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Real Time Digital Interpretation of Subsea Blowout Preventer Tests

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Abstract

A computer based method expedites interpretation of pressure data during subsea blowout preventer (BOP) tests. This can reduce the time and cost of current subsea BOP testing practices in a safe and objective manner.

Presently, individual tests can require more than 1 hr. of shut-in time and a complete series of subsea BOP tests may comprise at least 12 individual tests

The digital method employs computer software to produce an accurate model of the pressure decline behavior relatively early in each test. The model can thus predict if future pressures will stabilize at an acceptable level. With regulatory approval and a reliable method to forecast pressure, the duration of subsea BOP tests can be significantly reduced.

Comparison of the digital method to conventional subsea BOP testing on numerous field trials shows excellent agreement If implemented the digital method could save hours of valuable critical-path rig time during every series of subsea BOP tests.

Working in concert with regulatory authorities to gain endorsement of this method is integral to the project. Functionality of the software, example results and implementation status are reported.

Introduction

Industry trends toward deeper water, use of synthetic oil based fluids and subsurface conditions that require higher test pressures contribute to lengthy delays while waiting for pressures to stabilize during subsea blowout preventer (BOP) testing. Also, subsea BOP stacks with redundancy of components and use of multi-diameter drill strings leads to greater numbers of tests that must be conducted.

Franklin *et. al.* investigated the phenomenon of lengthy subsea BOP testing times.[1] They conclusively attributed the prolonged decay of pressure with time to heating of the test fluids during pressurization followed by cooling of the fluids during shut-in test periods. They proposed that real time digital analysis of the pressure decay could yield large time and cost savings with safety benefits gained through reduced exposure time of personnel to pressurized lines.

The current authors continued the aforementioned work. A digital algorithm for real time interpretation of subsea BOP tests was implemented in software and tested successfully in U.S. Gulf of Mexico trials. This document explains the algorithm and presents field trial results.

Current Subsea BOP Testing Practice

Current subsea BOP testing practice (in U.S. and generally worldwide) is to view shut-in test pressures on circular chart recorders and wait until a 5-minute period of reasonably stable pressures is obtained (see **Fig. 1**). The reasonably stable pressures must be greater than or equal to the required test pressure so, to allow for temperature-related pressure declines. tests are initiated well in excess of required pressures. A 5-minute period of reasonably stable pressures is required as proof of non-leaking tests since, absent additional analysis, the periods of overtly declining shut-in pressures could be indicative of leaks in the systems.

Subsea BOP tests recorded on 4-hr 15,000 psi circular charts are typically ended when pressure decline rates are in the range -4 to -3 psi/min This is because the pressure trace begins to appear steady once pressure decline rates diminish to the range -4 to -3 psi/min, making this the as-practiced limit of circular chart resolution. Given the subjective nature of visual chart interpretation, tests are sometimes stopped at pressure decline rates as high as -5 psi/min and as low as -2 psi/min. We consider -3 psi/min as representative of a high standard of current testing practice and designate the pressure at which this occurs as P_s or the "pressure at stabilization".

Pressure Behavior During Subsea BOP Tests

Individual subsea BOP tests can require upwards of an hour for pressures to stabilize acceptably. In the example of **Fig. 2**, 8 pipe ram tests averaged 53.5 minutes each, 4 annular preventer tests averaged 16.8 minutes each and the total shut-in time was 8.25 hours. The ideal combined shut-in time would be 1.0 hour given the U.S. Minerals Management Service (MMS) requirement that each of the 12 tests must hold the required pressure for 5 minutes. In this example an excess of 7.25 hours was expended waiting for pressures to stabilize.

Pressure declines of non-leaking tests are attributed to cooling of the fluids in the pressurized system:

- Surface-temperature fluids are pumped from the cementing unit into the kill and/or choke line(s) to apply elevated pressure to the subsea BOP components being tested. These fluids are warmer than their surroundings
- Fluids in the kill and/or choke line(s) compress as additional fluids are pumped-in. These fluids are displaced deeper to cooler surroundings.
- Fluids in the kill and/or choke line(s) undergo an internal energy rise when they are compressed. This heat of compression causes a slight elevation of fluid temperatures throughout the system.
- The pressurized fluids in the kill and/or choke line(s) cool as they lose heat to their surroundings.
- Shut-in test pressures decline as the testing fluids cool. The rate of pressure decline is fastest initially when the temperature differences (ΔT) between fluids and surroundings are greatest and slows as ΔT becomes less.

