

CORROSION TESTING IN MULTIPHASE FLOW, CHALLENGES AND LIMITATIONS

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ABSTRACT

The paper discusses the limitation and challenges of simulating field conditions in small scale corrosion flow loop experiments. It is focused on the importance of water chemistry control, the impact of mixing oil and water in the experiment, the simulation of shear stresses and flow regimes, and the effect of oxygen contamination. Small changes in any of these variables can give huge effects on corrosion and this will be illustrated with examples from previous lab work. The objective is to show how important it is to understand and control the dynamics of the test system before the test results are used to predict the performance of the carbon steel and corrosion inhibitors in the field.

Keywords: CO₂ corrosion, carbon steel, internal corrosion, mechanisms, corrosion films

INTRODUCTION

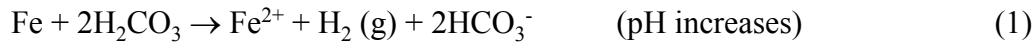
Corrosion of carbon steel in oil and gas systems is governed by a complex mixture of various mechanisms. A large number of parameters are involved and they affect the corrosion mechanisms differently. The most important parameters are related to steel properties, water chemistry, flow patterns, oil chemistry, oil vs. water wetting and operational conditions. To simulate all the field parameters in laboratory tests is impossible. The challenge is therefore to simplify the system without losing control of the main controlling parameters and without switching to other corrosion controlling mechanisms. Table 1 gives a survey of parameters that have to be considered. They are listed in two categories, easy to control and complicated.

IFE has been running flow and corrosion loop tests for more than 20 years. The present paper discusses some of the challenges encountered during this long history of laboratory experiments. It is focused on water chemistry, the impact of mixing oil and water, the importance of test duration, the importance of oxygen control, and the control of flow geometry and flow regime.

CONTROL OF WATER CHEMISTRY

Corrosion products in a CO₂ system

CO₂ corrosion of carbon steel can be fast (several mm/y) and large amounts of corrosion products are released to the water. Accumulation of corrosion products can have a rather drastic influence on the water chemistry and subsequently the corrosion rate and the type of attack. In a closed system, the dissolved iron concentration will increase until a balance is established where the release rate of Fe²⁺ is the same as the precipitation rate of FeCO₃ (or Fe₃O₄ at high temperature). When Fe²⁺ is released in the corrosion process, the double amount of bicarbonate forms according to eq 1. The pH increases until the bicarbonate + carbonate concentration becomes so high that solid FeCO₃ precipitates, eq 2.



When all the ferrous ions produced by corrosion precipitate as iron carbonate the pH remains constant, and the overall reaction becomes:

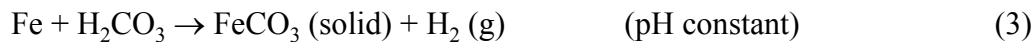


Figure 1 shows how pH is affected when the corrosion products accumulate in condensed water at 0.1 MPa CO₂ and 40 °C. If the initial corrosion rate is 10 mm/year and the surface area to water volume ratio 2 cm²/litre, the pH increases 1 unit in 10 hours. A large degree of FeCO₃ super saturation is possible in CO₂ systems and the pH can increase up to two units during exposure when the temperature is low (< 40 °C). At higher temperature (> 60 °C) iron carbonate precipitates more easily and the maximum achievable super saturation and the increase in pH become lower.

The temperature, pH and the dissolved concentration of iron carbonate are the main controlling parameters for protective corrosion product film formation. Without control of the dissolved corrosion product concentration large differences in corrosion rates can be obtained for apparently the same test conditions. This effect becomes more pronounced when the temperature is increased. An example¹ is shown in Figure 2 where an X-65 carbon steel was exposed in one of the loops in our laboratory. The test conditions are listed in Table 2. The only difference in the two exposures was the dissolved concentration of Fe²⁺ and this gave a shift in corrosion rate from less than 0.1 mm/year to 50-100 mm/year when the iron content was reduced from about 100 ppm to around 30 ppm. The experiments illustrate very well the importance of the dissolved Fe²⁺ concentration. When the solubility limit is exceeded, deposition of a protective FeCO₃ layer may take place. Since FeCO₃ precipitation is a slow process, super saturation is necessary in order to actually form a protective layer. The super saturation threshold for film formation depends strongly on temperature and mass transport of corrosion products and reactants to and from the surface. The first experiment was run below the threshold for protective films formation while the second experiment was run with a dissolved corrosion product concentration above the threshold.

A water conditioning system is necessary in order to control the environment. For simple water chemistries, ion exchangers can be used to remove the corrosion products and to maintain the

composition of the corrosive environment. For a system with sodium chloride, two ion exchangers are optimal. One ion exchanger can be loaded with sodium where Fe^{2+} is exchanged with Na^+ . With this ion exchanger, the Fe^{2+} concentration in the water can if desired be kept very low, but the pH will increase as bicarbonate accumulates in the solution. A second ion exchanger loaded with H^+ can be used to control and maintain the pH. Any pH level can be kept constant by controlling the flow through the ion exchanger with a magnetic valve operated by a pH meter with an on-off relay. The use of ion exchangers becomes complicated if the solution contains more than one type of cations in addition to Fe^{2+} .

