which increases the protective nature of the passive film. Iron and nickel are incorporated into the cuprous oxide film occupying cation vacancies, which increases corrosion resistance (North & Pryor, 1970). Chloride ions in seawater adsorb on the film occupying oxygen vacancies and contribute to passivation of copper-nickel alloys (Mathiyarasu &

<sup>3</sup>Forging (hot, warm, or cold) is a metal-forming process involving shaping of metals using localized compressive forces.

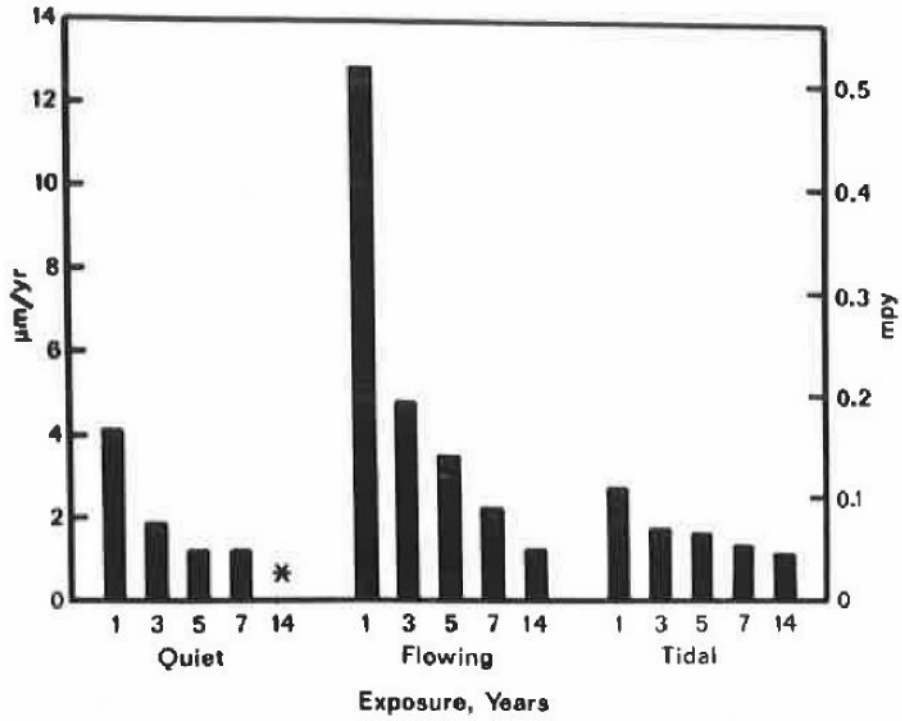


Muralidharan, 2000). As these processes proceed, the corrosion rate quickly decreases, as much as 10-fold in the first 10 minutes and 100-fold in the first hour (Tuthill, 1988). While the corrosion slows rapidly, it can take between two to three months for the film to fully mature at temperatures between 15-17 °C (Kievits & Ijsseling, 1972) (Tuthill, 1988). Further research supports that maturation of the film can occur more quickly at higher temperature (Materials Selection, 2002) (Jasner, Hect, & Beckam, 1998) (Tuthill, Todd, & Oldfield, 1977). Some of the copper ions are not incorporated into the cuprous oxide layer and these are precipitated as  $\text{Cu}_2(\text{OH})_3\text{Cl}$  (Pollard, Thomas, & Williams, 1989).

