New Technology Application

Digital BOP Testing

Issued January 30, 2008

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I. INTRODUCTION

As a leading deepwater operator in the Gulf of Mexico, BP has faced and found solutions to numerous technological challenges posed by the deepwater environment. One such challenge is that of increasingly time-consuming, costly subsea blowout preventer (BOP) tests.

A 2003 BP study showed the high-pressure shut-in periods of subsea BOP tests, which must hold the required pressures for 5 minutes, can take an hour or more for pressures to stabilize acceptably. This, combined with BOP stacks and drill strings requiring 12 or more separate pressure tests, contributes to prolonged delays of drilling activity during each periodic (typically every 14 days) set of BOP equipment tests.

The 2003 study linked the cause of lengthy BOP test times to operations at greater water depths where thermal effects are particularly evident when synthetic base drilling fluids are used. The study proposed that computer aided analysis of shut-in pressure behavior could greatly speed the interpretation of subsea BOP tests. BP launched a project called "Digital BOP Testing" in 2004 to develop a reliable, time-saving computer aided method for interpreting subsea BOP tests.

BP subsequently developed and thoroughly evaluated Digital BOP Testing software, concluding the software is accurate, reliable and capable of reducing subsea BOP test times by about 75%. The direct value of this time savings is estimated at $3-4 million annually per floating drilling operation. Added benefits include reduced exposure of personnel to pressurized lines, reduced wear and tear on BOP equipment and quicker resumption of drilling operations while metocean conditions are favorable.

BP advised MMS in July 2006 of a proposed approach to implementation of Digital BOP Testing in deepwater Gulf of Mexico drilling operations. BP presented to MMS in March 2007 the draft of a New Technology Application for Digital BOP Testing. MMS response was favorable and led to focus on the details of implementation.

BP has enhanced its Digital BOP Testing software to further aid implementation, and further detailed its proposed approach to implementation. These are elaborated in this newly revised New Technology Application for Digital BOP Testing.

II. CURRENT SUBSEA BOP TESTING PRACTICE

A. Interpretation with Chart Recorders

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.

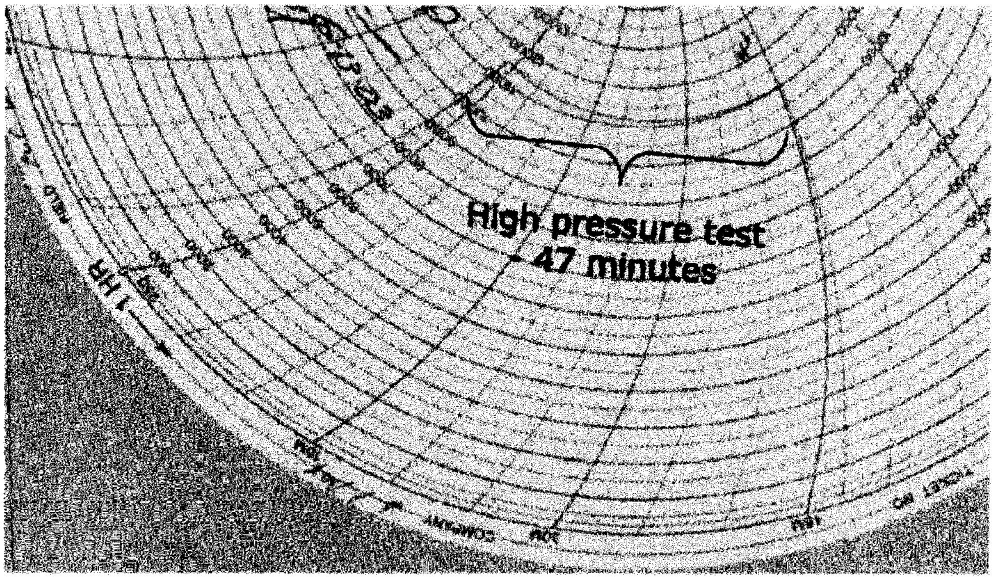

Fig. 1 - Presently, high-pressure subsea BOP tests are held shut-in until a 5-min. period of reasonably stable pressure (when viewed on a 4 hour 15,000 psi circular chart recorder) is obtained.

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 greater or lesser pressure decline rates. 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".

B. 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.

At current spread rates, the value of that time approaches $250K and in the course of a year exceeds $4 million per floating drilling rig.

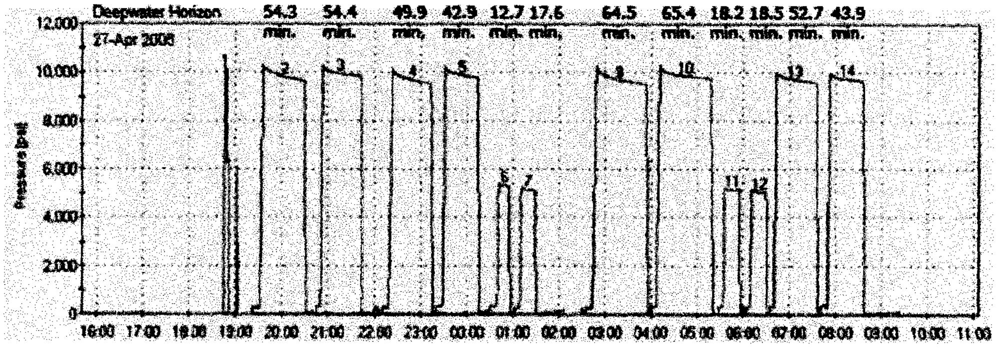

Fig. 2 - A typical series of subsea BOP tests spanning about 14 hours of elapsed time. Some high-pressure tests last an hour or longer.

Pressure declines of non-leaking tests are attributed to cooling of the fluids in the pressurized system (see **Fig. 3**):

- 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 already 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.
- During shut-in periods 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.

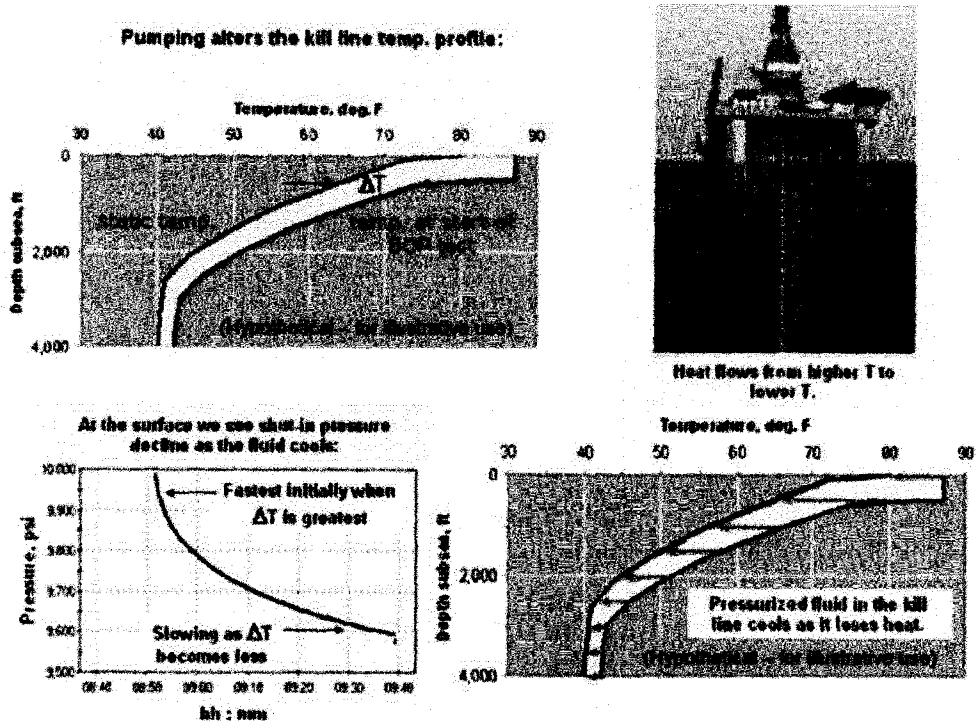

Fig. 3. Shut-in BOP test pressure declines as the pressurized fluids cool.

Subsea BOP tests tend to take longer with synthetic base muds (SBM) than with water base fluids (see **Fig. 4**) 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 so starts out warmer with more heat to lose during the test.
- SBM has lower heat capacity than water so loses heat more slowly and takes longer to cool.

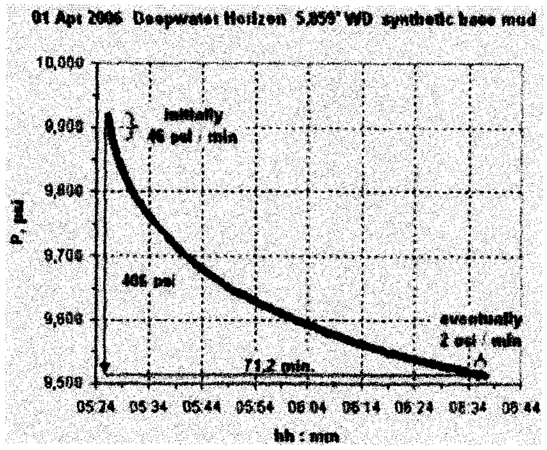

Fig. 4 - Synthetic base fluids are associated with prolonged pressure declines.

III. DIGITAL BOP TESTING AND ITS POTENTIAL BENEFITS

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. 6-8 hours of critical path rig time per test interval (typically every 14 days).
- Saving ca. $3-4 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 more efficient use of metocean conditions while favorable for drilling.

A. Digital BOP Testing Algorithm

BP developed a Digital BOP Testing Algorithm 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.

Figure 5 depicts the 6-step digital algorithm.

1 **A computer receives Pump Rate, Pump Volume and Pump Pressure data during subsea BOP tests.**

2 **The start of a shut-in test period is detected.**

3 **The shut-in pressure decline trend is analyzed for several minutes.**

4 **The computer fits a model to the pressure trend.**

5 **The model forecasts the rest of the pressure decline to a predicted stable pressure.**

6 **The computer indicates if the predicted stable pressure is above or below the required test pressure.**

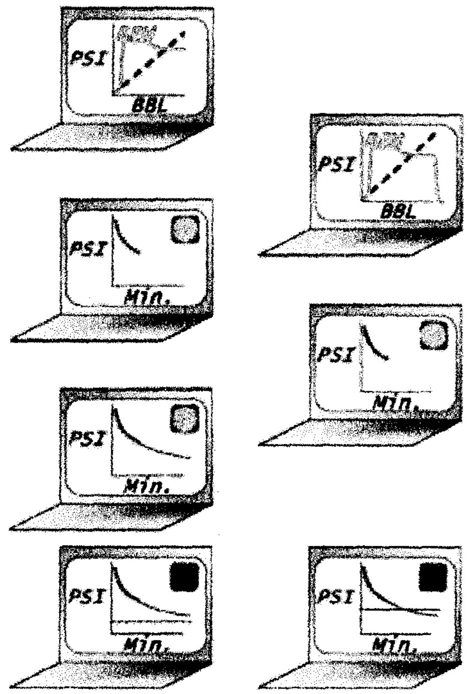

Fig. 5. The Digital BOP Testing algorithm comprises six steps.

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

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

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

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

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

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

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 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 then 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.

B. Digital Algorithm Performance Study

We quantified the P_s prediction accuracy of the Digital BOP Testing Algorithm in 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. 6**). 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.

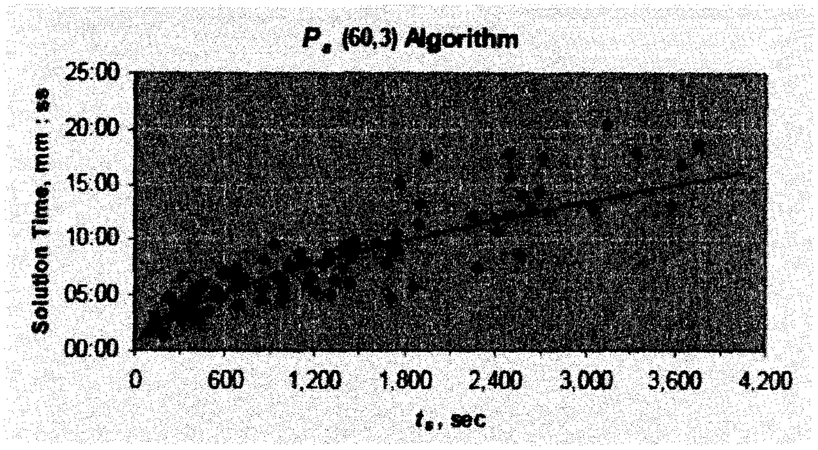

Fig. 6 – Digital BOP Testing solution times vary in proportion to the value of t_s.

