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A CORROSOMETER STUDY OF CORROSION IN ROTORUA GEOTHERMAL FLUIDS

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ABSTRACT

Corrosion performance and reliability will be of primary importance in the specification of materials for new process equipment for the more efficient use of geothermal energy in Rotorua. Electrical resistance Corrosometer probes were used to evaluate the materials performance of three commonly specified alloys in a range of geothermal environments derived from wells in the Rotorua area. In addition, a detailed study of the control valves being field tested by the Rotorua Geothermal Task Force was carried out to assess the reliability aspects of the materials exposed to the geothermal fluids.

The Performance of the test materials was found to be strongly dependent on fluid aeration. UNS G10100 carbon steel and C26000 brass exhibited low corrosion rates in non-aerated fluids. The stainless steel alloy S31600 suffered pitting corrosion at high temperatures in aerated fluids. Control valve failures were attributable to inadequate corrosion resistance, scaling, and build-up of corrosion products/scale causing seizure.

INTRODUCTION

The Rotorua geothermal field has been used for heating and bathing for over 40 years. There are over 350 shallow wells and there is a conflict of interest between exploitation and preservation of thermal features. The Rotorua Geothermal Task Force was set up to recommend ways of reducing geothermal fluid drawoff from the field. It is likely that heating systems with better thermal efficiencies will be required and that these systems will require critical control with proven reliability. The successful implementation of such systems will depend on the reliability and corrosion resistance of the process control devices used. One objective of the Rotorua Geothermal Task Force has been to appraise commercially available temperature/flow control valves. On the basis of an initial screening by Alabaster et al, 1983, several control valves were selected for long term reliability testing on a number of Rotorua wells. Current production techniques are a major factor in the cause of corrosion problems, which are made even more difficult by the wide range of physical and chemical characteristics of the geothermal fluids in the Rotorun area.

Information on the internal corrosion of process equipment is scarce. Reports are often based on visual observations and engineering experience with no overall correlation between corrosion chemistry and materials performance. Although guidelines are available, these are scattered and varied and generally deal with building services: Roberts, 1978; Burns et al, 1372; Sewell, 1973; and the University of Auckland, 1983. Publications dealing with materials performance in low temperature geothermal resources in other countries are available for guidance (for example: Ellis and Conover, 1983; Lichti, 1982; Nork and Bantz, 1383; and Eliasson and Einarson, 1983).

The objectives of this study have been to:
- Obtain baseline corrosion data for three engineering alloys in typical geothermal fluids derived from Rotorua wells.
- Provide advice on the materials performance of engineering alloys used for temperature/flow control devices by the Rotorua Geothermal Task Force.

GENERAL CORROSION CHEMISTRY

Approximately 90% of the wells in Rotorua are low pressure bores in the range 0.5 to 2.5 bar(g) (110 to 140°C). These wells are SO to 100 m in depth, are naturally non-artseian and require an air lift starting system. Most of these wells continue to flow after the air lifting is stopped. A small number (10 to 20) require continuous air injection to sustain production. The 20 or so high pressure bores, 3.5 to 7.0 bar(g) (150 to 170°C), which naturally discharge can supply sufficient bore fluid for heating 40 to 90 homes each while the low pressure bores can provide fluid for only 4 to 12 homes each.

Most of the wells produce alkaline-chloride waters of near neutral pH which have a low steam fraction (3 to 5 wt%). The two phase nature of the Rotorua geothermal fluids coupled with the complex fluid distribution systems - predominantly by small bore above ground pipes - results in a variable fluid chemistry which is difficult to theoretically define as the two separate phases are often preferentially tapped by side legs for individual users, Drew, 1985. In addition the individual wells have a wide range of water chemistry as reported by Glover, 1967:

pH	5.5 to 9.6
Cl^-	100 to 1000 mg kg^{-1}
SO_4^{2-}	10 to 1500 mg kg^{-1}
SiO_2	150 to 350 mg kg^{-1}
NH_3^-	nil to 2.5 mg kg^{-1}
HCO_3^-	40 to 800 mg kg^{-1}
H_2S	1 to 150 mg kg^{-1}

CORROSION RATE STUDIES

The corrosion rates of three engineering alloys, commonly used in the construction of control devices, were obtained in a variety of environments using electrical resistance Corrosometer ((R) Rohrback Corporation) probes.

