

DIRECT DIODE LASER SYSTEM REQUIREMENTS FOR LONG LIFE MICRO CHANNEL COOLERS

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Abstract

High power direct diode lasers have made significant impact in the industry as an alternative heat source for material processing. In order, to be readily adopted by the industry they have to show >99% uptimes. One of the much-discussed issues associated with copper based micro channel coolers has been the lifetime of the micro channel cooler in High Power Direct Diode Laser (HPDDL) systems. HPDDLs with micro channel coolers have shown long life in some installations, but have shown to work only a few thousands of hours in others. These have been attributed to the erosion, corrosion, or clogging of the micro channel coolers. This paper will describe the proper design of the water system for use with a micro channel cooled laser system. This paper focuses on the water chemistry and its impact on erosion and corrosion of the copper based micro channel coolers. Using previously reported data; we will give erosion rates for different water chemistries.

Introduction

Today High Power Direct Diode Laser [HPDDL] and High Power Diode Pumped Solid State Lasers [DPSSL] use copper based MicroChannel Cooled Package [MCCP] bars and stacks. The MCCP's are mini-heat exchangers with channels on the order of a few hundred microns in size. The integrity of these surfaces are critical to effective cooling, long life of the laser. These laser heat exchangers have to last for >100,000 hours. A HPDDL consist of several to hundreds of high power diode laser bars [30 – 150W / bar], which are mounted on individual MCCPs for cooling. Typically, 20 – 100 MCCP are stacked on top of each other to scale power into the multi-kiloWatt range. The electric system for the laser diodes is a series parallel connection, where the bars themselves represent a parallel electrical circuit to each of the laser diodes on the bar. When the individual MCCPs with the laser diode bars mounted on them are stacked they

form a series electrical circuit of all of the laser diode bars. The complication for these stacks arises when water is passed through the electrically biases stack in to the MCCP's. The water is delivered in parallel to each of the MCCP's in a stack, which are biased as noted above in a series fashion. Since each of the laser diodes bars has a voltage drop of up to 2 Volts, these water plenums can be under a constant bias in excess of 100 Volts. In a NuVonyx designed array, the water enters the cathode [- negative] end cap and exits the anode [+ positive] end cap. This design approach is used because the cathode [-] is where the copper is liberated and the anode is where the copper or copper oxide/ hydroxide is deposited. The water provides a conducting path for the copper to electroplate off. This is known as electrogalvanic corrosion. As with, galvanic corrosion, there must be a flow of current between two areas of metal surfaces or electrodes through a solution capable of conducting current. By forcing the ions to travel against the flow of the water, the migration rate between the cathode and the anode is significantly reduced. In addition, by keeping the water Deionized [DI] the ability of the water to conduct current is significantly reduced, resulting in a suppression of the electrogalvanic effect. Finally, with the presence of oxygen in the water the copper does not remain an ion in the water but becomes an oxide of copper, again suppressing the electrogalvanic effect. [1-11] However, the presence of oxygen in the water will lead to several other effects that can be just as damaging to an array, which includes erosion, and clogging of the MCCPs.

When using Deionized [DI] water it is critical to control the purity of the water, the dissolved oxygen [DO] levels and the CO₂, pH or H⁺, and the velocity of the water. [12,13] Otherwise erosion, corrosion and impingement corrosion can become serious problems greatly reducing the lifetime of the MCCP. The combination of high purity water, high dissolved oxygen and the natural low pH (<7.0) can produce very high erosion rates at regions of turbulent flow inside of the MCCP, these erosion rates will be

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excessive whether the MCCP is bare copper or plated with a non-oxidizing material such as gold.

Water System Design for MCCP Based Lasers

General Description

Present HPDDL laser systems are cooled with a closed loop system that is charged from several liters to hundreds of liters of DI water. The wetted surfaces are described below and are generally described as the laser head, chiller, and transport hoses.

Laser Head – critical component

The HPDDL head contains the MCCP stacks and other cooling surfaces for removal of heat from optics and electronics. Typically, all copper surfaces are electroplated with gold to minimize copper exposure. The purpose of this paper is to assume that copper is exposed somewhere in the primary cooling loop and that its corrosion/erosion is of primary concern.