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% or greater (see **Fig. 7**).

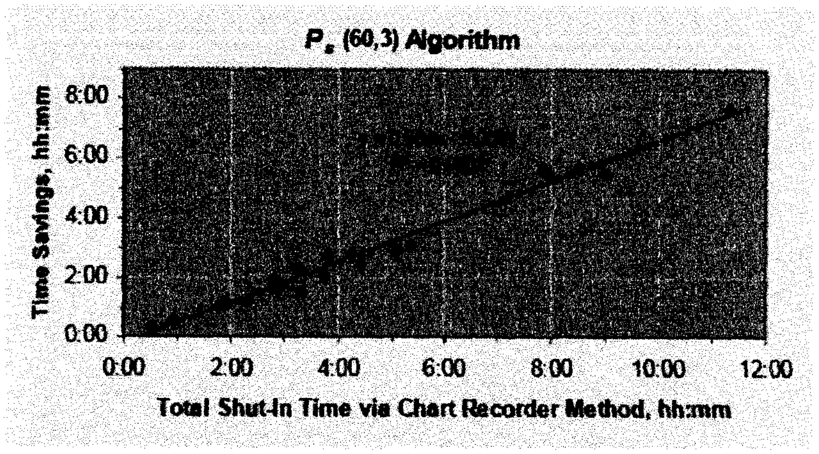

Fig. 7 - Digital BOP Testing can reduce the required shut-in time by 68%.

Figure 8 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.

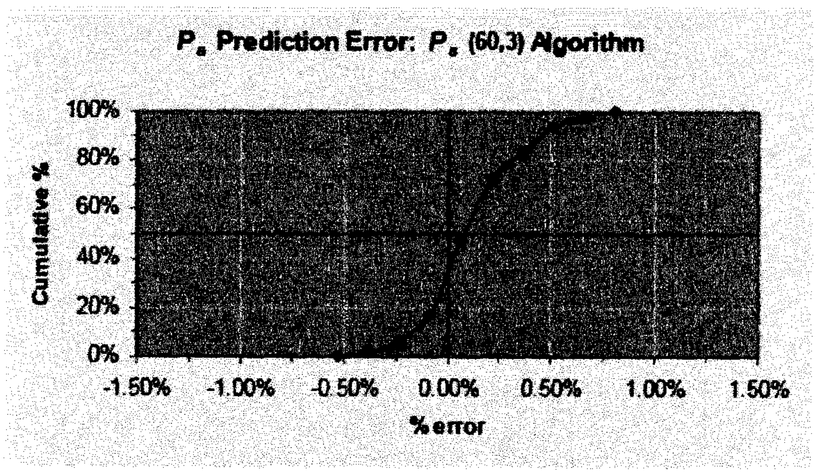

Fig. 8 - The mean P_s forecasting error is 0.11% with a standard deviation of 0.24%.

Figure 9 shows the data of **Fig. 8** in histogram format with a "bell curve" superimposed. This indicates an approximately normal distribution of error values.

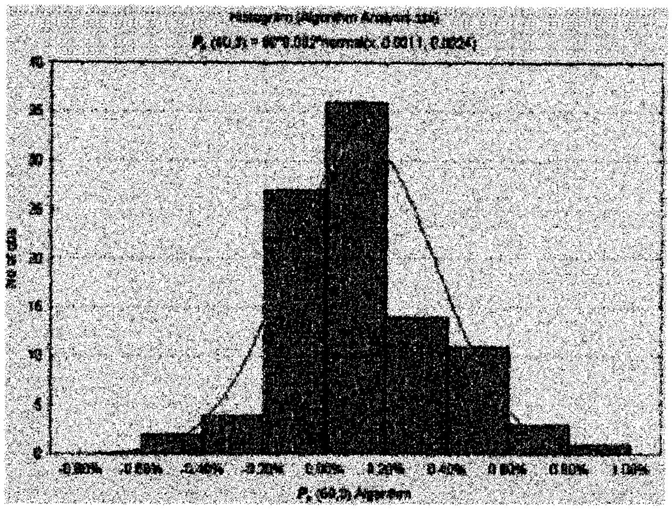

Fig. 9 - The Digital BOP Testing Algorithm produces an approximately normal distribution of P_s forecasting errors.

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 pressure transducers and chart recorders typically in use on cementing units where subsea BOP tests are interpreted.

- Knowledge of the Digital BOP Testing "error band" enables us in the Digital BOP Testing software to automatically perform a "validation check" on all pressure forecasts.

IV. 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.

Beginning November 2006 and continuing through July 2007, BETA version Digital BOP Testing software was run onboard *Deepwater Horizon* at every opportunity concurrently to BOP equipment testing interpreted via chart recorder method. The images shown in **Figures 10** through **17** and in **Figures 19**, **20** and **22** were generated by BETA version Digital BOP Testing software. These are sufficiently similar to the images generated by current commercial version Digital BOP Testing software to provide useful examples so are included in this document. Examples from current commercial version Digital BOP Testing software are presented later in this document (Appendix 1, pp 32-42).

Figures 10 and **11** depict 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 appears and 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.

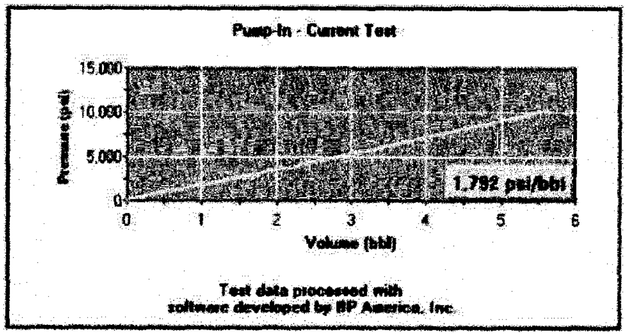

Fig. 10 - Digital BOP Testing software displays a pressure vs. volume graph during pressurization.

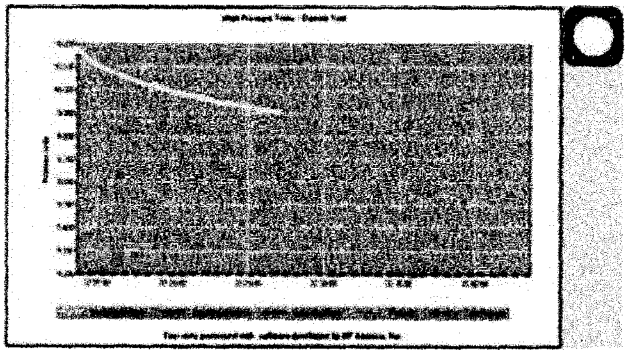

Fig. 11 - The initial shut-in pressure test data are displayed while being analyzed.

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A pressure forecast is displayed when the 1st stable solution is obtained (see **Fig. 12**) 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, the intent is for a test to end soon (at the discretion of the responsible testing personnel, as is presently the case) 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.

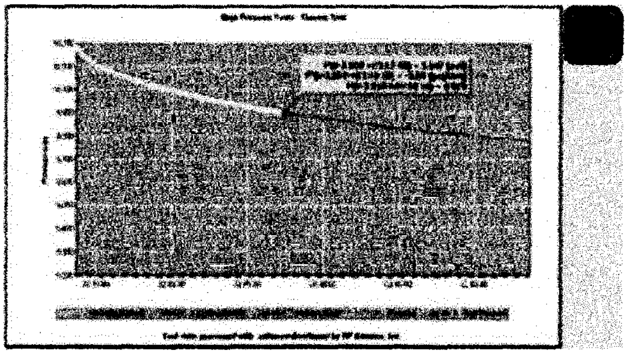


Fig. 12 – A pressure forecast is displayed and the test data are interpreted once a stable solution is obtained.

Figure 13 shows Digital BOP Testing software obtained a stable solution 15.9 min post shut-in and $P_{s\ predicted}$ was 9,629 psi. The test continued to a pressure decline rate of -3 psi/min from which $P_{s\ actual}$ was 9,661 psi. 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.

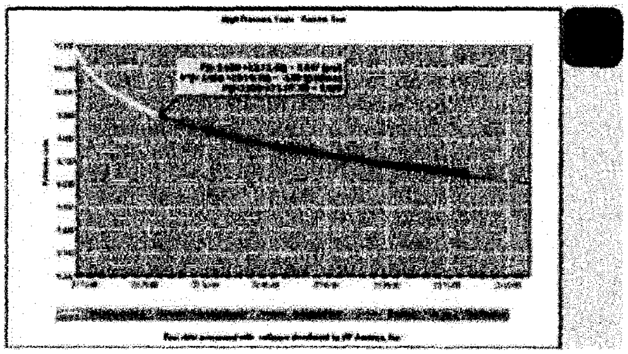


Fig. 13 – If the test remains shut-in following the initial pressure forecast, additional pressure data are displayed and we see the accuracy of the forecast. The Eq. 1 values of the pressure forecast are A=8,906.5 b=2.887E+5 c=2.246E+2 m=0.623.

Figures 14 thru **17** show similar results from the subea BOP test conducted subsequent to the examples of **Figs. 10** thru **13**.

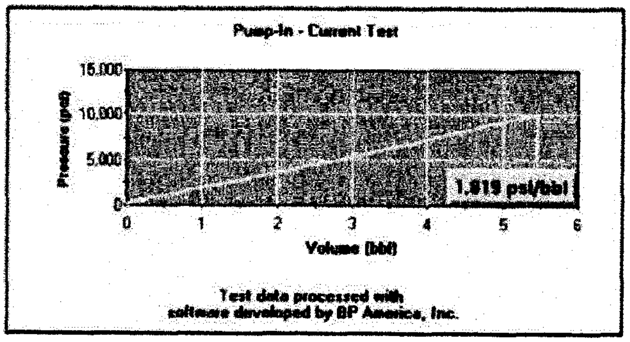


Fig. 14 - The pump-in graph shows the linear relation of pressure vs. volume, computed in this example to be 1,819 psi/bbl.

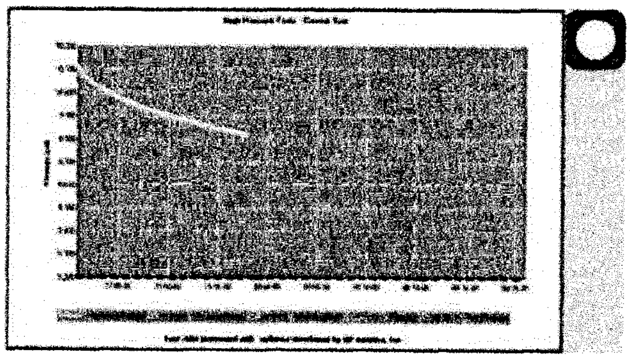


Fig. 15 - The initial shut-in pressure test data are displayed while analyzed, in this case for 17.2 min.

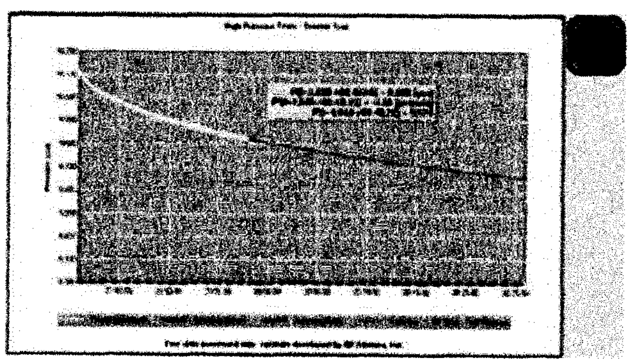


Fig. 16 – A pressure forecast is displayed once a stable solution is obtained and the test data are interpreted (positive in this example).

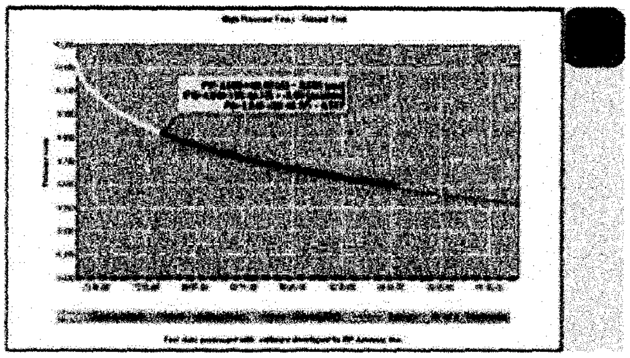


Fig. 17 – P_s was predicted with 99.7% accuracy 48 minutes ahead of the chart recorder result and Digital BOP Testing correctly interpreted the test as positive. The Eq. 1 values of the pressure forecast are A=8,802.3 b=3.689E+5 c=2.804E+2 m=0.635.

