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Experimental Study of Erosion in Diverter Systems Due to Sand Production

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ABSTRACT

When drilling from a bottom supported structure, the best procedure for handling a threatened blowout from a shallow gas formation is to divert the gas flow away from the structure and drilling personnel. Case histories were reviewed in which failures occurred during diverter operations due to erosion caused by sand production. A model diverter system was constructed to evaluate this problem and provide information that can be used in the design of diverter systems. A number of pipe fittings used at bends in diverter systems were experimentally evaluated. The effect of flow velocity, liquid content, and sand concentration were included in the study.

It was found that very rapid wear can occur at velocities near sonic velocity. Wear rates of 8-in./hr were measured for short radius "Ells." The rate of erosion was found to be about two orders of magnitude higher for gas/sand mixtures than for liquid/sand mixtures. An equation was developed for predicting the wear rate for various field conditions. Recommendations are given for improving the erosion resistance of diverter systems.

INTRODUCTION

Blowouts are among the most dangerous hazards of offshore oil and gas exploration. When a well threatens to blowout, the quick use of properly designed blowout prevention equipment is necessary to avoid harm to personnel and loss of the drilling structure. Well control is especially difficult when a threatened blowout situation occurs at a shallow depth, prior to setting surface casing in the well. Under these conditions, closing the blowout preventers can lead to severe well control complications. If the well is closed at the surface, hydraulic fracturing is likely to occur in an exposed shallow formation due to the build-up of pressure in the well. If one or more fractures reach the surface, the resulting flow can destroy the foundations of a bottom-supported structure (Figure 1).

Tables and illustrations at end of paper.

Because of the difficulties in handling gas flows while drilling at shallow depths, considerable attention should be given to preventing such flows when planning the well and when drilling the shallow portion of the well. Seismic techniques and data from nearby wells can sometimes be used to identify potential shallow gas zones prior to drilling. These data can also be used to estimate formation pore pressures and required mud weights to safely control the well through these zones. If localized gas concentrations are detected by seismic analysis, hazards can sometimes be reduced when selecting the surface well location.

Unfortunately, use of existing technology does not always prevent the occurrence of shallow gas flows. Historical drilling records since 1965 for the Outer Continental Shelf of the Gulf of Mexico indicate that shallow gas flows have been encountered approximately on 1 well out of every 900 drilled. Shallow gas blowouts have accounted for 25% of all blowouts experienced in this area. Thus, contingency plans must be developed to address this possibility. Since 1975, a diverter system has been required for rigs drilling on the Outer Continental Shelf of the Gulf of Mexico. The function of the diverter system is to permit flow from the well to be directed overboard, away from the drilling personnel and rig structure. The essential elements of a diverter system includes:

- (1) a vent line for conducting the flow away from the structure that is large enough to prevent a pressure build-up in the well to values above the fracture pressure.
- (2) a means for closing the well annulus above the vent line during diverter operations, and
- (3) a means for closing the vent line during normal drilling operations.

There has been considerable uncertainty as to the best procedure to follow when shallow gas flows are experienced. Some operators use a contingency plan which calls for a volume of weighted mud to be maintained and a dynamic well kill procedure to be attempted as soon as the well is placed on the diverter. However, a recent study [Koederitz et al., 1987]

has shown that a dynamic kill is usually not feasible with available rig pumps. Also, records available in the Events File of the Minerals Management Service indicate a diverter failure rate of approximately 50% during shallow gas flows.

The three most common modes of diverter failure have been:

- (1) a failure of the vent line valve to open,
- (2) formation fracture due to insufficient vent line size, and
- (3) erosion.

The first mode of failure can be essentially eliminated through proper selection of diverter valves and valve operators followed by periodic maintenance and testing. The second mode of failure can be addressed through proper sizing of vent lines, valves, and fittings, and by selection of an appropriate conductor casing depth [Beck et al, 1987]. The third mode of failure is more difficult to address and is the topic of this paper.

This study was broken into three main parts. First, Available data from several case histories were obtained and reviewed. In the second part of the study, a model diverter system was constructed and experiments conducted to better define the variables affecting the rate of erosion. In the third part of the study, methods for estimating the rate of erosion under various field conditions were developed. Based on this study, recommendations are given for improving the erosion resistance of diverter systems.

REVIEW OF FIELD CASE HISTORIES

Information was collected on 31 wells that encountered shallow gas. Typical locations of erosion type failures are shown in Figure 2 for a simplified diverter schematic. Problems tend to occur:

- (1) at bends in the diverter line.
- (2) at flexible hoses connecting the diverter to the wellhead.
- (3) at valves or just downstream from valves.
- (4) in the wellhead and diverter spool.

The severity of the erosion problems experienced was greatly affected by the quantity of sand produced by the well. When considerable sand was produced, diverter component failures started in the bends and valves and progressed back to the wellhead. The entire wellhead and annular preventer was cut from the well in an extreme case. For this well, sand piles of ten feet in height were reported on the rig floor after the well bridged.

Because of the sensitive nature of the data, available information on most of the field cases identified and studied was very limited. The time elapsed before the uncontrolled flow stopped was not known for three of the cases. Of the remaining 28 cases, two were successfully killed using a dynamic kill procedure shortly after the flow began. In one case, two relief wells had to be drilled before the well could be brought under control. In 25 cases (90%), the well plugged due to borehole collapse. In 14 cases (50%), flow stopped within a one day period. In 22 cases (79%), flow stopped within a one week period.

