# Effectiveness of Bypass-Pigging Solutions in Multiphase-Flow Pipelines With Waxy Crude Oil: Evaluation and Innovative Solution

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## Summary

Bypass pigging, compared with conventional pigging, reduces the damaging effects of the pig-generated liquid slug by redistributing gas and liquid in the pipeline. Oil- and gas-production rate, high liquid-slug flow to the slug catcher, high pipeline backpressure, and the capacity of the slug-handling facility at the receiving end are major considerations when designing a bypass-pigging solution. Various operational and engineering challenges are encountered while implementing the commonly known bypass-pigging solutions, and empirical correlations are developed on the basis of experimental results and compared with simulation results. This paper suggests an innovative bypass-pig geometry as a solution. The Thornhill-Craver equation is introduced to calculate the bypass-flow quantity and the pig velocity. A comparison between transient-flow simulation and field results showed some deviations. Empirical correlations are developed for prediction on the basis of experimental results. A new convergent/divergent bypass-pig geometry/profile is developed, followed by simplified model development. Through this innovative design, critical and constant gas-flow rate is achieved at lower pressure ratio through the bypass hole, where the gas enters through a nozzle, stabilizes at the throat, and recovers pressure through a diffuser section. At a predefined inlet pressure and area of cross section of the hole, a properly designed convergent nozzle with throat section will give maximum critical flow rate at the exit by reducing the gas pressure to the critical pressure ratio. However, with help from the diffuser section, the high-velocity energy is converted back into pressure energy, and the line pressure regains up to 90% of the upstream pressure. Adopting such a bypass-hole profile with suitable geometry can ensure required bypass-gas quantity through the pig and can avoid pig stalling and minimize process upset, thus ensuring better pipeline cleaning.

## Introduction

Pigging of multiphase-flow pipelines is highly complicated compared with pigging of single-phase-flow pipelines. Bypass pigging, as compared with conventional pigging, reduces the damaging effect of the pig-generated liquid slug by distributing gas and liquid in the pipeline. Allowable oil- and gas-production rate while pigging, high liquid-slug flow to the slug catcher, high pipeline backpressure, and the liquid-withdrawal rate/capacity of the slug-handling facility at the receiving end are major considerations for designing a suitable bypass-pigging solution. Most of the time, bypass pigging is not fully effective in waxy crude oil because of blockage of the bypass holes with wax.

Various operational and engineering challenges while implementing the commonly known bypass-pigging solutions include prediction of pig velocity, pig-generated slug volume, slug duration, backpressure increase in the pipeline, and process-plant upset. Control of these parameters is very difficult during bypass-pigging operations because of its transient nature. The fluid behavior through bypass holes, subsequent downstream flow regime, and the nature of turbulence are unknown. Transient modeling and simulation results of bypass pigging with help of the OLGA Dynamic Multiphase Flow Simulator (available from Schlumberger) do not match with actual field results. Wax blockage of bypass holes also leads to erroneous results. In this paper, efforts are made to develop empirical correlations to approximate various parameters on the basis of experimental results in comparison with simulation-model prediction. Later, an innovative bypass geometry/profile is proposed and designed, and experimental results are evaluated.

## Fluid-Flow Modeling and Dynamic Pig Modeling

Understanding the motion of pigs and pig trains in pipelines is important, in general, to avoid surprises. Missed inspection data, damage to pigs, or, in the extreme case, fatality caused by high speeds lead to the need to understand pig acceleration, peak velocity, and how the pig or train might be brought under control.

**Gas-Velocity and Pig-Velocity Calculations.** It is generally believed that in multiphase-flow pigging without bypass, the pig velocity is equal to the gas-stream velocity. Though this assumption is a fairly good approximation, the actual pig velocity is slightly lower than the gas velocity/mixture velocity in a long-distance pipeline. The initial pig velocity is high compared with the latter part of its travel because the pig generated liquid displacement. The pig speed is generally calculated on the basis of the ideal-gas law acoss a control section, as follows:

$$\left(P_1 \times V_1\right) / n_1 \times z_1 \times R \times T_1 = \left(P_2 \times V_2\right) / n_2 \times z_2 \times R \times T_2 ;$$

$$Actual\ Velocity = V_2 / A \text{ , } \quad \text{(1)}$$

where $P_1$ is the initial pressure (standard pressure condition) in bara; $P_2$ is the final pressure (actual pressure condition) in bara, $V_1$ is the initial volumetric-flow rate (standard volumetric rate) in $m^3/s$, $V_2$ is the final volumetric-flow rate (actual volumetric rate at pressure) in $m^3/s$, $T_1$ is the initial (standard) temperature in °R, $T_2$ is the final (actual) temperature in °R, $n_1$ and $n_2$ are the number of moles of gas at different pressures, $A$ is the area of the pipeline in $m^2$, $R$ is the gas constant, and $z_1$ and $z_2$ are the compressibility factors at different pressures.

Eq. 1 gives the superficial gas velocity, which can be approximated to the pig velocity in the pipeline without bypass. With bypass, the pig velocity will be different and shall be calculated by reducing the bypassed-gas quantity, as discussed in the following subsection.

**Pig-Motion Analysis.** The pig-motion analysis shows the following results (Tiratsoo 1999):



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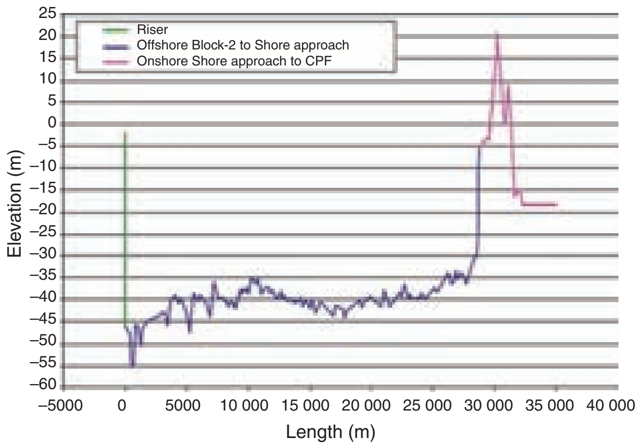



**Fig. 1—Typical 30-in. pipeline-elevation profile. CPF = central processing facility.**

$$\Delta P_p = C_D \times \rho \left(V - V_p\right)^2 / 2 = \left(C_D \times \rho \times V_d^2\right)/2 \text{ , } \quad (2)$$

where $P_p$ is the pressure difference across the pig, $C_D$ is the drag coefficient of the pig, $\rho$ is the density of the transportation medium in kg/m$^3$, $V$ is the velocity of the transportation fluid in m/s, $V_p$ is the velocity of the pig in m/s, and $V_d$ is the velocity difference between the fluid mixture and the pig in m/s.

The $C_D$ depends to a large extent on the size of the end disks of the pig and the degree of seal provided by the end disks. Accurate determination of $C_D$ requires testing of prototype capsules in a pipe. The Kosugi equation, as follows, can predict $C_D$ to within a 20% error margin:

$$C_D = 4k_d^4 / \left(1 - k_d^2\right)^2 \text{ , } \quad (3)$$

where $k_d$ is the disk-diameter ratio (diameter of the end disk divided by the internal pipe diameter while the pig is inside the pipe). In the case of a bypass pig, an effective disk diameter is calculated by reducing the bypass opening area. Hence, for a bypass pig, the disk-diameter ratio will be smaller, and correspondingly, the drag coefficient of the bypass pig will be smaller compared with a pig with no bypass of similar size. This will result in a lower pressure drop across the pig and also a reduced drag force. The drag force is calculated for a known cross-sectional pipe with area $A$, as follows:

$$F_D = A \times C_D, \quad (4)$$

where $F_D$ is the drag force in Newtons.

The pig moves at a constant velocity $V_p$ through a pipeline. Because of the presence of large contact friction between the pipe wall and the pig disks, the pig moves at a velocity that is less than the mean flow velocity of fluid.

$$V_d = V - V_p, \text{ or } V_p = V - V_d \text{ . } \quad (5)$$

During steady-state motion, the drag force $F_D$ is equal in magnitude, but opposite in direction, to the contact friction force $F_f$,

$$F_D = F_f = \eta \times N \text{ , } \quad (6)$$

where $N$ is the total normal force (Newtons) that the pig exerts on the pipe in the radial direction (scalar sum of forces) and $\eta$ is the contact friction coefficient. $N$ can also be considered as the weight of the pig.

From the pig-motion analysis and Newton's second law of motion, the following results can be obtained for the horizontal length of pipeline (Liu 2003):

$$V - V_p = V_d = \sqrt{\left(2 \times \eta \times N\right) / \left(C_D \times \rho \times A\right)} \text{ . } \quad (7)$$

**Calculation of Bypass-Gas-Flow Quantity.** In multiphase flow, though it is a mixture of oil and gas, it is generally assumed that the bypassing-gas quantity only will be calculated. The quantity of gas bypassed is a function of the pressure differential across the pig and the area of cross section for bypass. The larger the differential pressure across the pig, the higher the volumetric-flow rate. The gas-flow rate is given by the Thornhill-Craver equation through a choke/square-edged orifice, as follows:

$$Q = 155.5 \times C_d \times A_o \times P_1 \sqrt{\frac{2gk / (k-1) \times \left(r^{2/k} - r^{(k+1)/k}\right)}{S_g \times T_g}} \text{ , } \quad (8)$$

where $Q$ is the bypass-gas-flow rate in MMscf/D, $r = P_2/P_1$, $S_p$ is the specific gravity of gas, $A_o$ is the area of the cross section of each bypass hole/orifice in square inches, $P_1$ is the initial pressure in psia, $P_2$ is the final pressure in psia, $T_g$ is the temperature of gas in °R, $k$ is the specific-heat ratio $C_p/C_v$, and $C_d$ is the coefficient of discharge (accounts for the hole geometry and multidimensional-flow effects).

**Pig-Velocity Reduction Because of Bypass.** The bypass-pigging solution for single-phase fluid (liquid or gas) is generally clean in nature and is predictable to a good extent. Bypass pigging becomes complicated when the flow is multiphase, and all the more complicated when the crude oil is waxy and wax crystallization and precipitation/deposition starts on the pipe wall. This is evident from field experience, where in several cases, the bypass holes are being plugged by wax. The chance of bypass-hole blockage is high when the holes are small and peripheral because the scraped-out sticky wax could plug the holes easily (Lee et al. 2012; Minami and Shoham 1995).

