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MULTIPHASE FLOW CHARACTERISTICS AND THEIR EFFECT ON CORROSION RATE IN REGIONS OF ABRUPT CHANGES IN INCLINATION.

J. Laws, M. Gopal and D. Vedapuri

Institute for Corrosion and Multiphase Technology
340 ½ West State Street
Ohio University
Athens, Ohio 45701

ABSTRACT

A test facility has been constructed of 0.1 m ID acrylic pipe, with four 9-D, 90°, clear PVC bends to allow the visualization of flow characteristics in topographies with short elevation changes. Detailed visualization of multiphase flow regimes and flow characteristics using water-carbon dioxide mixtures has been carried out. The flow characteristics noted at different velocities for nine locations along the system. Different flow regimes are observed in each location for a given flow rate. Corrosion rates in these regions are significantly higher than that for horizontal flow at the same conditions. Results indicate that even at low superficial liquid and gas velocity, the localized corrosion rates are twice as high as the corrosion rates in horizontal flow.

INTRODUCTION

Deep-sea conditions and enhanced recovery techniques in oil production result in multiphase mixtures with water cuts as high as 90%. The multiphase mixture can include a mixture of oil, water, and gas. The gas contains carbon dioxide, which dissolves in the seawater to form carbonic acid. Owing to the large distances and volumes of the fluid involved, the material of choice for construction of transportation lines is carbon steel. Acid along with the multiphase flow causes severe internal corrosion of the steel.

Multiphase flow involves several flow regimes. These include stratified, slug, and annular flows. Typical flow rate conditions in the industry generate multiphase slug flow conditions. It has been shown by several previous researchers (Zhou 1994, Gopal et al., 1995, Bhongale, 1996, Rajappa, 1998) that slug flow involves unique corrosion mechanisms with pulses of bubbles collapsing on the metal surface. This severely enhances corrosion. Changes in elevation and hilly terrain encountered over the miles of pipeline needed to reach the separation station produce localized flow-dependent corrosion. It has been shown by Wilkens (1997) and Maley (1997) that a change in elevation as low as one degree can cause the transition from stratified flow to the highly turbulent slug flow. Laws (1997) showed that slug frequency increases as inclination increases at similar flow conditions. He has developed a program to predict Froude number in multiphase pipelines using existing models. The topography over which the pipeline runs needs to be accounted for to accurately track corrosion. Areas such as bends, sweeps, expansions, risers, tiebacks, and river crossings that are added to a pipeline to account for geography are regions of drastic changes in pipeline elevation or direction. Turbulence will be elevated in these regions, and subsequently, there will be localized flow dependent corrosion effects unique to each type of situation.

The chemistry of sweet corrosion has been presented by de Waard and Milliams (1975). The rate of reaction is limited by the pH of the system. The higher the concentration of acid the greater the rate of reaction. As more water in added to the system more carbonic acid is available to attack the metal surface and the reaction is elevated. The temperature and availability of aqueous solvent are important components to the concentration of acid in the system.

Iron carbonate, the major product of sweet corrosion, has poor solubility in water and its solubility further decreases with increasing system temperature. Consequently, the iron carbonate precipitates out of solution

and forms a film on the wall of the pipeline (Rajappa, 1998). The film creates a mass transfer resistance to reaction. This is where the flow conditions of the pipeline impact corrosion rates.

If the film is undisturbed by flow conditions, it continues to build and will slow the rate of the corrosion reaction, but if flow conditions are highly turbulent the product layer can be eroded away. When this occurs, the chemical reaction continues unchecked by mass transfer limited conditions. Erosion-corrosion causes the destruction of the product layer and the deterioration of the metal surface. It is dependent on the wall shear stress.