The monitoring technique utilises the change in electrical resistance of an exposed corroding element to provide a measure of material loss. The resistance (R) of the exposed test element is inversely proportional to the cross-sectional area (A) for a given material resistivity (p) and elemental length (L). As corrosion progresses the cross-sectional area is reduced by ΔA and the change in resistance is given by:

$$AR = \rho L/\Delta A$$

Temperature fluctuations may result in changes in material resistivity, however this error is reduced with the use of an unexposed "reference" element (which in effect normalises the material resistivity) A general corrosion rate may be obtained at steady state by differentiating material loss (penetration) with respect to time. No pitting information may be obtained from this technique during the exposure period, and an examination of the probes is required after the exposure.

Corrosometer Probe Exposure Conditions

This study included three bore (or well) types to characterise corrosion in the Rotorua system (Table 1). Corrosion rates were monitored at the well head and in a heat exchanger geothermal effluent stream for each bore type tested (Table 1). The latter location was selected to provide an environment similar to that experienced by the temperature control valves. The corrosion chemistry for these locations is summarised in Table 2. Both the high and low pressure bores flowed continuously once started, however the air lift bore required compressed air to be continuously pumped down the bore to bring slugs of geothermal fluid to the surface. Figure 1 shows a simplified process description of the heating systems tested and indicates the locations where Corrosometer probes were installed.

Fully welded tubular element carbon steel and stainless steel Corrosometer probes were used in the study. Brass probes were of the 'W40' wire element variety. Before exposure, each element was pumice blasted to provide a uniform base surface, wet abraded with silicon-carbide paper to a 600 grit finish and ultrasonically cleaned in 2-propanone. The resistance of each probe was measured and the surface inspected to ensure it was defect-free. The welded sections of the carbon steel and stainless steel probes were coated with an epoxy to prevent premature failure. The Corrosometer probes were installed in such a manner to prevent gas pocket formation or the collection of debris around the element which might produce erroneous results. Stainless steel probes were insulated from the pipework using nylon fittings to avoid any galvanic effects. The test elements of the brass probes are electrically isolated from the probe body. The exposure period was 98 days. During the laboratory examination the probes were cleaned following techniques described in ASTM Standard Recommended Practice for Preparing, Cleaning and Evaluating Corrosion Test Specimens (G1-72) and Braithwaite and Lichti, 1981. Evidence of pitting corrosion was determined in accordance with ASTM Standard Recommended Practice for Examination and Evaluation of Pitting Corrosion (G46-78).

Corrosometer Probe Results

Corrosion data for the various test sites is presented in Figures 2 to 4 in the format of material loss (accumulated) versus time. Results were not obtainzd for the carbon steel probe sited at the well head of the high pressure bore (Bore 501) because of probe fitting failure. (The probe was blown out one night.) Figures 2 and 3 display discontinuities in both high and low pressure bores and these were the result of system upsets (shutdowns for maintenance which result in air ingress). The detailed results of the laboratory examination of the Corrosometer probes are presented in Table 3. Where sufficient material was available, X-ray diffraction analysis was used to identify the corrosion products and scales removed from the Corrosometer probes. Initial and long term corrosion rates were calculated for all probes (at steady state conditions) and are presented in Table 4. Regression analysis was performed to provide the best approximation of long term corrosion rates. Table 4 also summarises pitting corrosion rates.

DISCUSSION OF CORROSOMETER PROBE RESULTS

The Corrosometer probe results show distinctly the difference in corrosivity between aerated and non-aerated geothermal fluids. Corrosometer probes exposed to high and low pressure geothermal fluids gave results that were similar to those observed previously for non-aerated solutions. The air lift bore gave significantly higher corrosion rates and again the results were similar to those observed previously for aerated geothermal fluids (Braithwaite and Lichti, 1981; Lichti et al, 1981).

Non-Aerated Geothermal Fluids

The results obtained for non-aerated fluids indicate the formation of passive films or protective scales for

Table 1: Experimental Matrix of Corrosometer Probes and Exposure Locations

Probe Location	Bore Type and Material Exposed		
	High Pressure (501)	Low Pressure (654)	Air Lift (725)
Well Head	G10100	G10100	G10100 S31600
Control Valve	G10100 S31600 C26000	G10100 S31600 C26000	G10100 S31600 C26000

Unified Numbering System, UNS. is used to describe alloys in this report.