Chiller-

The chiller is typically water to air chiller with;

- Pump Impeller - Stainless steel
- Heat exchanger - Stainless Steel
- Reservoir is made of 4" PVC pipe
- Hoses - Braided Tygon - PVC
- Hose fittings - PVC
- Stainless Steel
- Filter housing - Polypropylene
- Filter - polypropylene
- Di column - high capacity mixed bed

The impeller and the fittings in many chillers are typically brass. Red brass was found by Obrecht [9] to be strongly attacked by Sodium zeolite softened [DI] water at high flow rate and temperatures. He found that 90/10 cupro-nickel and admiralty brass tubes offer excellent corrosion resistance to DI water containing oxygen and carbon dioxide at all temperatures for velocities up to 4m/s. Stainless steel is impervious to attack by DI water and is more resistant to cavitation erosion. Therefore, it is required that all wetted chiller metallic components be constructed from stainless steel.

The DI water in some systems are monitored and controlled. The Nuvonyx, Inc. chiller is equipped with a DI sensor/controller to control the Resistivity of the water to 250K – 500K ohm or 2 to 4 microsiemens water with a mix bed cartridge. Therefore the DI columns are not always in the loop. The pH is not

monitored, but the PH is around 7.0 – 7.4 at this purity level and very rarely drops below 7.0.

The Reservoir of the chiller is made of 4" PVC pipe with an off the shelf PVC cap. This is tight enough to form a solvent joint that is tight enough to semi-seal the reservoir from the atmosphere. But air and water will leak out. When the chiller is turned on a vacuum is created in the reservoir as a direct result of the water level dropping because of the swelling of the Tygon hoses in the rest of the system as they accept the pressure from the pump. Depending on the chiller design, the amount of air drawn into the system can be several liters in volume.

Hoses

Several materials have been empirically tested, the best results have been obtained with PVC based hoses or piping. Nuvonyx currently recommends using braided Tygon PVC hoses. .

Water Velocity

It has been shown by modelling that the water velocity inside the MCCP can reach 220 inches per minute or ~ 5.6 m/s. Copper based MCCPs have been observed to erode in DI based water systems with certain dissolved oxygen conditions, in all areas where the flow is either turbulent or cavitating. In these regions, the dissolved oxygen creates a copper oxide surface, but the turbulence or cavitation rips the copper oxide protective layer from the surface. The process proceeds on a recurring basis until it generates enough copper-oxide particles in the water to create a clogging problem for the coolers. The copper oxide tends to deposit in the stagnation regions of the flow, or flow vortices, as the copper oxide sticks to the walls of the MCCP it changes the flow characteristics, increasing the stagnation zone. Eventually, the copper oxide creates a clog in the channel, which results in severe damage to the laser diode bar.

DI Water Source

The system should be initially charged with store bought DI water or distilled water, which typically comes from a carbon-filtered water to remove organics and chlorine and then a filtered through a mix bed resin ion exchange.

Fundamentals of Active Carbon Filtration

Activated carbon has been used for many years to solve water problems; today it is used effectively to

remove chlorine, synthetic organic chemicals and volatile organic compounds.

Synthetic Organic Chemicals (SOC) include all man-made organics, some of which are Volatile Organic Compounds (VOC) such as benzene, trichlorethane and carbon tetrachloride. Activated carbon adsorbs organic matter in its extensive network of pores. The adsorption process takes time, so service rates should be limited to 5 gpm/ft or less for these applications. An activated carbon filter should be used to remove organic compounds and chlorine from the system. Chlorine should not be used in the water systems since reacts readily with copper to form copper chloride [CuCl₂]

Fundamentals of Deionization by Ion Exchange

All naturally occurring water contains dissolved mineral salts. These salts separate into positively charged cations and negatively charged anions in solution. Deionization can reduce the amounts of these ions to very low levels through the process of ion exchange.

A cation exchange resin removes cations. This resin replaces sodium, calcium, magnesium and other cations with hydrogen ions (H⁺). This exchange produces acids, which must be removed or neutralized by anion exchange resin.

Two types of anion resin are used for deionization: weak base resin and strong base resin. Weak base resin absorbs strong acids, while strong base resin exchanges chloride, sulfate, and alkaline anions for hydroxide ions (OH⁻). The hydrogen ions from the cation exchange process combine with the hydroxide ions from the anion exchange process to form water (HOH or HO).

