Digital Interpretation of Subsea Blowout Preventer Tests aka 'Digital BOP'

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BP America Inc.

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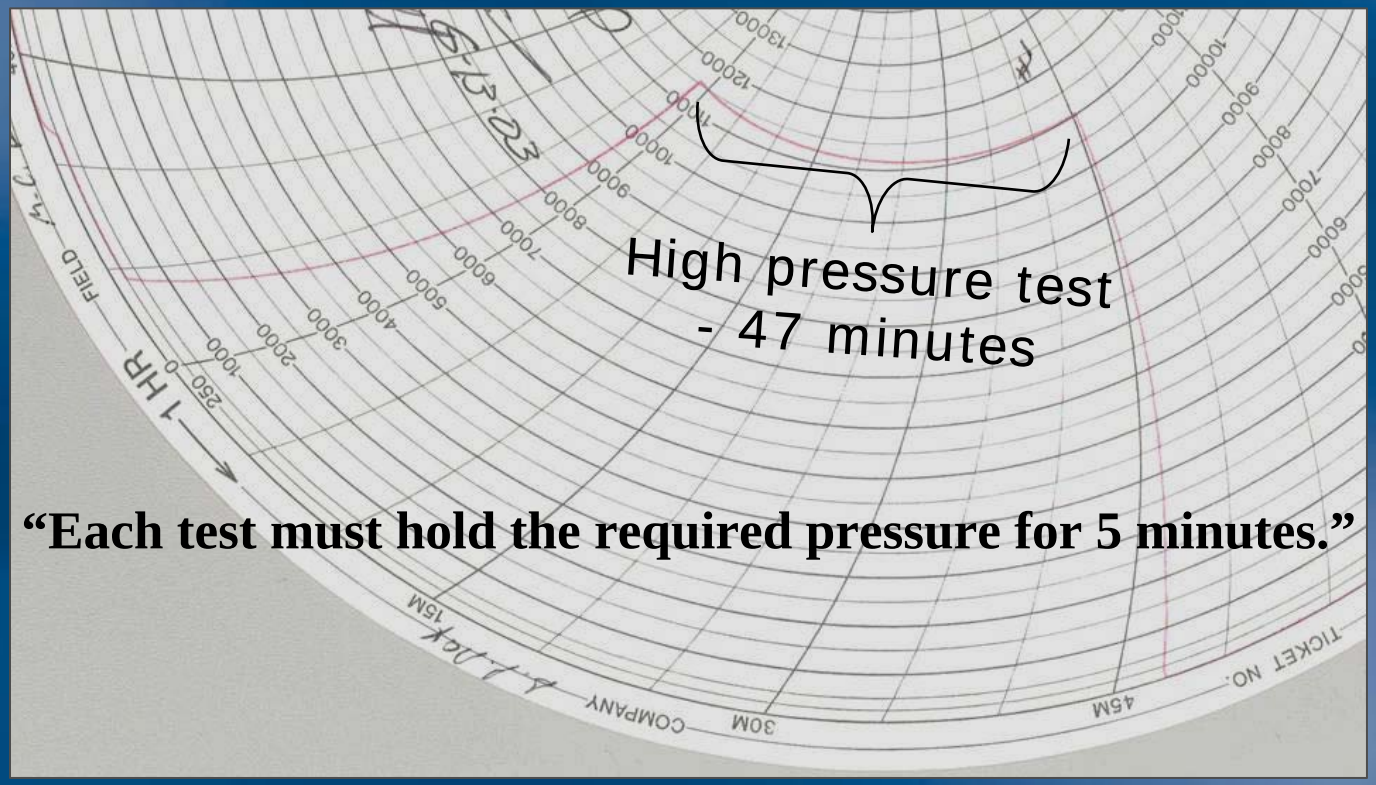
Hecate Software Inc.

Subsea BOP tests can take a long time to stabilize, especially with synthetic base mud.



"Each test must hold the required pressure for 5 minutes."