Subsea BOP tests tend to take longer with synthetic base muds (SBM) than with water base fluids (see **Fig. 3**) because:

- SBM is more compressible than water, hence more SBM (and heat) is pumped-in to attain a given test pressure.
- SBM has greater heat of compression (temperature rise) than water.
- SBM has lower heat capacity than water so loses heat more slowly and takes longer to cool.

Digital BOP Testing

Digital BOP Testing offers a means to substantially reduce the shut-in time needed to correctly interpret subsea BOP tests. The term "digital" refers to:

- Test data are recorded by a computer.
- A computer analyzes the pressure decline.
- A computer forecasts if the test is positive or negative.
- A computer generates a summary test report.

Given regulatory approval and a computer-aided forecasting method that can be applied safely, accurately and reliably, the envisioned benefits of Digital BOP Testing include:

- Correctly interpreting tests more efficiently.
- Applied repeatedly, saving ca. 6 hours of critical path rig time per test interval (typically every 14 days).
- Saving ca. $3 million dollars annually per floating drilling operation.
- Interpreting tests in a consistent, objective manner.
- Reducing personnel, exposure to high pressure during subsea BOP and surface manifold testing.
- Reducing wear and tear on BOP components and pumping equipment
- Making better use of metoceanic conditions while favorable for drilling

Digital BOP Testing Algorithm

A Digital BOP Testing Algorithm was developed to enable real time interpretation of subsea blowout preventer tests. The algorithm takes great care to obtain accurate pressure forecasts. An appropriate mathematical function with good predictive capability is fit to the observed pressure data, the pressure trend is extrapolated and a stringent test is applied to check for confidence in the pressure forecast.

Pump rate, volume pumped and pump pressure data are received in ca. 1-second intervals. These measurements are typically made at cementing units by cementing services providers. The end of pumping and beginning of shut-in test periods are detected.

During shut-in periods a function of the form

$$P(t) = A + \frac{b}{c + t^{m}} \qquad (1)$$

is regressed to the entire time and pressure data set whenever fresh data are received. The values of A, b, c and m that provide the best fit of the function to the data are computed

Given that Eq. 1 expresses shut-in test pressure as a function of time, the pressure decline rate is the 1st derivative of Eq. 1

$$P'(t) = \frac{-bmt^{m-1}}{(c + t^{m})^{2}} \qquad (2)$$

and for a particular value of the derivative such as P'_T, the time at which that value occurs is stated by Eq. 3.

$$t = \left[\frac{-P'_T(c + t^{m})^{2}}{bm}\right]^{\frac{1}{m-1}} \qquad (3)$$

An iterative technique is employed to solve Eq. 3 for the time at which a certain value of P'_T occurs. Eq. 1 is then used to predict the associated pressure.

Within each computation cycle the time at stabilization t_s (when P'_T = -3 psi/min) is predicted with Eq. 3 using the current best fit of the Eq. 1 function then the pressure at stabilization P_s is predicted with Eq. 1. This is compared with previous P_s forecasts and a test for convergence to a stable solution is applied. "Stable solution" means the forecast does not change appreciably as more data are added whereupon we are confident the solution correctly represents the pressure trend and can be used to interpret the subject BOP test

Our chosen "test for convergence to a stable solution" requires a minimum of 60 consecutive P_s predictions to be within 3 psi of one another. There are many possible tests with attendant trade-offs of solution time (elapsed shut-in time to obtain the 1st stable solution) and pressure forecasting accuracy. We investigated a range of these and found the combination of 60 samples and 3 psi to be an appropriate criterion in the subject Digital BOP Testing Algorithm.

When a stable solution is obtained, the predicted value of P_s is compared to the required test pressure P_{req}. If P_s is greater than or equal to P_{req}, the test is declared successful (positive) and, given confidence in the interpretation, can be ended in order to proceed to the next test. If P_s is less than P_{req}, the test is declared unsuccessful (negative) and, given confidence in the interpretation, can be "pumped up" or repeated.

Digital BOP Testing interpretations have been and will for some time continue to be compared with chart recorder results where the chart method is presumed correct and the digital method may or may not concur. It is therefore necessary to calibrate the digital method to the chart method to facilitate comparisons. The digital algorithm is therefore focused on predicting the pressure P_s at which a test done by chart method is likely to be ended and interpreted, i.e., the shut-in pressure at which the pressure decline rate is -3 psi/min.

Digital Algorithm Performance Study

We quantified the P_s prediction accuracy of the Digital BOP Testing Algorithm when applied to a study group of 98 high pressure subsea BOP tests obtained from 17 fortnightly test suites all conducted on the same floating drilling rig in U.S. Gulf of Mexico. This group is significant in that all tests were held shut-in to pressure decline rates of -3 psi/min or less thus enabling direct comparison of $P_{s\ predicted}$ and $P_{s\ actual}$.

