JKAU: Eng. Sci., Vol. **32** No. 2, pp: 77 – 87 (1444 A.H. / 2022 A.D.)
Doi: 10.4197/Eng. 32-2.6

Degradation of Condenser Tubes of a Nuclear Power Plant Exposed to Harsh Process Conditions

Dheya Sh. Al-Othmany[1]
Nuclear Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

Abstract. Nuclear Power Plants condensers face various problems during their lifetime. One of very common problem is the leakage of Al-brass condenser tubes. Usually with the extended operation of condensers for 20 year or so, one can expect replacement of about 15-20% of condenser tubes due to leakage. One of the significant reasons of leakages of condenser tubes is ammonical corrosion. This ammonical corrosion can be minimized by controlling temperature along with various prevention method of corrosion. Current method used in power plant condensers is Sacrificial Cathodic Protection (SCP). A number of experiments were performed in the lab to protect corrosion by using SCP as well as the Impressed Current Cathodic Protection (ICCP). It was found that the ICCP is much better than SCP.

Keywords: condensers, nuclear power plants, leakages of tubes, corrosion, sacrificial cathodic protection,

1. Introduction

The recent trend toward all volatile compound using ammonia and ammonia compounds to control feed water chemistry in nuclear power plant, accentuates, the need for careful selection of corrosion resistance condenser tube alloys. Hydrazine is commonly employed in steam generator power plant system to scavenge O_2, adjust PH and reduce the corrosion rate of steel. These chemicals are readily dissolved in boiler feed water [1,2]. In contrast to ammonia, they do not tend to concentrate in subcooled condensate in air cooler section of steam condenser. This hydrazine can breakdown to some extent ammonia with the result of ammonia concentration at somewhat lower level than occurs with straight ammonia injection [3].

Aluminum-Brass tubes are being used in condensers and heat exchangers since long time because of the fact that this material is relatively cheaper. But the tube failure history indicates a higher failure rate with this material [4]. The problems are being resolved by studying and implementing the recommendations to different power plants. Failure analysis of tubes removed from west water box of condensers reveals that central zone tubes (air cooler zone) suffered ammonia corrosion attack (on outside tubes) while remaining zones suffered internal erosion-corrosion and deposits of marine organism [5].

The concentration of ammonia and oxygen is sufficiently low to cause any corrosion. However high concentration of ammonia and oxygen can develop in air cooler sections of condensers, which can cause corrosion of copper alloys. To know the corrosion rate

[1] Corresponding author: **dothmany@kau.edu.sa**

with passage of time, experiments are performed for various time [6]. Experiments are also done to know the effect of temperature of ammonical corrosion of Al-Brass material. It is seen that, with the increase in temperature, corrosion rate increases. A study was conducted to determine the feasibility of cathodic protection of Al-Brass material with Zn metal. A laboratory cell was used to determine required current density for Al-Brass material using SCP. Also effective of Impressed Current Cathodic Protection (ICCP) is compared with sacrificial cathodic protection (SCP). It is seen that ICCP is more effective than SCP [8].

Ammonical Corrosion and its Prevention Aluminum-Brass tubes are being used in condensers and heat exchangers since long time because of the fact that this material is relatively cheaper [9]. But the tube failure history indicates a higher failure rate with this material. The problems are being resolved by studying and implementing the recommendations from plant to plant. Failure analysis of tubes removed from west water box reveals that central zone tubes (air cooler zone) suffered ammonia corrosion attack (on outside tubes) while remaining zones suffered internal erosion-corrosion and deposits of marine organism [10.11].

In power plant condensers, the ammonia attack has been observed in air cooler zone on external surface of condenser tubes on the hot well side. The severe grooving is found, more prominently at support plate with wall thickness reduction of more than 50%. The source of ammonia is from the breakdown of hydrazine (added to boiler feed water) dissolved in the condensed water in the air cooling zone. This ammonia trickles down the tube support plates creating groove-like corrosion. This is owing to poor resistance of Aluminum Brass against any ammonia present. This ammonical corrosion can be prevented by following ways [12-14].