For more complex water chemistries corrosion products can be precipitated by slowly passing the water of the loop through high temperature autoclaves. In such autoclaves the ferrous ions in the water precipitate as solid iron carbonate or magnetite, due to the lower iron solubility and higher precipitation rate at elevated temperatures. The production of ferrous ions by corrosion and the consumption of ferrous ions in the autoclave can be balanced by varying the temperature and the flow through the autoclave.

If the system is inhibited, neither ion exchanger nor high temperature autoclaves can be used as the inhibitor may be adsorbed in the ion exchanger or destroyed at the high temperature in the autoclave. The ideal solution in such cases is to use a type of once through system where all the liquid or part of the liquid is continuously replaced with fresh solution. For situations where the consumption of liquid becomes too high a system was developed where a small stream of gas and water is drained from the loop to a low pressure autoclave and then pumped back to the loop in a closed circuit. The pressure reduction in the autoclave gives an increase in pH due to the reduction in CO_2 partial pressure, with the result that corrosion products are precipitated at the same temperature as in the loop. One disadvantage with this method is that inhibitor might stick to the precipitated solids and thus be consumed and give a too low concentration in the test fluid.

Corrosion products in an H_2S system

When the water phase contains significant amounts of H_2S , FeS is easily formed. This makes it much easier to maintain a constant and low amount of dissolved corrosion products in the system. The pH therefore normally remains constant as long as the consumption of H_2S is compensated. It might be necessary to have a filter in order to take out the small particles of FeS that circulate in the liquid.

Control of added salts

In formation water the concentrations of most of the cations and anions are well below the saturation limit. However, Ca, Sr, and Ba may be slightly above or close to the solubility limit. When such a complex water chemistry is simulated in lab experiments it must be taken into account that some of the ions can be slowly consumed. The cations can precipitate on the test equipment (loop walls, autoclaves etc.) or co-precipitate in the corrosion product film formed on the steel surface. Co-precipitation can take place even when the water is under saturated, because the pH will be higher inside the corrosion product film or close to the metal. An example of such a film is shown in Figure 3. It is seen that the CaCO_3 precipitated close to the metal only, not in the outer part of the film where the concentration of Ca is below the saturation limit. When the cations are consumed, they have to be replenished in a controlled manner. This can be done by passing part of the test water through

autoclaves with solid CaCO_3 , MgCO_3 , etc. When the temperature is lower than in the loop, a slightly super saturated solution is achieved and at higher temperatures a slightly under saturated solution.

Contaminations

The results obtained in laboratory experiments can be very sensitive to certain contaminations in the test liquid. It has been experienced that even trace amount of Copper (Cu), Nickel (Ni), Lead (Pb), and Antimony (Sb) can change the corrosion rate and the mode of attack completely. These ions can be leached out from bearings in the pump, washers etc. Problems with such elements have been experienced at concentrations far below 1 ppm in the water phase.

Figure 4 shows an example of localized attack on carbon steel exposed at pH 5 in a flow loop experiment with a few ppb antimony. The non-attacked area was covered with a thin layer of corrosion product enriched with antimony. The attack looks like a traditional mesa attack, but the mechanism is totally different. Formation water contains a large number of trace elements and it can be speculated on whether some of the attack seen in the field also can be related to trace elements.

When loop systems are built or modified, reference tests should be run under conditions where the expected corrosion rate is well known.

EFFECT OF TEST DURATION

If CO_2 and water have free access to the steel surface, the corrosion rate will normally be several mm/year. The key issue is: will a corrosion film with protective properties be formed? It can take a long time to establish a corrosion film and therefore the test duration becomes an important parameter. Corrosion rates measured in short duration tests give information about the transient corrosion rate on bare steel, but do not say much about the corrosion rate and the risk for localized attack with time. An example of a film that took 3 months to form in a pH stabilized CO_2 environment is shown in Figure 5².

The problem of running long duration tests is the cost and the complexity of controlling the environment. It will always be a compromise, but the validity of running short tests should be analyzed for each project. It is typically accepted to run inhibitor screening tests much shorter (a few days) than tests where corrosion control is based on corrosion product coverage of the surface or interaction with corrosion products and the inhibitor. In the latter case, several weeks should be considered.

ONE, TWO OR THREE-PHASE LOOP TESTING

When corrosion loop studies are needed for a multiphase pipeline, the question sometimes arises whether multiphase loop testing is required. The answer to this depends on which effects one wants to study. If water wetting is expected in the application, water wetting should also be ensured in the testing. It should always be kept in mind that it is the water phase which is the corrosive phase, and ensuring the correct water chemistry and amount of dissolved CO_2 and/or H_2S have by far the most important effect on the corrosion behavior.

When water wetting is anticipated and the effect of water chemistry and flow velocity or shear stress is to be studied it is most likely that successful results are obtained when single-phase loop studies are used. Loop experiments with only water phase are much easier to control with respect to both water chemistry and flow conditions than two- or three-phase experiments. Fluid flow simulation computer programs may be used for estimating the actual liquid velocity or shear stress in a multiphase pipeline, and single-phase corrosion loop testing with this flow velocity or shear stress can then be used to simulate the actual corrosive conditions.

It is only when particular multiphase flow effects are to be studied that it may be required to perform two- or three-phase corrosion loop testing. Examples of this can be erosion studies, studies of oil or water wetting, studies of the effect of dispersions or emulsions on water wetting or inhibitor performance, or studies of top-of-line corrosion when water condenses in a wet gas pipeline.

