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EXPERIMENTAL STUDY OF THE EROSIONAL/CORROSIONAL VELOCITY CRITERION FOR SIZING MULTIPHASE FLOW LINES

Phase II–Experimental Results

By

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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. There has been much debate as to whether or not the API erosional velocity limit is overly conservative. If so, piping installations designed to meet API-RP-14E will be oversized and unnecessarily costly. Southwest Research Institute (SwRI) was commissioned to investigate the accelerated erosion/corrosion wear problem that sometimes occurs in two-phase gas/liquid flow lines and make recommendations as to the appropriateness of the API-RP-14E erosional velocity limit. This report documents the results of the SwRI investigation.

Prior work by various investigators indicated that accelerated erosion/corrosion in two-phase gas/liquid flow lines may occur when the flow stream is in certain flow regimes, such as the "annular mist" regime. It has also been found that the mechanism that produces the pipe wear is a function of the specific flow regime that develops in the pipeline. For instance, the wear mechanism for the annular mist flow regime is believed to be the removal of brittle corrosion products from the pipe inner wall surface by liquid droplet impact fatigue.

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" diameter steel pipe connected by 2" diameter 90° long-radius elbows (called test fittings). During the tests, the nominal flow velocity was varied from 45% to 104% of the current API-RP-14E erosional velocity limit.

The test data acquired by SwRI and other investigators suggest that the existing API erosional velocity limit is not appropriate for all possible field conditions, since it does not accurately define the onset velocity for accelerated erosion/corrosion in all applications. For instance, the SwRI test data, covering a range of operating conditions in the annular mist and stratified-wavy flow regimes, showed that the flow velocity at which the onset of erosion/corrosion occurs can be lower than the currently specified limit. In the SwRI tests, it was also found that erosion/corrosion wear pitting 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 entrained liquid droplets do not follow the gas flow around pipe bends but, instead, 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.

The SwRI test results also do not support the hypothesis that accelerated erosion/corrosion occurs only when the flow is in the annular mist regime. Liquid droplet generation and impingement on the fitting walls was observed in other test flow regimes besides annular mist. For example, localized erosional pitting developed in a stratified-wavy flow regime, but only on the upper half of the elbow walls, where the pipe surface was not covered by a liquid layer and was exposed to droplet impingement.

In each SwRI test, the erosion/corrosion wear rate exceeded the wear rate for bare metal corrosion measured in stirred liquid bath tests. The typical erosion/corrosion pit growth was in the downstream direction, with the pit growing wider and deeper with time. Once each pit reached a "critical" size, the growth rate appeared to accelerate. At the onset of an accelerated growth phase, pit geometry changed from a wedge shape to a shape having steep, typically undercut, walls and lateral pit expansion. Once wear pits formed, the erosive/corrosive process usually appeared to continue, and the pipe wall surface would not re-passivate with a protective corrosion product film.

The experimental results obtained during this test program support the need for a re-assessment of the current API-RP-14E "erosional velocity limit." SwRI recommends dividing the "erosional velocity criteria" into four different groups, with each group identified by a different wear mechanism that is active in multiphase flow lines in offshore piping systems. Thus, each group will have its own set of controlling parameters that affect the pipe wear rate. Proposed titles for the four groups are:

(1) Clean Service (no solids or corrosion).
(2) Erosive Service (solids (sand) present in the flow stream with no corrosion).
(3) Corrosive Service (corrosion without solids), and
(4) Erosive and Corrosive Service (both solids and corrosive media present).

Recommended velocity limits for "Clean Service" and "Erosive Service" are proposed, based on information available in the open literature. Further investigation is necessary to determine appropriate limits for "Corrosive Service" and "Erosive and Corrosive Service."

The SwRI test results obtained during this investigation do provide a partial mapping of the range of flow regimes in which accelerated wear may occur in the "Corrosive Service" category. Additional experiments are necessary before the flow regime mapping can be considered complete and recommended velocity limits for this category of service can be established.

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DISCLAIMER

The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies or recommendations of the U.S. Department of Interior.

1.0 INTRODUCTION

There continues to be a significant amount of debate regarding the American etroleum Institute (API) specification related to velocity limits [1] for horizontal two-phase flow lines for offshore production piping. Many investigators have reviewed the velocity limits specified by API-RP-14E and concluded that the limits are too conservative [2, 3, 4, 5]. To investigate possible changes to the existing erosional velocity limit, a series of projects was initiated by the API and the Minerals Management Service (of the U.S. Department of the Interior). The first project reviewed the information in the open literature on erosion/corrosion as it pertains to multiphase flow [6]. The second project was conducted to review pipe wear data provided by API member companies and to use this information to guide changes to the existing erosional velocity equation in API-RP-14E [7]. The third project was an experimental program to supplement the data obtained in the literature and company surveys. This report covers the results of the third project conducted to measure erosion/corrosion in a corrosive two-phase flow environment. The rest of this section contains a brief review of the existing erosional velocity limit in API-RP-14E. Summary results from the first two projects described above are presented in Section 2. The remainder of the report documents the experimental work conducted during the third project.

Presently, the design guidelines recommend limiting the fluid velocity in two-phase (gas and liquid) flow lines to an "erosional" velocity (V_e (ft/sec)) defined by [1]:

$$V_e = \frac{C}{\sqrt{\rho_m}} \tag{1.1}$$

C = empirical constant

ρ_m = mixture density (lbm/ft^3)

The value of the empirical constant, C, is equal to 100 for continuous service and 125 for intermittent service, if no solids (sand) are present. For corrosion-free service, or service where corrosion is controlled with corrosion inhibitors, C values of 150 to 200 may be used. It is required that the erosional velocity be reduced to some value less than the velocity calculated above if solids (sand) are present. Guidelines on the amount of reduction to the calculated erosional velocity are not given.

2.0 BACKGROUND

2.1 Review of the Problem

Many investigators have concluded that the erosional velocity limit recommended in API-RP-14E is overly conservative. Limiting the operating velocity in flow lines to an unnecessarily low value results in the costly practice of oversizing the lines. Critics of the existing erosional velocity limit have proposed alternative values for C in equation 1.1 for specific applications, such as for specific types of corrosion products or for specific pipe materials. Proposed changes to the value of C range from a factor of 1.5 times the existing limit, to an increase of several orders of magnitude.

For example, Salama and Venkatesh [2] calculated the velocity that would produce liquid impingement erosion corresponds to a C value of 300. For the case where stripping a corrosion inhibitor film from the pipe wall is the limiting velocity, Salama and Venkatesh estimated a velocity equivalent to a C value of 35,000 is required. They conclude the API-RP-14E limits are extremely conservative. Craig [3] showed that an operating velocity equivalent to a C value of 100,000 is calculated based on the shear stress required to remove a corrosion product film or an inhibitor film. He concluded this mode of erosion/corrosion would not be experienced under field conditions because actual operating velocities are too low. Craig argued that liquid impingement fatigue of a corrosion product film is a more realistic failure method and that C values of 90 to 150 can be predicted depending upon the composition of the corrosion product film on the pipe wall. Castle and Teng [4] presented results of field data showing that C values over 180 were conservative for alloy steels.

Salama [5] investigated the erosional velocity limits for water injection systems and concluded a C value of 450 is applicable for solids-free, non-corrosive conditions. For corrosive conditions, C values up to 250 are applicable, depending upon the corrosive condition and the desired pipeline lifetime. This application was for single-phase water flow. Contrastingly, Smart [8] reviewed the erosional velocity equation and concluded that it should not be applied to non-corrosive conditions or single-phase flow streams. He feels the erosional velocity equation is applicable to the removal of corrosion product films by liquid droplet impingement. Other researchers [9, 10, 11] have concluded that erosion/corrosion in multiphase flow lines is caused by increased turbulence or shear stress at the pipe wall.

Based on the examples presented above, it is apparent that the erosional velocity limit is applied to a variety of erosion/corrosion applications. The reason that the existing erosional velocity limit is applied to the diversity of applications is due to the fact there are no alternative methods for calculating flow line size for different materials, corrosive flow stream constituents, or for use of corrosion inhibitors. The many different modifications to the erosional velocity limit that have been proposed are for specific applications or are based on limited field data. These proposed modifications may work well for limited cases, but they cannot be broadly applied as design rules for all applications. In summary, pipe erosion/corrosion in two-phase flow is a very complicated process that is a function of many different parameters, and the present form of the API erosional velocity equation, that considers only the mixture density, is inadequate for the wide range of conditions encountered in field piping applications.

2.2 Recommended Modifications to the Erosional Velocity Criteria

Following is a brief summary of modifications proposed for the existing erosional velocity limit (equation 1.1). These recommendations are based on a review of the information available in the open literature [6] and from a review of pipe wear data supplied from API member companies [7]. This review revealed that the majority of the erosion/corrosion problems in gas-liquid flow lines can be traced to areas with flow disturbances. Excessive flow-related wear generally occurs near elbows, tees, chokes, valves, and protruding weld beads. Straight sections of piping, unaffected by local flow disturbances, do not generally experience excessive flow-related wear. Improvement of the erosional velocity limit should, therefore, focus on limiting the flow velocity such that accelerated erosion/corrosion is minimized at fittings, or chokes, and other points where flow disturbances exist in a piping system.

The existing erosional velocity limit does not account for many of the factors that influence wear in two-phase flow streams. Some of these factors are: solids production rate, presence of corrosive constituents (CO_2 or H_2S), water production, pH, temperature, and pipe material properties. All factors cannot be accounted for by simply changing the C value in equation 1.1. It is recommended that the flow velocity be limited, based on the appropriate wear mechanism rather than an empirical equation. For non-corrosive flow streams that are solids free, the wear is primarily governed by the nominal flow velocity and the two-phase flow regime. For two-phase flow streams with solids production and no corrosion, the most important parameters affecting the wear rate are the mass flow rate of solids, the liquid production rate, and flow velocity. For two-phase flow in a corrosive atmosphere without solids, the primary parameters that control the wear rate are CO_2 and H_2S concentration, flow properties, water content, temperature, fluid pH, and piping material. In flow streams with both corrosion and solids, the prediction of wear is significantly more complex because of the interactions of erosion and corrosion. All of the parameters identified as affecting erosion only and corrosion only would need to be considered to accurately predict wear under combined erosion/corrosion.

