

# **THE DESIGN AND DEVELOPMENT OF A LARGE-SCALE, MULTIPHASE FLOW LOOP FOR THE STUDY OF CORROSION IN SOUR GAS ENVIRONMENTS.**

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## **ABSTRACT**

A state-of-the-art laboratory flow loop has been researched, designed, and developed to study the corrosive effects of sour gas in multiphase flow. This unique system is housed in an environmentally isolated, explosion-proof area providing a safe location where an operator can study the effects of a single parametric change on corrosion. This report describes the fluid pumping system, the flow monitoring system, the corrosion monitoring methods, and safety systems associated with the new experimental loop. Initial baseline testing of the entire system consisted of slug flow and full-pipe flow regimes in seawater and the resulting effect on corrosion rates under partial pressures of CO<sub>2</sub>.

**keywords:** system design, sour system, slightly sour, multiphase flow, safety systems, CO<sub>2</sub> corrosion.

## **INTRODUCTION**

CO<sub>2</sub> and H<sub>2</sub>S content in produced fluids constitute a very corrosive environment that has been studied extensively in glass cells and autoclaves since the early 1970's, but little research work has been completed to model corrosion in slug flow of a sour system. Under various multiphase conditions, the slug flow regime has been shown to increase the corrosion damage to pipelines<sup>1,2</sup>. High velocity slugs are very turbulent with the existence of pulses of entrained bubbles in the mixing zone behind the front of the slug. These pulses of bubbles impact the pipe wall and collapse causing a cavitation-type effect, leading to increased corrosion rates in slug flow<sup>3</sup>.

H<sub>2</sub>S-related corrosion is a topic of great concern due to the increased oil and gas production technology that allows deeper wells producing more corrosive fluids and longer transmission lines. Longer transmission lines of multiphase fluids over various terrains provide opportune environments for slug flow regimes. In the presence of H<sub>2</sub>S, acidity of the corrosive media is a parameter known to play a determining role in the cracking phenomena (SWC, SSC, SCC) of low alloy steels as well as stainless steel and must be accurately evaluated<sup>4</sup>. Corrosion in the presence of H<sub>2</sub>S has resulted in the formation of an iron sulfide film that decelerated the corrosion rate at temperatures between 20°C and 60°C<sup>5</sup>. A similar film was seen at low concentrations of H<sub>2</sub>S in a brine containing CO<sub>2</sub> and acted as a corrosion film that greatly decreased the corrosion rates in 2-liter glass cells<sup>6</sup>. The addition of hydrogen sulfide to a corrosive system contained in a bubble cell or other small volume test apparatus provides information necessary for characterizing the reactions and by-products of the corrosion process. However, this information fails to show the mechanical action of the flow regime on the scale or corrosion product film. Sour gas corrosion research has been limited to small-scale studies, which do not provide an adequate environment for the simulation of corrosion in multiphase slug flow.

Current laboratory research associated with sour gas is conducted in autoclaves because of the ability to reproduce the wellhead temperature and pressure conditions; some even have circulatory pumps to achieve better mass transfer in the corrosion process. Srinivansan<sup>7</sup> describes an autoclave system developed to simulate fluid flow induced corrosion in CO<sub>2</sub>/H<sub>2</sub>S systems. This small-scale system provides an adequate environment for reproducing the corrosive constituents and wall shear stress effects, but lacks the size for development of certain flow regimes. Studies such as Pargeter<sup>8</sup> have provided valuable information on maximum permissible hardness levels for welded steels at risk of sulfide stress corrosion cracking, but he did have some concerns that the 16:1 solution volume to sample surface area was small and resulted in a higher contamination of the aqueous environment not seen in a production environment.

Concern over the construction of larger and more complicated flow loops was voiced by Nestic<sup>9</sup>. His study compares the hydrodynamic parameters in two different flow geometries, rotating cylinder and pipe flow, on the corrosion rate of low carbon steel in CO<sub>2</sub> environments. This information is used to transfer data from one laboratory scale flow-corrosion system (rotating cylinder) to another (pipe flow) and ultimately to field conditions. But his concern that “building larger and more complicated loops closer in scale to production pipelines means admitting that we do not know what goes on in our processes” is misleading. Our understanding of what goes on in the corrosion processes has reached a point that a larger system is necessary to fill in gaps of information not possible in smaller systems and provide another confirmation step to the transfer of data from small-scale conditions to field conditions.

Jepson and Taylor<sup>10</sup> found that, in order to mimic the mechanisms observed in large diameter pipelines, test facility pipeline should be above 7.5 cm in diameter. The advantage of large diameter research is the ability to produce repeatable flow regime phenomena similar to that of pipelines in field operations. Multiphase flow pattern reproduction in a controlled environment provides researchers with an opportunity to study corrosion and corrosion control mechanisms.

The greatest concern when developing a system involving hazardous materials is the amount of safety consciousness that must be focused on the project. Srinivasan<sup>7</sup> stated that H<sub>2</sub>S related corrosion has not been studied extensively in the laboratory due to the difficulty of working with H<sub>2</sub>S, but the

need for understanding CO<sub>2</sub>/H<sub>2</sub>S corrosion has grown with the advent of deeper and more corrosive production systems. Corrosion studies in an H<sub>2</sub>S/CO<sub>2</sub> environment could involve hydrogen sulfide concentrations in the gas phase of the system above the 100ppm value that is reported by the Occupational Safety and Health Association (OSHA) to be “immediately dangerous to life and health” (IDLH). The current testing program for the system involves the effects of low concentrations of H<sub>2</sub>S from 3ppm to 500ppm in the gas phase. The higher gas concentration means that systems must be put in place for personal and public safety. Using the proper materials of construction, installing hazardous gas sensors, purchasing personal protective equipment, and installing a gas removal system were the first steps to the physical control of the hazard while safety training, safety committees, and technical meetings provide the hazard awareness necessary during operations. The multiphase flow system must be developed of a suitable material with a procedure to maintain system integrity. The test parameters of the multiphase system must be stable and repeatable for each test run and should reflect field conditions as much as possible.

Safety consciousness began in the design phase with construction of a special environmentally closed room to house the multiphase flow loop and progressed to safety training. The major wetted portions of the loop were made of Hastelloy C-276 (UNS No. N10276) and ultrasound testing was completed in multiple locations before wetting the system with any materials to provide a baseline measurement for wall thickness and continuity. A combustion system was designed to evacuate the contaminated room air volume through a furnace to convert the H<sub>2</sub>S to SO<sub>2</sub>. The combustion system is automated to activate at 10ppm H<sub>2</sub>S, which is the current threshold limit value (TLV) set by OSHA. Addition of pure hydrogen sulfide to the system was used because it is less sensitive to the filling rate and the influence of temperature stability can be controlled<sup>11</sup>. The two hydrogen sulfide system operators attended an H<sub>2</sub>S instruction program that follows the ANSI Z390.1 – 1995 Hydrogen Sulfide Training Standard. This OSHA training course provided the knowledge required for teaching others how to work safely in the field with and around hydrogen sulfide. A certified course on hydrogen sulfide safety was taught to the others at the Institute. The effect of the training was to include all personnel at the Institute in the goal of maintaining a safe environment and providing multiple perspectives on safety strategies. Weekly technical meetings and bi-weekly safety committee meetings provide the necessary information transfer for the entire facility. System operation and measurements will be conducted from a location outside the environmental room with the “buddy system” in place for any excursions into the room when hydrogen sulfide is present.

