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MULTIPHASE SLUG FLOW-ENHANCED CORROSION IN LOW WATER CUT ENVIRONMENTS

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ABSTRACT

This paper discusses the results for corrosion rate in three phase oil/water/gas slug flow for water cuts of 10, 20 and 30% at carbon dioxide partial pressures of 0.13, 0.27 and 0.45 MPa (5, 25 and 50 psig) at a temperature of 40 °C for pipe inclinations of 0 and +2 degrees.

Corrosion rates decreased with decrease in water cut. For 10% water cut, no corrosion was observed for Froude 6 and a little corrosion was observed for Froude 12. A considerable increase in corrosion rate was measured when a water cut increased from 10% to 20%. The corrosion rate increased with a change in inclination from horizontal to +2 degree.

At 30% water cut, corrosion rate was found to increase as the slug frequency increased. After a slug frequency of 35 slugs/min was reached, the corrosion rate was found to be a constant. The turbulence in the flow reaches such high values that further increase in the slug frequency had no effect in corrosion rate. The corrosion rates also increased with carbon dioxide partial pressure, and Froude number. These results follow similar trends seen from the extensive experiments carried out at the higher water cuts.

A modification to the water cut term has been proposed to the existing corrosion rate model for slug flow.

INTRODUCTION

The flow of oil/water/gas mixtures in the pipeline is a common occurrence in the petroleum industry. Although oil wells initially consist of oil and natural gas, the water content increases significantly later in field life. Most of the wells are located nowadays in remote sites such as sub-sea. The multiphase mixture is transported through a single pipeline to separate facilities since it is very expensive and not practical to separate the produced oil/water/gas mixture at the well site. Carbon and low alloy steels are used as material of construction due to economic consideration. However, Internal corrosion of these pipelines is a major problem in the oil and gas industry.

Several flow regimes occur in the multiphase flow lines depending on the liquid and gas flow rates. Corrosion rates are very high in slug flow regime compared with other flow regimes. As the slug propagates along the pipe, the front of slug creates a highly turbulent mixing zone that has been shown to lead to a significant increase in the corrosion rate. The effect of inclination on the corrosion rate needs to be investigated since changes in inclinations cause changes in multiphase flow regime transitions and flow characteristics.

De Waard et al. (1993) proposed that no corrosion occurs if the water cut is less than 30%. Research at the institute for Corrosion and Multiphase Technology has been performed with the water

cut in the liquid phase at values of 40% and higher. It is of great importance and interest to study the effect of low water cuts on carbon dioxide corrosion in multiphase slug flow. This paper summarizes the results on slug flow corrosion for water cuts of 30% and less, and a model is presented to predict the effect of the water cut on corrosion rates in horizontal and inclined pipes.

De Waard et al. (1995) provided an improved semi-empirical model for prediction of corrosion rates. Carbon dioxide corrosion rates of carbon steel obtained from experiments in a high pressure test loop were fitted to a semi-empirical equation. This model combines a contribution of the flow independent kinetics of the corrosion with one from the flow dependent mass transfer of dissolved carbon dioxide by means of a resistance model. The model can be adjusted to reflect the influence of microstructure and composition of the steel. The model can be seen in the following equations:

$$V_{COR} = \frac{1}{\frac{1}{V_r} + \frac{1}{V_m}} \tag{1}$$

where, V_{COR} = corrosion rate in mm/year.
V_r = corrosion from reaction rate term, mm/year.
V_m = corrosion from mass transfer term, mm/year.

The mass transfer term is given by the following equation:

$$V_m = 2.45 \frac{U^{0.8}}{d^{0.2}} P_{CO2} \tag{2}$$

where, U = liquid velocity, m/s
P_{CO2} = partial pressure of carbon dioxide, bars
D = hydraulic diameter, m

The reaction term is given by

$$\log(V_r) = 4.93 - \frac{1119}{T} + 0.58 \log(P_{CO2}) - 0.34 (pH_{Actual} - pH_{DCO2}) \tag{3}$$

where, pH_{Actual} = actual pH in the presence of dissolved salts
pH_{CO2} = pH of dissolved carbon dioxide in pure water
T = temperature (K)

This model was based on results obtained flowing 100% salt water in a flow loop with no gas velocity. These conditions do not resemble conditions in multiphase flow pipeline, where three phases and slug flow conditions are present.