## Experiments and Simulations

**Empirical Correlations Based on Field-Study Results.** Correlations to determine the pig travel time on the basis of the production flow during pigging, the speed reduction because of bypass, the expected slug reduction with help of bypass, and the backpressure conditions in the pipeline can be evolved with a correlation developed from experimental results.

The liquid holdup in a long-distance pipeline is a function of the gas/liquid ratio prevailing in the pipeline, which is an indication of production level. Gas/liquid ratio has an inverse relation with the liquid holdup. On the basis of the liquid holdup in the pipeline, the backpressure starts increasing earlier or later while pigging. A simple correlation for the inventory collected during pigging is proposed in this paper. Empirical equations were developed to describe the flow characteristics of a bypass pig. The slope of best fit was performed. Regression fit is developed on the basis of the data by use of a straight-line model: $Y = m X + C$.

**Field and Experimental Description. Figs. 1 through 3** show a typical long-distance, offshore subsea-pipeline profile and pigging operation set up in the field. The subsea pipeline transports multiphase fluid (oil, gas, and water with small sand and wax particles) from wellhead platforms to the nearest block-collection platform. From the block-collection platform, the multiphase fluid is transported to the onshore processing plant through a subsea-trunk pipeline. The offshore riser portion is on the order of 30 to 40 m in length. The flow-pipeline profile has high potential for slugging at suboptimal flow rate.

Fig. 1 provides the elevation profile of a typical 30-in. subsea pipeline, which starts, from the top, at 20 m above the sea level. The approximate water depth in the area is 25 m. The pipeline terrain is nonuniform. Various colors are used for indicating the riser and the offshore and onshore portions of the pipeline. The receiving end also has a very bad profile, which leads to severe slugging phenomenon.

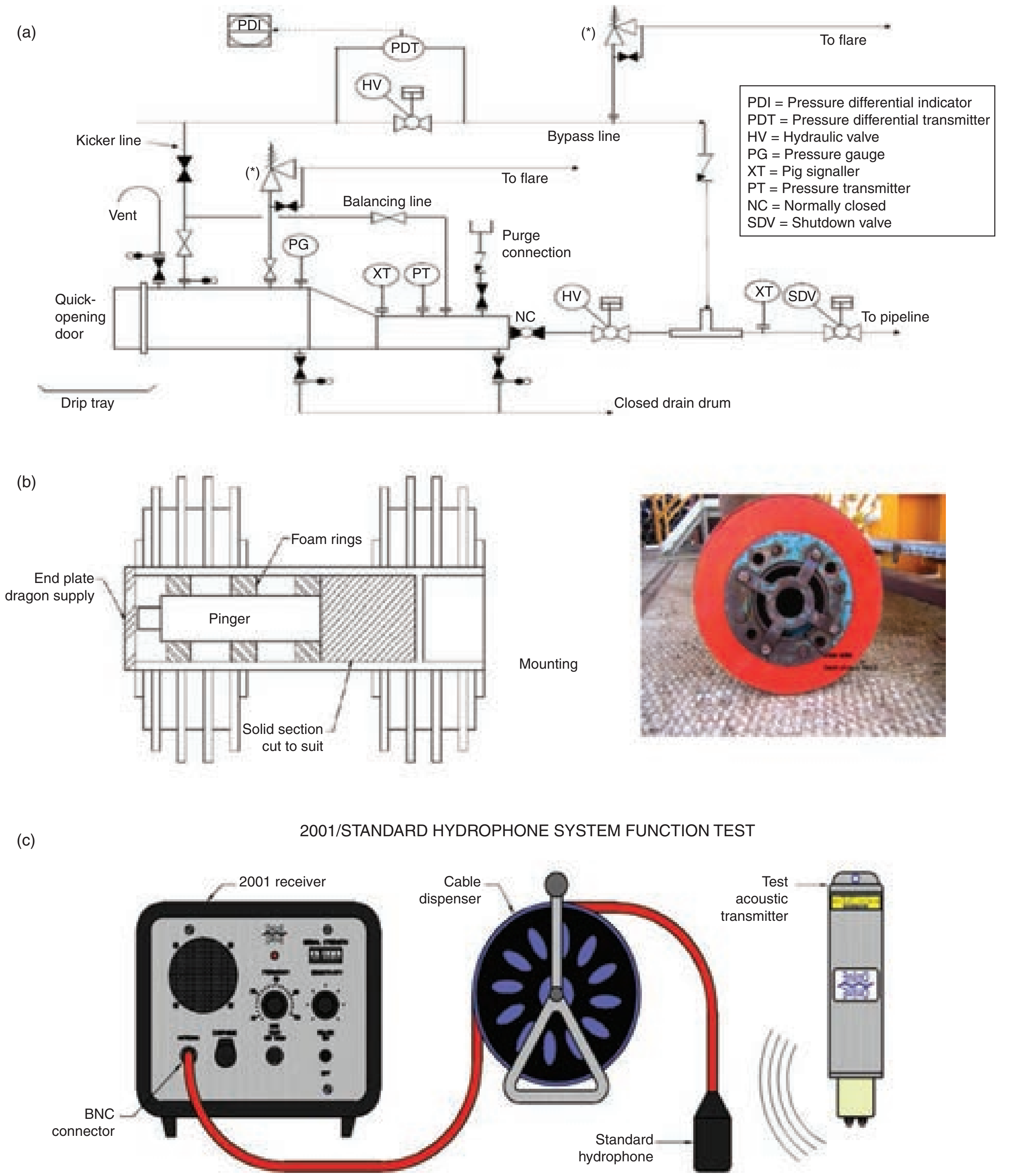



**Fig. 2—Pigging operations and tracking setup: (a) pigging-system setup with pig launcher/receiver and pipeline manifold, (b) data-monitoring and -acquisition arrangement with pinger, and (c) pig tracking unit.**

Fig. 2 shows an overall field arrangement for pigging operations. There are three main facilities for carrying out a successful pigging operation. The first facility is the pig-launching and -receiving system with pipeline manifold. Next is the instrumentation and data-acquisition system for collecting and recording valuable field data during actual operation, and the third is the advanced pig-tracking system for monitoring pig movement inside the pipeline.

Fig. 3 shows the field-flow schematic of a general pigging operation.

Key drivers of pigging in a system are wax and sand control, especially during winter conditions when the fluid temperature drops below the wax-appearance temperature.

Mechanical-pigging operation is a regular and vital flow-assurance tool in the field. Normal bidirectional bypass pigs are

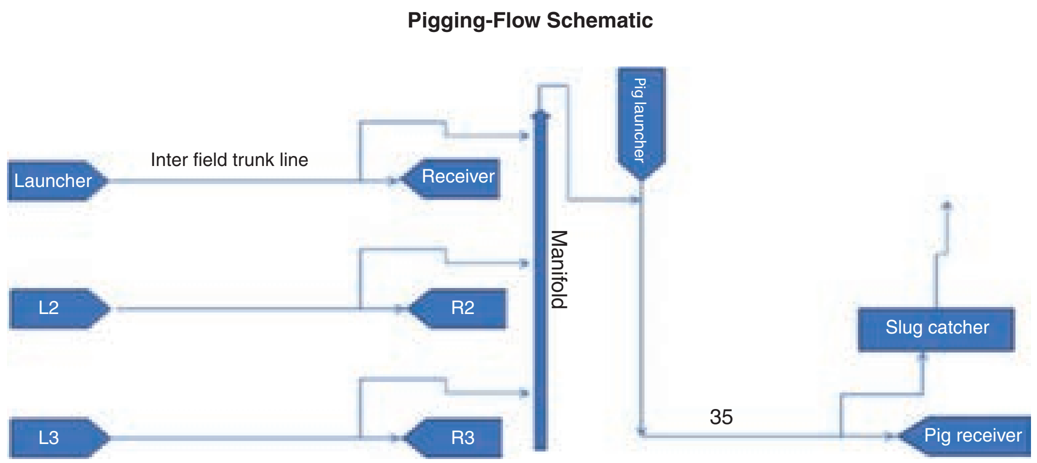



**Fig. 3—Offshore pipeline-pigging-flow scheme.**

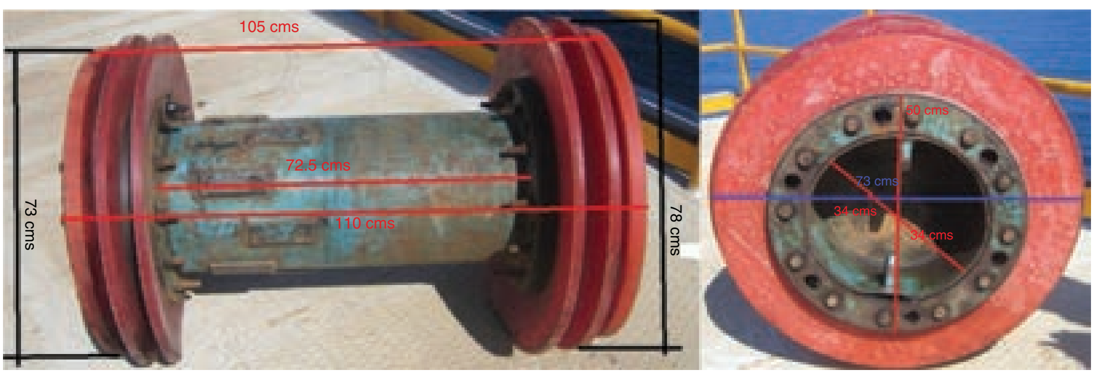



**Fig. 4—Profile 1.**

commonly used in the field to reduce production and process upset and to control the pig velocity. Several pigging operations were carried out in many of the selected pipelines with bypass pigs at different operating and flow conditions.

**Bypass-Pig Geometry/Profile. Figs. 4 through 6** show the different pig geometries used in the field for pigging operations. These bidirectional pigs have multiple disks and weigh approximately 150 kg. Bypass holes are drilled into the outer periphery of the pig body. The bypass area is controlled by increasing the number of bypass holes and the diameter of each hole. By this method, the bypass area can be increased to a maximum of 3 to 4% in a 30-in. pig. The three types of geometry used in the pigging operation are explained in the following.

Care should be taken when designing bypass-pig geometry. Pig stability, pig stalling, and the mechanical integrity of the pig are given prime importance during the design of bypass-pig geometry. In the first stage of experiments, bypass pigs with peripheral holes of 1 and 1.25 in. on the front and back disks were designed.