With typical flow loops with 1 to 2 inch inner diameter flow channels it is not realistic, or at least very difficult, to obtain representative three-phase flow conditions. This would require a loop with larger diameter, long straight sections in order to obtain a developed flow pattern, gas/oil/water separators and separate pumps and feeding lines for gas, oil and water. The strict water chemistry control and prevention of even minute amounts of oxygen ingress become extremely costly and difficult in such large-scale flow loops, which are often best suited for pure fluid flow studies without corrosion measurements. The best approach might be to study and understand how the different phases are distributed in pure flow experiments of short duration and then simulate the critical parameters in dedicated small scale corrosion test systems where long and controlled exposures can be conducted. If good separation cannot be ensured, it is recommended to focus the design and operation of dedicated corrosion flow loops to circulating either only the water phase with dissolved gases or the water phase with small amount of oil droplets or gas bubbles, or periodic circulation of oil in order to wet the wall with oil. Without sufficient separation capacity, circulation of water, oil and gas in a loop will very easily lead to uncontrolled formation of emulsion and/or foam due to the high velocity and the violent mixing of the phases in the pump. This will affect the water-oil wetting and the accumulation of inhibitor on the interfaces may remove a large fraction of the inhibitor from the bulk phases³.

CO₂ corrosion inhibitors are mostly amphiphilic, surface active compounds. These compounds may be preferentially soluble in the water or the oil phase, depending on the length of the hydrocarbon tail. However, the inhibitor molecules have a very high affinity for the oil-water interface, due to their amphiphilic nature. When oil is introduced in a loop test, the high shear in a centrifugal pump can create a dispersion of small oil droplets in the water phase (or conversely water droplets in the oil phase). These droplets may constitute a large interface area (order of m²/liter) that can accumulate a large amount of inhibitor and hence deplete the inhibitor concentration in the water phase to an inefficient level³. The inhibitor demand in a loop test with oil may therefore be significantly higher than in a test without oil, or a glass cell or autoclave test with low convection. On the other hand, the dispersion of oil in water may facilitate oil wetting of the test specimen under certain conditions. These factors are important to bear in mind when interpreting the test results.

A convenient way to minimize the tendency to emulsion and foam formation for a situation where presence of both water and oil is desired would be to circulate only the water phase in the loop, but with a small fraction of the loop water being continuously circulated through a storage tank in a

bypass to the main loop, where the loop water can be in contact with the oil, but with the liquid flow through the storage tank kept low to avoid excessive emulsion and foam formation.

If top-of-line corrosion is to be studied, it should be only necessary to circulate a representative moist gas with CO₂ and/or H₂S in the loop and use cooling to ensure condensation. The gas can then be saturated with water and hydrocarbons in a conditioning tank before entering the test circuit, and there is less need for a full three-phase flow in the loop.

It should be pointed out that from a corrosion viewpoint it is normally not regarded necessary to run loop tests with one or two liquid phases under the full field pressure in order to obtain representative results, as long as the actual CO₂ and/or H₂S fugacity is used in the experiments. It may be desirable to use a total pressure somewhat higher than the partial pressures of the acid gases in order to avoid gas bubble formation, but increasing the pressure above this to actual pipeline pressures seems to have no effect on the corrosion experiments to be performed in the loop. This means that corrosion experiments under representative field conditions can be performed for most cases in loops with maximum pressure in the range 1.5 – 3.0 MPa, resulting in a relatively easy operation of the loop.

FLOW GEOMETRY AND SHEAR STRESS IN ONE PHASE FLOW

It is not satisfactory to correlate corrosion rate with linear flow rate only. The flow exerts a shear force on the metal wall and flow also speeds up mass transfer of constituents from the fluid to and from the corroding metal. A linear flow rate of a given value does not have the same effect in tubes of different diameters. Shear forces and mass transfer are amongst other influenced by the diameter, geometry, surface roughness, temperature, viscosity and density. There are also other concerns in the calculation and use of the term shear stress:

- The corrosion process affects the surface roughness, and in turn affects shear stresses.
- If coupons are used, the surface roughness varies in the channel, as the roughness of the specimen is different from the surface of the specimen holder. The fluid shear stress also exhibits some variations over the specimen (as the flow will be slowed down at the edge)

The effect of the change in surface roughness can have a significant effect on the shear stress at high flow velocities. In the beginning of a lab exposure, the surface roughness (ϵ) of freshly machined surfaces is typically in the range 10 μm and a polished surface 1 μm . ϵ increases rapidly with time until a steady state situation is obtained. When field samples are exposed the surface roughness is usually much higher than machined lab samples and a higher shear stress will be experienced compared to lab samples that are exposed in the same test rack system. The surface roughness cannot be measured under the exposure, and is difficult to estimate.

When shear stress is used as a reference for comparing results between field and lab or between different labs or experimental systems, it is very important to use the same surface condition. Calculation of shear stress with one method can be significantly different from another method. In addition, a shear stress without a reference to surface roughness can be misleading, particularly for high flow velocities. Figure 6 shows the change in calculated shear stress in a water system as a

function of flow velocity when the surface roughness is changed. It is seen that large variations can be expected in the calculations. When results are presented and compared, the actual fluid flow velocity should also be included as this number is better defined and more accurate than the shear stress.

Several approaches can be used to calculate the shear stress. For both tubular samples and for flow channels where coupons are mounted along the diameter of tubular racks the following approach has been used to calculate the shear stress. This is the same approach as used in the NORSOK model to calculate shear stress for pipe geometries. The model is publicly available on the Internet⁴.