2. Materials and Methods

At laboratory scale, the electrolysis process is used to study the condenser tube corrosion. By using this process we can determine the effectiveness of ICCP, and compare to that of SCP. Required surface area of sample was determined with the help of Vernier caliper and following readings were obtained (Table 1);

Table 1: Dimensions of coupons

No.	*L1*	*L2*	*L3*	*W1*	*W2*	*W3*	*T1*	*T2*	T3
1	3.68	3.72	3.7	2.72	2.78	2.78	0.12	0.12	0.12
2	3.5	3.45	3.5	3.42	3.42	3.4	0.12	0.12	0.12
3	3.62	3.65	3.65	3.48	3.46	3.48	0.12	0.12	0.12
4	3.68	3.71	3.76	3.48	3.44	3.45	0.12	0.12	0.12
5	3.68	3.71	3.7	3.48	3.44	3.45	0.12	0.12	0.12
6	3.55	3.55	3.55	3.15	3.15	3.15	0.12	0.12	0.12

Table 2: Surface areas of coupons

No.	L_{avg}	W_{avg}	T_{avg}	*S.A (cm²)*	*S.A (dm²)*
1	3.7	2.76	0.12	21.9744	0.219744
2	3.483333	3.413333	0.12	25.43476	0.254348
3	3.64	3.473333	0.12	26.99307	0.269931
4	3.716667	3.456667	0.12	27.41616	0.274162
5	3.696667	3.456667	0.12	27.27309	0.272731
6	3.55	3.15	0.12	23.973	0.23973

By using following formula, surface area was obtained (Table 2).

$$S.A = 2 \times (L \times W + W \times H + H \times L)$$

To find out corrosion rate of Al-Brass, “Weight loss method” was adopted, and the corrosion rate was calculated using the following formula:

Corrosion rate = Wt. loss / (surface Area x Immersion Time)

Experiments were conducted to determine effect of time on corrosion rate of Al- Brass material. Also experiments to determine effect of temperature (open to atmosphere) on corrosion rate of Al-Brass material and same was repeated to determine effect of temperature (close to atmosphere) on corrosion rate of Al-Brass material. The effect of sacrificial cathodic protection (SCP) on corrosion rate of Al-Brass material was also investigated. Studies were also done to determine effect of ICCP on corrosion rate of Al-Brass material. The specimens were cleaned and polished by emery paper. Then specimens were weighed and surface area was measured. Then specimens were placed in 10% ammonical solutions for different time. Then it is dried and weighed again. Then corrosion rate in milligram per square decimeter (mdd) was determined by using weight loss method. Table 3 summarizes the experimental methodology for corrosion rate for Al-Brass materials when open to atmosphere.

Table 3: Corrosion rate for Al-Brass Materials when open to atmosphere

Experiment #	Coupon #	Initial weight (W1) gm	Final Weight W2 (gm)	Time of Dip (Hr)	Corrosion Rate mdd
1	6	9.9810	9.9810	2	3.75
2	3	12.0679	12.0058	40	5.75
3	4	11.8603	11.7668	90	3.79
4	3	11.7126	11.6615	143	1.32

Experiments were conducted to determine effect of temperature (open to atmosphere) on corrosion rate of Al-Brass material. The specimens were cleaned and polished by emery paper. Then specimens were weighed and surface area was measured. Then specimens were placed in beakers containing 10% ammonical solutions. Then these beakers were placed in water bath for different temperature (32°C, 40°C, 60°C, 80°). Then it is dried and weighed again. Then corrosion rate was determined by using weight loss method (Table 4).

Table 4: Effect of temperature on Al-Brass Materials when open to atmosphere

Experiment #	Coupon #	Temperature C	Initial weight (W1) gm	Final Weight W2 (gm)	Time of Dip (Hr)	Corrosion Rate mdd
1	6	32	9.9828	9.9810	2	3.75
2	3	40	11.7987	11.7945	3	5.19
3	3	60	12.1411	12.1304	5.45	7.27
4	3	80	11.9147	11.9079	5.30	4.75

Experiments to determine effect of temperature (close to atmosphere) on corrosion rate of Al-Brass material. The specimens were cleaned and polished by emery paper. Then specimens were weighed and surface area was measured. Then specimens were placed in beakers containing 10% ammonical solutions. These beakers are closed so that dissolved oxygen can not come out the solution. Then these beakers were placed in water bath for different temperature (32 ^{0}C, 40 ^{0}C, 60 ^{0}C, 80 ^{0}C). Then it is dried and weighed again. Then corrosion rate was determined by using weight loss method (Table 5).