The petroleum industry typically operates pipelines with slug flow conditions. The turbulent intensity of a slug is measured using the Froude number. The higher the Froude number, the higher the wall shear stress is within the slug (Jepson, 1986). Local changes in elevation and the mixture velocity control the amount and intensity of slugging. Nesic and Postlewaithe (1990) demonstrated that erosion was higher in bends and near constrictions and expansions. Corrosion rates are expected to be much higher under the same flow conditions at or near points of drastic elevation change, such as river and road crossings. Very little research has been done on multiphase flow in bends. Poulson (1987) studied erosion-corrosion in 180^0 bends with respect to increased mass transfer in single phase flow. Local turbulence increased through the bend, which destroyed the boundary layer. It was demonstrated that the geometry of flow impacted the degree of erosion, and the highest rates of corrosion occurred in the apex of the bends, as the turbulent intensity increases to its highest level at 90^0 through the bend.

A typical river crossing will exhibit all of the multiphase fluid dynamics found in horizontal, inclined, and vertical flow. The abrupt changes in pipeline elevation will have effects of the flow dynamics near the areas of change. It is expected that no corrosion or flow model will be consistent through the span of the crossing, and research is needed to accurately predict corrosion at these critical points.

EXPERIMENTAL SET UP AND PROCEDURE

Figure 1 shows a schematic of the experimental system. A test facility has been constructed from 0.1-m ID clear acrylic and PVC pipe to simulate multiphase oil-water-gas flow in a pipeline across hilly terrain, road/river crossings and other areas with abrupt changes in inclination.

The length of the system is 21-m and the height of the riser is 5-m. A specified amount of oil/water mixture is stored in a 2.6 m^3 stainless steel tank and is pumped by a 16 kW centrifugal pump into a 10-cm PVC line (j). The liquid flow rate is measured using an orifice plate (a) with a differential pressure transducer. Carbon dioxide from high-pressure storage is introduced into the system (e). Its flow rate is measure using a turbine gas flow meter.

The multiphase mixture then runs 10 m to the first 9-D, 90° clear PVC bend. It rises to a height of 5-m. It then passes through a second bend, where it crosses a 5-m horizontal expanse and down another 90^0 bend. The multiphase mixture then passes down a 5 m long vertical down comer into a fourth bend, and enters a 6-m horizontal run where it is returned to the storage tank. The gas is separated using a special de-entrainment plate and the liquid is recycled.

The clear pipe sections allow the flow to be video recorded and analyzed. This is done with a high-speed video camera. At each set of flow rate the multiphase flow in nine sections of the river crossing test facility is recorded.

Electrical resistance (ER) probes are inserted flush-mount on the pipe wall in the first and second bends at the entrance and exit of the vertical riser to monitor corrosion. Two ER probes are used in each case to test for reproducible results. The probes are connected to ER meters that record dial-reading changes and these are used to calculate corrosion rates.

Table 1: TEST MATRIX

Gas	Carbon dioxide
Water Cut, % (ASTM Salt Water)	100
Pressure, kPa (psig)	135 (5)
Temperature, ^{0}C	40
Superficial Gas Velocity, m/s	1, 4, 7, 10
Superficial Liquid Velocity, m/s	0.2, 0.5, 1.0, 1.5, 2

Table 1 shows the experimental fluids and conditions used in this study.

RESULTS AND DISCUSSION

A detailed visualization of multiphase flow regimes and flow characteristics using water-carbon dioxide mixtures has been carried out. The superficial liquid velocity was varied from 0.1 – 2 m/s and the superficial gas velocities varied from, 1 – 10 m/s. These ranges of velocities cover the multiphase flow regimes.

Visual observations of enhanced turbulence regions and characteristics were noted at different velocities for nine locations along the system. The first upward bend experienced the highest corrosion. The turbulence in this area is very high and will increase the erosion level experienced by any corrosion product layer. The second bend is also an area of unique flow characteristics, and due to increased turbulence, is another area of high corrosion.

