8-A4

LOUISIANA STATE UNIVERSITY
AND AGRICULTURAL AND MECHANICAL COLLEGE
Petroleum Engineering Research
and Technology Transfer Laboratory

September 29, 1993

Mr. Paul Schneider
Technology Assessment and Research
Minerals Management Service
381 Elden Street, MS 4700
Herndon, VA 22070-4817

Re: Progress Report
Contract Number 14-12-0001-30441
"Improved Contingency Procedures for Complications Arising During Offshore Blowout Prevention Operations"

Dear Mr. Schneider:

Attached is the final report for a year three project. This report is titled "Analysis of Injecting Water and/or a Friction Reducing Agent as a Means of Reducing Diverter Erosion During Diverter Operations." This project brings to a close the "Extension to Task 12" project described as Project 2 in the Year Three Funding Proposal dated September 17, 1990.

Reduced diverter line erosional benefits were found to be obtainable with injection of fluids into a dry gas/sand diverted flow stream. However as described in the paper, most of the benefits were identified to be derived from relative flow stream velocity changes in lieu of some form of lubrication or heat reduction effects resulting from the injected liquid/pipe wall contact.

The status of those projects currently funded under Year 4 of the LSU/MMS contract is as follows:

Project 1: **Experimental Analysis of Dynamic Kills for Wells on Diverters (Subtask 3A) (Funding Level: $91,938)**

Objective: To define and model the conditions in which kill fluids begin to move downward and collect in the lower part of the wellbore during kill operations.

3516 CEBA Building • Baton Rouge • Louisiana • 70803-6423 • 504/388-6058 • FAX 504/388-8433

Data collection was completed several weeks ago and is now in the final stages of data analysis. Mr. Yong Wang is currently writing up his thesis concerning the project (Dr. Bourgoyne is the major professor on the project) and is expected to be nearing completion in three weeks. Dr. Casariego was also assigned to the project and was in the development phase of a report to the MMS when he abruptly resigned and left LSU. As I relayed to you earlier, this has put the project behind schedule as far as the write-up is concerned since he had completed extensive literature review, but did not complete the writing before leaving.

Every effort is being made at present to bring the project to a close. The anticipated completion date is November of this year.

Project 2: Development of Improved Fracture Gradient Correlation For Deep Water Drilling Operations (Subtask 8A)

Objective: To develop improved methods for prediction fracture gradients in offshore deep water operations.

This project has been completed as far a research is concerned, but is in its third and final review/revision. It is anticipated that the review will be completed this week and be forwarded to you the following week. On November 17, 1993, portions of this work will be presented by Mr. Rocha at the IADC Well Control Conference of the Americas in Houston, Texas.

Should you have questions concerning the status of any of the above projects, please don't hesitate to call.

Yours truly,

O. Allen Kelly

O. Allen Kelly
Director

cc: A.T. Bourgoyne, Jr., Ph.D
Luis Alberto Rocha
Yong Wang

ANALYSIS OF INJECTING WATER AND/OR A FRICTION REDUCING AGENT AS A MEANS OF REDUCING DIVERTER EROSION DURING DIVERTER OPERATIONS

Principal Investigator: Dr. Adam T. Bourgoyne, Jr.
Associate Researchers: Dr. Vicente Casariego
O. Allen Kelly
Petroleum Engineering Department
Louisiana State University
Baton Rouge, Louisiana 70803-6417

OBJECTIVE:

To determine if the injection of water and/or a friction reducing agent into the diverter flow stream will effectively reduce diverter erosional rates and to determine the mechanism by which water injection alters the erosion rate.

INTRODUCTION:

In marine environments, the unexpected presence of abnormal formation pressures at very shallow depths is one of the most dangerous hazards faced by the drilling industry. When encountering shallow gas while drilling from a bottom supported structure, oftentimes the normal procedure for shutting-in a well due to a gas influx may not apply. In these cases, the shut-in pressures may create downhole pressures that exceed formation fracture. In the event that formation fracture occurs, an underground blowout may result, or worse, the gas might broach to the surface, resulting in a surface blowout.

The normal procedure for handling a threatened blowout from a shallow gas formation is to divert the gas flow away from the rig structure and drilling personnel. This requires the use of a diverter system designed to prevent a pressure build-up within the well bore, minimizing exposure of the weakest formation to fracture. A diverter system is mainly composed by the following elements: a vent line for conducting the flow away from the structure, a means for closing the well annulus above the vent line during diverter operations, and a means for closing the vent line during normal drilling operations.

Operationally, when a shallow gas influx is detected during drilling, the diverter system is activated. The drilling fluid being displaced from the wellbore is then "diverted" away from the rig structure by the simultaneous opening of the vent line and the closing of the annulus. Once the well is unloaded of drilling fluid, a semi-steady state condition is reached such that the formation gas, in combination with produced sand and oftentimes water, is flowing through the vent or diverter line. Although the concept of a diverter system is simple, the design, maintenance, and operation of an effective offshore system is a very expensive and difficult task.

Unfortunately, diverter system failures often occur in real life. These diverter operation failures can generally be attributed to either the erosion of its component parts or to excessively high downhole pressures that lead to formation fracture. Although the use of larger pipe sizes has reduced the risk of high back pressures due to plugging, excessive back pressure can still be generated as a consequence of fluid flowing at or near sonic velocity at the diverter system's exit. Even if the diverter system functions properly at these flow rates, the erosive nature of the entrained formation solids in the flow stream can severely limit the vent line life. Knowing that the erosion phenomenon occurs predominantly in the fittings where the flow changes direction, it becomes obvious that the combination of sonic gas velocities with abrasives laden fluids increase the ability of the fluid stream to erode critical parts of the diverter system.

PREVIOUS WORK:

In the past, erosion studies using flat plates [3,4,5] have shown that the mass of material abraded from a solid surface is proportional to the mass of abrasives striking the solid surface. Erosional rates have been shown to be dependent on the impact angle [5] of the solid particles with the eroding surface. A specific erosion factor, F_e, is often used to express the erosion caused by particle impact. This specific erosion factor is defined as the mass of steel removed per unit of mass of abrasive.