Table 5: Effect of temperature on Al-Brass Materials when close to atmosphere

Experiment #	Coupon #		Temperature C	Initial weight (W1) gm	Final Weight W2 (gm)	Time of Dip (Hr)	Corrosion Rate Mdd
1	6		40	9.8340	9.8321	3	2.64
2	4		60	11.9521	11.9258	5.45	17.87
3	6		80	9.9114	9.9040	5.15	5.99
4	4		80	11.5485	11.5378	3	13.21

Experiments to determine effect of sacrificial cathodic protection (SCP) on corrosion rate of Al-Brass material. The specimens were cleaned and polished by emery paper. Al-Brass (used as cathode, material to be protected) was placed along with Zn metal which is used as anode. These specimens were weighed and surface area was measured. Then specimens were placed in beakers containing 10% ammonical solutions for different time. Then it is dried and weighed again. Then corrosion rate was determined by using weight loss method. Experiments also conducted to determine effect of impressed current cathodic protection (ICCP) on corrosion rate of Al-Brass material. The specimens were placed in beakers containing 10% ammonical solutions for different time. Al-Brass (used as cathode, material to be protected) was connected to negative terminal of battery, while positive terminal is connected with Zn metal (used as anode) as done by a number of authors [15-18]. These specimens were weighed and surface area was measured. Then it is dried and weighed again. Then corrosion rate was determined by using weight loss method.

3. Results and Discussion

The effect of corrosion rate was studied, and it was found that the initially corrosion rate increases due to absence of oxide layer, and then decreases due to formation of oxide layer as shown in Figure 1.

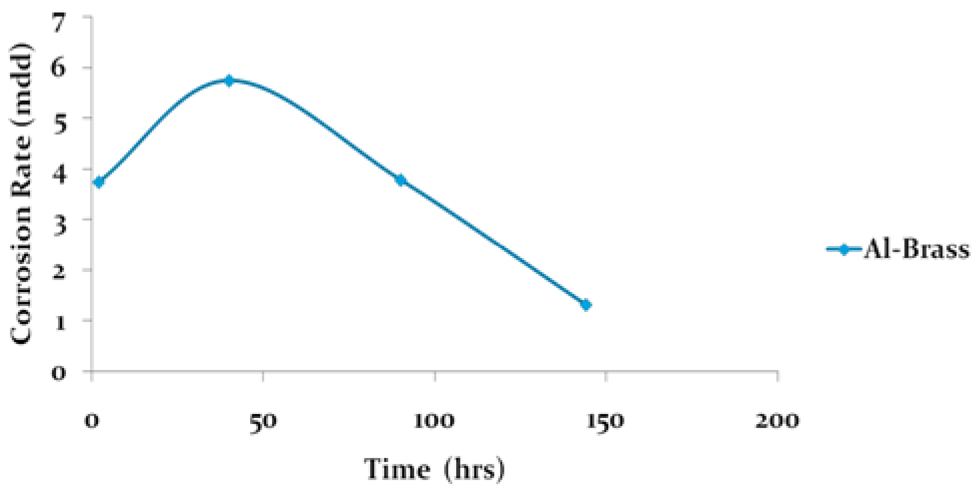

Figure 1: Corrosion rate vs time

An increase in temperature will tend to stimulate corrosive attack by increasing the rate of electrochemical reactions and diffusion processes. For a constant humidity, an increase in temperature would therefore lead to a higher corrosion rate as shown in Figure 2. Raising the temperature will, however, generally lead to a decrease in relative humidity and more rapid evaporation of the surface electrolyte [19-21].

For closed air spaces, such as indoor atmospheres, it has been pointed out that the increase in relative humidity associated with an increase in temperature will cause more corrosion rate (Figure 3). Comparison between corrosion rate of open to atmosphere (OTA) and closed to atmosphere (CTA). In case of OTA, there is less corrosion rate because of decrease in humidity than CTA (Figure 4).

