DEVELOPMENT OF AN EROSION-CORROSION TEST FACILITY FOR GEOTHERMAL STEAM CONDENSATE

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SUMMARY - A test facility for the evaluation of erosion-corrosion of carbon steel exposed to geothermal condensate has been developed. The test rig employs electrochemical and physical corrosion monitoring techniques to measure corrosion potentials and corrosion rates in near neutral pH solutions under controlled fluid flow conditions. Development of the test facility together with initial results for experimental conditions simulating those experienced in the Wairakei steam pipelines will be described.

1.0 INTRODUCTION

Low carbon steels can be used successfully in geothermal power generation systems provided the corrosion rate can be controlled to an acceptable level, typically less than 50 μm/yr, which can be accommodated by a corrosion allowance. Published data for corrosion rates of carbon steel in geothermal steam condensate of neutral pH show this criterion to be easily met. For example, coupons exposed to steam from Well BR22 at the Ohaaki geothermal field under low flowrates showed corrosion rates of less than 10 μm/yr (Lichti *et al.*, 1983). The best documented example when unacceptable corrosion rates were observed was in the steam pipelines at Wairakei during 1978-80, with the problem being resolved by the controlled injection of separated water. The mode of corrosion damage was erosion-corrosion, which depended on condensate formation as a result of heat losses (Thain *et al*, 1981). The threshold values of the controlling parameters, i.e. fluid velocity and pH, have not been established for either low sulphide steam, (e.g. encountered at Wairakei where magnetite films are stable), or for high sulphide type steam, (e.g. at Ohaaki where iron sulphide films are stable (Borshevska et *al.*, 1982)). This paper describes the development of a facility for measuring the parameters which control condensate induced erosion-corrosion within steam pipelines.

1.1 Design Requirements

The requirements of an erosion-corrosion test facility are:

(i) simulation of the fluid flow regime experienced in a pipeline;
(ii) the ability to vary the fluid velocity and to control the chemical composition of the condensate, in particular pH and sulphide content;
(iii) the ability to monitor the instantaneous corrosion rate and cumulative material loss;

Achievement of these requirements within realistic costs necessitates a degree of compromise. In particular, to minimise the problems associated with use and disposal of the steam, the size of the test rig must be minimised. To simulate the environment contained within both the Ohaaki and Wairakei steam pipelines, the following conditions must also be met:

(i) the velocity of geothermal condensate on the inside wall of the steam transmission pipes in the range 1 to 3 m/s (this was the range estimated for the Wairakei geothermal field (Braithwaite et *al.*, 1978); it is assumed that the condensate velocity in the Ohaaki pipelines is of the same magnitude);
(ii) the temperature of the steam approximately 160°C;
(iii) the pressure inside the pipelines approximately 6.5 bar;
(iv) the chemistry of the condensate similar to that given in Table 1.

Achievement of these conditions requires access to a continuous supply of geothermal steam or condensate. The test rig has been constructed at Well BR19 at the Ohaaki geothermal field. Steam is drawn from Well BR19, is conditioned to match the chemistry of the larger pipelines, and passed through a corrosion monitoring section where corrosion rates and potentials are measured on a daily basis.

2 DESIGN OF THE CORROSION TEST RIG

A flow diagram for the test rig is shown in Figure 1.

Table I Approximate Chemistry of Condensate in Contact with Steam in the Ohaaki and Wairakei Steam Pipelines. (Wilson et *al*., 1982)

Species	Ohaaki	Wairakei
$[CO_2+HCO_3^-]$ (mmol/kg)	0.65	0.04
$[H_2S+HS^-]$ (mmol/kg)	***0.05***	**0.01**
$[NH_3+NH_4^+]$ (mmol/kg)	[illegible]	[illegible]
$[SiO_2]$ (mmol/kg)	0.03	0.01

2.1 Steam Conditioning

Steam from Well BR19 was separated using a cyclone separator at T = 170°C and p = 8 bar. Silica and chlorides present in the steam were removed through a steam trap inserted prior to the heat exchanger. Thermocouples and pressure gauges inserted into the line at various points were used to monitor system conditions. The pipeline has been lagged using fibreglass encased in aluminium cladding from the first pressure gauge up to the test section, lowering the amount of heat loss prior to the test section.