UNS G10100 - Carbon Steel 0.1 wt% C
UNS S31600 - Stainless Steel 20 wt% Cr 12 wt% Ni 2.5 wt% Mo
UNS C26000 - 70/30 Brass 70 wt% Cu 30 wt% Zn

Table 2: Corrosion Chemistry of Corrosometer Probe Test Sites

	Bore Site Details					
Bore No.	High Pressure 501		Low Pressure 654		Air Lift 752	
Location	Well Head	Control Valve	Well Head	Control Valve	Well Head	Control Valve
Pressure bar(g)	5.5	≈0.05	0.8	-0.05	0.3	0.05 to 0.3
Temperature °C	160	90 max	117	90 max	107	70 max
Enthalpy $kJkg^{-1}$	850	-	565	-	≈450	
Wetness wt%	91.8	100	96.5	100	100	100
Gas Fraction In Steam wt%	0.18	Gas may be present	1.9	Gas may be present	Gas may be present	
Gas As A Fraction of Non-Condensible Gas mmol/mol (water free)						
CO_2	771	-	906			
H_2S	196	-	79.1	-		
NH_3	2.4	-	0.2	-		-
H_2	0.6	-	≈0.5	-		-
N_2	27.1	-	≈11.7	-		-
CH_4	2.9	-	≈1.9	-		-
Water Chemistry At 17°C And Atmospheric Pressure, $mg\ kg^{-1}$						
pH	8.98	8.45	8.3	8.4	-	7.25
Na	745	514	347	324	-	290
K	41.6	28.5	25	20.5	-	15.5
Ca	7.4	b.6	2.5	2.1	-	s.4
Mg	<0.01	0.01	0.03	0.03	-	0.06
Cl	1129	778	285	266	-	20s
SO_4	71	82	227	239	-	379
B	9.1	6.5	5.5	2.5	-	2.3
SiO_2	276	225	284	235	-	333
NH_3 (Total)	<0.5	0.71	-	0.73	-	1.12
HCO_3^- (Total)	25	22	239	298	-	101
H_2S (Total)	29	24	≈40	50	-	7

Results provided by Glover and Middendorf of Chemistry Division, DSIR, Wairakei.

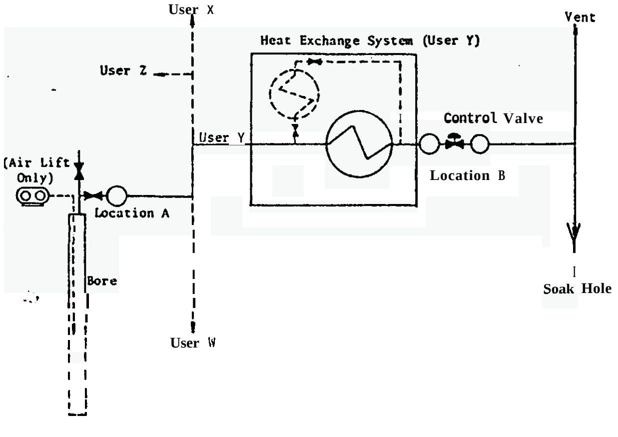

Figure 1: Schematic process diagram of typical Rotorua geothermal fluid production system showing locations used for Corrosometer probe studies.

UNS G10100 carbon steel and C26000 brass at steady state conditions (Figures 2 and 3). Both materials initially display high general corrosion rates prior to stable passive films forming and during which time the materials freely corroded. The formation of stable films and scales reduced the general corrosion rates to extremely low levels (<2 µm/yr). However, accidental or deliberate aeration of the fluid caused the passive film to break down as evident with the probes located in both the low pressure and high pressure systems. Aeration of the low pressure bore between days 48 and 55 is shown in Figure 2; a system upset in the high pressure bore between days 38 and 55 is displayed in Figure 3. Carbon steel, in the high pressure bore fluid, was considerably more susceptible to this "system upset" than the brass, which showed little increase in corrosion rate. Initial corrosion rates given in Table 4 can be expected for short periods after each shutdown or "system upset" as a result of cracking and loss of the protective films and scales. Lichti et al, 1981 provide a detailed discussion of the effect of shutdowns on corrosion in non-aerated geothermal systems.