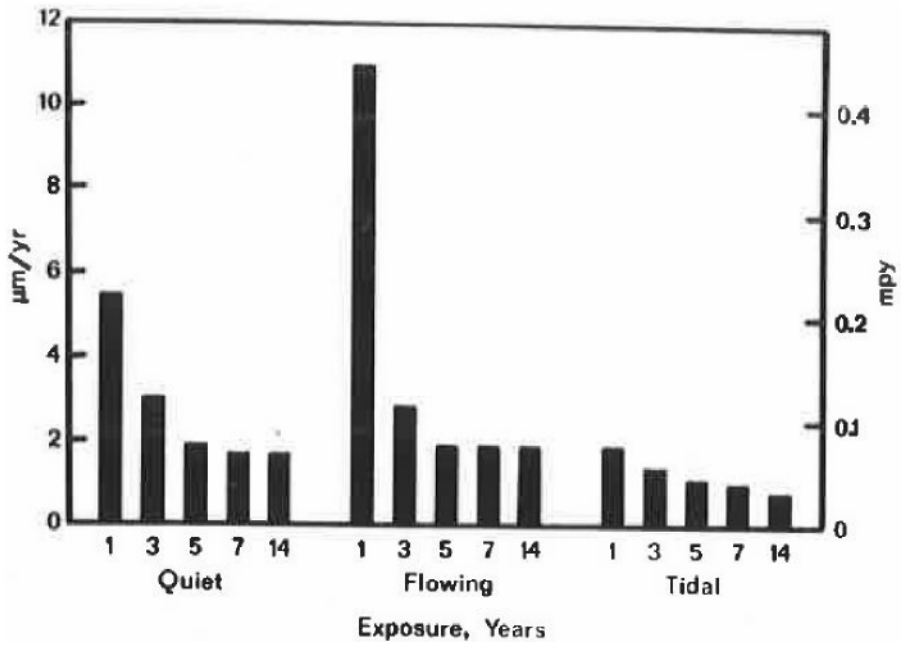
In large part due to the formation of the cuprous oxide layer, copper-nickel alloys in seawater can be expected to exhibit excellent corrosion resistance. Given clean seawater and the formation of a good surface film, the rate of corrosion will continue to decrease. Under normal circumstances, initial corrosion rates may be as high as 20 micrometers per year ( $\mu\text{m}/\text{year}$ ) for several minutes or hours, but will quickly diminish (Féron, 2007). A steady-state corrosion rate of approximately 1-2  $\mu\text{m}/\text{year}$  will then be established (Jasner, Hect, & Beckam, 1998) (Powell & Michels, 2000) (Johnsen, 1989). The average change in corrosion rates over a 14 year exposure period for both Cu-Ni 90/10 and 70/30 alloys are shown in Figure 4 and Figure 5, respectively (Efird & Anderson, 1975).

In one example, exposure to low velocity, quiescent seawater for 14 years indicated corrosion rates under 2.5  $\mu\text{m}/\text{yr}$  (0.1 mpy) for both Cu-Ni 90/10 and 70/30 (Efird & Anderson, 1975). Sixteen-year tests further confirmed this same low corrosion rate (Southwell, Bultman, & Alexander, 1976). This corrosion rate is equivalent to metal dissolution rates of 6.2 micrograms per square centimeter per day ( $\mu\text{g}/\text{cm}^2/\text{d}$ ) (Michel, Powell, & Michels, 2011). A technical memorandum (TM) was produced to provide an order of magnitude estimate of the potential concentration of copper in the water column from dissolution of copper from copper-nickel wedge wire screens using a long term, steady-state corrosion rate. The TM is provided as Attachment B and is summarized below in the subsection, *Dissolution Estimate of Copper Ions for the West Basin Ocean Water Desalination Project*.

The sequence of passive film formation on the proposed copper-nickel alloys is shown schematically in Figure 6 (Michel, Powell, & Michels, 2011). An over layer of cupric hydroxyl-chloride often forms on these alloys during secondary corrosion reactions forming a top oxide layer. This layer is not toxic and is more readily fouled, but the fouling is readily removed and sloughs off easily. Cu-Ni 90/10 and Cu-Ni 70/30 were equally resistant to fouling (Schumacher, 1979).