REVIEW OF PREVIOUS EROSION STUDIES

Erosion can be caused by cavitation, impingement of liquids, or impingement of solid particles. Erosion by impingement of solid particles is the most rapid, and is of primary concern for diverter operations. Previous erosion studies using flat plates. [Finnie, 1967]. [Goodwin, 1969]. [Ives and Ruff, 1978], have shown that the total mass of material abraded from a solid surface is directly proportional to the total mass of abrasives striking the solid surface. Thus, the erosion resulting from abrasive particle impact is often expressed in terms of a specific erosion factor, F_e , which is defined as the mass of steel removed per unit mass of abrasive.

Ives and Ruff [1978], working with 0.15 mm abrasives (100 mesh) and flat steel plates, showed that erosion rate was directly proportional to the velocity of the particles striking the plate, raised to a power. Measured velocity exponents ranged from 2.5 to 1.8, and decreased with increasing steel temperature. It was found that the specific erosion factor varied with the attack angle at which the abrasive stream approached the steel plate. The velocity exponent was observed to vary only slightly with attack angle.

Goodwin et al. [1969], studied the effect of the size of the abrasive particle on the specific erosion factor for particle sizes up to 0.2 mm (about 60 mesh). His data shows that erosion rates increase with particle size up to about 0.1 mm for velocities in the range of 200-300 m/s. Erosion rate remained essentially independent of particle size for diameters between 0.1 and 0.2 mm. The critical particle size, above which erosion rates became independent of particle size, tended to decrease with decreasing velocity.

Tolle and Greenwood [1977], studied the flow of gas/sand mixtures in tubulars for gas velocities of up to 30 m/s. Data was collected on the rate of weight loss of several types of fittings used to accomplish a 90 degree bend in a pipe. He found that weight loss tended to increase linearly with time. Several materials were evaluated for erosion resistance, showing only modest improvements could be achieved through material selection. The use of a larger diameter velocity reduction chamber upstream of the turn was found to be effective in combination with a plugged Tee.

EXPERIMENTAL STUDY

In the current study, two experimental set-ups were used to measure the rate of erosion in various fittings. The first set-up (Figure 3a) was used for mud/sand slurries. Drilling mud flowed from the right side of a partitioned tank to a centrifugal pump, through 20 feet of 2-in. inside diameter pipe, through the fitting being evaluated, and then back into the tank. Flow rates were periodically checked by temporarily closing an equalizing line connecting the left and right sides of the tank. Sand concentration in the mud was also periodically checked by taking a sample from the tank.

The second set-up (Figure 3b) was used for gas/sand and gas/water/sand mixtures. Compressor supplied air flowed first through a flow control valve and 2-in. orifice meter. The flow control valve maintained a constant flow rate by means of a process control computer. Sand was added to the flow stream from a 6000-lb capacity sand blasting pressure pot through a metering valve. The weight of the pressure pot was continuously monitored, and the sand flow rate was determined from the rate of change of weight with time. Water or mud could be introduced downstream of the sand injection point. The mixture then flowed through 56 feet of 2-in. inside diameter line, through the fitting being evaluated, through a 1 foot tail piece, and then exited to the atmosphere.

The fittings evaluated included steel Ells, plugged Tees, Vortice Ells, and rubber hoses (Figure 3c). Weight loss and wall thickness loss were periodically determined during the tests. Wall thickness measurements were made using an ultrasonic method. Thickness profiles were determined along both inside and outside radii of the bends. Data were collected to permit evaluation of sand rate, fluid velocity, fluid properties, and fitting type. The sand used in the experimental tests was No. 2 blasting sand. Grain size distributions measured for several different batches are shown in Figure 4.

Effect of Sand Rate on Erosion Rate

The use of the specific erosion factor, F_e , for characterizing the effect of sand concentration on erosion in pipe bends was evaluated using the data shown in Figure 5. Note that the wear rate was found to be directly proportional to the sand rate for the range of conditions studied. These sand rates were sufficient to result in sand concentrations of up to 0.12%. At high concentrations, significant decreases in the specific erosion factor would be expected due to interference between sand grains. However, the use of a constant value for the specific erosion factor appears acceptable for sand concentrations representative of diverter operating conditions.

Effect of Velocity on Erosion Rate

Experiments were conducted in the current study to determine the effect of velocity on the rate of erosion for velocities of up to 220 m/s. The experimental results are shown in Figure 6. The apparent slope of 2 includes the effect of increasing steel temperature with increasing flow velocity due to the sand particles impacting the wall of the fitting. At very high velocities, portions of the fittings were observed to smoke and begin to turn red due to very high temperature increases.

Effect of Fluid Type on Erosion Rate

Comparison of Specific Erosion Factors, F_e , obtained in similar fittings for mud carried abrasives and gas carried abrasives suggests that erosion rates are lower for mud by one to two orders of magnitude (Table 1). The addition of small quantities of liquid to a gas/sand mixture was found to increase the specific erosion factor. The observed increase was more than would be expected due to the increase in gas velocity caused by the liquid hold-up. The presence of liquid in the system appeared to increase the cutting efficiency of the sand. This was especially true in plugged Tees.

The higher erosion rates for gas is thought to occur because the transfer of momentum from the solids to the fluid is much less efficient. Thus, the solid particles strike the wall of a bend at a much greater angle in gas than in liquid (Figure 7). For ductile materials such as steel, the maximum rate of erosion occurs at an angle of impact with the eroding surface of about 20 degrees. For brittle materials, the maximum rate of erosion occurs at an angle of 90 degrees [Ives and Ruff, 1978].

The addition of liquids to the gas at volume fractions above 5% has been shown to have a large effect on the maximum (sonic) velocity of the mixture [Beck et al, 1987]. At atmospheric pressure, the maximum velocity is reduced from about 300 m/s to about 30 m/s by increasing the liquid fraction to 10%. Since velocity is the most important parameter affecting the erosion rate, the addition of liquids to the flow stream would be expected to have a favorable effect under some conditions.