The water's resistance to electric current (in Ohm-cm) is used to determine the quality of the deionization process. Deionized water quality depends on a variety of factors, including raw water composition, ion exchange resin types, quantities, the placement of the resins with respect to each other, and the number of resin tanks [surface area] in the system.

Two-bed or separate bed deionizers use separate tanks or separate beds, one containing cation resin, the other containing anion resin. A two-bed weak base deionizer typically produces water with electrical resistance of about 50,000 Ohm-cm. A two-bed strong base deionizer typically produces water with electrical resistance of about 200,000 Ohm-cm.

In a mixed-bed deionizer, cation and anion resins are thoroughly mixed in a single tank. The mixed resins act like a series of alternating cation and anion exchange tanks to produce very high quality water. A mixed-bed deionizer typically produces water with greater than 10,000,000 Ohm-cm resistance, which is equivalent to less than 0.05 mg/L [0.05ppm] of sodium chloride.

The means of controlling pH of the water is accomplished with the ion exchange resins. The pH drops with the use of cation resins and fall with the use of anion resins. Proper design of the DI systems is critical for controlling pH.

MCCP Corrosion

The deionized [DI] water presents a problem of erosion-corrosion/impingement corrosion of copper based coolers. Erosion corrosion is a direct result of the velocity and chemistry of the solution. See Figure 1.

Figure 1. Internal view of the turbulent flow region



showing how erosion can occur even in a gold plated MCCP after 2000 hours of cooling water flow.

The industry has seen severe deposits in cooling loops. An analysis of the black and red deposits revealed the primary element present to be copper (Figure 2). These deposits grow exponentially and rapidly accelerate to a clogging event most likely due to changes in the flow characteristics and the heat generated by the laser component.

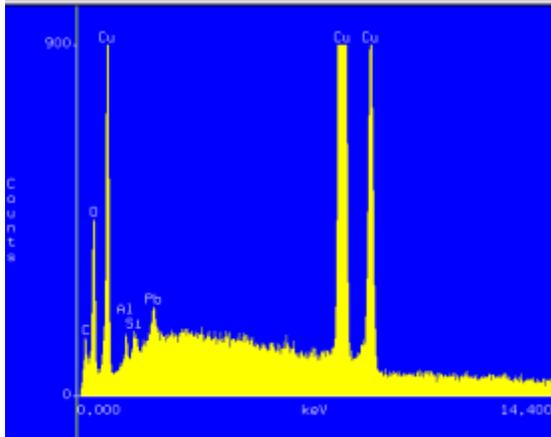


Figure 2. Elemental analysis of red and black deposits removed from inside MCCP channels.

Influence of pH

A corrosion attack on copper is most often associated with soft and acidic waters [low pH]. The corrosion process usually proceeds at a slow rate and is characterized by build-ups of cupric oxides.

The most important factors influencing the general corrosion of copper are the pH of the water, softness, temperature, and oxygen content. A water that is soft less than 60 ppm hardness and less than 6.5 pH will be aggressive on copper. If the water is heated, the aggressive nature will be greater due to the destruction of the protective metal oxide layer. This is evidenced by the large amount of erosion in the vicinity of the laser diode bar.

The source of the acid [pH lowering] in water is the absorption of carbon dioxide from the atmosphere, which is converted into carbonic acid in the water. If a DI cartridge is used it will neutralize this carbonic acid.

Dortwegt et al. have documented the influence of pH on copper with respect to DO and temperature. [12,13]. The Pourbaix diagram [12] indicates stable forms of copper in aqueous solutions. The corrosion rate versus pH is shown in Figure 3. This data correlates to copper solubility vs. pH and the copper solubility vs. temperature for different pH levels [12]. All these curve show that copper solubility and therefore corrosion is significantly reduced under all water conditions the more alkaline [>7.0 pH] becomes [12]. The optimum pH is around 8.5.

