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Biofouling and Microbial Induced Corrosion -A Case Study

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In industrial and fluid handling systems, frequently the protective film forming materials suffer from severe corrosion due to microbial effects. As an example, various micro-organisms, including bacteria, exist in seawater normally fed to power and desalination plants. Unless seawater intakes are properly disinfected to control these microbial organisms, biological fouling and microbial induced corrosion (MIC) will be developed. This problem could destroy metallic alloys used for plant construction. Seawater intakes of cogeneration plants are usually disinfected by chlorine gas or sodium hypochlorite solution. The dose of disinfectant is designed according to the level of contamination of the open seawater in the vicinity of the plant intake. Higher temperature levels, lower pH, reduced flow velocity and oxidation potential play an important role in the enhancement of microbial induced corrosion and bio-fouling.
This paper describes, in brief, the different types of bacteria, mechanisms of microbiological induced corrosion, susceptibility of different metal alloys to MIC and possible solutions for mitigating this problem in industry. A case study is presented for the power plant steam condenser at Al-Taweelah B-station in Abu Dhabi. The study demonstrates resistance of Titanium tubes to MIC.

Keywords *: microbial induced corrosion, biofouling, titanium, power generation, chlorination.*

1. Introduction

The role of micro-organisms in the deterioration of metal properties was first discovered in 1923[1)] when German scientists attributed the corrosion of buried pipe metals to the presence of the bacteria Desulfovibrio.

Microbial induced corrosion is developed by two mechanisms; active mechanism and passive mechanism. In principle, corrosion is attributed to the products of the metabolic processes of active biological microorganisms. These products are normally present in the form of acids, sulfur compounds, and/or metal's oxidizing agents. The passive mechanism is related to surface deposits. This paper gives a brief outline of different species of micro-organisms, bio-film formation, mechanisms of MIC, mitigation methods and a case study.

The destructive effects of MIC normally go beyond expectations. Many factors affect MIC development and problem diagnosis requires knowledge in many areas such as material science, biology, civil, mechanical and electrochemical engineering. The relationship between sciences is not obvious and nobody can be an expert in all of them. Meanwhile, few corrosion engineers could understand biology and not many biologists would be interested in corrosion science. This is why MIC remained to be an unknown area for a long time. Still, this subject is unknown to most corrosion engineers. The difficult terminology used in biological sciences made that problem even worse..

MIC represents a serious problem in many industries such as oil industry, gas transportation lines, conventional and nuclear power stations, desalination industry, wastewater treatment plants, pulp and paper industry, chemical industries, cooling water systems and aircraft fuel tanks.[2)]

MIC is very evasive and may be considered as the most hazardous type of corrosion since it attacks underground metal objects such as pipelines and sometimes it takes place under water. Normally it is discovered in a late stage after the corroded metal has been fully destroyed. In addition, MIC takes different forms and occurs in complex media containing different types of bacteria of counter effects. One of the factors that enhance the destructive effect of MIC is the possible recurrence after mechanical or chemical suppression of bacteria, where few species of it spring back to flourishing once the system conditions revert back to normal.

Bad system design may lead to the development of MIC due to the presence of hidden zones where fluids may come to stagnation or where the flow is intermittent.[3)]

