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## EROSIONAL/CORROSIONAL TESTING FOR MULTIPHASE FLOW LINES

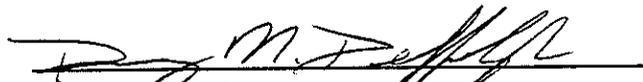
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## EXECUTIVE SUMMARY

The American Petroleum Institute's (API's) Recommended Practice for the design and installation of offshore production platform piping systems (API-RP-14E) includes design criteria aimed at preventing accelerated erosion/corrosion wear in two-phase gas/liquid flow lines. These criteria impose limits, called the "erosional velocity criteria," on the nominal flow velocity in the pipe as the means for avoiding flow conditions that will produce accelerated erosion/corrosion wear. Southwest Research Institute (SwRI) investigated the accelerated erosion/corrosion wear problem that sometimes occurs in two-phase gas/liquid flow lines and made recommendations as to the appropriateness of the API-RP-14E erosional velocity limit. This report documents the results of the SwRI investigation.

In the SwRI study, the past work of other investigators was evaluated. Then, an experimental test program was devised to produce supplemental data for the development of a more representative API erosional velocity limit. The experiments were conducted at SwRI in a test facility capable of producing a simulated full-scale corrosive, two-phase gas/liquid flow environment. Its test section included two straight runs of 2-in.-diameter steel pipe connected by 2-in.-diameter 90° long-radius elbows (called test fittings). During the tests, the nominal flow velocity was varied from 30% to 104% of the current API-RP-14E erosional velocity limit.

Prior work indicates that accelerated erosion/corrosion in two-phase gas/liquid flow lines may occur when the flow stream is in a certain two-phase flow regime. The accelerated attack was expected to occur in the "annular flow" regime. Tests were conducted to check this hypothesis. The test results showed that even a tightly adhering, protective corrosion product film could not be depended on to prevent pitting attack. Pitting attack was experienced for operating velocities below 20 ft/sec and for operation in the stratified wavy, slug, and annular flow regimes.

In the SwRI tests, it was also found that erosion/corrosion wear developed only in the test fittings (i.e., flow bends) for nominal velocities up to 175 ft/sec. The straight runs of test piping showed no evidence of measurable erosion/corrosion wear. This finding suggests that, at least for the flow conditions tested, the pipe wear mechanism is related to inertial effects of the liquid whereby liquid droplets impact the pipe wall at the bends. These droplet impacts appeared to produce accelerated erosion/corrosion of the pipe wall. Consequently, the experimental results support the philosophy of using wear rate data generated from flow through fittings or chokes, rather than wear in straight pipe runs, to establish an appropriate erosional velocity limit.

In each SwRI test, the erosion/corrosion wear rate exceeded the wear rate for bare metal corrosion measured in stirred liquid bath tests. The wear was in the form of localized pitting, not general wall loss. Once wear pits formed, the erosive/corrosive process usually continued, and the pipe wall surface would not re-passivate with a protective corrosion product film. The

high rate of attack at the base of the pits, and the failure to reform the protective corrosion product film suggests galvanic corrosion. The iron carbonate film forms a large cathodic area, and the base of the pit forms a small anodic area subject to accelerated attack.

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# 1. INTRODUCTION

## 1.1 EXISTING EROSIONAL VELOCITY LIMIT

The current recommended practice for sizing two-phase flow lines in piping systems for offshore production platforms is to limit the flow velocity by a simple erosional velocity criteria contained in API-RP-14E.<sup>1</sup> The velocity limit is set to avoid excessive pipe wall loss due to erosion/corrosion. The erosional velocity limit,  $V_e$ , is determined from the following empirical equation:

$$V_e = \frac{C}{\sqrt{\rho_m}}$$

where  $\rho_m$  is the two-phase mixture density (lbm/ft<sup>3</sup>) and  $C$  is an empirical constant. The empirical constant,  $C$ , is equal to 100 for continuous service and 125 for intermittent service. For corrosion free service, or where corrosion is controlled,  $C$  values of 150 to 200 may be used. The API recommendations also require reducing the operating velocity when solids are present. Guidelines on the amount of reduction are not given.

## 1.2 PROPOSED MODIFICATIONS TO THE EROSIONAL VELOCITY LIMIT

In an effort to upgrade the existing velocity limit for two-phase flow, the API and the Minerals Management Service initiated a project to review the existing erosional velocity criteria and to determine where changes would be appropriate. A review of the information available in the open literature and from a review of field piping wear data revealed that the existing erosional velocity criteria did not account for many of the factors that influence wear in two-phase flow.<sup>2,3</sup> To account for these different factors, it was proposed that the erosional velocity criteria should be based on the actual wear mechanisms, not a simple empirical correlation. Four different wear mechanisms were identified for two-phase flow in oil and gas production piping, and different methods for determining the erosional velocity limits are needed for each type of wear. Therefore, four different categories of service were proposed with a different velocity limit needed for each type of service. The categories are:

1. Clean Service (no solids or corrosion)
2. Erosive Service (solids present without corrosion)
3. Corrosive Service (corrosion without solids)
4. Erosive and Corrosive Service (solids and corrosive media present)

References 2 and 3 summarize the basis for the selection of the different service categories and the recommendations for the allowable operating velocities. This report focuses on experimental tests conducted to evaluate the allowable operating velocity for "Corrosive Service."

### 1.3 BACKGROUND ON CORROSIVE TWO-PHASE FLOW

The Corrosive Service classification applies to gas-liquid flow streams with corrosive fluids and no solids. The present erosion velocity criteria in API-RP-14E does not provide clear guidelines on how to determine the maximum operating velocity when corrosive fluids are present. There is a need to identify the controlling wear mechanisms and develop an erosional velocity limit based on the parameters that control the wear rate. The investigation is limited to the effect of fluid flow on metal loss (and not the broad subject of corrosion in general) in horizontal two-phase flow lines.

Under corrosive flow conditions, the pipe walls are covered with a layer of corrosion products that provide protection from further corrosion. When corrosion products are removed from the pipe wall by the flowing fluid, the corrosion rate increases to the bare metal corrosion rate, and accelerated erosion/corrosion can occur. It is important to note that the material being removed from the pipe wall is the corrosion product, not the base metal. The removal of bare pipe metal by liquid droplets is not a concern until the flow velocity is well in excess of 100 ft/sec. Corrosion products are more brittle and loosely adhering and can be removed by the flow stream. Once the corrosion products are removed, the corrosion rate increases to the bare metal corrosion rate and the combined actions of erosion and corrosion accelerate the pipe wall loss.