Effect of Fitting Type on Erosion Rate

Long radius Ells and flexible hoses are currently the most common fittings used to make a turn in a diverter system. The effect of radius of curvature, r , on the specific erosion factor, F_e , is shown for liquid/sand mixtures in Table 1 and for gas/sand mixtures in Figure 8. Note that the erosion factor increases with increasing radius of curvature for liquid/sand mixtures, but decreases with increasing radius of curvature for gas/sand mixtures. Since the expected flow velocity and rate of erosion is much higher for gas flows, the effect shown in Figure 8 is of greater importance in the design of diverter systems. For gas/sand mixtures, the specific erosion factor decreases rapidly with increasing radius of curvature, up to an r/d value of about 9. Above this value, the erosion factor decreases much more slowly with increasing r/d values.

Rubber was found to be less erosion resistant than steel when tested at a common r/d value. However, the expected field performance of flexible rubber hoses is about the same as for steel Ells because of the inherently larger r/d values for flexible hoses.

Specific erosion factors for plugged Tees are shown in Table 1. A plugged Tee was found to be about two orders of magnitude more erosion resistant than a long radius or short radius Ell for dry gas/sand mixtures. When small quantities of water is produced along with the gas, the observed improvements obtained using a plugged Tee drops to about one order of magnitude. When only liquid and sand are present, the plugged Tee is less erosion resistant than the long radius or short radius Ell.

Specific erosion factors for Vortice Ells are also shown in Table 1. The Vortice Ell fitting was found to be superior to all other types for gas/sand mixtures. The pipe just downstream of the Vortice Ell was found to fail more quickly than the fitting. After replacing downstream sections of pipe several times during an extended test, no appreciable wear was noted in the Vortice Ell.

The location of the areas of maximum wear rate for the various fittings studied are shown in Figure 9. For gas/sand mixtures in Ells and flexible hoses, failure occurred on the outside wall of the bend, at a point approximately where the centerline of the upstream pipe would intersect the wall of the bend. For mud/sand mixtures, the point of failure remained on the outside wall of the bend, but moved downstream to a point near the exit of the fitting.

For the plugged Tee and Vortice Ell fittings, the most severe wear occurred near the exit for gas/sand mixtures. However, wear was more uniform with some wear occurring throughout the fitting. No metal targets were used in dead-end portion of the plugged Tees. For runs made with 0.4 bbl/mmscf liquid present in the gas, maximum wear was observed in the dead-end portion of the plugged Tee. This suggests that the use of metal targets can be beneficial. However, field problems have been reported due to metal targets breaking loose and moving downstream. Thus, targets should be designed as an integral part of the fitting.

EROSION RATE EQUATION

Based on the experimental work performed in this study, the following equation is proposed for estimating the rate of erosion in diverter systems:

Gas Continuous Phase (Dry Gas or Mist Flow)

$$\frac{dh}{dt} = F_c \frac{\rho_a}{\rho_s} \frac{q_a}{A} \left[\frac{v_{sg}}{100 f_g} \right]^2 \dots \dots (1)$$

Liquid Continuous Phase

$$\frac{dh}{dt} = F_c \frac{\rho_a}{\rho_s} \frac{q_a}{A} \left[\frac{v_{sl}}{100 f_l} \right]^2 \dots \dots (2)$$

Recommended values for specific erosion factor, F_c , are given in Table 2.

The accuracy of the proposed calculation method was verified using the experimental data collected in this study. A comparison of the calculated and observed erosion rates are given in Table 3. The average error observed was 29%. This was felt to be an acceptable level of accuracy for diverter design considerations. The following example illustrates the use of the erosion equations and the adopted system of units.

Example

Estimate the life of a diverter having an inside diameter of 9.25-in. (0.235 m) and a wall thickness of 0.375-in. (9.525 x 10⁻³ m) for a gas rate of 100 MMSCFD (32.77 m³/s). The last bend in the system is a seamless steel Ell having an r/d value of 1.5. The estimated pressure at this fitting, which is 150 ft (45.7 m) from the exit, is 70 psia (483 kPa) and the design sand rate is 2.12 f³/s (1.0 x 10⁻³ m³/s). The temperature of the gas is 150 °F (66 °C) and the reference temperature is 60 °F (16 °C). The specific gravity is 2.65 for sand and 7.85 for steel.

Solution

The gas flow rate at the fitting is

$$32.77 \text{ m}^3/\text{s} \frac{101 \cdot 66 + 273}{483 \cdot 16 + 273} = 8.04 \text{ m}^3/\text{s}$$

The gas fraction for no liquid (dry gas) and no slip is

$$\frac{8.04}{8.04 + 0.001 + 0} = 0.9999$$

The superficial gas velocity is

$$\frac{8.04 \text{ m}^3/\text{s}}{\frac{\pi}{4} (0.235)^2 \text{ m}^2} = 185 \text{ m/s}$$

The specific erosion factor from Table 2 is 0.89 g/kg or 0.89 x 10⁻³ kg/kg. The Erosion rate from Equation 1 is

$$\frac{dh}{dt} = 0.00089 \frac{2.65}{7.85} \frac{0.001}{\frac{\pi}{4} (0.235)^2} \left[\frac{185}{100(0.9999)} \right]^2 = 2.37 \times 10^{-5} \text{ m/s}$$

The estimated life of the Ell is

$$\frac{9.525 \times 10^{-3} \text{ m}}{2.37 \times 10^{-5} \text{ m/s}} = 402 \text{ s or } 6.7 \text{ min}$$

Equations 1 and 2 were used to estimate the erosion life of various diverter components under a variety of assumed field conditions. Calculated erosion rates for Ells having an r/d of 3.5 and for a sand rate of 0.001 cubic meters per second are shown in Figure 10 as a function of diverter inside diameter and superficial gas velocity. Note that erosion rates increase by two orders of magnitude as velocity increases from 30 m/s to the maximum (sonic) velocity of about 300 m/s. Note also, that for a given sand production rate, the erosion rate decreases with increasing diameter, when referenced at the same velocity. However, the velocity at a bend depends on the pressure as well as the flow rate. Thus, the effect of diverter size on erosion rate at an upstream fitting is quite complex and depends upon a number of factors.