Previous work[1,2], funded by the MMS, conducted at the LSU Petroleum Engineering Research and Technology Transfer Laboratory, resulted in the development of erosional coefficient correlations for abrasives transported by gas or mist, and muds. The specific erosion rate, F_e, of various fittings were experimentally determined. The fittings evaluated included steel elbows, plugged tees, vortex elbows, and rubber hoses. Specific erosion factors for abrasives transported by muds were smaller than those transported by gas by one or two orders of magnitude. These point out that increasing liquid content in the erosional stream eventually will reduce the erosional capability of the stream. This current work focused on the effect of injecting water directly into the diverted flow stream as a means of minimizing the erosional capability of the abrasives contained within the gas flow stream.

Wall thickness rate-of-loss models –

In our previous study, we proposed two equations for estimating the rate of loss in wall thickness for various fittings. One equation was recommended when gas was the continuous fluid which contained the abrasive solids and another was recommended when liquid was the continuous fluid.

- Dry Gas Flow and Mist Flow

The loss in thickness, h_w, with time, t, of a fitting in a diverter system where gas or mist is the transporting fluid is given by the following expression in SI units:

$$dh_w/dt = F_e\, u_{sa}\, [\rho_a/\rho_s]\, [\, u_{sg} / (u_{Ref}\, \lambda_g)\,]^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

- Liquid Flow

The loss in thickness, h_w, with time, t, of a fitting in a diverter system where liquid is the transporting phase is given by the following expression in SI units:

$$dh_w/dt = F_e\, u_{sa}\, [\rho_a/\rho_s]\, [\, u_{sl} / (u_{Ref}\, \lambda_l)\,]^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where F_e is the specific erosion factor, ρ_s is the density of the diverter system's component, ρ_a is the density of abrasive material, u_{sa} is the (volumetric) superficial abrasive velocity, u_{sg} is the superficial gas velocity, u_{sl} is the superficial liquid velocity, u_{Ref} is a reference velocity of 100/m/s, λ denotes the volume fraction (hold-up) and subscripts g and *l* denote the gas and liquid phases present.

Specific erosion factors for mist and gas were obtained for gas velocities in the range of 32 to 222 m/s. Specific erosion factors for abrasives transported by muds were smaller by one or two orders of magnitude. The gap between these extremes could be of practical importance for dampening down the erosion rates of bends in diverter systems. Thus, this first study pointed out the need for additional data involving the simultaneous flow of gas and liquid mixtures as the fluid medium for carrying the abrasives. The initial study also indicated that the fitting became hot enough to smoke and burn paint when a gas-sand mixture was used at high gas velocities. Thus, a question arose as to whether or not water cooling could significantly reduce the observed erosion rates.

EXPERIMENTAL SET-UP AND PROCEDURE:

The experimental set-up and procedure was designed to evaluate the rate of erosion for a wide range of gas-liquid ratios. The test matrix designed focused on (1) determining the effect of externally cooling the target or sacrificial elbow as a means of reducing the erosional rates being observed, (2) evaluating the effect of internal water content on the erosional capability of sand loaded gas/water mixtures, and (3) evaluating the effect of a water-surfactant/lubricant solution on the erosional capability of sand loaded gas streams.

The experimental test apparatus consisted of six major components: (1) a 6-inch diameter gas flow meter station utilizing a 4-inch orifice plate for monitoring the gas (air in this case) flow rate, (2) a pressurized sand hopper instrumented capable of measuring the abrasives mass flow rate, (3) a calibrated liquid injection system capable of flow rates ranging from 10 to 150 gallons per minute, (4) a diverter line pipe, (5) test elbow fittings (or erosional targets) installed at the exit of the diverter pipe to provide a change in flow direction, and (6) a data collection system. Schematics of the model diverter system used for the earlier erosion tests have been presented in previous reports.[1,2] **Figure 1** illustrates the equipment test set-up used

in this study.

Due to safety concerns, the gaseous fluid used in these experiments was air rather than natural gas. Air was supplied by a 1,600-SCF/min compressor connected to the input of the 6-inch metering station. No. 2 blasting sand was the abrasive material for these tests. Liquid fluids were supplied by a triplex pump. The erosional targets were long radius elbows (2.0-inch nominal diameter pipe, 0.154-inch wall thickness) made of seamless carbon steel, ASTM-234, grade WPB.

The test procedure was as follows: (1) A sacrificial elbow was flanged to the exit of the vent line. Air from the compressor was routed throughout the metering station . When required, water flow was supplied by the triplex pump. (2) Once the desired range of steady state gas and liquid flow rates were obtained, the data acquisition system was activated simultaneously as the sand from the pressurized hopper was injected at a given mass flow rate. Also, an observer started a timer and a videotape recorder.