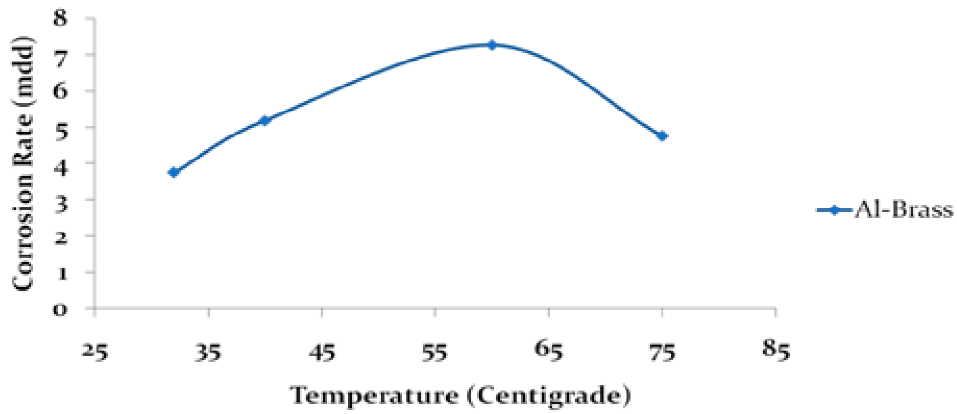

Figure 2: Corrosion rate vs temperature

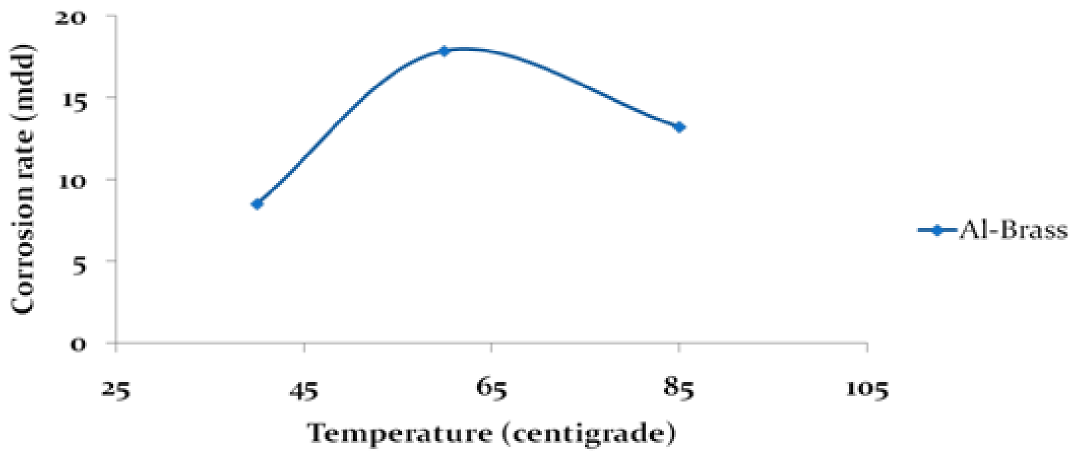

Figure 3: Corrosion rate vs temperature (Close to atmosphere: CTA)