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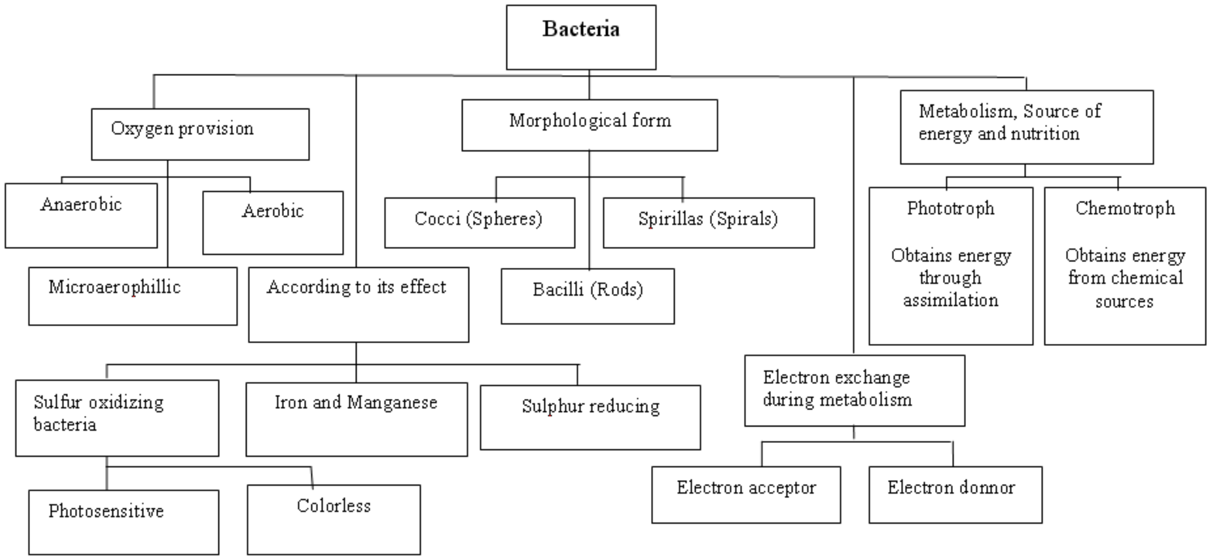

Fig. 1. Classification of bacteria according to morphology, effect and assimilation etc.

Also, MIC may occur as a result of using untreated or improperly treated water for cooling purposes.

In many instances MIC is incorrectly termed as "biological corrosion" since it does not occur as a result of direct reaction between the metal and the microorganisms present in the surrounding medium. In fact, MIC occurs and gets accelerated through a definite series of electrochemical reactions that take place between the metabolic products of bacteria and the metal where electrochemical cells are established.

Higher temperature levels, lower pH, reduced flow velocity and oxidation potential play an important role in the enhancement of microbial induced corrosion and bio-fouling.[4)] Meanwhile, MIC follows two mechanisms, namely active mechanism and passive mechanism. While micro-organisms play a direct and active role in the first, we find that the second is related to the effect of the metabolic products of bacteria.

Most of the time, it is difficult to differentiate between the active effect of bacteria and the passive effect of its metabolic products.

As shown in Fig. 1, different species of bacteria may be classified according to; morphology, effect and assimilation. In principle, two main types of bacteria are normally found, namely; aerobic bacteria, which utilizes oxygen to produce the energy necessary for multiplication and biological activities and, anaerobic bacteria, which can live and multiply in absence of air or oxygen. However, some types of bacteria can survive and grow in different media of limited and low concentrations of oxygen where they adapt their metabolism to the prevailing conditions.[5)]

Bacteria grow on the metal surface in the form of colonies containing a variety of micro-organisms which have a synergistic effect. The dynamics of the bio-film, so formed, change in a cyclic form.

2. Mechanisms of MIC

2.1 Active biological corrosion

Active MIC is attributed to bacteria which include four strains, namely:

Sulfate reducing bacteria, acid producing, metal depositing and slime forming bacteria.[6)]

Sulfate reducing bacteria is the most effective in MIC enhancement where it reduces inorganic sulfates to sulfides which results in localized attack of the metal in the form of pitting corrosion. Fig. 2, illustrates the chemical reactions taking place and the role of the sulfate reducing bacteria.[7)]

During their metabolic processes certain types of aerobic bacteria produce organic and inorganic **acids** which enhance metallic corrosion.[6)]

Metal depositing bacteria oxidize ferrous ions, Fe^{2+}, to ferric ions, Fe^{3+}. As a result, ferric and manganic hydroxides form, thus increasing corrosion rate.[8)]

Slime forming bacteria produce slime which is a continuous network of a polymeric material mixed with bacteria, water and gas. Normally, various particles of dust, dirt and mud are attracted to slime formed on the metal surface and micro-organisms present in this mass consume the oxygen below it. Oxygen deficiency at that location relative to some more aerated points on the surface of