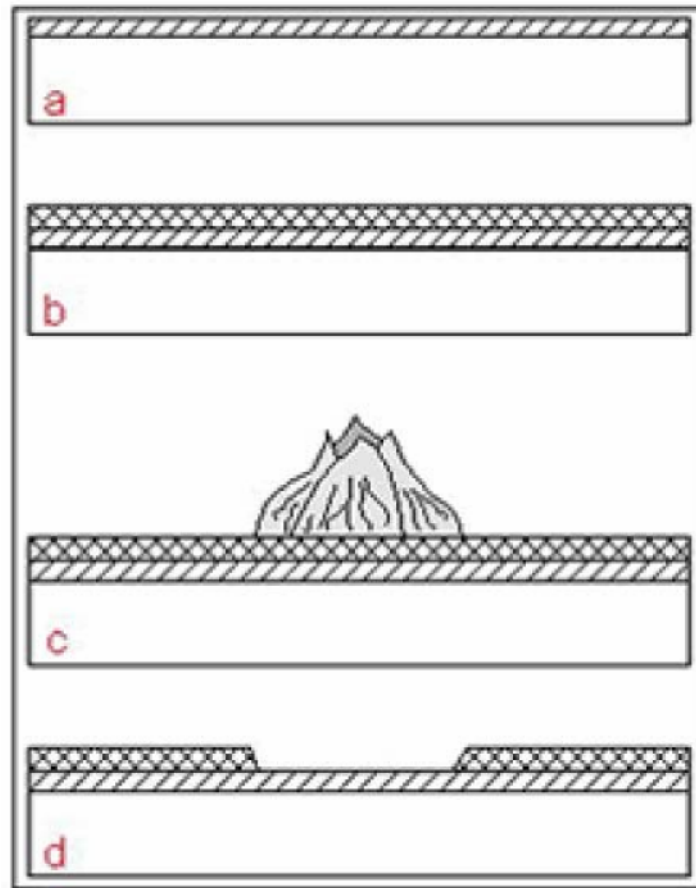


**Figure 4 Change in corrosion rate with time for 90/10 Cu-Ni in quiet, flowing and tidal zone seawater**



**Figure 5 Change in corrosion rate with time for 70/30 Cu-Ni in quiet, flowing and tidal zone seawater**





**Figure 6 Prevention of Fouling by Cuprous Oxide Film**

*a) Initial formation of protective cuprous oxide film (establishment of fouling is prevented by release of cuprous ions), b) Establishment of non-toxic top layer, c) Settlement of the surface by fouling organisms, d) Removal of fouling organisms leaving the protective  $Cu_2O$  film intact (Michel, Powell, & Michels, 2011)*

Some specialists are of the opinion that copper alloys do not need antifouling protection due to the release of copper ions and the structure of oxide layers that are established during natural corrosion processes (Féron, 2007). The mechanism is not yet fully understood and one thought is it could be partially linked to copper ion release from the complex protective surface film plus effect of the nature of the surface film itself. Releasing the copper ions does not necessarily mean that it will adversely affect the environment.

General experience with copper–nickel in open seas has shown micro-biofouling does not typically build up sufficiently to support macrofouling. Calm conditions for extended periods can result in some loosely attached macrofouling that will slough away during more turbulent intervals or can be easily removed with light pressure (Efird, 1976) (Manzoliillo, Thiele, & Tuthill, 1976) (Boulton, Hudson, & Powell, 1999) (Powell & Michels, 2000). In worst cases, divers may need to manually clean the screens periodically.



***Dissolution Estimate of Copper Ions for the West Basin Ocean Water Desalination Project***

This section presents the results of the TM, Attachment B, developed to estimate the dissolution of copper ions from potential copper-nickel wedge wire screens and compare them to Water Quality Objectives outlined in the California Ocean Plan (California Ocean Plan, 2015). The California Ocean Plan specifies the following copper objectives for protection of marine aquatic life, outlined in Table 2:

**Table 2 California Ocean Plan Water Quality Objectives for Copper**

Objective	Units	6 Month Median	Daily Maximum	Instantaneous Maximum
Copper	µg/L	3.	12.	30.

Calculations performed in the TM use the West Basin Desalination Project as an example, with an intake flow of 45.3 MGD through four screens for the Local Project. An estimated surface area for a wedge wire screen was provided by Hendrick Screen Company. Steady-state corrosion rates used for 70/30 and 90/10 Cu-Ni were 2.03 µm/yr and 1.27 µm/yr respectively (Efird & Anderson, Mater. Perform., 1975). The results are presented in Table 3. Note that for this example, the number of screens correlates closely with the intake flowrate, such that increasing the number of screens does not increase the mean concentration of copper due to the coinciding higher flow.