It was found that over the range of velocities studied, there was little impact of flow rates on flow characteristics. No stratified flow was observed in the horizontal section before the first bend in the crossing. The presence of the bend upstream shifted the slug flow transition to lower mixture velocities similar to the effects of inclination. Slug flow developed at superficial gas and liquid velocities as low as 1m/s and 0.2 m/s, respectively (Figure 2). When compared to Lee (1994) for the same flow rates a shift in slug predominance is observed. The first riser was always either in slug flow or churn flow, with the transition to churn flow happening at a gas velocity of 6 m/s and liquid velocities above 0.4 m/s (Figure 3). It was also interesting to note that hydraulic jumps were witnessed at all velocities at 45° through both of the first two bends (Figure 4 and 5).

Corrosion rates were recorded in the first two bends of the flow loop system. Data was recorded every 20 to 30 minutes and the results were compared to horizontal corrosion data found at horizontal Froude numbers found at the same flow conditions.

Figure 6 shows the corrosion rates found at the bottom of the pipe in the first and second bend of the riser system; the corrosion rates were determined for Froude numbers in horizontal flow between 4 and 12.

Bend 1 always had a higher corrosion rate than Bend 2. At 2 m/s gas, 0.2 m/s liquid, and a Froude number of 4 Bend 1 (Figure 6) had a corrosion rate of 2.8 mm/yr. and Bend 2 had a value of 2.3 mm/yr. At a gas and liquid velocity of 2 m/s and 1 m/s, respectively, and a horizontal Froude number of 6 Bend 1 had a corrosion rate of 4.2 mm/year. Bend 2 had a corrosion rate of 3.3mm/yr at the same conditions. Finally, at a Froude number of 9 and a gas and liquid velocity of 4 m/s and 0.5 m/s respectively, the corrosion rate in Bend 1 was 4.7 mm/year, and Bend 2 was found to have a corrosion rate of 4.1 m/s. In general, Bend 1 experienced a corrosion rate between 13- 20 % higher than that found in Bend 2.

The comparison of corrosion rates found in Bend 1 plotted against corrosion rates found in horizontal flow at similar mixture velocities (Zhou, 1993) is shown in Figure 7. When compared to corrosion rates found in horizontal multiphase flow at the same mixture velocities and Froude numbers, both the bends show enhanced localized flow-induced corrosion. At a gas and liquid velocity of 2 m/s and 0.2 m/s respectively, Bend 1 (Figure 7) had a corrosion rate of 2.8 mm/year. At the same conditions, horizontal flow measured corrosion rate of 1.8 mm/year. At a gas velocity of 2 m/s and liquid velocity of 1 m/s, and a Froude number of 6, the horizontal flow corrosion rate was 2 mm/year. The corrosion rate in Bend 1 for the same condition was 4.2 mm/year. At a Froude number of 9 and a gas and liquid velocity of 4 m/s and 0.5 m/s, respectively, the corrosion rate found in horizontal flow is 2.5 mm/year, and Bend 1 showed a corrosion rate of 4.8 mm/year. When compared to horizontal flow at the same mixture flow rate conditions Bend 1 shows local corrosion rate twice the horizontal value. This is consistent with the flow conditions found in the bend.

Figure 8 shows the Corrosion rate found in Bend 2 plotted against horizontal corrosion rates. The plot clearly shows that Bend 2 has consistently higher corrosion rate than those measure in horizontal flow at the same conditions. At a gas and liquid velocity of 2 and 0.2 m/s Bend 2's corrosion rate was found to be 2.8 mm/year. In horizontal flow, at the same conditions, a corrosion rate of 1.8 mm/year is observed. When the liquid velocity is increased to 1 m/s, Bend 2 has a corrosion rate of 4.2 mm/year, and in horizontal flow a corrosion rate of 2 mm/year is observed. At a Froude number of 9, a gas velocity of 4 m/s, and a liquid velocity of 0.5 m/s the corrosion rate found in a horizontal section is 2.4 mm/year. The Corrosion rate found in Bend 2 is 4.8 mm/year. Bend 2 also show a significant, between 30 and 45%, enhancement of corrosion due to localized flow conditions found in the bend.