The shear stress τ can be calculated from the following equation for one phase flow in uniform circular pipes:

$$\tau S = \frac{dp}{dz} A \quad (4)$$

where $\frac{dp}{dz}$ is the frictional pressure drop, S the wetted perimeter and A the cross section area.

The Fanning equation is used to calculate the frictional pressure drop:

$$\frac{dp}{dz} = \lambda \rho U^2 / (2D) \quad (5)$$

where λ is the friction factor, ρ the density, U the fluid velocity and D the diameter of the pipe.

For cross sections other than circular the Fanning equation is applicable in the turbulent region for channels running full, when the diameter in the equation above is replaced by $D_H = 4 A/S$ where D_H is the hydraulic diameter.

λ , the friction factor, is obtained from the following formula for turbulent flow in rough tubes:

$$\lambda = 0.0055 \left[1 + \left(\frac{2 \times 10^4 \varepsilon}{D_H} + \frac{10^6}{Re} \right)^{0.33} \right] \quad (6)$$

where ε = surface roughness and Re = Reynolds number. The Reynolds number can be calculated from the following equation:

$$Re = U \rho D_H / \mu \quad (7)$$

where μ = dynamic viscosity.

INGRESS OF O₂

Ingress of oxygen from the surrounding atmosphere constitutes a significant problem for many types of experiments to be performed under anaerobic conditions. The effect of oxygen ingress is most critical in inhibitor testing. In recent IFE work⁵⁻⁶, the effect of dissolved O₂ (0 – 100 ppb) on the

inhibition of CO₂ corrosion was studied using carbon steel rotating cylinder electrodes (RCE). The test condition was 40 °C, 0.1 MPa CO₂, pH 5.5, 1 wt% NaCl solution.

At a dose of 20-30 ppm inhibitor the CO₂ corrosion rate with less than 1 ppb O₂ was reduced to 0.01 mm/y, see Figure 7. Inhibitor performance was not affected by RCE rotation rate (100-5000 rpm) when the concentration of dissolved oxygen was kept below 1 ppb. With 100 ppb O₂ the inhibited corrosion rate increased with increasing rotation, the corrosion rate being determined by O₂ reduction at the diffusion limited rate. Similar results were obtained in a recent study where the effect of extreme shear stresses was investigated in a loop with jet impingement flow geometry.⁷ When the O₂ concentration was 2-4 ppb the inhibitor performance was not affected by wall shear stresses up to 1400 Pa, see Figure 8. With 10-30 ppb O₂ the inhibited corrosion rate was determined by the O₂ diffusion rate.

Traces of O₂ thus constitute an error source in corrosion inhibitor testing, and may give rise to impaired inhibitor performance and spurious flow effects under flowing conditions. The diffusion limited oxygen corrosion rate is plotted in Figure 9. The figure shows that 10 ppb O₂, which is a typical concentration in many test conditions, can significantly influence the result of an inhibitor test in a high flow velocity test. It is therefore of special importance to have good control of the oxygen level for inhibitor experiments.

If ingress of O₂ is likely to occur in the actual field application, the inhibitor testing program should include studies of O₂ sensitivity performed under controlled O₂ concentrations.

IFE's experience is that CO₂ corrosion inhibitor performance is little affected by the shear stress when the oxygen concentration is kept under strict control⁵⁻⁹, see Figures 7 and 8. The kinetic energy of the water molecules caused by the ordered flow movement is very small compared with the energy of the thermal motion of the molecules. The flow forces are thus probably small compared to chemical bond strengths involved in inhibitor adsorption⁷.

CORROSION RATE MEASUREMENTS

In flow loop experiments with H₂S large fluctuations in LPR and other electrochemical measurements may occur as a result of electrical bridging between the electrodes due to precipitation of electrically conducting iron sulfide on test coupons, coupon holders and the internal surface of the flow loop and the spacers between the specimens. This is a general problem in corrosion experiments with H₂S. The FeS flashover problem becomes more pronounced with increasing corrosion rates and amounts of FeS formed. All corrosion rates obtained by electrochemical measurements during sour flow loop experiments should be verified against weight loss measurements.

Furthermore, after sour service testing one should carefully check for any development of localized corrosion attack at the test coupon edges. These may be experimental artifacts caused by galvanic cells that are formed in the loop, but are not likely to form in the field. Depending on the edge-to-surface ratio, such edge attacks may represent a significant part of the total weight loss of the test coupon. A test coupon geometry with low edge-to-surface ratio should be applied if edge attack is a problem, e.g. sections of pipe instead of flat coupons. Severe corrosion may also occur due to galvanic corrosion around wetted connection points between the test coupons and electric wiring.

CONCLUSIONS

Corrosion of carbon steel in oil and gas systems is governed by a complex mixture of various mechanisms. A large number of parameters are involved and they affect the corrosion mechanisms differently. To simulate all the field parameters in laboratory tests is impossible. The challenge is to simplify the system without losing control of the main controlling parameters and without switching to other corrosion controlling mechanisms.

Without proper control of the dissolved corrosion product concentration, the corrosion rate can vary 1-2 orders of magnitude for apparently the same test conditions.

Trace amounts of copper, nickel, lead, and antimony can change the corrosion rate and the mode of attack completely. These ions can be leached out from bearings in the pump, washers etc.