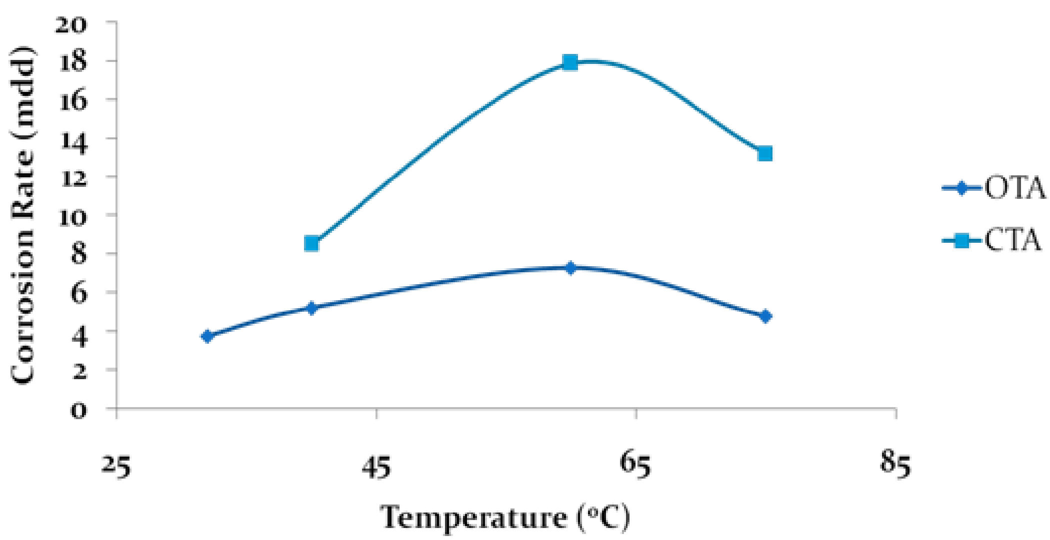

Figure 4: Comparison of OTA and CTA

SCP is efficient method to reduce ammonical corrosion, as shown in Figure 5. In this case, the Al-Brass material act as cathode, while Zn act as anode. So, Al-Brass material is protected, while Zn corroded [20], see Table 6. ICCP is an excellent method to reduce corrosion. In this case, a DC current is applied externally with the help of power supply. Only less than 1 mA/dm^2 is required (Table 7).

Table 6: Sacrificial cathodic protection

Exp. No.	Time (hrs)	Coupon No.	Surface Area (dm2)	Initial Weight (g)	Final Weight (g)	Corrosion Rate (mdd)
1	3.20	01 (Al-Brass)	0.22	9.0933	9.0922	1.56
		4 (Zn)	0.15	4.8170	4.8130	8.33
2	90	01 (Al-Brass)	0.22	9.0587	9.0594	!
		2 (Zn)	0.15	8.5112	8.4066	7.75

Table 7: Impressed Current Cathodic Protection

Exp. No.	Current (mA)	Coupon No.	Surface Area (dm2)	Initial Weight (g)	Final Weight (g)	Wt. deposited (mg)
1	14.5	07 (Al-Brass)	0.11	4.3161	4.3262	10.1
		4 (Zn)	0.15	8.1470	8.1140	33
2	9	07 (Al-Brass)	0.11	------------	------------	-----------
		2 (Zn)	0.15	7.8773	7.8546	22.7
3	3.0	07 (Al-Brass)	0.11	4.2243	4.2236	6
		06 (Zn)	0.15	8.0498	8.0366	13.2
4	1.0	07 (Al-Brass)	0.11	4.2047	4.2043	4
		04 (Zn)	0.15	4.7341	4.7285	5.6

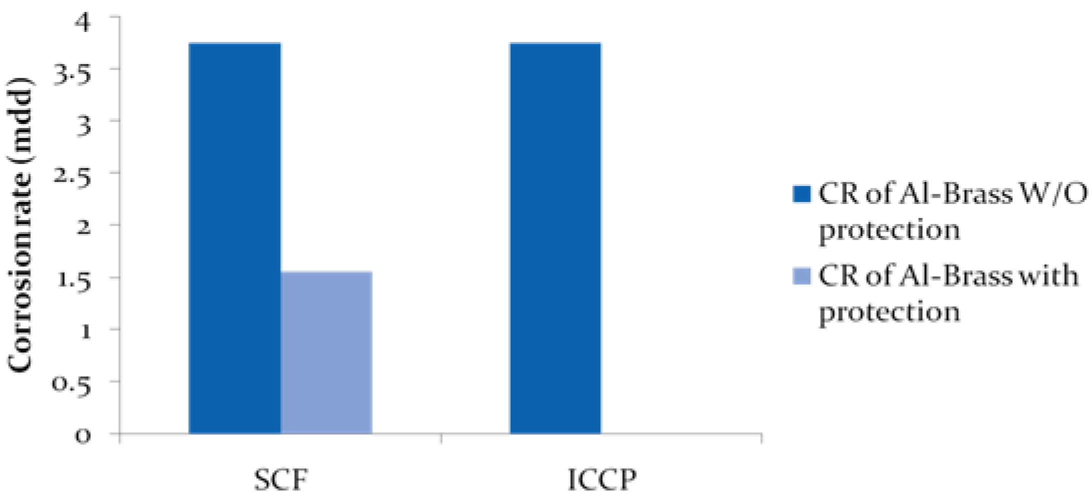

Figure 5: Comparison between SCP and ICCP

If ICCP were to compare with SCP, then it can be seen that ICCP is much better than SCP (Figure 5), with negligible corrosion rate in the case of ICCP. It was found that the condenser tubes had the corrosion deposit because of biopolymer/slime formation and stress corrosion cracking in presence of ammonia. Copper alloys also exhibits the Erosion corrosion mechanism until the water flow in the tube reaches the critical velocity which then accelerates the erosion. The normal protective film on Al-brass is not formed in the presence of chlorine.