CONCLUSIONS

The test facility was constructed of clear acrylic and PVC to allow the visualization of localized turbulence. High-speed videos and digital photographs have been taken of the flow and the points of localized turbulence have been noted. High levels of localized turbulence occur in the bends. Hydraulic jumps, standing slugs, and phenomena like tidal bores occur across the length of the river crossing. Several flow patterns occur due to the presence of extreme changes of inclination. This is not the case in a horizontal or vertical multiphase study. Hilly terrain and other changes in pipeline topography dictate that a study of multiphase flow needs to studied near these changes of pipeline topography to fully understand and predict corrosion rates in the field.

The first two horizontal sections should result in higher rates of flow enhanced corrosion due to increased turbulence. Increased predominance of slug flow at lower superficial velocities will produce higher Froude numbers at the same flow conditions for normal horizontal flow. As Froude numbers increase so does the level of destructive erosion of the corrosion product layer. This allows the chemical corrosion of the pipe wall to go unchecked by mass transfer resistance.

The highest rates of corrosion are observed at the apex of the first two bends where the hydraulic jumps are witnessed. The jumps are caused when liquid falls backward down the bend and is encountered by a forward moving slug. The turbulent intensity in this section will increase the rate of erosion in the bend. An increase in the thickness of the aqueous layer at the bottom of the bend may also result due to gravitational effects.

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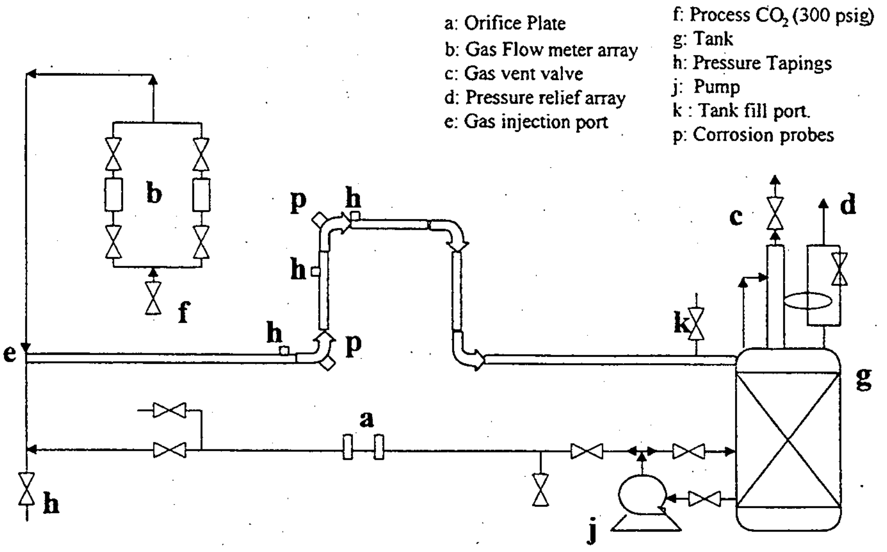