In respect to the culmination of research work done in carbon dioxide corrosion, research on the effect of mixtures of carbon dioxide and hydrogen sulfide on corrosion is relatively new with no information available under slug flow conditions. Research information is desperately needed in this area. This information is used to better define corrosion rate models, which, in turn, predict corrosion rates under various conditions helping engineers to design better methods of corrosion control in the field. Laboratory simulation of corrosive environments has brought information from wheel tests, glass cell experiments, autoclave experiments, and flow loop studies. Each has its own place. Models developed for the simulation of flow are also used to enhance corrosion prediction. Providing research conditions in flow regimes that cannot be established in small-scale testing will aid the cause and help to modify existing corrosion prediction models for increased accuracy.

With all these factors, the development of a large-scale research system capable of reproducing conditions of a sour gas environment was absolutely necessary. Few such rigs exist. This report

describes the systems developed for the operation of a closed-loop, large-scale, sour-gas, multiphase flow loop for corrosion research data collection.

## SYSTEM DESIGN

### Schematic Interpretation

The basic design of a system relies on the requirement to provide a fully developed flow and repeatable conditions in a test area for corrosion testing. This is accomplished by moving quantitative amounts of liquid and gas to a mixing point, allowing enough pipe length for fully developed flow from that mix, and providing an area for insertion or connection of instruments for measurement in a closed system. Figure 1 is the piping and instrumentation diagram for the multiphase research system built to study corrosion under sour gas conditions. This schematic representation shows the H<sub>2</sub>S system to be a closed system using three pumps, two test sections, one tank, and one heat exchanger.

### The Pumping System

The liquid pump (P1) and gas pump (P2) are both progressive cavity pumps. Progressive cavity pumps were chosen because of their ability to move multiphase mixtures and provide positive-displacement flow qualities under most conditions. These progressive-cavity pumps use a double-helix design stator made of nitrile in the outer shell with a single helix rotor that is chrome-plated stainless steel. The liquid pump (P1) has a 50 horsepower (Hp) motor with a 4.93 to 1 step down ratio from motor speed to rotor speed. Calculation of the flow rate, as shown in Equation 1, is based upon manufacturer calibrated rotor-stator combinations that provide a specific volume per 100 revolutions.

$$MotorRPM \left( \frac{1RotorRotation}{4.93MotorRotations} \right) \left( \frac{115gal}{100RotorRotations} \right) \left( \frac{1m^3}{264.2gal} \right) \left( \frac{31.2mPipeLength}{1m^3PipeVolume} \right) \left( \frac{min}{60sec} \right) = m/s \quad (1)$$

Pump P1 provides a 0.5-2.5 m/s liquid flow rate in linear response to the 200-1000 RPM motor speed as calculated from Equation 1. These values were calibrated against an ultrasonic flow meter as shown in Figure 2. The gas pump (P2) has a 150 Hp motor with a 5.68 to 1 step down ratio from motor speed to rotor speed with the same operating techniques as P1. The third pump (P3) is a positive displacement gear pump that provides a percentage of the total liquid flow added to the gas pump (P2) to provide a lubricating seal required in moving the gas phase. Pump P3 provides a 0-114 lpm (0-30 gpm) in response to 0-1725 RPM change in motor speed. The volumetric flow from P3 is subtracted from the volumetric flow determined from the rotational speed of P2 to provide the gas volumetric flow rate.

### Physical Characteristics

The H<sub>2</sub>S system is 95 ft (29 m) long by 12 ft (3.6 m) wide by 9.6 ft (2.9 m) high at its highest point in the gas pump suction line from the top of the tank. Two test sections are named “Upstream” and “Downstream” because of their location within the system in relation to the mixing point. The tank is a gas-liquid separation device with a diffusion plate located just under the return stream. The

heat exchanger was a necessary addition from previous experience in obtaining high gas velocities because P2 will add excess heat to the system that must be removed. All piping is made of N10276 because of its ability to withstand this type of a “wetted” corrosive environment better than other alloys. The pump rotors, pump suction, and pump discharge housings are made of 316L stainless steel.

The Upstream test section is located 9 m (354 in.) downstream from the gas-liquid mixing point and 1.2 m (48 in.) upstream from the first 90-degree bend. This location is 88 pipe diameters downstream from the turbulent gas-liquid mixing point and 12 pipe diameters upstream from the 90-degree bend. The Downstream test section is 130 pipe diameters from the second 90-degree bend and 24 pipe diameters from the tank entrance. These are both acceptable locations for achieving fully developed flow.

Each test section has numerous ports. Figure 3 shows a diagram of the test section where fluid flow is from the left to the right. Ports A, D, E, and F are used in differential pressure drop relationships for determining the flow pattern. Each of these ports is a 1” (2.54 cm) flange and pipe welded into position with a 1/8” (0.3175 cm) hole through the pipe wall. Ports B and C are the insertion points for electrical resistance (ER) and linear polarization (LPR) probes; each having a 1.5” (3.8 cm) opening for insertion of a 1.25” (3.175 cm) flush probe element. Each of these has a 2” N10276 ball valve to provide for mounting and inserting the probe into the pipe wall while the system is under pressure. Port G is similar in design to port A, but port H has a 1” (2.54 cm) opening into the pipeline from its 1” flange. Ports G and H are used for different purposes in the upstream and downstream locations. The Downstream test section uses these two locations for a thermocouple and pH probe, respectively, for measuring a temperature compensated pH. The Upstream test section uses these two locations for gas injection and a pressure measurement location downstream of Valve #1.

Technical grade gases are added through a 316L stainless steel (UNS No. S31603) tubing and valve system shown in Figure 4 as the “Gas Mix Panel.” Stainless steel has excellent corrosion resistance to dry hydrogen sulfide gas, which is the most corrosive of gases to be used. The last valve before entering the system (“Main”) and the associated tubing to the system is made of N10276 because they will be exposed to “wetted” hydrogen sulfide gas.

## **Combustion System**

The purpose of this system is to oxidize  $H_2S$  or  $CH_4$  should it need to be vented from the pressure vessel in a controlled manner, or in the event of a gas leak. A combustion chamber system of gas incineration was chosen for this process because only colorless flue gas will exhaust from the stack. Primary air for combustion will be drawn from outside while the secondary air for combustion will be drawn from the environmental chamber where the  $H_2S$  System is located. The combustion system can be activated by a manual switch or by a signal from a calibrated, fixed gas sensor. There are eight (8)  $H_2S$  gas sensors and four (4)  $CH_4$  sensors placed about the test cell and there is a ventilation system that provides an exit route for hazardous gases to safely exit the room. Should one or more of the gas sensors be exposed to more than 10ppm  $H_2S$  or 50% Lower Explosive Limit (LEL)  $CH_4$  concentrations, the exhaust blower will remove the air from the test cell and route it through the combustion system.