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. $P_{s\ actual}$ was recorded as 9,608 psi. $P_{s\ predicted}$ 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.

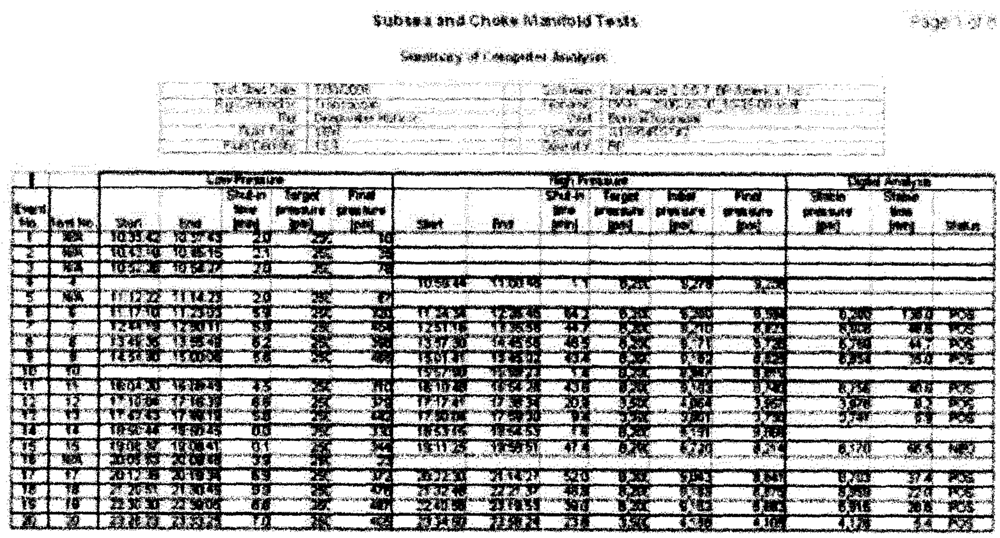
Digital BOP Testing software performs similarly when applied to high pressure surface manifold tests. Surface manifold testing is not necessarily a "critical path" rig time expenditure where Digital BOP Testing can reduce well cost. However, surface manifold testing is required along with subsea BOP 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 18 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.

DWH 2006-05-11 SURFACE MANIFOLD TESTS				
[illegible]				
P[illegible]	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
5,196	-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. 18 – Digital BOP Testing software performs well when applied to high pressure surface manifold tests.

Digital BOP Testing software generates a summary report for each series of subsea BOP and surface manifold tests (see **Fig. 19**). This report is intended to be placed on file same as circular chart records are kept onboard the rig.


Subsea and Choke Manifold Tests

Summary of Computer Analysis

Low Pressure | High Pressure | Digital Analysis

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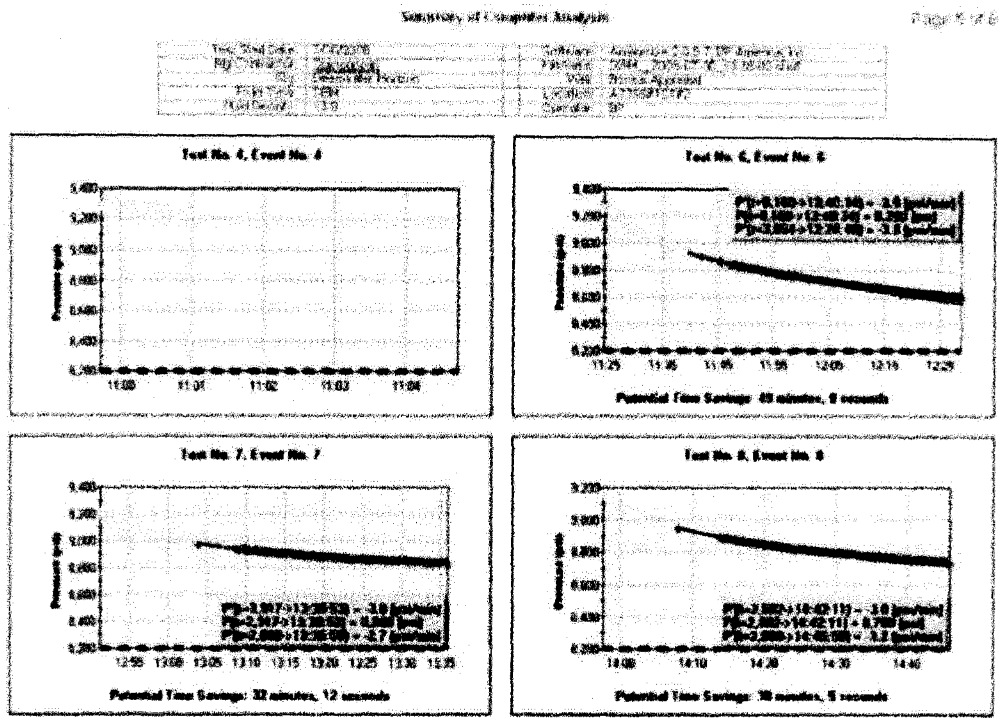


Fig. 19. Examples from the Summary Report generated by Digital BOP Testing software.

A. Software Details

Following are further details of how Digital BOP Testing is implemented in software:

- A green "light" is assigned to a test when:
  1. P_s predictions satisfy the (60,3) criterion <u>and</u>
  2. $P_s \geq P_{req}$ <u>and</u>
  3. $(P_s - P_z) / P_s \leq 0.125$.
- A red "light" is assigned to a test when:
  1. P_s predictions satisfy the (60,3) criterion <u>and</u>
  2. $P_s < P_{req}$ <u>or</u>
  3. $(P_s - P_z) / P_s > 0.125$.
- The Digital Algorithm sometimes obtains stable solutions during analysis of high pressure subsea BOP tests in less than 5 minutes of shut-in time. When this happens, and the interpretation is positive, Digital BOP Testing software does not display a green "light" until at least 5 min. of shut-in time have elapsed. This is in accordance with the MMS requirement of "each test must hold the required pressure for 5 minutes".

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

> P_s is the pressure associated with prediction of the time t_s when $P'_T = -3$ psi/min. P_z is defined as the pressure associated with prediction of the time t_z when $P'_T = -1$ psi/min. The pressure forecast is examined at times t_s and t_z 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 $(P_s - P_z) / P_s$.

The $(P_s - P_z) / P_s \leq 0.125$ requirement addresses improbable, but possible, instances of tests with very small leaks initiated at sufficiently high pressures to satisfy the $P_s \geq P_{req}$ 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.

B. Safeguards Against Error

This section discusses how Digital BOP Testing software responds to pressure tests potentially indicative of leaks. As previously stated, the software interprets tests as negative (red "light") for either of two reasons: either (i) $P_s < P_{req}$ or (ii) $(P_s - P_z)/P_s > 0.125$. This creates three possible combinations of Conditions (i) and (ii) that will cause a red "light":

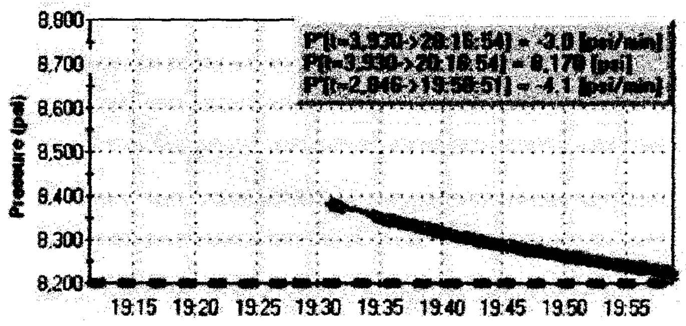
1. (i) True (ii) False
2. (i) True (ii) True
3. (i) False (ii) True .

Each is discussed next:

1. (i) True (ii) False
   This indicates the pressure at stabilization P_s is predicted to be less than required but the modeled pressure decline trend extrapolates to a relatively high pressure (indicative of no leak). The recommended solution is a pump-up to a sufficiently high pressure such that the predicted value for P_s passes the test.

Figure 20 depicts such an example. Digital BOP Testing assigned a "red light" because P_s was predicted to be 8,170 psi vs. a required digital value of at least 8,200 psi. The test was held shut-in to a pressure decline rate of -4.1 psi/min. This is near the limits of chart recorder resolution, meaning the pen trace appeared nearly constant for at least 5 minutes at a pressure greater than the required chart value of P_{req} = 8,200 psi, hence the test could be deemed positive per chart recorder method although the Digital BOP Testing interpretation was negative.

Test No. 15, Event No. 15



Potential Time Savings: 27 minutes, 50 seconds

Fig. 20. Digital BOP Testing interpreted this test as negative because P_s was predicted to be less than required. In practice, the solution would be to "pump-up" the pressure upon 1st indication of "red light" status then confirm via Digital BOP Testing that P_s is greater than required.

The values of P_s and P_z were 8,170 psi and 7,936 psi meaning $(P_s - P_z)/P_s = 0.029 < 0.125$ (indicative of no leak). The recommended solution in this instance is for the cementing unit operator to "pump-up" the pressure to about 8,500 psi then wait for Digital BOP Testing to analyze the new pressure decline with the likely outcome being a green "light". The total elapsed time would be less than the 47.2 min. of shut-in time depicted in the example, thus saving time and producing an unambiguous result.

2. (i) True (ii) True

This indicates the pressure at stabilization P_s is predicted to be less than required plus the modeled pressure decline trend extrapolates to an anomalously low (possibly zero) pressure (indicative of a leak). A pump-up is unlikely to remedy this so, unless a leak can be located and remedied, repeat tests are likely to be negative also.

Figure 21 depicts such an example. This comes from a study in which a very small computationally simulated leak was superimposed on a real data set of a non-leaking BOP test. The simulated leak caused the final pressure decline rate to be -7.2 psi/min (vs. -4.2 psi/min in the non-leaking case) and the predicted value of P_s was 8,544 psi (vs. 9,414 psi). The $(P_s\text{–}P_2)/P_s$ value corresponding to the 1st stable solution in the non-leaking case was 2.9% and for the leaking case was 16.4%. This supports the selection of 12.5% as the $(P_s\text{–}P_2)/P_s$ cutoff value in Condition (ii).

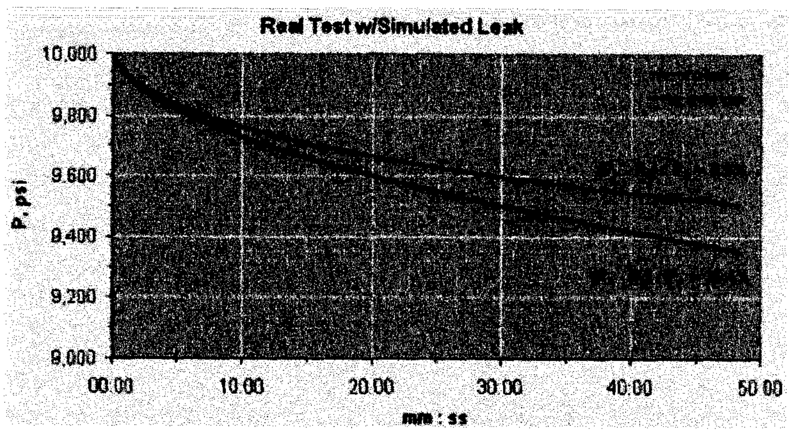


Fig. 21. Analysis of a simulated leak.

3. (i) False (ii) True

This indicates the pressure at stabilization P_s is predicted to be greater than required but the modeled pressure decline trend extrapolates to an anomalously low (possibly zero) pressure (indicative of a leak). Unless a leak can be located and remedied, repeat tests are likely to be negative also.

This could occur if the leaking test in **Figure 21** was pumped-up by at least 900 psi causing the predicted value of P_s to be greater than required. However, the value of $(P_s\text{–}P_2)/P_s$ would likely remain > 12.5% thus correctly causing a red "light" interpretation.

Very few instances of confirmed leaks have been observed during development of Digital BOP Testing. In the majority of instances the leaks have been immediately obvious whereupon the pump operators quickly released the pressure within seconds of initial shut-in. Digital BOP Testing software is not needed in such cases, nor does it obtain a stable pressure forecast within such a short time period hence the "light" remains YELLOW.

We attempted to create small, steady surface leaks during high-pressure testing on *Deepwater Horizon* by slightly opening a needle valve installed expressly for this purpose and observed:

1. The smallest steady leaks caused pressures to fall within minutes to below the required test pressures. Digital BOP Testing software did not obtain a stable pressure forecast hence the "light" remained YELLOW until obvious that pressures had become too low whereupon the "light" turned RED.

