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MSF evaporator materials evaluation after 20 years in service

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ABSTRACT

Phase 2-A and Phase 2-B of the Al-Jubail multistage flash (MSF) evaporation plants were commissioned in 1982. The two phases consist of 40 desalination units and were designed and built by different contractors. A wide variety of materials was used in the construction of different components of the evaporators, namely, flash chambers (carbon steel, AISI 316L cladded carbon steel), heat transfer tubes (90/10 Cu/Ni, Ti), water boxes (AISI 316L cladded carbon steel, Al bronze-cladded carbon steel), tube sheet [90/10 Cu/Ni, AISI 316L cladded carbon steel) and tube support (carbon steel and 316L cladded carbon steel). The role of design of the flash chamber and venting system on corrosion behavior of the evaporator construction materials was studied. Based on the corrosion rates of the materials at different locations of the desalination units and type and nature of the failures that occurred, the performance of the materials after years in service has been evaluated. The root cause of material failure has also been investigated. The results of the studies indicate that during 20 years operation, the desalination units encountered many corrosion problems. It has been concluded that a good ventilation design will minimize the corrosion in flash chambers. Good operation and maintenance would prolong the lifetime of the flash chambers.

Keywords: MSF evaporator; Flash chamber; Heat exchanger; Heat recovery; Heat rejection; Brine heater; Condenser; Vent system; Corrosion rate; Material performance

1. Introduction

Seawater multistage flash (MSF) evaporation plants have a multitude of corrosion problems due to their operation in relatively aggressive environments comprising seawater, seawater air and salt-air aerosol, corrosive gases, very fast or slow moving liquids, particulates contained in high velocity fluids, etc. Therefore, a study on the corrosion behavior of materials of construction in desalination plant environments constitutes an essential aspect of desalination technology. Material selection is the most dominant consideration for a trouble-free, efficient, reliable and economically viable operation of the desalination plant. The prime requirement for the trouble-free operation of a thermal desalination plant is the application of corrosion-resistant but cost-effective construction materials.

In recent years, a considerable number of studies has been carried out concerning the corrosion performance of MSF thermal desalination plants, mostly in the Middle East. Corrosion problems in low-temperature units of Abu Dhabi desalination plants during their early stages of operation were reported [1]. Severe crevice corrosion occurred at the joints of Ti tubes and 904L tube sheets. Anodes, initially Al alloy but replaced within 3 to 4 months with iron, were installed to provide CP and to neutralize acidity inside the crevices. Al-brass tubes suffered impingement corrosion and were replaced with

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90/10 Cu Ni. Erosion–corrosion was mitigated by replacement with 254 SMO.

A study on the vapor side corrosion of the 70/30 and 90/10 Cu Ni condenser tubes of the Jabel Dhana distillers at the Umm Al-Nar power plant was carried out [2]. Two different types of corrosion problems were noted, namely, pitting corrosion when some of the pits penetrated the entire thickness of the tube wall; the second type of damage failure involved circumferential cracks which appeared in a number of tubes thought to be from the upper edge of the tube bundle. Pitting was attributed to the corrosive oxygenated carbonic acid, the source of which is non-condensable gases. Vapor corrosion of evaporators in MSF unit #100 of the Al-Khafji desalination and power plants was investigated [3]. Corrosion rates of CuNi coupons exposed to non-condensable (NC) gases in vent lines were much higher than those exposed in different evaporator stages. High reactivity of CuNi was attributed to the presence of sulfur in NC gases. A maxima in corrosion rates was found in the middle stages (10–13) in all the alloys. This has been explained by a combined effect of temperature, air leakage into the vent line and cascading of NC gases, all providing the most favorable condition for corrosion in these stages. Failure of condenser tubes in stage 4 of the Jeddah plant was also reported [4]. Corrosion of condenser tubes appeared to be mainly due to dissolution of the CO_2 along with some S-containing compounds. It was recommended that stages 1–4 should be directly connected to the vent line for quick and complete ventilation of non-condensable gases present at the vapor side of the evaporator. Corrosion of flash chamber floor plates in #11 to 16 stages of a MSF desalination plant was reported [5]. The flash chamber plates were made of steel cladded with AISI 317 SS showed pitting after 4 years of service. The cause of the problem appeared to be incomplete drainage of high chloride water during a fairly long period of shut-down, creating conditions favorable to pitting corrosion of austenitic steel. The absence of drainage was attributed to an uneven level of floor plates at different stages of the desalination unit.