The hazardous gas monitors provide a 4 – 20 mA output in relation to a 0 – 100 ppm concentration of H<sub>2</sub>S or to a 0 – 100% lower explosive limit (LEL) of methane (CH<sub>4</sub>). The output of each H<sub>2</sub>S sensor is sent through a 243-ohm resistor where 0 ppm will give 0.9720 volts and 100 ppm will give 4.86 volts. A 10 ppm concentration would therefore be equivalent to 1.3608 volts ( $1.3608 = 0.9720 + 10 \cdot 0.03888$ ). The output of each CH<sub>4</sub> sensor is also sent through a 243-ohm resistor where 0% LEL will give 0.9720 volts and 100% will give 4.86 volts. The 50% LEL set point is equivalent to 2.916 volts ( $2.916 = 0.9720 + 50 \cdot 0.03888$ ).

Located outside the test cell, the control box for the combustion system contains five circuit boards. Three of these boards all have the same signal comparators. Each of the signal comparators has hysteresis. For example, the H<sub>2</sub>S sensor comparators are set to go high at 1.3608 V, but will not return to a low until the input signal is less than 1 volt. The outputs of all comparators are logically “OR’d” together so that any single sensor will turn on the system if its output exceeds 1.3608 V. The other two circuit boards within the control box contain the combustion system interface and the power supplies.

Three H<sub>2</sub>S monitors are located within 6” (15.24 cm) of the floor, one is located in the H<sub>2</sub>S gas storage cabinet, and two are located 15’ (5 m) off the ground. All are set to trigger an alarm system for any concentration of H<sub>2</sub>S over 10ppm. H<sub>2</sub>S has a density greater than air (1.189) and will concentrate in low-lying areas, but, if mixed with a less dense gas, the buoyant effect could lift the hydrogen sulfide gas. Three CH<sub>4</sub> monitors are all located at the 15’ (5 m) level due to the lighter density of the gas.

The ventilation system within the room is comprised of 4” PVC in three flow lines that converge into a 6” PVC manifold and a liquid containment box. A 4” carbon steel pipeline entering the box from outside the building, leads the gas through a combustion system before being released from a stack, 20 feet above ground level. The ventilation system can be activated by a manual switch and is automatically activated as part of the combustion system. A portable hood is also available from the ventilation system to draw gases that escape during probe insertion away from the user.

## **System Operation**

When using multiple gases in a test procedure, the gases are to be added to the system based upon partial pressure. The Gas Mix panel is designed for injection order of the lowest partial pressure gas to the highest partial pressure gas (ie. H<sub>2</sub>S, CH<sub>4</sub>, CO<sub>2</sub>, N<sub>2</sub>) and to use the higher partial pressure gases to purge the Gas Mix panel tubing lines into the system. It should be noted from Figure 4 that nitrogen gas has the longest path through the tubing to the system input. The last valve on the tubing string, after the “Main” valve is the “Vent” valve, which is used to exhaust the contents of the Gas Mix Panel out to the combustion system by using nitrogen or carbon dioxide as a purge gas.

Liquid velocities are measured/calibrated by using an ultrasonic flow meter. For non-diverted flow in the main 4” flow line, a calibration curve was established between the motor RPM and the flow rate for the liquid progressive cavity pump. If lower flow velocities are required, a 2” flow diversion line and recycle valve can be used and flow measured with an ultrasonic flow meter on the smaller line. Valves #3, #4, and #5 from Figure 1 are used in this process. The progressive cavity pump for the gas flow is capable of moving 3 m/s to 10 m/s gas directly with only the addition of

lubrication fluid (pump #2) and calculations from the rotational speed of the gas pump (pump#1). Gas flow rates lower than 3 m/s begin to show signs of pulses from the progressive cavities. Partial closure of valve #1 can produce gas flow rates in the test section as high as 20 m/s. This partial closure of valve #1 alters the gas flow by changing the area between the exit of pump #1 and valve #1 into a storage vessel and gas flow rate in the main flow line ( $v_2$ ) is calculated by the ideal gas law comparison.

$$v_2 = P_2 / P_1 v_1 \quad (2)$$

Where:  $P_2$  = pressure downstream of valve #1,  
 $P_1$  = pressure upstream of valve #1, and  
 $v_1$  = velocity or volumetric flow rate upstream of valve #1.

### **SAFETY AND DESIGN CONSIDERATIONS**

When using hazardous gases, many safety considerations must be taken into account during the initial design phase of a research facility. System location, piping and instrumentation, safety systems, and operational procedures are four of the core considerations during construction. Each of these topics will be discussed as it pertains to the sour-gas multiphase flow loop located at Ohio University.

#### **System Location**

The sour-gas system is located in a 100 ft (30 m) long by 20 ft (6 m) wide by 25 ft (7.6 m) high isolated room. The two doors connecting the room to the main laboratory area each have a 21" x 24" (0.53m x 0.61m) reinforced window for viewing the full room without entering. A full opening garage door on the east wall has windows for viewing and allows forklift access into the room, although the system must be shut down and dismantled before entry, there is enough room for drums to be transferred into or out of the room from that access. A total of five doors allow exiting the room without locks, but each door requires a key to re-enter. If needed, an eye wash station and two fire extinguishers are within the room. An additional eyewash station and fire extinguisher are located nearby within the main laboratory. A combustion system for conversion of  $H_2S$  to  $SO_2$  is located in close proximity outside the southwestern wall. A release of  $H_2S$  within the test cell will be detected by at least one of eight  $H_2S$  monitors located close to the floor since  $H_2S$  is heavier than air ( $\rho_{H_2S} = 1.182$ ). Assuming a perfect dispersion of  $H_2S$  along the floor, a gas release within the room would be detected before more than 1/1000 lb (0.45 g) was released. When 10ppm  $H_2S$  is detected, the ventilation and combustion system will automatically switch on and draw the gas-air mixture from the room; the ventilation and combustion systems remain on until the concentration detected by any one sensor is less than 10 ppm. An audible alarm also sounds throughout the main laboratory when  $H_2S$  is detected.

#### **Building Location**

Since  $H_2S$  is a toxic gas, the location of the building with respect to the community and the amount of release possible is of concern. The possibility of a release of the total 2.2 kg (1.0 lb) of  $H_2S$  onsite was also considered for its impact on the community. Using the room volume of 1133m<sup>3</sup>

(40,000ft<sup>3</sup>) and assuming the 0.16 m<sup>3</sup>/s (340 CFM) room evacuation fan can exchange the room air in 2 hours, a catastrophic spill of 2.2kg of H<sub>2</sub>S onsite would result in a release rate (Q) of 6.3x10<sup>-5</sup> kg/s. If the level of concern for hydrogen sulfide exposure is 0.042ppm, the concentration distance can be calculated as a hazard distance. The hazard distance is the maximum dispersion distance in which ground-level chemical concentrations of the plume centerline exceed the specified exposure levels. This concentration as a function of release rate, wind speed, and effective stack height is shown in Equation 3<sup>12</sup>:

$$C = \frac{Q}{\pi\sigma_y\sigma_zU} \exp\left[-0.5\left(\frac{H}{\sigma_z}\right)^2\right] \quad (3)$$

Where: C = ground-level ambient concentration, g/m<sup>3</sup>  
 Q = toxic release rate, g/s  
 $\sigma_y$  = crosswind dispersion coefficient, m  
 $\sigma_z$  = vertical dispersion coefficient, m  
 U = mean wind speed at the stack height, m  
 H = effective stack height, m

Through regression analysis and choice of the worst-case conditions (having rural locations within 500 m of the release and a minimal wind turbulence), calculation of the hazard distance as related to release rate and ground-level concentration is shown in Equation 4.

$$HD = 6200f_hf_U\left(\frac{Q}{C}\right) \quad (4)$$

Where: HD = hazard distance, m  
 Q = toxic release rate, kg/s  
 C = ground-level ambient concentration or level of concern, mg/m<sup>3</sup>

Correction factor for height of dispersion, H

$$f_h = 1.07 - 0.0086H \quad (5)$$



Correction factor for wind speed, U

$$f_U = 2.80U^{-0.64} \quad (6)$$

Using Equations 4, 5, & 6 to calculate the concentration gradient through a linear distance from the release point, Figure 5 shows the acceptable exposure limit of hydrogen sulfide is reached within 5 meters from the point of the release at ground level.