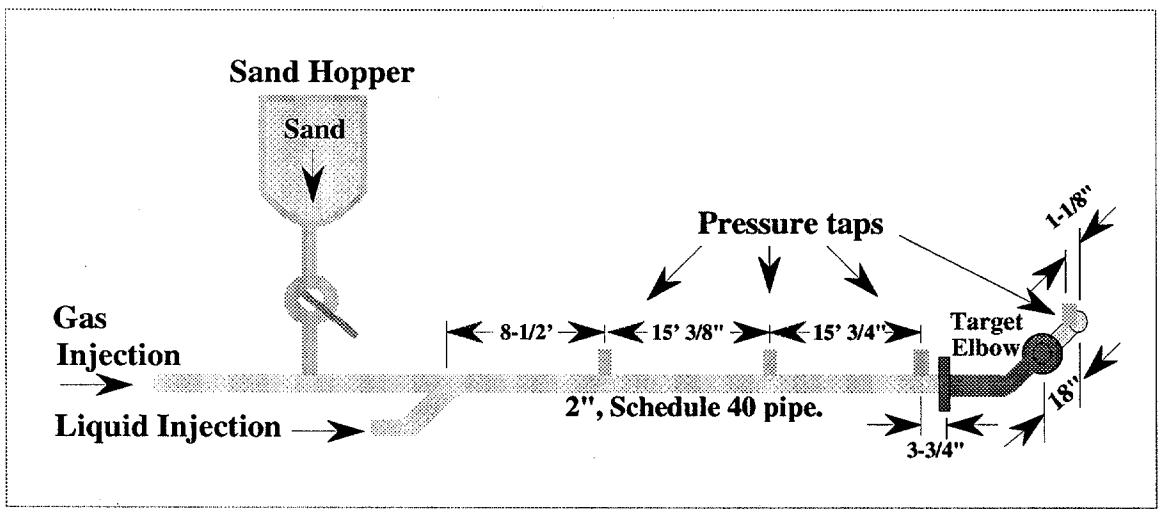

Figure 1. Schematic of model diverter system used for the study of erosional capacity of solids laden fluids.

Data was recorded as a function of time, inclusive of air flow rate, upstream elbow entrance pressure, differential pressure across the elbow, two upstream line pressures, and the sand mass flow rate. Data collection continued for each run up till failure of the targeted elbow was observed.

TEST RESULTS AND DATA ANALYSIS:

The test results have been described by evaluating the potential for reducing the erosion

of the target or sacrificial elbow by (1) the application of an external coolant on the test elbow and by (2) the effect of injecting water or a surfactant/lubricant solution into the diverted erosional flow stream.

Effect of External Coolant –

During times of extreme erosion, when the gas/sand mixture flow rate approaches sonic velocity, it was observed that internal friction caused localized outer elbow wall temperature increases concentrated in the area determined to be the impact zone for the abrasive laden fluid. In an effort to determine the effect of elbow temperature increases to elbow failure as a consequence of erosion, a series of tests were completed to help clarify the effect of temperature on erosion rate. To better define the mechanism by which failure occurred for these tests, external cooling was applied to the elbow to minimize the wall temperature increase which isolated and allowed only the parameter of elbow wall temperature to be altered. It should be noted that water temperatures of ambient and ice water (approaching 32 °F) were used as the cooling medium, representing the temperature range of water available at the rig site.

Three methods were used to cool the sacrificial or target elbows and two methods were utilized to measure the temperature. To cool the target elbows, one method consisted of utilizing a stream of water or an external water spray that was applied tangentially to the external surface area of the elbow bend, while the second and third methods immersed the target elbows in external water baths and external iced water baths respectively. During testing and while cooling the target elbows, a consistent or repetitive gas/sand stream was diverted through the model diverter system to facilitate erosion. Temperature measurements were made by both infrared and thermistor temperature devices; however, the infrared readings for the external coolant tests were excluded from this analysis because of difficulties isolating the temperature of the cooling medium from that of the target elbows.

Appendix 1 tabulates the test data collected for the complete test matrix for this study. Six test runs were made using external cooling and five of the runs have temperature data. The thermistor data is somewhat influenced during external spraying by the water directly hitting the sensor which was strapped directly against the area of predicted elbow failure. When comparing the temperature data taken during test runs that had no internal or external water, it appears that water application, both internal and external, did reduce the elbow outside temperature by at least a factor of 2 to 3. Also when comparing the "Elbow Erosion Factor" data in **Appendix 1**, it can be seen that external cooling made no appreciable difference in erosion.

Figure 2 summarizes the results obtained from the use of external coolants. This plot depicts the measured or actual wear rate ratio as a function of the theoretical wear rate ratio for an average gas flow rate of 62,000-SCFH as was used for these tests. As plotted, the wear rate ratio is defined as the ratio of the experimental erosion rate obtained (external water coolant data in this case) compared to an erosion rate (or standard) obtained utilizing dry gas

as the only transport medium with no external water coolant. Parameters defined by this theoretical average erosion rate, utilizing dry gas as the transport medium, were used in the denominator of the following definitions:

$$\text{Actual wear rate ratio} = (dh_w/dt) / (dh_w/dt)_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

and,

$$\text{Theoretical wear rate ratio} = (u_{sa}\, u_{sm}^2) / (u_{sa}\, u_{sm}^2)_0 \quad \ldots\ldots\ldots\ldots \quad (4)$$

where, the subscript "0" denotes dry gas tests (zero liquid rates in the internal flow stream) and "m" denotes a gas-liquid mixture. For this ratio comparison, the values used in the denominators of the above expressions were defined as follows:

$(dh_w/dt)_0 = 4.56$ E-5 m/s, $(u_{sa})_0 = 0.08710$ m/s, and $(u_{sm})_0 = 234.3$ m/s.

These conditions were average for the dry gas tests conducted as part of this study (see the first section of Table 1).

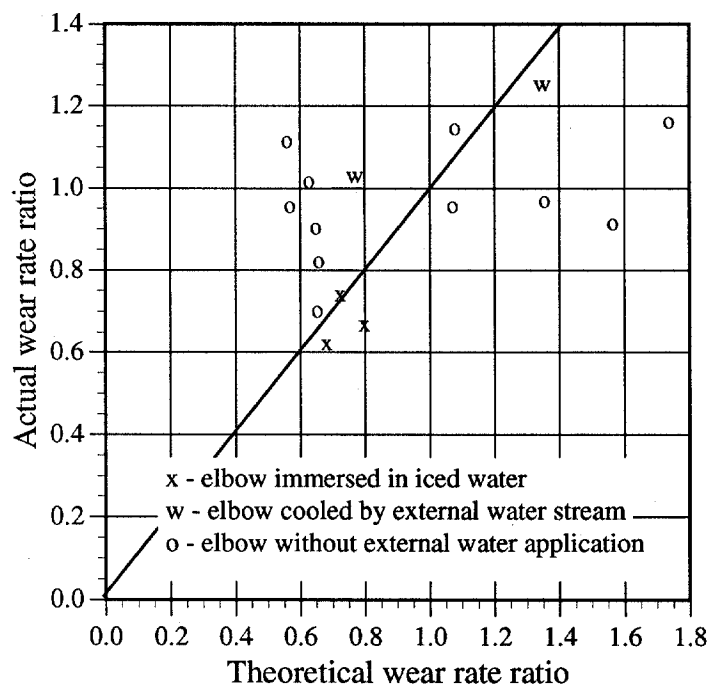

Figure 2. Actual erosion rate ratio as a function of theoretical erosion rate ratio for elbows worn while coolant was externally applied. Average gas flow rate 62,000-SCFH. Average sand rate 1-lbm/s. Diverter system of 2-inch, Schedule 40 pipe.