The effect of fitting type on predicted erosion rates is shown in Figure 11. Note that an order of magnitude decrease in erosion rate is predicted for changing from an Ell to a plugged Tee or Vortice Ell.

RECOMMENDATIONS

The data obtained in this study suggests that bends in diverter systems should be avoided when possible. When a bend is required, a plugged Tee or Vortice Ell should be used. A diverter system should be used during a shallow gas flow on a bottom supported structure primarily to provide time for an orderly rig abandonment. When high flow rates are experienced, the diverter system should not be depended upon for an attempt to regain control of the well. The use of sand probes at the diverter exit is recommended as a warning device.

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NOMENCLATURE

- A - Cross sectional area, m²
- f_g - Fractional volume of liquid.
- f_l - Fractional Volume of gas.
- F_e - Specific Erosion Factor, kg/kg
- h - thickness, m
- Q_a - Flow rate of abrasives, m³/s
- v_{sg} - Superficial gas velocity, m/s
- v_{sl} - Superficial liquid velocity, m/s
- ρ_a - Density of abrasive, kg/m³
- ρ_s - Density of steel or wall material, kg/m³
- t - Time, s

| Fluid Type | Specific Erosion Factors (g / kg) | | | |
|--|-------------------------------------|----------------------------------|---------------------------|---------------------------|
| | Cast Steel Ell (r/d = 3) | Cast Steel Ell (r/d = 3.25) | Cast Steel Plugged Tee | Cast Steel Vortice Ell |
| Clay/Water Mud Plastic Viscosity = 6 cp ² Yield Point = 3 lb/100 ft | 0.0014 | 0.0076 | 0.0046 | 0.0028 |
| Air | 1.6 | 1.54 | 0.0255 | 0.0078* |
| Air with 0.1 BBL/MMSCF Water | — | — | 0.064 | — |
| Air with 0.4 BBL/MMSCF Water | — | 1.66 | 0.057 | — |
| Air with 0.1 BBL/MMSCF Mud | — | — | 0.032 | — |

* Failure occurred in pipe wall just downstream of fitting.

Table 1 - Effect of Fluid Type on Specific Erosion Factor For Cast Steel
(ASTM A 216, Grade WBC)

| Fitting Type | r / d | Material | Specific Erosion Factors (g / kg) | | | |
|---------------|-------|-----------------------------|-------------------------------------|-----------|-------------|--|
| | | | Dry Gas Flow | Mist Flow | Liquid Flow | |
| Ell | 1.5 | Cast Steel Grade WBC | 2.2 | 2.8 | 0.001 | |
| | | Seamless Steel Grade A79 | 0.89 | 1.1 | | |
| | 2.0 | Cast Steel Grade WBC | 2.0 | 2.4 | 0.001 | |
| | | Seamless Steel Grade A79 | 0.79 | 0.93 | | |
| | 2.5 | Cast Steel Grade WBC | 1.7 | 2.0 | 0.001 | |
| | | Seamless Steel Grade A79 | 0.69 | 0.77 | | |
| | 3.0 | Cast Steel Grade WBC | 1.5 | 1.65 | 0.0014 | |
| | | Seamless Steel Grade A79 | 0.60 | 0.66 | | |
| | 3.5 | Cast Steel Grade WBC | 1.2 | 1.32 | 0.0076 | |
| | | Seamless Steel Grade A79 | 0.52 | 0.55 | | |
| | 4.0 | Cast Steel Grade WBC | 0.9 | 1.0 | 0.01 | |
| | | Seamless Steel Grade A79 | 0.45 | 0.49 | | |
| | 4.5 | Cast Steel Grade WBC | 0.7 | 0.77 | 0.01 | |
| | | Seamless Steel Grade A79 | 0.40 | 0.44 | | |
| | 5.0 | Cast Steel Grade WBC | 0.5 | 0.55 | 0.01 | |
| | | Seamless Steel Grade A79 | 0.35 | 0.38 | | |
| Flexible Hose | 6.0 | Rubber | 1.00 | 1.22 | 0.02 | |
| | 8.0 | | 0.40 | 0.45 | | |
| | 10.0 | | 0.37 | 0.39 | | |
| | 12.0 | | 0.33 | 0.35 | | |
| | 15.0 | | 0.29 | 0.31 | | |
| Plugged Tee | — | Cast Steel Grade WBC | 0.026 | 0.064 | 0.0046 | |
| | | Seamless Steel Grade WBC | 0.012 | 0.040 | 0.01 | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Vortice Ell | 3.0 | Cast Steel Grade WBC | 0.0078* | | 0.0028 | |