Figure 1: Schematic of the test facility

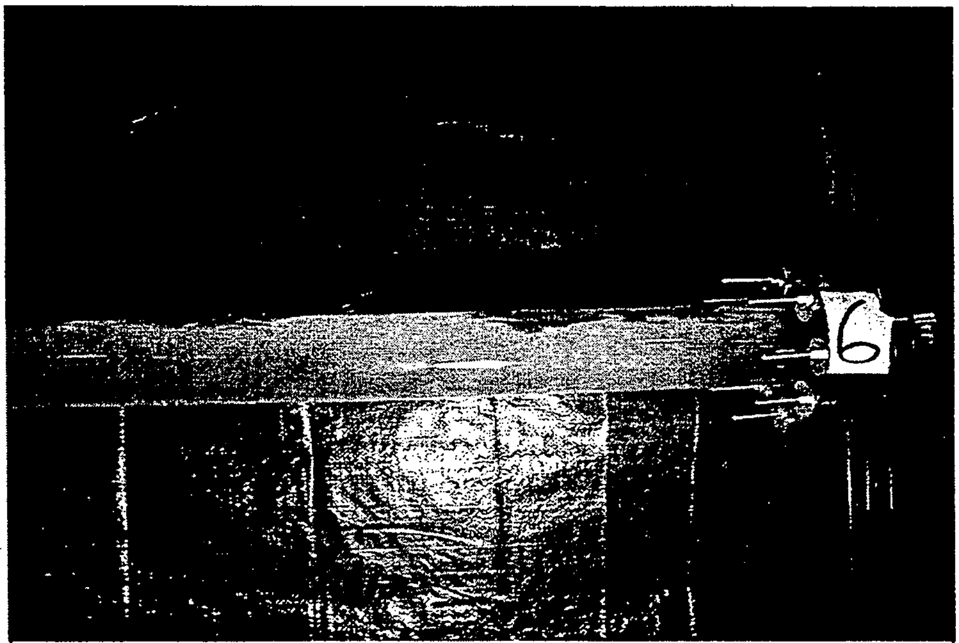

Figure 2: Horizontal Slug (Superficial liquid velocity = 0.2 m/s, Superficial gas velocity = 1 m/s)

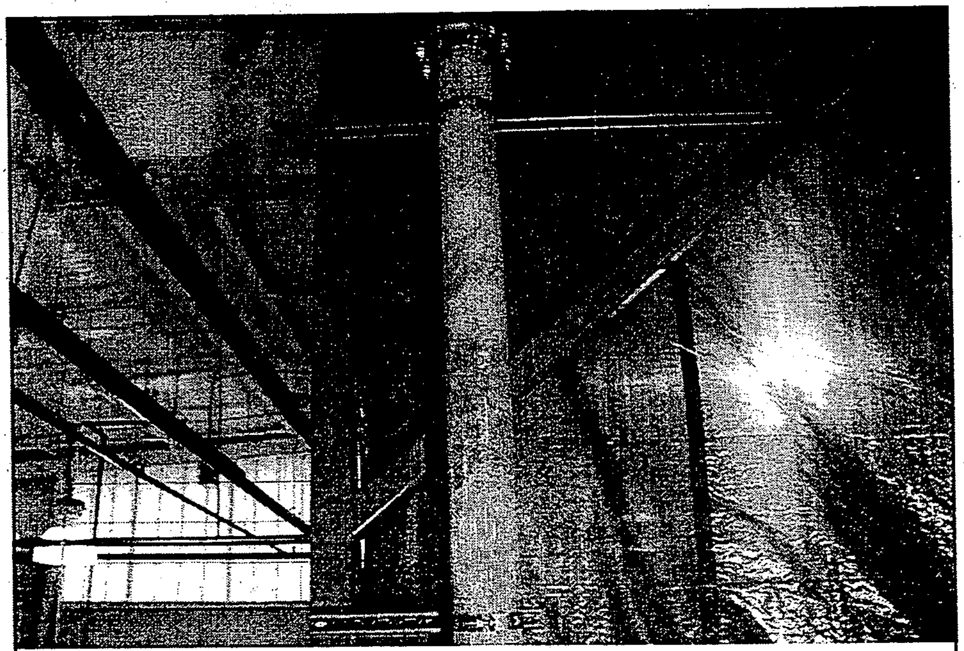

Figure 3: Vertical churn flow (Superficial liquid velocity= 0.4 m/s, Superficial gas velocity = 6 m/s)