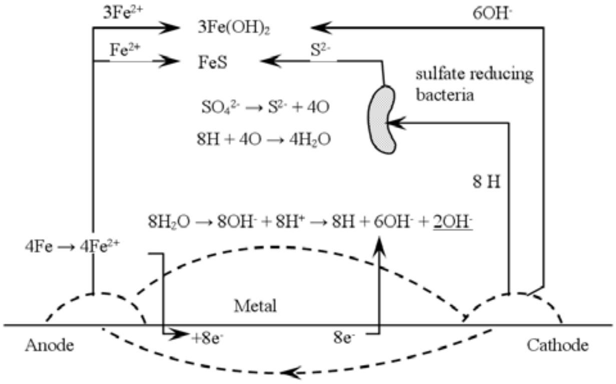

Fig. 2. Chemical reactions ending with ferrous sulfide and ferric hydroxide (corrosion products), where sulfate reducing bacteria play an active role.[7)]

metal will result in an oxygen concentration cell[9)] thus leading to localized corrosion of the metal.

In cooling systems, slime formation means an added thermal resistance which reduces significantly the heat transfer rate across the fouled surface. It may also result in the reduction of the thermal conduction coefficient which in turn develops internal thermal stresses inside the metal alloy and ends up with the stress corrosion cracking.[10)]

2.2 Passive microbial corrosion

This type of MIC results from both live and dead forms of micro-organisms where they get attached to the metal surface changing the flow nature which sometimes produces turbulent conditions and consequently erosion corrosion. Also, as in the case of slime forming bacteria, oxygen concentration cells can be created and localized corrosion is developed.

Meanwhile, hydrogen gas may result from the metabolic processes of some kinds of anaerobic bacteria.[8)] This hydrogen can cause hydrogen embrittlement to austenitic stainless steel, known of its resistance to corrosion.[11)]

Ammonia gas is one of the products of the decay of dead bacteria. This gas gets concentrated at some locations in the metallic substance and may cause stress corrosion cracking to the brass-made condenser tubes.[6)]

As it was mentioned above, the rate of MIC depends on the conditions of the environment surrounding the metallic material, acidity or pH, oxidation potential, temperature, concentration and distribution profile of micro-organisms and flow velocity of the medium. However, the boundary conditions of fluid film next to the metal surface are normally totally different from those of the bulk of the fluid.

As a general approach, MIC is normally verified through:

- Investigation of morphology, composition and distribution of the deposits present on the metal surface.
- Investigation of metal surface and composition of the corrosion products
- Biological analysis of the surrounding medium.

3. Affection of different metals by MIC

Stainless steels including high molybdenum steels[12)] corrode due to the effect of bacteria where pitting corrosion is normally developed. This type of corrosion is attributed to the deposition of the debris of dead bacteria and other products of metabolism which creates concentration-difference cells. MIC in stainless steel alloys is most emphasized at and nearby the welding locations.[11)]

Aluminum and its alloys are known to be corrosion resistant due to the formation of a passive oxide film. **Nevertheless**, halides can attack certain locations of this film where the metal, at the attacked locations,[8)] is exposed and become subject to MIC attack. In this case corrosion is attributed to the soluble acids which dissolve readily in water or to the formation of concentration-difference cells.[10)]

Copper alloys are subject to attack by MIC[9),13)] especially localized corrosion. This could take place by different mechanisms such as oxygen concentration- difference cells, selective dissolution underneath microbial and metabolic deposits and depolarization. Some microbial products will enhance localized corrosion of copper alloys, examples of such products are: carbon dioxide, hydrogen sulfide, ammonia, organic and inorganic acids.