Cooling of the steam to the desired temperature and wetness was achieved using an annular heat exchanger, 4 m in length and with an internal diameter of 50 mm. The heat exchanger was constructed from AISI type 316 stainless steel. Cooling water flows counter-currently to the steam.

The steam could be partially or fully condensed using a maximum cooling water flow rate of around 5300 kg/hr. A range of steam flow rates could also be achieved by adjusting the line pressure of the steam using the control valve after the cyclone separator. It is difficult to control an annular film of condensate on the inside of the pipe. Therefore, to obtain the optimum conditions for measuring corrosion rates and corrosion potentials the steam was fully condensed to T = 153°C and p = 6 bar using a cooling water flow rate of approximately 2100 kg/hr. As it is primarily the effect of the condensate on the steel which causes the corrosion and not the steam, the applicability of the results of the experiments to full scale pipelines is maintained. The mass flow rate of the steam is around 240 kg/hr, which results in a condensate velocity of approximately 1.5 m/s in the corrosion monitoring section.

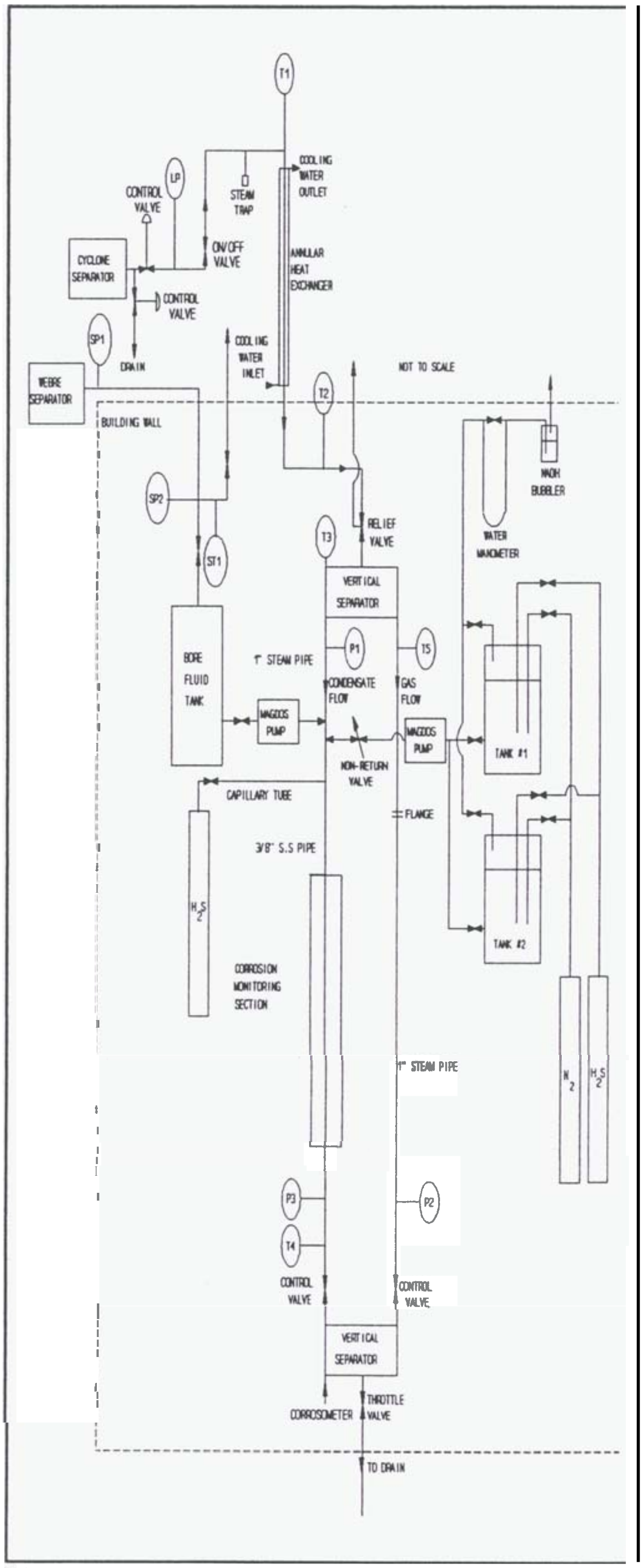

Figure 1 Flow Diagram of Corrosion Test Facility

After the steam has been condensed, 4% by weight of non-condensible gases, mainly CO_2, remain present in the condensate. This would produce slug flow in the corrosion monitoring section, as opposed to the desired laminar flow, due to the large difference in density between CO_2 and H_2O. As this would have introduced noise into the electrochemical experiments, causing the results to be inaccurate, the gas/condensate mixture was separated prior to the test section using a vertical separator.