The line drawn in **Figure 2** represents those ratios where the theoretical (Eqn. 1) and observed data ratios are equal. Should improvements in the wear ratio have been experienced with the water baths/sprays, the external coolant data should have plotted consistently below the 45° line drawn, but they did not. Part of the data with no external coolant was plotted along with the external coolant data and it can be seen that both groups of data demonstrate scatter along the theoretical line. The scatter in the test data is thought to be due to possible variations in the steel properties and in the sand size distribution between runs. The No. 2 blasting sand that was used as an abrasive could not be uniformly mixed on site and was accepted as delivered. The two extreme right points were obtained while using high sand mass flow rates, approximately 2-lbm/s or twice the targeted average used for the remaining tests. These points may reflect interference between particles of abrasive material as discussed in earlier reports.

Effect of water and/or friction reducing agents being injected into erosional streams –

Previous work on erosion of diverter systems indicate that small additions of water in erosive streams could increase the erosion rate of fittings. However, specific erosion factors for fittings being eroded by abrasives being transported by liquids only were smaller by one to two orders of magnitude[1] when compared to erosion factors for abrasives laden dry gas flow streams. The current study was intended to provide sufficient data to better define the effect of water over a wider range of concentrations.

During testing, the base or standard flow averaged gas rates of 62,000-SCFH and sand rates approximating 1-lbm/sec were consistently used as the constants in the diverted flow stream. A series of 14 tests were conducted to establish a adequate statistical benchmark for comparison. **Appendix 1** contains the data collected during these tests.

Once the two-phase tests were completed, similar tests were completed using the same gas and sand rates as before but now water would be injected independently into the flow stream. A series of 26 tests was completed in which water was injected into the flow stream at rates of 26, 45.5, 65, and 100 gallons per minute, representing a water production rate of 891, 1,560, 2,230, and 3,428 barrels per day while producing gas at a rate of 1.49-MMSCFD (Gas/water ratios of 1,670, 953, 667, and 434 SCF/bbl respectively). Again the data for these tests is contained in **Appendix 1**.

A third series of tests was then completed to ascertain the benefits of adding a surfactant/lubricant to the water being injected as a means of minimizing the effects of flow stream friction. An oil based surfactant/lubricant was added to water to yield a 5% solution concentration by volume as recommended by the manufacturer. Again for all tests, average gas rates approximating 62,000-SCFH and sand rates of 1-lbm/sec represented the base or standard flow rates. The surfactant/lubricant liquid solution was introduced into the flow stream of independently run tests at rates of 26, 45.5, and 65 gallons per minute, the same as for the water tests except that the 100-gpm tests were not repeated. A total of 10 tests were

completed using the fluid solution and the test data is documented in **Appendix 1**.

Data Analysis –

When analyzing the data with respect to failure, **Figure 3** demonstrates that the time till failure is greater with increased fluid content in the erosional flow stream. Note that at zero water injection, the time till failure is approximately 100 seconds; whereas with 100 gpm water injection, the time till failure approximates 550 seconds or a 5.5 multiple increase over the time till failure with no water in the erosional stream.

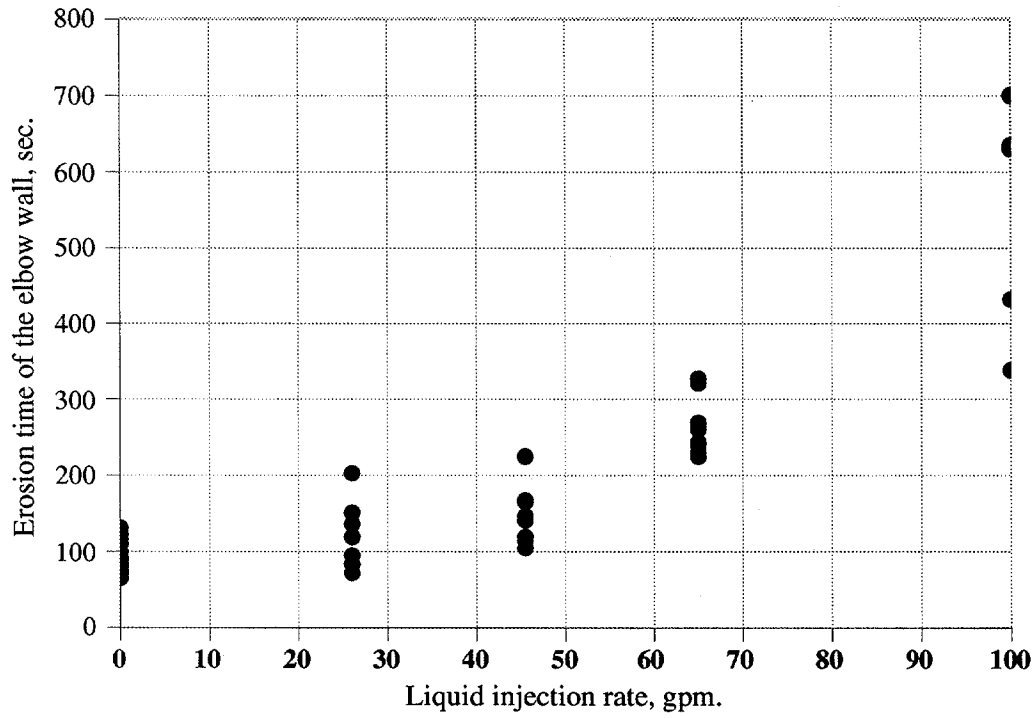

Figure 3: Erosion time versus liquid rate injected into a sand loaded gas stream
ASTM, grade WPB, seamless carbon steel , 2-in. nominal diameter, Schedule 40 diverter system. Elbows with 1.5 curvature radius to pipe diameter ratio.