2. Smaller "leaks" became smaller with time possibly due to a tendency toward plugging of the tiny valve orifices. Digital BOP Testing software did not obtain a stable pressure forecast due to the unsteady pressure influence of the leaks hence the "light" remained YELLOW. Pressures eventually fell to below the required test pressures leading to an obvious negative test interpretation obtainable by either chart or digital methods.

We concluded that Digital BOP Testing software either remains YELLOW in the presence of the most likely leaks or will correctly indicate RED as in response to the small, steady -3.0 psi/min leak depicted in **Figure 21**. We have not seen and do not expect to see an instance where a leaking pressure response was misinterpreted.

C. Implementation Status

The Digital BOP Testing Algorithm was evaluated initially through retrospective analysis of hundreds of digitally recorded subsea BOP tests conducted in U.S. Gulf of Mexico during the period July 2004 through September 2005. Once the algorithm was incorporated in BETA version software then, commencing October 2005, Digital BOP Testing software was run in real time at every testing opportunity, remotely from land at first followed by live onboard operation. Our knowledge and conclusions about Digital BOP Testing are supported by a large data sample spanning greater than 3 years of subsea BOP test results.

Field trials have accomplished the not-trivial challenge to acquire sufficiently high quality data flows and interface to existing signal processing infrastructure onboard floating drilling operations.

A dedicated Digital BOP Testing computer, monitor and BETA version software were installed in the cementing unit on *Transocean Deepwater Horizon* in November 2006 (see **Figure 22**). This was accompanied by training of cementing unit personnel. Since then, Digital BOP Testing software has been run concurrently to the chart recorder method of test interpretation (which remains the deciding factor) whenever BOP testing occurs.

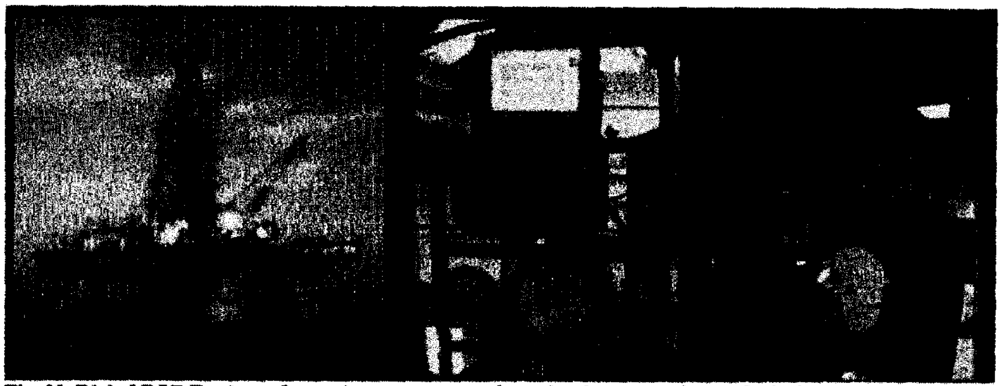


Fig. 22. Digital BOP Testing software is run concurrently to the chart recorder method of test interpretation on Transocean Deepwater Horizon.

Figure 23 depicts results obtained during inaugural use of Digital BOP Testing software by cementing unit personnel onboard *Deepwater Horizon*.

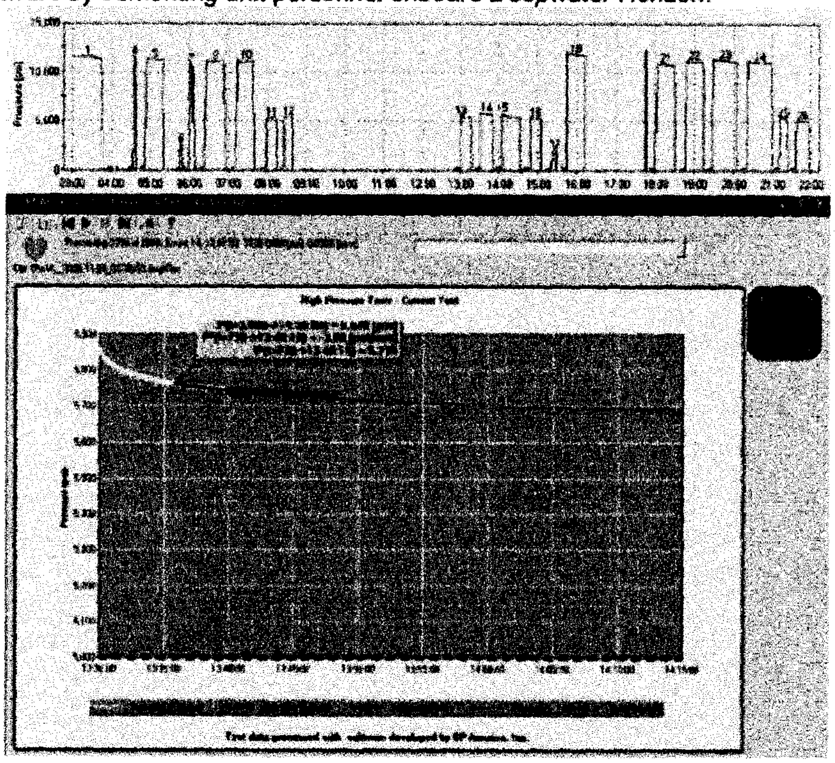


Fig. 23. Results obtained during inaugural use by cementing unit personnel of Digital BOP Testing software onboard Transocean Deepwater Horizon in November 2006.

The BETA version software on *Deepwater Horizon* was replaced by "commercial release" software in July 2007. The commercial release software is considered fully verified and ready for inaugural application as the primary subsea BOP test interpretation method.

D. Onboard Installation of Digital BOP Testing Software

The Digital BOP Testing software installation on *Transocean Deepwater Horizon* is schematically depicted in **Figure 24**. Cementing pump pressure, rate and volume measurements are sent via intranet connection to the Digital BOP Testing computer located near the cementing unit. The computer is attached to a touch screen monitor located on the cementing unit where Digital BOP Testing software images are displayed.

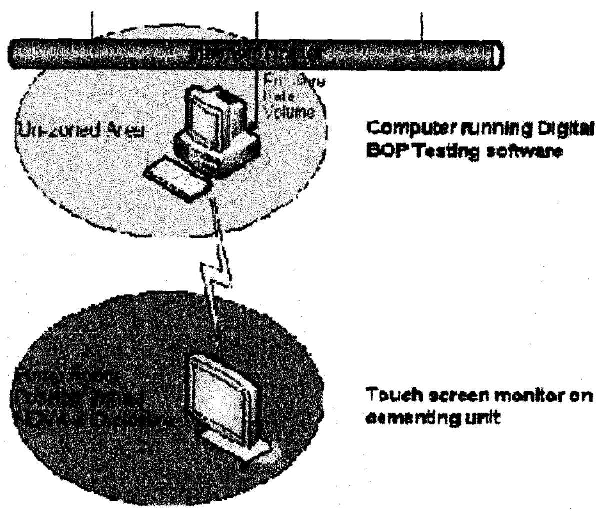


Fig. 24. Schematic of the Digital BOP Testing software installation on Transocean Deepwater Horizon.

Each installation configuration may vary somewhat from rig to rig but with the common requirement that the Digital BOP Testing computer program Anatomize receives valid measurements of pump pressure, rate and volume via an Ethernet source. The general installation scheme for any rig is depicted in **Figure 25**.

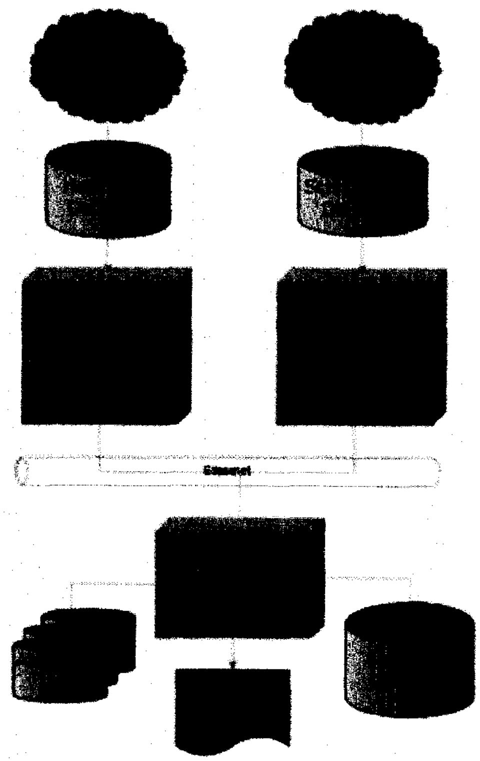


Fig. 25. Generalized Digital BOP Testing software installation on any rig.

Data are initially captured electronically by the onboard cementing or data logging service company and internalized for storage. A service company process (a program acting as a server) makes the data available on an Ethernet connection at a particular IP address and Port. Anatomize appears as a client to the service company's server.

Time, pressure, flow rate and cumulative volume data are made available by the server approximately every second. Anatomize reacts by storing the data in fast memory and in the case of a high-pressure test analyzing all data in the test, creating a forecast and displaying the results of the analysis. Periodically the fast memory version of the data is stored to a local hard drive and will serve as long-term storage. There is one data file per test series. Reference to these test series files is maintained in a database. This allows easy reference and high-level management.

V. PROPOSED ADOPTION of DIGITAL BOP TESTING

BP proposed to MMS an approach to introducing Digital BOP Testing in deepwater Gulf of Mexico drilling operations (July 2006, Lafayette). MMS response was favorable and BP was advised to submit an application to use new or unusual technology to the Technical Assessment and Operation Support (TAOS) Section, New Orleans. A draft of this New Technology Application was presented to MMS in March 2007 (New Orleans).

MMS response was once again favorable and accompanied by helpful suggestions that are incorporated in this document.

The time since March 2007 was used to: (1) conclude thorough BETA testing of Digital BOP Testing software on *Deepwater Horizon*; (2) author, install and thoroughly test commercial release Digital BOP Testing software on *Deepwater Horizon*; (3) prove and document reliable, accurate performance of the commercial release Digital BOP Testing software. We are confident that BP's Digital BOP Testing method is qualified and fully ready for use in Gulf of Mexico, so are now making this request for approval to commence implementation.

BP proposes, beginning 1Q 2008, to use Digital BOP Testing on Transocean *Deepwater Horizon* as the primary basis for interpreting high pressure subsea BOP equipment and surface manifold tests. Contingent upon demonstrating successful implementation to MMS, BP would then seek approvals to introduce Digital BOP Testing on additional BP operated deepwater drilling rigs.

BP believes Digital BOP Testing is compatible with all requirements of 30 CFR 250.447 through 30 CFR 250.450, hence does not require a change of rules. Pending approval of this application, BP proposes to use the Application for Permit to Drill (APD) to gain authorization of Digital BOP Testing use on specific wells. This will enable MMS to retain control and knowledge of the wells where Digital BOP Testing will be applied.

A. Rules

Six proposed rules for using Digital Interpretation of Subsea Blowout Preventer Tests, applicable also to high-pressure testing of surface pressure control equipment, are stated as follows:

Rule 1

In floating drilling operations, the 1st high-pressure test of any BOP equipment *testing sequence*[1] shall be interpreted by chart recorder method. Digital BOP Testing software may be run concurrently to *demonstrate validation*[2].

[1] A *testing sequence* constitutes (a) a series of high-pressure subsea BOP tests only, or (b) a series of high-pressure surface manifold tests only, or (c) high-pressure tests commenced more than 4 hours since the previous full-duration high-pressure test.

[2] *Demonstrate validation* means the test lasts sufficiently long to (a) obtain both a chart recorder interpretation and a software interpretation (i.e., green light or red light) and (b) the 1st-light Digital Testing pressure forecast is proven to be within acceptable bounds of the actual pressure result.

Rule 2

If during a testing sequence Digital BOP Testing software demonstrates validation, then it may be used to interpret subsequent tests *in that testing sequence*[3].

[3] *In that testing sequence* means if the equipment being tested changes from subsurface BOP to surface manifold or vice versa, then by definition the next high-pressure test begins a new testing sequence and must be interpreted according to Rule No. 1.

Rule 3
If during any test the Digital BOP Testing 1st-light pressure forecast is invalid, then

(a) the current test should be interpreted per chart recorder method and the next test must be interpreted by chart recorder method with the option of once again running Digital BOP Testing software concurrently to demonstrate validation (per Rule 2), or

(b) the current test can either be "pumped-up" or ended, then repeated, with the option of once again running Digital BOP Testing software concurrently to demonstrate validation (per Rule 2).