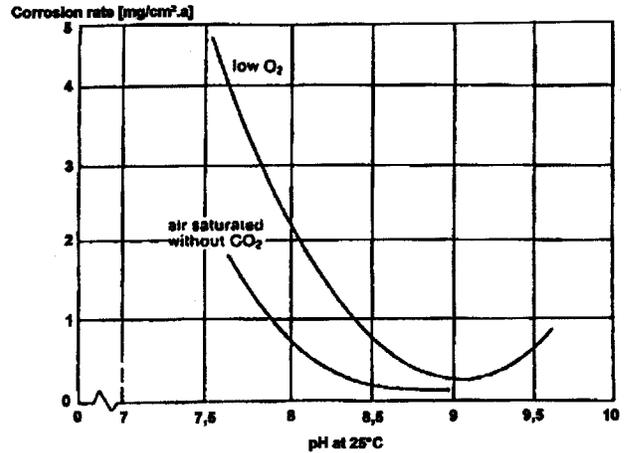


Figure 3. Corrosion rate of copper vs. pH. [12]

The relationship of pH and resistivity of DI water is shown in Figure 4 [12]. Nuvonyx recommends keeping the resistivity of the water between 500Kohm and 250 K ohm to prevent substantial erosion of the copper based MCCP. This resistivity requirement forces the maximum pH to be above 8.5, which is the optimum pH level for copper systems. This is shown in Figure 4.

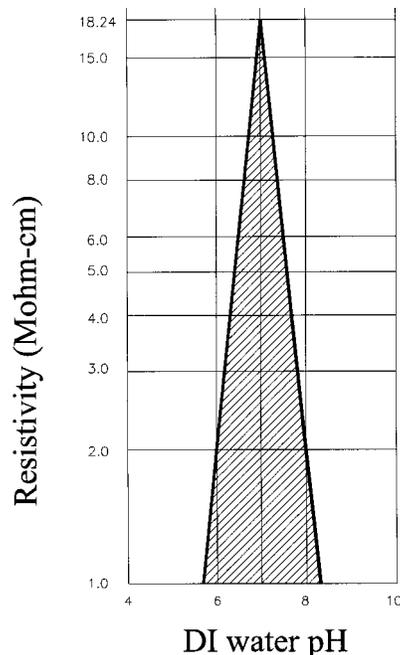


Figure 4. Resistivity Limits of DI water. [12]

Dissolved Oxygen

A system consisting of copper and pure water open to the atmosphere would contain dissolved oxygen. At room temperature, the oxygen concentration can be 8ppm. See Figure 5 for saturated oxygen concentration vs. temperatures.

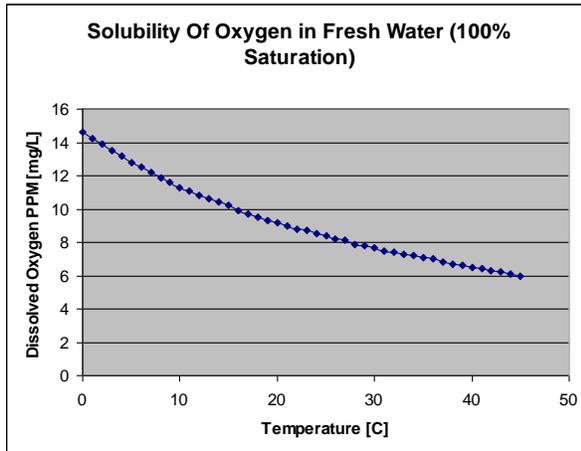


Figure 5. Saturation concentration vs. Temperature.

Fundamentals of Corrosion of Copper

Corrosion of nonferrous metals in aqueous solutions may be due to any one of following: (1) direct oxidation, (2) pitting corrosion, (3) galvanic corrosion, (4) erosion-corrosion or impingement corrosion, (5) cavitation corrosion, (6) corrosion by biologicals. [1-11]

Oxidation of Copper

Copper has two common oxidation states: Positive one [CuO - cuprous] and positive two [CuO₂ cupric]. Cuprous oxide can be a variety of colors even bright red. Cupric oxide is characterized by a black color. Both of these oxides are insoluble in water. For simple system of copper immersed in pure degassed water, the only films capable of forming would be oxides or hydroxides of cupric or cuprous copper.

Corrosion Mechanism [12]

Oxygen (O₂) and carbon dioxide (CO₂) are present in water due to interactions with the atmosphere. An oxide forms at the metal surface, which, in the absence of other influences, is stable. The presence of CO₂ in the water results in the formation of carbonic acid (H₂CO₃), which dissociates into HCO₃⁻ and hydrogen ions (H⁺). H⁺, which has an affinity for the oxygen component of the oxide, readily forms water. The copper at the surface is now left in its ionic form and readily dissolves. The metal surface, now unprotected

by the oxide, is again exposed to water, DO, and H⁺ allowing the process to recur. [12]

Influence of Oxygen

The compounds of the metals formed in corrosions may be either relatively soluble or relatively insoluble as determined by the Pourbaix diagram. [12] If they are relatively insoluble the product may serve as a protective layer to hinder corrosion, provided the compactness and porosity of the compound are favourable for forming an adherent film on the metal surface. If the compound is soluble, the wearing away of the metal is enhanced. The rates of corrosion depend upon the characteristics of the metal or alloy, the nature of adhering films, the corroding medium, the velocity of flow, the temperature, etc.