4. Conclusions

It is concluded that the initially corrosion rate was high, so more protection against ammonical corrosion was required at the start. Ammonical corrosion increase with increase in temperature, so temperature should be controlled to minimize ammonical corrosion. The air ejection system must be efficient to remove ammonia in air cooler zone. By comparing sacrificial cathodic protection (SCP) and impressed current cathodic protection (ICCP), it is concluded impressed current cathodic protection is better. Small amount of current will be required in impressed current cathodic protection i.e. only less than 1mA/dm^2. Zn is suitable anode material used in impressed current cathodic protection. By adding alloy elements such as Be metal, corrosion resistance properties of Al-Brass can be increased.

References

[1] **Hu, S., Liu, L., Cui, Ying, Y. and Fuhui, W.** Influence of hydrostatic pressure on the corrosion behavior of 90/10 copper nickel alloy tube under alternating dry and wet condition, Corros. Sci. 146 (2019) 202-212.

[2] **Jawwad, K.A. and Mohamed, I.K**. The combined effects of surface texture, flow patterns and water chemistry on corrosion mechanisms of stainless steel condenser tubes,

Engineering Failure Analysis 109 (2020) 104390.

[3] **Rezaei, M., Mahidashti, Z., Eftekhari, S. and Abdi, E**. A corrosion failure analysis of heat exchanger tubes operating in petrochemical refinery, Engineering Failure Analysis 119 (2021) 105011.

[4] **Rao, T.S. and Bera, S**. Protective layer dissolution by chlorine and corrosion of aluminum brass condenser tubes of a nuclear power plant, Engineering Failure Analysis 123 (2021) 105307.

[5] **Sun, B., Ye, T., Feng, Q., Yao, J. and Wei, M**. Accelerated degradation test and predictive failure analysis of B10 copper-nickel alloy under marine environmental conditions, Materials 8 (2015) 6029–6042.

[6] **Traverso, P. and Canepa, E**. A review of studies on corrosion of metals and alloys in deep-sea environment, Ocean. Eng. 87 (2014) 10–15.

[7] **Zhang, T., Yang, Y., Shao, Y., Meng, G. and Wang, F**. A stochastic analysis of the effect of Hydrostatic pressure on the pit corrosion of Fe–20Cr alloy, Electr ochim. Acta 54 (2009) 3915–3922.

[8] **Liu, B., Zhang, T., Shao, Y.W., Meng, G.Z., Liu, J.T. and Wang, F.H.** Effect of hydrostatic Presse on the corrosion behavior of pure nickel, Int. J. Electro chem. Sci. 7 (2012) 1864–83.

[9] **Yang, Y.G., Zhang, T., Shao, Y.W., Meng, G.Z. and Wang, F.H**. New understanding of the effect of hydrostatic pressure on the corrosion of Ni-Cr-Mo-V high strength steel, Corros. Sci. 73 (2013) 250–261.

[10] **Wang, Z.Y., Cong, Y. and Zhang, T**. Effect of hydrostatic pressure on the pitting corrosion behavior of 316L stainless steel, Int. J. Electro chem. Sci. 9 (2014) 778–798.

[11] **Badawy, W.A., Ismail, K.M. and Fathi, A.M.** Effect of Ni content on the corrosion behavior of Cu–Ni alloys in neutral chloride solutions, Electro chim. Acta 50 (2005) 3603–3608.

[12] **Ma, A., Jiang, S., Zheng, Y. and Ke, W.** Corrosion product film formed on the 90/10 copper–nickel tube in natural seawater: composition/structure and formation mechanism, Corros. Sci. 91 (2015) 245–261.

[13] **Mansfeld, F., Liu,G., Xiao, H., Tsai, C. and Little, B**. The corrosion behavior of copper alloys, stainless steels and titanium in seawater, Corros. Sci. 36 (1994) 2063–2095.

[14] **Cao, C.N. and Zhang, J.Q.** An Introduction to Electrochemical Impedance Spectroscopy, Science press, China, 2002.

[15] **Assis, S.L., Wolynec, S. and Costa, I**. Corrosion characterization of titanium alloys by electrochemical techniques, Electro chim. Acta 51 (2006) 1815–1819.