Rule 4
During tests for which it is permissible to use Digital BOP Testing software as the primary interpretation method, it will be permissible to end tests and interpret them as POSITIVE when, and only when, the software displays a green "light".

Rule 5
If, during tests for which it is permissible to use Digital BOP Testing software as the primary interpretation method, a red "light" is displayed, it will be permissible to either

(a) remain shut-in then if the interpretation changes to POSITIVE it will be permissible to interpret the test as POSITIVE and end it (per Rule 4), or

(b) "pump up" the pressure and interpret the new pressure decline via Digital BOP Testing software, or

(c) repeat the test by releasing then reapplying pressure to the same components and interpret the new pressure decline via Digital BOP Testing software, or

(d) remain shut-in until a definitive interpretation is made via chart recorder, and declare the chart recorder result as definitive irrespective of the Digital BOP Testing software result.

Rule 6
All test results shall be documented and filed for inspection via traditional charts in combination with Digital BOP Testing software-generated reports.

Software-generated reports shall document the valid or invalid status of Digital BOP Testing 1st-light pressure forecasts, and indicate the Digital BOP Testing software interpretation of each test.

The same personnel responsible for approving chart recorder test records are responsible for approving Digital BOP Testing records.

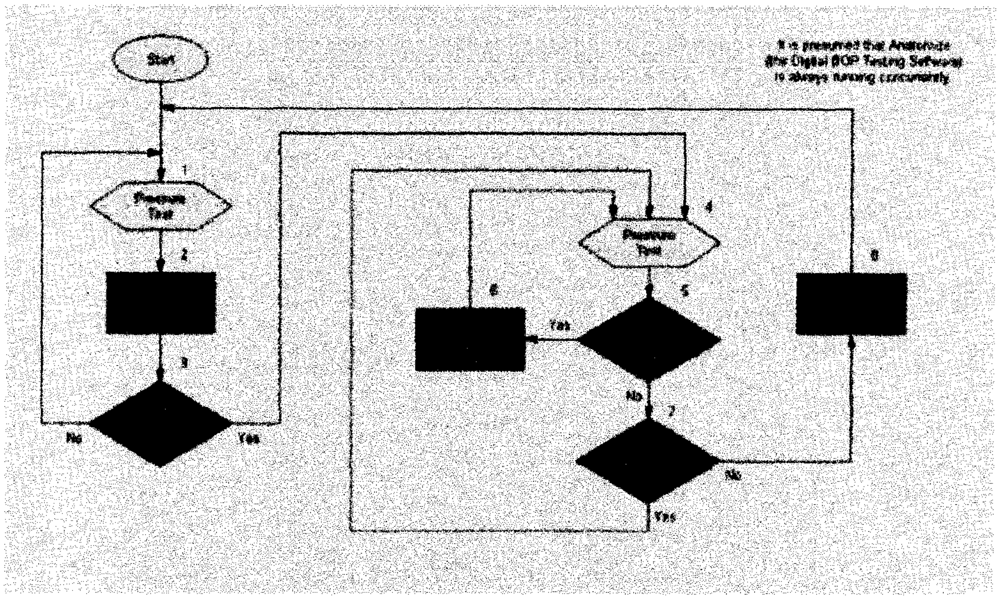


Fig. 26. Digital BOP Testing sequence logic.

Figure 26 (above) is a flow chart depicting the logic of Rules 1 through 5. Each possible step is numbered, with the corresponding captions as follows:

Start Anatomize and leave it running throughout the testing operations.

1. Perform a pressure test.
2. Interpret test by Chart Recorder Method.
3. If Anatomize Forecast invalid go to Step 1.
4. Perform a pressure test.
5. If Anatomize Forecast is valid go to Step 7.
6. Interpret using Anatomize and go to Step 4.
7. If it looks like a pump-up and reevaluation is appropriate go to Step 4.
8. Interpret test by Chart Recorder Method then go to Step 1.

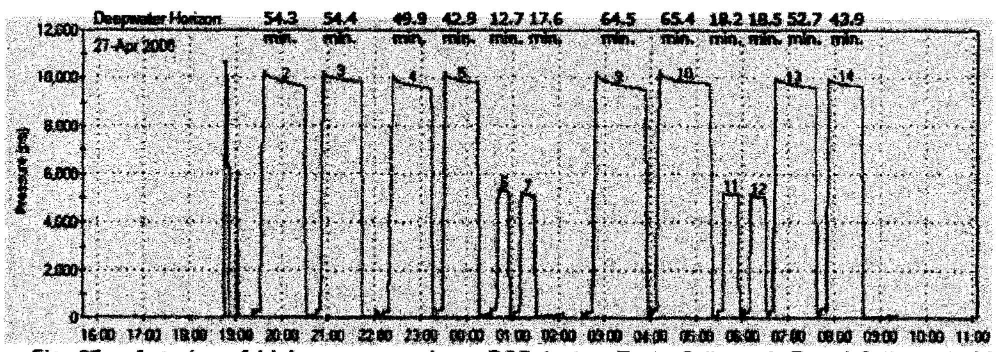


Fig. 27 – A series of high-pressure subsea BOP tests. Tests 2 through 7 and 9 through 14 constitute a testing sequence.

In the example of **Figure 27** the subsea BOP test labeled 2 would be interpreted by chart recorder method according to Rule 1 because it is the 1st high-pressure test of a new sequence. If the Digital BOP Testing software were to be validated during test 2, then subsequent tests 3 thru 7 and 9 thru 14 could potentially be interpreted via Digital BOP Testing software because (a) the type of equipment being tested remained the same (in this case subsea BOPs) and (b) the elapsed time between adjacent tests was in all cases less than 4 hours. If at any time during tests 3 thru 7 or 9 thru 14 the Digital BOP software were to produce an invalid status, then Rule 3 would apply.

B. Calibration of Sensors

A question arose in the March 2007 meeting with MMS regarding how can we be assured that electronic pressure sensors used in Digital BOP Testing are correct.

Different sensors send pressure signals to Digital BOP Testing software as opposed to the circular chart recorders used on cementing units for interpreting subsea BOP and surface manifold tests. This means it is possible that separate pressure measurements of the same pressure source may not agree.

The pressure sensor connected to the chart recorder is the one already relied upon during chart recorder interpretation of pressure tests, so tends to be presumed correct. The cementing services provider is responsible for assuring correctness of this sensor and documenting proof of calibration. This remains true when Digital BOP Testing is used concurrently.

The pressure sensor connected to Digital BOP Testing software may come from several possible sources. Using *Deepwater Horizon* as an example, there are two pressure transducers installed at the cementing unit. One belongs to the cementing unit and feeds its data collection system, so Halliburton is responsible for it. The other, mounted adjacent to the cementing unit transducer, belongs to the Sperry Sun Insite data logging system, so Sperry Sun (Halliburton) is responsible for it. We have connected the filtered and processed output of both sensors to Digital BOP Testing software and found both to be satisfactory. A third possibility would be to install a pressure sensor dedicated strictly to Digital BOP Testing. We have not done that on *Deepwater Horizon* because it has not been necessary, but it would be an option on any rig if needed to assure reliable pressure measurements.

Regardless of the source of electronic pressure measurements used in Digital BOP Testing, BP holds the respective providers responsible to supply properly calibrated and functioning sensors with documentation of correct calibration. To facilitate comparison of chart vs. digital measurements, and their interpretations, BP will require the pressure measurements recorded on charts and by Digital BOP Testing software to be within reasonable agreement, with the greater of 50 psi or 1% difference being the suggested tolerance.

C. Software Ownership and Responsibility

It is important to understand who owns and controls the Digital BOP Testing software, and how it will be handled.

BP developed, owns, and is responsible for maintaining, verifying and documenting the performance of its Digital BOP Testing software. BP is seeking MMS approval to use the specific BP-owned software described in this document per the specific rules, terms and conditions proposed herein. BP is not seeking MMS approval of all forms of digital BOP testing and software.

BP does not intend to distribute the source code of its Digital BOP Testing software. This is to prevent unintended or unauthorized revisions to the source code or distribution of unverified software versions. The goal is to assure that the Digital BOP Testing algorithm actually in use is the same algorithm presented to and approved by MMS.

BP may occasionally elect to make minor software revisions that constitute useful improvements. BP will, in such instances, assure software revisions are performed correctly by well qualified programmers.

BP does not anticipate making major revisions to the Digital BOP Testing algorithm but would, in such instances, inform and seek approval from MMS to implement software considered significantly different than that already approved.

BP intends to distribute, or license use of, only executable versions of its Digital BOP Testing software. Executable versions will not be readily alterable nor will unauthorized alteration or replication be allowed under terms agreed between BP and licensed users.

D. Installation and Maintenance

It is helpful to understand who will install and maintain Digital BOP Testing software on deepwater drilling rigs.

BP demonstrated on *Deepwater Horizon* ability to successfully contract qualified services for making the necessary computer equipment installations and providing onsite training in addition to effective remote support. This approach will be replicated as Digital BOP Testing is introduced to additional BP-operated deepwater rigs in Gulf of Mexico. Ultimately, a stable arrangement for long-term service support of Digital BOP Testing will be established with one of several potential qualified service providers.

E. End Users

The question has arisen if Digital BOP Testing changes the personnel currently required to conduct pressure testing. The answer is no.

Digital BOP Testing does not require additional or different personnel during testing. For example, Halliburton cementing unit operators on *Deepwater Horizon* are readily trained and have demonstrated proficient use of Digital BOP Testing software.

Digital BOP Testing software is tailored to support the current workflow of subsea BOP and surface manifold testing. The software is therefore designed to be viewed and used at cementing units by cementing unit operators. Additionally, it is designed to be readily understood by all responsible for inspecting and approving BOP test records including subsea specialists, wellsite leaders and MMS Inspectors.

F. Training

It is recognized that MMS Inspectors will be key participants in the successful implementation of Digital BOP Testing. There has been an often-expressed concern from MMS about how will MMS Inspectors learn what they need to know about Digital BOP Testing. The answer is that BP will willingly provide the right training to MMS District and Region staff at mutually convenient times and locations, and will provide points of contact for questions that may arise afterward. It has been our experience that those already familiar with subsea BOP testing quickly learn to appreciate Digital BOP Testing and understand how it works.

BP will prepare and provide training materials to explain the principles and practices of Digital BOP Testing to all who are responsible for the conduct of subsea BOP and surface manifold testing. Additionally, these are included and easily accessed in the help section of the Digital BOP Testing software.

Another important aspect of training is to educate the oil & gas industry about Digital BOP Testing. BP has and will continue to explain Digital BOP Testing to industry through publication of technical papers and articles.

G. Sharing with Other Operators

The question has arisen whether BP is seeking sole approval to use Digital BOP Technology or if the technology will be shared with other operators.

BP believes it is in the mutual interests of MMS, offshore operators and supporting services to promote a uniform practice of Digital BOP Testing in Gulf of Mexico. BP therefore intends to, in a timely manner, make Digital BOP Testing available to industry.

It is our expectation that we should first prove to MMS the ability to successfully implement Digital BOP Testing on multiple BP-operated drilling rigs. BP will, in the process of doing this, establish a practical service arrangement by which Digital BOP Testing is made available and competently supported in its operations. If MMS becomes willing to permit other operators to use Digital BOP Testing, and BP is confident of its service provider(s), then BP will license its service provider(s) to provide Digital BOP Testing to other operators.

We wish to assure successful introduction of Digital BOP Testing in Gulf of Mexico, and are best able to do that on BP-operated rigs, so first priority is to implement Digital BOP Testing on multiple BP-operated drilling rigs. It is through this means that it will become possible to share Digital BOP Testing with other operators in a manner that offers the best chances for success.

APPENDIX 1. ANATOMIZE COMMERCIAL RELEASE SOFTWARE

Screen-Shot Examples

Commercial release Digital BOP Testing software known as Anatomize Version 3.3 was evaluated on Transocean *Deepwater Horizon*, 29 September 2007. Results from 11 of 12 subsea BOP tests were documented (initial data from the 1st test were missed while a new data connection was being verified). Screen-shots are presented in Figures A1 thru A11.

Figure A1. The pressure declines labeled 2 thru 4 and 7 thru 10 represent high-pressure pipe ram tests; those labeled 5,6 and 11,12 represent annular preventer tests. At bottom the touch-screen software display, mounted in a NEMA Type 2 enclosure above the cementing unit circular chart recorder, is shown.