Copper-Nickel alloys are more resistant to microbial induced corrosion than other copper based alloys. The reason is that Cu-Ni alloys develop a passive film that sticks firmly to the metal surface even under erosive or turbulent flow conditions. In order to ensure passivity of the film, a critical Ni concentration of 35% is required; otherwise, if the Ni concentration is lower, then the alloy will behave the same as normal copper alloys.[13)-15)]

Microbial induced corrosion of titanium and its alloys

Reviewing the open literature and published research work on biological corrosion of different metals and their alloys, no single case has been reported about the MIC of titanium or any of its alloys. The only study[16)] published in this context reviews the mechanisms of MIC and the behavior and corrosion of titanium, in a general form, under the system's conditions which were not defined. The most important conclusions reported in this study states that titanium will not be attacked by the different forms of MIC at temperatures below 100℃ regardless of the type of bacteria present in the system and whether it is sulfate reducing, sulfur or iron oxidizing or acid producing bacteria.

Similarly, the existence of aeration or chlorine concentration difference cells will not encourage attack of titanium or its alloys by MIC. Also, titanium and its alloys are resistant to hydrogen embrittlement below 100℃.

However, a study had been conducted on the welded joints of titanium where MIC was detected but to a limited extent.[17]

This paper presents another proof which confirms the reported resistance of titanium to MIC. The case study relates to the steam condenser in one of the power plants at Al-Taweelah, The Emirate of Abu Dhabi, UAE.

4. Mitigation of microbial induced corrosion

To control MIC, one or more of the following methods, see Fig. 3, may be followed[3]:

- All possible microbial pollutants must be avoided and prevented from reaching the medium.
- The system has to be cleaned periodically. All deposits on the surface must be removed.
- Medium conditions should be controlled in order to prevent microbial or bacterial growth.
- Proper selection of the materials of construction and the use of materials which are highly resistant to MIC.
- Implementation of the proper coating film or the use of cathodic protection.
- Proper equipment design to avoid stagnant and intermittent flow conditions.

5. Diagnosis of microbial induced corrosion

Diagnosis of MIC is a difficult job to do and one has to be very careful since bacteria exist in all cooling systems whether they are corroded or not.[6] Meanwhile, investigation of corroded systems proved that many microbial species found in corroded systems do exist in corrosion-free systems as well.[18] Accordingly, we can say that the presence of micro-organisms in the vicinity of the corroded system cannot be taken as a proof that the corrosion under investigation is a microbial induced one.

Hence, the search for the causes of corrosion should be carefully conducted by a group of investigators with wide experience in the diagnosis of materials failure in industry. In addition, proofs given for MIC should be in harmony with each other and should not be confused with reasons for other types of corrosion. To end up with a final and definite judgment, the work team has to study all possible interpretations with care.

6. Case study:

Bio-fouling at the steam turbine condenser of unit 2-Taweelah Power Company

6.1 Operating conditions and problem description

Al-Taweelah - B power station comprises six steam turbines each of which is coupled with a Multi-Stage Flash, MSF, desalination unit, thus forming six co-generation power/water plants. At the same time an extension of Al-Taweelah - B, comprising an additional three gas turbines and three MSF units, was annexed at a later stage.