The simulation model with different bypass percentages is run and pig travel time, pressure conditions, slug volume and slug-initiation time and duration are predicted with the OLGA Dynamic Multiphase Flow Simulator (available from Schlumberger). The following are the physical input parameters:

- Pipeline diameter = 30 in.
- Pipe-wall thickness = 12.7 mm.
- Total pipeline length = 35 km (running from an offshore manifold platform to an onshore process complex). The pipeline is


**Fig. 5—Profile 2.**

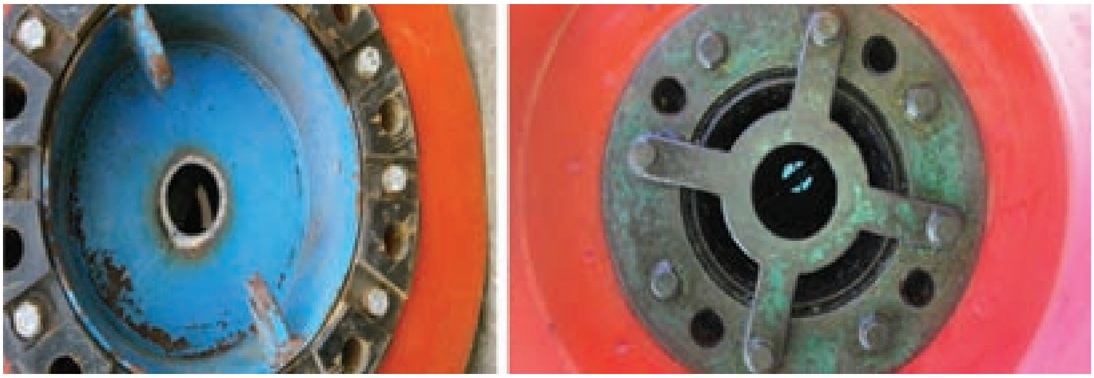


**Fig. 6—Profile 3.**

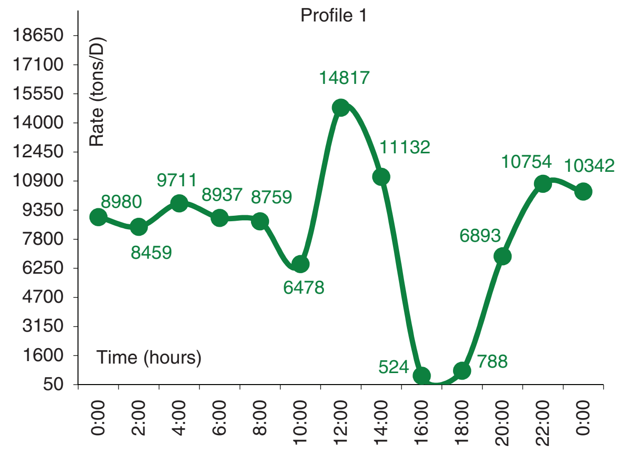



**Fig. 7—Liquid withdrawal during pigging with Profile 1.**

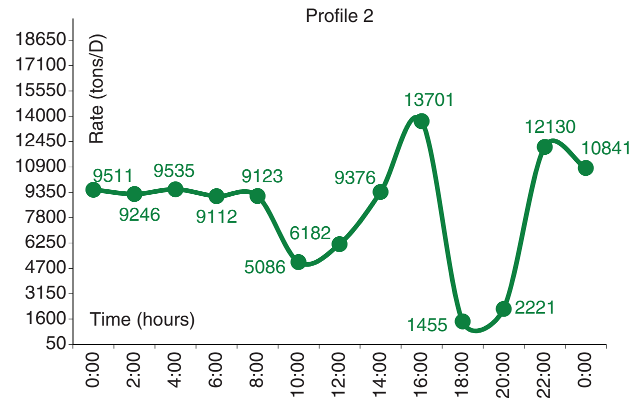



**Fig. 8—Liquid withdrawal during pigging with Profile 2.**

cement coated, and the pipeline profile used for modeling is as shown in Fig. 1.

- A 30-in. bidirectional pickup pig is used, with two front disks, two rear disks with support disks, and up to 12 bypass holes in the front and rear. The hole size varied from 25 to 34 mm for initial pigging.

The following are the operating parameters used during pigging:

- Total gas-flow rate through the pipeline = 80 MMscf/D, which is reduced to 60 MMscf/D at least 12 hours in advance of pigging to maintain a steady-state condition.

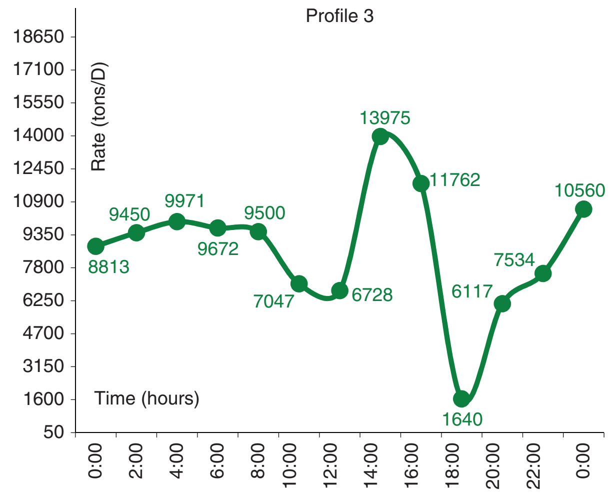



**Fig. 9—Liquid withdrawal during pigging with Profile 3.**

- Total liquid-flow rate = 70,000 BLPD with 8% water (approximately).
- The inlet pressure at the start of pigging is 17 to 18 barg. The receiving-end pressure, which is the normal operating pressure of the plant, is 7 barg.

***Profile 1.*** Initial geometry with six peripheral holes in the front disk and rear disks, with a hole size of 25 mm. Many experiments with different oil- and gas-flow rates were carried out with various percentages of bypass area (bidirectional, 150 kg, six disks).

***Profile 2***. The geometry is revised with 12 holes in the front and rear disks and a hole size of 34 mm. Many experiments were carried out with different oil- and gas-flow rates and various percentages of bypass area.

***Profile 3***. The geometry is revised with 12 holes in the front and rear disks, a hole size of 34 mm, and a central hole of 75 mm. Three experiments are carried out with different oil- and gas-flow rates and various percentages of bypass area.

**Pigging-Operation Data.** Many field-pigging runs are analyzed in this paper on the basis of the three cases mentioned in the preceding. The pigging operations were carried out with a varying time gap of 1 to 3 months at different oil- and gas-production rates. Different production rates resulted in different liquid inventories, backpressures, and process conditions during pigging operations. The liquid withdrawal from the pipeline during pigging **(Figs. 7 through 9)** with different profiles is made almost constant on the basis of the design capacity of the processing plant, which is assumed to be equal to the trunk pipeline-design capacity. The slug-catcher capacity at the processing plant is assumed to be equal to the trunk-line capacity, and very limited slug volume can be handled at the receiving end. It is also important that the incoming flow and

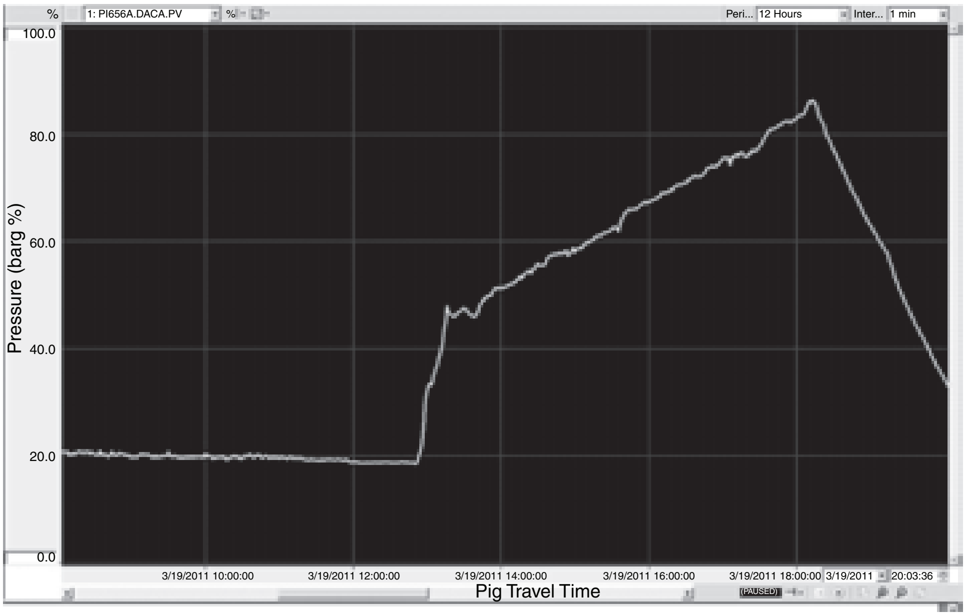



**Fig. 10—Backpressure increase during pigging.**

slugs be suppressed and controlled by use of inlet-control valves. This results in high backpressure in the trunk pipeline, which is closely monitored and controlled during pigging operations to remain within the maximum allowable working pressure of offshore platforms. Because of this, the pigging operation of a long-distance trunk pipeline always results in some kind of production loss and process upset.

**Fig. 10** shows a real-time photo of backpressure increase in a trunk pipeline during a bypass-pigging operation. The graph indicates a gradual pressure rise in the pipeline even after use of a bypass pig.