The removal of corrosion products by two-phase flow streams has been investigated for steam piping systems and oil and gas piping systems. Sanchez-Caldera et al.<sup>4</sup> studied erosion/corrosion in steam power plant piping elbows and found wear was localized in the outside of the bend where water droplets impacted the wall and, also, on the inside of the bend where a water film developed from secondary flow in the elbow. Efforts to characterize the wear mechanism focused on the kinetics of the chemical reactions and neglected the influence of hydrodynamic forces.

Duncan<sup>5</sup> reported the results of wear measurements taken over a ten-year period in corrosive wet gas wells in Bahrain. Duncan found a critical velocity in the region of 30 to 40 ft/sec. Above the critical velocity, wall loss increased rapidly. He felt the critical velocity coincided with either a transition to the mist flow regime, or the velocity at which the inhibitor film or corrosion products were no longer able to provide protection for the pipe surface. Duncan also reported that wear rates were higher at flow disturbances, compared to straight sections.

Green et al.<sup>6</sup> reported the results of laboratory and field tests on flow-related corrosion in two-phase flow lines. The results showed increased corrosion near flow disturbances, such as protruding weld beads or in bends. Two-phase flow-regime-dependent corrosion rates were also reported. Increased corrosion rates were noted when operating near the transition between slug flow and annular flow. A study of field data supplied by API member companies showed an increased frequency of wear problems in flow lines operating near the transition to the annular flow regime.<sup>3</sup> The majority of the failures were reported near flow disturbances, such as elbows or chokes.

Smart<sup>7</sup> suggested that the basis for the existing erosional velocity limit in API-RP-14E is the combination of the transition to the annular mist flow regime, and the removal of the

corrosion product films by liquid droplet impingement fatigue. Based on the above observations, liquid droplet impingement is a plausible cause for accelerated wear rates near flow disturbances. In this scenario, liquid droplet momentum would be too great to allow the droplets to follow the gas flow stream as it changes direction. The droplets would impact the pipe surface and remove the corrosion product film. This would substantiate accounts that wear problems occur at flow disturbances.

The two-phase flow streams must also generate the large number of liquid drops necessary to cause fatigue of the corrosion product film. This type of two-phase flow has been observed in the annular mist flow regime. All of these observations indicate that the wear mechanism for Corrosive Service may be droplet impingement removal of the corrosion product film. To limit pipe wear, the velocity should be kept below the transition velocity for the annular mist flow regime (where droplet impingement at flow disturbances is expected).

While it appears that the erosional velocity limit should be based on the transition velocity for annular mist flow, not enough data are available to clearly show this is appropriate. In order to provide the needed data, an experimental program was initiated. This report summarizes the experimental work.

## 2. EXPERIMENTAL FACILITY

The experimental tests were conducted in a two-phase flow loop that was constructed specifically for performing the erosion/corrosion tests. A schematic of the flow loop is shown in Figure 2.1. The flow loop consisted of a liquid flow loop, gas flow loop, test section, and separator that separates the two-phase flow into a liquid stream and a gas stream.

A description of the flow loop, control system, and instrumentation is presented in two API reports.<sup>8,9</sup> To improve the flow loop operations, some modifications were made to the flow loop after the initial set of erosion/corrosion tests were completed. The modifications included:

- The liquid storage capacity of the flow loop was increased from about 20 gallons to about 125 gallons to ensure adequate storage capacity when the loop ran unattended for extended time periods.
- A new gas-liquid separator was installed in the flow loop to reduce the “carry-over” of liquid into the compressor.
- A new liquid pump was installed so the liquid flow would not need to be stopped when more liquid was added to the flow loop.
- A higher capacity heater was installed to keep the liquid in the storage tank heated.

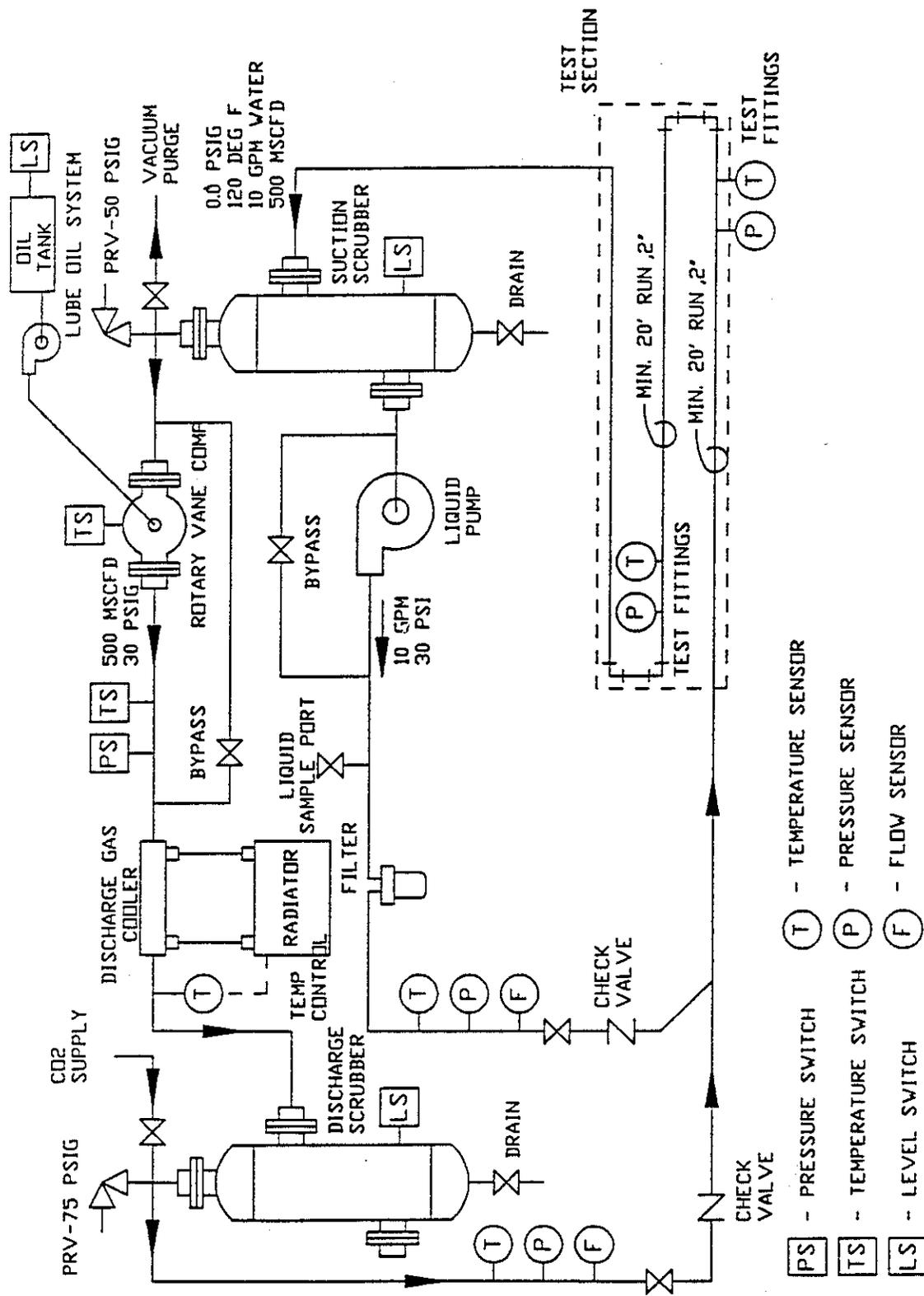


Figure 2.1. Schematic Diagram of the Erosion/Corrosion Test Facility.