2.2 Injection of Additives

The pH of the condensate was controlled by additions of H_2SO_4 and NaOH. Na_2SO_4 was added to improve the conductivity of the condensate and so allow the use of electrochemical (LPR) methods for measuring corrosion rates. NaCl was added for those tests where a Ag/AgCl reference electrode has been used for monitoring corrosion potentials. For those experiments in which the influence of dissolved SiO_2 was investigated, bore fluid from BR19 was pumped in separately to give the required SiO_2 concentration.

The additive solution was stored in a plastic tank and bubbled with nitrogen for oxygen removal. The gas pressure inside the tank was maintained at just above 1 bar. Attempts to inject hydrogen sulphide saturated fluids into the test rig were frustrated by the dissolved H_2S coming out of solution in the diaphragm of the pump causing 'vapour lock' and preventing injection. An alternative method of injecting H_2S by bleeding the gas directly through a capillary tube is currently being trialled.

The additive solution was pumped into the pipeline using a MAGDOS MD4 pump, the injection point being just prior to the corrosion monitoring section. The solution was injected after the vertical separator to ensure that injected gases such as H_2S were not removed with the non-condensible gases. A non-return valve prior to the final injection point prevented condensate flowing into the injection line and flashing.

2.3 Corrosion Monitoring Section

After the injection point the condensate flows from the steam pipe into the corrosion monitoring section. Laminar flow through the test section was desired although given the roughness of the inside wall of the test section it was unlikely that this could be achieved.

Figure 2 shows the design of the electrochemical part of the corrosion rate monitoring section. Electrodes, made from UNS G10120 low carbon steel typical of steam pipelines, were push fitted into PTFE pieces which were pressed into a steel holder. Pressure was applied using AISI type 316 stainless steel plugs to push the electrodes together, preventing leakage of the condensate between the electrodes. Pressure was maintained by locking the plugs at either end. Electrical access to the electrodes was made through insulated fittings drilled through the holder. The 25% glass fibre filled PTFE was used between the electrodes as it provides the required electrical insulation and mechanical stability.

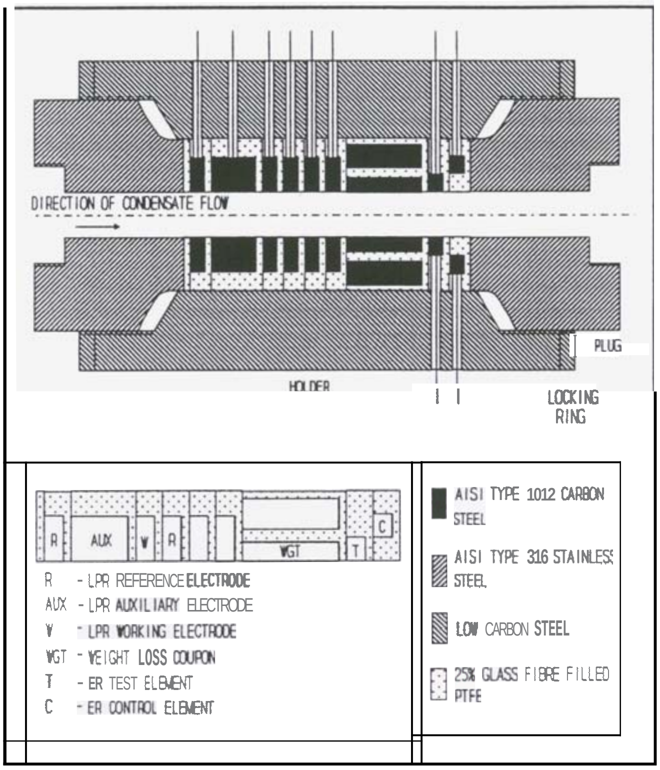

Figure 2 Design of the Corrosion Monitoring Section

The advantages of this design are that the holder can be reused and the type and arrangement of monitoring techniques can be easily modified, and that the effect of solution resistance on the electrochemical measurements has been minimised by standardising the distance between electrodes.