There is a positive relation between t_s (elapsed shut-in time at which the pressure decline rate is predicted to be -3 psi/min) and Digital BOP Testing Algorithm solution times (see Fig. 4). The average solution time in the 98-test study group was 07:37 with a maximum of 20:29 and a minimum of 01:14.

The potential time savings via Digital BOP Testing for a given test series are a linear function of the total shut-in time required to complete the series by chart recorder method. Digital BOP Testing can consistently reduce the required shut-in time of the chart recorder method by ca. 68% (see Fig. 5).

Figure 6 shows the cumulative distribution of P_s prediction errors in the study group. The error range is -0.53% to 0.81% with a mean of 0.11% and standard deviation of 0.24%. Hence, if a chart recorder test starts at 8,850 psi and the actual P_s value is 8,020 psi, we conclude that the Digital BOP Testing forecast will be within the range 8,010 psi to 8,048 psi with the most likely value being 8,029 psi.

Figure 7 shows the data of Fig. 6 in histogram format with a "bell curve" superimposed. This indicates an approximately normal distribution of error values. Assuming the rules of normal distributions apply to these data, statistically significant conclusions can be drawn from an errors analysis:

- The mean P_s prediction error of a subset (the study group of 98 high-pressure subsea BOP tests held shut-in to pressure decline rates of -3 psi/min or less) of the total population (all subsea BOP tests of which the study group is representative) falls within the range 0.11% ± 0.05% 95% of the time (or 19 times out of 20).
- The error term falls within the range -0.62% to 0.75% 99.5% of the time with 95% confidence
- The upper bound error will be less than 0.69% 199 times out of 200 (99.5% of the time)

The practical result of this errors analysis is that:

- The Digital BOP Testing Algorithm is shown to be highly accurate, on par with or better than measurement accuracies of the electronic pressure transducers and mechanical chart recorders typically in use on cementing units where subsea BOP tests are interpreted
- The condition for a test to be deemed positive (stated previously as $P_{s\ predicted} \geq P_{req}$) can incorporate our knowledge of the 99.5% upper bound error so is implemented in Digital BOP Testing software as $P_s\,(1-\delta_{upper\ 99.5}) \geq P_{req}$ where $\delta_{upper\ 99.5} = 0.0069$.

Digital BOP Testing Software

Digital BOP Testing is implemented in software with intent of supporting the current workflow of subsea BOP testing. The software is therefore designed to be seen and used at cementing units by cementing unit operators.

Figure 8 depicts the displays seen during initiation of high pressure subsea BOP tests. A pump-in graph obtained during pressurization shows the linear relation of pressure vs. volume, computed in this example to be 1,792 psi/bbl. Once pumping ends, a graph of shut-in pressure vs. time is updated with each new pressure measurement. A yellow "light" is displayed while Digital BOP Testing software analyzes the data and seeks a stable pressure forecast.

A pressure forecast is displayed when the 1st stable solution is obtained (see **Fig. 9**) and the test is interpreted as either positive or negative. The test is positive in this example so the "light" is green. The "light" would be red in the event of a negative test interpretation. Pending regulatory approval of Digital BOP Testing, the intent is for a test to end soon upon receipt of a conclusive interpretation. The test in this example was shut-in for 51 minutes additional time because it was interpreted by chart recorder method. This enables us to see how well the observed data overlay the pressure forecast.

Figure 9 shows Digital BOP Testing software obtained a stable solution 15.9 min post shut-in and $P_{s\ predicted}$ was 9,629 psi occurring at 23:19:38. The test continued to a pressure decline rate of -3 psi/min from which $P_{s\ actual}$ was 9,661 psi occurring at 23:13:12. The -32 psi difference between $P_{s\ predicted}$ and $P_{s\ actual}$ is a forecasting error of -0.33%. Digital

BOP Testing software correctly interpreted the test as positive but did so 51 minutes ahead of the chart recorder result.

Figure 10 shows a similar result from the subsea BOP test conducted subsequent to the example of **Fig. 9**. The test was held shut-in for 65 minutes to a pressure decline rate of -3 psi/min. Digital BOP Testing software obtained a stable solution 17.2 minutes post shut-in and P_s was predicted as 9,577 psi occurring at 00:48:22. $P_{s\ actual}$ was recorded as 9,608 psi occurring at 00:42:01. $P_{s\ predicted}$ was 31 psi less than $P_{s\ actual}$ representing a -0.32% forecasting error. Digital BOP Testing correctly interpreted the test as positive but did so 48 minutes in advance of the chart recorder result.