Bhongale (1995) proposed a model for the calculation of corrosion rates slug flow conditions using the parameters of carbon partial pressure, pressure gradient, overall water fraction and temperature.

$$CR = 31.15 \frac{\Delta P^{0.3}}{L} \nu^{0.6} P_{CO2}^{0.8} \; T \; e^{-(2671/T)} \tag{4}$$

where, CR = corrosion rate (mm/yr)
$\Delta P/L$ = pressure gradient (N/m^3)
ν = water cut
E = activation energy (Joules/mole)
P_{CO2} = partial pressure of carbon dioxide (MPa)
T = temperature (K)

Jepson et al. (1997) modified Bhongale's model, which include the effect of slug frequency and oil type on corrosion rates. Using this equation with a correction factor developed to correct for a slug frequency, which is seen in equation (4).

The slug frequency term is as follows:

$$Cr_{freq} = 0.023\,(F) + 0.35 \qquad (5)$$

where, Cr_{freq} = the normalized factor to account for slug frequency ($0 < Cr_{freq} < 1$)
F = slug frequency to a maximum of 35 slugs/minute

The modified equation obtained is as follows:

$$CR = 31.15\, Cr_{freq}\, Cr_{crude}\, \frac{\Delta P^{0.3}}{L}\, v^{0.6}\, P_{CO2}^{0.8}\, T\, e^{-(2671/T)} \qquad (6)$$

where, Cr_{crude} = the normalized factor to account for crude oil type ($0 < Cr_{crude} < 1$)

Kang et al. (1996) and Maley (1997) have shown that the slug frequency and Froude number have a large effect on the corrosion rate. The corrosion rate increases with an increase in the slug frequency at each Froude number. They also showed that the slug flow dominates the entire flow regime map when the pipe is inclined upwards.

Kouba and Jepson (1989) have shown that the strength of the slug depends on the Froude number calculated in the liquid film ahead of the slug. The Froude number is calculated from the following correlation.

$$Fr = \frac{V_t - V_{lf}}{\sqrt{g h_{eff}}} \qquad (7)$$

where, V_t = translational velocity of the slug
V_f = velocity of the film ahead of the slug
g = acceleration due to gravity
h_{eff} = effective height of the film

EXPERIMENTAL SETUP AND PROCEDURE

The flow loop is a unique 18-m long, 10-cm diameter, high pressure, high temperature, inclinable system. A schematic diagram of this system is shown in Figure 1. The entire flow loop is manufactured from 316 stainless steel. A predetermined oil-water mixture is stored in a 1.4 m^3 stainless steel tank which serves as a storage tank as well as a separation unit for the multiphase gas-oil-water mixture. The tank has a heating jacket around it. Oil is heated in a separate heating tank using four 15KW heaters and pumped to the heating jacket, to heat the contents of the storage tank. Liquid is moved through this system by a 3-15 kW variable speed centrifugal pump. The flow is then controlled within a range of 0 to 100 m^3/hr with the variable speed pump in conjunction with a recycle stream. Flow rate is metered with an inline turbine meter.

Carbon dioxide gas is introduced into the system by means of a 2 MPa feed line from a 20,000 kg storage tank. The gas flow rate is measured by means of a variable area flow meter. The multiphase mixture then flows into the system through compression flange, which allows the inclination to be set at any angle. The multiphase mixture then flows into an 18-m long section where flow pattern, pressure drop, corrosion rate and slug characteristics are measured. The multiphase mixture then flows through a separator after leaving the test section. This separator is used to prevent siphoning due to declined angle of return flow and to destroy the flow pattern. The multiphase mixture then returns to the storage tank and gas is vented to the atmosphere after it passes through a de-entrainment plate, which separates liquid and gas, through a back pressure regulating control valve and through a separator.

DESCRIPTION OF THE TEST SECTION

The test section is a 10.16 cm ID, 0.95 cm wall thickness and 2 m long pipe. A schematic of this section is given in Figure 2.

A sampling tube (A) is used to determine the distribution of the phases. The sampling tube in the system is also used to measure the concentration of oxygen and iron. The concentration of oxygen and iron in the system is kept below 20 ppb and 10 ppm.

The two pairs of ports at the top and at the bottom are used to insert flush-mountable electrical resistance probes for corrosion rate measurements. Two sets of pressure taps (one set 132 cm apart and the other 10 cm apart) are used to measure the pressure drop across the test section. There are ports for inserting the pH probe, the thermocouple and pressure sensors for a new flow regime determination program.