Dortweg et al. has studied the corrosion of copper in water [pH 7.0] as a function of DO [12, 13]. The maximum rate occurs in the range of 200 – 300 ppb. See Figure 6. This has been well documented for stator cooling systems. It is clear that for long life MCCP one would engineer the systems for the lowest oxygen concentrations.

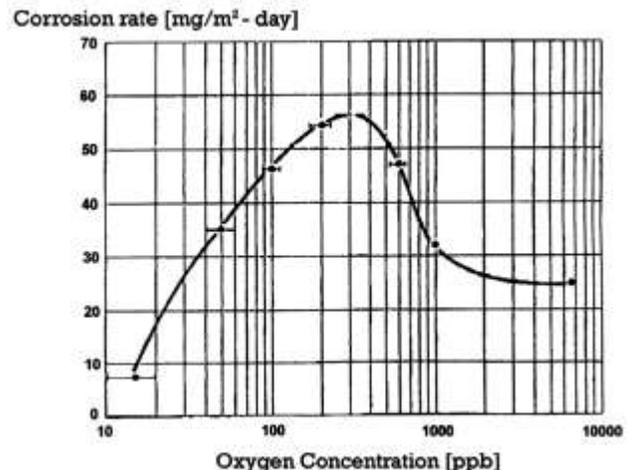


Figure 6. Corrosion rate vs. Dissolved oxygen ph = 7.0.

Pitting Corrosion

Pitting corrosion is the result of local cell action, which is usually brought about when particles are deposited on a metal surface either as flakes of solid or bubbles of gas. Often, the effect is due to an oxygen concentration cell. The pitting is a localized accelerated attack resulting in cavity or pit formation around which the surrounding metal is relatively non-attacked. The pitting is due to anode condition set up under deposits setting up an oxygen deficiency in area under a deposit.

Pitting can be a destructive form of corrosion because of pin-hole leaks which develop. A good illustration of localized pitting corrosion of a copper tube exposed to steam condenser containing only dissolved oxygen and carbon dioxide was shown by Obrecht [4].

Galvanic Corrosion

Electrochemical corrosion may also result from a chemical reaction involving the metal or alloy and the corroding medium. It differs from the direct chemical attack in that the electrons move indirectly from the metal to the corroding medium.

Conditions for galvanic corrosion must be such that there is flow of electricity between two areas of metal surface or electrodes through a solution capable of conducting an electric current. These reactions may be thought of as occurring between two electrodes with the solution and the walls completing an electrical circuit. The electrodes may consist of two different kinds of metals, or they may be different areas on the same piece of metal. In either case, there must be a potential difference between the electrodes so that electricity will flow.

At the anode, positively charged atoms of metal detach themselves from the metal surface and enter the solution as ions, while electrons are left in the metal. The electrons travel through the metal to the cathode. At the cathode, the electrons reaching the surface through the metal cause reduction of some species, such as hydrogen ions, which have, migrated through the solution. If the hydrogen ions lose their charge and become neutral atoms again, they may combine to form hydrogen gas. Water molecules may also be reduced directly. The release of hydrogen ions results in a build-up of hydroxyl ions. However, on copper the oxygen does not combine with absorbed hydrogen, because in the case of copper and its alloys, hydrogen ions are not reduced at the cathode. The cathodic reaction in the transfer of electrons from the metal to dissolved oxygen.

Reduction of oxygen dissolved in the solution can occur to complete the cathode reaction. Any cathodic reduction will permit corrosion to proceed, thus, the cathodic reactions can involve hydrogen evolution, reaction with oxygen, or reaction with some reducible substance.

For MCCP based system it is important to not have any metals that have a significantly different galvanic potential than copper. One example is the use of aluminium in the water systems. It has been observed that aluminium in MCCP based system will lead to rapid clogging and galvanic erosion.