General corrosion rates were lower than the pitting corrosion rates experienced by most probes in non-aerated environments (Table 4), however similar trends were evident for both types of corrosion with respect to location and material. The pitting density for UNS G10100 carbon steel was high (A3 to A5) although the pit size was small; the maximum pit depth detected was 75 µm. Several areas on the surface of the carbon steel probe located at the control valve in the low pressure bore displayed a total absence of pitting corrosion and would suggest that stable protective layers formed rapidly on these areas when exposed to the geothermal fluid. The pitting rates for carbon steel were higher in the low pressure bore than the high pressure bore, but this may be attributed to variations in solution chemistry, stability and protective qualities of the passive layers or scales, or historical variations such as the opening of the bore. Temperature differences in the low pressure bore, between the wellhead (117°C) and control valve (90°C) gave little variation in pit depth. The differences in carbon steel pitting rates at the two locations for non-aerated solutions were not considered unusual or unacceptably high.

The UNS C26000 brass and S31600 stainless steel probes in the high pressure bore fluid suffered lower pitting rates than carbon steel, and pitting corrosion was not detected on either material in the low pressure bore environment.

The identification of corrosion products was not possible for some of the probes exposed to non-aerated fluids because the amount present was insufficient to allow X-ray analysis. However, products were collected from the carbon steel probe exposed to the high pressure bore fluid at the control valve and the predominant crystalline species was identified as Greigite (Fe_3S_4). Quartz was also observed (α-SiO_2). Examination of the probe revealed that about 10% of the element surface was covered with a white material (possibly silica). An inspection of the stainless and brass probes at the same location showed uniform scaling 2 to 5 µm in thickness, over most of the stainless steel surface and between 10 to 20% of the surface scaled on the brass probe. The inference may be drawn that the corrosion product on carbon steel and brass is non-adherent, periodically spalling off and taking any deposited scale with it. The stainless steel surface was stable, allowing scale deposition to occur. An examination of the probes exposed to the low pressure bore fluid showed scale formation on the carbon steel probes at the control valve. Calcite was seen on the probe exposed at the well head of the low pressure bore. This is frequently observed where flashing of the two phase fluid occurs.

Aerated Geothermal Fluids

Exposure of the UNS G10100 carbon steel and C26000 brass probes in the air lift bore (aerated fluid) produced

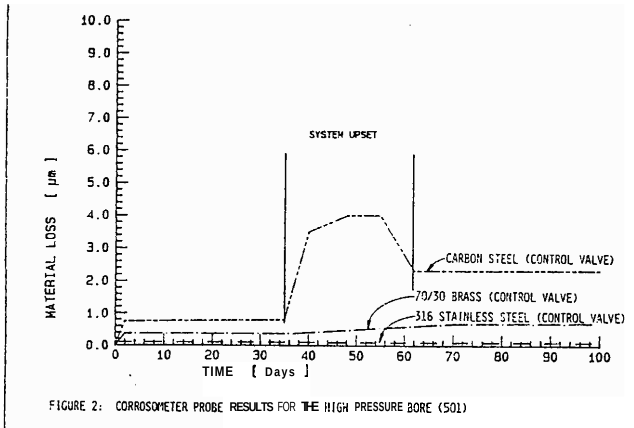

FIGURE 2: CORROSOMETER PROBE RESULTS FOR THE HIGH PRESSURE BORE (501)

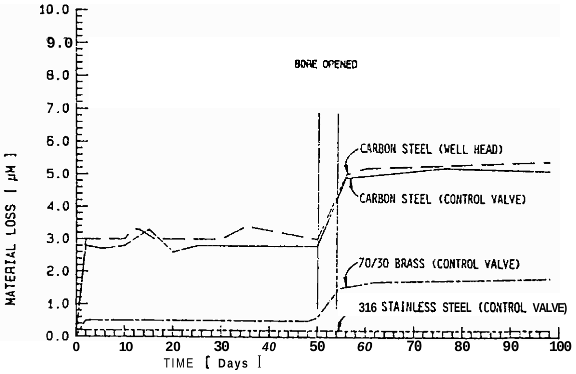

FIGURE 3: CORROSOMETER PROBE RESULTS FOR THE LOW PRESSURE BORE (654)

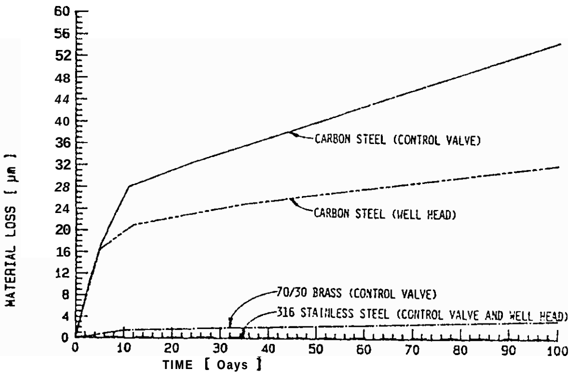

FIGURE 4: CORROSOMETER PROBE RESULTS FOR THE AIR LIFT BORE (725)