To cover the wide variety of flow conditions described above, it is recommended that the sizing criteria for multiphase flow lines be divided into four different groups, based on the different wear mechanisms. Each different wear mechanism will have a different set of controlling parameters that needs to be evaluated to limit pipe wear. The four different wear categories are:

(1) Clean Service (no solids or corrosion),
(2) Erosive Service (solids (sand) present in flow stream with no corrosion),
(3) Corrosive Service (corrosion without solids), and
(4) Erosive and Corrosive Service (both solids and corrosive media present).

Recommended erosional velocity limits for "Clean Service" and "Erosive Service" are already available in the open literature [7]. Further investigation is necessary to determine appropriate limits for "Corrosive Service" and "Erosive and Corrosive Service." A summary of the recommendations for replacing the existing erosional velocity limit (section 2.5.a) in API-RP-14E is given below.

Sizing Criteria for Gas/Liquid Two-Phase Lines

Velocity Limits. Flow lines, production manifolds, process headers, and other lines transporting gas and liquid in two-phase flow should be sized primarily on the basis of flow velocity. The limiting velocity is determined based on the fluid properties (corrosive or non-corrosive service) and whether or not solids (sand) are present.

(1) ***Clean Service.*** Sand-free/corrosion-free service does not require any erosional velocity limitations. Pressure drop limitations will generally limit the velocity to below the threshold for erosion initiation. Velocities above 60 ft/sec should generally be avoided to prevent excessive noise.

(2) ***Erosive Service.*** The flow velocity above which erosional damage may exceed an acceptable limit can be determined from the following equation:

$$V_e = K_s \frac{d}{\sqrt{Q_s}}$$

where:
V_e = fluid erosional velocity [ft/sec]
K_s = fitting factor from Table 2.1
d = pipe inside diameter [in]
Q_s = solids (sand) flow rate [ft^3/day]

(3) ***Corrosive Service.*** To be determined.

(4) ***Erosive and Corrosive Service.*** To be determined.

Table 2.1 Erosive Service Fitting Factor Table

Fitting	Radius to		Ks Factor		
Type	Diameter Ratio	Material	Dry Gas Flow	Mist Flow	Liquid Flow
Elbow	1.5	ASTM 216-WBC	0.95	0.84	44.51
		ASTM A234-WPB	1.49	1.34	
	2.0	ASTM 216-WBC	1.00	0.91	44.51
		ASTM A234-WPB	1.58	1.46	
	2.5	ASTM A216-WBC	1.08	1.00	44.51
		ASTM A234-WPB	1.69	1.60	
	3.0	ASTM 216-WBC	1.15	1.10	37.62
		ASTM A234-WPB		1.73	
	3.5	ASTM 216-WBC	1.28	1.23	16.14
		ASTM A234-WPB	1.95	1.90	
	4.0	ASTM 216-WBC	1.48	1.41	14.07
		ASTM A234-WPB	2.10	2.01	
	4.5	ASTM 216-WBC	1.68	1.60	14.07
		ASTM A234-WPB	2.23	2.12	
	5.0	ASTM 216-WBC	1.99	1.90	14.07
		ASTM A234-WPB	2.38	2.28	
Plugged Tee	-	ASTM 216-WBC	8.73	5.56	20.75
		ASTM A234-WPB	12.85	7.04	14.07
Vortice Elbow		ASTM 216-WBC	15.94		26.60

The work performed during this project was a first step in determining an appropriate erosional velocity limit for "Corrosive Service." The experimental work focused on evaluating the theory that accelerated erosion/corrosion occurs at the transition to the annular mist flow regime. This theory was proposed by Duncan [12] based on his experience that accelerated wear was observed in field piping systems operating in transition to the annular mist flow regime. Data from a number of companies confirmed that accelerated wear occurs in the annular mist flow regime [7]. The likely cause of accelerated wear in this flow regime is removal of brittle corrosion products from the pipe walls by droplet impact fatigue. In the annular mist flow regime, liquid droplets flow in the core region of the pipe, and a thin layer of liquid coats the pipe walls. At disturbances in the flow stream, the droplets can impact the pipe wall and remove the protective corrosion products. Once corrosion products are removed by droplet impingement, accelerated erosion/corrosion can occur.

3.0 TEST FACILITY

3.1 Flow Loop

A test facility was built at Southwest Research Institute to gather experimental data for the development of a new erosional velocity limit for the corrosive service category described in the preceding section of this report.

A piping and instrumentation diagram for the experimental facility is given in Figure 3.1. The facility consists of a liquid flow loop and a gas flow loop that merge into a common test section. The test section consists of two parallel straight runs of horizontal 2" diameter carbon steel pipe (27 ft long). Elbows (called fittings) connecting the straight runs of pipe are 2" diameter 90° long radius carbon steel elbows. Downstream of each test fitting is a 3-ft section of straight-pipe and then another test fitting.

The major components of the experimental facility are the gas compressor, liquid pump, scrubber to separate the gas and liquid, and the test section where the fittings were tested for erosion/corrosion wear. The compressor is a 60 HP rotary vane unit capable of delivering 500,000 SCFD with a 15 psia suction pressure and a 45 psia discharge pressure. The fluid pump is a centrifugal type, designed for 10 GPM at 30 psid. The scrubber is designed to separate the liquid from the gas stream before it enters the gas compressor. The scrubber also acts as the liquid reservoir for approximately 20 gallons of brine. A secondary scrubber downstream of the compressor is necessary to remove the lubrication oil coming from the compressor. A cooling system is also required to cool the compressor case and the gas at the compressor exit. All of the flow loop piping (except the test section) is internally plastic-coated for corrosion resistance. A filter is installed in the liquid pump discharge line to remove any solids in the liquid stream so wear in the test section will not be from solids flowing in the pipe.

3.2 Instrumentation and Controls

The flow loop was instrumented to monitor and record the flow conditions in the test section piping. The gas was metered through one of two different-sized orifice meter runs, depending upon the flow rate. The liquid flow rate was metered by a turbine-type flow meter, and several thermocouples were used to monitor the temperature within the flow loop. A summary of the instrumentation is given in Table 3.1. A data acquisition system was assembled to record the instrumentation readings, convert the data into engineering units, and store the data. The individual instrument readings were converted from analog signals to digital information with a Fluke Hydra 2620A, and the digital information was transferred to a PC over an RS-232 interface.

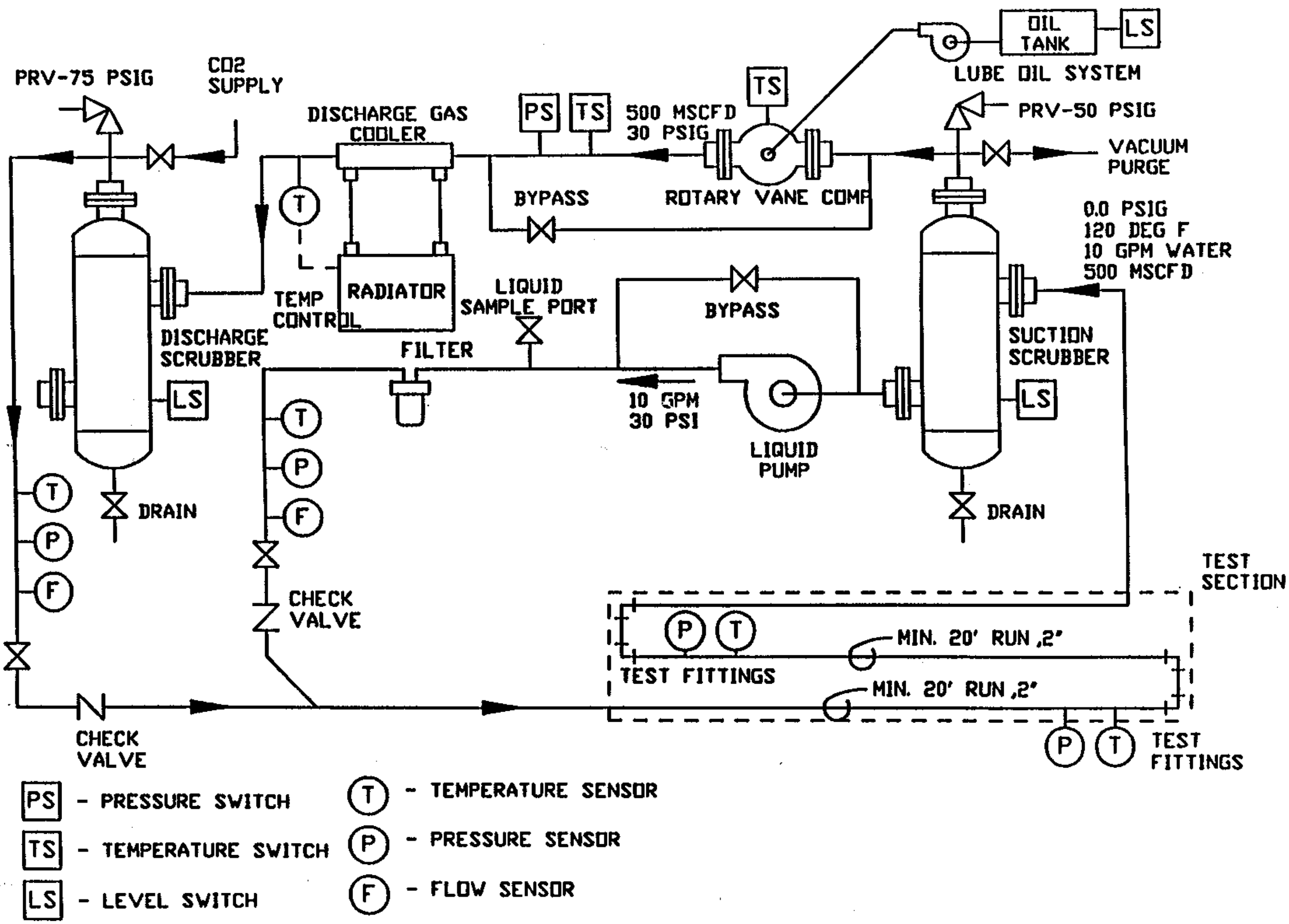


Figure 3.1 Experimental Facility Piping Diagram.