## 3. EXPERIMENTAL PROGRAM

### 3.1 TEST OBJECTIVES

The experimental program was conducted to obtain data to help develop a new erosional velocity limit for corrosive two-phase flow streams. As discussed above, the cause of accelerated wear in corrosive two-phase flow streams appears to coincide with the removal of the protective corrosion product film by the two-phase flow stream. When the protective film is removed, the corrosion rate increases to the bare metal corrosion rate, and accelerated erosion/corrosion can occur. It appears that the accelerated erosion/corrosion occurs at the transition to the annular flow regime. The likely cause of accelerated wear in the annular flow regime is removal of corrosion products from the pipe walls by liquid droplet impact fatigue. In the annular flow regime, liquid droplets flow in the core region of the pipe and a thin layer of liquid coats the pipe walls. At flow disturbances, droplets can impact the pipe wall and remove the protective corrosion products. The laboratory tests were conducted to evaluate the assumption that accelerated erosion/corrosion occurs in the annular mist flow regime, but not in other flow regimes (at lower operating velocities).

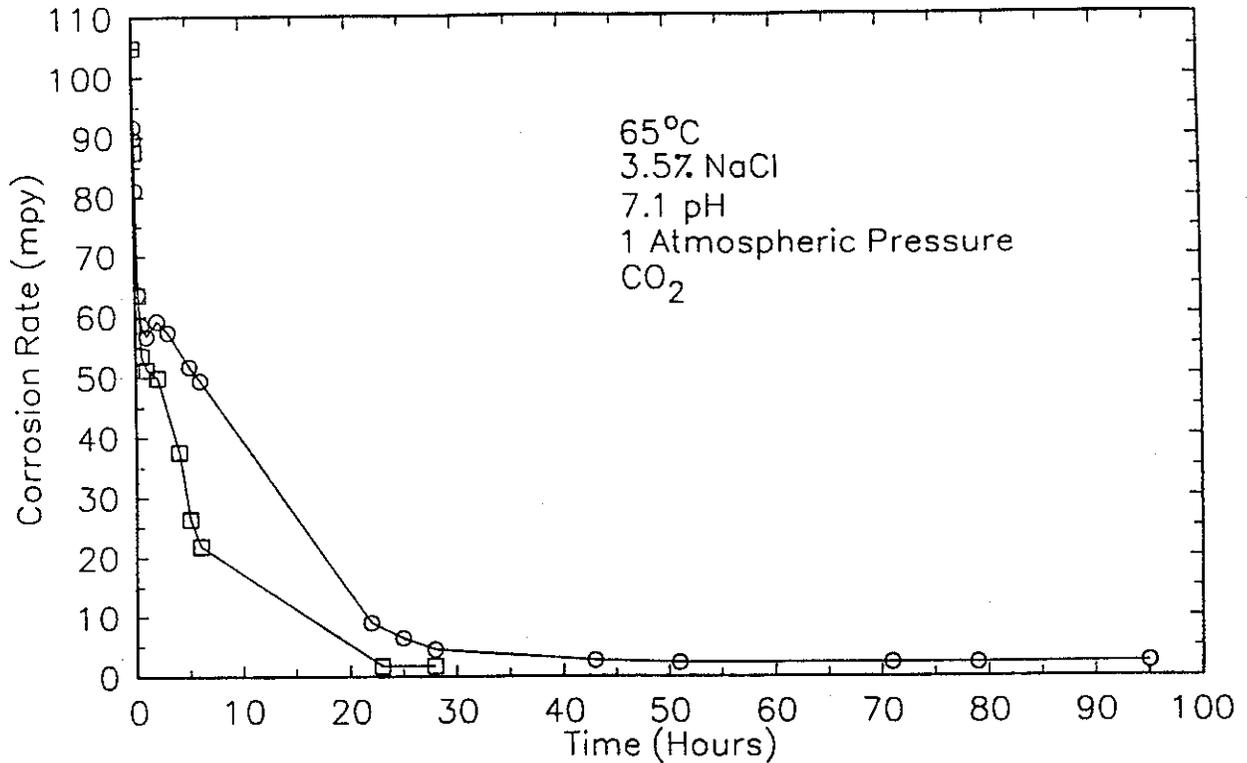
### 3.2 TEST CONDITIONS

The experimental testing was to determine the flow conditions (velocity and flow regime) necessary to remove a protective corrosion product film from the pipe wall. Once a protective film is removed by the flow stream, the corrosion rate increases back to the "bare metal" corrosion rate. It should be noted that the intent of this testing was not to investigate the acceleration of corrosion due to improved transport of reactant species to the pipe wall (due to increased flow rate). Acceleration of corrosion by increasing the flow velocity is a common problem, but it is typically related to mass transfer enhancement.

The increase in the corrosion rate due to enhanced mass transport is typically on the order of a factor of two. The corrosion rate change for removal of a protective film is typically one to two orders of magnitude. Problems that are due to corrosion that produces non-protective films are considered "corrosion problems" (that are enhanced by flow) and not erosion/corrosion problems. "Corrosion problems" typically can be mitigated by using corrosion inhibitors or by using corrosion resistant alloys. Modifying the flow velocity will not eliminate these types of problems.

Benchtop corrosion tests were performed at the outset to verify that the selected flow loop operating conditions would produce a protective film on the surface of the pipe. The first set of tests produced loosely adhering, unprotective, corrosion products on the AISI 1018 carbon steel samples. The corrosion rate for these films remained relatively steady over several days, with no tendency to form a protective film. In order to produce more protective iron carbonate film, the test solution pH and temperature were changed. The resulting iron carbonate films were tightly adhering, and the corrosion rate dropped almost two orders of magnitude in a day. Figure 3.1 shows a plot of corrosion rate versus time for two different

samples. It was desired that, for the experimental testing, the corrosion rate would drop rapidly as the corrosion products formed.



**Figure 3.1. Bench Top Corrosion Test Results.**

The test solution for the benchtop tests consisted of 3.5% by weight of reagent grade NaCl in de-ionized water. The solution was de-aerated with CO<sub>2</sub> to remove the dissolved oxygen. Sodium bicarbonate was added to the solution to buffer the pH to 7.1. The gas pressure was maintained at 1 atmosphere during the benchtop testing and was slightly higher during the flow loop testing. The test temperature was 150°F.