Al-Jubail Phase-I and II MSF desalination plants, commissioned in the early 1980s to cater to the water requirements of the cities of Al-Jubail and Riyadh are the largest agglomeration of thermal desalination units in the world, having a production capacity of about 240 million gallon (240 MIG) of water per day. The plants are dual-type cogeneration water–power plants. The plants are located on the Arabian Gulf coast and have been providing an overall satisfactory performance since their inception in 1983.

This paper presents the results of a materials performance study of the Al-Jubail desalination plant phase-II evaporators after 20 years of operation. The material evaluation is based on observations from visual inspection and corrosion rate data obtained for different components of four desalination units (C-2 an C-3, C-4 and C-5).

2. Plant operating conditions

Table 1 summarizes the operational conditions inside each stage of an MSF plant. There are 22 stages: the heat recovery section consists of 1–19 stages; #1 and #2 are the high-temperature stages. The heat rejection section is confined to stages 20–22. The table shows inlet and out brine temperatures, steam pressure and quantity of the steam. The table also provides data for brine heaters. The brine flow rates for heat recovery and heat rejection are also given.

Table 1
Operation conditions of an MSF plant

Stage no.	Brine temp. (°C)		Steam		
	In	Out	Temp. (°C)	Pressure (Kpa)	Quantity (kg/h)
Heat recovery section:					
1	82.7	85.0	87.0	62.44	52,000
2	80.3	82.7	84.6	56.99	51,400
3	78.0	80.3	82.3	51.96	50,800
4	75.7	78.0	80.0	47.43	50,100
5	73.4	75.7	77.7	43.09	49,400
6	71.1	73.4	75.4	39.18	48,800
7	68.9	71.1	73.1	35.61	48,100
8	66.6	68.9	70.9	32.33	47,400
9	64.4	66.6	68.6	29.33	46,700
10	62.2	64.4	66.4	26.59	46,000
11	60.0	62.2	64.2	24.09	45,200
12	57.8	60.0	62.0	21.82	44,600
13	55.7	57.8	59.8	19.74	43,900
14	53.5	55.7	57.7	17.88	43,600
15	51.4	53.5	55.5	16.14	42,700
16	49.3	51.4	53.4	14.56	41,800
17	47.2	49.3	51.3	13.14	40,800
18	45.2	47.2	49.2	11.86	39,800
19	43.3	45.2	47.2	10.69	38,800
Heat rejection section:					
20	40.9	43.3	45.6	9.89	31,000
21	38.2	40.9	43.2	8.93	35,800
22	35.0	38.2	41.5	7.96	40,300
Brine heater:					
***	85.0	90.6	98.8	97.4	125,750
Brine flow rate:					
Heat recovery		(kg/h)		13,035,400	
Heat rejection		(kg/h)		8,629,000	