It can take a long time to establish a corrosion film. Corrosion rates measured in short duration tests give information about the transient corrosion rate on bare steel, but do not say much about the corrosion rate and the risk for localized attack with time. Several weeks of exposure may be necessary for experiments under conditions where corrosion product films are formed.

When water wetting is expected in the application, water wetting should also be ensured in the testing. This is most easily obtained when single-phase loops are used. Two or three-phase corrosion loop testing might be required for erosion studies, studies of oil or water wetting, studies of the effect of dispersions or emulsions on water wetting or inhibitor performance, or studies of top-of-line corrosion when water condenses in a wet gas pipeline.

Without sufficient separation capacity, circulation of water, oil and gas in a loop will very easily lead to uncontrolled formation of emulsion and/or foam due to the high velocity and the violent mixing of the phases in the pump. This will affect the water-oil wetting and the accumulation of inhibitor on the interfaces may remove a large fraction of the inhibitor from the bulk phases.

If good separation can not be ensured, it is recommended to focus the design and operation of dedicated corrosion flow loops to circulating either only the water phase with dissolved gases or the water phase with small amount of oil droplets or gas bubbles, or periodic circulation of oil in order to wet the wall with oil.

If top-of-line corrosion is to be studied, it is only necessary to circulate a representative moist gas with CO₂ and/or H₂S in the loop and use cooling to ensure condensation. The gas can then be saturated with water and hydrocarbons in a conditioning tank before entering the test circuit, and there should be less need for a full three-phase flow in the loop.

It is normally not regarded necessary to run loop tests with one or two liquid phases under the full field pressure in order to obtain representative results, as long as the actual CO₂ and/or H₂S fugacity is used in the experiments.

The calculation of shear stress with one method can be significantly different from another method and a shear stress without a reference to surface roughness can be misleading, particularly at

high flow velocities. When results are presented and compared, the actual fluid flow velocity should also be included as this number is defined better and more accurately than the shear stress.

Traces of O₂ constitute an error source in corrosion inhibitor testing, and concentrations as low as 10 ppb O₂ may give rise to impaired inhibitor performance and spurious flow effects in high flow velocity tests.

CO₂ corrosion inhibitor performance is little affected by the shear stress when the oxygen concentration is kept under strict control. The kinetic energy of the water molecules caused by the ordered flow movement is very small compared with the energy of the thermal motion of the molecules. The flow forces are thus probably small compared to chemical bond strengths involved in inhibitor adsorption.

ACKNOWLEDGMENT

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TABLE 1. Parameters affecting the corrosion rate and the execution of lab experiments.

	Easy to control	Complicated to control	Comments
Temperature	x		
CO ₂	x		Consumed and has to be replenished
High H ₂ S	x		Consumed and has to be replenished
Low H ₂ S (ppm)		x	Consumed and has to be replenished, low concentrations are difficult to control
HAc		x	Consumed, sensitive to pH, low concentrations are difficult to control
Flow rate	x		
Flow regime		x	Scale up problems
Oil/water wetting		x	Difficult to run live oil experiments
Oil properties		x	Large differences between model oils, stabilized oil and live oil
Steel composition	x		Use the same batch of steel as in the field if possible.
Water chemistry:			
Fe ²⁺		x	Produced and has to be removed
Ca ²⁺ , Sr ²⁺ , Ba ²⁺		x	Consumed and has to be replenished
Other salts	x		
Steel surface properties		x	Mill scale, rust, corrosion films
Operational parameters		x	Shut down, changing parameters
pH	x		Depending on the buffering capacity of the water

TABLE 2. Test parameters.

	Experiment A	Experiment B
Flow velocity (m/s)	5	5
Shear stress (Pa)	59	59
Temperature (°C)	120	120
CO ₂ pressure (MPa)	3.0	3.0
pH	4.1 - 4.5	4.0 - 4.7
Fe ²⁺ (ppm)	≈ 30	≈ 100
Fe ²⁺ saturation ¹⁰ (ppm)	29	29
pH at saturation ¹⁰	4.12	4.12
NaCl (%)	0.5	0.5

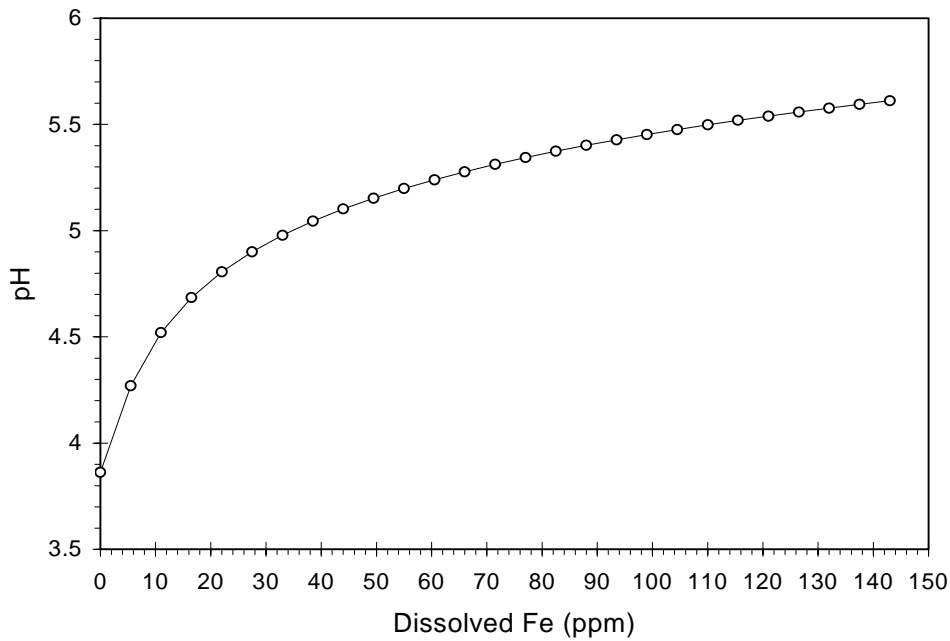


FIGURE 1 - Increase in pH as a function of increased amount of dissolved corrosion products in a system with condensed water, 0.1 MPa CO₂ and temperature 40 °C.