To better understand the mechanism by which the time till failure increased, shown in **Figure 3**, a plot of "Liquid Injection Rate" versus "Average Velocity of Gas in the Elbow" was made and given as **Figure 4**. Note that as the volume of water injected or rate of injection was increased, the average gas velocity in the elbow decreased. Even though the flow rate of gas and sand referenced at standard conditions did not vary, the velocity varied considerably due to gas compressibility. In essence, the water being injected is acting as a "liquid choke." The pressure inside the diverter upstream of the exit increases with

increasing liquid rate. When comparing the actual velocities inside the target or sacrificial elbows of these tests with earlier tests which did not have internal water injection but were of similar erosional local flow velocity, the erosional factors closely resemble each other. Recalling that erosion rates are a function of the second power of the gas velocity, small changes in gas velocity can cause significant changes in erosion rates.

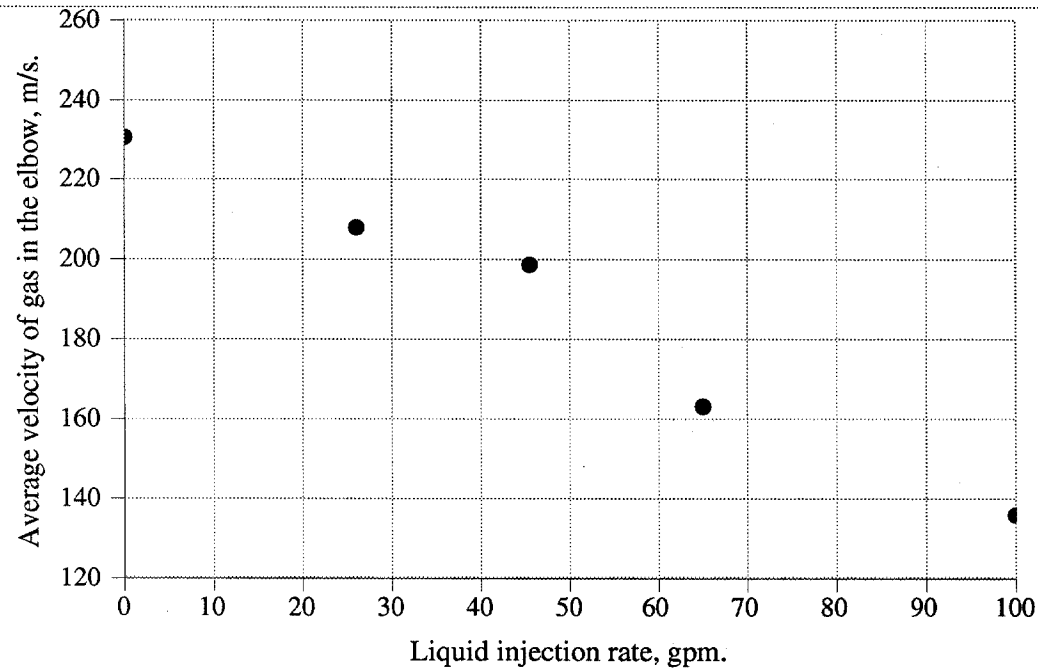

Figure 4: Average gas velocities in the elbow vs liquid injection rate

ASTM, grade WPB, seamless carbon steel, 2-in. nominal diameter, Schedule 40 diverter system. Elbows with 1.5 curvature radius to pipe diameter diameter.

As can be seen from the data in **Appendix 1**, when comparing equivalent liquid flow rates the life span of the elbows eroded by sand laden gas streams containing the surfactant/lubricant solution was in the range of that observed when eroded when injecting plain tap water. In other words, using the surfactant/lubricant mixture did not demonstrate an advantage over using water injection into the abrasive loaded gas streams for reducing erosion. During testing a mist flow pattern prevailed at the high gas velocities (exceeding 0.40 Mach number velocity), typical of a diverter operation. Based on the observed erosional rates obtained, gas/sand streams with a surfactant/lubricant solution appears to have no advantage over injecting only tap water.

Figure 5 is a plot of the data collected relating erosional fluid flow "Liquid Mass Fraction" to the "Specific Erosion Factor"; included are two 100% liquid/sand data points earlier reported by Rohleder.[6] As can be seen, there is data scatter which resulted from small variations in the gas and sand rates, sand size distributions, and steel properties. This figure

shows that the Specific Erosion Factor does not correlate strongly with the liquid mass fraction. No improvements over the use of **Equations (1) or (2)** appear to be possible from correlating the specific erosion factor with liquid mass fraction.

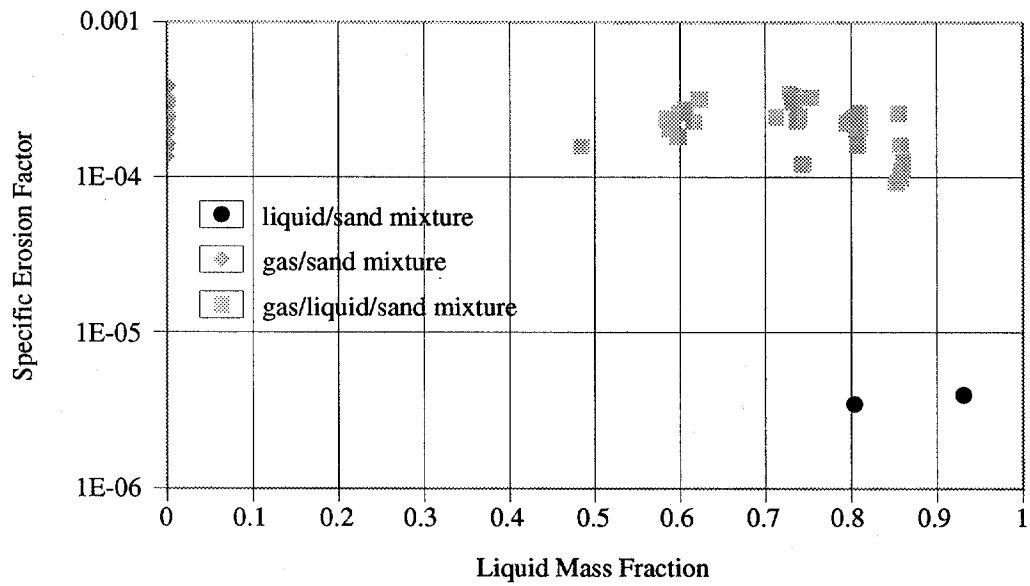

Figure 5: Erosion factor versus liquid mass fraction in the stream.