* Failure in Pipe Wall Downstream of Fitting

Table 2 - Recommended Values of Specific Erosion Factor

| Fitting Type | r / d Ratio | Superficial Velocity | | Sand Rate m ³ /s | Specific Erosion Factor kg/kg | EROSION RATE | | | Location of Max Wear, 0 (See Fig 9) deg |
|----------------------|-------------|----------------------|------------|--------------------------------|----------------------------------|--------------|----------|-------|--|
| | | Liquid m/s | Gas m/s | | | Observed | Calc | Error | |
| Seamless Ell | 1.5 | 0 | 32 | 1.74e-05 | 8.87e-04 | 3.74e-07 | 2.59e-07 | -31 | 48 |
| | 1.5 | 0 | 47 | 2.55e-05 | 8.87e-04 | 3.32e-07 | 8.29e-07 | 150 | 48 |
| | 1.5 | 0 | 72 | 4.46e-05 | 8.87e-04 | 1.65e-06 | 3.44e-06 | 108 | 48 |
| | 1.5 | 0 | 93 | 4.93e-05 | 8.87e-04 | 3.70e-06 | 6.76e-06 | 69 | 48 |
| | 1.5 | 0 | 98 | 4.52e-05 | 8.87e-04 | 4.23e-06 | 6.36e-06 | 50 | 48 |
| | 1.5 | 0 | 98 | 5.26e-05 | 8.87e-04 | 4.94e-06 | 7.54e-06 | 53 | 48 |
| | 1.5 | 0 | 103 | 5.32e-05 | 8.87e-04 | 5.29e-06 | 8.30e-06 | 57 | 48 |
| | 1.5 | 0 | 122 | 6.01e-05 | 8.87e-04 | 3.43e-05 | 1.33e-05 | -61 | 48 |
| | 1.5 | 0 | 167 | 7.72e-05 | 8.87e-04 | 3.73e-05 | 3.20e-05 | -14 | 48 |
| | 1.5 | 0 | 169 | 9.44e-05 | 8.87e-04 | 4.77e-05 | 3.99e-05 | -16 | 48 |
| | 1.5 | 0 | 177 | 1.32e-04 | 8.87e-04 | 8.33e-05 | 6.08e-05 | -27 | 48 |
| | 1.5 | 0 | 177 | 1.10e-04 | 8.87e-04 | 7.38e-05 | 5.12e-05 | -31 | 48 |
| | 1.5 | 0 | 178 | 1.09e-04 | 8.87e-04 | 6.52e-05 | 5.11e-05 | -22 | 48 |
| | 1.5 | 0 | 203 | 1.12e-04 | 8.87e-04 | 7.76e-05 | 6.82e-05 | -12 | 48 |
| | 1.5 | 0 | 205 | 1.44e-04 | 8.87e-04 | 7.96e-05 | 8.98e-05 | 13 | 48 |
| | 1.5 | 0 | 222 | 1.14e-04 | 8.87e-04 | 7.01e-05 | 8.30e-05 | 18 | 48 |
| | 1.5 | 0 | 108 | 1.89e-05 | 8.87e-04 | 3.56e-06 | 3.25e-06 | -9 | 48 |
| | 1.5 | 0 | 109 | 2.49e-05 | 8.87e-04 | 5.64e-06 | 6.14e-06 | 9 | 48 |
| | 1.5 | 0 | 108 | 3.63e-05 | 8.87e-04 | 5.29e-06 | 6.22e-06 | 17 | 48 |
| | 1.5 | 0 | 104 | 5.78e-05 | 8.87e-04 | 9.88e-06 | 9.17e-06 | -7 | 48 |
| 1.5 | 0 | 108 | 6.46e-05 | 8.87e-04 | 1.38e-05 | 1.11e-05 | -20 | 48 | |
| 1.5 | 0 | 108 | 7.84e-05 | 8.87e-04 | 1.37e-05 | 1.35e-05 | -1 | 48 | |
| 1.5 | 0 | 107 | 1.12e-04 | 8.87e-04 | 1.43e-05 | 1.89e-05 | 32 | 48 | |
| 1.5 | 0 | 111 | 1.45e-04 | 8.87e-04 | 2.23e-05 | 2.62e-05 | 18 | 48 | |
| 1.5 | 0 | 107 | 2.27e-04 | 8.87e-04 | 3.56e-05 | 3.83e-05 | 8 | 48 | |
| 1.5 | 0 | 106 | 2.40e-04 | 8.87e-04 | 3.26e-05 | 2.99e-05 | 22 | 48 | |
| 1.5 | 0 | 103 | 2.82e-04 | 8.87e-04 | 2.95e-05 | 4.39e-05 | 48 | 48 | |
| Rubber Flexible Hose | 5.5 | 0 | 104 | 1.39e-04 | 4.00e-04 | 8.62e-06 | 1.01e-05 | 14 | 39 |
| | 5 | 0 | 116 | 9.87e-05 | 1.00e-03 | 2.81e-05 | 2.97e-05 | 6 | 25 |
| | 6 | 0 | 103 | 1.52e-04 | 1.00e-03 | 3.25e-05 | 3.19e-05 | -2 | 27 |