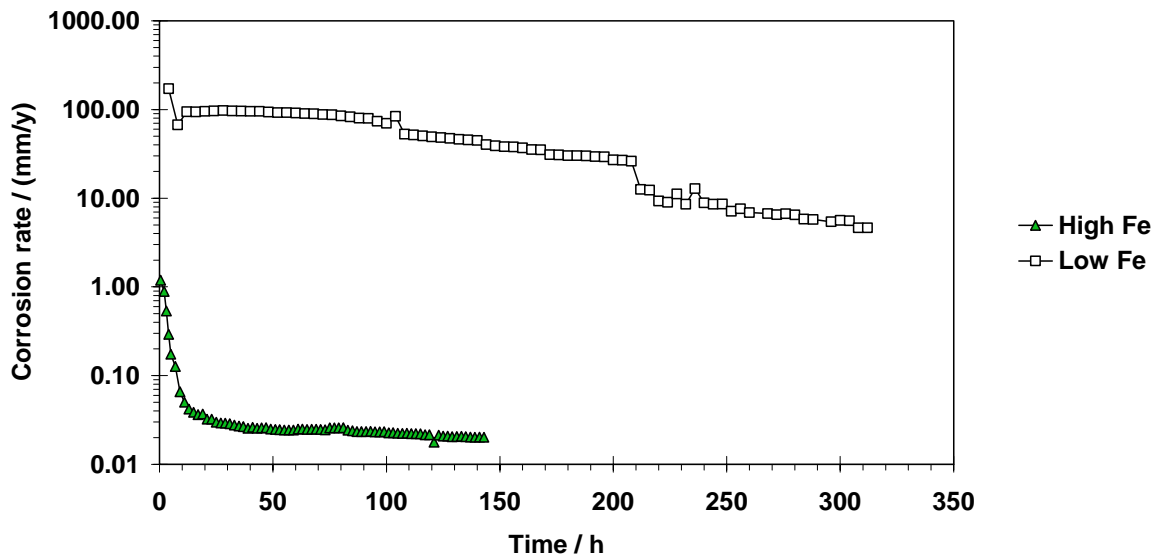


FIGURE 2 - Corrosion rates (LPR) obtained at 120 °C. The experiment was performed at high and low iron concentration in the solution.

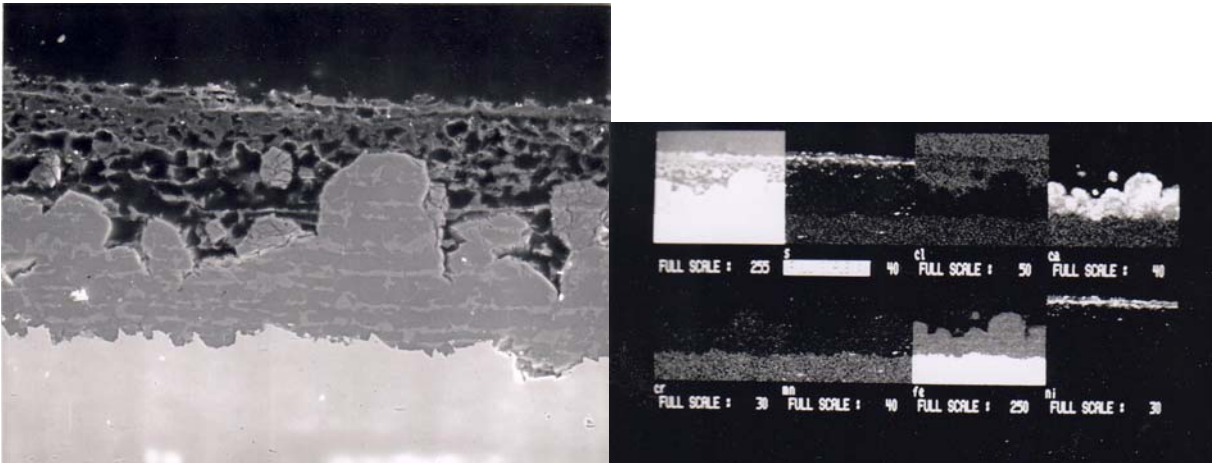


FIGURE 3 – Cross section of corrosion film formed at 0.2 MPa CO₂ partial pressure, 80 °C and pH 5.8. The water was slightly undersaturated with respect to CaCO₃. CaCO₃ and FeCO₃ precipitated in the inner part of the film. Magnification about 400 x.



FIGURE 4 - Corrosion attack obtained in a test with a few ppb antimony, 0.2 MPa CO₂ partial pressure, pH 5. Two phase gas-water flow, 60 °C. The system was undersaturated with respect to FeCO₃. Magnification about 2x.