ASTM, grade WPB, seamless carbon steel, 2"-in. nominal diameter, Schedule 40 diverter System. Elbows with 1.5 curvature radius to pipe diameter ratio.

A statistical analysis of data the collected was done to test for the significance of the differences seen for the various conditions tested. **Table 1** groups the data by category, giving the test type, averages and statistical results.

The variance ratio test (F test) was applied to the pairs of data groups given in **Table 1.** No significant difference was found between the groups of data; therefore, it is valid to apply the Student or t-test in an effort to ascertain if the sets of data belong to the same population. The t-distribution values were determined as a function of the level of significance and the degrees of freedom; the degrees of freedom being defined as the number of samples in the groups minus two and the levels of significance were obtained from t-distribution tables.

The data had a high standard deviation for each group which resulted in a low t-value (i.e., a low probability, or confidence level). The results show that you cannot say with confidence that there is absolutely no effect on specific erosion factors due to internal or external liquid flow or due to the use of a surfactant/lubricant. On the other hand, the results show that you also cannot conclude with confidence there is an effect. However, study of the data clearly shows that there is not a major effect on the specific erosion factor.

Table 1

Statistical Analysis of the Apparent Erosion Factors for the Groups of Tests Made to Evaluate Additives, and Comparison of its Means by the Student, t, Test.

Data Set	Test Group	Number of Tests, n., in the Group	Average Apparent Erosion Factor, Fe. (kg/kg)	Standard Deviation of the Group Based in n-1 Tests (kg/kg)	t-Test, or Student Test by Data Set	Level of Significance from Tabulated Value of t*	Probability the Test Groups belong to the Same Data Set
I	Gas with No External Cooling	14	2.653 E-4	8.657 E-5	0.534	0.607	39%
	Gas with External Cooling	6	2.452 E-4	4.427 E-5			
II	Gas /Liquid Mixture	26	2.389 E-4	11.15 E-5	0.370	0.719	28%
	Gas/Liquid Mixture with Additive	10	2.250 E-4	6.471 E-5			
III	Gas with No External Cooling	14	2.653 E-4	8.657 E-5	0.769	0.458	54%
	Gas/Liquid Mixture	26	2.389 E-4	11.15 E-5			

* From Table 12 of Biometrika Tables for Statistics, Vol I. by E.S. Pearson and H. O. Hartley.

As a final analysis, liquid/sand erosional mixture data, collected and reported by Rohleder,[6] was added to the data set of this study and a composite graph, **Figure 6**, was created. This graph includes test data where the erosional flow stream ranged from a 100% liquid/sand mixture to a gas/liquid/sand mixture with a volumetric gas-liquid ratio of 300 (i.e., 300-ft^3 of gas to 1-ft^3 of liquid). As can be seen, the specific erosion factors are almost two orders of magnitude smaller when no gas is present in the fluid flow stream and when lower velocities are present. Also note that once the volumetric gas liquid ratio approximates 50, shown in **Figure 6**, the erosion factors become reasonably consistent with the average erosional factor falling being between 0.00024 and 0.00026 . When calculating theoretical values for erosion rate for the elbows studied, **Equation 1** can be applied to that part of the graph in **Figure 6** that applies to the horizontal portion or right side of the plot (where gas is

the continuous phase); whereas, **Equation 2** would be applied to the left of the mist flow boundary line shown (where liquid is the continuous phase).

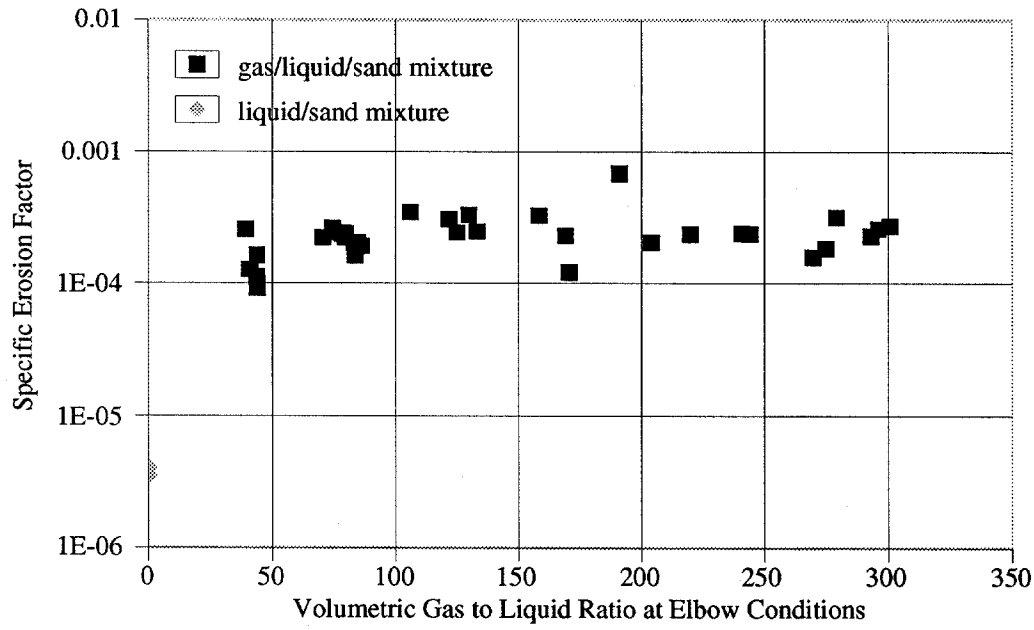

Figure 6: Erosion Factor versus Gas to Liquid Ratio at Elbow Conditions.
ASTM, grade WPB, seamless carbon sreel, 2"-in. nominal diameter, Schedule 40 diverter system. Elbows with 1.5 curvature radius to pipe diameter.