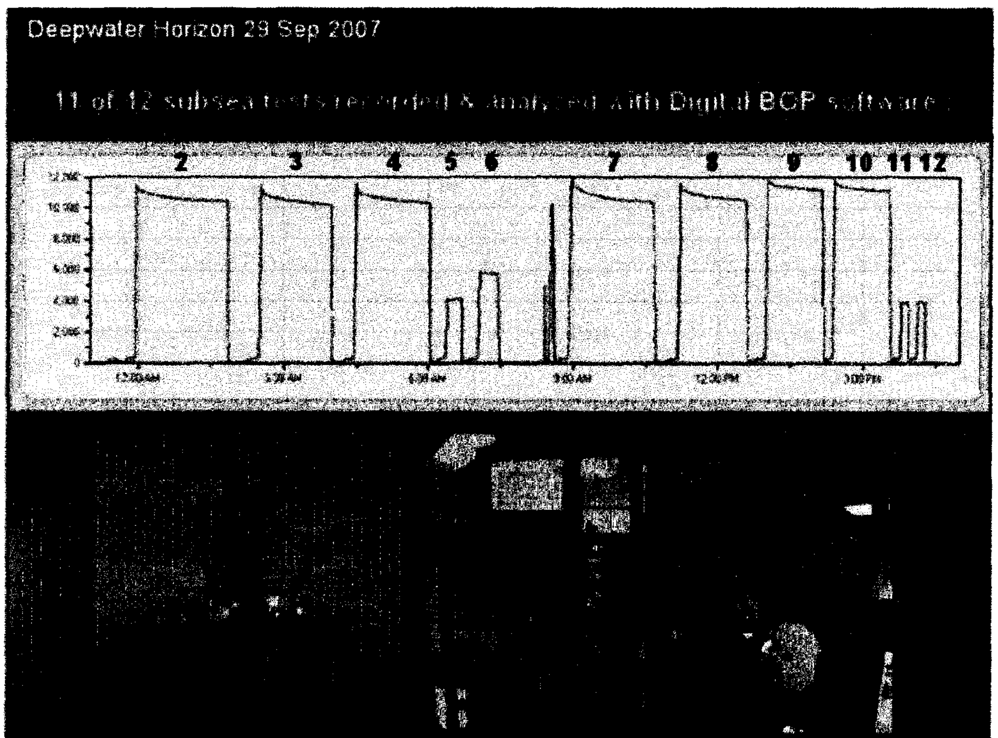


Fig. A1.

Figure A2. Shows the software display when building up pressure for a high-pressure test. We see the nearly linear relation between pressure and the volume pumped-in. In this case the value is 3715 psi/bbl. This was a pipe ram test with only the kill line pressurized.

Figure A3. Shows a similar display for a pipe ram test with both the choke and kill lines pressurized. The pressure-volume relation is 1876 psi/bbl which is almost half that of the previous example. This makes sense because adding the choke line volume almost doubles the pressurized system volume, and almost twice the fluid volume was required to pump-up to ca. 11 ksi initial test pressure.

These pump-in graphs provide the first opportunity in any test to detect a leak in the system. Leaks tend to make the normally linear pressure-volume trend become non-linear.

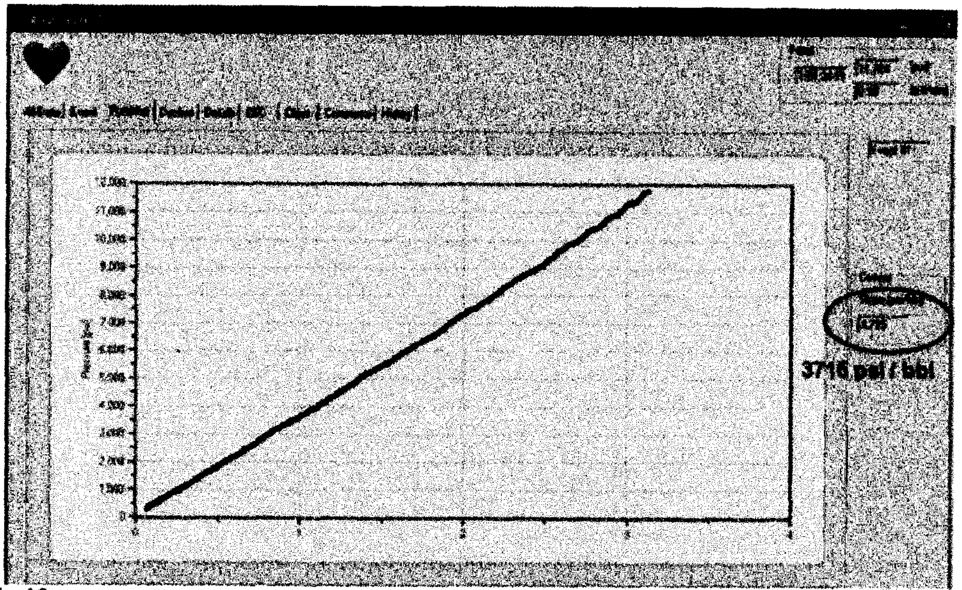


Fig. A2.

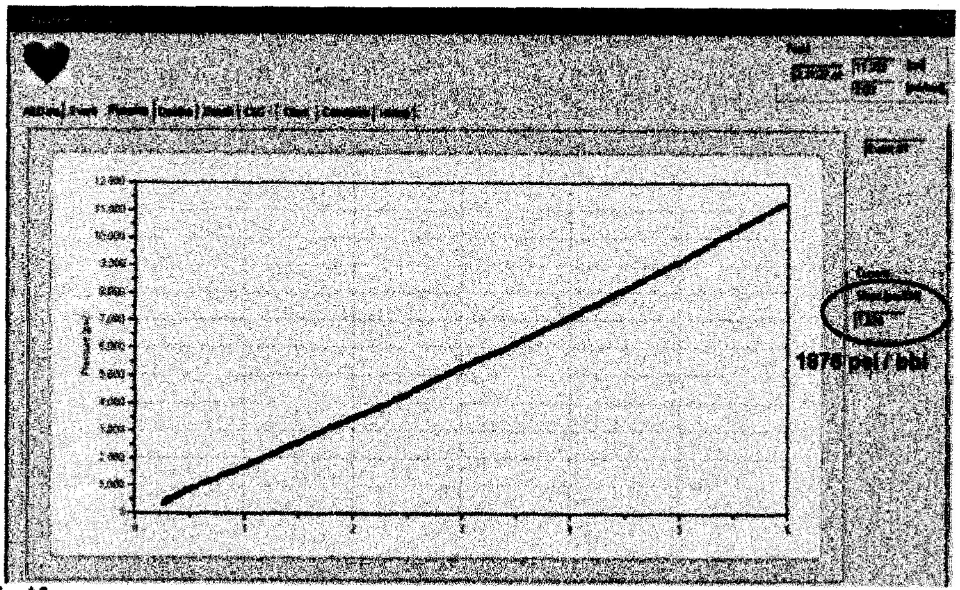


Fig. A3.

Figure A4. Digital BOP software detected the end of pumping and beginning of a shut-in test period, so automatically switched from the Fig. A3 graph to this display of pressure vs. time. The blue points are the actual pressure data recorded thus far during the test. The purple curve is the current pressure forecast generated from digital analysis of that data. The horizontal line at 9500 psi represents the target test pressure. The 'light' is yellow which indicates the computer is still seeking a sufficiently stable solution. There is additional information, such as the pressure decline rate is currently 25.9 psi/min.

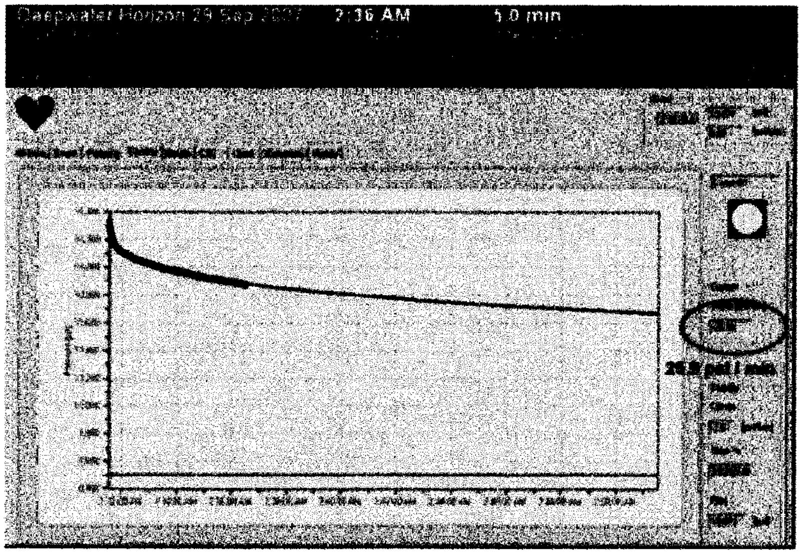


Fig. A4.

Figure A5. A stable pressure forecast was obtained 19.0 minutes after shut-in. The stabilized pressure is predicted to be 9959 psi, which is greater than the target test pressure, hence a green 'light' is displayed. The test could be reliably interpreted as positive and ended at this point.

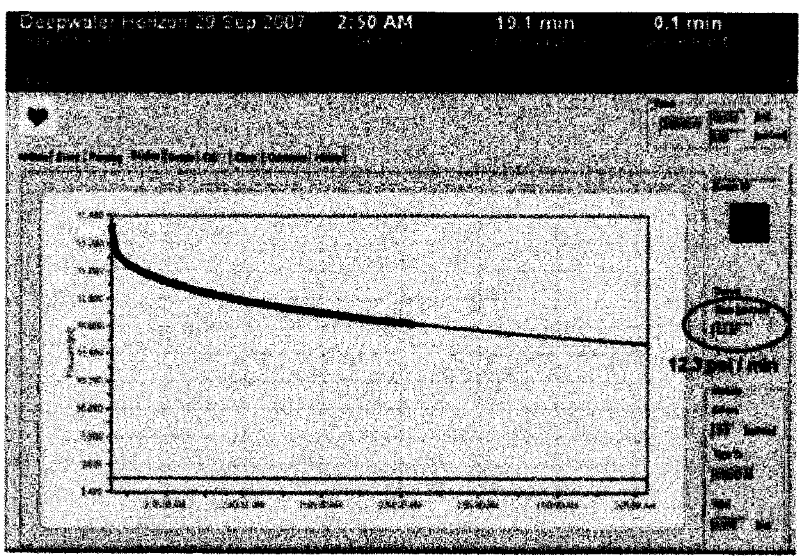


Fig. A5.

Figure A6. The Fig. A5 test was held shut-in for a total of 87 minutes to a pressure decline rate of 3.4 psi/min. This makes sense since the pressure trace on circular charts starts to appear steady once pressure decline rates diminish to the range -4 to -3 psi/min. Digital BOP Testing could have saved 68 minutes thus reducing shut-in time by 78%.

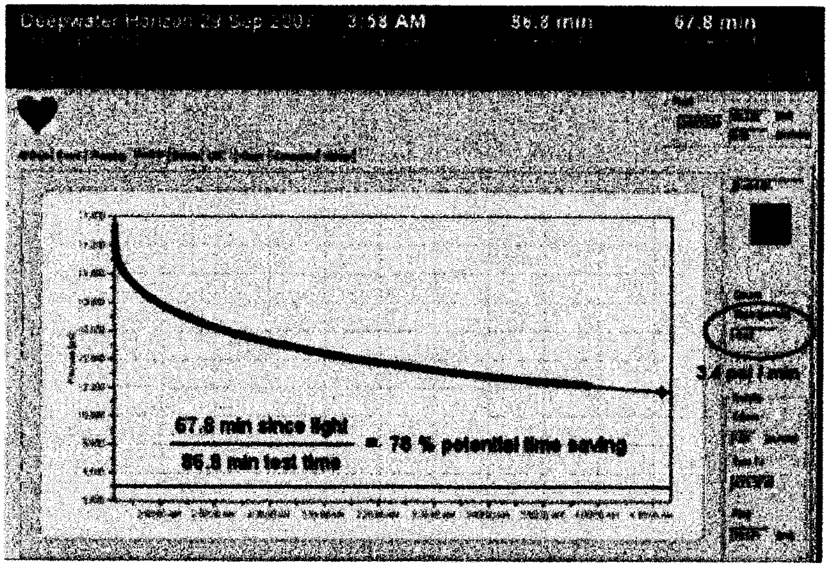


Fig. A6.

Figure A7. Subsea Test #6 involved an annular preventer. The pressure-volume relationship is different, but repeatable, for annular preventers than with pipe rams, in this case 2741 psi/bbl.