Digital BOP Testing software performs similarly when applied to high pressure surface manifold tests. Surface manifold testing is not necessarily a "critical path" rig time expenditure where Digital BOP Testing can reduce well cost. However, surface manifold testing is required along with subsea BOP testing so there is safety benefit to reduced personnel exposure to pressurized lines, work benefit to completing tasks more efficiently, reliability benefit to objectively interpreting each test plus it is preferable that subsea BOP and surface manifold tests are conducted and documented in the same manner.

Figure 11 states results from a series of 10 surface manifold tests held shut-in to pressure decline rates of -3 psi/min or less thus enabling quantification of P_s prediction accuracies and potential time savings obtainable through use of Digital BOP Testing software. The average solution time was 6.9 minutes with a mean error of -0.08% ±0.04% yielding a potential 50% reduction of the total shut-in time required by the chart recorder method of interpreting surface manifold tests.

Implementation Status

The Digital BOP Testing Algorithm has been thoroughly evaluated through retrospective analysis of hundreds of digitally recorded subsea BOP tests conducted in U.S. Gulf of Mexico. Digital BOP Testing software has been run in real time at every opportunity via remote live acquisition of subsea BOP testing data.

Digital BOP Testing software performed successfully in all trials conducted onboard *Transocean Deepwater Horizon* in U.S. Gulf of Mexico during 2006. Digital analysis was employed concurrent to the chart recorder method of test interpretation which remained the deciding factor. Field trials accomplished the not-trivial challenge to acquire sufficiently high quality data flows and interface to existing signal processing infrastructure onboard floating drilling operations.

We informed the U.S. Minerals Management Service of status and results throughout development and trials of Digital BOP Testing. We proposed a period commencing January 2007 wherein a subset of subsea BOP tests will be interpreted via digital analysis in lieu of the chart recorder method. An application to MMS for approval to use this new technology is currently in process

Conclusions

1. Individual subsea BOP tests can require upwards of an hour for pressures to stabilize acceptably when interpreted by chart recorder method.
2. In a 98-test study, digital analaysis correctly interpreted all tests in an average solution time of 07:37 with a maximum of 20:29 and a minimum of 01:14.
3. In the same 98-test study, the digital pressure prediction error range was -0.53% to 0.81% with a mean of 0.11% and standard deviation of 0.24%.
4. Digital subsea BOP test interpretation can consistently reduce the required shut-in time of the as-practiced chart recorder method by ca. 68%.
5. Digital BOP Testing software performs similarly well when applied to high pressure surface manifold tests.

Nomenclature

A, b, c, m = coefficients in pressure function
P = shut-in test pressure, psi
P_{req} = required test pressure, psi
P_s = pressure at stabilization, psi
P'_T = pressure decline rate, psi/min
t = time since shut-in, sec
t_s = time at stabilization, sec

Acknowledgement

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References

1. Franklin, C.M., Vargo, R.F., Sathuvalli, U.B. and Payne, M.L.: "Advanced Analysis Identifies Greater Efficiency for Testing BOPs in Deep Water," *SPEDC* (December 2005) 242-250.

Appendix

We list here further details of how Digital BOP Testing is presently implemented in software:

- A green "light" is assigned to a test when:
  1. P_s predictions satisfy the (60,3) criterion and
  2. $P_s(1-\delta) \geq P_{req}$ where $\delta = 0.0069$ and
  3. $(P_s - P_2)/P_s \leq 0.125$.
- A red "light" is assigned to a test when:
  1. P_s predictions satisfy the (60,3) criterion and
  2. $P_s(1-\delta) < P_{req}$ where $\delta = 0.0069$ or
  3. $(P_s - P_2)/P_s > 0.125$.

- The Digital Algorithm sometimes obtains stable solutions during analysis of subsea BOP tests in less than 5 minutes of shut-in time. When this happens, and the interpretation is positive, Digital BOP Testing software should not display a green "light" until at least 5 min of shut-in time have elapsed. This is necessary to comply with the MMS requirement of "must hold the required pressure for 5 minutes"
- If shut-in pressure falls below P_{req} before a test is ended, activate a red "light" if not already activated This rule pertains to cases where the "light" was previously yellow because a stable solution was not yet obtained

The green "light" requirement of $(P_3 - P_1) / P_3 \leq 0.125$ is explained as follows:

P_3 is the pressure associated with prediction of the time t_3 when $P'_T = -3$ psi/min. Similarly, P_1 is defined as the pressure associated with prediction of the time t_1 when $P'_T = -1$ psi/min. The purpose of examining the pressure forecast at times t_3 and t_1 is to discern if the modeled pressure decline trend extrapolates to a relatively high pressure (indicative of no leak) or a relatively low (possibly zero) pressure which would be indicative of a leak. The conditional value of 0.125 was empirically determined from a study of 145 high pressure subsea BOP tests to discern the range of normal vs. anomalous values of the quantity $(P_3 - P_1) / P_3$.