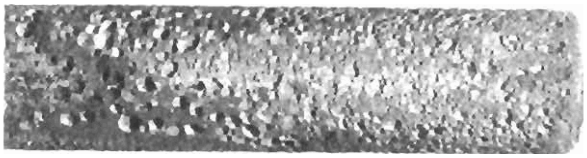

Figure 5: Cleaned surface of carbon steel, G10100 Corrosometer probe exposed at the control valve location of the air lift bore 725. The maximum pit depth was 400 µm.

Table 5: Summary of Laboratory Examination of Electrical Resistance Corrosometer Probes

Position	Material UNS Classification	Appearance After Exposure	Appearance of Corrosion	Pit Density (See ASTM G46-72)	Pit Size	Maximum Pit Depth Detected	Crystalline Products Identified by X-Ray Diffraction[1]
High Pressure (Control Valve)	Carbon Steel C10100	Scale on 10% of surface	Narrow to medium size pitting	A5	<<B1	25 µm	Quartz (α-SiO_2) Greigite (Fe_3S_4)
High Pressure (Control Valve)	316 Stainless S31600	Scale 2 to 5 µm thick	Even general and some pitting	A1	<B1	20 µm	
High Pressure (Control Valve)	70/30 Brass C26000	Some scale and black adherent films	Even general	A1	<B1	20 µm	-
Low Pressure (Well Head)	Carbon Steel G10100	Scale on 20% of surface	Medium size pitting	A4 to A5	B1	65 µm	Calcite ($CaCO_3$)
Low Pressure (Control Valve)	Carbon Steel G10100	Some scale	Wide and medium size pitting	A3 to A4	<<B1 to B1	75 µm	
Low Pressure (Control Valve)	516 Stainless S31600	No scale	NIL				
Low Pressure (Control Valve)	70/30 Brass C26000	Scale to EO µm and black adherent films	Uneven general		-	-	
Air Lift (Well Head)	Carbon Steel G10100	Thick poorly adherent films	Medium size pitting	A4 to A5	B1 to B3	200 µm	Magnetite (Fe_3O_4) Goethite (α-$Fe_2O_3 \cdot H_2O$)
Air Lift (Well Head)	316 Stainless S31600	Scale to 100 µm	Some medium size pitting	A2	B1	30 µm	-
Air Lift (Control Valve)	Carbon Steel G10100	Thick poorly adherent films	Medium size pits	A4 to A5	B1 to B4	400 µm	Magnetite (Fe_3O_4) Goethite (α-$Fe_2O_3 + H_2O$) Akaganeite (β-FeOOH) Pyrite (FeS_2)
Air Lift (Control Valve)	316 Stainless S31600	No scale	None detected	-	-	-	-
Air Lift (Control Valve)	70/30 Brass C26000	Scale and films	General even and medium size pitting	A5 to A4	B1	100 µm	

1. X-ray diffraction results taken from Chemistry Division Reports by M Ryan.

Table 4: Summary of Laboratory Examination of Electrical Resistance Corrosometer Probes

Position	Material	Initial Corrosion Rate (After 5 Days)	Steady State General Corrosion Rate (98 Days)	Maximum Pit Depth Detected (96 Days)	Extrapolated Pit Depth (After 1 Year)
High Pressure (Control Valve)	Carbon Steel G10100	80 µm/yr	3.5 µm/yr	25 µm	90 µm
High Pressure (Control Valve)	316 Stainless Steel S31600	15 µm/yr	<2 µm/yr	20 µm	65 µm
High Pressure (Control Valve)	70/30 Brass C26000	33 µm/yr	<2 µm/yr	20 µm	65 µm
Low Pressure (Well Head)	Carbon Steel G10100	220 µm/yr	12.5 µm/yr	65 µm	235 µm
Low Pressure (Control Valve)	Carbon Steel G10100	220 µm/yr	<2 µm/yr	75 µm	275 µm
Low Pressure (Control Valve)	316 Stainless Steel S31600	17 µm/yr	<2 µm/yr	None detected	
Low Pressure (Control Valve)	70/30 Brass C26000	37 µm/yr	<2 µm/yr	None detected	
Air Lift (Well Head)	Carbon Steel G10100	1320 µm/yr	60 µm/yr	200 µm	730 µm
Air Lift (Well Head)	316 Stainless Steel S31600	14 µm/yr	<2 µm/yr	30 µm	110 µm
Air Lift (Control Valve)	Carbon Steel G10100	1460 µm/yr	120 µm/yr	400 µm	1460 µm
Air Lift (Control Valve)	316 Stainless Steel S31600	7 µm/yr	<2 µm/yr	None detected	
Air Lift (Control Valve)	70/30 Brass C26000	65 µm/yr	10.5 µm/yr	100 µm	365 µm