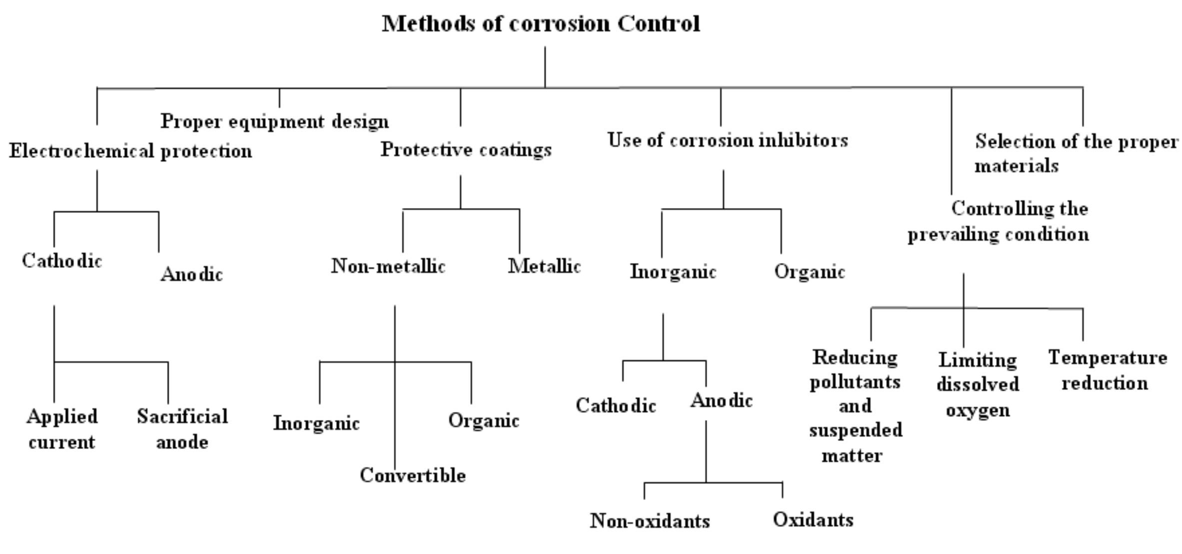

Fig. 3. Methods of Corrosion Control

All desalination sections and the steam turbines condensers are fed with seawater from a common basin where sodium hypochlorite solution is injected according to a planned scheme and dose to prevent bacterial growth and biological fouling inside the distillers at the desalination plants and condensers of the steam power plants.

The case study reported here belongs to the steam turbine condenser number 2 of Al-Taweelah B power plant. The data sheet of this condenser is given in appendix A. The condenser is a shell and tube one with a single pass at the tube-side and the shell-side. Exhaust steam from the turbine condenses at low pressure outside the tubes while cooling seawater at a rate of 5.85 m^3/s flows inside the condenser tube bundle comprising 6584 tubes. The tube material is grade 2 titanium alloy (ASTM B 338 GR 2). Tube dimensions are: 23 mm O.D, tube thickness 0.7 mm and tube length 12,450 mm.

Seawater velocity inside tubes is 2.45 m/s and the water temperature ranges between 18-35℃ depending on the season. The allowable pressure drop across the condenser tubes is 0.38 bar.

The Water boxes on the shell-side are made of carbon steel with hard rubber lining. On the shell-side, the low pressure steam flow rate is 110 kg/s and the vacuum is 0.135 bar. The condenser is cathodically protected through a steel X37 sacrificial anode connected to the water box at the coolant water exit.

It is important to point out that by the time the MIC problem was reported, March 2004, chlorination system at Taweelah B was to ensure 0.1-0.2 ppm residual chlorine at the suction point of the intake feed pump to the power plant.

The problem was discovered when the pressure drop across the condenser tubes increased up to a critical value which called for shutdown of unit 2 to find out the reason behind that increase in pressure drop. When the condenser was opened, visual inspection showed a thick layer of a slimy, reddish-brown material deposited on the interior surface of most of the tubes. A huge lump, about 80-100 kg, of the same material was found inside the water box at the cooling water exit.

Samples of the deposited material were taken and sent for physical, chemical and biological analysis.

The deposits were flushed with a jet of hydrochloric acid solution and the tubes, water boxes and the whole coolant water piping and pumping system were inspected. All metallic surfaces along the cooling water path, upstream of the condenser, were found in a good condition without any type of corrosion noticed.

Table 1. Chemical analysis of deposited sample in the steam turbine condenser No.2 of Al Taweelah Power Company

Mateial	%
Occluded water	17.25
Organic matter	21.9
Insoluble matter	1.10
MnO_2	45.92
Fe_2O_3	15.67
Total	101.93

6.2 Results and discussion

Chemical analysis of the deposited matter, Table 1, revealed significantly high concentrations of manganese and iron. Expressed as oxides, the percent mass fraction of the two compounds came to be 45.92% MnO_2 and 15.67% Fe_2O_3 respectively. In the mean time X-Ray elemental analysis gave 37.7 % Mn and 30.8% Fe as metals. The mismatch between the results could possibly be due to human errors, the techniques used and basis of calculation.