Table 2
Evaporator construction materials

	C-2 and C-3	C-4	C-5
Flash chamber			
1st and 2nd stages	CS Cladded by 316L SS	CS Cladded by 316L SS	CS Cladded by 316L SS
3rd–last stage	CS	CS	CS
Brine gate	316L SS	316L SS	316L SS
Distillate trough	316L SS	316L SS	316L SS
Distillate tray	316L SS	316L SS	316L SS
Condenser heat recovery:			
Tube	90/10 Cu/Ni	90/10 Cu/Ni	90/10 Cu/Ni
Tube sheet	CS cladded 90/10 Cu/Ni from brine side and 316L from vapor side for first two stages For other stages CS cladded by 90/10 Cu/Ni from brine side only.	CS cladded 90/10 Cu/Ni from brine side and 316L from vapor side for first two stages For other stages CS cladded by 90/10 Cu/Ni from brine side only.	CS cladded 90/10 Cu/Ni from brine side and 316L from vapor side for first two stages For other stages CS cladded by 90/10 Cu/Ni from brine side only.
Tube Support	316L SS for first two stages and CS for other stages.	316L SS for first two stages and CS for other stages.	316L SS for first two stages and CS for other stages.
Water box	CS cladded by 90/10 Cu/Ni	CS cladded by 90/10 Cu/Ni	CS cladded by 90/10 Cu/Ni
Condenser heat rejection			
Tube	Titanium	Titanium	Titanium
Tube sheet	Al-bronze	Al-bronze	Al-bronze
Tube support	CS	CS	CS
Water box	CS cladded by Al-bronze	CS cladded by Al-bronze	CS cladded by Al-bronze
Condenser brine heater			
Tube	Modified 70/30 Cu/Ni	Modified 70/30 Cu/Ni	Modified 70/30 Cu/Ni
Tube sheet			
Water box			

3. Information on the materials

Table 2 provides information about the materials of construction of the evaporators in C-2, C-3, C-4 and C-5 desalination units — a total of 40. The information about the construction materials of the flash chamber and heat exchanger tubes, namely heat recovery, heat rejection and brine heater, is detailed.

4. Evaluation of the materials

4.1. Division and side walls

The division and side walls are made of carbon steel for all stages except the first two, which are cladded by 316L SS. The corrosion in these sections is normally general corrosion.

The corrosion rate was calculated based on thickness measurement on division and side walls. The calculations were made at three different locations, namely, brine, flash and vapor sections. Table 3 provides the maximum corrosion rate values at different locations of flash chamber. Figs. 1 and 2 show the corrosion behavior of two different desalination units at three locations. In general, the average corrosion rates of the flash chambers at the three locations are in the design range with different characteristics in individual stages. The corrosion rate measurements of flash chambers show that the corrosion rates in vapor zone were in the same range for all the stages with a slight increase in stage #3 and the last stage. In the flash zone, the highest corrosion rate was observed in the last stage and fluctuated in the other stages.

While in the brine section, the corrosion rate fluctuated within a very small range then started to increase in the last three stages until it reached the maximum at the last stage. The concentration of non-condensable gases and vapor velocity is higher in the high temperature stages as compared to the low temperature stages. But at the low temperature stages, the oxygen concentration is playing a key role in influencing the corrosion rate due to the high possibility of air ingress [6].The maximum corrosion was found near the demister in the form of low pitting which could be related to the galvanic action between 316 SS demister material and division wall (carbon steel). Also, some pits were found at the water line due to the existence of concentration and dearation cells.

Table 3
Material performance inside flash chamber

	C-2 and 3	C-4	C-5
Flash chamber			
Max. corrosion rate brine section (mm/y)	0.18	0.213	0.22
Max. corrosion rate flash section (mm/y)	0.173	0.20	0.207
Max. corrosion rate vapor section (mm/y)	0.094	0.176	0.28
Design life (y)	20	20	20
Condensers			
Actual situation (1st stage)			
Plugged tubes	—	189	58
Over 60% penetration	—	263	143
Over 30% but less than 60% penetration	—	306	610
No defect	—	1032	854
Rejection stages			
With defect	0	0	0