Application-specific software converted the digital data to engineering units, performed some calculations, and wrote the data to a hard disk. During testing, the flow loop water pH, oxygen content and iron concentration were periodically checked with colorimetric test kits (Chemetrics, Inc.).

Table 3.1 Instrumentation on the Erosion/Corrosion Test Loop

Description	Manufacturer	Model No.
Orifice Plate #1	Daniel Industries	3" Pipe, 1.450" Bore
Orifice Plate #2	Daniel Industries	1.5" Pipe, 0.600" Bore
Orifice Pressure Drop (Flange Taps)	Rosemount	3051CD2A52A1A
Orifice Upstream Static Pressure	Foxboro	1125-09A-C54
Test Section Static Pressure	Foxboro	1125-09A-C54
Barometric Pressure	Foxboro	1125-09A-C54
Orifice Gas Temperature	Omega Engineering	Thermocouple TMQSS-062U-6
Water Supply Temperature	Omega Engineering	Thermocouple TMQSS-062U-6
Test Section Temperature	Omega Engineering	Thermocouple TMQSS-062U-6
Room Temperature	Omega Engineering	Thermocouple TMQSS-062U-6
Water Flow Rate	Halliburton	Turbine Meter 458.8506

Safety and control equipment were installed in the test loop to allow automated operation. The loop was controlled with a General Electric Series One programmable logic controller which operated the motor starters (compressor, compressor cooling water pump, liquid pump, and the heat exchanger fan motor) and monitored the control sensors checking for hazardous operating conditions. The following list identifies the hazard sensors which, when alarmed, would automatically shut the test loop down.

Low Pressure in Suction Scrubber
Suction Scrubber Liquid Level High
High Compressor Discharge Temperature
High Compressor Discharge Pressure
High Compressor Coolant Temperature
Compressor Lubrication Oil No-Flow Switch
Compressor Lubrication Oil Low Level
Discharge Scrubber Liquid Level High

3.3 Test Fittings

The fittings selected for the initial 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 that could be successfully completed. 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" diameter, Schedule 40, ASTM A234 Grade WPB butt-weld elbows. The elbows were attached to 2" 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.

4.0 EXPERIMENTAL PROGRAM

4.1 Test Conditions

The experimental testing was intended 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 the mass transfer enhancement. The increase in the corrosion rate due to enhanced mass transport is typically on the order of a factor of 2. The corrosion rate change for removal of a protective film is typically 1 to 2 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 iron oxide films remained relatively steady over several days, with no tendency to form a protective film. In order to produce a more protective, iron carbonate film, the test solution pH and temperature were changed. The iron carbonate films that formed were tightly adhering, and the corrosion rate dropped almost 2 orders of magnitude in a day. Figure 4.1 shows a plot of corrosion rate versus time for 2 different samples. It was desired that, for the experimental testing, the corrosion rate would drop rapidly as the corrosion products formed.

The test solution consisted of 3.5% by weight of reagent grade NaCl in de-ionized water. The solution was de-aerated with CO_2 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 all flow loop testing, the gas phase was CO_2 saturated with water vapor.

4.2 Two-Phase Flow Regime Map

The erosion/corrosion tests focused on determining the effect of the two-phase flow regime on the rate of pipe wall loss. For this reason, it was important to document where the transition

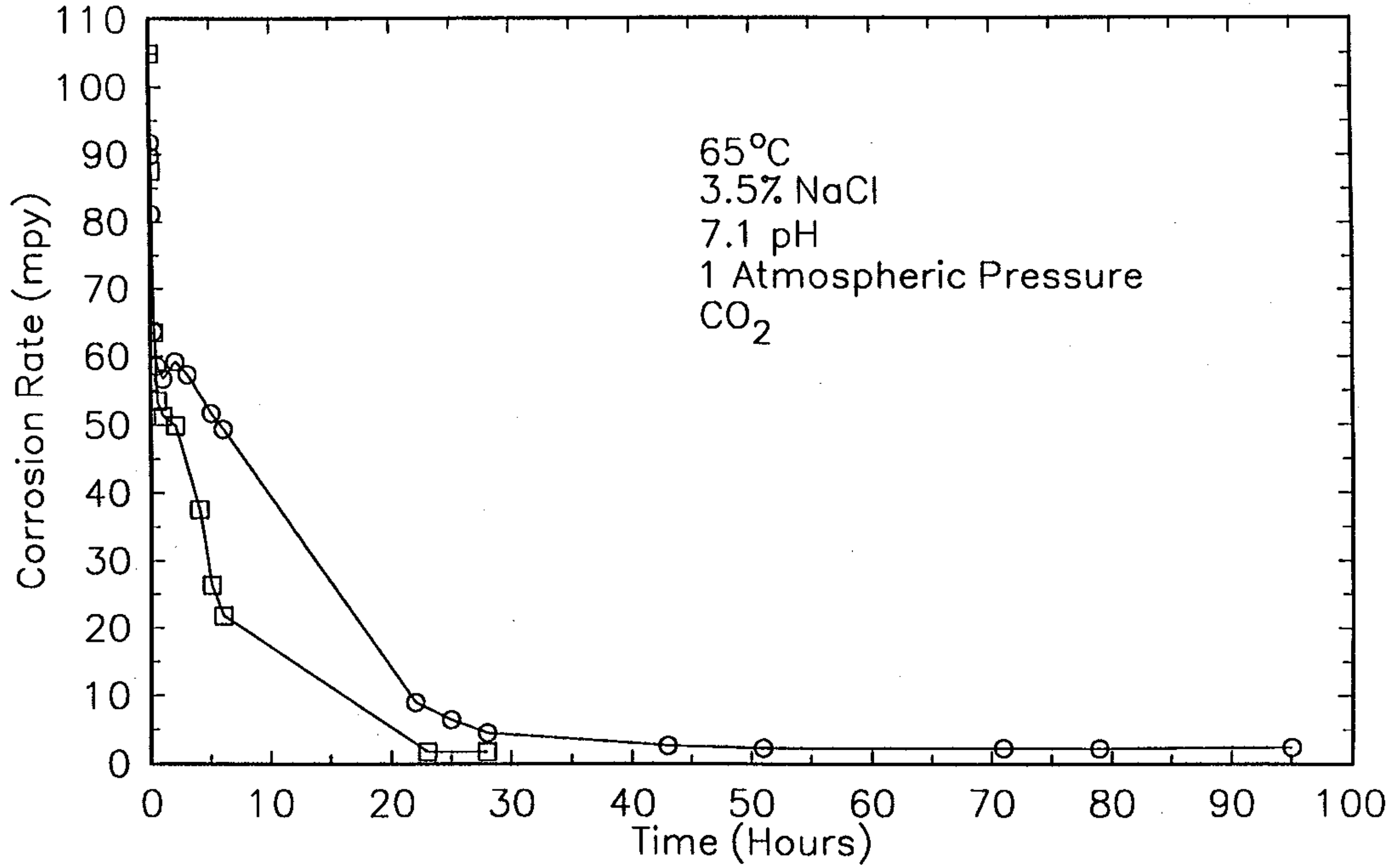


Figure 4.1 Bench Top Corrosion Test Results.

from slug or stratified flow to annular flow occurred. This was done with both air-water and CO_2-water mixtures (because CO_2 has a higher density than does air at the same temperature and pressure) at about 100°F and a test section pressure of about 10 psig. A clear pipe section was installed in place of the test section so that visual determination of the flow regime could be made. The flow regime transition points were then determined by varying the gas and liquid flow rates and recording the flow regime for each setting. The results are plotted in Figure 4.2 as superficial gas velocity versus superficial liquid velocity. From this plot, it can be seen that the transition to annular flow occurs when the nominal flow velocity reached about 60 or 70 ft/sec. Below this transition, the flow is either stratified-wavy or slug flow, and above this transition, the flow is annular.

4.3 Test Results

Four different flow tests were conducted to determine the wear in the 2" diameter long-radius, 90° elbows in a corrosive, two-phase flow environment. Each test ran continuously for about two months. This relatively long test time allowed growth of the corrosion product film and a long enough time period for measurable wear to occur. Table 4.1 summarizes the test parameters, and Table 4.2 summarizes the flow conditions for each different test. Also included in Table 4.2 is the calculated erosional velocity limit (equation 1.1 with C=100) for the given flow rates. As the table indicates, Test 1 was conducted using an operating velocity very close to the erosional velocity limit (169 versus 175 ft/sec). Test 2 was conducted with the operational velocity set at about 80% of the erosional velocity limit. Tests 3 and 4 were conducted at operational velocities of about 55% and 45% of the erosional velocity limit, respectively. Tests 1 through 3 were in the annular-mist flow regime, and Test 4 was in the stratified-wavy flow regime.