| | 6 | 0 | 112 | 1.38e-04 | 1.00e-03 | 3.46e-05 | 3.88e-05 | -17 | 29 |
| | 16.5 | 0 | 105 | 1.37e-04 | 1.00e-03 | 5.28e-06 | 5.62e-06 | 5 | 27 |
| Cast Ell | 3 | 0 | 88 | 1.40e-04 | 7.00e-06 | 1.75e-07 | 1.75e-07 | -1 | EXIT |
| Cast Ell | 3 | 11.49 | 0 | 1.40e-03 | 1.40e-06 | 4.39e-09 | 4.31e-09 | -2 | 85 |
| Cast Ell | 3.25 | 14.63 | 0 | 8.89e-04 | 7.00e-06 | 2.41e-08 | 2.41e-08 | 0 | EXIT |
| Cast Tee | | 12.8 | 0 | 1.08e-03 | 4.00e-06 | 2.65e-08 | 2.61e-08 | -2 | 80 |
| Cast Ell | 3 | 13.99 | 0 | 3.12e-03 | 3.00e-06 | 2.82e-08 | 2.85e-08 | 1 | EXIT |
| Seamless Ell | 1.5 | 9.45 | 0 | 3.75e-04 | 1.00e-06 | 3.42e-09 | 2.55e-10 | -75 | |
| Ell | 1.5 | 14.33 | 0 | 2.86e-03 | 1.00e-06 | 3.42e-09 | 9.78e-09 | 186 | |
| Cast Ell | 2.125 | 0 | 116 | 1.32e-04 | 1.00e-03 | 5.74e-05 | 5.63e-05 | -2 | 41 |
| Cast Ell | 2.625 | 0.53 | 86 | 1.26e-04 | 2.00e-03 | 4.23e-05 | 3.14e-05 | -26 | 46 |
| Cast Ell | 2.625 | 0.53 | 92 | 1.44e-04 | 2.00e-03 | 4.61e-05 | 4.13e-05 | -11 | 46 |
| Cast Ell | 2.625 | 0.12 | 89 | 1.48e-04 | 2.00e-03 | 4.23e-05 | 3.93e-05 | -7 | 45 |
| Cast Ell | 2.625 | 0.53 | 84 | 1.54e-04 | 2.00e-03 | 3.81e-05 | 3.62e-05 | -5 | 45 |
| Cast Ell | 2.875 | 0 | 141 | 7.15e-05 | 1.60e-03 | 3.32e-05 | 3.76e-05 | 14 | 39 |
| Cast Ell | 2.875 | 0 | 107 | 1.54e-04 | 1.60e-03 | 4.94e-05 | 4.66e-05 | -6 | 36 |
| Cast Ell | 2.875 | 0 | 141 | 6.55e-05 | 1.60e-03 | 3.02e-05 | 3.45e-05 | 14 | 36 |
| Cast Ell | 2.875 | 0 | 107 | 1.21e-04 | 1.60e-03 | 4.35e-05 | 3.68e-05 | -15 | 36 |
| Cast Ell | 3.25 | 0 | 111 | 2.08e-04 | 1.35e-03 | 6.15e-05 | 5.78e-05 | -6 | 36 |
| Cast Ell | 3.25 | 0 | 141 | 7.46e-05 | 1.35e-03 | 4.10e-05 | 3.32e-05 | -19 | 36 |
| Cast Ell | 3.25 | 0 | 141 | 3.06e-05 | 1.35e-03 | 1.55e-05 | 1.36e-05 | -12 | 38 |
| Cast Ell | 3.25 | 0 | 148 | 5.78e-05 | 1.35e-03 | 3.20e-05 | 2.85e-05 | -11 | 38 |
| Cast Ell | 3.25 | 0.53 | 72 | 1.58e-04 | 1.50e-03 | 2.25e-05 | 2.09e-05 | -7 | 43 |
| Cast Ell | 3.25 | 0.12 | 84 | 1.95e-04 | 1.50e-03 | 3.88e-05 | 3.41e-05 | -12 | 43 |
| Cast Ell | 3.25 | 0.12 | 92 | 9.64e-05 | 1.50e-03 | 2.54e-05 | 2.05e-05 | -19 | 44 |
| Cast Ell | 3.25 | 0.53 | 107 | 5.41e-05 | 1.50e-03 | 2.33e-05 | 2.42e-05 | 4 | 44 |
| Cast Ell | 4.5 | 0 | 111 | 1.52e-04 | 7.00e-04 | 2.12e-05 | 2.20e-05 | 4 | 35 |
| Cast Plugged Tee | | 0 | 127 | 1.32e-04 | 2.60e-05 | 5.57e-07 | 9.27e-07 | 66 | EXIT |
| | | 0 | 141 | 2.27e-05 | 2.60e-05 | 3.81e-07 | 1.95e-07 | -49 | EXIT&PLUG |
| | | 0 | 141 | 1.46e-04 | 2.60e-05 | 4.73e-07 | 1.25e-06 | 165 | UNIFORM |
| Cast Plugged Tee | | 0.53 | 70 | 6.06e-05 | 6.40e-05 | 3.25e-07 | 3.23e-07 | -1 | EXIT&PLUG |
| | | 0.12 | 76 | 1.90e-04 | 6.40e-05 | 1.06e-06 | 1.18e-06 | 12 | PLUG |
| | | 0.53 | 81 | 1.58e-04 | 6.40e-05 | 5.57e-07 | 1.12e-06 | 100 | PLUG |