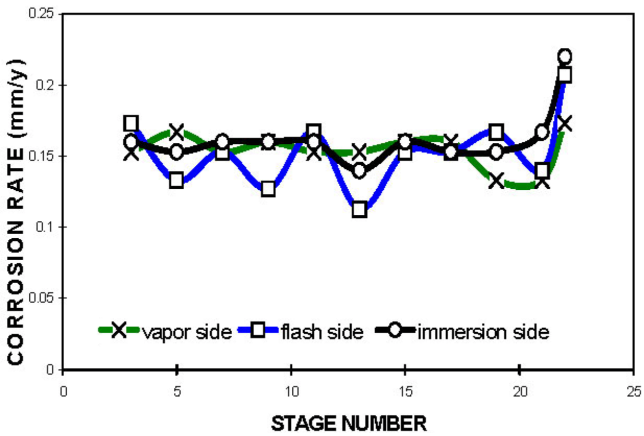

Fig. 1. Corrosion behavior of flash chamber in different stages on the basis of thickness measurement (Desal #3, C-5).

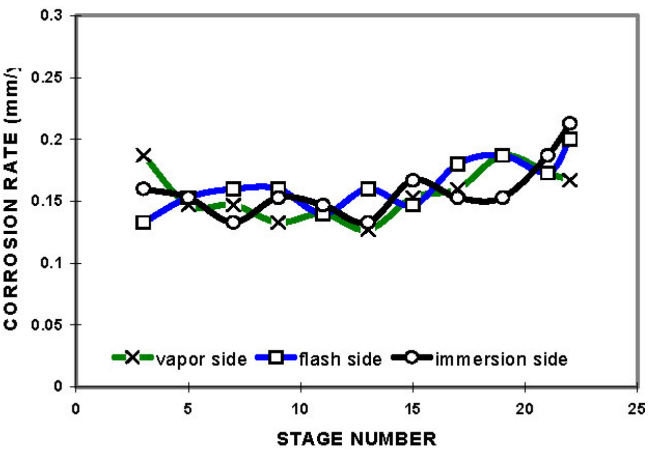

Fig. 2. Corrosion behavior of flash chamber in different stages on the basis of thickness measurement (Desal #21, C-4).

4.2. Floor plate

The pitting of the floor plate was observed mainly near the brine gate at different stages with maximum depth of 12 mm which has been caused by galvanic action between brine gate material (316l SS) and floor material (carbon steel). Figs. 3 and 4 show the pitting on the floor near the brine gate.

In general, the corrosion activity at brine side during the running of the evaporator is low due to the low oxygen concentration and high pH value of the brine, but the corrosion activities while the unit is down tend to be high.

4.3. External roof

During the inspection of the flash chamber external roof surface, severe corrosion was found in this area (all ten units) (Fig. 5). Two across beams are installed in stages #5 and #15 and the corrosion was found concentrated in this area. All the T-beams were found badly corroded with localized thinning on the roof plate. The main reason of

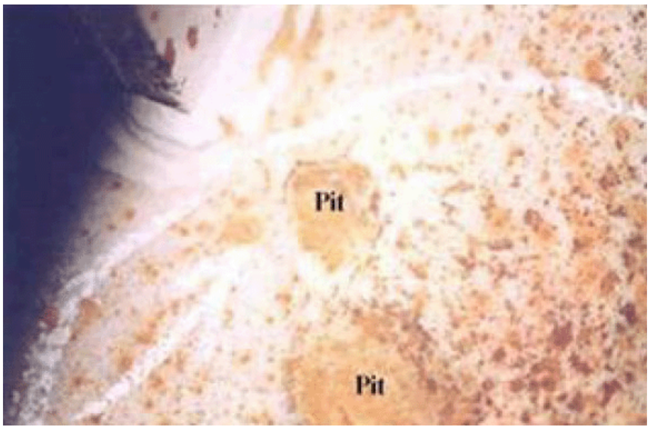

Fig. 3. Pitting corrosion in the floor of flash chamber.