Erosion-Corrosion, Impingement Corrosion

Erosion-corrosion is usually characterized by rapid and repeated destruction of protective surface films in the presence of rapidly moving water.

Major factors affecting the rate of erosion-corrosion are the velocity, temperature, DO and pH of the water solution being passed through a distribution system. The impingement type of corrosion is often associated with entrained gases and high velocities.

The different types of corrosion and erosion-corrosion concerned with the wearing away of copper and its alloys in water distribution and condenser systems have been outlined. In these corrosive events, cell actions are involved which may be defined as; (1) the metal-metal oxide cell, (2) the solution concentration cell, and (3) the oxygen concentration cell.

In impingement corrosion, when the water impinges on a metal surface, the bare metal is anodic to the surrounding oxide covered surface. Essentially, there is a small anode area surrounded by a large cathodic area. The flow of current is concentrated toward the anode with increased anodic oxidation or corrosion of the anode area. The impinging water rapidly removes the copper ions formed by the anodic oxidation, thus causing the bare metal surface to be more anodic than it would be under stagnant conditions. The flowing water also increases the rate of diffusion of dissolved oxygen to the metal surface, causing it to be cathodic with respect to any surrounding area toward which the oxygen is moving less rapidly. With more noble metal such as copper the metal ion concentration cell potential becomes greater than the reduction of oxygen concentration cell potential with the net results that the exposed metal becomes more anodic under impinging water flow conditions.

It was observed that copper tubing in which the water does not flow continuously undergo a "healing process". This most likely involves the formation of a protective oxide film, which takes time to erode away in the turbulent areas. In high velocity water up to 7.5 m/min, impingement attack is negligible when the water is oxygen free and the pH is > 7.0 .

Cavitation Corrosion

Cavitation damage is caused by the repeated nucleation, growth and collapse of bubbles against a metal surface in a liquid. Cavitation is a form of erosion-corrosion, which occurs on surfaces such as propellers, hydrofoils, pipelines, valves, engines, pump components and impellers that undergo large changes in liquid pressure. Bubbles that form rapidly collapse, producing shock waves against the surface resulting

ultimately in metal removal. Cavitation can occur in an MCCP if the flow velocities are very high. This condition should be avoided because it will lead to the rapid destruction of the MCCP.

Biologicals

Biologicals will not grow on copper surfaces, however since chlorine cannot be used in copper based system due to the formation of copper chloride, micro-organisms may grow in the water system. The most common types of bacteria are sulphate producers, methane producers, nitrate reducers, sulphur bacteria and iron bacteria. In oxygen free water, anaerobic bacteria can form on surfaces that support their growth. The most vulnerable surfaces are vulcanized rubber and iron [cast iron]. The bacteria forms a corrosive slime that can clog filters and lead to corrosion products that lead to detrimental effects on the MCCP. MCCP based HPDDL systems should be designed such that all hoses are PVC based with stainless steel or PVC fittings to suppress the growth of bacteria by not giving it a surface that can support the growth.

Corrosion Rate

For the longest life MCCP these laser heat exchangers have to last for >100,000 hours. The lowest corrosion rates have been documented for various operating regimes for stator cooling systems (Figure 7). [12]. The lowest corrosion rates are for elevated pH with low < 10 ppb oxygen content. The corrosion rates are < 0.1 micro-grams/annum. The water velocity is the unknown condition.

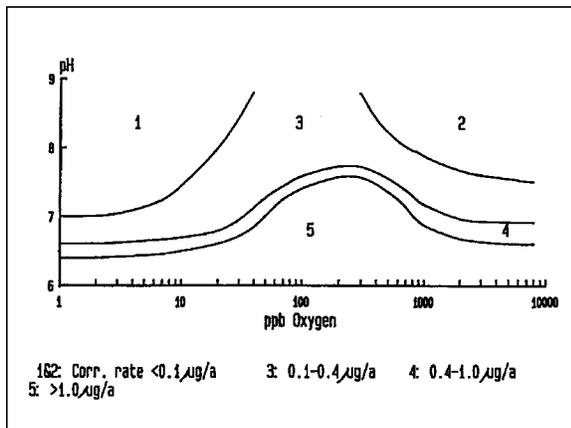


Figure 7. Corrosion rate at various operating regimes. [12]

If we assume that this chart corresponds to a surface area of 1 cm² as in Figure 3 we can estimate the lifetime of an MCCP for a laminar flow condition. The density of pure copper is 8.96 grams/ cm³. Assuming that an MCCP is past its useful life after the

erosion of 100 microns of copper in any area. In addition, it is reasonable to assume the following two conditions; 10 mg [10000 micro grams/cm² year] and 0.1 micro-grams/cm² year. Using Table 1 for a surface area of 1 mm², theoretically worst case condition for proper systems design would be approximately 9 years of life. Under more optimum water conditions the estimated lifetime of the copper MCCP's is on the order of ~900,000 years.