The $(P_3 - P_1) / P_3 \leq 0.125$ requirement addresses improbable, but possible, instances of tests with very small leaks initiated at sufficiently high pressures to satisfy the $P_3 (1 - \delta) \geq P_{req}$ requirement This use of the Digital BOP Testing pressure forecast is meant to provide an appropriate safeguard, in addition to those already described, to assure Digital BOP Testing meets or exceeds the capability of the as-practiced chart recorder method to correctly interpret subsea BOP tests.

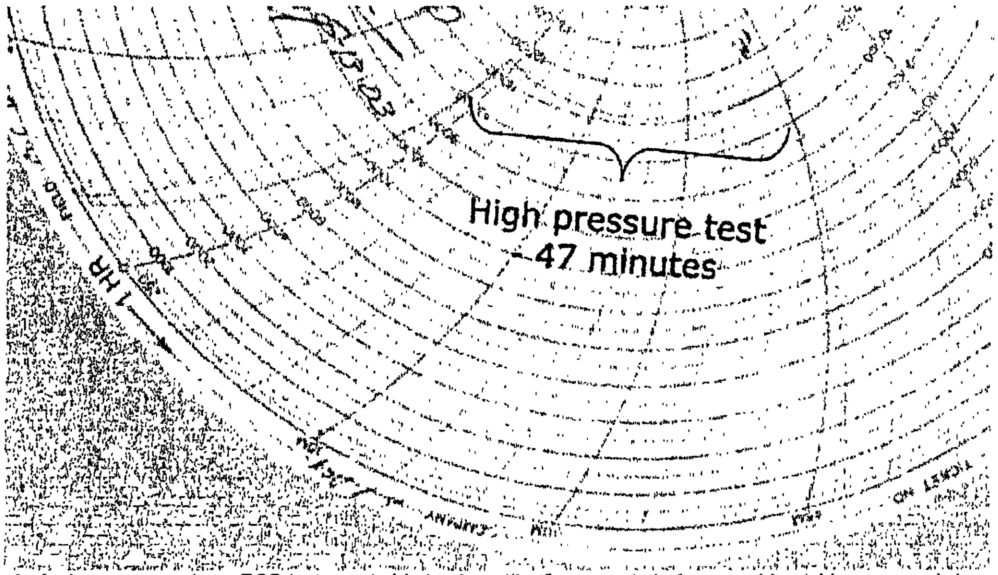

Fig. 1 - Presently, high-pressure subsea BOP tests are held shut-in until a 5-min. period of reasonably stable pressure (when viewed on a 4 hour 15,000 psi circular chart recorder) is obtained.

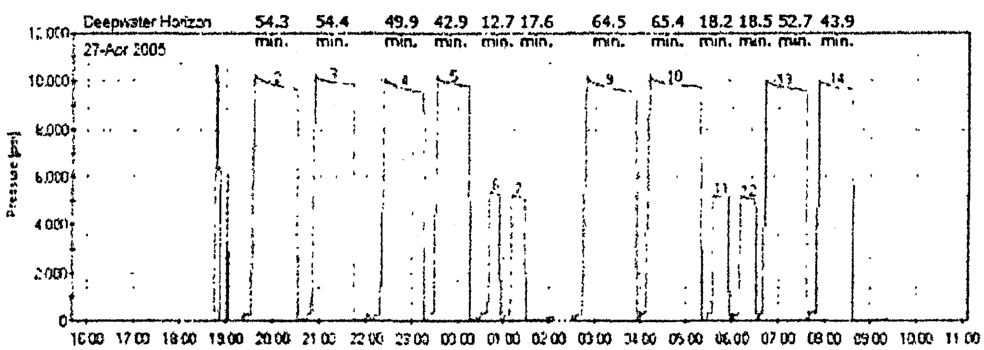

Fig. 2 - A typical series of subsea BOP tests spanning about 14 hours of elapsed time. Some high-pressure tests last an hour or longer.