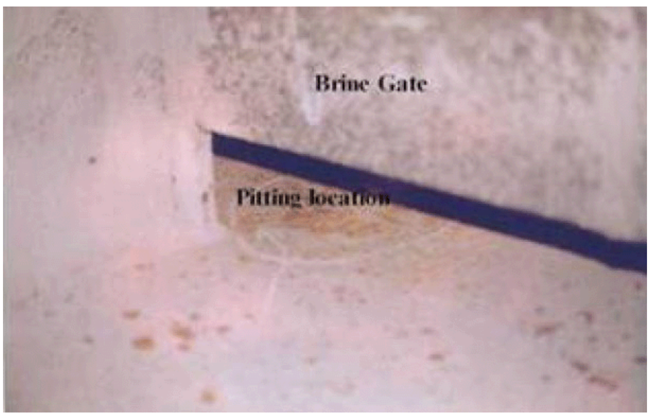

Fig. 4. Pitting on carbon steel desalination floor near the brine gate manufactured from 316 SS.

this corrosion is the poor ventilation and stoppage of water in that area.

In general, the corrosion of the flash chamber roof under insulation can be affected by many factors. The most important factors are: (1) temperature, (2) time of wetness and (3) salinity of the atmosphere.

4.3.1. Temperature

The effect of temperature on the corrosion rate is well known. An increase of 10°C can increase the corrosion rate by one order of magnitude [7]. With regard to the corrosion of the flash chamber roof, the increase in temperature has two side-effects: one is positive and the other is negative. The negative effect is the increase in the roof plate corrosion rate and the positive effect is the reduction in time of wetness with increase of temperature.

4.3.2. Time of wetness

Considering the flash chamber roof corrosion, wetness can arise from the following sources: (1) rain, (2) humidity and (3) process pipe lines. The corrosion rate will be constant with increase in time of wetness, but cumulative metal loss will be increased with increase in time of wetness.

4.3.3. Salinity of the atmosphere

Atmospheric salinity is one of the main factors affecting corrosion of metals in the atmosphere. The monitoring of atmospheric salinity was carried out at SWDRI at the Al-Jubail plant area. The following mechanistic path appears to be followed:

The condensation was observed on the aluminum sheet. This condensation carried over some salts from the atmosphere. During the drying process, the water was evaporated and salts were deposited on the top of aluminum sheet or on insulation material. Due to high humidity in the atmosphere, any water on the top of the aluminum sheet would penetrate through the sheet and likely corrode the underneath metal as a result of the corrosive nature of seawater. To avoid roof corrosion problems, three points should be considered: (1) good ventilation in order to minimize wetness time, (2) application of a good quality epoxy coating considering the lifetime of the coating and (3) periodic inspection of coating and roof material.

Fig. 5. Photograph showing severe corrosion of stiffeners and roll plates in Area C-5

4.4. Distillate trough

Shallow pits were found in the distillate trough constructed of 316 L. The main cause of these pits is the presence of water during long shut-down periods. The pitting initiation of stainless steel is markedly affected by stagnancy of water with a high chloride concentration, while in the propagation stage, the concentrations of oxygen and chloride with low flow velocity are the main factors in defining the rate of penetration. To avoid this problem, the unit should be dried well before it is handed over to maintenance, especially the product water trough.

4.5. Tube support

The tube supports were manufactured from 316 L in the first two stages and from carbon steel for the other stages. The stainless steel supports were in good condition but the carbon steel supports were not. The corrosion was observed at two locations: at the bottom, which is welded to the product water tray, and at the tube opening. The mechanism of corrosion in both locations appeared to be galvanic.

The lower section of the tubes support was connected to the product water tray which was fabricated from 316 L; therefore, the galvanic corrosion occurred. Almost 35% of the original thickness was lost due to corrosion. The main factors controlling the galvanic action in this location are: (1) pH, (2) conductivity of product water and (3) oxygen content.

The second problem facing tube support is the tube opening. The carbon steel tube support was in contact with the tube material made from 90/10 Cu/Ni. Due to the difference in corrosion potential between these materials, the galvanic action was actuated. The main factor controlling the galvanic action in this location was non-condensable gases, which affected the pH of condensing water over the tubes.

Figs. 6 and 7 show the severity of corrosion on the lower part and lug of tubes support.