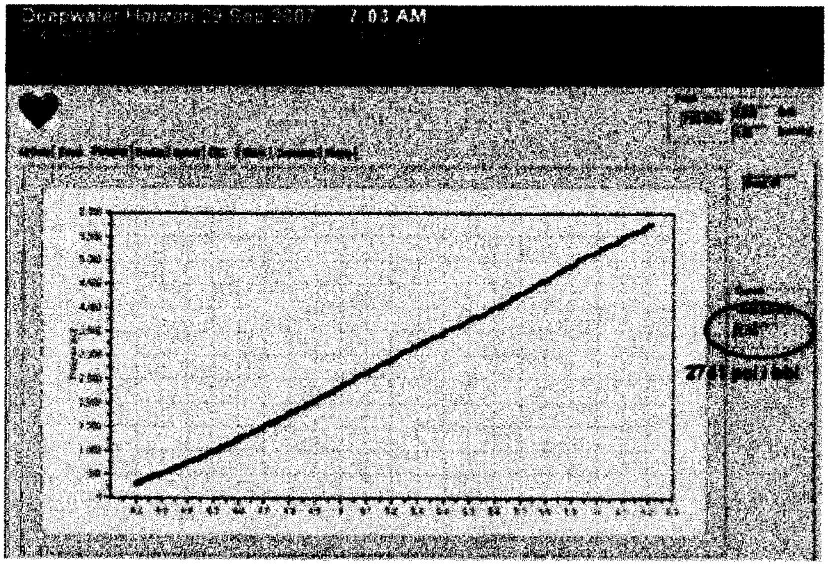


Fig. A7.

Figure A8. This is the initial shut-in pressure display for Subsea Test #6. Annular pressure tests tend to stabilize more rapidly than pipe ram tests. The 1st light occurred 5.4 minutes after shut-in. The predicted stable pressure is 5783 psi, indicated by the diamond-shaped symbol. This is greater than the target pressure of 5000 psi so the 'light' is green indicating a positive test.

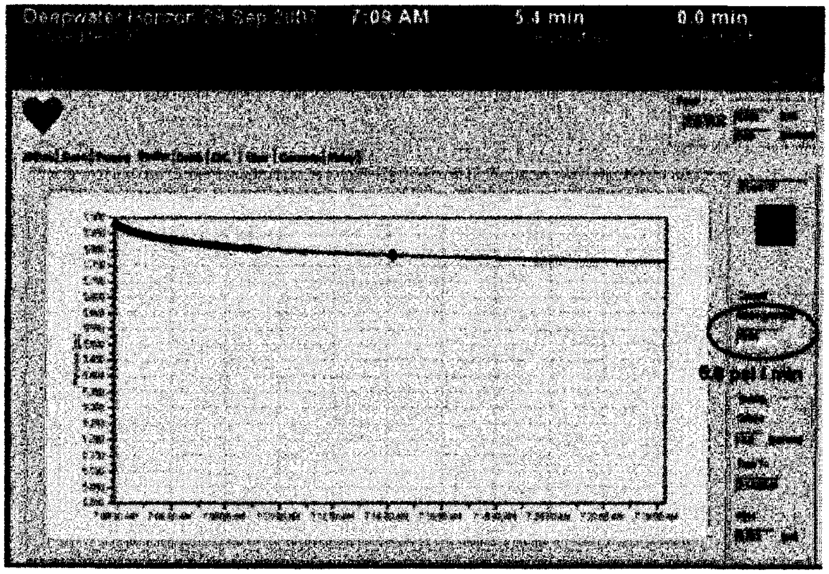


Fig. A8.

Figure A9. This is Subsea Test #6 when the pressure decline rate was exactly 3.0 psi/min. We see very close agreement between the 1st light prediction and actual value of the stabilized pressure.

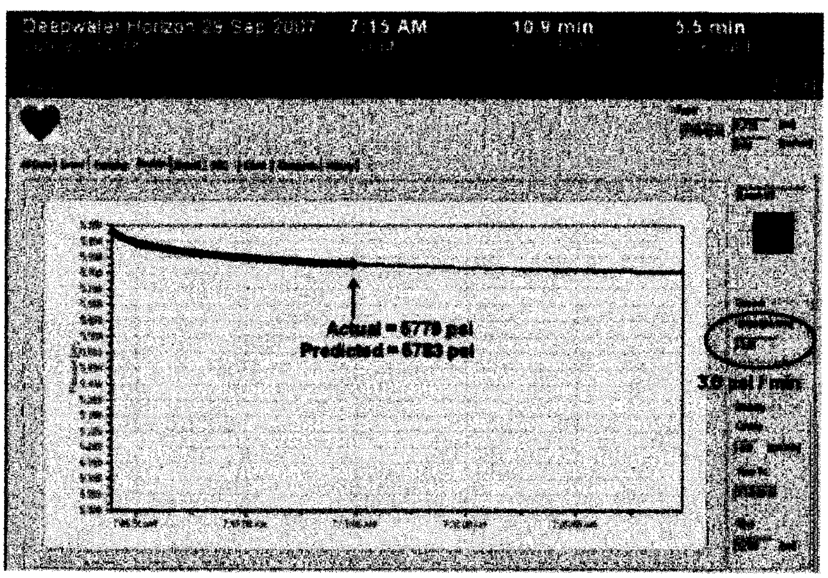


Fig. A9.

Figure A10. Since annular preventer tests stabilize more quickly than pipe ram tests, the potential Digital BOP Testing time savings are proportionately less yet still represent a ca. 75% reduction of shut-in time.

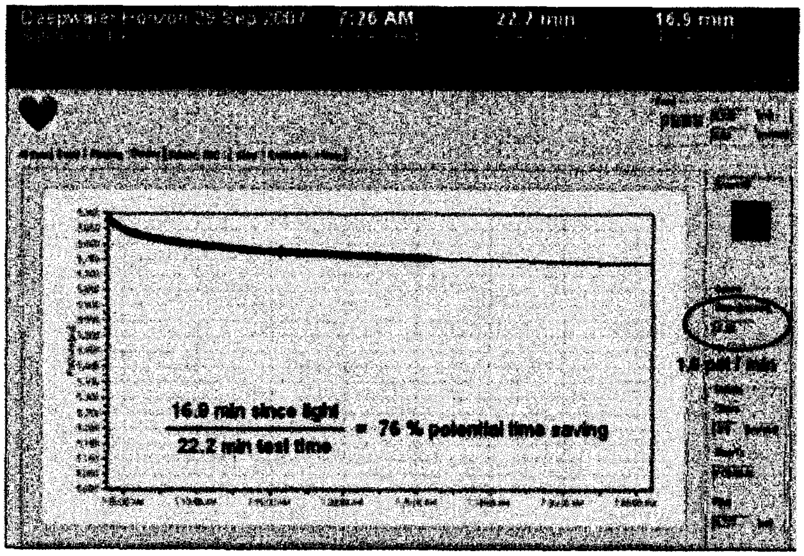


Fig. A10.

Figure A11. Estimated potential times savings for the 12 subsea BOP tests on 29 Sep 2007 was ca. 9 hours, worth ca. $300K. We see that a 75% reduction of shut-in time is a generally reliable expectation for Digital BOP Testing.

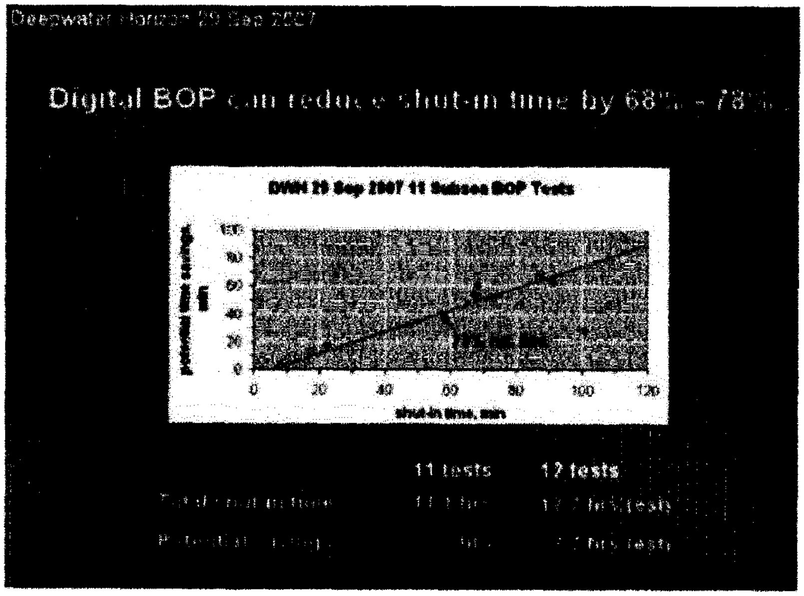


Fig. A11.

Figure A12. A summary similar to Fig. A11 but from tests conducted 29 Jan 2007. Here again we see potential for at least 75% reduction of shut-in time. These are not 'hand-picked' results but typical of all Digital BOP field testing done on *Deepwater Horizon*.

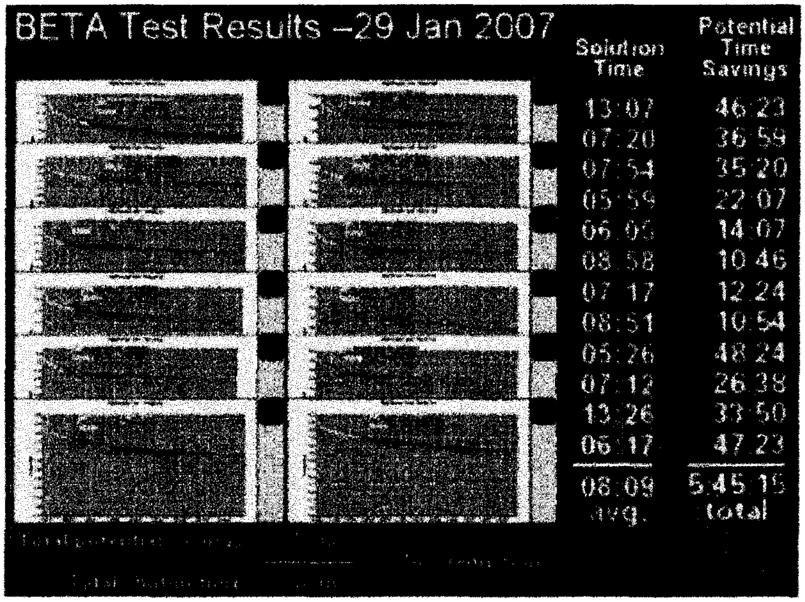


Fig. A12.

Response to Leaks

Figure A13. We are often asked how the Digital BOP Testing software responds to leaks, but in our experience leaks are rare. However, there is a good example of a leaking test in the event labeled 22. Event 24 is the successful re-test.

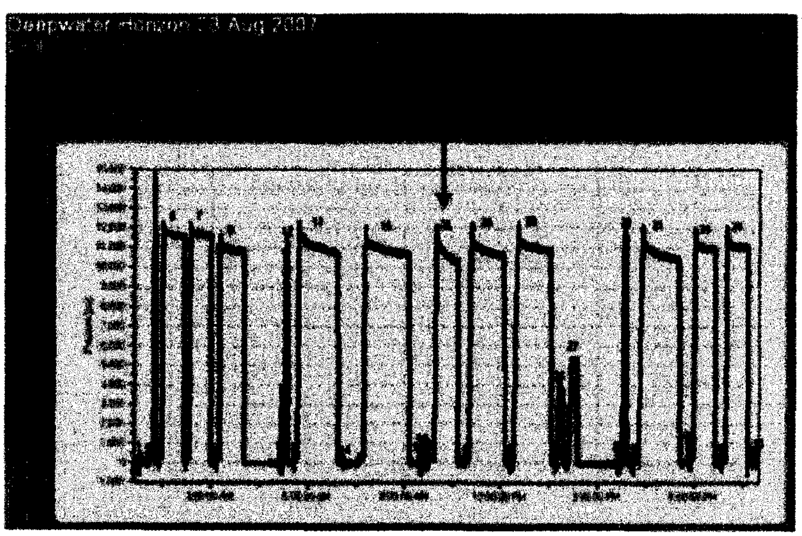


Fig. A13.

Figure A14. The 1st light was obtained 25 minutes after shut-in. The stabilized pressure forecast was 7373 psi, well below the 9500 psi target pressure, so the 'light' was red. We see the test continued 15 minutes after the 1st light, meaning Digital BOP Testing could have saved 15 minutes here plus more in the re-test.