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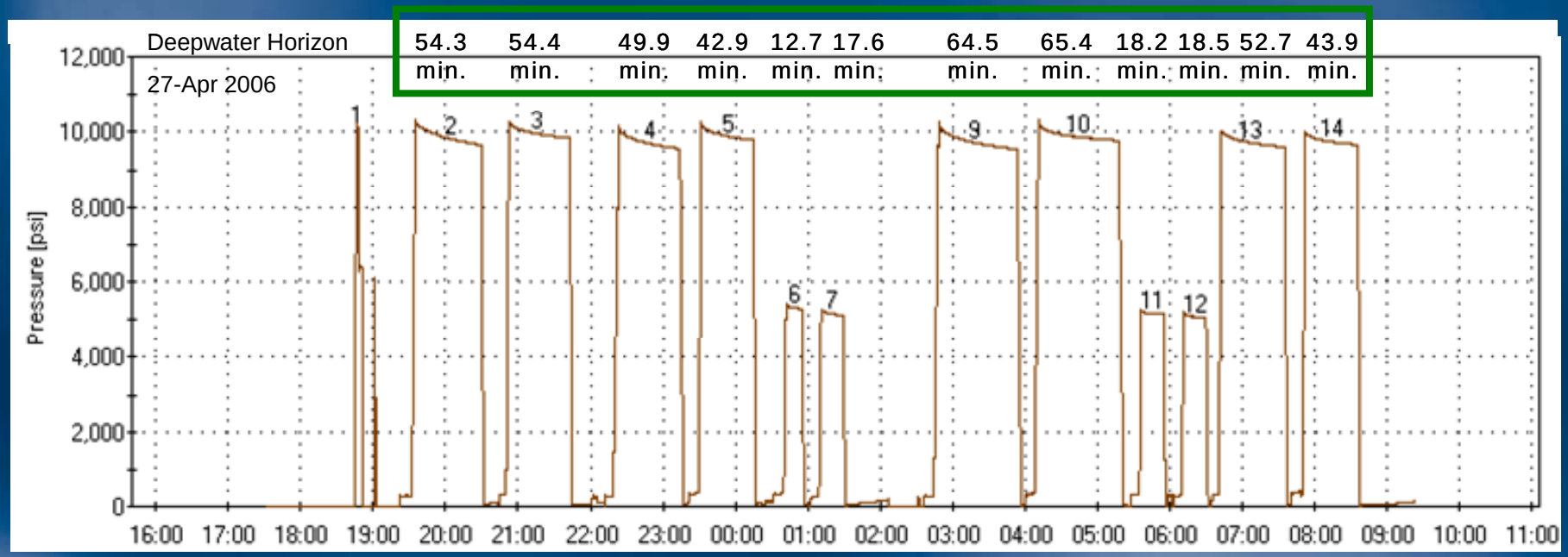
Here, 12 tests combined shut-in time = 8.25 hrs :



Excess shut-in time = 7.25 hrs

BP developed Digital BOP software to shorten tests.