4.6. Condenser collar

Fig. 8 shows a schematic of condenser collar in a flash chamber. The corrosion of the condenser collar was

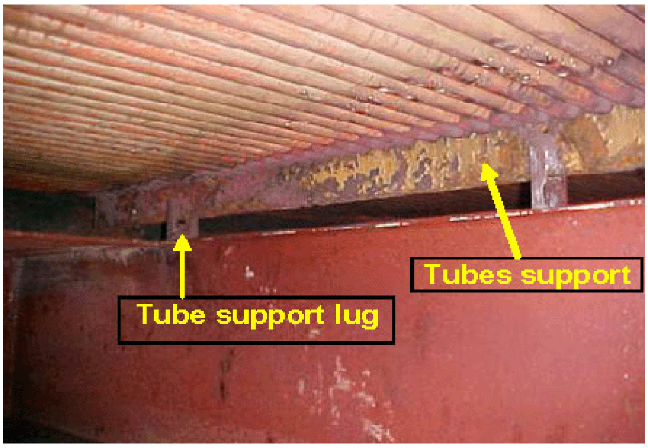

Fig. 6. Corrosion of lower section of tube support and lugs.

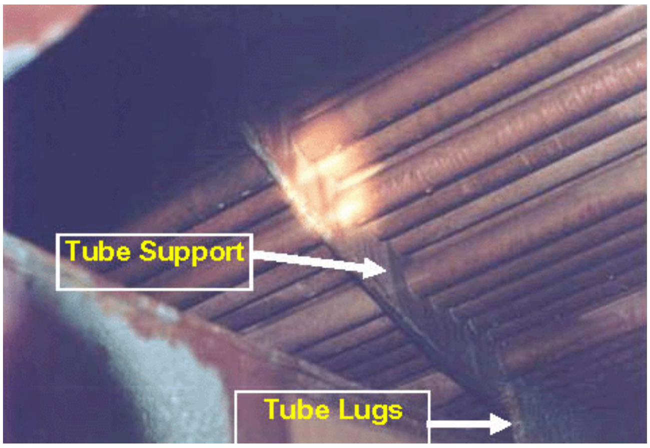

Fig. 7. Corrosion of tube support lugs.