**Table 3 Estimate of Copper Dissolution from Wedge Wire Screens**

Screen Composition	Corrosion Rate (µm/yr)	Mean Concentration (µg/L)
90/10 Cu-Ni	1.27	0.03
70/30 Cu-Ni	2.03	0.05

Source: Attachment B

As corrosion is generally a slow and steady chemical process (though it decelerates relatively quickly in copper-nickel after the development of the protective oxide layer), the 6 Month Median concentration is likely the most representative objective with which to compare. The mean concentrations for all scenarios presented in Table 3 are well below the objective. These results are particularly conservative as no copper speciation or precipitation as  $Cu_2(OH)_3Cl$  was considered.

**2.2.2 Duplex Stainless Steels**

Stainless steels have been used as construction materials in marine environments for many decades. Duplex stainless steels typically contain approximately 21-25% chromium, 5-7% nickel, 3-4% molybdenum and nitrogen, with 2205 duplex stainless steel being on the lower end of each weight percent and 2507 super duplex being on the higher end. Compared to austenitic stainless steels (e.g. 304 or 316) duplexes have higher yield strength and greater stress corrosion cracking resistance to chloride.

Ordinary steel is composed of carbon and iron. Stainless steel is characterized by the addition of chromium in weight percent greater than 10.5%. The chromium in stainless steel provides a



protective passive layer in the presence of oxygen that is self-healing and prevents rusting, when intact. Deposits can prevent the formation of a continuous passive film. Nickel improves general corrosion resistance and formability, and molybdenum and nitrogen further enhance resistance to localized corrosion.

For stainless steels, resistance to pitting corrosion is rated using a pitting resistance equivalent number (PREN)-with the higher the PREN, the higher the resistance to pitting corrosion. Equation 1 shows how the PREN is calculated where element contents are given in weight percent (External Corrosion- Introduction to Chemistry and Control).

$$\text{PREN} = \%Cr + 3.3(\%Mo) + 16(\%N) \quad (\text{Eq 1})$$

Table 4 provides PREN values for materials commonly used in water treatment and SWRO facilities. Stainless steel alloys containing a higher percentage of molybdenum are known to have better resistance to corrosion in marine environments (Missimer).

**Table 4 PREN Values for Common Materials (Weight %)**

Type	Material	UNS Number	PREN
Austenitic	304 L	S30403	18-20
	31 6L	S31603	24-28
	31 7L	S31 703	29-31
	904L	N08904	35-36
Super Austenitic	AL-6XN	N08367	47-48
	254 SMO	S31254	43-46
Duplex	2205	S32205	35-37
	329	S32900	34
Super Duplex	SAF2507	S32750	42
	Zeron 100	S32760	≥ 40 (42)
Austenitic Nickel-based	Alloy 20 (20Cb-3)	N08020	31
	Hastelloy C-276	N10276	68
	Hastelloy C-22	N06022	65

Typical duplex stainless steel used in desalination should have a PREN of 40 or more and when in constant contact with seawater, a PREN of 42 or more is recommended (Desalination of Seawater, Manual of Water Supply Practices). As indicated previously in Table 4, 2205 duplex stainless steel has a PREN of 35-37. Super duplex 2507, with a PREN of 42, is the stainless steel alloy most commonly used for long-term continuous submersion in seawater. This is supported by the application of super duplex 2507 in numerous seawater desalination plant settings.

All grades of stainless steel are susceptible to marine organism growth, and higher-grade stainless steel has no apparent beneficial impact on resistance to biofouling. Amending stainless steel with copper is one avenue of investigation currently being considered to help curb biofouling (Missimer). Stainless steel intake screens will require frequent cleaning to remove biofouling.