If there is a release of H<sub>2</sub>S greater than 10ppm within the hydrogen sulfide test area, the wall-mounted sensors will automatically turn on the room air evacuation fan and the combustion system. If the previous assumption of 2.2 kg of H<sub>2</sub>S released within 2 hours holds true, then complete combustion of 2.2 kg of H<sub>2</sub>S in 2 hours would produce 22.4x10<sup>-5</sup> kg/s of SO<sub>2</sub>. Also considered a hazardous gas, the use of Equations 4, 5, & 6 to calculate the concentration gradient of sulfur dioxide through a linear distance from the release point provides a more acceptable result than the release of hydrogen sulfide. An acceptable limit of 0.8ppm SO<sub>2</sub> as set by the State of Ohio is reached within 2 meters of the point of the release at ground level as shown in Figure 6.

With corrosion testing beginning with low ratios of H<sub>2</sub>S/CO<sub>2</sub>, it is possible to maintain a low inventory of hydrogen sulfide. The low inventory of less than 2.2 kg H<sub>2</sub>S provides that even under catastrophic release conditions, the public vicinity surrounding the test cell will be unaffected.

### **Piping and Instrumentation Diagram**

The system is made up of three “positive-displacement” pumps that calibrate linearly against rpm. Progressive cavity pumps are used for the main liquid and gas movement and a gear pump is used for the liquid lubrication feed to the gas pump. Since a minimal amount of compression transpires from the inlet to the outlet of a progressive cavity pump, it can be ideally considered a multiphase transport pump. Since valves are located at the discharge of the pumps (Figure 1: V1, V3, V4, & V5), over pressure control (OPC) circuits must also be installed to sense the pressure at the discharge and shut down the pumps if a maximum set pressure is attained. Each OPC is set for a maximum pressure much larger than the operating pressures, but lower than maximum possible pressures. For operating ranges of 0.27MPa (25 psig) to 1.5MPa (200 psig), the OPC is set for 3.45MPa (500psig). A fault caused by an overpressure condition at the outlet of the pump will immediately shut the pump motor controller off. If an overpressure condition exists at the outlet of the pump when it shuts off, the progressive cavity pump in the off condition is free to rotate to come to equilibrium and will reverse direction to feed the high pressure back to the suction.

A rupture disk is located in the gas phase at the top of the gas/liquid separation tank. The 2” Teflon lined, stainless steel, rupture disk is set at 1000 psi with the understanding that failure can occur between 70 to 100% of this burst pressure in a pulsating system. Failure of the rupture disk would send gas and fluid down a 2” pipeline to the liquid containment box connected directly to the combustion system. Any hydrogen sulfide gas concentration above 10ppm released from the system will actuate one of two fixed sensors within the box and automatically turn on the combustion system.

## Operation of the Flow Loop

A closed system design is used to minimize the amount of products that are used and to help maintain chemical equilibrium. The operational order of each system of the flow loop is very important from the aspect of safety and experimental repeatability.

The system is cleaned in between each experiment and, before filling with the test solution, the system is tested for cleanliness. To do this, the system is filled with tap water and operated for 20 to 30 minutes. A sample is drawn and tested against an unused tap water sample in a tensiometer for determination if any oils or surfactants exist.

The current procedure in use is:

1. An ASTM sea salt mixture is added to de-ionized water to create the test solution as it is filled into the system under ambient temperature and pressure.
2. All valves are checked for proper orientation. The valves on the base of the tank are checked after introduction of the ASTM salt water to make sure the valve from the bottom of the tank to the gear pump suction is open while the valve used to add the solution is closed. Valve 1, 2, & 3 from Figure 1 should be open.
3. The heating system is then turned on and set for 60°C.
4. Two hydraulic pumps are then started that pressure mechanical seals on the rotating shafts of the progressive cavity pumps. These mechanical seals maintain a set differential pressure above the pump suction pressure through a differential pressure feedback mechanism known as a Tascom<sup>®</sup> valve. Both of these valves are currently set to maintain approximately 25 to 40 psi differential pressure. The positive differential pressure across the mechanical seal provides a safety that leakage through the seal will occur into the system, so that H<sub>2</sub>S will not be lost to the hydraulic pumps.
5. CO<sub>2</sub> is then used to purge the gas cap of the system of oxygen by flowing through the stagnant system and out valve #6, Figure 1. After a 20-minute purge, valve #6 is closed while the CO<sub>2</sub> is still entering the system and the fluid flow pumps are turned on.
6. The fluid flow pumps are turned on in order. First the gear pump, then the liquid pump, and finally the gas pump. RPM settings to provide 1.0m/s Vsl and 3.5m/s Vsg are used to create a turbulent slug flow to aid in the deoxygenating process.
7. After the system reaches 25 psig (0.27MPa), the CO<sub>2</sub> flow is stopped and the system allowed to circulate.
8. The CO<sub>2</sub> gas pressure is released and replaced numerous times at 30-minute intervals while heating and circulating in order to deoxygenate the fluid.
9. After deoxygenation is complete, the pumps are set to the predetermined flow rates and the system allowed to come to temperature equilibrium overnight.
10. Corrosion studies begin the next day by retesting oxygen content, iron content, and pH before insertion of the probes. If H<sub>2</sub>S is to be used, it is added at this point, allowed time to come to equilibrium, and the gas phase tested through the portable gas analyzer.
11. When hazardous gases are in use, the “buddy system” will *ALWAYS* be used requiring that an observer be outside the room during any necessary excursion into the test area.

## Operation of the Combustion System

The status of any sensor can be observed from the front panel of the control box in the operator area. In the upper left hand corner is the 'power on/off' switch. When all systems are in working order and the monitors do not detect gas in the test cell, all lights on the panel will be green. Along the bottom of the front panel is the sensor status /sensor test switches. With all these switches in the down position, all sensors are activated.

In the center of the front panel are 4 switches labeled SW1, SW2, SW3, and SW4. These allow the user to override the logic circuits to test the various parts of the system. Above these switches are 4 LEDs that indicate the status of the various parts of the system. SW1 tests the siren. SW2 tests the combustion system. SW3 tests the combustion blower. SW4 tests the exhaust blower. If the combustion system is tested, the combustion blower indicator light along with the combustion system light will turn red because the combustion system requires the blower in order to operate correctly.

At the upper right is a manual override switch. This can be used to turn on the combustion system when a controlled venting of the pressure vessel is needed. Once activated, one 340 CFM fan draws air from the H<sub>2</sub>S environmental room and mixes it with another 340 CFM fan providing ambient air for combustion. A differential pressure switch is activated which allows natural gas to enter the flow and a spark plug provides the necessary ignition.