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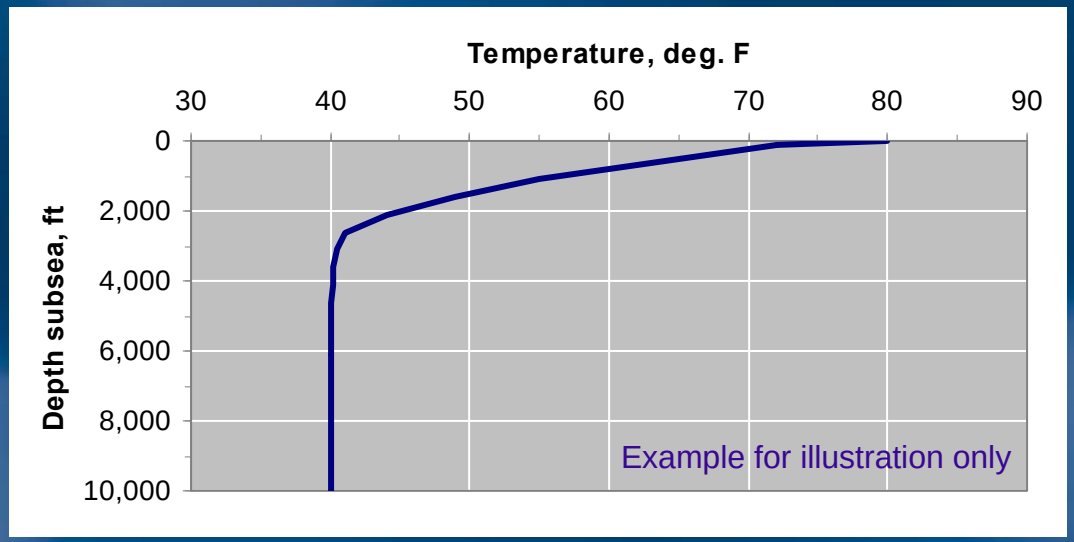
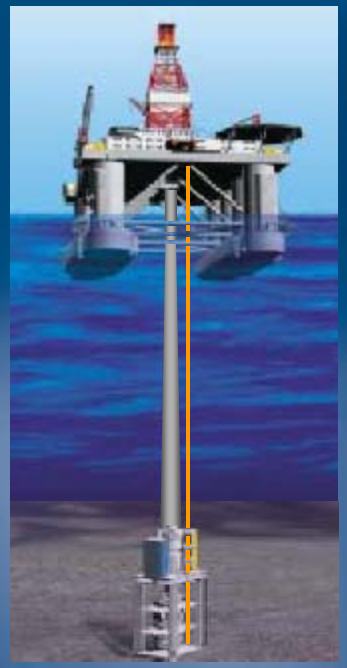
Q: Why does the pressure decrease?

A: The water is cold. Warm fluid in the kill / choke lines cools off during shut-ins. Temperature affects pressure.

Typical Gulf of Mexico water temperature profile:





Temperatures in drill pipe, riser, choke & kill lines tend toward this same profile.

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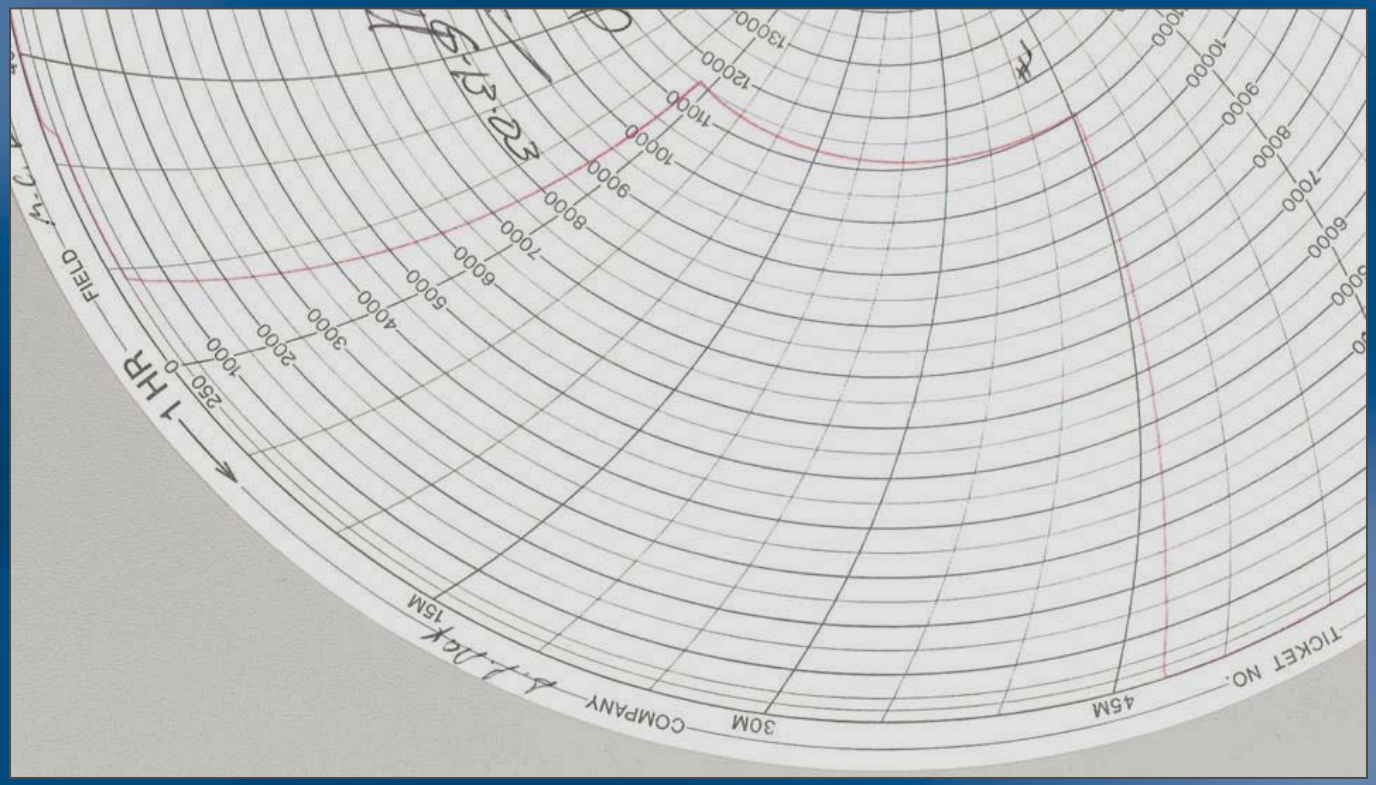
Q: Why does it take so long?