For testing in the flow loop, the gas phase was CO<sub>2</sub> saturated with water vapor. During the tests, the oxygen concentration, pH, and iron concentration were periodically monitored, by removing samples of the brine solution. The oxygen concentration was kept below 100 ppb and was generally less than 30 ppb. The pH ranged from 6.8 to 7.3 and typically remained between 7.1 and 7.2. The soluble iron concentration ranged from less than measurable (i.e., less than 0.1 ppm), when the new solution was first injected, to about 5 ppm. The flow loop temperature varied from the set point due to changes in ambient temperature, but it typically ranged between 130°F and 150°F.

### 3.3 TEST FITTINGS

The fittings selected for the erosion/corrosion testing were standard 90° long-radius plain carbon steel elbows. These fittings were selected because they are typically installed in flow lines where erosion/corrosion is experienced. The duration of each flow test was relatively long, which limited the number of tests that could be run. Consequently, it was not possible to investigate a variety of materials, fitting geometries, and corrosive conditions. Instead, the experimental effort focused on determining the mechanism(s) of accelerated erosion/corrosion in two-phase gas/liquid flow. Once the mechanism is understood, methods to extend the results to other test materials and corrosive conditions can be explored.

The test fittings were 2-in.-diameter, Schedule 40, ASTM A234 Grade WPB butt-weld elbows. The elbows were attached to 2-in.-diameter, Schedule 40, ASTM A106-B pipe. Care was taken to accurately align the fittings with the pipe prior to welding. The welds were not fully penetrating, to assure no weld bead would protrude past the inside surface of the pipe/elbow joints. Flanges were welded on the ends of the straight sections of pipe to make "L-shaped" test articles that could be easily installed and removed from the flow loop. Prior to welding the elbows, the inside surface of the elbows was bead-blasted to bare metal and then inspected to ensure a smooth inside surface finish. Many candidate test elbows were rejected because of large imperfections in the inside surface finish. After welding, the test articles were cleaned and installed into the flow loop. To limit oxide growth, the test articles were not fabricated until just prior to installation in the flow loop.

### 3.4 EXPERIMENTAL RESULTS

#### 3.4.1 Summary of Test Results

An overall summary of the tests conducted is presented in this section. The following section presents a brief discussion of the results of each test. Table 3.1 summarizes the general test conditions. Table 3.2 gives the gas and liquid flow rates for each of the tests. Also presented in Table 3.2 are the calculations of the erosional velocity limit based on API-RP-14E. This value is compared with the actual operating velocity (based on no slip between the gas and liquid phases).

Figure 3.2 shows the operating velocity for each test plotted on a two-phase flow regime map. Tests were conducted with flow in the annular, slug and stratified wavy flow regimes. Table 3.3 shows the maximum wear rate measured for each test, along with the dimensions of the largest pit. The following section discusses the results of each test in more detail.

**Table 3.1. Experimental Facility Test Parameters.**

Pipe	Horizontal, 2-inch SCH 40, ASTM A106-B
Test Fittings	Long-radius Elbow, 2-inch SCH 40, A234 Grade WPB, Weld
Gas	CO <sub>2</sub> with water vapor (saturated)
Liquid	Water with 1.0% by weight NaCl, pH 7.1
Temperature	130-150°F
Pressure	10 psig

**Table 3.2. Test Conditions and Erosional Velocity Limits.**

Test	Superficial Gas Velocity (ft/sec)	Superficial Liquid Velocity (ft/sec)	Mixture Density (lbm/ft <sup>3</sup> )	Calculated Erosional Velocity* (ft/sec)	Operating Velocity (ft/sec)	Flow Regime
1	175	0.5	0.349	169	175.5	Annular
2	175	0.1	0.207	220	175.1	Annular
3	70	0.5	0.613	128	70.5	Annular
4	50	0.5	0.788	113	50.5	Stratified-wavy
5	40	0.78	1.36	86	40.8	Slug
6	55	0.11	0.295	184	55.1	Stratified-wavy
7	15	0.8	3.33	55	15.8	Slug
8	25	0.8	2.10	69	25.8	Slug
9	36	0.36	0.788	113	36.4	Stratified-wavy
10	19	1.3	4.16	49	20.3	Slug

\*Using *RP 14E* (Eq. 1) with C = 100.

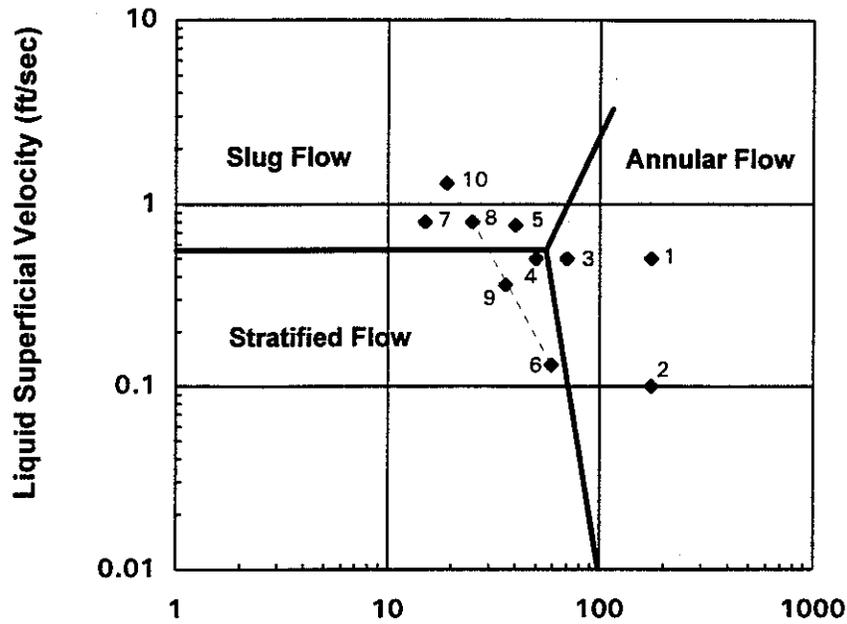


Figure 3.2. Test Conditions Plotted on a Two-Phase Flow Regime Map.