Table 1. Test matrix for slug characteristics and corrosion.

Oils Tested	2 cP Oil at 40 °C
Temperature	40 °C
Pressure	0.13, 0.27 and 0.45 MPa
Water Cuts	10, 20 and 30 %
Water	Salt Water
Superficial Liquid Velocity	0.1 ~ 1.5 m/s
Superficial Gas Velocity	1 ~ 9 m/s
Inclination	0 and +2 Degrees

RESULTS AND DISCUSSION

Oil composition plays an important role in corrosion. It was observed that for a water cut of 10%, no measurable corrosion occurred at Froude number 6 for any slug frequency and inclination. The same trend was observed for low slug frequencies at Froude number 12. At high slug frequencies, a small amount of corrosion was measured. The corrosion rate in 2-degree upward flow was a little higher than that in horizontal flow. For example, at the Froude number 12, the corrosion rate for a slug frequency of around 35 slugs/minute was 3 and 5 mils/year in horizontal and +2 degree pipes respectively. This can be seen plotted in Figure 3, which shows corrosion rate vs. slug frequency for 10% water cut in horizontal and +2 degree pipes.

A modification to the existing model (Eq. 6) was carried out to accommodate low water cuts. Equation (6) predicts corrosion rates under slug flow conditions but over predicts corrosion rates for low water cuts. From the experimental results, the modification of model for low water cut can be written as:

$$CR = 31.15\, Cr_{freq}\, Cr_{crude}\, \frac{\Delta P^{0.3}}{L}\, v^{1.6}\, P_{CO2}^{0.8}\, T\, e^{-(2671/T)} \tag{8}$$

Equation (8) is a predictive model for corrosion rates under the slug flow for water cuts of 30% and below. The modified water cut term, which has been changed from $v^{0.6}$ to $v^{1.6}$ accounts for corrosion at various water cuts below 30%. The comparison between experimental data and modeling data is shown in Figures 4 ~ 8.

Figure 4 and 5 show plots of corrosion rate vs. slug frequency at 0.13 MPa in 20% and 30% water cuts respectively in horizontal pipes. The corrosion rate increased with increase in slug frequency at the same Froude number. For example, it can be seen from Figure 4 that the corrosion rate increased from 7 to 18 mils/year as the slug frequency increased from 12 to 46 slugs/minute. It is also seen that the corrosion rate has almost the same value after a slug frequency of 35 slugs/minute was reached. The turbulence in the flow reaches such high values that further increase in the slug frequency had no effect in corrosion rate.

The corrosion rate also increased with an increase in Froude number. For example, it can be seen from Figure 5 that the corrosion rate increased from 24 to 32 mils/year as the Froude number increased from 6 to 12 for a comparable slug frequency of 35 and 33 slugs/minute for Froude number 6 and 12 respectively.

Increasing the water cut to 30% led to more corrosion. For example, the corrosion rate for Froude number 12 at a slug frequency of around 25 slugs/minute was 11 and 26 mils/year for water cuts of 20% and 30% respectively.

It can be seen that a predictive corrosion model for low water cuts is fitted well with experimental data at low pressure.

Figures 6 and 7 show equivalent plots for 2-degree upward flow. Very similar results were observed. It is seen that the model is also fitted well in slight inclined pipes. It can be seen from Figures 6 ~ 9 that the corrosion rate in +2 degree pipes was higher than that in horizontal pipes. For example, if can be seen from Figures 5 and 7 that the corrosion rate for Froude number 12 at a slug frequency of around 25 slugs/minute was 26 and 32 mils/year in horizontal and +2 degree pipes respectively.

Figures 8 and 9 show equivalent plots for 0.27 and 0.45 MPa respectively in horizontal pipes. It can be seen that at higher pressure, the model is also predicted well. The corrosion rate significantly increased with an increase of pressure. It can be seen from Figures 5, 8 and 9 that the corrosion rate for Froude number 6 at a slug frequency of around 35 slugs/minute increased from 24 to 58 mils/year and from 24 to 80 mils/year with increasing the pressure from 0.13 to 0.27 MPa and from 0.13 to 0.45 MPa respectively.

CONCLUSIONS

Experiments for corrosion and slug characteristics have been carried out at carbon dioxide partial pressures up to 0.45 MPa and temperature of 40 °C in horizontal and +2 degree pipes. From the experimental results, a model for low water cuts has been developed.