Table 4.1 Experimental Facility Test Parameters

Pipe	Horizontal, 2" SCH 40, ASTM A106-B
Fittings	Long-radius Elbow, 2" SCH 40, A234 Grade WPB, Weld
Gas	CO_2 with water vapor (saturated)
Liquid	Water with 3.5% by weight NaCl, pH 7.1
Temperature	150°F
Pressure	15 to 25 psig

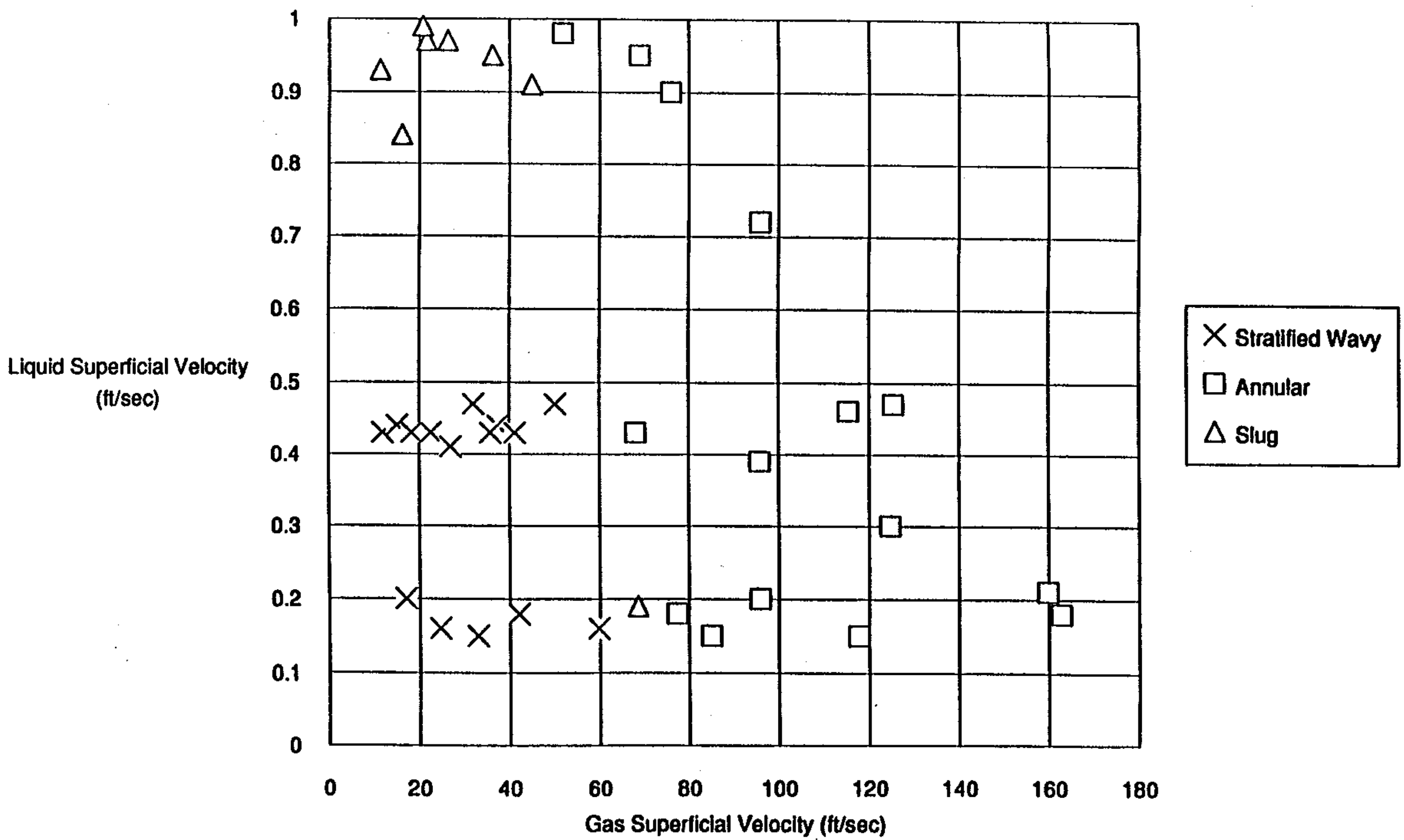


Figure 4.2 Flow Regimes for CO_2-Water in Horizontal 2" Pipe.

Table 4.2 Test Conditions and Erosional Velocity Limits

Test	Superficial Gas Vel. (ft/sec)	Superficial Liquid Vel. (ft/sec)	Mixture Density (lbm/ft^3)	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

All four tests were conducted using the same piping geometry. Four elbows were installed in the test section for each test. The elbows were labeled #1 through #4 in the direction of the flow. Fitting #1 was located downstream of a 27 ft run of straight-pipe, fitting #2 was located 3 ft downstream from fitting #1, fitting #3 was located 27 ft downstream from fitting #2, and fitting #4 was located 3 ft downstream from fitting #3. The flow velocity profile entering fittings #1 and #3 was fully developed. The flow in fittings #2 and #4 was not fully developed, since the test fittings were only 15 pipe diameters downstream from an elbow.

During testing, the flow loop temperatures, pressures and flow rates were recorded at 15-minute intervals by the automated data acquisition system. The oxygen concentration, pH, and iron concentration were periodically monitored during the test by removing samples of the brine solution. During the tests, the oxygen concentration was kept below 100 ppb and was generally about 50 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 10 ppm.

Several modifications to the flow loop were implemented after Test 1 was completed. These modifications were intended to improve the operation of the flow loop. A settling tank was installed to collect the fluid from the discharge scrubber and allow the water to be reinjected into the flow loop after the oil had been separated. This kept the brine solution in the flow loop from continuously increasing in salt concentration, since the condensed water in the discharge scrubber was reinjected into the flow loop. The solution's starting salt concentration was reduced from 3.5% to 1% by weight. An in-line heater was installed in the liquid line so the brine temperature could be controlled more closely. The liquid lines were also insulated to reduce heat loss to the environment, and another section of the gas line was insulated in an attempt to keep the test loop temperature close to the 150°F operating temperature. The CO_2 injection line was also moved from the test section inlet to the test section outlet, so the compressor inlet pressure could be more closely regulated.

4.3.1 Test 1 Results

The operating conditions for Test 1 were very close to the allowable erosional velocity calculated from equation 1.1. The erosional velocity, calculated based on the gas and liquid flow rates, was 169 ft/sec, and the actual operating velocity was 175 ft/sec. The high erosional velocity was due to the low liquid flow rate and the low gas density (that is, the mixture density was low). This test condition was selected for the first experimental data point because wear was expected to occur (at this high velocity), and if the wear were quickly detected, the test could be stopped early. If the fittings were wear-free, there would be no point in performing the tests at lower velocities.

The first erosion/corrosion test ran continuously for 63 days. During the test, wall thickness measurements showed no significant pipe wall loss at any of the 148 measurement points on the test fittings (long-radius, 90° elbows). Special fixtures were fabricated and attached to the elbows to ensure that wall thickness measurements were taken in the same location every time. Measurements were taken at the top, bottom, and both sides of the pipe along the elbow and slightly upstream and downstream of each elbow. The uncertainty in the wall thickness measurements was about ±0.002", so a wear rate of more than 12 MPY (Mils Per Year) would have been detected by the end of the test.

After Test 1 was completed, the test fittings were removed from the flow loop and cut in half so that the inside surfaces could be inspected. Each elbow was cut along the centerline, as shown in Figure 4.3. The elbows that were not in fully developed flow (#2 and #4) did not show any pitting or wear. The inside surface of these fittings was covered with a dark, protective layer of corrosion products. Elbows #1 and #3 had a number of pits along the outside bend of the elbow. Table 4.3 lists the number of pits in each elbow and gives the size of the largest pits.

Fitting #1 had over 30 small pits located in a 1" wide band centered along the outside radius of the elbow and concentrated between 25° and 65° from the elbow inlet (where 0° is at the elbow inlet and 90° is at the outlet). The pits were typically between 0.010" and 0.040" in diameter and about 0.010" to 0.020" deep. Some of the pits were elongated in the direction of the flow, with the largest about 0.2" long. Fitting #3 had a large number of small pits, similar to fitting #1, and five much larger "pits." The large pits appeared to have grown in the direction of the flow, becoming deeper and wider as they grew. The largest "pit" was 0.35" long and 0.2" wide and 0.040" deep. All of the wear was located in a 1" wide band centered along the outside radius of the elbow and between 30° and 65° from the elbow inlet. The reason that the pits were not detected during the wall thickness measurements was that none of the pits coincided with the wall thickness measurement locations. Figure 4.4 shows a view of the pitting in elbow #3.

The straight sections of pipe upstream and downstream from the elbows were free from localized wear or pitting. The inside surface of the pipe was covered with a dark corrosion layer, and small deposits of particulate were stuck to the surface. The particulate material appeared to be corrosion products and could be easily removed by hand rubbing of the surface. The inside radius of each elbow also collected a small amount of particulate material (in zones that looked like stagnation regions). The outsides of each elbow were free from the accumulation of particulate, indicating that the higher flow velocity prevented accumulation of the material.

The test results showed that there was no pipe wall loss in the straight sections of pipe or in the elbows where flow was not fully developed. The only areas that showed significant wall loss were the portions of the elbows exposed to droplet impingement caused by the inability of the droplets to follow the bulk flow stream as it turned through the bends. The inertia of the droplets at the bends caused the droplets to impact the outside of the elbow with a moderately high angle of impact (not a grazing impact). The observed pits tended to grow in the downstream direction and got wider and deeper. The downstream lip of the larger wear areas had a very steep face. Some undercutting was also visible.

The rate of wall loss in the larger pits exceeded the maximum corrosion rate determined in laboratory tests, which was about 100 MPY on bare metal. For a 0.04" deep pit formed in 63 days of testing, the wear rate is about 230 MPY. Thus, the measured wear rate demonstrated that the protective corrosion products were not effective at eliminating erosion/corrosion in the elbow under the high velocity, annular mist flow conditions.