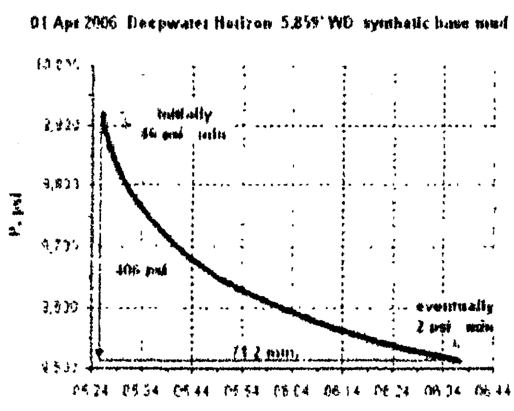

Fig. 3 - Synthetic base fluids are associated with prolonged pressure declines during subsea BOP tests.

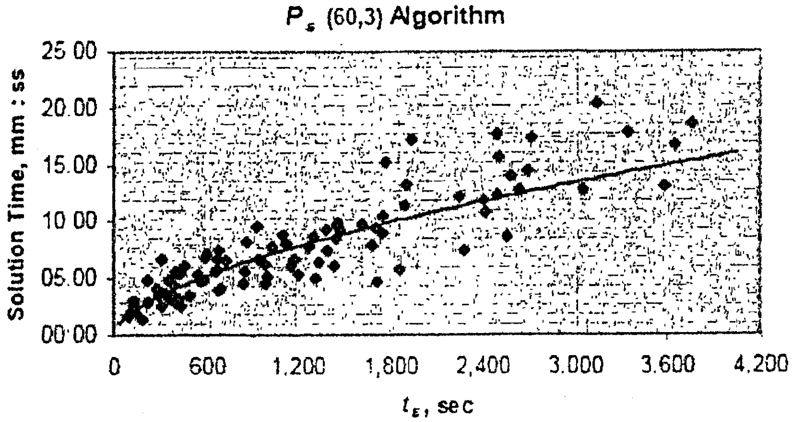

Fig. 4 – Digital BOP Testing solution times vary in proportion to the value of t_s.

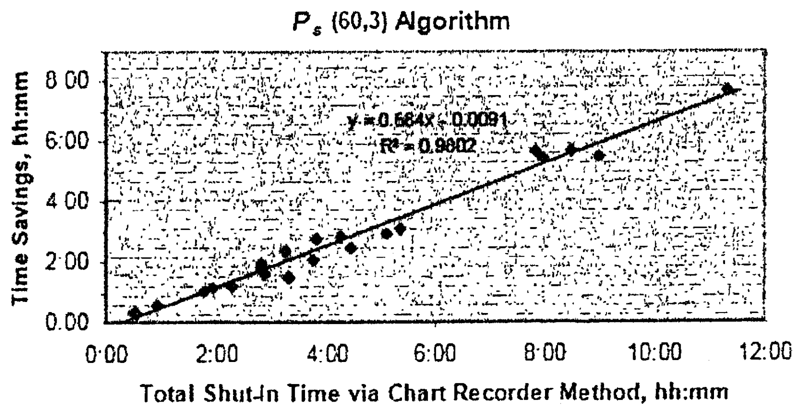

Fig. 5 - Digital BOP Testing can reduce the required shut-in time by 68%.

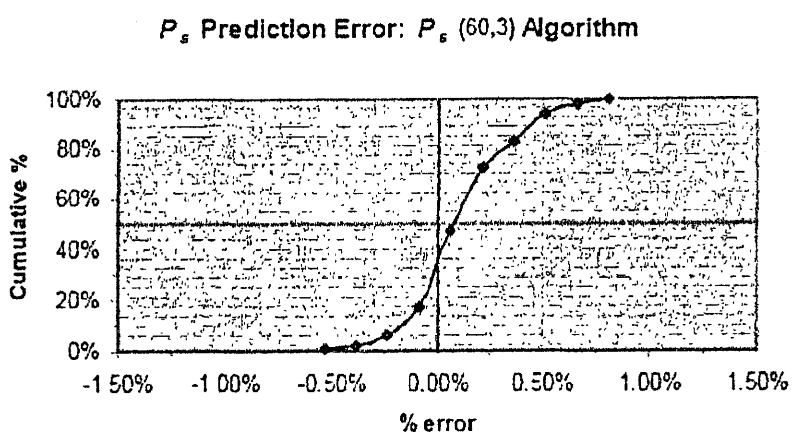

Fig. 6 - The mean P_s forecasting error is 0.11% with a standard deviation of 0.24%.