## EXPERIMENTATION

### Set-up

The current operating procedure was used up to step 9, so the system would be ready for probe insertion. The test matrix is shown in Table 1. Two electrical resistance (ER) probes, one linear polarization probe, and one set of four coupons was used for each test, but only results for ER probes will be provided in this report.

### Flow Regime

From empirical data<sup>13</sup>, relationships between gas velocity, film Froude number, and slug frequency were estimated. Table 2 and 3 show the data for each liquid velocity tested by Wilkens and the linear relationship calculated for Froude number and slug frequency. From this information, the gas velocity was calculated from the given liquid velocity to provide a Froude 6 slug flow at 0.45MPa. The measurement of slug frequency would provide the assurance of the attained flow regime.

The hydrogen sulfide system uses a closed circulatory system that maintains environmental equilibrium while separating and re-mixing the gas and liquid phases. The re-mixing of the flows to provide the desired flow pattern is based upon the volumetric flow rates of three pumps. But changes in the total pressure produce changes in flow densities and interfacial tension between the phases, which, in turn, alters the slug frequencies as shown in Figure 7. The volumetric flow rates used in the following testing were based upon Froude 6 slug flow at 0.45MPa for each liquid velocity (i.e. 0.5, 1.0, and 1.5 m/s), but by maintaining constant volumetric flows, this flow regime changed with total pressure.

## Results

Comparison to previous testing shows the trends in the measured corrosion rate to be as expected. The corrosion rate increases with an increase in liquid velocity and also increases with an increase in pressure of CO<sub>2</sub>. Slug frequency is investigated and is shown to decrease with an increase in system pressure, although this seems to have a negligible effect on the corrosion rate.

As seen in Figure 8, previous work<sup>14,15</sup> done at the Institute for Corrosion and Multiphase Technology provided corrosion rate information for a Froude 6 stationary slug under specific multiphase flow conditions. It was assumed that the trends in measured corrosion rates would be similar between a stationary slug system and a moving slug system with changes apparent in overall corrosion rate. Figure 9 shows the measured corrosion rates in slug flow for the three different liquid velocities of 0.5, 1.0, and 1.5 m/s.

Compared to the stationary slug corrosion rates of Figure 8, corrosion rate values measured for the moving slug environment were approximately one-quarter (1/4) of those measured for the stationary slug environment. Figure 9 shows an increasing corrosion rate at each mixture velocity for increases in CO<sub>2</sub> pressure. Figure 10 shows increasing corrosion rates at each pressure for increasing liquid velocities. A stationary slug provides a highly turbulent zone with high relative corrosion rates. On the other hand, a moving slug environment has an associated slug frequency that lowers the amount of time that the turbulent zone is in contact with the corrosion measurement instrument. Corrosion rates produced in a moving slug environment would thus be lower due to intermittent turbulence designated by slug frequency instead of the constant exposure to turbulence of a stationary slug.

## CONCLUSIONS

1. Large systems are a necessary addition to the large array of testing systems available to the research community. They provide flow patterns not possible in smaller systems.
2. Use of progressive cavity pumps for multiphase flow studies is feasible and the pumps are easily calibrated for use in the laboratory.
3. Gas flow rates larger than the volumetric flow capacity of the progressive cavity pump are possible by using a pipe segment at the output of the pump as a reservoir to hold a volume of gas. The output of this pipe segment uses a pressure drop across a valve to increase flow rate while the input from the pump continually supplies the excess gas to the reservoir.
4. Initial corrosion testing with low ratios of H<sub>2</sub>S to CO<sub>2</sub> total pressure makes it possible to maintain a low inventory of hydrogen sulfide, providing that, even under catastrophic release conditions, the public vicinity surrounding the test cell will be unaffected.
5. Since changes in pressure alter the moving slug flow pattern, there is a need to choose a better “marker” than volumetric flow for repeatable conditions. Namely, for constant slug frequency, each coupon would experience similar time effects of turbulence under different total pressures.

6. CO<sub>2</sub> corrosion rate trends under moving slug conditions are similar to CO<sub>2</sub> corrosion rate trends of previous testing.

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## TABLES

Table 1.  
Multiphase Baseline Corrosion Test Matrix

|                          |                                      |
|--------------------------|--------------------------------------|
| Temperature              | 60°C                                 |
| Fluid                    | 100% ASTM Seawater                   |
| Flow Regime              | Slug Flow, Froude 6                  |
| Vsl                      | 0.5, 1.0, & 1.5 m/s                  |
| CO <sub>2</sub> Pressure | 0.27, 0.45, & 0.79 MPa               |
| Calculated Vsg           | 3.3, 3.5, & 4.9 m/s,<br>respectfully |

Table 2.  
Froude Number Correlation for 100% Saltwater, 0.45MPa, horizontal multiphase flow.

| Vsl (m/s) | Vsg (m/s) | film Froude No. | Fr. No. vs. Vsg               | R <sup>2</sup> |
|-----------|-----------|-----------------|-------------------------------|----------------|
| 0.5       | 1.4       | 2.1             | <b>Fr. = 2.33(Vsg) – 1.67</b> | 0.975          |
|           | 3.3       | 5.7             |                               |                |
|           | 5.1       | 9.5             |                               |                |
|           | 7.5       | 17.8            |                               |                |
|           | 10.3      | 19.6            |                               |                |
|           | 13.6      | 31.3            |                               |                |
| 1.0       | 1.3       | 2.1             | <b>Fr. = 2.23(Vsg) – 1.75</b> | 0.993          |
|           | 3.4       | 5.3             |                               |                |
|           | 4.9       | 8               |                               |                |
|           | 7.8       | 16.1            |                               |                |
|           | 9.3       | 19.1            |                               |                |
|           | 12.2      | 25.5            |                               |                |
| 1.5       | 1.7       | 2.8             | <b>Fr. = 2.14(Vsg) – 1.65</b> | 0.989          |
|           | 3.4       | 5.1             |                               |                |
|           | 5.6       | 9.3             |                               |                |
|           | 8.1       | 15.9            |                               |                |
|           | 9.1       | 18.6            |                               |                |
|           | 10.3      | 20.1            |                               |                |

Table 3.  
 Slug Frequency Correlation for 100% Saltwater, 0.79MPa, horizontal multiphase flow.

| <b>Vsl (m/s)</b> | <b>Vsg (m/s)</b> | <b>Fv (min<sup>-1</sup>)</b> | <b>Fv vs. Vsg</b>       | <b>R<sup>2</sup></b> |
|------------------|------------------|------------------------------|-------------------------|----------------------|
| 0.5              | 1.3              | 16                           | $Fv = 2.07(Vsg) + 17.2$ | 0.95                 |
|                  | 3.3              | 8                            |                         |                      |
|                  | 5.6              | 6                            |                         |                      |
|                  | 7.6              | 2                            |                         |                      |
| 1.0              | 1.2              | 20                           | $Fv = 1.59(Vsg) + 20.8$ | 0.92                 |
|                  | 3.5              | 14                           |                         |                      |
|                  | 5.1              | 12                           |                         |                      |
|                  | 7.4              | 10                           |                         |                      |
| 1.5              | 1.2              | 26                           | $Fv = 3.94(Vsg) + 29.6$ | 0.94                 |
|                  | 3.4              | 14                           |                         |                      |
|                  | 5.3              | 10                           |                         |                      |