## 3. Findings

### 3.1 Comparison of Long-Term Corrosion Resistance

In short, copper–nickel alloys have good resistance to pitting and crevice corrosion in seawater (Féron, 2007). Stainless steels are more susceptible to crevice corrosion and deposit attack. The hydrolysis reaction of iron and subsequent acid formation within the crevice produces a change in pH and chloride concentration in the crevice environment. Resistance to crevice corrosion in stainless steel is increased by increasing the content of molybdenum and nitrogen (External Corrosion- Introduction to Chemistry and Control).

Stainless steels tend to be more prone to pitting corrosion due to their passive oxide film, which when damaged or poorly applied, can lead to initiation of a pit. Flowing seawater keeps the surface uniformly aerated and passive, and reduces potential for localized corrosion (Corrosion, 1987). Attachment of foulants increases the chance for corrosion by shielding the surface from oxygen. Pitting and under deposit corrosion are not normally a problem for copper–nickel alloys in seawater due to their superior resistance to fouling, and particularly macro-biofouling (Schumacher, 1979) (Féron, 2007).

Given anaerobic conditions, stainless steels are susceptible to MIC by iron and manganese bacteria, and sulfur reducing/oxidizing bacteria (Desalination of Seawater, Manual of Water Supply Practices). Copper–nickel alloys are subject to some types of microbiologically influenced corrosion, most commonly in the presence of sulfate reducing bacteria (Corrosion, 1987). Though these bacteria thrive in an anaerobic environment, and seawater in the epipelagic zone is typically oxygen rich, oxygen quickly depletes within a biofilm if aerobic respiration is greater than the oxygen diffusion rate and conditions can become anaerobic at the metal/biofilm interface (Little, Wagner, Ray, & McNeil, 1990).

The Burrup Peninsula SWRO desalination plant in Australia provides water to local urban areas. The plant was placed into full operation in 2004. The intake screen had an aperture spacing of 300 mm and was made of copper-nickel alloy 70/30 to reduce marine growth and minimize the requirement for screen cleaning by divers. Since operation in service no corrosion or fouling failure has been reported so far (Blair L Shackleton 2017<sup>4</sup>).

### 3.2 Comparison of Long-Term Biofouling Resistance

Copper-nickel alloys inherent resistance to biofouling due to development of the cuprous oxide thin film protective layer is well supported (Abdul Azis, 2003) (Schleich & Steinkamp, 2003).

Recent results from three and eight year exposure trials on coupon samples at the Marin Municipal Water District pilot desalination plant in San Francisco Bay and Langstone Harbour, UK, respectively, confirm that colonization of fouling species is restricted on copper-nickel alloys which remained largely free of macrofouling. Where macrofouling is present it is loosely attached and sloughs off fairly readily, particularly in the presence of flows greater than 0.5 m/s (Missimer).

<sup>4</sup> [Blair.Shackleton@ghd.com](mailto:Blair.Shackleton@ghd.com), GHD WA Market Leader - Water



It is now widely accepted that biofilm growth causes oxygen reduction depolarization on stainless steel in seawater. This can lead to:

- Increase the likelihood of the onset of localised corrosion as a result of the ennoblement of the free corrosion potential of the alloy in the passive state, and
- Speed up the propagation rate of ongoing localised corrosion (active state).

The common finding was that much more corrosion resistant stainless steels (i.e. PREN  $\geq$  42) are required for intake screens, which are immersed for extended periods. Biofilm presence on the surface of stainless steel is a key factor in reduction of corrosion resistance of several alloys in seawater.

## 4. Conclusions

The literature indicated copper-nickel alloys have a unique combination of good resistance to both corrosion and biofouling in marine environments. The main reasons for premature failure of copper-nickel alloys in seawater are associated with incorrect chemical composition, and improper fabrication and installation techniques for intake screens.

2205 duplex stainless steel is resistant to marine corrosion, but more expensive higher grade stainless steels with higher PREN's, such as duplex 2507, are recommended by the literature for long-term submersion in the marine environment. Additionally higher-grade stainless steels were found to have no significant impact on preventing biofouling on the surface of the screen and require regular cleaning. A summary of the findings is provided in Table 5.