The electrochemical and physical techniques used to monitor the corrosion of low carbon steel in that environment are described below.

Weight Loss Measurements-Weight loss coupons were prepared using ASTM Standard G1-88 (ASTM G1-88, 1988) as a guideline. Since the pH of the condensate was changed over the course of the experiment, corrosion rates at each pH could not be obtained by this method. However, an overall material loss and an average corrosion rate could be calculated and used for calibration purposes.

Linear Polarization Resistance- (Lichti et *al.*, 1980) The instrument used to measure corrosion rates in the project experiments was a Model M-103 Petrolite Corrosion Rate Meter. The M-103 polarizes the test electrode away from its equilibrium potential by 10 mV and measures the polarization resistance. The corrosion current is calculated and the corrosion rate obtained based on a known electrode surface area and composition. As the probes used in these experiments were not of standard dimensions, the LPR readings were adjusted using the weight loss data.

Electrical Resistance Method- (Lichti et *al.*, 1981) A T10 Corrosometer probe was inserted into the pipeline at the bottom of the second vertical separator and was to be used as a calibration device for the electrical resistance probe contained within the test section.

Thin Layer Activation- Thin Layer Activation (TLA) is a method of measuring wear, corrosion and erosion of materials. The surface to be exposed is irradiated using a nuclear accelerator and therefore labelled with a low amount of radioactivity. As material is lost from the surface the intensity of γ-rays emitted from the surface decreases. The relationship between the amount of radioactivity measured and the depth into the surface is known, so the rate of corrosion can be measured on a semi-cumulative basis (Boulton, 1989). However, if material lost from the surface is not removed from the test area, but is incorporated into a passive film, the accuracy of the results is affected, most likely giving rise to low material loss readings.

A 1 mm diameter spot on the surface of the electrical resistance test piece was irradiated to a depth of approximately 30 pm. The intensity of radiation emitted was then measured on a daily basis and compared with a standard to ensure that the detector was correctly calibrated.

Hydrogen Collection Probe- (McAdam et *al.*, 1981) A hydrogen collection probe was made from a 7/8" mild steel sheath welded around a section of 3/8" pipe made from AISI 1012 low carbon steel. The probe measures the volume of hydrogen generated by the corrosion process which gives an indication of the semi-cumulative corrosion rate.

Corrosion Potential Measurements- An external reference electrode holder was constructed using a PTFE tube encased in a length of 3/8" diameter 316 stainless steel pipe. The PTFE provided electrical insulation between the reference electrode and the rig. An annular heat exchanger surrounded the stainless steel to ensure that the temperature of the reference electrode remained at room temperature. A bleed valve at the top of the holder allowed the solution to be replaced.

A Ag/AgCl reference electrode was used to measure the corrosion potential of mild steel under flowing conditions in the environments containing negligible hydrogen sulphide. The corrosion potential of the steel was corrected for a thermal liquid junction potential, taken as approximately 45 mV (MacDonald et *al.*, 1979), which existed between the reference and working electrodes.

2.4 Condensate Disposal

The non-condensible gases could not be vented directly to atmosphere as this would have reduced the pressure in the line causing flashing of the condensate. Therefore, the gases were remixed with the condensate after the test section using a second vertical separator. Control valves on both the condensate and gas flows were manipulated to ensure flow through both pipelines.

A throttle valve was located after the second separator to control the pressure inside the rig. The condensate then flows through a length of steam pipe, approximately 7 m, to drain outside the building.

3. INITIAL EXPERIMENT

The initial experiment carried out was based on the conditions encountered within the Wairakei steam transmission lines. The pH of the condensate was changed every 3 days, from pH 4 through to pH 7.5. Three days were considered enough time for a steady state corrosion rate to be established at each pH. Guidance as to the influence of pH on corrosion rates under these conditions is available from conventional power station conditions (ASM, 1987). At the time of reporting the composition of the condensate had not been analysed. It was assumed to have a sulphide content equal to or less than that of Wairakei condensate.

3.1 Results and Discussion

Two of the measurement techniques, the hydrogen collection probe and the electrical resistance coupons, were unsuccessful in that no data were obtained. The hydrogen probe failed due to leakage of air into the probe. The electrical resistance probe lacked sensitivity and did not respond to the loss of metal.