much higher corrosion rates and did not result in the formation of stable passive films or protective scales. High initial corrosion rates were experienced by carbon steel and brass (Table 4). For carbon steel these corrosion rates were an order of magnitude greater than those experienced in the non-aerated environment and between 2 and 5 times greater for brass. It is noteworthy that the carbon steel probe exposed at the control valve (70°C) in the aerated fluid produced higher corrosion rates than the well head probe (107°C). This may be in part due to the stability of corrosion products and variations in solution chemistry at the lower temperatures. The installation of more efficient heat exchangers in the air lift systems could therefore be expected to increase the general corrosion rate of carbon steel components downstream of the heat exchanger.

The S31600 stainless steel alloy produced low general corrosion rates when exposed to the air lift bore environment as indicated in Figure 4. The initial corrosion rates were similar to the rates experienced in non-aerated Fluids by this alloy and the steady state rates show the existence of a stable passive film

In the aerated fluids general corrosion rates were also lower than the pitting corrosion rates. Carbon steel pitted rapidly (Figure 5), producing pitting rates of 750 µm/yr and 1500 µm/yr for well head and control valve locations respectively. In fact much of the measured general corrosion rate can be expected to have resulted from pitting corrosion and it is interesting to note that the initial slope of Figure 4 is similar to the pitting rate. As the material corroded a thick film formed over the surface which, although it may not be described as passive, provided some degree of protection to the adjacent metal and reduced the general corrosion rate. The pitting density for both carbon steel probes was high (A4 to A5), being the same as that experienced in the non-aerated fluids, however the pit sizes were considerably larger (B3 or B4 as opposed to B1). The brass probe indicated substantial increases in pitting density and pit size in the aerated fluid, and the maximum pit depth was at least 5 times greater than that found in the non-aerated fluid (Table 4). The stainless steel alloy did not pit at the control valve location but pitted at the well head site of the air lift bore. This is consistent with previous experience (Wells, 1985a) which suggested UNS 31600 would pit at a temperature between 55 and 75°C in chloride containing geothermal condensate.

Large amounts of adherent corrosion products were seen on the surface of the carbon steel and brass probes and scale formation (approximately 100 µm thick) on the stainless steel probe located at the well head. X-ray diffraction analysis of corrosion products indicated magnetite (Fe_3O_4), goethite (α-$Fe_2O_3.H_2O$), akaganeite (β-FeOOH) and pyrite (FeS_2) were the predominant crystalline species on the carbon steel (control valve) probe. These species clearly did not constitute a passive film in this environment however protection against general corrosion was afforded, as evidenced in the reduction from the initial corrosion rate and the long-term rate.

Implications for Materials Selection

Pitting corrosion rates are considerably greater than general corrosion rates for all materials exposed to both aerated and non-aerated fluids and should be adopted as the effective corrosion rates. Carbon steel and brass suffer unacceptably high pitting rates in aerated fluids and should not be selected for these applications. The production technique of air lift pumping will result in extremely high corrosion rates because of fluid aeration and requires highly resistant alloys to be specified (eg UNS S30400 or S31600 stainless steel components may be replaced with higher alloy stainless steels such as Avesta 254SMO or Sandvik 2RK65). Pitting corrosion of the low alloy stainless steels would be expected at temperatures above 70°C and stress corrosion cracking is also possible. Alternate production techniques like pumping would probably be cheaper than using corrosion resistant materials in this situation.

Corrosion rates for materials in non-aerated environments are a function of the number of system shutdowns per year. For example carbon steel would be expected to pit to a depth in the order of 50 µm for a 10 day shutdown. On this basis carbon steel and brass would be expected to provide adequate corrosion resistance in non-aerated fluids provided sufficient Corrosion allowance is specified for shutdown periods and proper maintenance procedures are adopted.