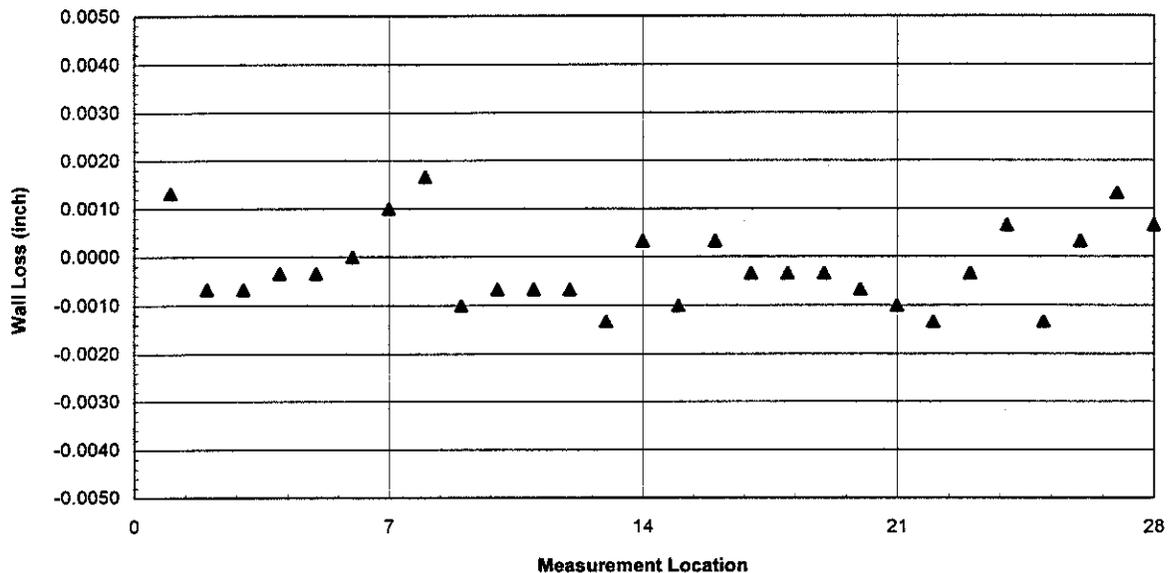
Table 3.3. Test Results—Maximum Wear Rate and Pit Size.

MAXIMUM WEAR RATE AND PIT SIZE				
Test	Test Duration (days)	Maximum Wear Rate (mils/yr)	Pit Depth (mils)	Pit Diameter (mils)
1	63	230	40	350
2	60	140	23	64
3	65	270	48	220
4	56	510	78	400
5	33	550	50	220
6	33	No Wear		
7	35	100*	10	20
8	35	No Wear		
9	36	150	15	24
10	32	220	19	70

\*Pits were healed—Pitting probably occurred when the test section temperature dropped below 140°F for a couple of days.

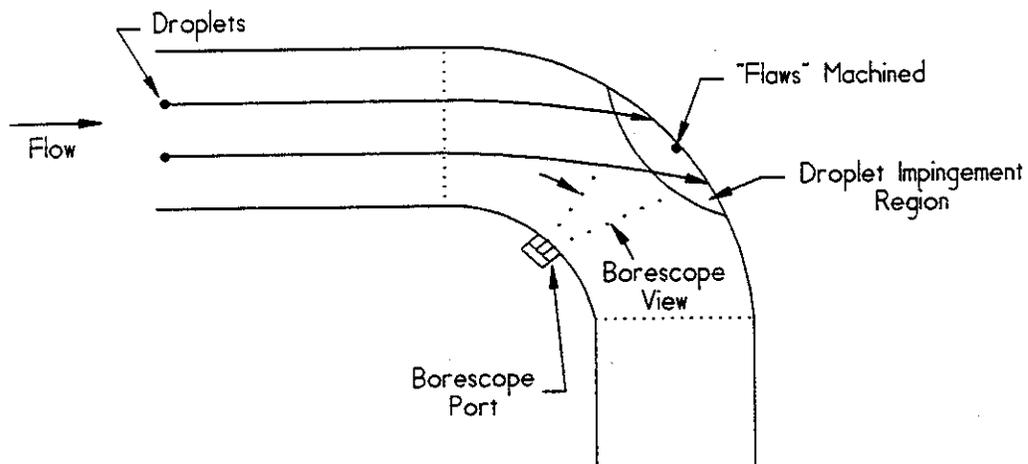
### 3.4.2 Discussion of Test Results

During each test, the general pipe wall loss was determined using ultrasonic wall thickness measurements. Measurements were taken along the outside bend of each elbow at seven locations (15°, 25°, 35°, 45°, 55°, 65°, 75° from the inlet plane of the elbow). This location was chosen because it is where the highest wear would be expected (it is located where the liquid impinges on the elbow bend). No general wall loss was recorded during any of the tests (only localized pitting wear was seen). An example of the wall loss measurements for Test 7 is shown in Figure 3.3. The wall thickness measurements were repeatable to about  $\pm 0.002$  in., so wall loss measurements less than this amount are not significant. For comparison, if the bare metal corrosion rate of 100 mpy were maintained (by removal of the corrosion product film by the two-phase flow stream) for a period of 30 days, the wall loss would be about 0.008 inch. Since this amount of wear would be measurable with the ultrasonic probe, the protective corrosion product film prevented general wall loss.