X-Ray analysis of the insoluble matter showed that Silica, SiO_2, represents the major component of the insoluble matter with 54.7% weight fraction. Phosphorous and Aluminum assume percent mass fractions of 16.31% and 15% respectively. Similarly, Titanium was present in the insoluble matter with a mass percent of 10 %.

Biological analysis of the deposits proved that three types of iron bacteria, namely; Galionella, Sphaerotilus and Crenothrix are present.

6.3 Diagnosis and mitigation

In order to be able to interpret the chemical and biological analyses reported, we have to be aware of certain facts about iron bacteria and international standards recommended for chlorination to control biological fouling at the desalination and power generation plants.

Iron Bacteria belong to a group of non-disease producing bacteria which grow and multiply in water and use dissolved iron as part of their metabolism. They oxidize iron into its insoluble ferric state and deposit it in the slimy gelatinous material which surrounds their cells. These filamentous bacteria grow in stringy clumps and are found in most iron-bearing surface waters. They have been known to proliferate in waters containing iron as low as 0.1 mg/l. In order to function, these aerobic bacteria need at least 0.3 ppm of dissolved oxygen in the water.

Iron bacteria do not cause health problems in people, but they may have the following unpleasant and possibly expensive effects:

- Unpleasant odors and taste following the death of the bacteria

- Increased organic content in water favoring the multiplication of other bacteria
- Piping clogged with rusty sludge
- Corroded piping and plumbing equipment
- Increased chances of sulfur bacteria infestation

If the iron bacteria build-up becomes thick enough, anaerobic conditions may develop at the wall of the fitting or pipe which can cause corrosion of stainless steel or growth of sulfate-reducing bacteria.

Standard Chlorination Schemes: Chlorination is a process commonly used to limit sea fouling of intake structures, and minimize the passage of marine organisms into the distillers. The magnitude of bio fouling is a function of both chlorine demand and water temperature. It should be emphasised that seawater with a chlorine demand of only 1.5 ppm will support the growth of various organisms such as; bryozoa, barnacles, sponges, and slimes, as long as the temperature is above 5℃. The soft forms of these organisms can be controlled by **intermittent** chlorination of 1.0 ppm residual, at the end of 1 hour contact time. This level of treatment once every 8 hours is almost internationally applied. The hard-shelled organisms are most effectively controlled by **continuous** low-level chlorination, which may require free chlorine residuals of between 0.25 and 0.5 ppm.[19]

Shock Chlorination: Chlorine is a common disinfectant used in water systems, and is highly toxic to coliform and similar types of bacteria. Iron and sulfur bacteria are more resistant to chlorine's effects. This is because iron and sulfur bacteria occur in thick layers and are protected by the slime they secrete. A standard chlorine treatment may kill off bacterial cells in the surface layer but leave the rest untouched. In the case of iron bacteria, iron dissolved in the water may absorb disinfectant before it reaches the bacteria. For these reasons, iron and sulfur bacteria may be able to survive a chlorine treatment that would kill other types of bacteria.[8]

In view of the above quoted figures, a target residual chlorine of 0.1-0.2 ppm, which used to be applied at Taweelah B plant intake points, seems to be low to minimise sea fouling and prevent organisms to reach the power plant steam condenser. A second possibility for the presence of iron bacteria at the disinfected condenser is contamination during shutdown and maintenance period.

To explain the excessive growth of iron bacteria on the interior surfaces of the disinfected condenser, ferrous ions necessary for bacterial metabolism could have been furnished by the sacrificial anode and seawater itself. It is known that iron concentration in the Arabian Gulf waters near Al-Taweelah is 0.06 mg/l or ppm.

Meanwhile, Manganese ions exist at a level of 0.002 ppm.

Removing the sacrificial anode, although could solve the problem, it would have exposed condenser tubing and tube support plates to more corrosive conditions. Replacement with zinc alloy was believed to be the optimal solution in this case.