[16] **Kear, G., Barker, B., Stokes, K. and Walsh, F**. Electrochemical corrosion behavior of 90-10 CuNi alloy in chloride-based electrolytes, J. Appl. Electro chem. 34 (2004) 659–669.

[17] **Campbell, S.A., Radford, G.J.W., Tuck, C.D.S. and Barker, B.D**. Corrosion and galvanic compatibility studies of a high-strength copper-nickel alloy, Corrosion 58 (2002) 57-71. 57–71.

[18] **Alfantazi, A.M., Ahmed, T.M. and Tromans, D.** Corrosion behavior of copper alloys in chloride media, Mater. Des. 30 (2009) 2425–2430.

[19] **El-Aziz, A.M., Hoyer, R., Kibler, L.A. and Kolb, D.M.** Potential of zero free charge of Pd overlayers on Pt(111), Electrochim. Acta 51 (2006) 2518–2522.

[20] **Morad, M.S. and Sarhan, A.A.O**. Application of some ferrocene derivatives in the field of corrosion inhibition, Corros. Sci. 50 (2008) 744–753.

تدهور أنابيب المكثف في محطة طاقة نووية معرضة لظروف عملية قاسية

ضياء شجاع العثماني
الهندسة النووية، جامعة الملك عبد العزيز
جدة المملكة العربية السعودية

مستخلص. تستخدم أنابيب الألمنيوم والنحاس في المكثفات والمبادلات الحرارية لمحطات الطاقة النووية منذ زمن بعيد بسبب حقيقة أن هذه المادة أرخص نسبيًا. لكن سجل فشل الأنبوب يشير إلى معدل فشل أعلى مع هذه المادة. من المشاكل الشائعة جدا تسرب أنابيب المكثف النحاسية. عادة مع التشغيل الممتد للمكثفات لمدة ٢٠ عامًا أو نحو ذلك، يمكن للمرء أن يتوقع استبدال حوالي ١٥-٢٠ ٪ من أنابيب المكثف بسبب التسرب .يكشف تحليل فشل الأنابيب أن أنابيب المنطقة المركزية عانت من هجوم تآكل الأمونيا بينما عانت المناطق المتبقية من التآكل الداخلي والتآكل ورواسب الكائنات البحرية. على الرغم من أن تركيز الأمونيا والأكسجين منخفض بدرجة كافية لإحداث أي تآكل للأنابيب، إلا أن التركيز العالي من الأمونيا والأكسجين يمكن أن يتطور في أقسام تبريد الهواء في المكثفات، مما قد يتسبب في تآكل سبائك النحاس .أحد الأسباب المهمة لتسرب أنابيب المكثف هو التآكل الأموني. ومع ذلك، يمكن تقليل هذا التآكل الأموني عن طريق التحكم في درجة الحرارة جنبًا إلى جنب مع طرق الوقاية المختلفة من التآكل. يُلاحظ أنه مع زيادة درجة الحرارة، يزداد معدل التآكل. ومع ذلك، فإن الاتجاه الأخير نحو جميع المركبات المتطايرة التي تستخدم مركبات الأمونيا والأمونيا للتحكم في كيمياء مياه التغذية في محطة الطاقة النووية، يبرز الحاجة إلى الاختيار الدقيق لسبائك أنابيب المكثف المقاومة للتآكل. يستخدم الهيدرازين بشكل شائع في نظام محطات توليد الطاقة البخارية لإزالة O2 وضبط درجة الحموضة وتقليل معدل تآكل الفولاذ. يتم إذابة هذه المواد الكيميائية بسهولة في مياه تغذية الغلايات .الطريقة الحالية المستخدمة في مكثفات محطة توليد الكهرباء هي الحماية الكاثودية القربانية .(SCP) أيضًا، تم إجراء عدد من التجارب في المعمل لحماية التآكل باستخدامSCP ، وكذلك الحماية الكاثودية للتيار القسري (ICCP) ، أي بتطبيق تيار صغير أقل من ١ .mA / dm2وجد أن ICCP أفضل بكثير من .SCP على ما يبدو، تم العثور على Zn على أنه مادة أنود مناسبة تستخدم في.ICCP

الكلمات المفتاحية: المكثفات، محطات الطاقة النووية ، تسرب الأنابيب ، التآكل ، الحماية الكاثودية القربانية، ملخص تنفيذي