Table 4.3 Size of Largest Pits for Erosion/Corrosion Test 1

Test Fitting	Total # of Pits	Pit Depth (mils)	Pit Length (mils)
Elbow #1	33	14	200
Elbow #2	0	-	-
Elbow #3	83	40	350
Elbow #4	0	-	-

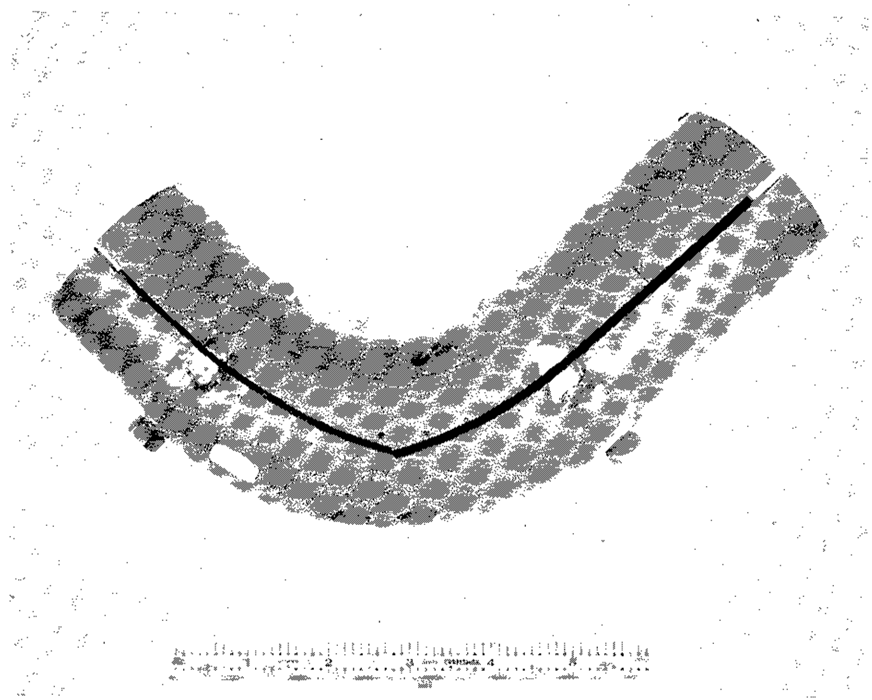


Figure 4.3 Test Fitting After Removal From Test Section and Cut Open for Inspection.

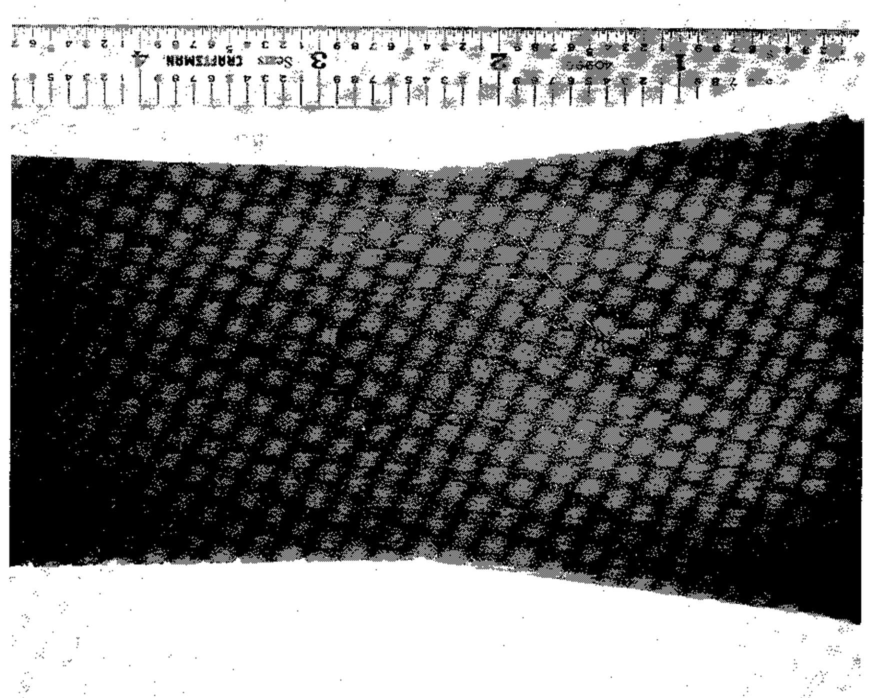


Figure 4.4 Inside Surface of Fitting #3 in Test 1. Flow is From Right to Left. Top of Fitting is Up.

4.3.2 Test 2 Results

The conditions for the second erosion/corrosion test were the same as for Test 1, with the exception that the liquid superficial velocity was reduced from 0.5 ft/sec to 0.1 ft/sec. As with Test 1, the two-phase flow was in the annular mist regime. With gas and liquid superficial velocities of 175 ft/sec and 0.1 ft/sec, respectively, the actual operating velocity was 175.1 ft/sec, which is 80% of the allowable erosional velocity limit.

Erosion/Corrosion Test 2 ran continuously for 60 days. Wall thickness measurements were taken during the test at 13 locations along the outside radius (the location where erosion/corrosion from droplet impingement would be expected) of each of the four elbows. No general wall loss was recorded. At the end of the test, the fittings were removed from the test section and inspected. All of the fittings were covered with a protective corrosion product film. The straight sections of pipe were free from wear with the exception of the pipe just downstream from elbows #1 and #2. One pit formed 2.4" downstream from elbow #1, and it was located on the outside of the bend along the centerline of the pipe. Three pits formed just downstream from elbow #2, and they were also located along the outside of the bend near the pipe centerline. The three pits were downstream of the elbow about 0.5", 1.2" and 1.4". These pits were very similar in shape to the pits in the elbows in that they were elongated in the direction of flow. There were no other pits in the straight sections of pipe upstream of the elbows, or downstream of the elbows, away from the influence of the bends. It appeared these pits were formed because of the flow disturbance caused by the presence of the elbow.

All four of the 90° elbows experienced localized pitting wear that was confined to a 1" wide band that ran along the outside portion of the bend. The pits were elongated in the direction of flow. The sketch in the Figure 4.5 presents the general shape of the pits. It appears the pits grew in the downstream direction and widened and deepened as time passed. Table 4.4 summarizes the average pit size, maximum pit size, and the approximate total number of pits for each of the four test fittings. The average and maximum pit sizes were determined by measuring individual pits that were selected as representative by visually inspecting each test fitting. With a maximum pit depth of 0.023" achieved in 60 days of testing, the maximum wear rate for the test was about 138 MPY.

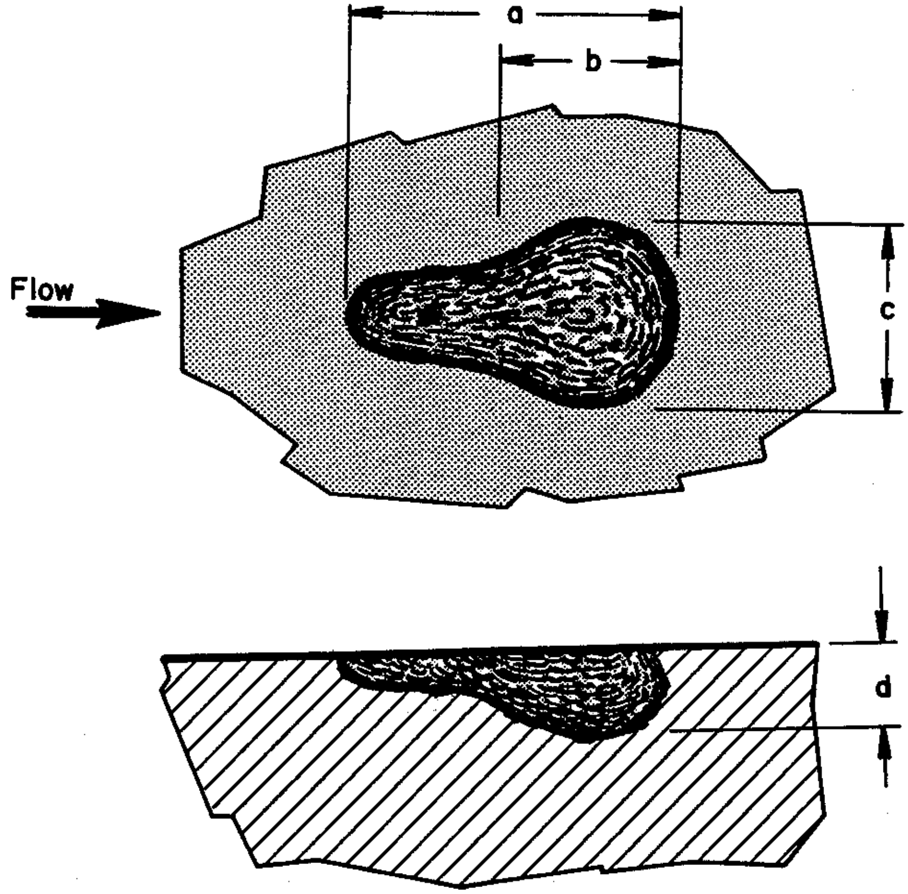


Figure 4.5 Typical Erosion/Corrosion Pit Geometry.