For a water cut of 10%, no measurable corrosion was observed at Froude number 6 for any slug frequency and inclinations. However, at high slug frequencies, negligible or a small amount of corrosion was measured.

At higher water cuts (20% and 30%), considerable corrosion was observed. The corrosion rate increased with increase in slug frequency at the same Froude number in all cases. The corrosion rate had almost the same value at all inclination and pressures after a slug frequency of 35 slugs/minute was reached. The turbulence in the flow reaches such high values that further increase in the slug frequency had no effect in corrosion rate.

The corrosion rate increased with an increase in Froude number, water cut, carbon dioxide partial pressure, and inclination.

A predictive corrosion model for low water cuts was fitted well with experimental data at all conditions.

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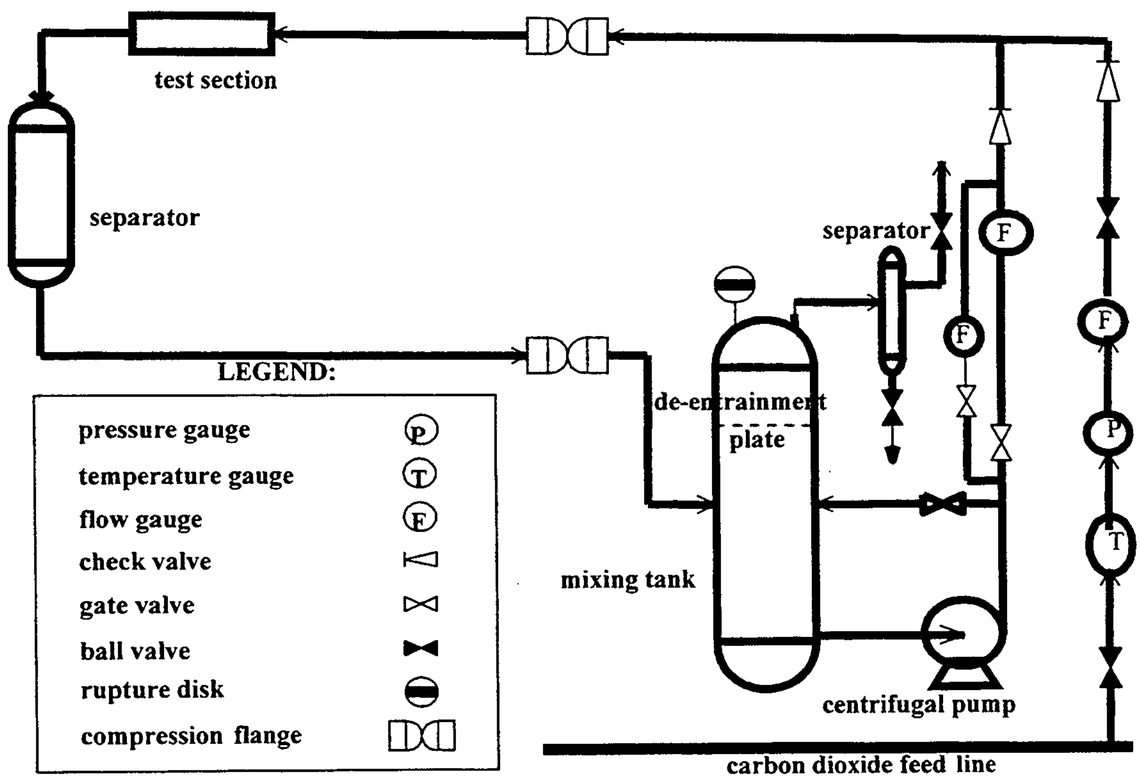