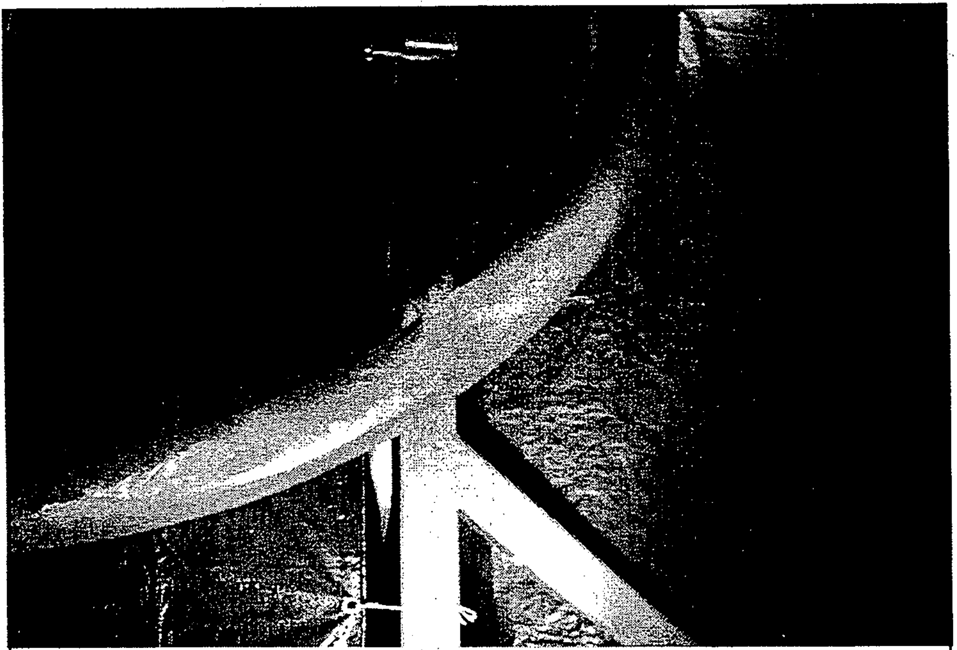

Figure 4: Jump in bend riser (Superficial liquid velocity = 0.6 m/s, Superficial gas velocity = 3 m/s)

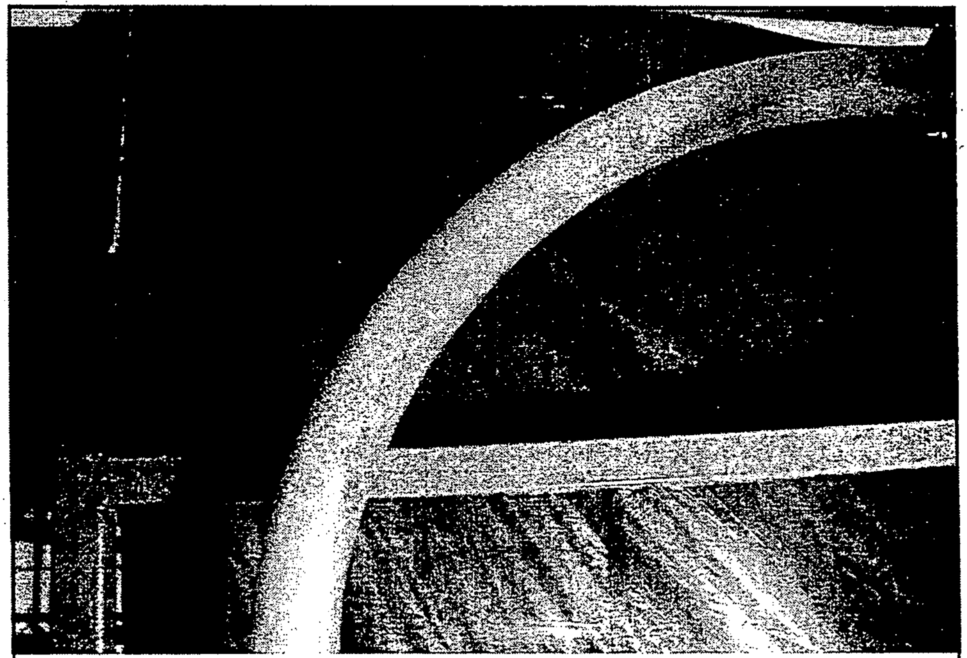

Figure 5: Second bend (Superficial liquid velocity = 0.6 m/s, Superficial gas velocity = 3 m/s)