Table 3 - Comparison of Calculated and Observed Erosion Rates

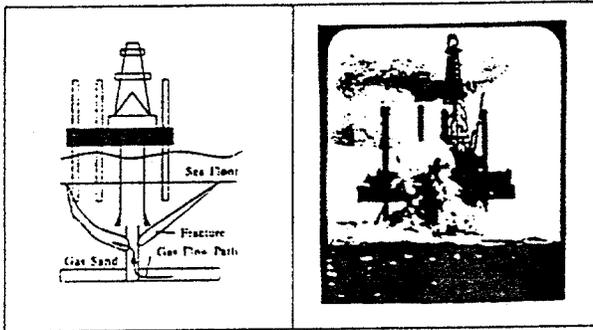


Figure 1 - Example blowout illustrating the need for a diverter system.

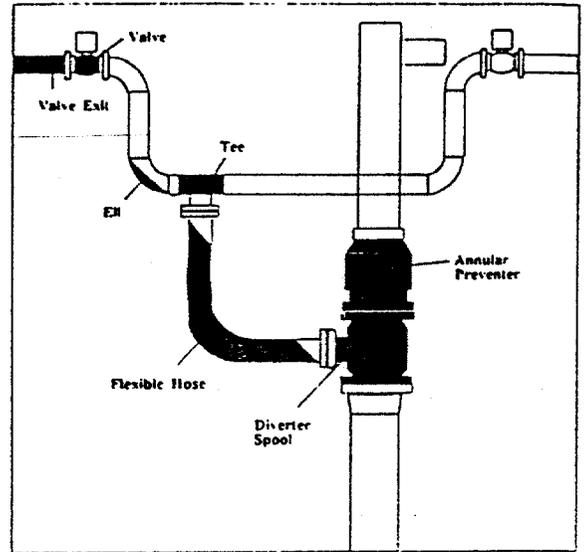


Figure 2 - Typical Locations of Erosive Wear on Diverter System For Bottom Supported Rig

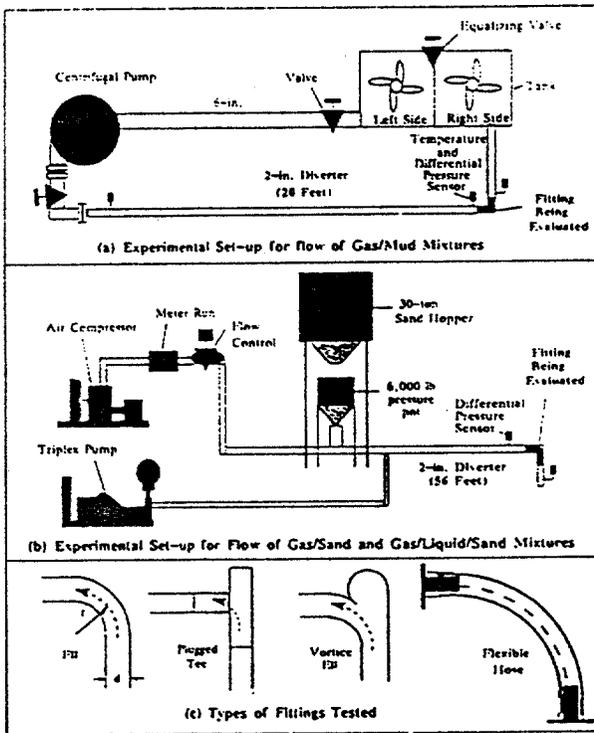


Figure 3 - Schematic of Model Diverter Systems

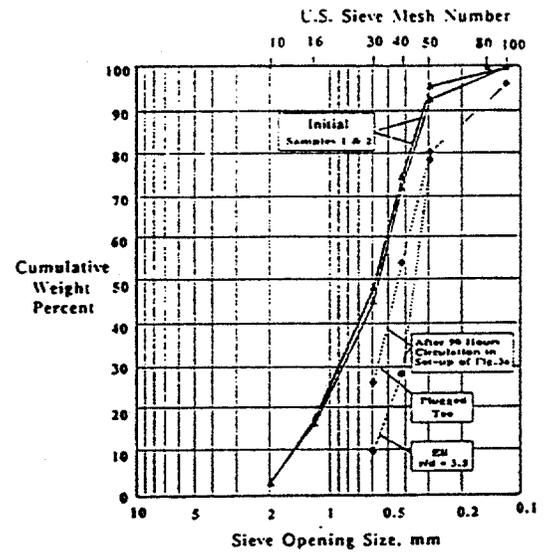


Figure 4 - Grain Size Distribution of Sand Used (Number 2 Blasting Sand)

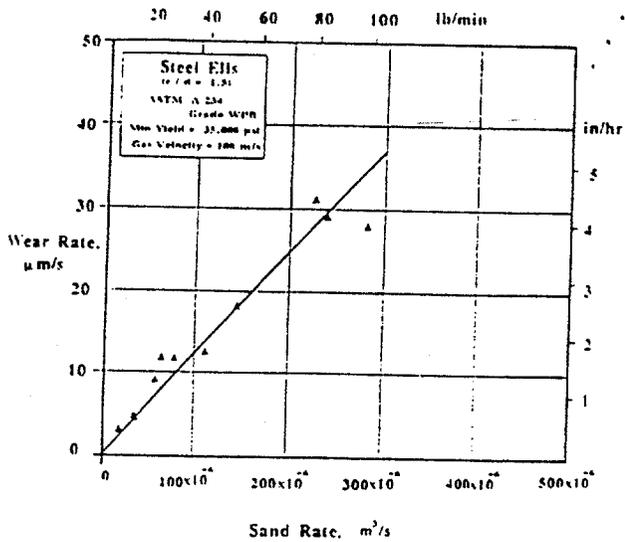


Figure 5 - Effect of Sand Concentration on Rate of Erosion at Gas Velocity of 100 m/s for ASTM A-234, Grade WPR Ells with $r/d = 1.5$ (Number 2 Blasting Sand)

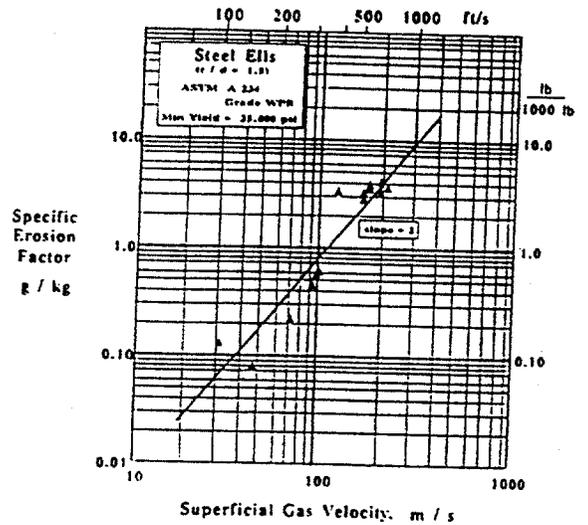


Figure 6 - Effect of Gas Velocity on Rate of Erosion for ASTM 234, Grade WPR Ells with $r/d = 1.5$ (Number 2 Blasting Sand)