| Run No. | Liquid-Flow Rate (BLPD) | Gas-Flow Rate (MMscf/D) | Actual Pigging Time (hours) | Pig Speed (m/s) | Maximum Pressure at Start (barg) | Calculated Minimum Pigging Time (hours) | Calculated Maximum Pigging Time (hours) | Time Taken for Pressure Rise (hours) | Distance Travelled by Pig Before Pressure Rise (km) | Upstream *m* Value | Upstream *C* Value | Downstream *m* Value | Downstream *C* Value | Actual Bypass Gas Rate (MMscf/D) | Calculated Bypass Gas Rate (MMscf/D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 36640 | 32.0 | 12.5 | 0.86 | 34 | 8.29 | 15.95 | 2.5 | 12.1 | 1.7145 | 14.617 | 2.306 | 3.186 | 0 | 7 |
| 2 | 49478 | 56.0 | 6.5 | 1.61 | 28 | 4.32 | 7.84 | 3 | 27.8 | 2.3598 | 12.001 | 3.159 | 3.003 | 0 | 6.1 |
| 3 | 51478 | 27.0 | 10 | 1.05 | 25 | 9.02 | 14.57 | 1 | 4.4 | 1.213 | 14.694 | 1.664 | 4.071 | 0 | 6.1 |
| 4 | 52747 | 55.0 | 7.5 | 1.42 | 35.2 | 4.68 | 9.96 | 2 | 17.1 | 2.7314 | 12.898 | 3.545 | 3.008 | 0 | 6.5 |
| 5 | 57522 | 55.0 | 7.5 | 1.43 | 35.5 | 4.68 | 10.04 | 1.5 | 12.8 | 2.8206 | 12.806 | 3.651 | 3.143 | 0 | 6.5 |
| 6 | 57663 | 56.0 | 8.5 | 1.31 | 34 | 4.46 | 9.46 | 1.5 | 13.5 | 2.7162 | 11.789 | 3.213 | 3.517 | 0 | 6.3 |
| 7 | 65658 | 57.0 | 7.5 | 1.46 | 34 | 4.51 | 9.29 | 2 | 17.7 | 2.6594 | 12.765 | 3.581 | 3.183 | 0 | 6.5 |
| 8 | 67180 | 57.0 | 9.5 | 1.17 | 39 | 4.01 | 10.62 | 1.5 | 15.0 | 2.9786 | 11.131 | — | — | 0 | 6.2 |
| 9 | 68197 | 26.0 | 10.5 | 1.04 | 33.9 | 10.2 | 20.31 | 2 | 7.9 | 1.5725 | 15.458 | 2.134 | 3.395 | 0 | 6.8 |
| 10 | 67642 | 21.0 | 13.5 | 0.8 | 40 | 13.7 | 29.54 | 1.5 | 4.4 | 1.951 | 16.595 | 2.430 | 3.680 | 0 | 7.2 |
| 11 | 68819 | 46.0 | 7.4 | 1.42 | 34 | 5.59 | 11.51 | 1.5 | 10.7 | 2.4985 | 12.765 | — | — | 0 | 6.5 |
| 12 | 59686 | 35.3 | 7.25 | 1.46 | 32.8 | 7.72 | 14.50 | 1.5 | 7.8 | 2.3711 | 13.827 | — | — | 0 | 6.9 |
| 13 | 67708 | 70.2 | 7.41 | 1.41 | 36 | 4.09 | 7.97 | 3 | 29.3 | 2.6593 | 14.551 | 3.363 | 4.696 | 3 | 7.2 |
| 14 | 72433 | 63.5 | 6.22 | 1.7 | 35 | 3.93 | 8.58 | 1.5 | 15.3 | 3.2659 | 12.229 | 4.122 | 3.160 | 4 | 6.3 |
| 15 | 79044 | 55.6 | 6.25 | 1.69 | 33 | 5.14 | 9.25 | 1.5 | 11.7 | 2.7081 | 13.534 | 3.576 | 3.750 | 2 | 8.1 |
| 16 | 78285 | 59.6 | 6.17 | 1.72 | 29.2 | 4.83 | 7.67 | 1.5 | 12.4 | 2.9345 | 13.606 | 3.906 | 3.369 | 3 | 9 |
| 17 | 62504 | 82.4 | 5.55 | 1.57 | 39 | 3.30 | 7.34 | 1.5 | 18.2 | 3.7982 | 13.406 | 4.925 | 3.394 | 2 | 8.2 |
| 18 | 66691 | 63.5 | 6.4 | 1.63 | 35.7 | 4.29 | 8.75 | 1 | 9.3 | 3.5875 | 12.76 | 4.364 | 3.840 | 4 | 8 |
| 19 | 75592 | 71.5 | 6.15 | 1.73 | 32.8 | 3.81 | 7.15 | 1.5 | 15.8 | 3.8242 | 12.418 | 4.709 | 2.956 | 2 | 9 |
| 20 | 75447 | 69.2 | 5.38 | 1.92 | 34 | 3.94 | 7.66 | 1.5 | 15.2 | 2.9164 | 12.293 | 3.851 | 2.233 | 3 | 7 |
| 21 | 78089 | 65.3 | 6.12 | 1.75 | 37.2 | 4.17 | 8.85 | 2 | 19.2 | 3.4686 | 12.849 | 4.459 | 2.138 | 2 | 8 |
| 22 | 77017 | 66.0 | 5.55 | 1.83 | 35 | 4.13 | 8.25 | 1.5 | 14.5 | 3.4399 | 12.137 | 4.433 | 1.974 | 3 | 9 |
| 23 | 67479 | 55.8 | 8.1 | 1.32 | 37.8 | 4.88 | 10.51 | 1.5 | 12.3 | 3.0651 | 13.076 | 3.734 | 3.257 | 11 | 31 |
| 24 | 63703 | 44.6 | 9.16 | 1.19 | 30.5 | 6.11 | 10.70 | 1 | 6.5 | 2.5396 | 12.918 | 3.119 | 2.071 | 12 | 32 |
| 25 | 71655 | 53.8 | 7.04 | 1.53 | 34 | 5.06 | 9.84 | 1.5 | 11.9 | 2.8457 | 12.836 | 3.508 | 2.630 | 12 | 32 |
| 26 | 71284 | 59.1 | 6.45 | 1.58 | 35 | 4.61 | 9.22 | 1.5 | 13.0 | 3.0579 | 12.468 | 3.848 | 3.042 | 14 | 32 |
| 27 | 68948 | 60.3 | 5.33 | 1.95 | 35 | 4.52 | 9.04 | 1.5 | 13.3 | 3.6612 | 12.924 | 4.771 | 2.957 | 13 | 31 |
| 28 | 71024 | 53.7 | 7.45 | 1.39 | 38 | 5.07 | 10.99 | 2 | 15.8 | 3.2431 | 11.457 | 3.733 | 2.822 | 15 | 32 |
| 29 | 70839 | 57.0 | 7.56 | 1.36 | 34.3 | 4.78 | 9.37 | 1.5 | 12.6 | 3.2652 | 13.039 | 4.047 | 2.243 | 19 | 43 |
| 30 | 81752 | 61.0 | 6.35 | 1.64 | 30.8 | 4.47 | 7.89 | 1.5 | 13.4 | 3.5385 | 12.5 | 4.270 | 2.894 | 18 | 43 |
| 31 | 71980 | 67.0 | 5.5 | 1.85 | 30.6 | 4.07 | 7.14 | 1.5 | 14.8 | 3.5242 | 12.912 | 4.555 | 3.435 | 20 | 43 |
| 32 | 73807 | 89.8 | 4.5 | 2.24 | 36.2 | 3.03 | 6.27 | 2.5 | 13.2 | 4.2564 | 13.159 | 5.480 | 2.609 | 38 | 43 |
| 33 | 79028 | 82.2 | 5.25 | | 36.4 | 3.39 | 6.89 | — | — | **2.9121** | **13.075** | **3.740** | **3.092** | 37 | 43 |
| 34 | 83388 | 88.3 | 6.25 | 0.86 | 42.3 | 3.29 | 7.42 | — | — | — | — | — | — | 39 | 43 |

Notes:
Average regression constants are given in red.
Pig Runs 1 through 21 are carried out with Profile 1.
Pig Runs 22 through 28 are carried out with Profile 2.
Pig Runs 29 through 31 are carried out with Profile 3.
Pig Runs 32 through 34 are carried out with Profile 4.

Table 1—Tabulation of bypass-pigging input and output parameters.

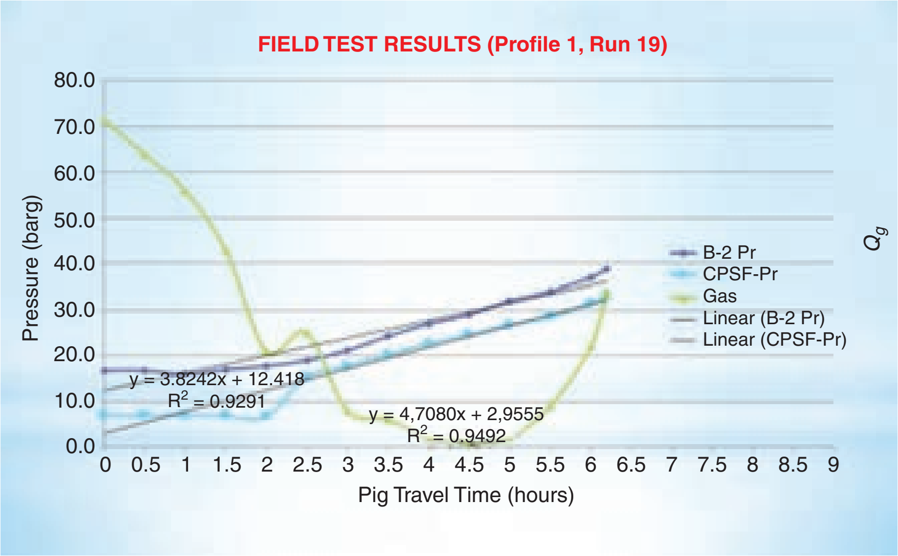



**Fig. 11—Pigging with Profile 1.**

**Empirical Correlations Based on Field-Pigging Results.** Many field-pigging runs were carried out over the past 2 years with bypass pigs (bypass area up to 4%) and analyzed. Different gas- and liquid-production rates resulted in different liquid inventories in each run. Each pigging operation was unique, and took different pig traveling time. Each run brought different results in terms of wax recovery and gas surge. It is also to be noted that the pressure differential across the source and sink also varied in a small range, though efforts were made to control the variation. Another risk in pipeline pigging was the presence of sand content, though to a smaller percentage, which was unknown. Regular desanding operations from the pipeline and downstream process equipment, close monitoring of liquid samples, and analysis are a routine part of the operation. It is also a fact that enough slug-handling capacity is unavailable for handling the total production during the transient pigging operation. The pigging operation has evolved to minimize production downtime and surge risks. For example, to achieve a steady-state condition and slow down of the pig before starting the pigging operation, the gas-flow rate is reduced to a certain extent on the basis of simulation results. The gas-flow rate has been reduced, while keeping the liquid-flow rate the same to avoid production loss. It is also to be noted that to have good control on the process operation in the plant, the liquid drain rate at the process-plant inlet has been controlled by throttling the subsea-pipeline exit-control valve downstream of the pig receiver.

The use of a pig-tracking system provides authentic information of pig travel and assists in locating the pig journey at various points in time. This also provides an idea of the pig travel velocity at different travel segments, pig acceleration and deceleration on the basis of the pipeline profile, and the terrain conditions. Pig tracking gives an advance indication about any blockage in the system on the basis of the travel speed.