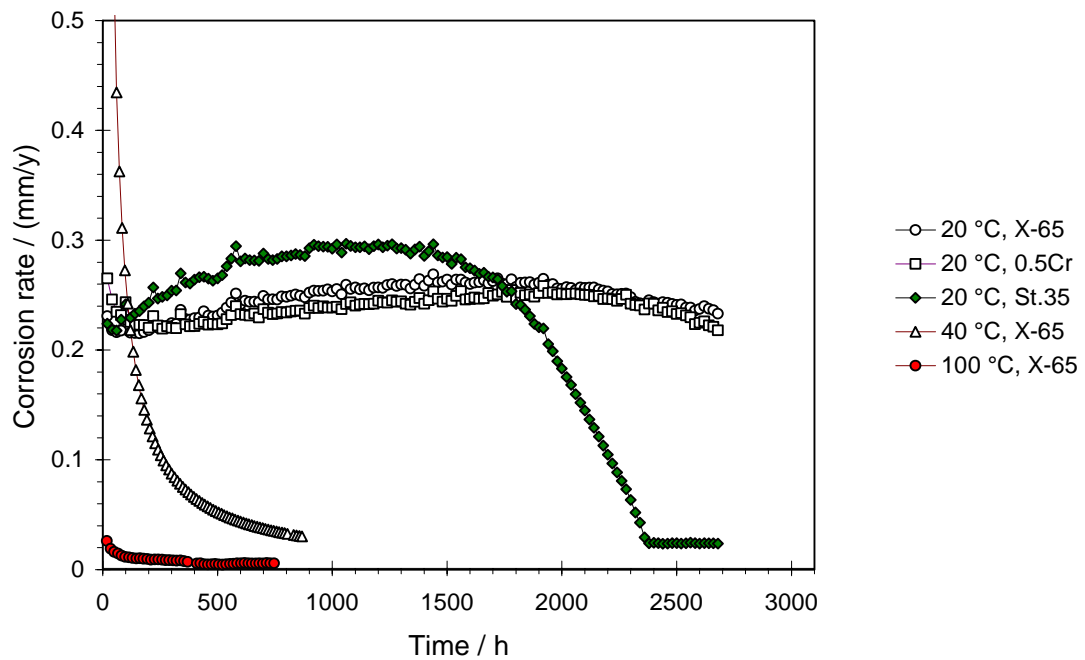


FIGURE 5. Corrosion rate as a function of time, 50 % DEG, 1 % NaCl, 0.6 MPa CO₂, pH 6.5, flow 3 m/s

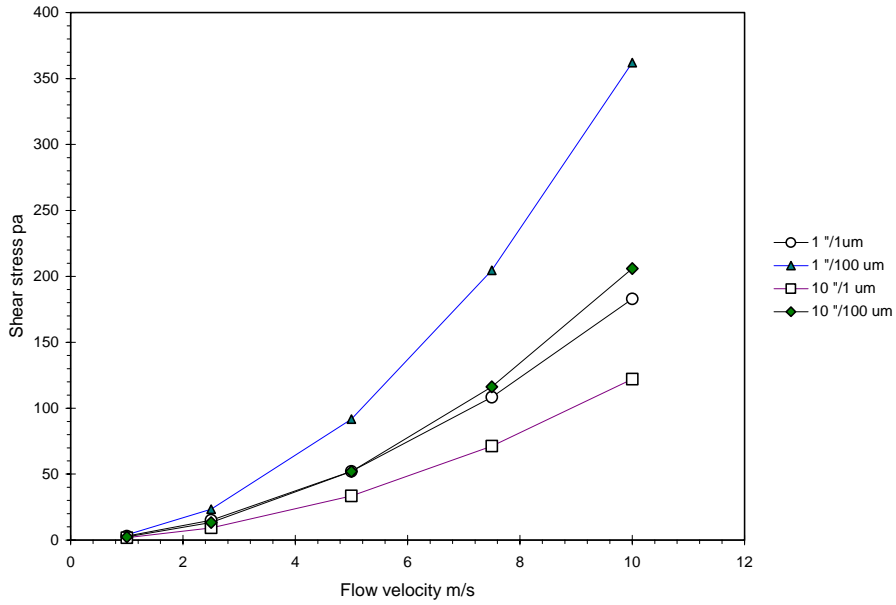


FIGURE 6 - Calculated shear stress as a function of flow velocity for 1" and 10" pipes. Calculations have been done for surface roughness of both 10^{-6} and 10^{-4} m.