**Table 5 Performance Summary of Proposed Intake Screen Materials**

Material	General Corrosion	Localized Corrosion (Pitting and Crevice)	Marine Fouling
Cu-N i-90/10	Good	Fair to good	Good
Cu-N i-70/30	Good	Good	Good
2205 Duplex Stainless Steel	Good	Fair	Poor
2507 Super Duplex Stainless Steel	Good	Good	Poor



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# Attachments





## Attachment A Stainless Steel Comparison Table

Type	Material	UNS No.	Cr%	Ni%	Mo%	N%	Other	PREn	Cost Factor
Austenitic	304L	S30403	18	8	-	-	-	1820	0.9
	201LN	S20153	17	4.5	-	0.2	7.0 Mn	23	NA
	316L	S31603	18	12	2.2	-	-	2428	1.0
	317L	S31703	19	13	3.2	-	-	2931	1.3
	904L	N08904	20	25	4.5	-	-	3336	2.0
Super Austenitic	254 SMO	S31254	20	18	6.1	-	-	4346	2.1
	AL6XN	N08367	20	25	6.3	0.2	-	4248	2.4
Duplex	LDX 2101	S32101	21	1.5	0.45	0.22	5 Mn	29	NA
	329	S32900	28	4.5	1.5	-	2 Mn	34	NA
	2205	S32205	22	5	3	0.15	-	3638	1.0
Super Duplex	SAF2507	S32750	25	7	4	-	-	42	1.5
	Zeron 100	S32760	25	7	3.5	0.22	0.7 Cu, 0.7 W	4042	1.5
Austenitic Nickel-Based	Alloy 20 (20 Cb3)	N08020	19	32.5	2	-	3 Cu	2831	3.1
	Altemp 625	N06625	22	60	9	-	3.5 Nb+Ta	51	NA
	Hastelloy C276	N10276	16	57	16	-	1.3 Co, 3.8 W	6668	7.0
	Hastelloy C22	N06022	22	59	13	-	2.5 Co, 3 W	6570	7.0





# **Attachment B Dissolution Calculation Memo – Applied Marine Sciences**

***Dissolution Estimate of Copper: Nickel Corrosion from Wedgewire Screens; West Basin Ocean Water Desalination Project***  
*Prepared by Applied Marine Sciences*  
*3/13/18*

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**Background:**

Water quality objectives in the California Ocean Plan call for maximum copper concentrations of 3 µg/L (6-month median), 12 µg/L (daily maxima), and 30 µg/L (instantaneous maxima). The proposed West Basin Ocean Water Desalination Local Project may consist of up to 4 Wedgewire screens drawing up to 45.3 million gallons of seawater per day (MGD) for the Local Project or up to 12 Wedgewire screens drawing up to 136.2 MGD for the Regional Project. In either case, the Wedgewire screens would consist of a 90:10 or 70:30 copper:nickel (Cu-Ni) alloy. In the following technical memo, the methodology and results from a thought experiment to estimate the relative magnitude concentration of copper that would potentially be lost to the environment during corrosion of Wedgewire screens is performed for the Local and Regional Project proposals. It should be acknowledged that the intent of this dissolution estimate was solely to obtain an order of magnitude estimate of copper concentration that would potentially be lost into the water column. The information contained within this document should not be applied beyond specific assumptions used to conduct the thought experiment as it was not designed nor is it intended to be an extensive evaluation or estimate of metal loss or corrosion of a wedgewire screen under ocean conditions.

**Methodology:**

A commonly used calculation to determine the corrosion rate (CR) of a metal has been solved for the weight loss of the metal as a function of corrosion rate, metal density, and exposed surface area (Equation 1). The loss of metal per screen per year was subsequently multiplied by the number of screens and divided by the number of days in a year to give the total metal loss (Equation 2). This total metal loss was divided by the flow rate to give the mean concentration (Equation 3). In order to do the last calculation, the units were converted from gal to L for comparison to copper objectives in the Ocean Plan. Note that two key assumptions underlie the following estimates: 1) the calculation method assumes total concentration loss, and does not distinguish between ionic forms; and 2) since instantaneous corrosion rates were unavailable, the instantaneous concentration was determined by simply converting the estimated daily mean to seconds.