**FIGURES**

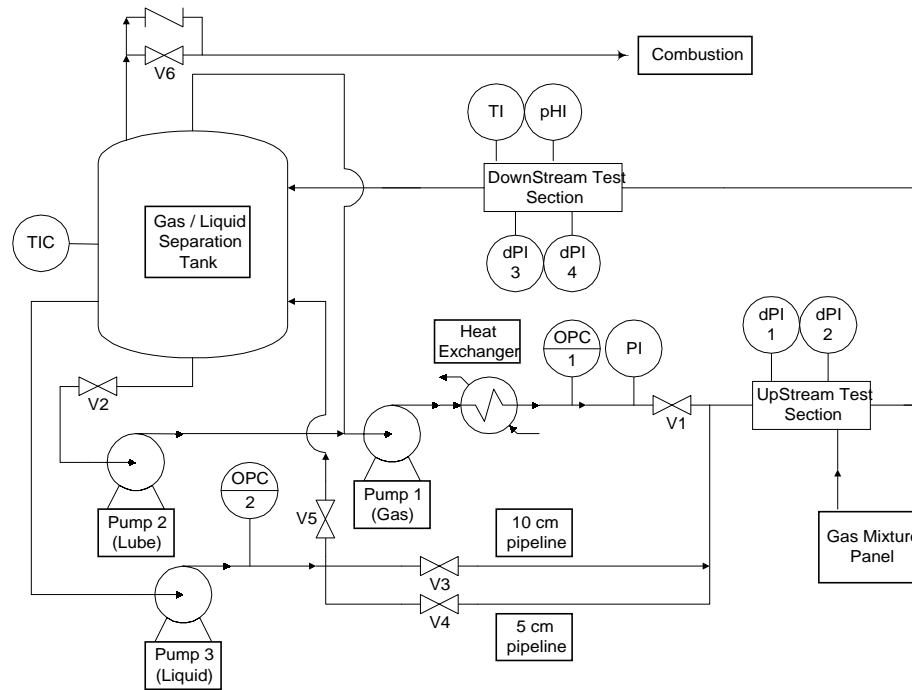


Figure 1. Schematic diagram of Multiphase flow loop (P&ID).

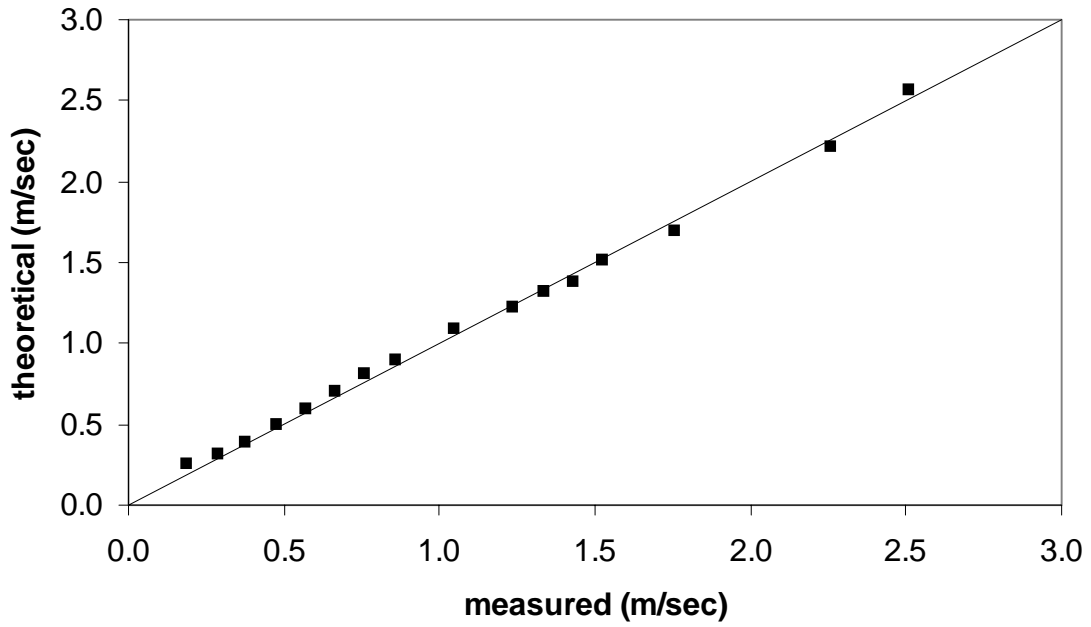


Figure 2. Comparison of Theoretical to Empirical Liquid Pump Flow Rate

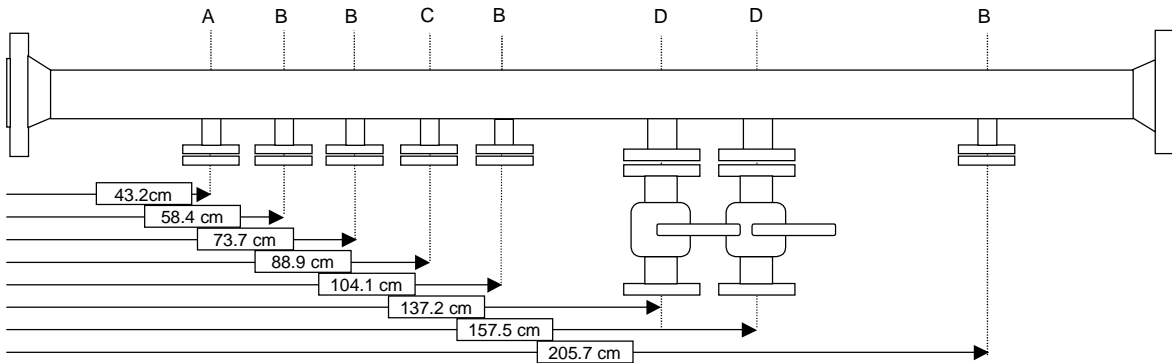


Figure 3. Test Section Layout.

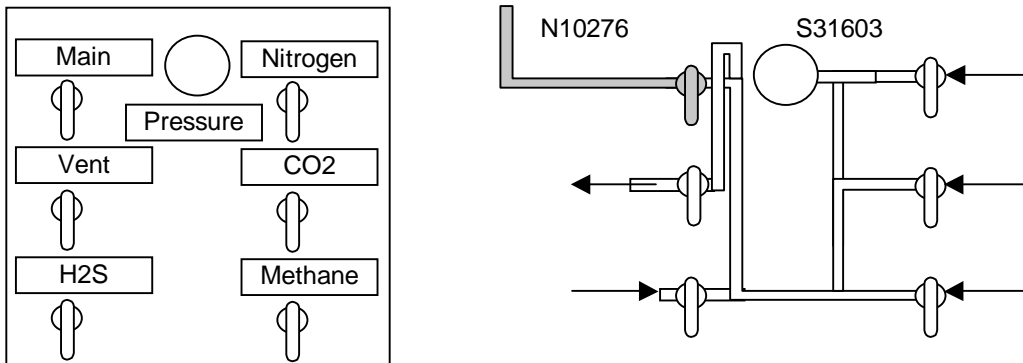


Figure 4. Gas mixture panel and tubing configuration.