Erosion Rate grams/ mm ² * year	Surface area [mm ²]	Max depth [mm]	Grams of Copper [g]	Years	Hours
1.00E-04	1.00E+00	1.00E-01	8.96E-04	8.96	7.85E+04
1.00E-09	1.00E+00	1.00E-01	8.96E-04	896000	7.85E+09

Table 1. Estimated lifetime for MCCP with two different erosion rates.

Recommendations

1. The pH of the water should be monitored and controlled above 7.0 in all cases. Separate bed or mixed bed DI cartridges will maintain a Neutral pH [7.0].
2. If using a mixed bed DI cartridge the starting water should be alkaline and be polished down between 2 ppm [2 microsiemen] and 4 ppm [4 microsiemens] DI to stem electro-galvanic corrosion and prevent impingement corrosion due to low pH DI water taking copper into solution. The water conductivity should be monitored and controlled.
3. The system should be sealed as much as possible from the atmosphere to prevent oxygen and carbon dioxide take-up. The presence of CO₂ in the water results in the formation of carbonic acid. If the system requires it to be open to atmosphere then a nitrogen cover [bubbler] should be implemented to “seal” the water from the oxygen and carbon dioxide rich atmosphere. In addition, for large systems, membrane contactors can be used for degassing water. They are widely used for O₂ removal from water as well as CO₂ removal from water. They can be used in place of a vacuum tower, forced draft deaerator, and oxygen scavengers. [14]
4. If a system is deaerated, vulcanized rubber and iron should be eliminated from the system, to prevent anaerobic bacterial from forming in the system.
5. All copper surfaces wetted by water should be electroplated with gold to minimize exposure of copper to the DI water.

6. Brass parts, especially in the pump, should be changed to stainless steel, admiralty brass, or cupronickel.

7. There should be no aluminium in the water system to prevent clogging due to galvanic corrosion. Even anodized aluminium cannot be trusted, pinholes in the anodization can spell disaster for a MCCP based system.

8. The chiller should not be allowed to run continuously during non-use. The system chiller should be shut down or a by-pass switch should be installed to prevent continuous flow within the laser diode heads during non-use. This might include a timer in which the laser water would be bypassed if inoperable for 30 minutes to 1 hour.

Upon implementation of these recommendation one can achieve very long life MCCP's, which can match or exceed the diode lifetimes. Figure 8 shows the inside an unplated copper MCCP after 2000 hours of continuous operation with no signs of corrosion or clogging.

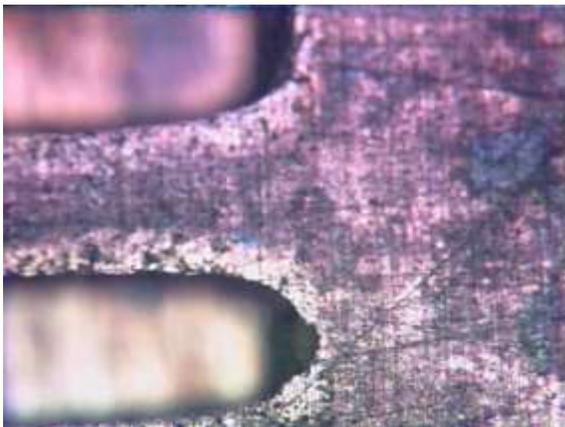


Figure 8. Internal view of turbulent region of a copper MCCP showing no change in the surface of the unplated copper channels after 2,000 hours of operation in optimum DI water.

Further Studies

Further studies are under way to investigate custom DI cartridges to insure polished water is always above 7.0 pH. Life tests on gold plated surfaces are currently underway to determine the long term effects of DI water on such surfaces. It is clear that erosion corrosion is the main failure mechanism. Further studies are under way to generate corrosion rate curves for MCCP based systems vs. flow rates.

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