SUMMARY:

The trend of larger life spans for the target or sacrificial elbows with increased liquid content is mainly a function of the increased pressure and reduced velocity of the erosional fluid flow stream. This trend should hold true for inertia dominated flow patterns which are associated with high gas velocities normally encountered in diverter operations.

Relative small additions of water to a erosive gas streams are capable of increasing the life span of diverter system bends. The benefit of decreased erosional rates at the exit of the diverter pipe is mainly obtained from the increased pressure losses of the multiphase stream which can be thought of as choking the gas stream. Therefore, the use of water injection as a method to reduce the erosional capability of a sand laden gas stream must be balanced with the fact that large diameter diverter lines are used to prevent excessive frictional head loads on the exposed formations in the wellbore. The potential benefits and detriments of adding water to the flow stream must be evaluated for the system geometry employed. This can be done using a systems analysis procedure for the diverter and casing system used and for an expected range of formation properties. A computer program for performing the systems analysis has been developed as a separate part of this research.

CONCLUSIONS:

1. **Equations 1 and 2** were verified over a wide range of gas-liquid ratios. However, the use of a different specific erosion factor in **Equation 1** (as indicated in our previous study) for single phase gas flow and for mist flow was not confirmed. The use of a single specific erosion factor for both gas flow and mist flow is now recommended.

2. Compared to water injection, significant additional benefits were not observed by the injection of a friction reducing chemical solution into the erosional flow streams.

3. External cooling of erosional target zones does not appear to be an effective means for reducing erosion, demonstrating that erosion cannot be effectively influenced by external cooling sources readily available at the rig site.

4. Water injection increases the pressure and reduces the velocity inside the diverter line. Reduced fluid velocity results in a lower rate of erosion but increases the pressure at the casing seat. A systems analysis procedure can be used to evaluate the potential benefits and detriments for a given field situation.

NOMENCLATURE

A - Cross sectional area, m.
d - Diameter, m.
f - Fanning friction factor (Laminar flow : f= 16 / Reynolds Number.)
F - Specific factor, g/kg.
h - Thickness, m.
Ma - Mach velocity number.
q - Flow rate, m^3 /s.
t - Time, s.
u - Velocity, m/s.
λ - Fractional volume or holdup.
ρ - Density, kg/$m.^3$

Subscripts

a - Abrasives.
e - Erosion.
ell - Elbow or fitting.
exit - Exit of diverter system.
g - Gas.
l - Liquid.
m - Mixture.
o - Output or exit.
p - Probe.
Ref - Reference velocity that is equal to 100 m/s.
s - Steel,or superficial.
w - Wall.
0 - Zero liquid content, or dry gas.

ACKNOWLEDGEMENTS:

This research work was supported by the U.S. Minerals Management Service, Department of the Interior. However, the views and conclusions contained in this document are those of the authors, and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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Appendix 1*