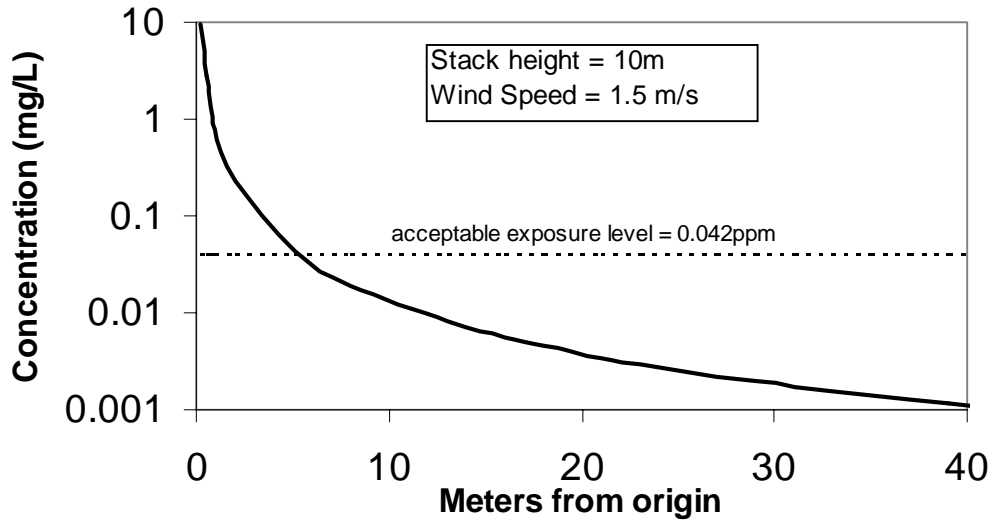


Figure 5. Concentration vs. Distance from Release Point for Hydrogen Sulfide gas

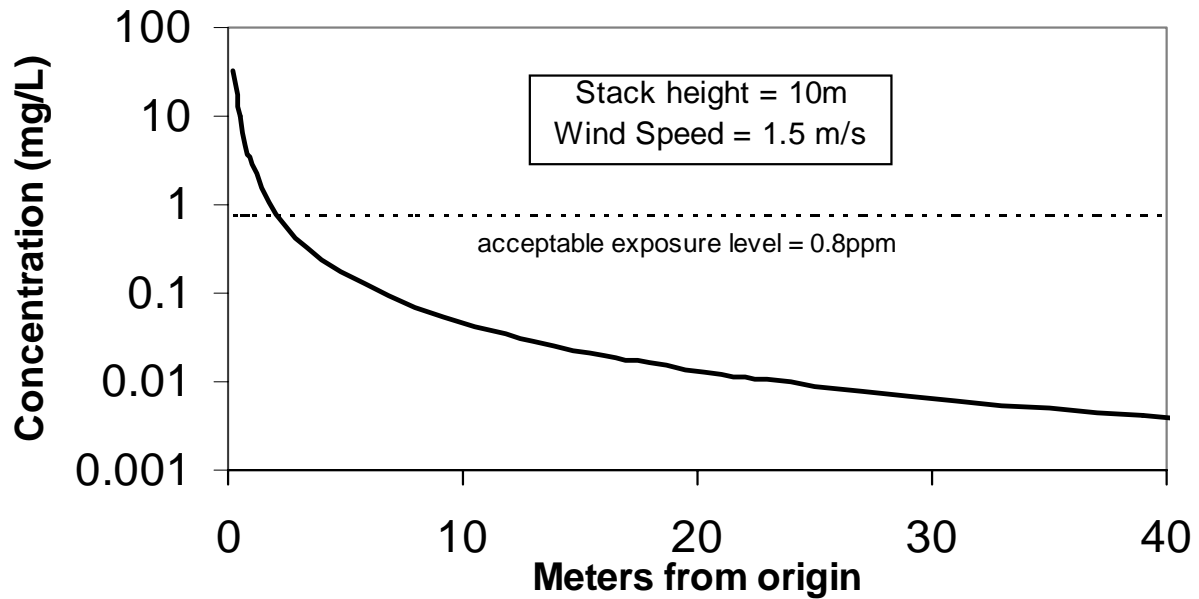


Figure 6. Concentration vs. Distance from Release Point for Sulfur Dioxide gas

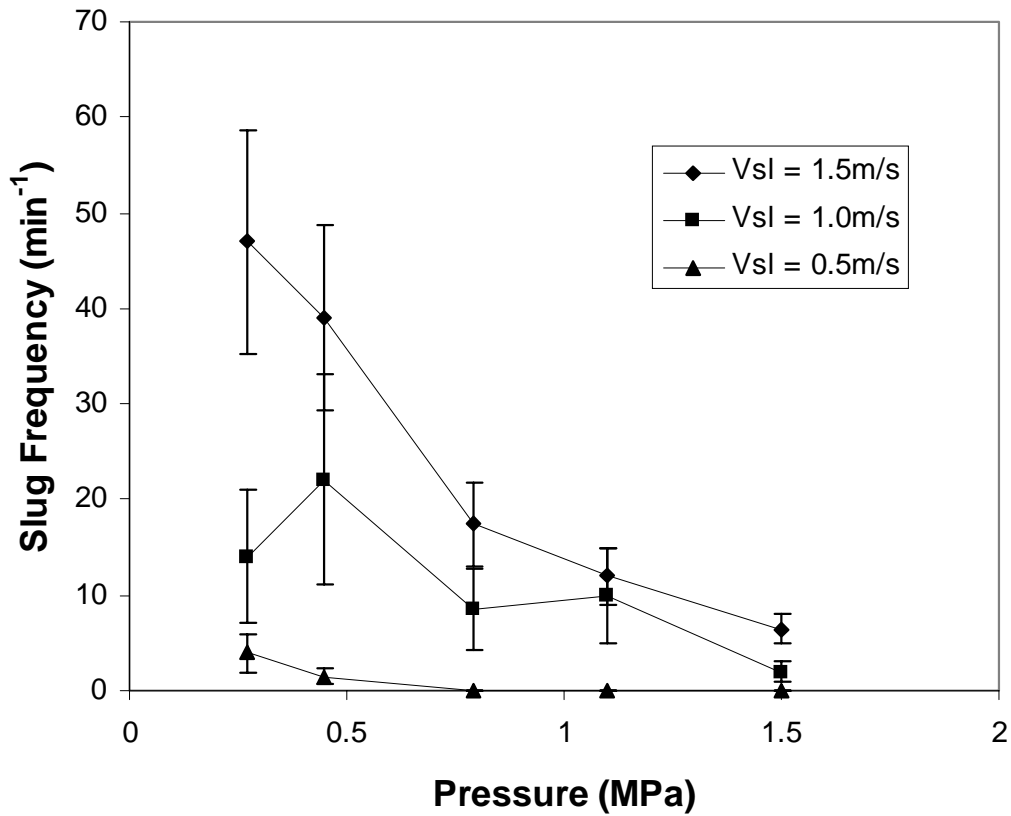


Figure 7. Decrease in Slug Frequency with Increase in Total Pressure.