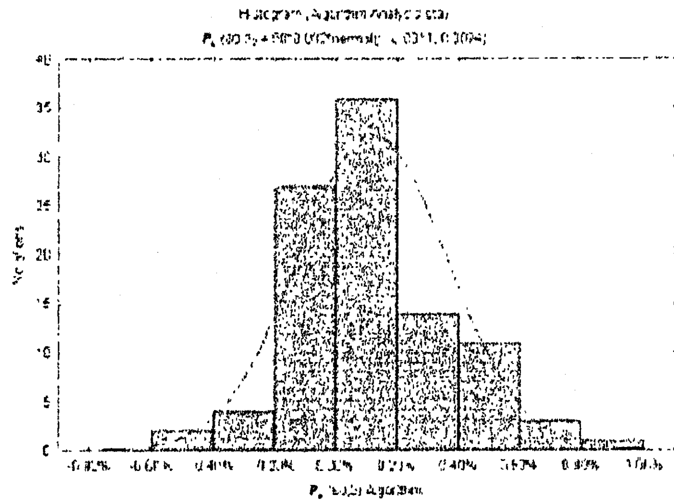

Fig. 7 - The Digital BOP Testing Algorithm produces an approximately normal distribution of P_s forecasting errors.

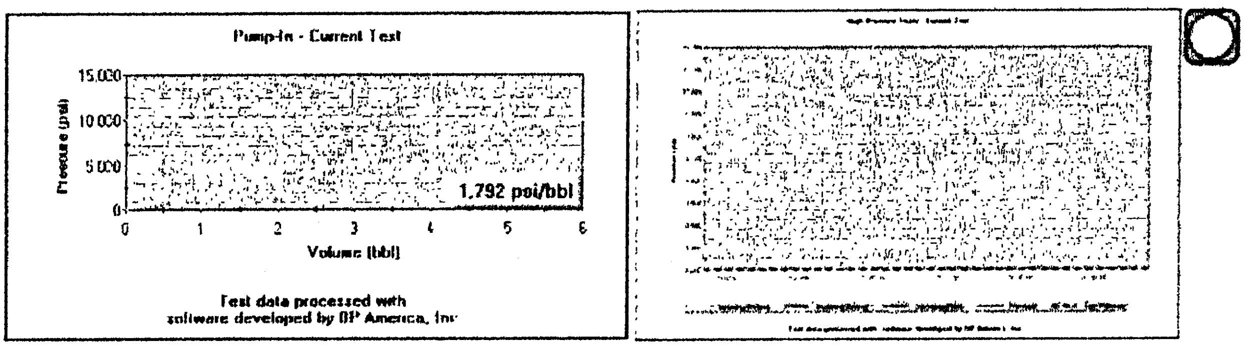

Fig. 8 - Digital BOP Testing software displays a pressure vs. volume graph during pressurization (left), then the initial shut-in pressure test data are displayed while being analyzed (right).

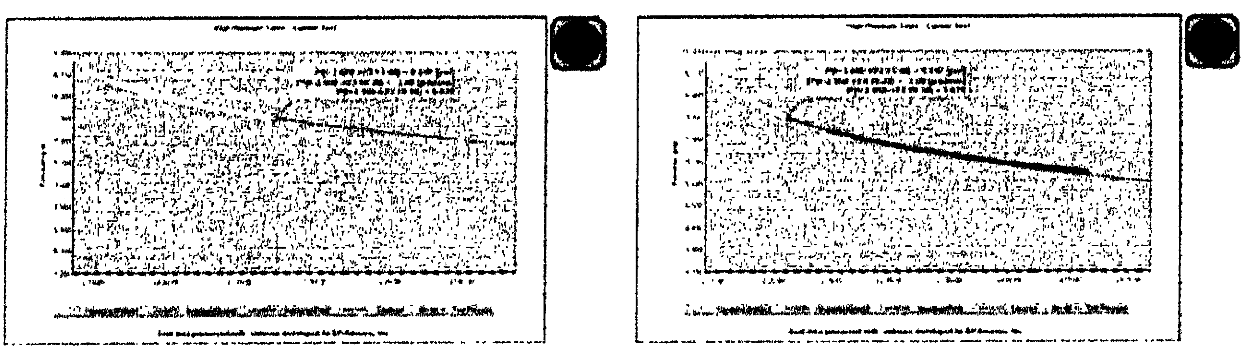

Fig. 9 – A pressure forecast is displayed and the test data are interpreted once a stable solution is obtained (left). If the test remains shut-in following the initial pressure forecast, the additional pressure data are displayed and we see the accuracy of the forecast (right). The Eq. 1 values of the pressure forecast are A=8,906.5 b=2.887E+5 c=2.246E+2 m=0.623.