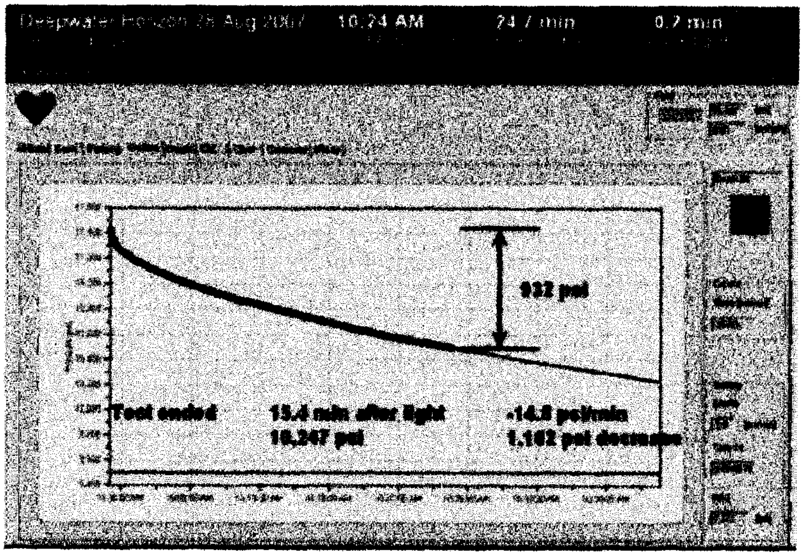


Fig. A14.

Figure A15. This is the re-test of the leaking test in Fig. A14. The 1st light occurred 22 minutes after shut-in, and was green. This screen shot was taken exactly 24.7 minutes after shut-in, same as in Fig. A14, showing considerably less pressure decrease within that time thus suggesting a non-leaking result.

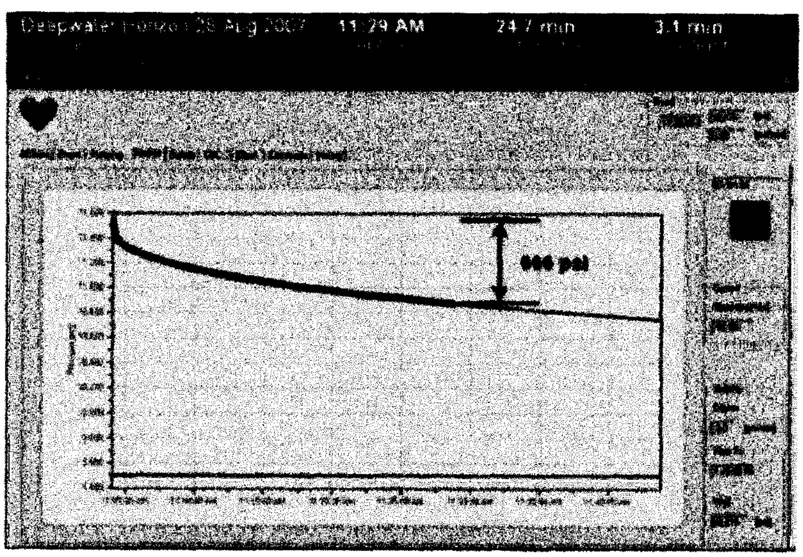


Fig. A15.

Figure A16. The re-test was held shut-in for 58 minutes. The stabilized pressure forecast was 10,453 psi, well above the target pressure. The Digital BOP interpretation was correct and could have saved 36 minutes.

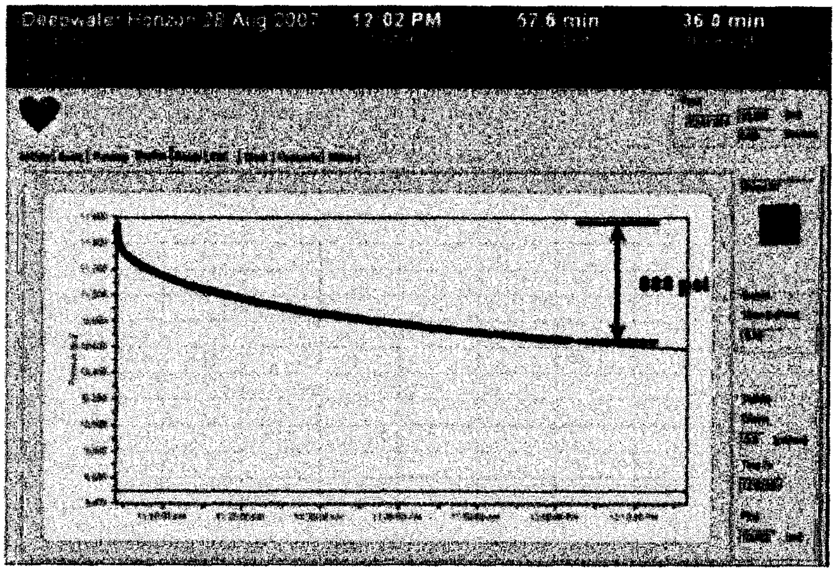


Fig. A16.

Validity Check

MMS stated in the March 2007 meeting that the 1st BOP test in a series should be interpreted by chart recorder so that Digital BOP software can be verified before using it to interpret subsequent tests. The details were left for BP to work out, and are incorporated in this document in the proposed Rules and further explained here.

Checking a Digital BOP forecast to see if it is correct before proceeding to rely on the Digital BOP software to interpret subsequent tests is a simple and worthwhile concept. We established a basis and method for performing such checks and determining what is valid vs. invalid. Also, we felt it was important to automate the validation check in the software so that it can be done in consistent, correct fashion without asking end users to shoulder the responsibility of making such determinations. The resultant validation check method is illustrated next.

Figure A17. This type of graph is available in the Digital BOP software but is not prominently featured because end users are not required to draw conclusions from it. However, it does help to illustrate the validation check method.

The blue curve represents real pressure data recorded up to the present during a shut-in test period. When the 1st light occurs, there is an associated pressure forecast represented by the black curve. Also associated with the 1st light forecast are upper and lower error bounds represented by the red curves. The error bounds reflect our knowledge of the Digital BOP Algorithm forecasting accuracy, as previously discussed (Section III-B "Digital Algorithm Performance Study" pp 10-12).

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The validation consists of checking throughout the test, from the 1st light onward, if the real pressure data (blue) fall within the acceptable error bounds (red). This is done computationally by the Digital BOP software.

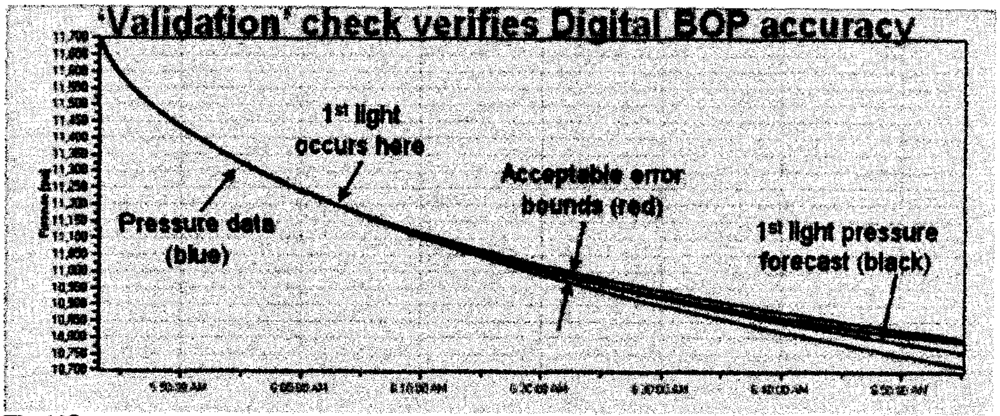

Fig. A17.

If for the duration of the test all real pressure data lay within the acceptable error bounds, then the 1st light forecast is considered valid, meaning it was sufficiently accurate to make a correct interpretation.

If at any time the real pressure data lay beyond acceptable error bounds, then the 1st light forecast is considered invalid, meaning it was not sufficiently representative of the actual result.

The validation check is always computed during all tests. However, the notion is that the first test of a testing sequence should be conducted sufficiently long (i.e., interpreted by chart recorder) to obtain a complete validation check, whereas subsequent tests may be ended almost immediately after the 1st light. End users always have the option to hold a particular subsequent test shut-in beyond the 1st light if wishing to confirm validity of the 1st light pressure forecast. We think through experience end users will gain confidence that, once validated the 1st time, Digital BOP software will be reliable in all subsequent tests.

We expect very few instances in which a Digital BOP pressure forecast becomes invalid. After all, the algorithm performs a stringent check on stability of the solution before displaying a green or red 'light'. However, it is always possible that something unusual may affect the pressure response after the 1st light occurs, thus making the initial pressure trend and forecast no longer representative of the current pressure behavior.

Figure A18. If a 1st light pressure forecast becomes invalid, an 'Invalid' warning is clearly displayed next to the 'light'. This particular test was unusual in that the pressure quickly stabilized to a decline rate of zero, then the pressure rose slightly (we think due to fluid in the test lines heating slightly) and exceeded the upper error bound thus prompting an 'Invalid' message. This does not mean the Digital BOP stable pressure forecast was wrong, nor was the green 'light' incorrect. The test was interpreted per chart recorder as positive, as predicted by Digital BOP software. However, this does show that if the pressure trend during a shut-in test period deviates much at all beyond the 1st light Digital BOP pressure forecast, the software detects and reports this as a safeguard against error. In the event of an 'Invalid" result, clear rules are proposed (for example, the logic of Fig. 26, p. 28) to enable smoothly proceeding and continuing to apply Digital BOP Testing software to best possible benefit.

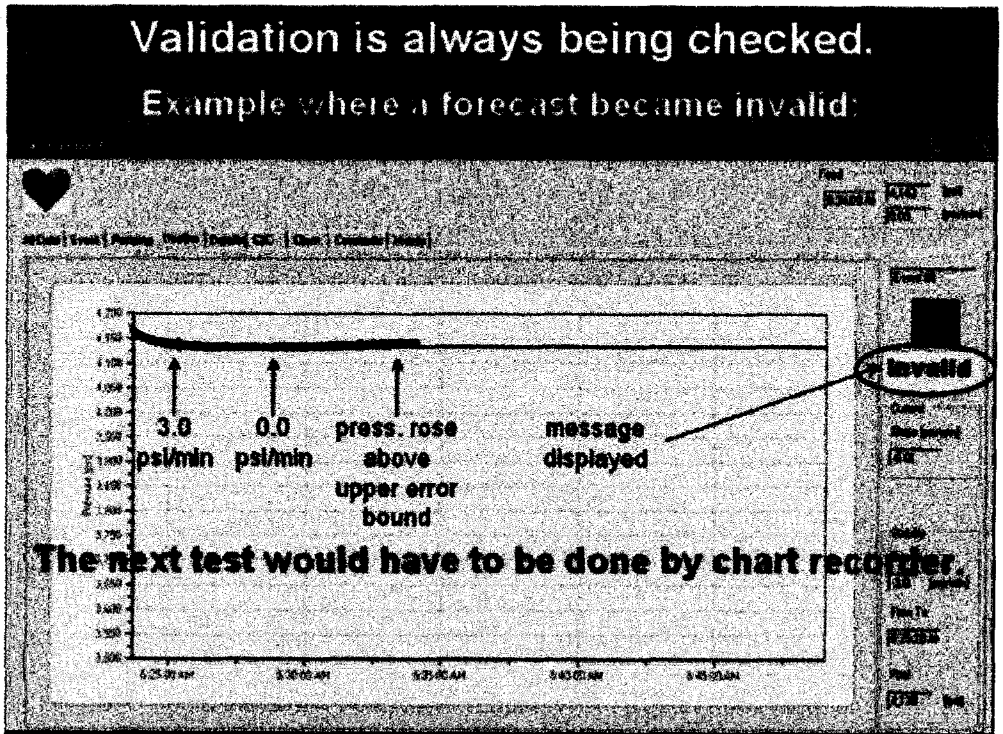
Validation is always being checked.
Example where a forecast became invalid:
3.0 psi/min
0.0 psi/min
press. rose above upper error bound
message displayed
Invalid
The next test would have to be done by chart recorder.

Fig. A18.

APPENDIX 2. BP Gulf of Mexico Exploration BOP Testing Procedure

GoMX BOP Testing
Procedures.doc

APPENDIX 3. BP Deepwater BOP Testing Procedure

BP Deepwater BOP
Testing Procedure.dc

APPENDIX 4. Transocean Deepwater Horizon BOP Test Diagrams

Horizon BOP Test Diagram.xls