Table 4.4 Size of Typical and Largest Pits for Erosion/Corrosion Test 2

	Typical Pit Dimensions (mils)				Maximum Pit Dimensions (mils)				
Test Fitting	Overall Length "a"	Core Length "b"	Width "c"	Depth "d"	Overall Length "a"	Core Length "b"	Width "c"	Depth "d"	Total # of Pits
Elbow #1	52	29	25	10	70	37	51	22	198
Elbow #2	32	22	17	6	35	22	22	11	113
Elbow #3	21	15	12	5	49	27	32	10	175
Elbow #4	23	12	15	7	64	42	36	23	271

4.3.3 Test 3 Results

Erosion/Corrosion Test 3 ran for 65 days. The flow in the pipe was in the annular-mist flow regime, with gas and liquid superficial velocities of 70 ft/sec and 0.5 ft/sec, respectively. This operating condition was only 55% of the allowable erosional velocity. The wall thickness measurements taken during the test showed no general wall loss. After Test 3 was completed, the test fittings were removed from the test section and inspected. The inside surface of the pipe was covered with a tightly adhering layer of dark corrosion products. The straight sections of pipe were free from any pitting or local wear.

Each of the four long-radius elbows experienced pitting wear that was located along the outside radius of the elbow, between 30° and 75° from the elbow inlet (the inlet plane of the elbow being 0°). The pits were located non-symmetrically, with more pitting in the top half of the pipe and very few pits located below the centerline of the pipe. The pits located near the centerline of the elbow (that is, halfway up from the bottom of the elbow and running along the outside of the elbow) were circular and fairly small, typically about 0.030" in diameter and about 0.02" deep. The pits that were located closer to the top of the elbow were generally bigger and elongated in the direction of flow. The sizes of these pits varied considerably, with the larger pits being about 0.4" long and about 0.04" deep. Table 4.5 gives the size of the largest pit in each elbow and the total number of pits in each elbow. It should be noted that the pit depths reported here (for Test 3) differ from the results presented in Progress Report No. 8. A post-test calibration check on the depth gage, used to measure pit depth, showed the gage was out of calibration. The correct values are reported here. Figure 4.6 shows the pitting in elbow #2, with two large, elongated pits and a number of smaller, circular pits. Based on the maximum pit depth of 0.048", the maximum wear rate for Test 3 was 270 MPY.

The pattern of wear seen in the elbows for Test 3 suggests that the flow was partially stratified, and a liquid film protected the bottom half of the pipe from droplet impingement wear. Some stratification of the flow was expected since the flow conditions were selected to be just above the transition from stratified-wavy flow to annular mist flow. The presence of two distinct types of pitting wear (circular pits and those elongated in the direction of flow) at different elevations in the elbow also indicated local flow conditions and wear mechanisms changed with elevation. The results of Test 3 confirmed that significant flow-induced wear could occur in elbows, even when operating well below the erosional velocity limit in API-RP-14E.

Table 4.5 Size of Largest Pits for Erosion/Corrosion Test 3

Test Fitting	Total # of Pits	Pit Depth (mils)	Pit Length (mils)
Elbow #1	24	22	400
Elbow #2	35	48	220
Elbow #3	113	47	300
Elbow #4	14	26	210

4.3.4 Test 4 Results

Test 4 was conducted with the same liquid flow rate as were Tests 1 and 3, but the gas superficial velocity was reduced to 50 ft/sec. For gas and liquid superficial velocities of 50 ft/sec and 0.5 ft/sec, respectively, the operating velocity for the test was only 45% of the erosional velocity limit. At this gas velocity, the two-phase flow regime was stratified-wavy. The operating point was selected as close as possible to the transition between the annular mist flow regime and the stratified-wavy flow regime. The transition between these flow regimes does not occur at a discrete velocity. As the gas flow rate is decreased, for a fixed liquid flow rate, the liquid distribution becomes more and more stratified until the annular film of fluid no longer exists. The gas flow rate for Test 4 was selected to be as close to the transition region as possible.

Test 4 ran continuously for 56 days. The ultrasonic wall thickness measurements taken during the test showed no general wall loss. In post-test inspection, the straight sections of pipe were free from any localized pitting or wear and were covered with a dark, protective layer of corrosion products. Along the bottom of the pipe, there was a light deposit of reddish material that approximately marked the level of the liquid flowing along the bottom of the pipe. Based on this indication of liquid level, it appeared the liquid layer was about 0.3" deep. The reddish material was loosely adhering and could be wiped off easily by hand. Table 4.6 summarizes the number of pits seen in each elbow and gives the size of the largest pit in each elbow.

Fitting #1 had one large pit that looked like 3 pits that formed in a row (they were connected). The row of pits grew wider and deeper in the downstream direction, as shown in the closeup view of the pit in Figure 4.7. The pit was located 55° from the elbow inlet, and 0.5" above the pipe centerline. The maximum pit width was 0.21", and the overall length was 0.4". The depth of the three segments of the pit increased from 0.022" to 0.048" to 0.078". As shown in Figure 4.7, the

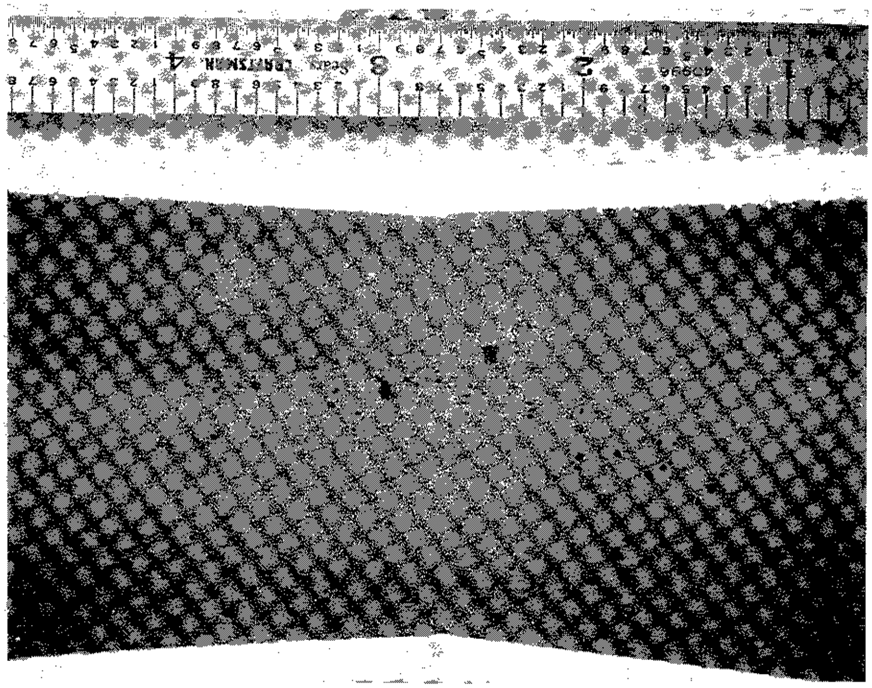


Figure 4.6 Inside Surface of Fitting #2 in Test 3. Flow is From Right to Left. Top of Pipe is Up.

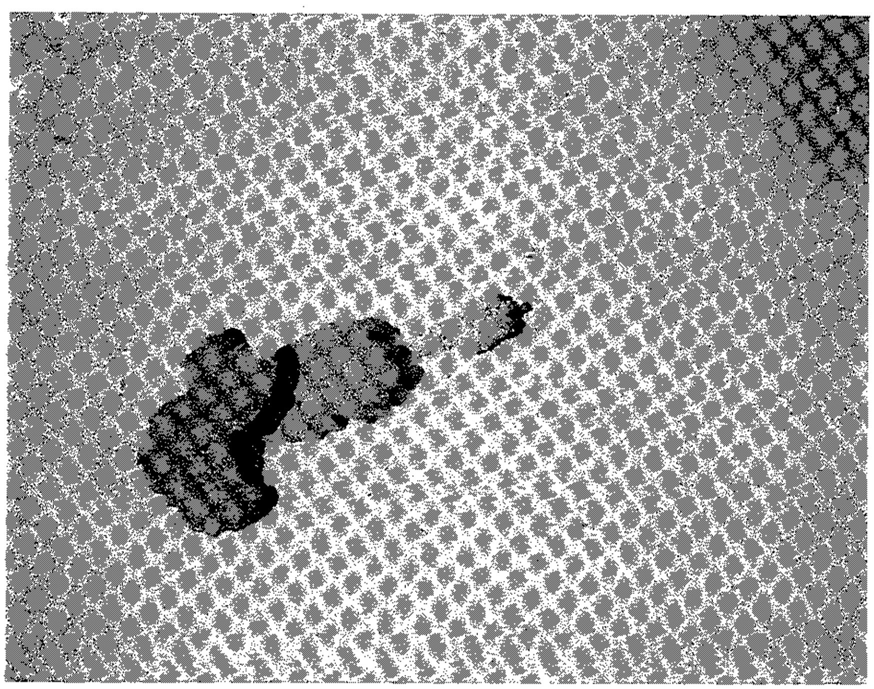


Figure 4.7 Close-up View of Pit in Fitting #1 in Test 4. Flow is from Right to Left. Top of Fitting is Up.

string of pits did not grow straight downstream, but angled downward at about 20° relative to the pipe centerline axis. This same trend was seen in the other elbows, with the magnitude of the angle increasing with the distance from the centerline.

In addition to the one large pit, the surface of the elbow was covered with voids that looked like small pits. These voids were located all the way from the inlet to the outlet of the fitting (along the outside of the bend), and under the microscope they were covered with a layer of corrosion products (and, therefore, were not "active pits"). These voids were noted in the pre-test inspection of the elbows and, therefore, were not considered as erosion/corrosion induced pits. The inside portion of the elbow was free of pits.