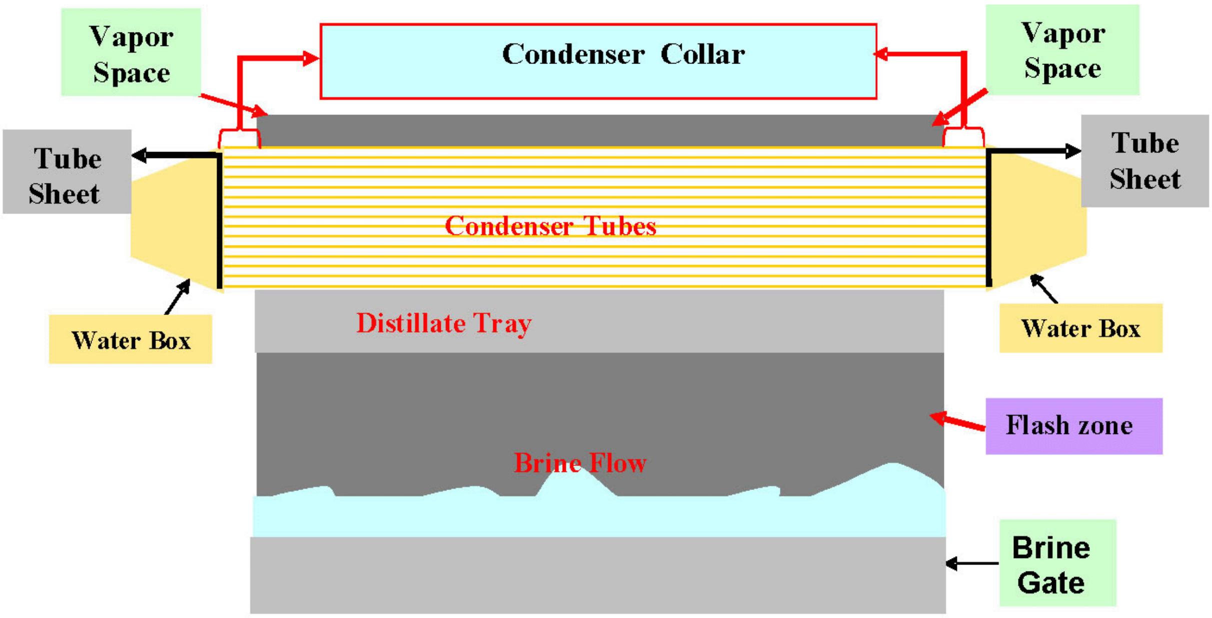

Fig. 8. Schematic of condenser collar in a flash chamber.

observed in C-4 area due to design problems. Fig. 9 shows the presence of pinholes in this area.

The pitting and general corrosion were observed in this area with full through wall pitting penetration in some areas. The tube length was longer than the width of flash chamber, so as to increase the heat transfer area. Therefore, the flash chamber was extended in the tubes bundle area only which will result in a layer of low pH water which will always be present in the condenser collar. Also, the water level in this area could cover the first row of the tubes. With the presence of non-condensable gases which could be dissolved in this layer, the pH will be decreased, and also the galvanic action between the carbon steel support and 90/10 Cu/Ni and

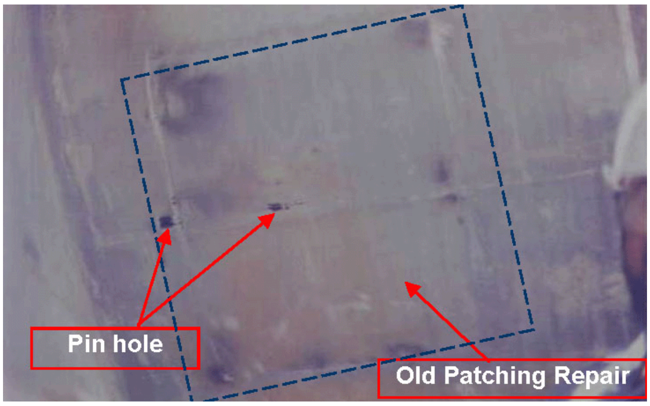

Fig. 9. Corrosion in condenser collar of one flash chamber.

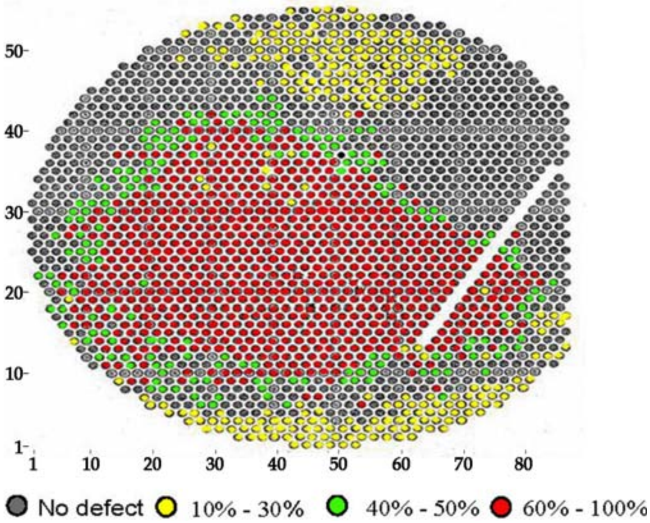

Fig. 10. Results of eddy current studies of the first stage condenser.

tubes would play a main role in the corrosion process. This problem can be resolved by modifying the design stage, this can be done by decreasing the length of tubes.