Figure 1: High-pressure, inclinable flow system

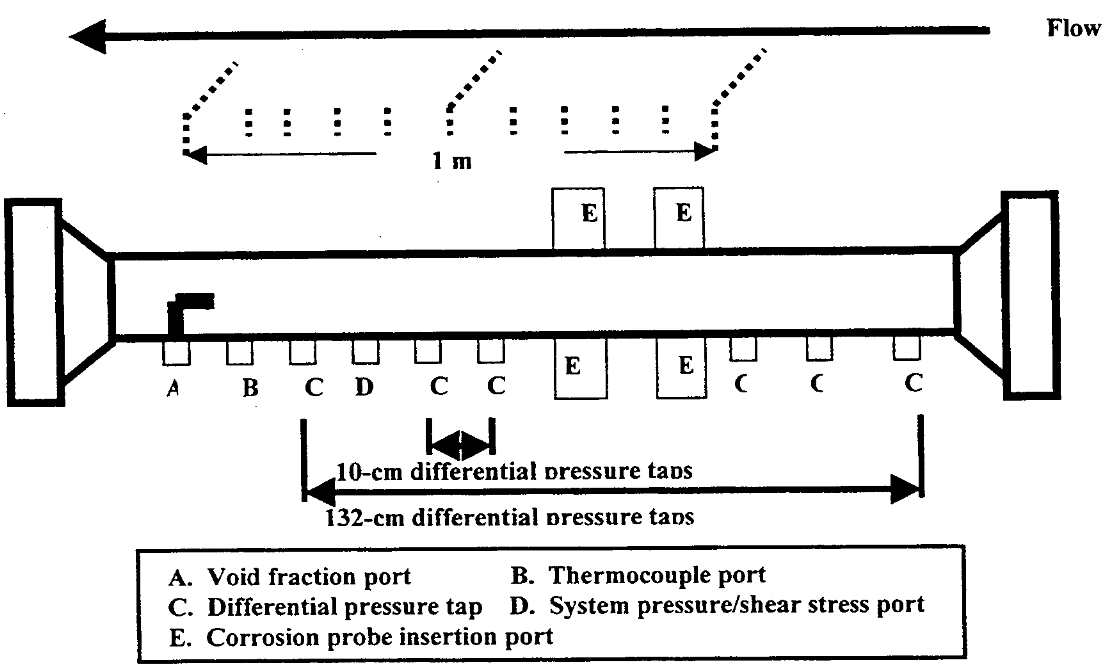

Figure 2: Test Section Diagram

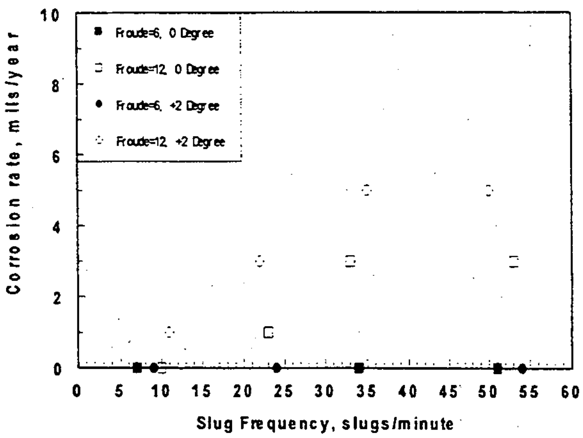

Figure 3. Corrosion Rate vs. Slug Frequency
10% Water Cut, 0.13 MPa, 40C

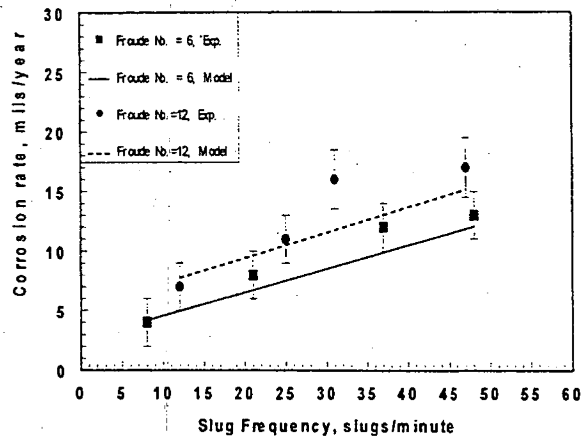

Figure 4. Corrosion Rate vs. Slug Frequency in Horizontal Pipes
20% Water Cut, 0.13 MPa, 40C

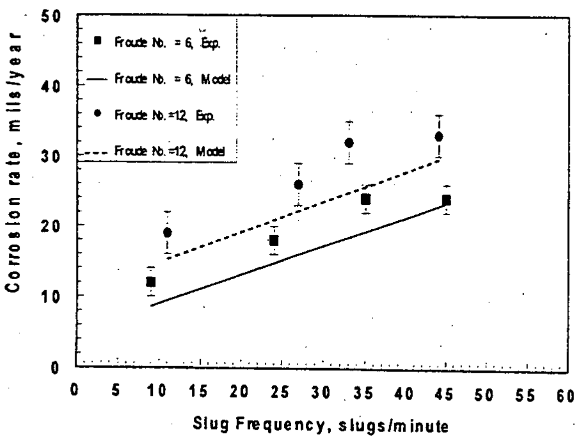

Figure 5. Corrosion Rate vs. Slug Frequency in Horizontal Pipes
30% Water Cut, 0.13 MPa, 40C