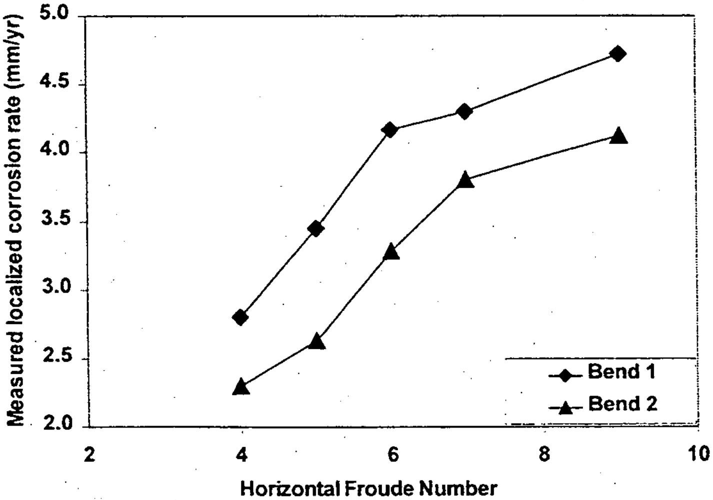

Figure 6: Comparison of the effect of Froudenumber on the corrosion rates in Bend 1 and Bend 2

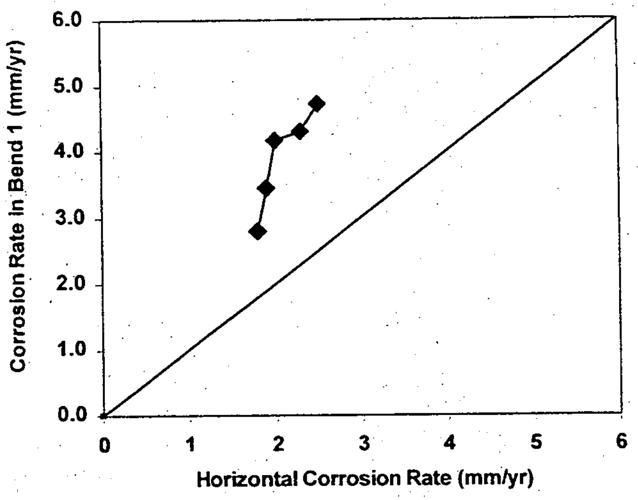

Figure 7: Comparison of the corrosion rate observed in horizontal flow to that observed in Bend 1 for the same flow conditions

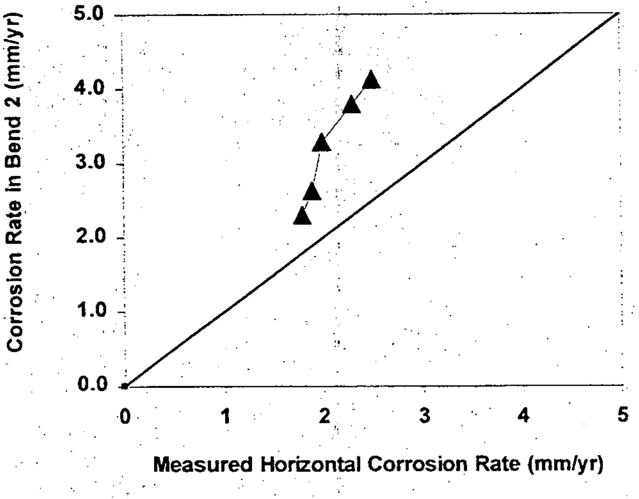

Figure 8: Comparison of the corrosion rates observed in horizontal flow to that observed in Bend 2 for the same flow conditions