Fitting #2 contained three larger pits and a number of smaller pits. The pits were located along the pipe centerline and above it, with the lower section free from pits. It appeared the stratified layer of liquid covered and protected the bottom portion of the elbow and prevented pit formation near the bottom of the elbow. All of the pits were located between 25° and 70° from the elbow inlet. The two larger pits, located above the pipe centerline, were elongated in the direction of flow and were angled from straight downstream as discussed above. The largest pit was 0.32" long, 0.18" wide, and 0.065" deep. The second largest pit was 0.25" long, 0.13" wide, and 0.045" deep. The third largest pit was located near the pipe centerline and was more oval in shape; that is, it did not grow in a wedge shape as did the other large pits. This pit was 0.13" long, 0.08" wide, and 0.040" deep.

Approximately 46 smaller pits formed in fitting #2, and all of these were less than 0.05" in diameter. A number of these smaller pits grew as a line of pits that were aligned with the direction of flow as discussed above. These pits were not touching one another, but separated by pit-free regions. The inside radius of the elbow was free from local pitting or wear.

Fitting #3 had three pits that were located from 55° to 65° from the elbow inlet and between 0.1" and 0.3" above the elbow centerline. All of the pits were almost circular in shape, and only slightly elongated in the direction of flow. The largest pit was 0.09" in diameter and 0.037" deep. The other 2 pits were close to the same size. Each of the pits showed considerable undercutting of the surface, with the downstream edge being more undercut than the upstream portion. The rest of the elbow was covered with a very smooth layer of corrosion products and was pit free.

Fitting #4 was covered with a very smooth layer of corrosion products and was free from pitting wear. An examination of the inside surface of fitting #4 prior to the test showed the surface was very smooth, with no major flaws. This fitting completed the test without any pit formation.

The pre-test inspection for the other fittings identified some minor surface flaws. All of these fittings experienced pitting wear. Thus, this test result suggests that surface finish may be an important parameter that influences erosion/corrosion pit growth in a stratified-wavy flow regime.

Based on a maximum measured pit depth of 0.078", the maximum wear rate for Test 4 was 508 MPY. This high wear rate occurred while operating at 45% of the allowable erosional velocity in API-RP-14E. The wear pattern in the elbows showed more attack in the top half of the elbow. The bottom half appeared to have been covered with a protective liquid film. Observations of the stratified-wavy flow regime in a transparent test section (at gas and liquid superficial velocities of 50 ft/sec and 0.5 ft/sec, respectively) showed significant droplet generation from the tops of the liquid waves. These droplets became entrained in the gas and impinged on the outside of the elbow bend. Thus, even though the flow regime was not annular mist, droplet impingement was still occurring in the top half of the elbow.

Table 4.6 Size of Largest Pits for Erosion/Corrosion Test 4

Test Fitting	Total # of Pits	Pit Depth (mils)	Pit Length (mils)
Elbow #1	1	78	400
Elbow #2	49	65	320
Elbow #3	3	37	90
Elbow #4	0	-	-

4.4 Discussion of Test Results

4.4.1 Wear in Straight-Pipe Sections

The erosion/corrosion testing was performed under conditions that allowed the formation of a protective corrosion product film on the pipe walls. The tests were designed to determine the flow conditions necessary to remove the protective corrosion products and produce accelerated pipe wear. The test results showed there was no general wear or localized pitting wear in the straight sections of pipe. This result is important for two reasons. First, very high gas/liquid flow velocities (up to 175 ft/sec was tested) can be sustained in straight-pipe runs without producing the onset of erosion/corrosion; i.e., no erosional velocity limit may be required for straight sections of pipe. This result is confirmed by field data that also show erosion/corrosion problems typically occur only in elbows, tees, chokes, protruding weld beads, and other regions of flow disturbance. Secondly, the lack of wear in the straight-pipe test sections suggests that the "wear mechanism" is lacking, or minimal, in straight sections of pipe. Further efforts to determine the precise wear mechanism(s) and predict wear rates should, therefore, focus on pipe fittings that produce flow disturbances, rather than on straight pipe runs.

Shear-stress-induced stripping of corrosion product films has been reported as a probable wear mechanism by several researchers. This phenomenon was not observed in any of the tests with nominal flow velocities up to 175 ft/sec. Even at very high velocity, the average shear stress at the pipe wall is very small (on the order of 0.01 psi). For the tightly adhering iron carbonate films, it appears shear stresses several orders of magnitude higher would be required to strip them from the walls.

4.4.2 Wear in Test Fittings

In all four tests, localized pitting wear was observed in at least some of the elbows. The wear was confined to the outside portion of the bends, where liquid droplets traveling along the straight sections of pipe would impinge on the wall as the flow turned. The maximum wear rate for each test exceeded the corrosion rate measured for bare metal in stirred liquid bath tests. Three of the tests were conducted in the annular mist flow regime, and one was in the stratified-wavy flow regime. The hypothesis being tested was that the onset of accelerated erosion/corrosion would occur when the flow was in a transition to the annular mist regime. The wear mechanism that was expected to become "active" in annular mist flow was droplet impingement attack at flow disturbances. In the annular mist flow regime, a thin liquid film covers the walls and high velocity liquid droplets flow in the pipe core. At piping locations where the flow changes direction suddenly, such as flow in an elbow, the high velocity droplets have too much inertia to follow the gas flow, and consequently impact the pipe wall.

The result of Test #4 in the stratified-wavy flow regime showed that localized pitting wear occurred when the nominal velocity was below that required to produce transition to annular mist flow. The wear was limited to the top half of the elbow. It appeared the bottom half of the elbow was covered with the stratified liquid layer. The liquid film apparently protected the wall from droplet impingement wear. The top half of the pipe was free of the liquid film and subject to droplet impingement attack similar to that observed in the annular mist flow regime. In the stratified-wavy flow test, droplet flow in the gas phase was generated by entrainment of wave tops in the flowing gas. The operating point for the stratified-wavy erosion/corrosion test (operating superficial gas velocity of 50 ft/sec (15 m/sec) and liquid superficial velocity of 0.5 ft/sec (0.15 m/sec)) was in the transition region between several different flow regimes, as can be seen in Figure 4.8 [13]. The flow regimes identified in Figure 4.8 are for flow in straight-pipe. It may not be appropriate to apply the two-phase flow regimes determined in straight pipe sections to the flow conditions experienced in an elbow.

As the operating conditions move away from the annular flow regime, less and less droplet entrainment in the gas stream occurs. Operating at lower gas velocities in the stratified-wavy flow regime (away from the transition to annular mist flow), may prevent the localized pitting that occurs at higher velocities.

Another variable that appears to affect fitting wear is the amount of liquid present. The presence of a liquid film on the fitting wall can provide protection from droplet impingement. It remains to be determined if operating at higher liquid flow rates, with the same gas velocity, can provide added protection from fitting attack. Higher liquid flow rates will generally place the operating conditions in the slug flow regime. The added liquid may provide a protective liquid film, but the violent action of high velocity slugs in a fitting may contribute to the attack on the fittings.

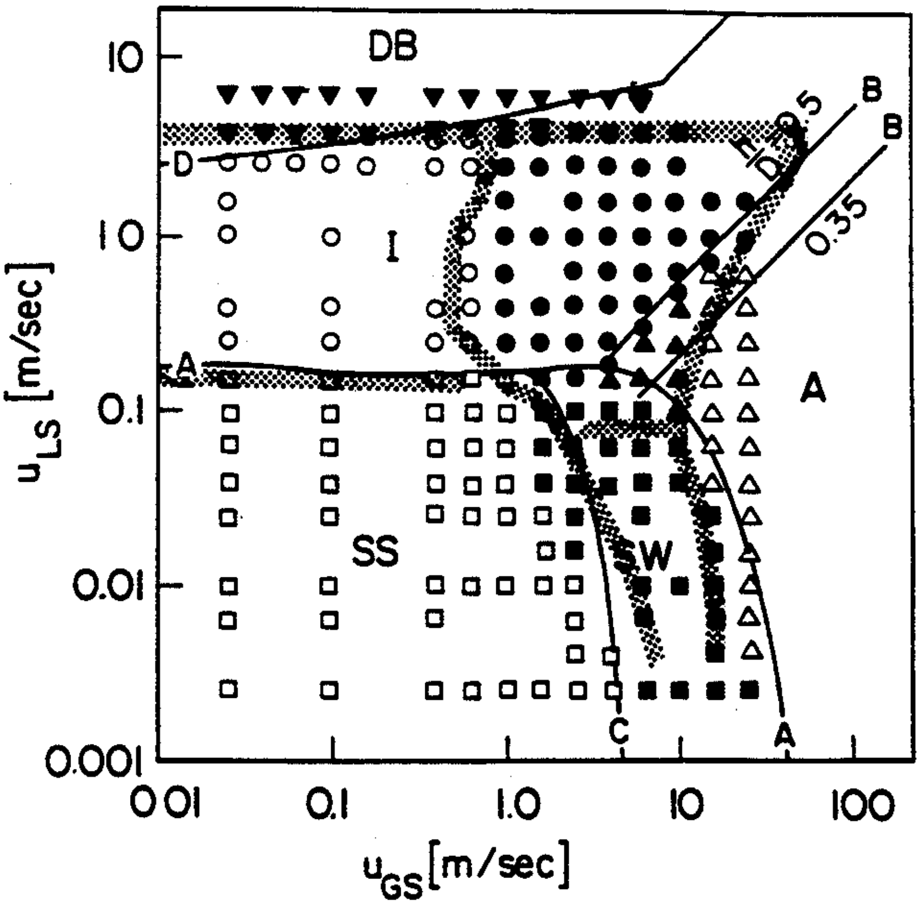
The results of the erosion/corrosion tests suggest that the mechanism of accelerated erosion/corrosion in the fittings is droplet impingement attack on the corrosion product film. The hypothesis that accelerated erosion/corrosion coincides with the transition to the annular mist flow regime is not necessarily true because liquid droplet generation and impingement at flow disturbances may occur in flow regimes other than annular mist.