The penetration depth measured on the weight loss coupons over the 12 days was 3.68 μm, which corresponded to an average corrosion rate of 113.3 μm/yr. The LPR data were corrected by equating the total weight loss from the coupon results to the area under a graph of corrosion rate vs time. The results are presented in Figure 3. The graph shows an expected decrease in corrosion rate with increasing pH (ASM, 1987). However, although a steady state corrosion rate was reached, at no stage could the steel be said to be passivated.

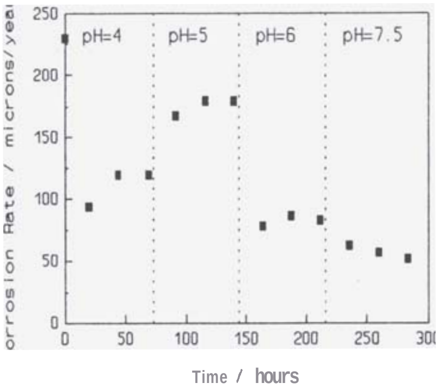

Figure 3 Linear Polarization Resistance Results

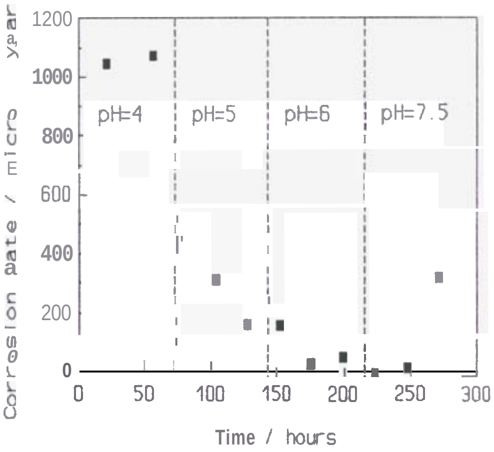

Figure 4 Carbon Steel Corrosometer Results

The Corrosometer probe located at the bottom of the second separator also showed a decrease in corrosion rate with pH, Figure 4. This probe yielded a higher corrosion rate than the LPR technique at the lower pH's, perhaps due to the more turbulent conditions at the bottom of the separator.

The material loss results from the Thin Layer Activation data, Figure 5, show some scatter around zero. The negative values, i.e. material gain, can probably be discounted as equipment malfunction. It is possible that the material loss data are correct, given that they are similar in magnitude to the weight loss data. However, it is apparent that the TLA method requires improvement in instrument reliability.

The Ag/AgCl reference electrode malfunctioned during the experiment, probably due to direct exposure to the hydrogen sulphide in the condensate. A modification has been made to the design of the reference electrode holder to eliminate this problem. The Ag/AgCl reference electrode has been separated from the sulphide-containing condensate using a PTFE tube packed with asbestos, which has been soaked in saturated KCl.

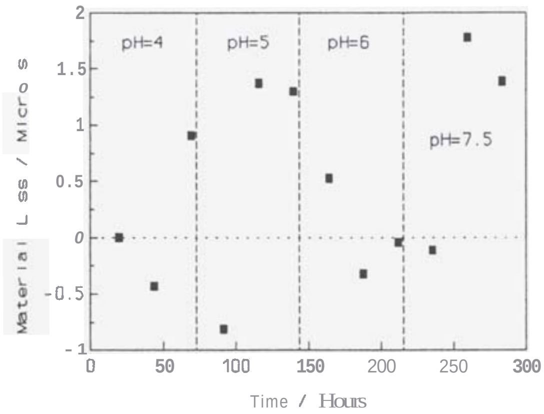

Figure 5 Thin Layer Activation Results

4. CONCLUSIONS

A test rig has been designed and commissioned to study erosion-corrosion phenomena of materials subjected to geothermal environments. The test rig uses condensed steam from a well and conditions it to match the chemistry of the pipeline under investigation. Several techniques were used to evaluate the erosion-corrosion performance of low carbon steel exposed to the condensate.

In an initial experiment, all of the techniques used did not function correctly. Nevertheless, the ability of the test facility to simulate the erosion-corrosion conditions within the larger scale steam pipelines has been demonstrated.

5. ACKNOWLEDGEMENTS

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