*Equations:*

$$\text{weight loss, } \frac{g}{yr} = \left( \text{corrosion rate, } \frac{cm}{yr} \right) \times \left( \text{metal density, } \frac{g}{cm^3} \right) \times \left( \text{surface area, } cm^2 \right) \quad [1]$$

$$\text{total weight loss, } \frac{g}{d} = \left( \text{weight loss, } \frac{g}{yr} \div 365 \right) \times \left( \text{number of screens} \right) \quad [2]$$

$$\text{mean concentration, } \frac{g}{L} = \left( \text{total weight loss, } \frac{g}{d} \div \text{flow, } \frac{G}{d} \right) \times (1/3.7854) \quad [3]$$

**Table 1. Constants Used in Calculations**

Parameter	Value	Unit	Source
Corrosion Rate [CR] 90:10	0.000127	cm/yr	<sup>2</sup>
Corrosion Rate [CR] 70:30	0.000203	cm/yr	<sup>2</sup>
Exposed Area	415244.33	cm <sup>2</sup>	Client obtained from Hendrick Screen Company
Density 90:10	8.9	g/cm <sup>3</sup>	<sup>3</sup>
Density 70:30	8.95	g/cm <sup>3</sup>	<sup>4</sup>
Flow Rate - Local	45.3	MGD	Client obtained from SPI
Number of Screens - Local	4	Screens	Client obtained from SPI
Flow Rate - Regional	136.2	MGD	Client obtained from SPI
Number of Screens - Regional	12	Screens	Client obtained from SPI

**Example Calculation for 90:10 Alloy at 45.3 MG per day flow rate for Four Screens**

Weight loss per screen = 0.000127 x 8.9 x 415244.33 = 469.4 g / yr

Weight loss for 4 screens = 469.6 x 4 = 1877.6 g/yr ÷ 365 = 5.14 g/d

Mean concentration = 5.14 / (45.3 x 10<sup>6</sup> x 3.7854) = 2.99 x 10<sup>-8</sup> g/L x 10<sup>6</sup> = 0.030 µg/L

**Results**

Number of Screens	Screen Composition (Cu:Ni)	Flow Rate (Gallons per d)	Mean Concentration of Cu-Ni Alloy (µg/L)	Instantaneous Concentration of Cu-Ni Alloy (µg/L/sec)
4	90:10	45.3 x 10 <sup>6</sup>	0.03	0.0000003
4	70:30	45.3 x 10 <sup>6</sup>	0.05	0.0000006
12	90:10	136.2 x 10 <sup>6</sup>	0.03	0.0000003
12	70:30	136.2 x 10 <sup>6</sup>	0.05	0.0000006

In comparison to the 3 µg/L copper water quality objective, the estimated daily mean concentration of Cu:Ni alloy lost through corrosion in either the 4 screen or 12 screen scenarios are approximately one hundred times smaller. Since no information on instantaneous corrosion rates were available and actual corrosion is typically not linear or constant after initial exposure of the metal, the instantaneous concentrations estimated are considered a crude estimate and as previously stated, only intended to provide some “order of magnitude” metal loss concentration for comparison purposes with regulatory criteria.

However, since the estimated daily mean concentration of Cu:Ni alloy is 60 – 150 times smaller than the lowest water quality objective, and since corrosion is typically a slow chemical reaction (as indicated by their measurement in centimeters per year), it is unlikely that the instantaneous copper objective would be exceeded. These results represent a conservative estimated of total concentration, as no copper speciation information was considered.

Finally, it should be noted that the method described in this document has been peer-reviewed by a statistician who determined the same estimates of mean concentration while employing an alternative method for exposure area, further supporting the indications that copper dissolution is unlikely to be a water quality issue in the proposed project.

## References

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