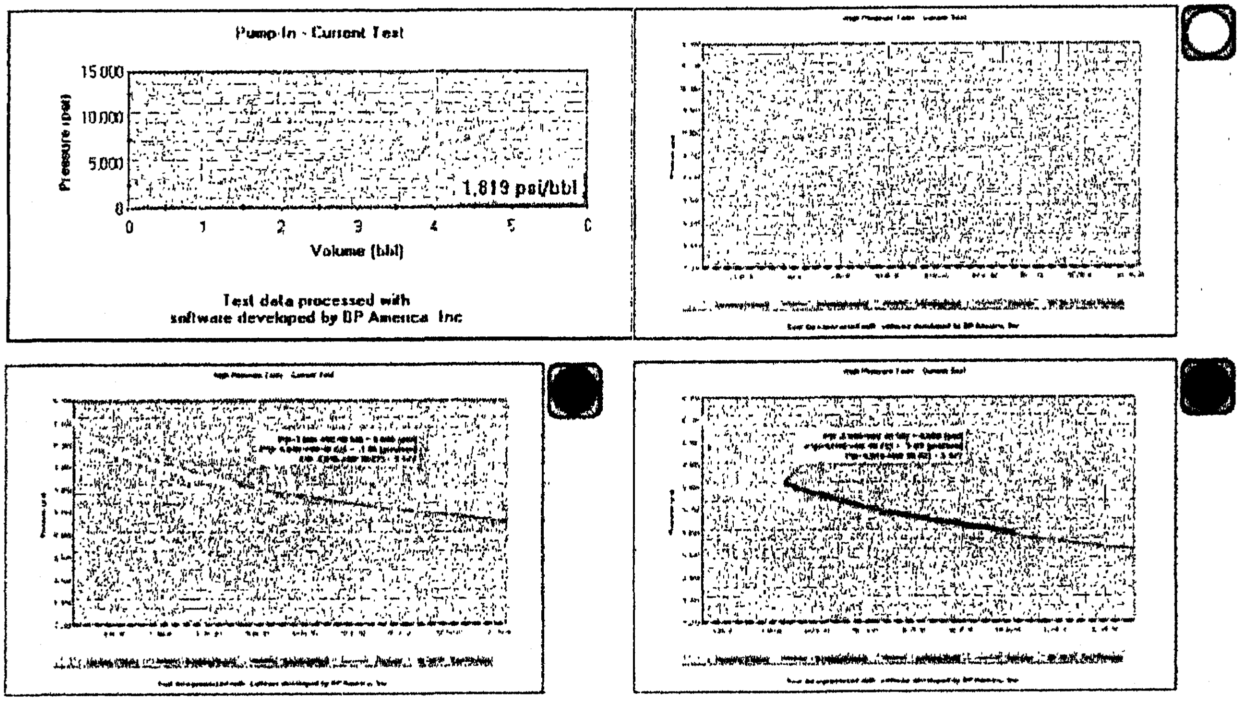

Fig. 10 – A solution was obtained 17 minutes post shut-in. P_s was predicted with 99.7% accuracy 48 minutes ahead of the chart recorder result and Digital BOP Testing correctly interpreted the test as positive. The Eq. 1 values of the pressure forecast are A=8,802.3 b=3.689E+5 c=2.804E+2 m=0.635.

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P_s (3,60) Algorithm Forecast				
Ps[psi]	error [psi]	error %	solution time	time savings
7,702	-1	-0.01%	0:04:52	0:01:19
7,656	-6	-0.08%	0:07:11	0:04:56
7,631	-3	-0.04%	0:06:54	0:06:14
5,142	-6	-0.11%	0:05:32	0:08:09
5,157	-7	-0.13%	0:05:42	0:06:52
5,195	-5	-0.09%	0:05:26	0:08:41
5,179	-6	-0.12%	0:06:09	0:07:36
7,553	-6	-0.09%	0:15:13	0:14:24
6,542	-6	-0.10%	0:06:45	0:08:45
7,702	-2	-0.03%	0:04:56	0:02:13
avg	-5	-0.08%	0:06:52	0:06:55
max	-1	-0.01%	0:15:13	0:14:24
min	-7	-0.13%	0:04:52	0:01:19
std dev	2.10	0.04%	0:03:03	0:03:41
	total shut-in time		2:17:49	
	total time savings		1:09:09	

Fig. 11 – Digital BOP Testing software performs well when applied to high pressure surface manifold tests.