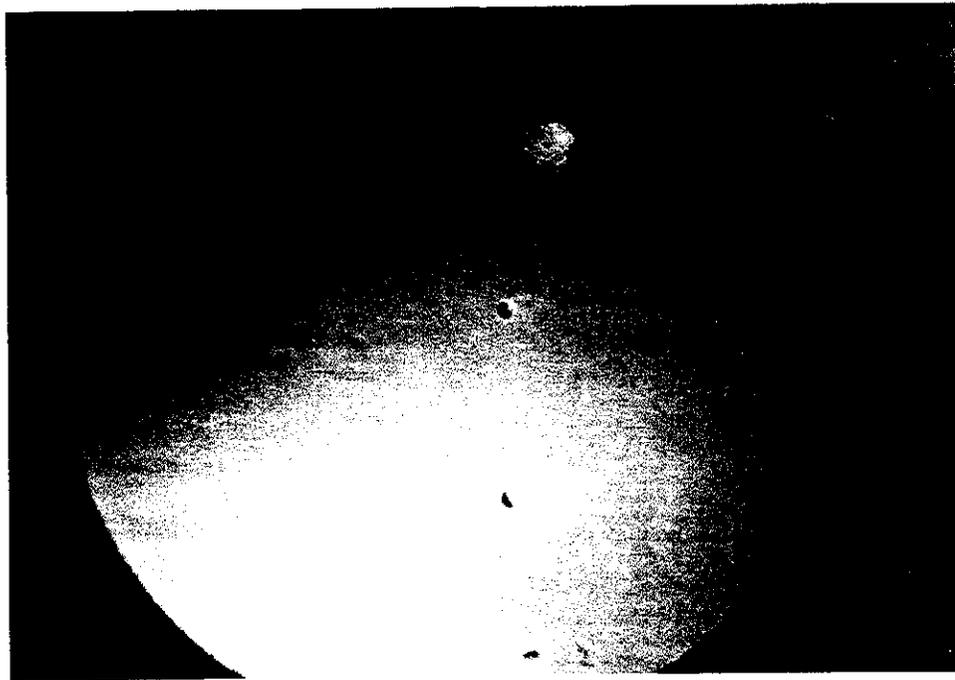
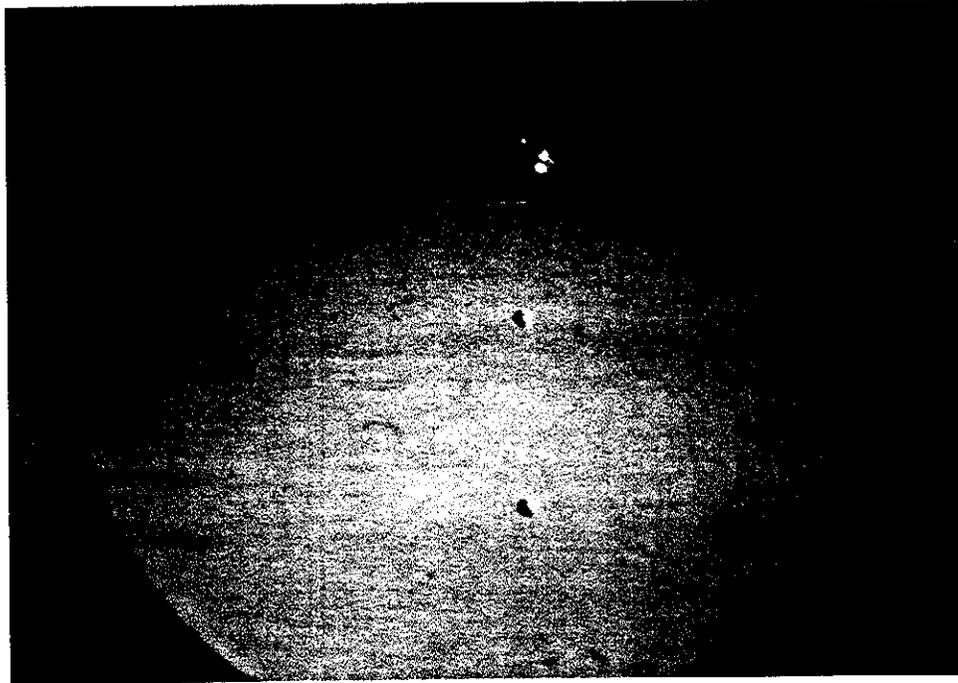
**Figure 3.3. Wall Loss Measured in the Elbows During Test 7. Seven measurements were made in each of the four elbows.**

Localized pitting wear was determined in two ways. The first method was to inspect and photograph the inside surface of the elbow during the test with a borescope. The borescope was inserted through a fitting welded to the elbow as shown in Figure 3.4. The borescope could only view a limited portion of the elbow inside surface, but its position was selected to view the region where pits were most likely to form. The photographs taken during the test were used to know when to stop the test and to determine if pit growth were steady, or if some incubation time were needed to start pit growth. Figure 3.5 shows photographs taken with the borescope during Test 5. The photographs show the pit growth from day 21 to day 31. The small objects are the three flaws that were machined into the elbow prior to starting the test.

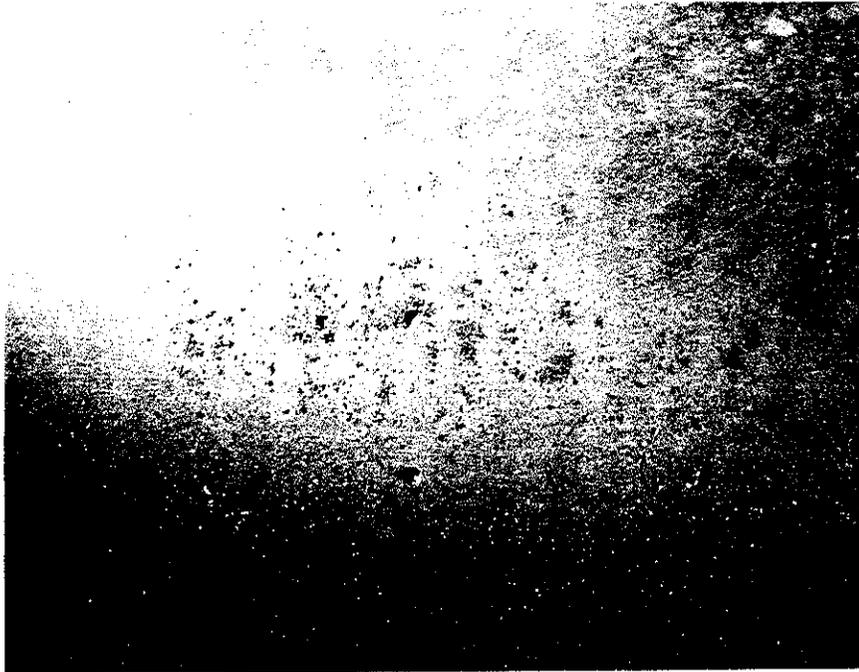
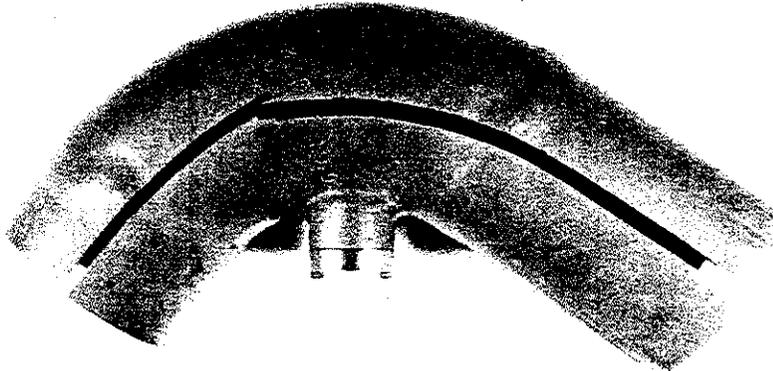


**Figure 3.4. Drawing Showing the Region Photographed by the Borescope.**

The second method of determining localized pitting wear was to inspect the fitting after the test was stopped. At the conclusion of each test, the test fittings were removed from the test section and cut open for inspection. Measurements were then made of the pit size. Figure 3.6 shows how the elbow was cut open for inspection, along with a view of the pitting attack seen inside the elbow for Test 9.



**Figure 3.5. Borescope Photographs of the Erosion/Corrosion Pits Formed During Test 5. The top figure was taken on day 21 of the test and the bottom photograph was taken on day 31.**



**Figure 3.6. Photographs of Test Fitting. The top figure shows the test fitting cut open for inspection. The bottom figure shows the pitting wear experienced during Test 9. The view is of the inside surface of the elbow near the three flaws that were machined into the elbow.**

Descriptions of the results of Test 1 through 4 were presented in an earlier report.<sup>8</sup> Descriptions of test results for Tests 5 through 10 are presented below.