		Average Elbow Absolute Pressure (Pa)	Average Gas Inlet Temperature (Celsius)	Areal Gas Velocity ...Usg... (m/s)	Areal Liquid Velocity ...Usl... (m/s)	Areal Abrasive Velocity ...Usa... (m/s)	Elbow Erosion Rate (m/s)	Liquid Mass Fraction (d'less)	Elbow Erosion Factor (d'less)	Time Till Elbow Failure (sec)	Maximum Elbow Wall Temperature	
											Infrared Reading (Celsius	Thermistor Reading (Celsius)
No liquid & no cooling of elbow	Run J1	124588.3	62.2	226.18	0.00	1.90E-01	4.40E-05	0	0.000134	89	399	NA
	Run J2	120589.3	72.8	244.34	0.00	1.12E-01	5.51E-05	0	0.000234	71	NA	1092
	Run J3	120589.3	66.7	238.95	0.00	1.89E-01	5.59E-05	0	0.000153	70	NA	NA
	Run J4	121071.9	65.6	235.33	0.00	1.52E-01	4.66E-05	0	0.000164	84	NA	400
	Run J5	124450.4	65.0	228.40	0.00	1.61E-01	6.02E-05	0	0.000212	65	NA	425
	Run J7	120865.1	60.0	229.49	0.00	7.61E-02	5.36E-05	0	0.000396	73	394	NA
	Run J8	131138.3	62.8	218.60	0.00	8.46E-02	4.35E-05	0	0.000319	90	344	NA
	Run J13	129414.6	57.2	214.85	0.00	8.46E-02	4.89E-05	0	0.000371	80	NA	NA
	Run J35	118658.8	57.8	229.22	0.00	1.27E-01	4.60E-05	0	0.000204	85	NA	160
	Run J36	118865.6	56.7	228.72	0.00	6.76E-02	4.60E-05	0	0.000385	85	NA	670
	Run M5	116521.4	53.0	241.17	0.00	8.29E-02	5.22E-05	0	0.000321	75	NA	NA
	Run M6	120658.2	53.0	224.72	0.00	8.88E-02	4.60E-05	0	0.000304	85	NA	NA
	Run M7	119968.8	53.0	235.16	0.00	9.30E-02	4.45E-05	0	0.000256	88	NA	NA
	Run M8	114590.9	53.0	242.70	0.00	9.22E-02	4.66E-05	0	0.000254	84	NA	NA
External water spray	Run J6	115280.3	64.4	247.99	0.00	7.78E-02	4.95E-05	0	0.000306	79	NA	229
	Run J9	129690.4	66.7	219.87	0.00	8.46E-02	3.95E-05	0	0.000286	99	NA	165
	Run J10	127277.2	62.8	219.29	0.00	8.46E-02	3.37E-05	0	0.000245	116	NA	90
External Iced bath	Run J32	118727.7	57.8	231.17	0.00	9.30E-02	3.21E-05	0	0.000191	122	NA	NA
	Run J33	118383.0	57.8	230.74	0.00	8.46E-02	3.56E-05	0	0.000234	110	NA	0
External Water bath	Run J34	120727.2	55.6	224.11	0.00	8.46E-02	2.99E-05	0	0.000208	131	NA	0
Internal water @ 26 gpm	Run J15	135344.1	66.7	218.26	0.81	2.11E-01	5.43E-05	0.48406	0.000158	72	34	NA
	Run J17	155269.9	58.9	177.94	0.81	1.01E-01	2.59E-05	0.59167	0.000236	151	33	NA
	Run J18	174782.1	63.9	165.12	0.81	1.01E-01	1.93E-05	0.58805	0.000204	203	34	NA
	Run J19	148306.2	68.3	194.91	0.81	1.06E-01	3.29E-05	0.58472	0.000240	119	34	NA
	Run J20	146651.5	65.6	197.55	0.81	1.03E-01	3.26E-05	0.58629	0.000238	120	34	NA
	Run M9	130035.1	65.0	222.51	0.81	9.30E-02	2.88E-05	0.59786	0.000184	136	NA	NA
	Run M10	120658.2	64.0	239.72	0.81	9.13E-02	4.66E-05	0.59950	0.000261	84	NA	NA
	Run M11	181952.6	64.0	154.66	0.81	8.46E-02	4.71E-05	0.61128	0.000682	83	NA	NA
	Run M12	120382.5	65.0	243.54	0.81	8.46E-02	4.66E-05	0.60612	0.000273	84	NA	NA
Internal water @ 45.5 gpm	Run J21	162992.1	71.7	177.04	1.42	1.06E-01	2.77E-05	0.71254	0.000243	141	35	NA
	Run J22	166853.1	68.9	172.48	1.42	8.46E-02	2.66E-05	0.73259	0.000308	147	36	NA
	Run M18	151891.5	55.0	183.92	1.42	8.46E-02	3.26E-05	0.73128	0.000332	120	NA	NA
	Run M19	187606.3	55.0	150.20	1.42	8.62E-02	2.34E-05	0.72862	0.000349	167	NA	NA
	Run M20	146031.0	55.0	188.53	1.42	7.86E-02	2.37E-05	0.73890	0.000247	165	NA	NA
Internal water @ 65 gpm	Run J23	198224.3	63.6	142.67	2.02	7.61E-02	1.20E-05	0.80375	0.000223	327	28	NA
	Run J24	178918.9	63.3	161.32	2.02	8.46E-02	1.70E-05	0.79469	0.000223	230	29	NA
	Run J25	173610.0	69.4	158.76	2.02	8.46E-02	1.74E-05	0.80052	0.000236	225	30	NA
	Run M14	179677.4	70.0	159.55	2.02	7.61E-02	1.62E-05	0.80423	0.000241	241	NA	NA
	Run M15	176919.5	71.0	161.24	2.02	7.61E-02	1.63E-05	0.80496	0.000238	240	NA	NA
	Run M16	179056.8	70.5	154.20	2.02	8.03E-02	1.61E-05	0.80421	0.000243	243	NA	NA
Internal water @ 100 gpm	Run J26	210703.8	73.9	135.77	3.11	8.46E-02	6.16E-06	0.85897	0.000112	635	NA	NA
	Run J27	241316.5	69.4	122.59	3.11	8.46E-02	1.16E-05	0.85575	0.000257	338	NA	75
	Run J28	211875.9	71.1	136.33	3.11	8.46E-02	9.05E-06	0.85776	0.000163	432	NA	90
	Run J29	217047.0	71.7	127.65	3.11	8.46E-02	6.21E-06	0.86070	0.000127	630	NA	65
	Run M21	213048.0	71.0	136.86	3.11	9.13E-02	5.58E-06	0.85288	9.23E-05	701	NA	NA
	Run M22	209600.6	70.0	137.09	3.11	8.46E-02	5.59E-06	0.85790	9.95E-05	700	NA	NA
Internal additive 5% @ 26 gpm	Run M23	125484.6	65.5	225.99	0.81	7.44E-02	4.12E-05	0.62349	0.000319	95	NA	NA
	Run M24	125622.5	65.0	237.27	0.81	7.44E-02	3.26E-05	0.61621	0.000229	120	NA	NA
Internal additive 5% @ 45.5 gpm	Run M26	121416.7	54.4	224.28	1.42	6.59E-02	3.73E-05	0.75314	0.000329	105	NA	NA
	Run M27	119830.9	57.2	239.46	1.42	7.61E-02	3.43E-05	0.73751	0.000230	114	NA	NA
	Run M28	122244.0	71.1	241.59	1.42	7.19E-02	1.74E-05	0.74329	0.000121	225	NA	NA
Internal additive 5% @ 65 gpm	Run M30	163681.5	71.0	169.18	2.02	7.61E-02	1.22E-05	0.80768	0.000162	321	NA	NA
	Run M31	163474.7	71.0	174.65	2.02	7.19E-02	1.45E-05	0.80848	0.000191	269	NA	NA
	Run M32	167060.0	65.0	168.06	2.02	7.44E-02	1.47E-05	0.80624	0.000202	267	NA	NA
	Run M33	164508.9	70.0	171.57	2.02	7.19E-02	1.50E-05	0.80928	0.000205	260	NA	NA
	Run M34	185744.8	71.0	150.61	2.02	7.19E-02	1.48E-05	0.81037	0.000262	264	NA	NA

* Observed erosion factors and data for ASTM, Grade WPB, schedule 40 seamless carbon steel elbows in a 2" diverter system. Elbows have a 1.5 curvature radius to pipe diameter ratio.