The following input parameters were collected:

- Bypass percentage
- Liquid- and gas-flow rate before start of pigging
- Pressure and temperature at the start and end of the pipeline at constant intervals
- Pigging start and end times

The output parameters that were generated are as follows:

- Pig travel time vs. pressure graph at source and sink
- Gas velocity at start and end
- Pig-travel-time calculation on the basis of gas velocity
- Bypass-gas quantity calculation
- Time at which pressure increase started
- Distance traveled by the pig before the pressure rise started
- Surge-/inventory-estimation calculation
- Average liquid holdup in the pipeline (Cunliffe's method)
- Distance traveled before pressure increase
- Straight-line trend fitting
- Slope and intercept of the pressure curve
- Empirical formula with average slope and intercept

**Table 1** shows the details of the pigging operations carried out during the last 2 years with different bypass pigs and flow parameters. The input and output data are tabulated.

**Figs. 11 through 13** are typical examples of graphs depicting the relation between pig travel time [*x*-axis (hours)], pipeline pressure at start and end points [*y*-axis (barg)], and gas-flow rate [*y*-axis (MMscf/D)] observed in the plant during pigging.

**Summary of Experimental Results.** The following are the main observations and conclusions of the experimental results:

1. The pig travels a certain distance before pressure increase in all pigging operations.
2. The liquid slug observed during pigging at the receiving end is very high and is unable to be accommodated with the current design capacity.
3. Conventional methods of increasing the bypass-hole size do not give positive results.
4. The bypass-gas-flow rate is not increasing per the design requirement as the bypass-hole size increases.
5. Conventional bypass pigging is ineffective because of less gas bypass and less differential pressure across the pig.
6. The differential pressure across the pig is proportional to the drag force, which in turn depends on the pig weight.
7. The distance traveled before pressure rise is proportional to the liquid holdup in the pipeline.
8. The liquid holdup in the pipeline depends on the gas/liquid ratio maintained in the pipeline before the pigging operation.
9. The multiphase fluid stream in the pipeline tends to act as a mechanical spring.

**Trend Analysis and Analytical Modeling.** Correlations to determine the pig travel time on the basis of the production flow during pigging, the speed reduction because of bypass, the expected slug reduction with help of bypass, and the backpressure conditions in the pipeline can be evolved with a correlation developed from previously calculated results.

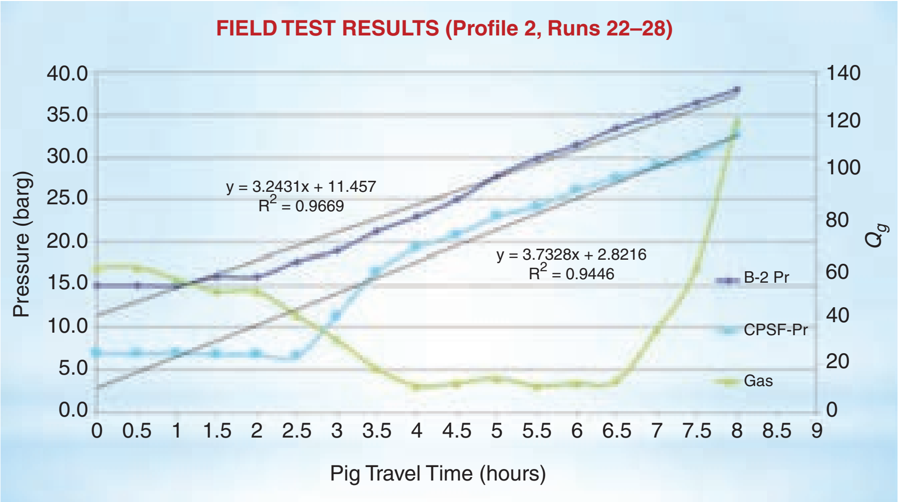



**Fig. 12—Pigging with Profile 2.**

The liquid holdup in a long-distance pipeline is a function of the gas/liquid ratio prevailing in the pipeline, which is an indication of the production level. Gas/liquid ratio has an inverse relation with the liquid holdup. On the basis of the liquid holdup in the pipeline, the backpressure starts increasing earlier or later during pigging operation. A simple empirical correlation that is based on the data collected during the pigging operation is proposed in this subsection. This empirical equation describes the flow characteristics of bypass pigging. The slope of the best-fit curve was calculated. Regression fit is developed from the data by use of the straight-line model $Y = mX + C$.

From the preceding tabulated results and on the basis of the linear-trend fitting curve, the following equations are derived:

$$Y = 2.9121X + 13.0756, \quad (9)$$

$$m = 2.9121, \quad (10)$$

and

$$C = 13.0756. \quad (11)$$

With this formula, the backpressure at the starting point ($Y$) can be calculated during pigging at any point of time to determine the maximum backpressure that can be attained for calculated pig travel time. Therefore, if the start pressure before pigging is 17 barg and the calculated maximum pig travel time is 6 hours, the highest pressure at the source while pigging can be calculated as $Y = 2.9121X6 + 13.0756 = 30.5482$ barg.

Developed empirical correlations show a good match with experimental results for the conventional profiles (Profiles 1 through 3), and they can be used for future prediction purposes and quick estimation of the maximum expected pressure in the pipeline for decision making and precautionary actions. For the new profile, the high pressure at B2 is caused by the low pig travel time, which led to uncontrolled flow rate, necessitating throttling of the inlet valves. **Table 2** shows the validation of pig travel time and backpressure in the line, which are highlighted in green and yellow, respectively. The table shows the results of available limited runs.

**Simulation Results and Field Results: Comparison Study.** A comparison between OLGA transient simulation and field results for the surge volume, pigging backpressure, pig travel time, and bypass-flow quantity shows some deviations. The mismatch could

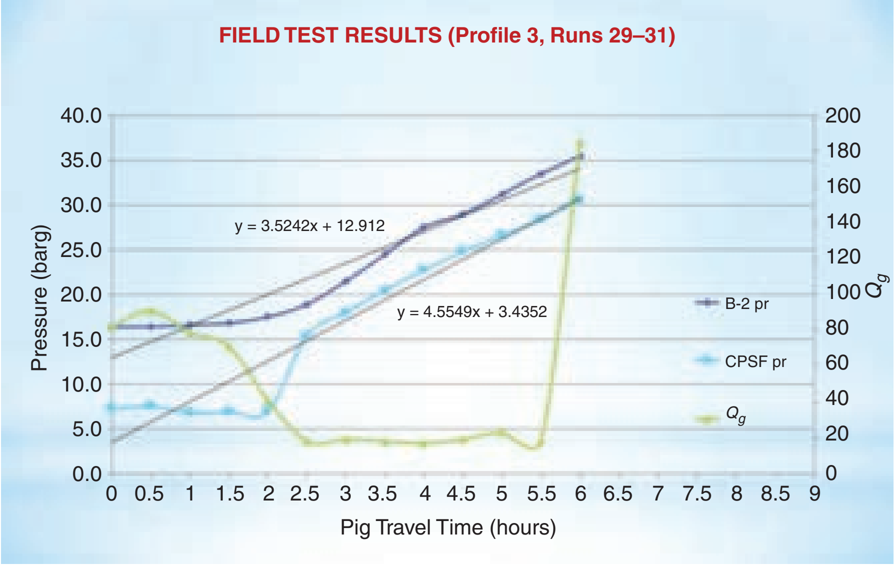



**Fig. 13—Pigging with Profile 3.**

| Profile Type | Run No. | Bypass Area (%) | Liquid-Flow Rate (BLPD) | Gas Rate (MMscf/D) | Actual Pigging Time (hours) | Maximum B2 Pressure (hours) | Calculated Pigging Time at Start (hours) | Calculated Pigging Time at End (hours) | Pig Travel Time Based on Average Velocity (hours) | Calculated Maximum B2 Pressure (barg) |
|---|---|---|---|---|---|---|---|---|---|---|
| Profile 1 | 19 | 0.8 | 65,592 | 71.5 | 6.3 | 36.8 | 3.8 | 7.2 | 4.3 | 34.04 |
| Profile 2 | 28 | 2.6 | 71,024 | 53.7 | 7.8 | 38 | 5.1 | 11.0 | 11.6 | 45.11 |
| Profile 3 | 29 | 4 | 70,839 | 57.0 | 7.9 | 40.5 | 4.8 | 9.4 | 19.6 | 40.5 |
| Profile 3 | 30 | 4 | 81,752 | 61.0 | 6.6 | 36.5 | 4.5 | 7.9 | 15.2 | 36.09 |
| Profile 3 | 31 | 4 | 71,980 | 67.0 | 5.1 | 35.5 | 4.1 | 7.1 | 11.3 | 33.75 |
| Profile 4 | 32 | 1.05 | 73,807 | 89.8 | 4.1 | 36.2 | 3.0 | 6.3 | 4.6 | 31.42 |
| Profile 4 | 33 | 1.05 | 79,028 | 82.2 | 5.5 | 36.4 | 3.4 | 6.9 | 6.6 | 33.17 |
| Profile 4 | 34 | 1.05 | 83,388 | 88.3 | 6.5 | 42.3 | 3.3 | 7.4 | 5.8 | 34.63 |

Table 2—Validation data for pigging time and backpressure.

be because of the failure to predict a bubbly liquid surge caused by the turbulence of bypass pigging. Surge-volume prediction and surge-initiation timing and its duration are very complicated. Pigging-surge models that are based on empirical formulations are sometimes very helpful.

The effect of increasing the bypass area on the drag coefficient and drag force is verified. The effect of increasing the drag force by increasing the weight of the pig is proposed. Seal leakage through the disks is reviewed and discussed. Software results are validated, and differences are discussed for better understanding. **Figs. 14 through 16** show different scenarios of simulation runs.

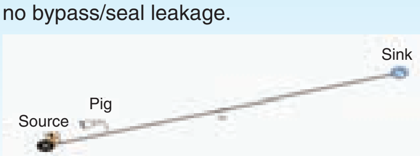
## Summary of Software Simulations

1. Pig travel time calculated on the basis of simulation without bypass holes more or less matches with actual pig travel time obtained during field-pigging operations, though there are some mismatches. This is evident in the smaller-diameter-pipeline pigging, in which pigging was carried out without any downstream control in liquid-withdrawal rate.
2. The pig travel time calculated on the basis of simulation with bypass holes does not match with the actual pig travel time observed during field application.
3. The liquid slug is predicted to start much earlier than was observed in the field. This time gap could be because of the failure to predict a bubbly slug flow caused by the turbulence of bypass pigging. Moreover, the liquid arriving is also controlled by throttling the inlet-flow-control valve.
4. The liquid-surge volume, duration, and arrival time are dependent on the normal production rate maintained in the pipeline before pigging and the pigging rate (BLPD, gas/liquid ratio)
5. Simulation results show less of an increase in backpressure compared with actual backpressure observed during field-pigging operations. This is because of the difference in the

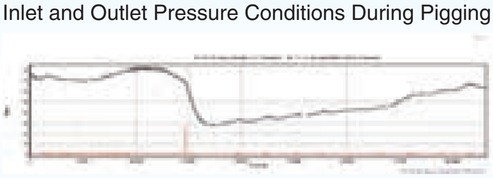
**SOFTWARE SIMULATION RESULTS (RUN 1)**

**Pigging of 30-in. Trunk Line**

Oil rate = 70,000 BOPD; gas/oil radio = 900 scf/STB; water content = 8%; CPSF pressure = 7 barg with no bypass/seal leakage.