*Test 5* was conducted in slug flow conditions and ran for 33 days. The test results are summarized as follows:

- Corrosion pits formed in all four test fittings.
- No general wall loss was recorded in regions away from the pits.
- The pits formed near the exit of the elbow on the outside radius of the elbow.
- The pits only occurred in the upper half of the pipe. The lower half of the pipe may have been protected by the liquid layer flowing along the bottom of the pipe. This same wear pattern was also seen in Test 4.
- Straight sections of pipe, away from the elbows, were free of pits.
- Corrosion coupons (1/4-in. diameter) placed in the center of a straight section of pipe were covered with corrosion pits on the upstream face, but free of pits on the sides and downstream face.
- The small “flaws” placed in the elbows as incubation sites for corrosion pits did not generate any pits.
- The pits that were within the view of the borescope formed early in the test and continued to grow during the tests. The pits did not “heal.”

The results from Test 5 confirm the results found in Test 4. The localized pitting wear was confined to the outside portion of the bend where droplet impingement wear would be expected. The hypothesis that accelerated wear coincides with annular flow is not necessarily true. This test was in the slug flow regime, and wear did occur. The postulated wear mechanism of droplet impingement fatigue of the corrosion product film, however, may still be plausible. Droplet generation and impingement can occur in stratified flow and slug flow, especially when the operating point is near the transition to annular mist flow. Tests 4 and 5 were conducted with operating velocities just below the transition to the annular flow regime, where a significant amount of the liquid is entrained in the gas.

<b>LARGEST PITS FOR EROSION/CORROSION TEST 5</b>		
<b>Test Fitting</b>	<b>Pit Diameter (mils)</b>	<b>Pit Depth (mils)</b>
Elbow #1	185	50
Elbow #2	100	39
Elbow #3	220	50
Elbow #4	150	31

*Test 6* ran for 33 days, with the operating conditions just below the transition to annular mist flow in the stratified wavy two-phase flow regime. The gas superficial velocity was 55 ft/sec, and the liquid superficial velocity was 0.11 ft/sec. The ultrasonic wall thickness measurements showed that there was no general wall loss during the test. After the test was stopped, the test section was removed and the pipe inspected for localized pitting wear. The straight sections of piping and the long radius 90° elbows were both free from pitting wear.

*Test 7* was conducted with a gas superficial velocity of 15 ft/sec and a liquid superficial velocity of 0.8 ft/sec. The flow was in the slug flow regime. The test ran for a period of 35 days. The ultrasonic wall thickness measurements taken during the test showed no general wall loss during the test. No pitting or general wear was found in the straight sections of pipe. One of the test fittings did not have any pitting, but the other three had some pitting. One of the fittings had a number of small pits located along the outside bend of the elbow between 40° and 60° from the elbow inlet (inlet plane is 0° and exit plane is 90° degrees) and located in a 1 in. diameter region that was centered slightly above the centerline of the pipe. The pits were very shallow and irregularly shaped. The pit diameters were typically about 0.01 in., and the pit depth was about 0.005 inch. The second elbow experienced pitting in a 0.4-in.-diameter region located 60° from the elbow inlet and centered 0.3 in. above the pipe centerline. The largest pit was about 0.07 in. in diameter and 0.008 in. deep. The second largest pit was 0.01 in. in diameter, but deeper (0.020 in.). The third elbow had a rough surface texture in a 0.4-in.-diameter region located 55° degrees from the elbow inlet and centered slightly below the centerline of the pipe. The attack was very shallow (less than 0.005 in. deep) and appeared more like a removal of the corrosion product film (leaving islands where the film remained) than pitting.

Photographs taken of the inside surface of the elbow during the test (using a borescope) showed the pitting occurred between the start of the test and day 17 when the first photographs were taken. Subsequent photographs showed no substantial growth in the pits. In addition, the pitted regions appeared to be "passivated" (that is, no longer actively corroding when the test was stopped). For most of the tests, the bottoms of the pits were generally "bare metal" as opposed to covered with a layer of corrosion products. These two factors indicate that the corrosion may have occurred when the flow loop temperature dropped below 120°F for a short period of time near the start of the test. After the flow loop temperature was brought back above 140°F, the pitting attack appeared to stop. For these reasons, it appears that the pitting occurred because the flow loop temperature dropped below the temperature needed to form a tightly adhering corrosion product film, and not because the flow rate was high enough to remove the corrosion product film.

<b>LARGEST PITS FOR EROSION/CORROSION TEST 7</b>		
<b><u>Test Fitting</u></b>	<b><u>Pit Diameter (mils)</u></b>	<b><u>Pit Depth (mils)</u></b>
Elbow #1	10	5
Elbow #2	None	
Elbow #3	N/A	<5
Elbow #4	10	20

*Test 8* ran for 34 days. The superficial gas velocity was 25 ft/sec, and the liquid superficial velocity was 0.8 ft/sec, resulting in slug flow. The ultrasonic wall thickness measurement taken on the outside of each of the four test elbows showed that there was no general wall loss during the test. After the test was completed, the test fittings were removed from the test section and cut open to inspect for localized pitting wear. There was no localized wear in either the straight sections of pipe or in the elbows.

*Test 9* was conducted with a gas superficial velocity of 36 ft/sec and a liquid superficial velocity of 0.36 ft/sec. These test conditions resulted in stratified wavy two-phase flow. The test ran for 36 days. The ultrasonic wall thickness measurement showed that no general wall loss occurred during the test. Inspection of the test fittings after completion of the test showed no localized pitting wear in the straight sections of pipe and no pitting wear in three of the four test fittings (the long radius 90° elbows). One of the fittings showed some pitting located in the upper half of the elbow at the location where drops flowing straight down the pipe would impinge on the surface of the elbow. The largest pit was 0.024 in. in diameter and 0.015 in. deep. The second largest pit was 0.020 in. diameter and 0.012 in. deep. The rest of the pits were less than 0.010 in. in diameter.

Most of the corrosion pits appeared to be passivated (no longer actively growing). The exceptions were the two largest pits, which appeared to be active. The bottoms of these pits were not covered with a protective corrosion product film. Since some of the fittings experienced pitting and some did not, it appears the test may have been conducted near the upper limit of an acceptable operating velocity.