Increasing the shock and continuous chlorination doses was recommended according to the following figures:

Residual chlorine, from continuous dosing at the suction point of the intake pump, should be maintained at 0.25-0.35 ppm in winter, and 0.35-0.45 ppm in summer.

Shock dosing at 1.0 ppm was recommended to be practiced at 18 hours intervals in winter and 12 hours intervals in summer to ensure the reaching the recommended values mentioned above at the suction points in within 60 min. in winter and 45 min. in summer.

7. Conclusions

(1) Microbial induced corrosion has been presented briefly in this paper. Different classifications of bacteria, mechanisms of MIC due to the effect of bacteria have been outlined and the behavior of different metal alloys toward MIC has been described in short.

(2) A case study has been reported for the condenser of the steam turbine at unit 2 of Taweelah B station. Although the exit coolant water box was severely fouled with metabolic deposits of bacteria, acid washing was enough to wipe these deposits away. Hard rubber lining proved to be protective against MIC for the water boxes made of carbon steel.

(3) This experience added another proof confirming resistance of titanium alloys of the condenser tubes to MIC.

(4) Sacrificial anodes made up of zinc rather than steel alloys were recommended to avoid bio-fouling and subsequent MIC.

(5) Residual chlorine at the level of 0.15 to 0.2 proved to be insufficient to control bio fouling at Taweelah B, unit 2 steam condenser. However, proper cleaning of the deposited bio mass and maintaining a residual chlorine level of 0.25-0.35 ppm in winter and 0.35-0.45 ppm in summer proved to be quite efficient to mitigate MIC.

(6) Shock dosing of hypochlorite was recommended for residual chlorine of 1.0 ppm at time intervals of 12 hours in summer and 18 hours in winter in order to ensure the safe concentrations at the suction points within 45 min. in summer and 60 min. in winter.

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Appendix : Condenser data Sheet

Data Sheet

ABB ASEA BROWN BOVERI

Designation in schematic diagram
0165 VS 2220 R 0003

Design		ABB	Type	CB 39-1-124.5-2x3292/23/0.7	
Total no. of tubes		6584	No. of condensers/passes	1	1
Total surface area	m^2	5894	Bundle tubes O.D. × s × L	mm	23x0.7x12450
Support plate(Ratio of spacing to outer dia.)		-31.17	Outer tubes O.D. × s × L	mm	23x0.9x12450
Hotwell contents	m^3	25	Air cooler tubes O.D. × s × L	mm	23x0.9x12450

Cooling water system

- ☐ River water ☐ Lake water ☒ Sea water
- ☐ Wet cooling tower ☐ Dry cooling tower
- ☒ Siphon operation ☐ Pressure operation

Operating data (with MR turbine load)

Turbine exhaust flow	kg/s	110	Cooling water flow	m^3/s	5.85
Vacuum	bar	0.135	Water velocity in tubes	m/s	2.45
Cooling water temp.	°C	35	Pressure drop	bar	0.38
Min. cooling water temp.	°C	18	Max. cooling water temp.	°C	35

O_2 content for operation without makeup water

O_2 content	mg/kg	0.01	at turbine load	%	MC
O_2 content	mg/kg	0.01	at turbine load	%	MCR

Design data

Test pressure before erection	bar		
Test pressure after erection	bar		

Materials (according to DIN)

Bundle tubes	ASTM B 338 GR 2	Tubesheet	ASTM B 265 GR 3
Outer tubes	ASTM B 338 GR 2	Tubesheet cladding	–
Waterbox		☒ Hard rubber lined	☐ Coated

Additional measures: ☐ $FeSO_4$ dosing ☐ Debris filter

Tube cleaning: ☒ Sponge ball ☐ Brush

Plant: Al Taweelah B Unit 1	ABB order number (WBZ): 1-360 449-023-101		Language: E	Sheet no.: 1	No. of sh.: 1
Denomination: Condenser, Type CB		Document no.: HTDM 405 017			
Identification no.: HTDM 001798	Power station designation: 11 MAG 10 AC 001				