4.4.3 Pit Growth

The pitting wear seen in each of the erosion/corrosion tests had similar traits. Observations based on inspection of the test fittings include:

- The pits appeared to grow in the downstream direction.
- The pits widened and deepened as they grew downstream.
- Once the pit reached some critical size, the growth rate appeared to accelerate rapidly. At this point, the pit growth changed from a wedge shape (getting wider and deeper in the flow direction) to a shape having steeply undercut walls and lateral pit expansion, as seen in Figure 4.5.
- Once formed, the pits did not seem to readily "heal over" and stop growing.

One possible explanation for rapid pit growth is that more of the droplet momentum would be dissipated at the pipe wall when the impact was incident in an already-formed pit. A droplet impacting into a deep, cup-shaped pit probably dissipates all of its momentum within the pit (confined to a small area) and imparts high surface loading stresses. This is compared with the



□ STRATIFIED SMOOTH	(SS)	STRATIFIED (S)	
■ STRATIFIED WAVY	(SW)		
○ ELONGATED BUBBLE	(EB)	INTERMITTENT (I)	
● SLUG	(SL)		
△ ANNULAR, ANN./DISP.	(AD)	ANNULAR (A)	
▲ WAVY ANNULAR	(AW)		
▼ DISPERSED BUBBLE	(DB)		

Figure 4.8 Flow Pattern Map For Air-Water Flow in a 2" Diameter Horizontal Pipe (from Barnea et al. [13]).

"glancing" impact a droplet would have on a smooth elbow surface. In this case, droplet momentum may be dissipated over a large area, as the droplet spreads over the surface. Droplet momentum would not be totally dissipated because the droplet would continue moving downstream, with only a small change in the flow direction. This would result in lower surface loading stresses compared to a droplet impact in a confined pit.

The above discussion may help explain the test observation that pits did not form another protective corrosion products film after the surface film was initially removed. Another factor is suggested by Videm and Dugstad [14]. The large regions of the elbow that are covered with an iron carbonate layer become cathodic, and this condition may speed up the attack on the smaller film-free regions. Videm and Dugstad believed velocities in excess of 50 ft/sec (15 m/sec) were required to maintain separate anodic and cathodic regions.

4.4.4 Pit Initiation

An interesting result of the experimental testing was that pitting wear was not seen in all of the elbows in every test. For example, in Test 4, one elbow was free from pit formation while the other three elbows experienced significant pitting. This result highlights the potential importance of pipe surface finish. Since all of the elbows were in the same flow stream, they all experienced the same exposure conditions. The one elbow that did not experience pitting was noted to be very smooth and free from surface flaws, or voids, prior to the test. The other elbows were also selected because they were comparatively free from surface defects on the inside surface. They were not, however, totally free from small surface flaws. The existence of small surface flaws in the elbow may have contributed to the onset of pit formation.

Based on this observation, future testing should include a measure of the surface roughness of standard, commercially available elbows. Flaws of this size could be introduced into test fittings in a controlled manner, to study their effect. The practice of carefully selecting flaw-free fittings for testing may not be appropriate to accurately simulate field conditions. Commercially available fittings will typically have large surface flaws which may enhance the erosion/corrosion process in field installations. The careful selection process used in the SwRI lab experiments was implemented so that at the end of testing, the erosion/corrosion pits could be distinguished from pre-existing flaws.

The lack of test information on when the pit growth was initiated and on the pit growth rate makes it difficult to speculate on the wear mechanisms. If the pits start to form immediately, then it is reasonable to assume that a minimum corrosion product film thickness is not necessary before the liquid droplet impingement attack begins. Based on the assumption of droplet impingement fatigue failure, a certain amount of time is required to obtain the threshold number of cycles to initiate failure. The test method used here did not provide this information; the only information available was the final pit size. The difference in pit sizes seen in these tests might simply be determined by time of initiation, with the "oldest" pits being the largest. Consideration should be given to obtaining more complete information on the pit growth history during any future testing. Periodic visual inspection is one possible method, as is periodic x-ray inspection. Implementing one or more of these approaches may also shorten the test duration.

4.4.5 Existing Erosional Velocity Criteria

The test flow velocity ranged from 104% to 45% of the allowable erosional velocity limit (from equation 1.1 with C=100). All of the tests produced significant wear in at least some of the test fittings. These results show the present erosional velocity limit does not predict the onset of accelerated wear for all possible flow conditions. The tests were run at low pressure and low liquid flow rates. For these conditions, the mixture density is low and the calculated erosional velocity limit is fairly high. The erosional velocity limit for two-phase/gas-liquid flow covers a broad range of flow conditions, from a liquid stream with a small amount of gas to a gas stream with a small amount of liquid. For the extremes, the erosional velocity limit ranges from 13 ft/sec for liquid flow (water) to over 480 ft/sec for gas flow (natural gas at STP). The limit for liquid flow is reasonable, but the limit for gas flow is clearly not practical. A velocity limit of about 60 ft/sec for gas flow is recommended in API-RP-14E to limit noise level. The upper velocity limit for two-phase gas/liquid flow should approach the limit for gas flow, as the liquid content in the gas stream decreases. The existing erosional velocity limit does not.

Another shortcoming of the existing erosional velocity limit for gas/liquid flow lines is that the limit is not dependent on the type of service and, thus, not dependent on the wear mechanism that would apply for a given type of service (e.g., clean service, erosive service, corrosive service, etc). The only flow-related parameter considered in the present criteria is the two-phase mixture density. For two-phase gas/liquid flow in horizontal pipes, the mixture density, as calculated in API-RP-14E, is not generally representative of the flow in the pipe. This is because the calculation is based on the "no-slip" liquid holdup. That is, it is assumed that the gas and liquid flow at the same velocity in the pipe. For most cases, the gas and liquid velocities are unequal (there is "slip" between the two phases), and the liquid typically moves slower than the gas, causing the liquid to accumulate in the pipe. The actual mixture density, at any discrete location in the pipe, can be considerably different from the "no-slip" mixture density. The erosional velocity limit should be based on parameters that control the actual wear mechanism, rather than an empirical formula that lacks any physical basis in predicting the occurrence of erosion/corrosion. For the experiments conducted here, it appeared the wear mechanism was related to droplet impingement attack of the corrosion products film.

5.0 CONCLUSIONS AND RECOMMENDATIONS

A new form of the erosional velocity limit for sizing multiphase flow lines has been recommended. The proposed sizing criteria are divided into four different groups, based on the different wear mechanisms active in multiphase flow lines on offshore piping systems. Each different wear mechanism will have a different set of controlling parameters that needs to be evaluated to limit pipe wear. The four different wear categories are:

(1) Clean Service (no solids or corrosion),
(2) Erosive Service (solids (sand) present in flow stream with no corrosion),
(3) Corrosive Service (corrosion without solids), and
(4) Erosive and Corrosive Service (both solids and corrosive media present).

Recommended erosional velocity limits for "Clean Service" and "Erosive Service" have been made based on information available in the open literature [7]. Further investigation is necessary to determine appropriate limits for "Corrosive Service" and "Erosive and Corrosive Service."

The work reported here is an initial step in determining an appropriate erosional velocity limit for "Corrosive Service." The experimental work focused on substantiating that accelerated erosion/corrosion occurs at the transition to the annular mist flow regime. The likely cause of accelerated wear in this flow regime is removal of brittle corrosion products from the pipe walls by liquid droplet impact fatigue. In the annular mist 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. Once the protective corrosion products are removed by droplet impingement, accelerated erosion/corrosion of the fitting can occur.

Experimental erosion/corrosion tests were performed in the stratified-wavy and annular mist two-phase flow regimes. The corrosive test conditions produced a protective iron carbonate film on the pipe walls. Standard 2" diameter long-radius 90° carbon steel elbows were used as test fittings. The test results showed there was no general wear or localized pitting in straight sections of pipe for nominal test velocities up to 175 ft/sec. This result agrees with the findings of other investigators who have reported that wear problems occur in areas where the flow stream is disturbed, such as elbows, tees, weld beads, or chokes. The lack of wear observed in straight pipe sections reinforces the contention that the erosional velocity limit should be based on wear rates experienced in fittings, rather than in straight pipe. The lack of wear observed in the straight sections also indicated the "wear mechanism" creating accelerated erosion/corrosion was lacking or its effect is weak in straight flow streams. The wall shear stresses generated in the straight sections of the high velocity two-phase flow stream were apparently not great enough to strip the protective corrosion products film from the wall.

Localized pitting wear was observed in the elbows in each of the erosion/corrosion tests. The wear was confined to the outside portion of the bend where droplet impingement wear would be expected. The test results suggest that the erosion/corrosion mechanism in the elbows is droplet impingement attack on the corrosion products film. The hypothesis that accelerated erosion/corrosion coincides with the transition to the annular mist flow regime is not necessarily true because droplet generation and impingement at flow disturbances can occur in other two-phase flow regimes. Localized pitting was experienced in the stratified-wavy flow regime, but only in the upper half of the elbow, where the elbow was free from the stratified liquid layer. Visual observations of gas-liquid flow in a clear pipe section confirmed that the upper portion of the elbow experienced liquid droplet impingement even in the stratified-wavy flow regime (when operating near the transition to the annular mist flow regime).

All of the experimental results indicate that droplet impingement attack caused accelerated erosion/corrosion of the fittings in the corrosive two-phase flow. Since all of the tests produced localized erosion/corrosion attack in the test fittings, additional testing is needed to fully map the flow conditions where erosion/corrosion can occur. Lower gas velocities, increased liquid flow rates (so a liquid film protects the fitting from attack), or a combination of both may be required to prevent the onset of erosion/corrosion wear. The test results also indicate that the initial surface finish of the fittings may determine whether or not localized erosion/corrosion pitting occurs. Introducing small flaws in the test fittings, in a controlled way prior to testing, should be considered for future tests.

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