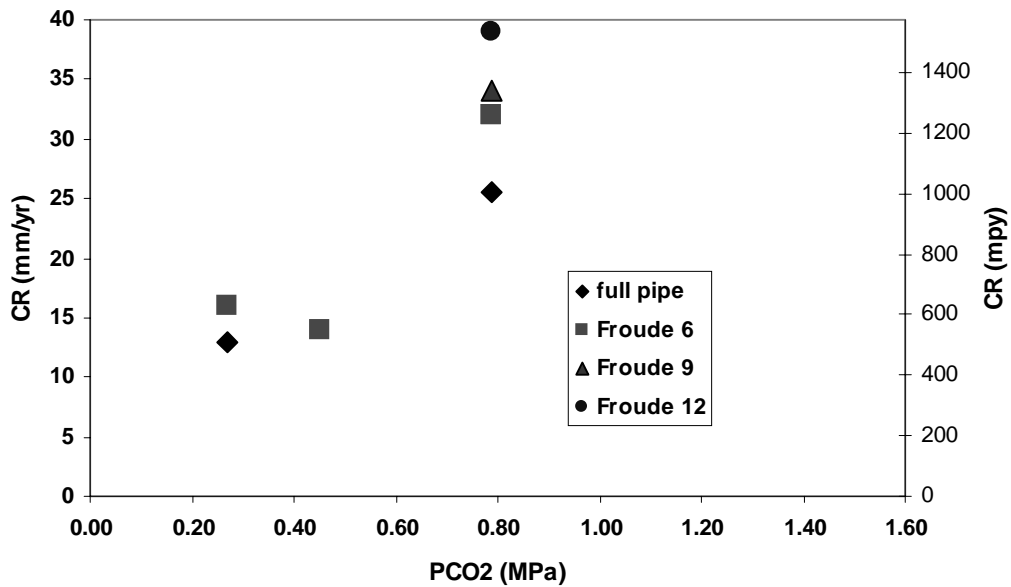


Figure 8. Corrosion Rate in "Standing Slug" Multiphase flow, CO<sub>2</sub> & 100% Seawater, 60°C. (Vuppu, 1994) (Jepson and Bohngale, 1996)

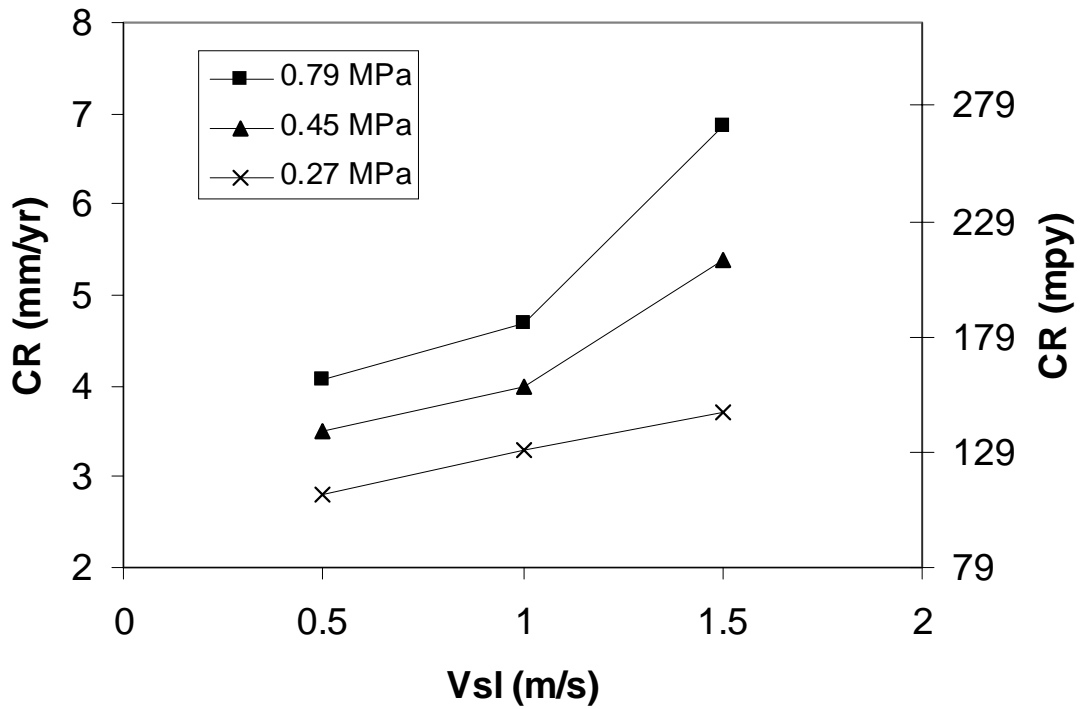


Figure 9. Corrosion Rate in “Moving Slug” Multiphase flow, CO<sub>2</sub> & 100% Seawater, 60°C.

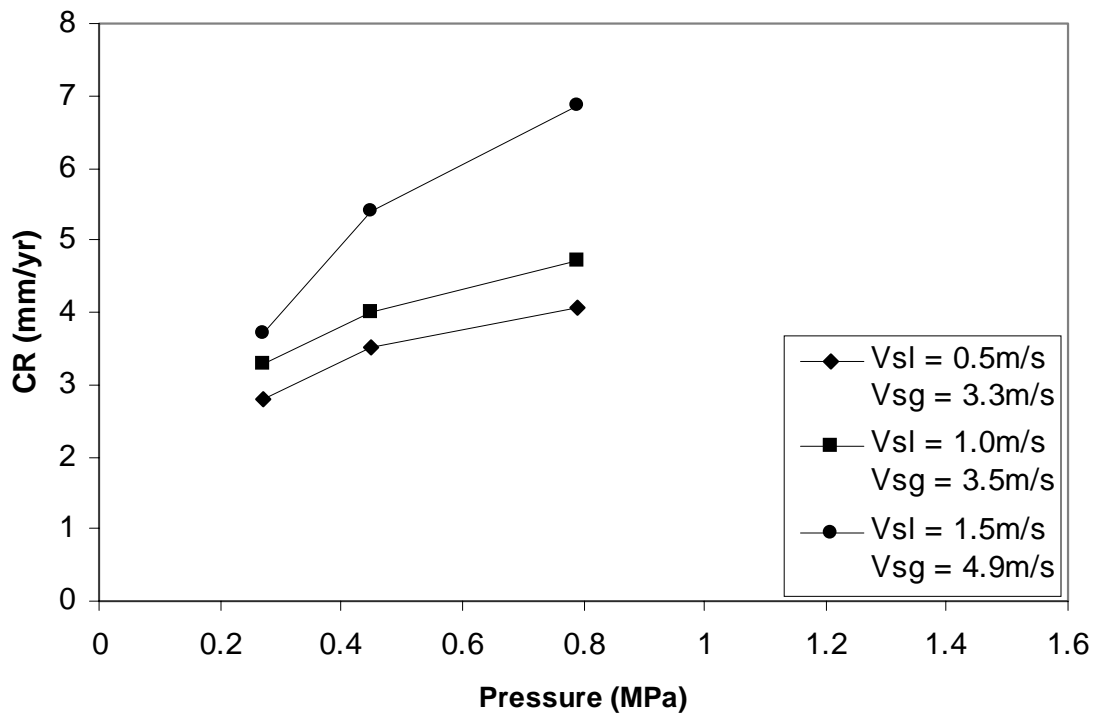


Figure 10. Corrosion Rate From Change in Vsl, Fr. 6 @ 0.45MPa, CO<sub>2</sub> & 100% Seawater, 60°C.