CONTROL VALVE SURVEYS

Control valves being tested by the Rotorua Geothermal Task Force were inspected at approximately 6 monthly intervals to document their corrosion performance. The reliability of the valves was assessed on the basis of a 10 year economic life, with yearly maintenance during this period. The survey concentrated on four specific areas that were considered likely to result in failure of the valve before this time:

- Corrosion of the "control surfaces" (eg valve sent).
- Deterioration of components producing a drastic loss of performance or valve integrity (eg thermal sensor unit).
- Atmospheric corrosion
- Scale formation.

Three surveys were conducted after 5,500, 10,000 and 15,000 hours of service. During the surveys, the valves were removed from service, examined and photographed, and then reinstalled. Quantitative corrosion rate measurements were not obtained to preserve the control valves. Control valves which failed in service were examined in greater detail to establish the cause of failure.

SURVEY RESULTS AND DISCUSSION

Significant deterioration was evident in most of the valves, however the operational performance was generally not impaired. The performance of new and exposed valves was evaluated by the Rotorua Geothermal Task Force in their test facility. The following comments summarise the principal observations of the surveys. Detailed results of the valve surveys will be reported elsewhere (Wells, 1985b).

(a) Temperature sensors made from copper base alloys placed directly into the geothermal fluid displayed significant levels of corrosion and failed rapidly. Sensors coated and sealed by tin based alloys were also not sufficiently resistant and consequently failed. Austenitic stainless steel thermopockets have performed successfully, however the specification of a more resistant sensor material would provide suitable performance, allowing direct immersion into the geothermal fluid and avoid the need for thermopockets.

(b) Atmospheric external corrosion (although not affecting the integrity of the control valves) was relatively severe, especially on flexible capillary coupling between the valve sensor and the valve actuator. Coating of external .surfaces has been recommended, as failure of uncoated components could be expected within five years.

(c) Deterioration of rubber components, resulting primarly from wear, was observed and would necessitate regular inspections and maintenance to ensure reliability. The use of these types of materials in critical applications may require additional maintenance and should be included in the economic appraisal of individual valves.

(d) Stainless steel valve tips, valve stems and valve seats provide good corrosion resistance in the majority of control devices surveyed. Pitting and crevice corrosion were noted on some valve components, especially valve stems, where air ingress was suspected. Air ingress is also expected to make some stainless steel components susceptible to stress corrosion cracking at operating temperatures above 70°C (although no cracking was observed during the surveys).

(e) Cast iron and leaded brass valve components displayed substantial amounts of uniform corrosion, prior to a protective film forming. The thickness of the castings in all valves surveyed suggest that premature failure would not be expected in the non-aerated environments. The electrical resistance Corrosometer probe study reported above for similar materials in geothermal fluids suggests that extremely high corrosion rates would also occur with these materials in aerated environments. These conditions may arise in non-aerated environments at shutdown or from poor design or fabrication or from lack of maintenance, and can not be tolerated for long periods.

(f) Control devices in which scale deposition had occurred, were relatively unaffected due to wide tolerances and few flow restrictions. Premature failure due to scaling had been experienced in some of the originally installed test valves which had fine tolerances and relatively severe flow restrictions (in the form of perforated plate strainers). Corrosion product fouling and scaling are cspected to be significant for some valves in aerated environments.

The majority of control valves displayed adequate corrosion resistance to ensure a lifetime of from 5 to 10 years, if appropriate maintenance procedures are adopted. It is clear that premature failures can be expected, primarily in situations where the valve stem packing is not maintained and leakage occurs. Air ingress can not be tolerated for long periods and maintenance procedures should attempt to minimise this risk. (For example, heavy emphasis on frequent superficial inspections.) The use of more resistant materials (eg Avesta 254 SMO or Sandvik 2RK65 stainless steels) may reduce the maintenance requirements- but will be reflected in a considerably higher capital cost.

CONCLUSIONS

The geothermal waters of Rotorua may be classified as either aerated or non-aerated fluids. The Corrosometer probe study showed UNS G10100 carbon steel and C26000 brass (70 Cu/30 Zn) corroded at unacceptably high rates in aerated fluid but provide relatively good corrosion performance in non-aerated solutions. S31600 stainless steel produced acceptable corrosion rates in non-aerated environments and in aerated fluids below 70°C. Control valve surveys highlighted the need for regular, superficial inspections to ensure leakage and air ingress had not occurred.

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