4.7. Condenser tubes

After approximately 14 years of evaporator operations, a sudden appearance of large numbers of 90/10 Cu/Ni tube failure in the first stage was noted. Fig. 10 shows the result of eddy current testing. The results of eddy current can be summarized as followed:

- The defective tubes are concentrated at the center of the lower half of the tube bundle.
- The corrosion started on the external surface (vapor side).
- Most of the defects are concentrated at the tube end closer to the tubes sheet.
- All units in C-4 area show same severity of corrosion.
- Metal losses from the external surface have also been noticed on some of the tubes at the tube support points.
- The severity of corrosion in the tube is higher at one end compared to other end.
- The rotary scan by eddy current is required and important with long tube testing in order to evaluate the condenser tubes condition.

It was found that tube failure is due to crevice corrosion, which is accelerated by the following conditions [3]:

- Galvanic action between 316 SS and 90/10 Cu/Ni.
- Low pH due to the accumulation of CO_2.
- Vibration of tube due to the gap created between tube and tube support.

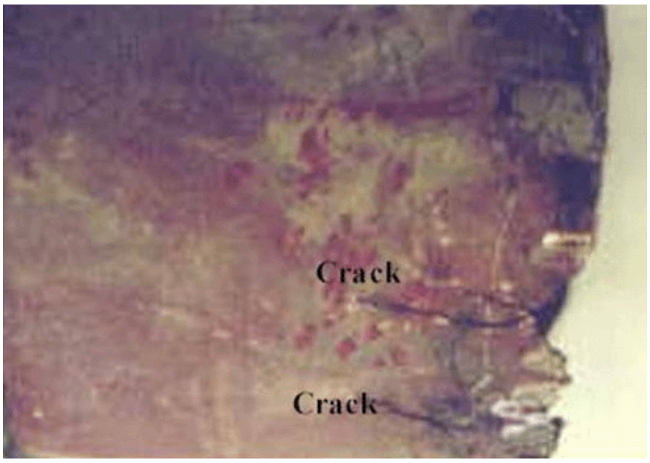

Fig. 11. Outside surface of vent line.

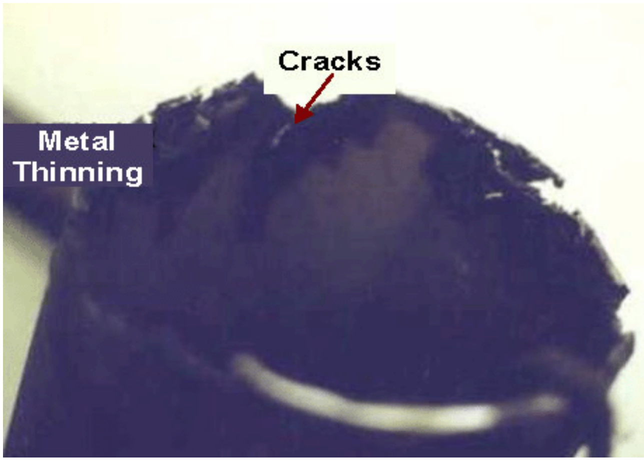

Fig. 12. Inner surface of vent line.

4.8. Vent lines piping

The vent piping system is made from stainless steel 316 for high-temperature stages and FRP for low-temperature stages. The visual inspection of inner and outer surfaces shows many cracks and pipe thinning. The cracks are initiated from a thinner area with many branches from the inner surface. All the cracks are found near the weld joints. Figs. 11 and 12 show the extent of damage on vent line pipe. The corrosion in the pipe can be attributed to the low pH.

5. Conclusions

1. Many severe corrosion problems were observed in desalination units during 20 years of service.

2. The corrosion above the demister is more severe compared to under the demister during normal operation.

3. A good ventilation system design will minimize corrosion activities inside flash chambers during normal operation.

4. Good operation and maintenance activities increase the lifetime of flash chambers.

6. Recommendations

1. Improve ventilation system design to minimize corrosion inside the flash chamber.

2. Monitor residence time of CO_2 inside the flash chamber to improve performance of ventilation system.

3. During shut down, complete flushing and subsequent drying of flash chambers must be carried out before opening for maintenance.

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