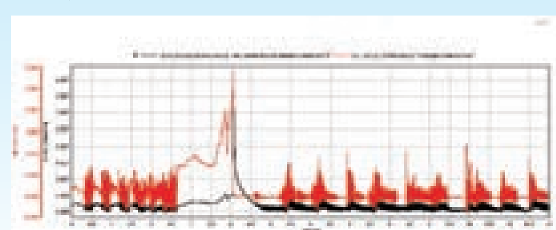



Inlet and Outlet Pressure Conditions During Pigging



Pigging time = 4.07 hours = 243 minutes

The Liquid-Flow Rate and Gas-Flow Rate at Various Time, at Sink/CPSF



**Initial Liquid- and Gas-Flow Rate = 12 650 m$^3$/d, 1.782 million std m$^3$/d**

The liquid-flow rate fluctuated up to 45 000 m$^3$/d until 2.5 hours after the pig launched, and started further increasing to greater values, even up to 10 times that of the starting production rate. In between, no liquid flow was observed many times.

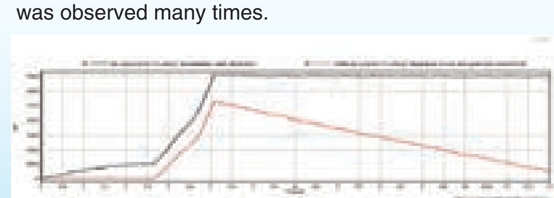
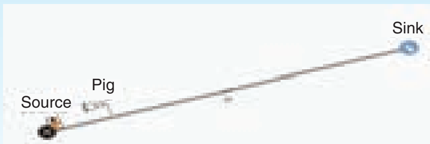


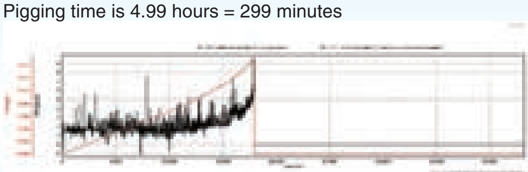
**Fig. 14—Software simulation, Run 1.**

## SOFTWARE SIMULATION RESULTS (RUN 2)

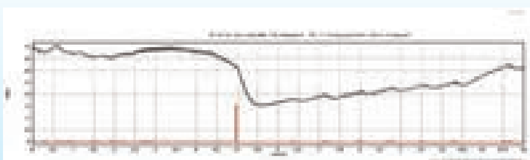
**Pigging of 30-in. Trunk Line**
Oil rate = 70,000 BOPD; gas/oil ratio = 700 scf/STB; water content = 8%; CPSF pressure = 7 barg; 2.6% bypass/seal leakage.



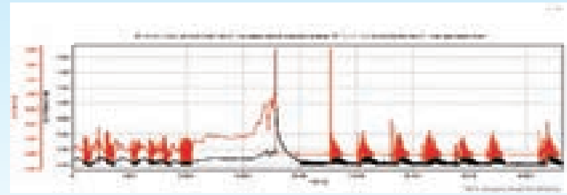

Pigging time is 4.99 hours = 299 minutes



Inlet and Outlet Pressure Conditions During Pigging



The Liquid-Flow Rate and Gas-Flow Rate at Various Time, at Sink/CPSF



**Initial Liquid- and Gas-Flow Rate = 12 650 m$^3$/d, 1.782 million std m$^3$/d**

The liquid-flow rate fluctuated up to 40 000 m$^3$/d until 2.5 hours after the pig launched, and started further increasing to greater values, even up to 20 times that of the starting production rate. In between, no liquid flow was also observed for many times. The gas-flow rate also reached higher values, dropped down to double, and touched zero at many times, and started to increase after 2.9 hours.

Accumulated liquid volume is 7940 m$^3$ and surge volume is 5097 m$^3$.

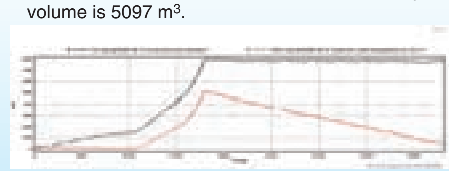


**Fig. 15— Software simulation, Run 2.**

liquid-withdrawal rate considered in the simulation study and the actual field case.

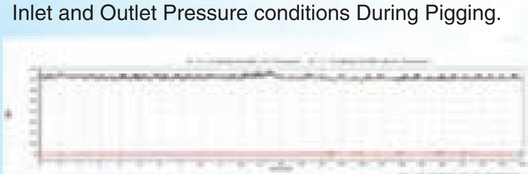
6. Bypass pigging, as such, cannot be modeled with the OLGA simulation software. Bypass pigging has to be modeled through allocating a certain percentage of seal leakage across the pig.
7. After allocating the calculated percentage of seal leakage in the simulation, the simulation is unable to complete and is aborted.

## SOFTWARE SIMULATION RESULTS (RUN 3)

**Pigging of 30-in. Trunk Line**
Oil rate = 70,000 BOPD; gas/oil ratio = 900 scf/STB; water content = 8%; CPSF pressure = 7 barg; 20% bypass/seal leakage.


Pigging time is 14.35 hours.

Inlet and Outlet Pressure conditions During Pigging.



The Liquid-Flow Rate and Gas-Flow Rate at Various Time, at Sink/CPSF

Accumulated liquid volume is less and maximum surge volume is 317 m$^3$.

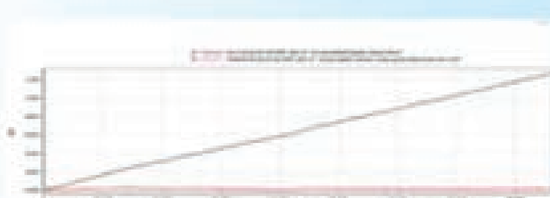


**Fig. 16— Software simulation, Run 3.**

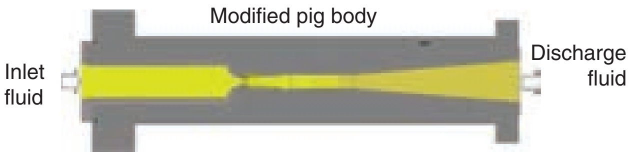



**Fig. 17—Innovative new geometry profile.**

## New Bypass-Hole Geometry/Profile

A new bypass-pig geometry/profile **(Fig. 17),** the convergent/divergent profile, is suggested in this paper, followed by simplified model development. Various aspects of the proposed profile are discussed and suggested through field trial with selected cases.

Through this innovative design, the critical flow is achieved at a lower pressure ratio so that a stable constant-gas-flow rate can be achieved through the bypass holes by use of the convergent/divergent profile, in which the gas enters through a nozzle section, stabilizes at the throat, and recovers the pressure through a diffuser section. The nozzle converts the high-pressure energy into velocity energy, and the diffuser regains the pressure back before it exits the hole. At a predefined inlet pressure and area of cross section of the hole, a properly designed convergent nozzle with a throat section will provide maximum critical flow rate at the exit by reducing the gas pressure to the critical pressure ratio **(Fig. 18).** However, with assistance from the diffuser section, the high-velocity energy is converted back into pressure energy, and the line pressure is regained up to 90% of the upstream pressure.

**Salient Features of the New Geometry.**

- In conventional bypassing, increase in bypass area reduces the $C_D$ and $\Delta P$, and hence does not increase gas-flow rate correspondingly. This is evident from experiments.
- New, innovative bypass-hole geometry design (convergent/divergent nozzle design at the center) maintains high gas-flow rate at higher $\Delta P$.
- The throat diameter is decided on the basis of the quantity of gas bypass required.
- At the throat, sonic velocity is achieved with critical gas-flow rate **(Fig. 19).**
- In the diffuser section, the pressure energy is recovered.
- In the diffuser section, the pressure energy is recovered even up to 90%
- In the nozzle and diffuser section, the isentropic expansion and compression process is anticipated.
- Material selection shall be low-temperature carbon steel/stainless steel to withstand low temperature.

**Typical Design of Convergent/Divergent Profile.**

- Oil rate = 70,000 BOPD; gas/oil ratio = 1,300 scf/STB; water content = 8%; source pressure = 17 barg; sink pressure = 7 barg.
- Total gas at starting point = 90 MMscf/D.
- Critical gas-flow rate at 17 barg = 43 MMscf/D.
- Calculated throat diameter = 7.5 cm.
- Critical pressure at throat = 17×0.53 = 9.01 barg.
- Considering an angle of convergence of 10° (total), the length of the convergent section = 149 cm, with an inlet diameter of 23 cm.

For isentropic flow at $P_o$ = 17 barg, $T_o$ = 293 K, $A^*$ = 44.156 cm$^2$ (throat diameter = 7.5 cm), and gas density $\rho_0 = P_o/RT_o$ = 21.41 kg/m$^3$. Sound velocity at the entrance and the throat and gas velocity at the entrance and the throat are calculated along with density. The diffuser diameter is calculated at $M_2$ = 0.10 and $M_2$ = 0.05, which is 18.1 and 25.5 cm, respectively. Diffuser length ($L$) is calculated as shown in **Fig. 20.**

***Profile 4: New Profile With Convergent/Divergent Geometry***. The inlet diameter of the hole is 25 cm, the throat diameter is 7.5 cm, the exit-diffuser diameter is 18.1 cm, and the overall length is 105 cm **(Fig. 21).**

The additional force that is exerted on the diffuser wall is also calculated. This force is equal to the thrust of the flow in the backward direction, which is equal to the change in the impulse function:

$$T = F_2 - F_1 \quad\text{.....(12)}$$

and

$$F_1^* = F_2^* = P_1^* A_1^* (1+\gamma)\ . \quad\text{.....(13)}$$

From gas tables, for $M_2$ = 0.1:

$$F_1/F_1^* = 1;\ F_2/F_2^* = 4.30;\ F_2 = 4.30F_2^* \quad\text{.....(14)}$$

and

$$T = (4.30-1)F_1^* = 3.30 P_1^* A_1^* (1+\gamma)$$
$$= 3.30 * 9.504 * 10^5 * 3.14 * 0.075 * 0.075 * (1+1.4)$$
$$= 33{,}237N \quad\text{.....(15)}$$

The pig body shall be able to withstand this additional force acting on it because of the new profile.