<b>LARGEST PITS FOR EROSION/CORROSION TEST 9</b>		
<b><u>Test Fitting</u></b>	<b><u>Pit Diameter (mils)</u></b>	<b><u>Pit Depth (mils)</u></b>
Elbow #1	24	15
Elbow #2	None	
Elbow #3	None	
Elbow #4	None	

*Test 10* was conducted with a gas superficial velocity of 19 ft/sec and a liquid superficial velocity of 1.3 ft/sec. The test ran for 32 days. The flow was in the slug flow regime. The liquid flow rate was set to the highest flow rate possible in the test facility. The ultrasonic wall thickness measurements showed no general wall loss in the elbows. The straight sections of pipe were free from pitting wear. Three of the elbows were free of localized pitting wear, but one elbow did have some pitting. The pits were located along the outside portion of the elbow about 1/4 in. from the elbow exit. The pitting clearly followed the heat-affected zone of the weld, with the pitted region in the form of a line that ran perpendicular to the flow direction. The largest pitted region ran for about 1 in. and was 0.07 in. at the widest spot. The maximum depth measured for the pit was 0.019 in., giving a maximum wear rate of 220 mpy.

The pitting experienced in the one fitting in Test 10 was different than the pitting experienced in any of the other tests. The pitting was located right at the exit to the elbow. In all of the other test, pits formed closer to the center of the bend where drops flowing straight down the tube would impact the elbow. The exact cause of the pitting for this test cannot be determined but it appears to be related to the heat-affected zone caused by welding the elbow to the pipe.

<b>LARGEST PITS FOR EROSION/CORROSION TEST 10</b>		
<b><u>Test Fitting</u></b>	<b><u>Pit Diameter (mils)</u></b>	<b><u>Pit Depth (mils)</u></b>
Elbow #1	70	19
Elbow #2	None	
Elbow #3	None	
Elbow #4	None	

#### **4. DISCUSSION AND CONCLUSIONS**

##### ***Wear in Test Fittings***

Experimental tests were performed to test the theory that accelerated erosion/corrosion in two-phase corrosive flow coincides with the transition to the annular flow regime. The hypothesized wear mechanism in the annular flow regime was the removal of the protective corrosion product film by droplets impinging on the pipe walls at flow disturbances (such as elbows, tees, protruding weld beads, etc.).<sup>2,3,5,7</sup> With the corrosion product film removed, the corrosion rate can increase and accelerated erosion/corrosion can occur. Test results showed the theory was not correct, since pitting wear was observed in flow regimes other than just the annular flow regime.

Test results showed that the protective corrosion product film could not be depended upon for protection of the piping system, even if the operating velocity were limited. Accelerated erosion/corrosion was experienced for operating velocities below those considered practical for production piping systems. Since the corrosion product film cannot prevent wear under the corrosive flow conditions, other methods of protection must be used. Corrosion inhibitors or corrosion resistant alloys must be employed to eliminate the erosion/corrosion.

For most of the tests, the pitting attack was confined to a few major pits in one or more of the test fittings. Once formed, the pits did not reform a protective corrosion product film and the maximum wear rate in the pits exceeded the bare metal corrosion rate (determined in benchtop tests). These factors suggest that there may be an "anodic-cathodic" type reaction that keeps the pitted regions from reforming a protective film. Videm and Dugstad<sup>10</sup> suggested that the iron carbonate film provides a large cathodic area and the base of the pit forms a small anodic area where accelerated attack occurs. Videm and Dugstad felt that a minimum velocity of about 50 ft/sec was necessary to maintain the separate anodic and cathodic areas. Even with average velocities below this value, the disturbance of flow in the test fittings will create an "effective" velocity (increased local velocity and increased wall shear stresses) that is considerably higher than the average velocity. Therefore, the anodic-cathodic regions could be maintained at lower average velocities. For some corrosive flow conditions, it may be possible to limit the pitting attack by using a sacrificial anode in or near any flow disturbances.

### ***Wear in Straight Pipe Sections***

Test results verified the contention that the operating velocity limit should be based on wear at flow disturbance in the pipeline rather than the onset of wear in the straight sections of pipe. Tests were conducted with operating velocities up to 175 ft/sec with no general wear or localized pitting seen in the straight sections of pipe (pitting was seen only in the elbows). The test results showed that the shear stress at the wall of the straight pipe (in annular flow, slug flow, or stratified flow) was not high enough to remove the protective corrosion product film. Pitting was only observed near regions where the flow changed direction and fluid drops could impact with the pipe walls. The attack was generally in the upper half of the elbow, presumably because the lower part was covered, and somewhat protected, by a film of liquid. Therefore, the maximum operating velocity, to limit piping system wear, should be based on wear experienced in the piping fittings, not wear in the straight pipe sections.

### ***Pit Initiation***

For Tests 5 through 10, small "flaws" were introduced in the test fittings as incubation sites for pit growth. Three flaws were placed in each elbow at a location 55° from the elbow inlet and located (1) on the centerline of the elbow, (2) 0.25 in. above the centerline, and (3) 0.25 in. below the centerline. The flaws were 0.025 in. diameter by 0.013 in. deep. This location was selected since it was in the region where drops flowing straight down the pipe would impact the inside of the elbow. The flaws were introduced to determine if small surface imperfections disturbed the fluid flow enough to start the formation of corrosion pits. None of the flaws placed in the fittings formed corrosion pits, even though pits formed near the flaws

for several tests. This implies that the pit formation site may be more related to factors such as metallurgy rather than local fluid dynamics.

It is not clear what initiated the corrosion pit formation. While the pits were located in the regions of the elbow that would be subject to droplet impingement, the entire corrosion product film was not removed in the impact region. Only very limited areas were attacked with corrosion pits. This shows that the iron carbonate film was not removed by the flowing fluid stream except in certain regions. Limited information indicates that iron carbonate films provide a tightly adhering protective film that should not be removed by low velocity flow streams.<sup>11</sup> The pit initiation sites may coincide with local material imperfections. This would help explain why, for some of the tests, there was pitting in some of the test fittings but not in others (the same flow stream passed through each test fitting).

### ***Pit Growth***

Photographs taken of test fittings during some of the tests showed that pit growth started soon after the test started and continued until the test was stopped. In Test 5, for example, photographs were taken of the inside of the elbows at one-week intervals during the test (see Figure 3.5). A small pit was seen at the end of the first week, and the pit continued to grow until the test was stopped. One of the reasons that the photographs were taken was to determine if the pit growth were continuous, or if it took some incubation time for the corrosion product film to form and then be removed before the pit would start to grow. The photographs showed that pit growth could start immediately and continue during the test.

### ***Corrosive Service Recommendations***

The experimental tests were conducted to determine if a limiting velocity could be found where accelerated erosion/corrosion did not occur for corrosive two-phase flow conditions (when a protective corrosion product film is formed). The test results showed that the corrosion product film could not be depended upon to prevent pitting attack, even for low operating velocities (below 20 ft/sec). For these conditions, corrosion inhibitors or corrosion resistance alloys will be required to limit the corrosion.

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