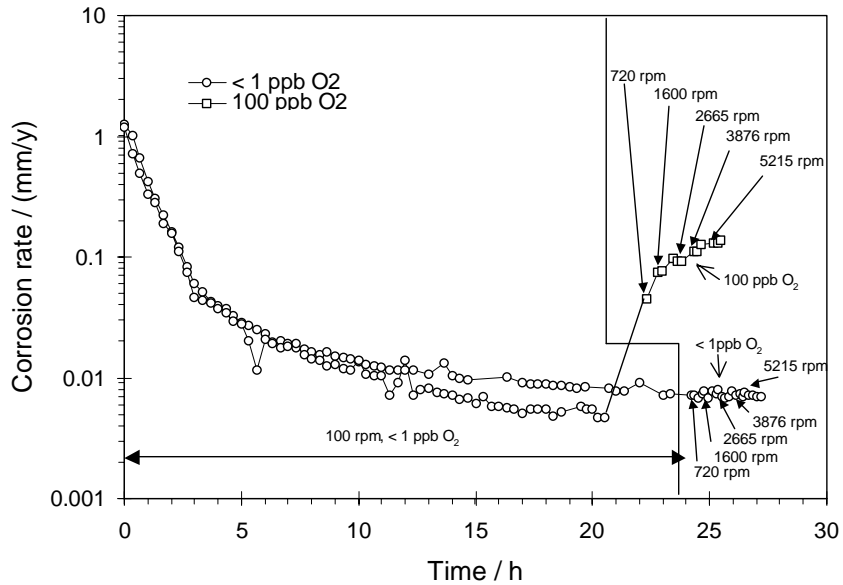


FIGURE 7 - LPR corrosion rate vs. time in RCE tests with 30 ppm Inhibitor C. 40 °C, 0.1 MPa CO₂, pH 5.5, 1 % NaCl. Rotation rates and dissolved O₂ concentrations are given in the graph. From Ref. 5.

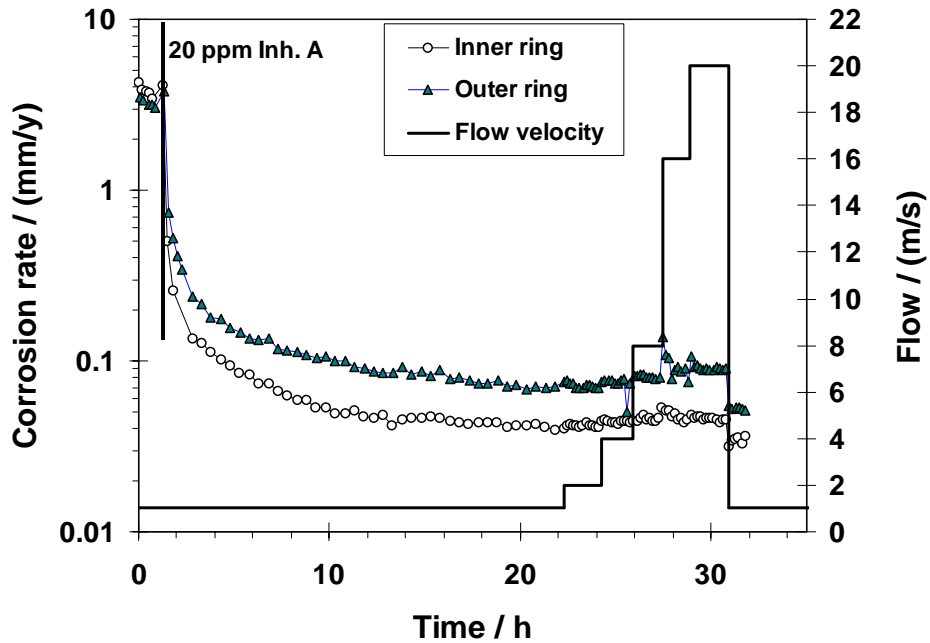


FIGURE 8 - LPR corrosion rate vs. time during test with Inhibitor A (20 ppm). Test conditions: pH 5, 40 °C, 0.1 MPa CO₂, 2-4 ppb O₂. A jet flow rate of 20 m/s corresponds to 1400 Pa wall shear stress on the Inner ring specimen. ©Society of Petroleum Engineers, Ref. 7.

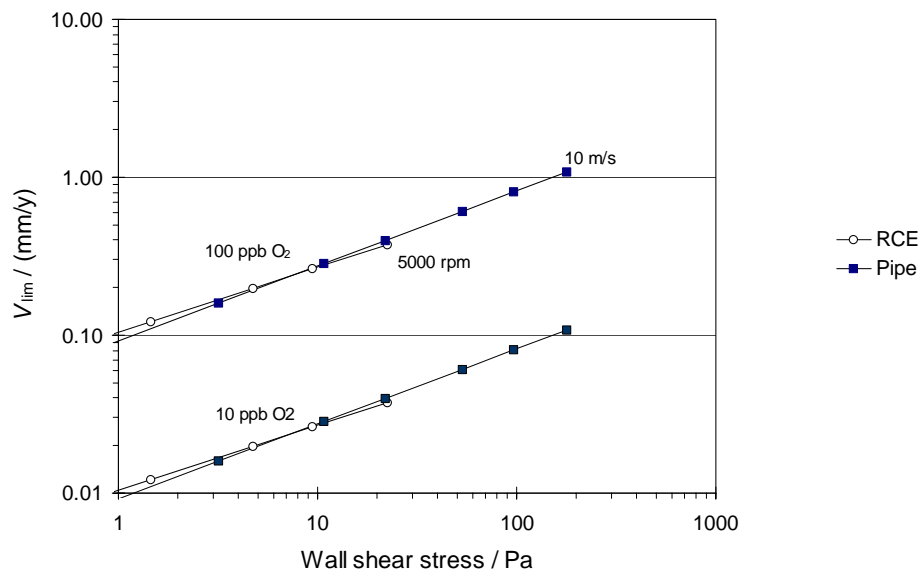


FIGURE 9 - Diffusion limited oxygen corrosion rates as a function of wall shear stress for rotating cylinder electrode (10 mm diameter) up to 5000 RPM, and tubular pipe flow (ID 15 mm) up to 10 m/s. Aqueous brine, 40 °C.