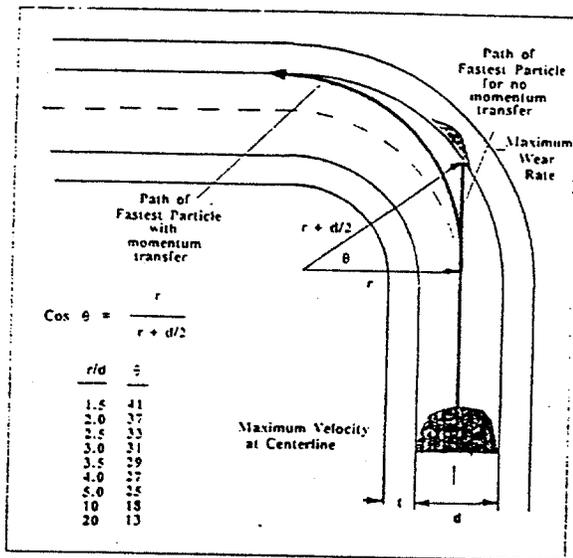


Figure 7 - Typical Wear Pattern for Gas/Sand Mixtures

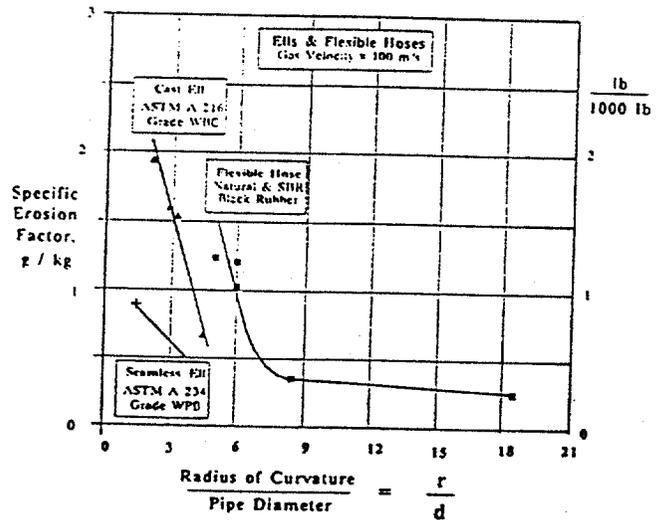


Figure 8 - Effect of Radius of Curvature on Specific Erosion Factor at Gas Velocity of 100 m/s (Number 2 Blasting Sand)

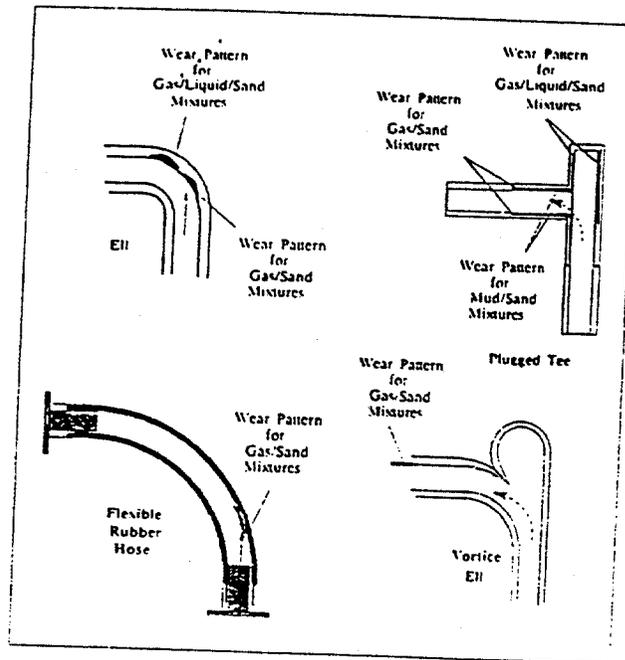


Figure 9 - Location of Points of Maximum Rate of Erosion

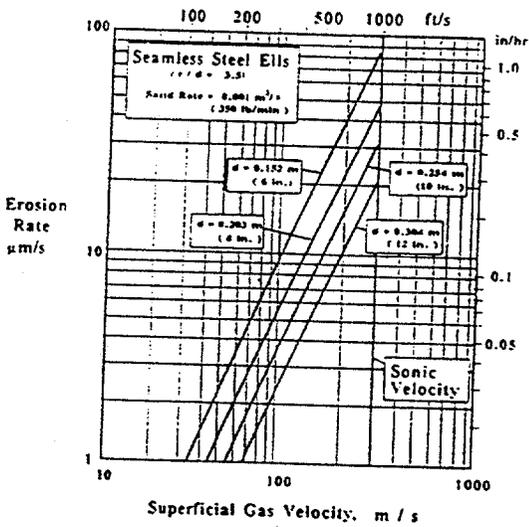


Figure 10 - Effect of Diverter Size on Predicted Erosion Rate

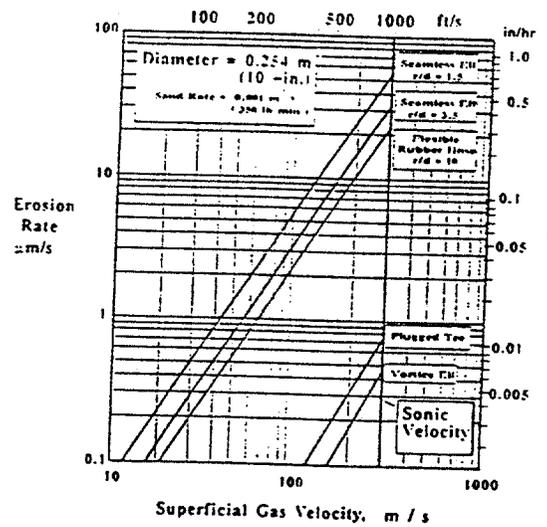


Figure 11 - Effect of Fitting Type on Predicted Erosion Rate