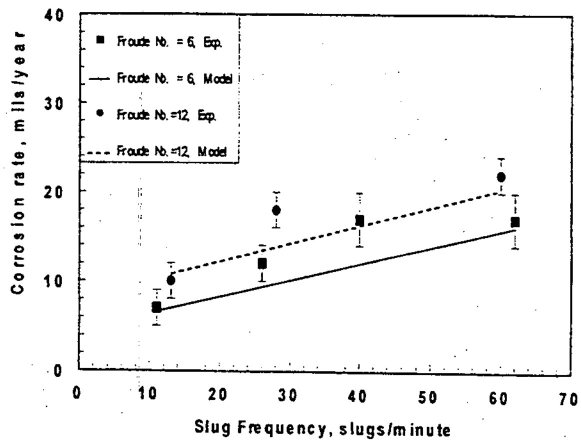

Figure 6. Corrosion Rate vs. Slug Frequency in +2 Degree
20% Water Cut, 0.13 MPa, 40C

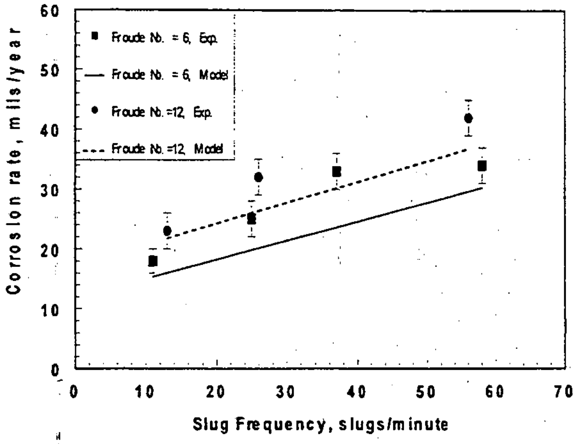

Figure 7. Corrosion Rate vs. Slug Frequency in +2 Degree
30% Water Cut, 0.13 MPa, 40C

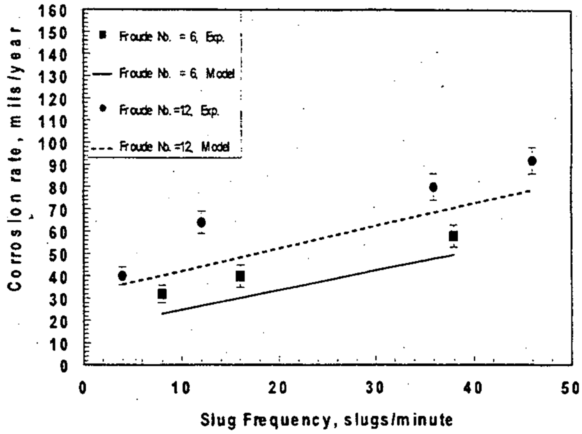

Figure 8. Corrosion Rate vs. Slug Frequency in Horizontal Pipes
30% Water Cut, 0.27 MPa, 40C

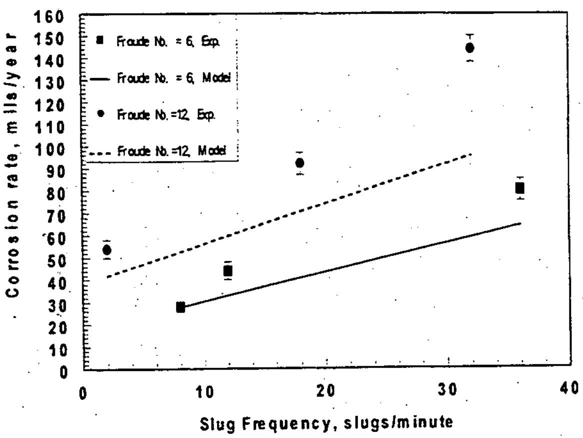

Figure 9. Corrosion Rate vs. Slug Frequency in Horizontal Pipes
30% Water Cut, 0.45 MPa, 40C