**Table 3** shows the validation of bypass-gas-flow rate observed during pigging operations using the new profile with the calculated bypass-gas-flow rate with the Thornhill-Craver equation.

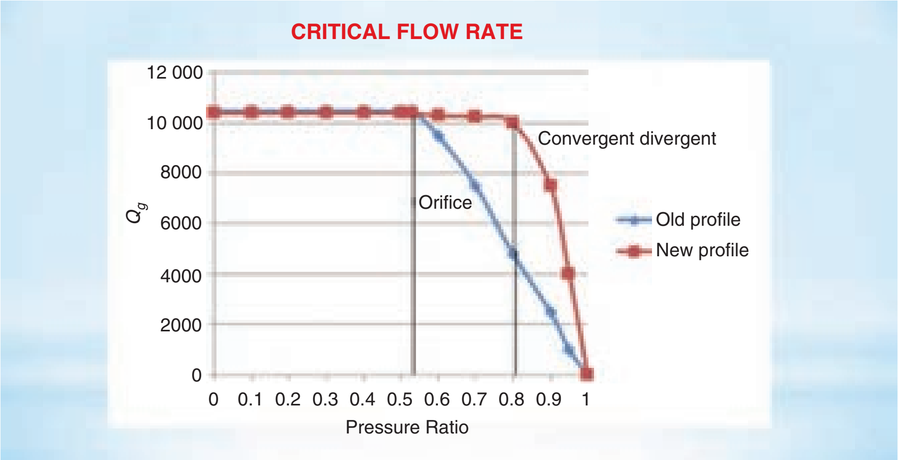



**Fig. 18—Typical expected flow profile through convergent/divergent nozzle.**

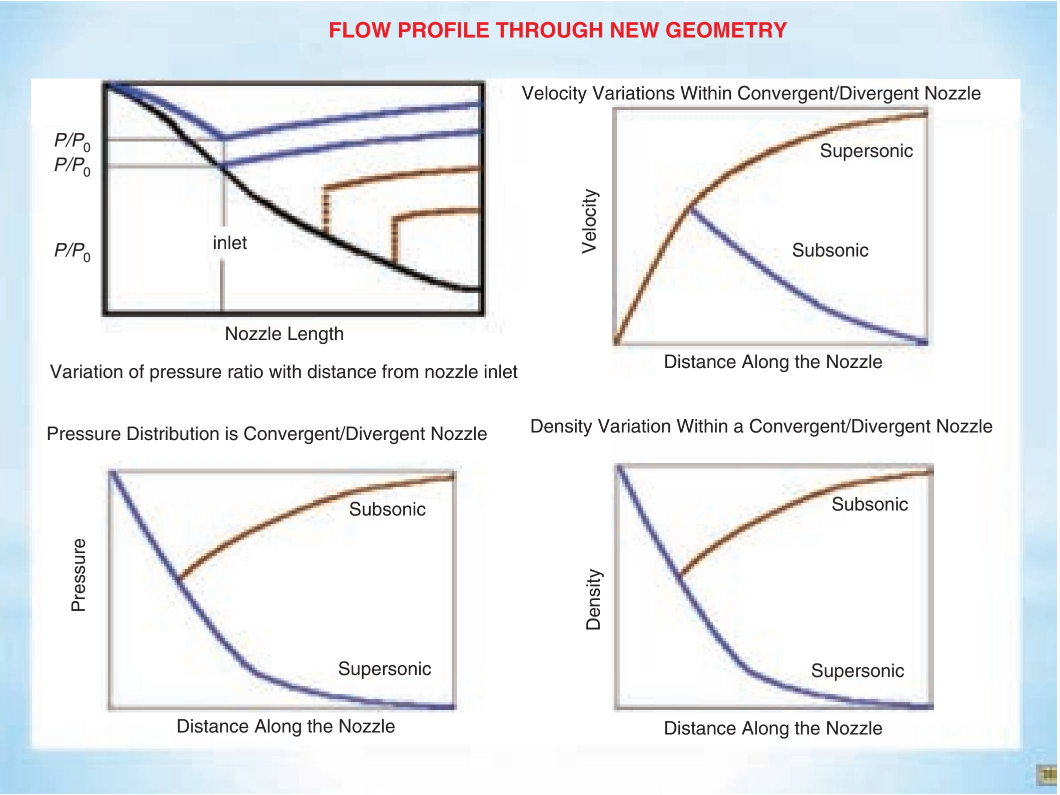



**Fig. 19—Typical expected flow profile through convergent/divergent nozzle.**

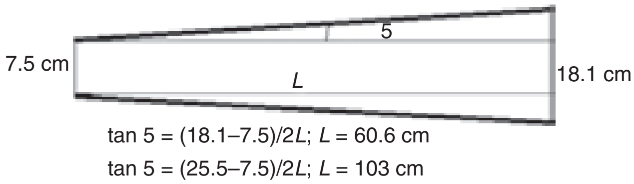



**Fig. 20—Divergent section design.**

- The bypass-gas quantity almost matches with the calculated value/design value.
- In the new design, the bypass-area percentage is very low compared with conventional bypass pigging.
- The bypass-gas-flow rate is very high because of near-critical flow.
- OLGA simulation software validates the new design, assuming an equivalent high bypass-area percentage or seal leakage.
- The software simulation shows that the upstream-pressure conditions and the liquid-slug conditions have been changed dramatically.
- Uniform pig speed is indicated.

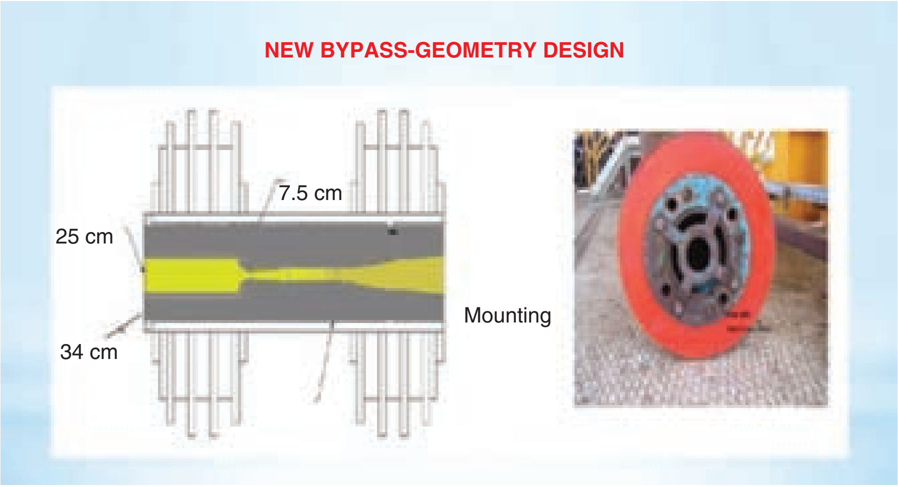



**Fig. 21—New bypass geometry, Profile 4.**

| Profile Type | Run No. | Bypass (%) | Liquid-Flow Rate (BLPD) | Gas Rate (MMscf/D) | Actual Pigging Time (hours) | Maximum B2 Pressure (barg) | B2 Initial Pressure (barg) | Calculated Pigging Time at Start (hours) | Calculated Pigging Time at End (hours) | Pig Travel Time Based on Average Velocity (hours) | Recorded Bypass-Gas Rate (MMscf/D) | Calculated Bypass-Gas Rate (MMscf/D) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Profile 1 | 19 | 0.8 | 65592 | 71.5 | 6.3 | 36.8 | 17.0 | 3.8 | 7.2 | 4.3 | 2 | 8.20 |
| Profile 2 | 28 | 2.6 | 71024 | 53.7 | 7.8 | 38 | 17.0 | 5.1 | 11.0 | 11.6 | 15 | 31.00 |
| Profile 3 | 29 | 4 | 70839 | 57.0 | 7.9 | 40.5 | 17.0 | 4.8 | 9.4 | 19.6 | 17 | 43.00 |
| Profile 3 | 30 | 4 | 81752 | 61.0 | 6.6 | 36.5 | 17.0 | 4.5 | 7.9 | 15.2 | 19 | 43.00 |
| Profile 3 | 31 | 4 | 71980 | 67.0 | 5.1 | 35.5 | 17.0 | 4.1 | 7.1 | 11.3 | 18 | 43.00 |
| Profile 4 | 32 | 1.05 | 73807 | 89.8 | 4.1 | 36.2 | 17.0 | 3.0 | 6.3 | 4.6 | 38 | 43.00 |
| Profile 4 | 33 | 1.05 | 79028 | 82.2 | 5.5 | 36.4 | 17.4 | 3.4 | 6.9 | 6.6 | 37 | 43.00 |
| Profile 4 | 34 | 1.05 | 83388 | 88.3 | 6.5 | 42.3 | 18.2 | 3.3 | 7.4 | 5.8 | 39 | 43.00 |

Table 3—Validation data for actual and calculated gas-flow rate.

- The software simulation shows that the accumulated liquid and surge liquid are reduced.
- The simulation shows a no-pig-travel status as a result of high seal leakage, which is a limitation of the OLGA simulation software.

## Experimental Results and Analysis

- With the new geometry, gas quantity and liquid quantity increased. Gas-flow rate need not be curtailed, unlike in previous cases. High gas rate of 85 to 90 MMscf/D was maintained during pigging.
- The design bypass-gas quantity was 43 MMscf/D; however, the actual achievement was approximately 38 MMscf/D, which is in line with expectations, considering many influencing parameters **(Figs. 22 through 24).**
- The backpressure rise was much lower than expected, unlike conventional bypass pigging of previous cases.
- There was not much temperature-reduction effect noticed during the operation.
- Slug-catcher liquid-withdrawal rate and level were better controlled with the help of the flow-control valve.
- The pig-generated volume was controlled effectively.
- Properly designed bypass geometry can minimize the liquid/solid surge effectively by spreading the collected liquid/solid in front of the pig.

## Conclusion

The new profile will ensure sufficient bypass-gas quantity through the pig, which is required for very efficient and effective pigging operation, without compromising differential pressure and while avoiding the pig becoming stuck. The availability of more bypass quantity will reduce the high amount of pig-generated-liquid volume and enable delivery of a uniformly mixed fluid during the pigging time. This will also avoid high slugging during pigging and eliminate the requirement for a large slug-catching-facility arrangement. This will enable ease of compressor operation during the pigging time by minimizing the gas-quantity fluctuation. The following are major conclusions of this study:

- The existing normal square-edged hole operates in the subcritical region of the pipeline. The present bypass-hole configuration induces variable gas-flow rate through the pig, which can cause pressure fluctuations in the pipeline, leading to instability in flow.

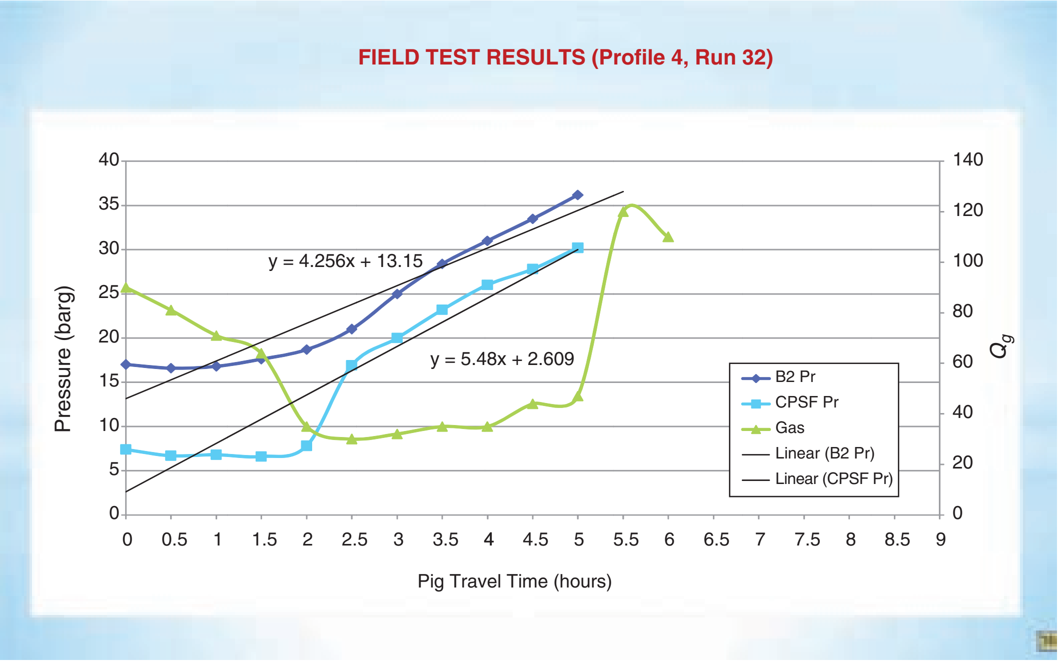



**Fig. 22—Pigging results with new geometry, Profile 4.**

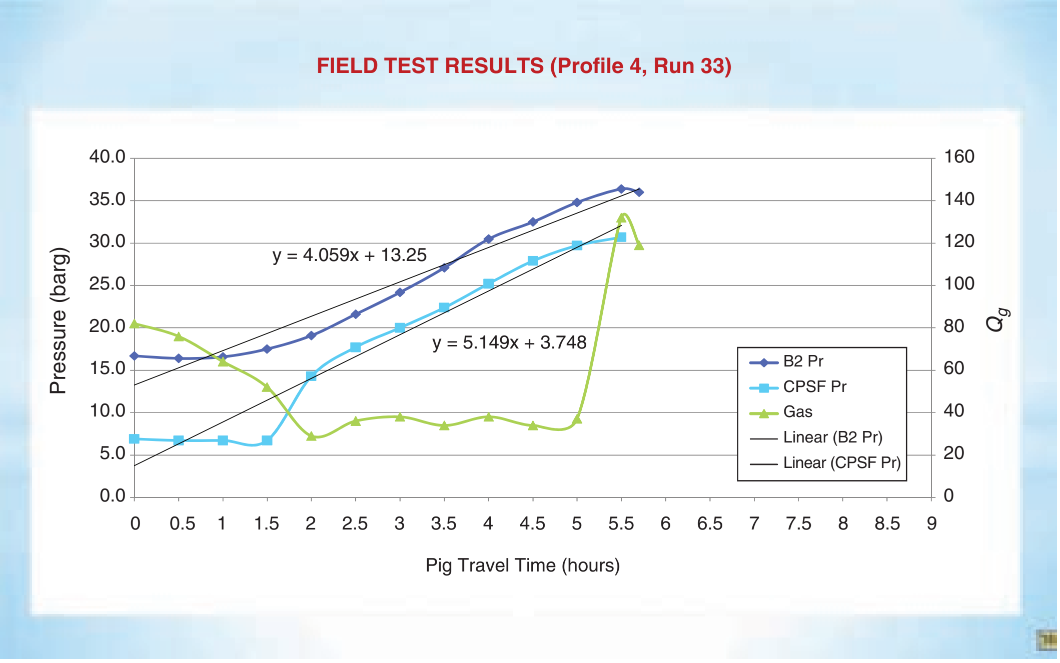



**Fig. 23—Pigging results with new geometry, Profile 4.**

- Modified convergent/divergent-type bypass-geometry profiles were designed on the basis of the continuity equation to achieve critical flow at a lower pressure differential across the pig.
- The experiments carried out on modified profiles indicated that critical flow rate through convergent/divergent nozzles was achieved at ratio of downstream pressure to upstream pressure of 87 to 82% for smaller hole sizes of $^3/_{16}$, $^1/_4$, and $^5/_{16}$ in. sizes compared with 53% in existing square-edged bypass holes.
- The results indicate that the increase in area ratio of exit to throat section beyond a limit did not result in greater pressure recovery.
- The most-ideal total angle of convergence, as indicated from test results, is approximately 10 to 12°.
- Care shall be taken during material selection of the pig body in view of the anticipated temperature drop across the nozzle. Additional care shall also be taken in design to account for the additional force exerted on the diffuser wall of the pig geometry.
- The effectiveness of wax removal/disintegration with the bypass pig of new geometry is better.
- Effective slug control/process operation/backpressure reduction is achieved with the new geometry.

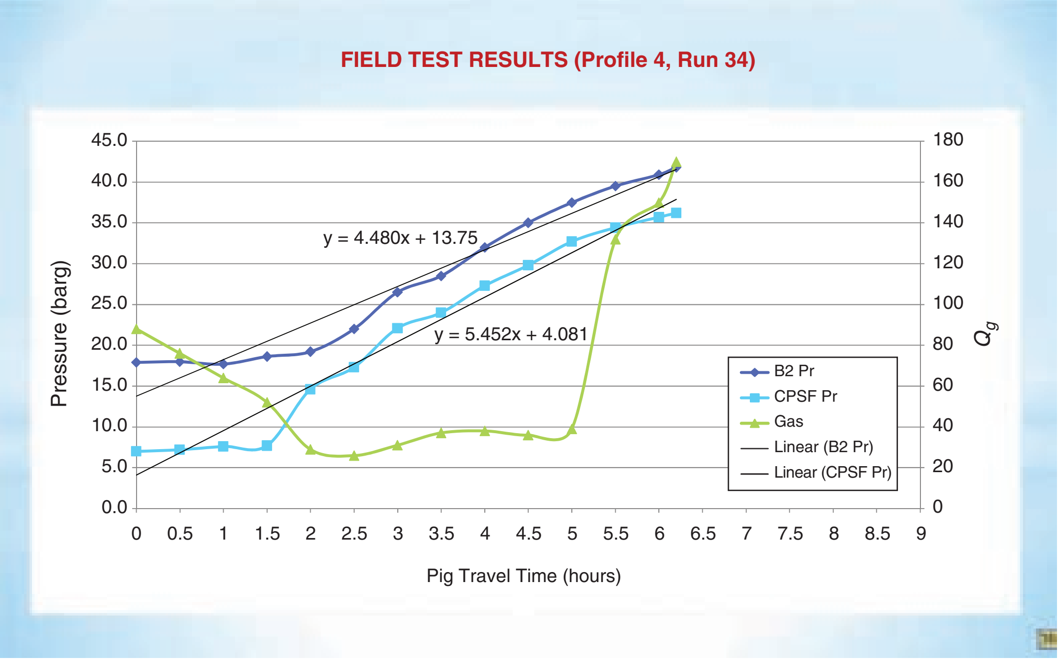



**Fig. 24—Pigging results with new geometry, Profile 4.**

- The new-geometry bypass pigging is used to reduce the pigging risks, such as separator trip caused by a surge in liquid/solids and the potential for lost production as the result of a stuck pig.
- Only limited success in predicting slug size, slug duration, and backpressure rise has been reported in bypass pigging through use of software simulation.
- Field data and model-prediction results will enable the development of liquid-surge prediction practices for pipelines.
- Results that are based on the new geometry will help designers estimate the required surge capacity at the process complex accurately and reduce the capital expenditures of the surface-slug-handling facility.
- The new empirical equation and geometry proposed in the study may be very useful in safe and economical pigging applications in the field.

## Nomenclature

$A$ = area of the pipeline, m$^2$
$A_o$ = area of the cross section of each bypass hole/orifice, in.$^2$
$C_d$ = discharge coefficient
$C_D$ = drag coefficient of the pig
$F_D$ = drag force, N
$F_f$ = contact friction force
$F_2$, $F_1$ = impulse function
$k$ = specific-heat ratio $C_p/C_v$
$k_d$ = disk-diameter ratio
$n_1$, $n_2$ = number of moles of gas at different pressures
$N$ = total normal forces (weight of the pig), N
$P_p$ = pressure difference across the pig
$P_1$ = initial pressure, psia
$P_2$ = final pressure, psia
$Q$ = bypass-gas-flow rate, MMscf/D
$r = P_2/P_1$
$R$ = universal gas constant
$S_p$ = specific gravity of gas
$T$ = force on the diffuser
$T_g$ = gas temperature, °R
$T_1$ = initial or standard temperature, °R
$T_2$ = final or actual temperature, °R
$V$ = velocity of the transportation fluid, m/s
$V_d$ = velocity difference between the fluid mixture and the pig, m/s
$V_p$ = velocity of the pig, m/s
$V_1$ = initial volumetric-flow rate (standard volumetric rate), m$^3$/s
$V_2$ = final volumetric-flow rate (actual volumetric rate at pressure), m$^3$/s
$z_1$, $z_2$ = compressibility factors at different pressures
$\eta$ = contact friction coefficient
$\rho$ = density of the transport medium, kg/m$^3$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