A: Heat loss rate is proportional to temperature difference -- fastest initially then slowing.



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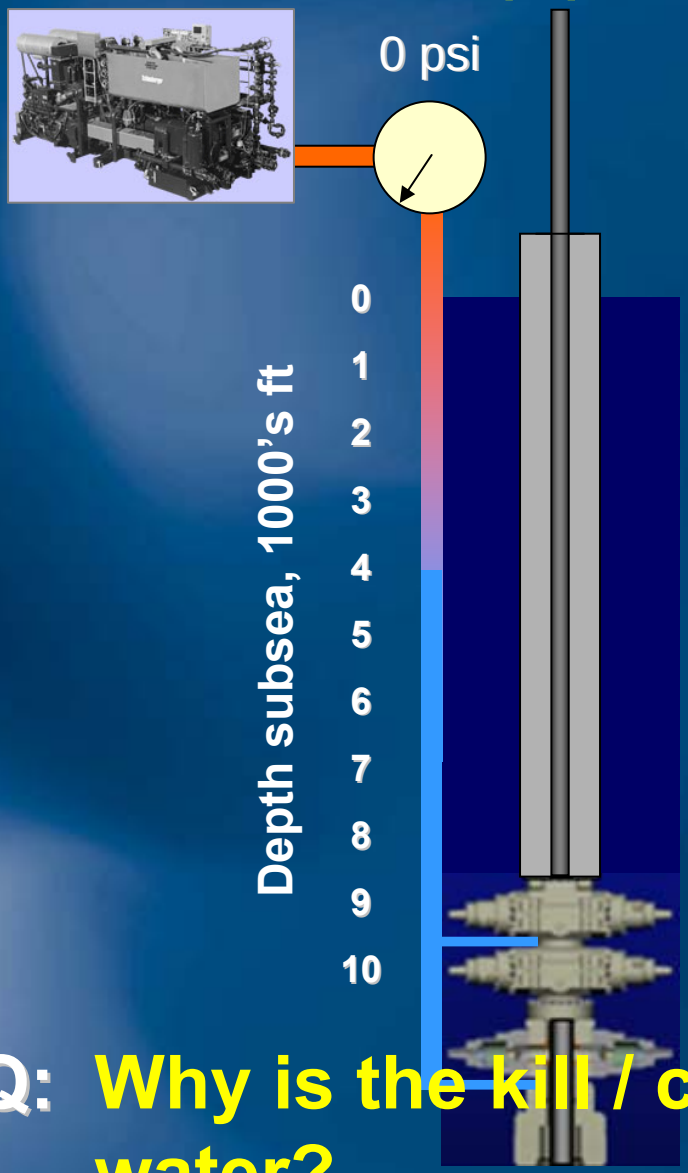
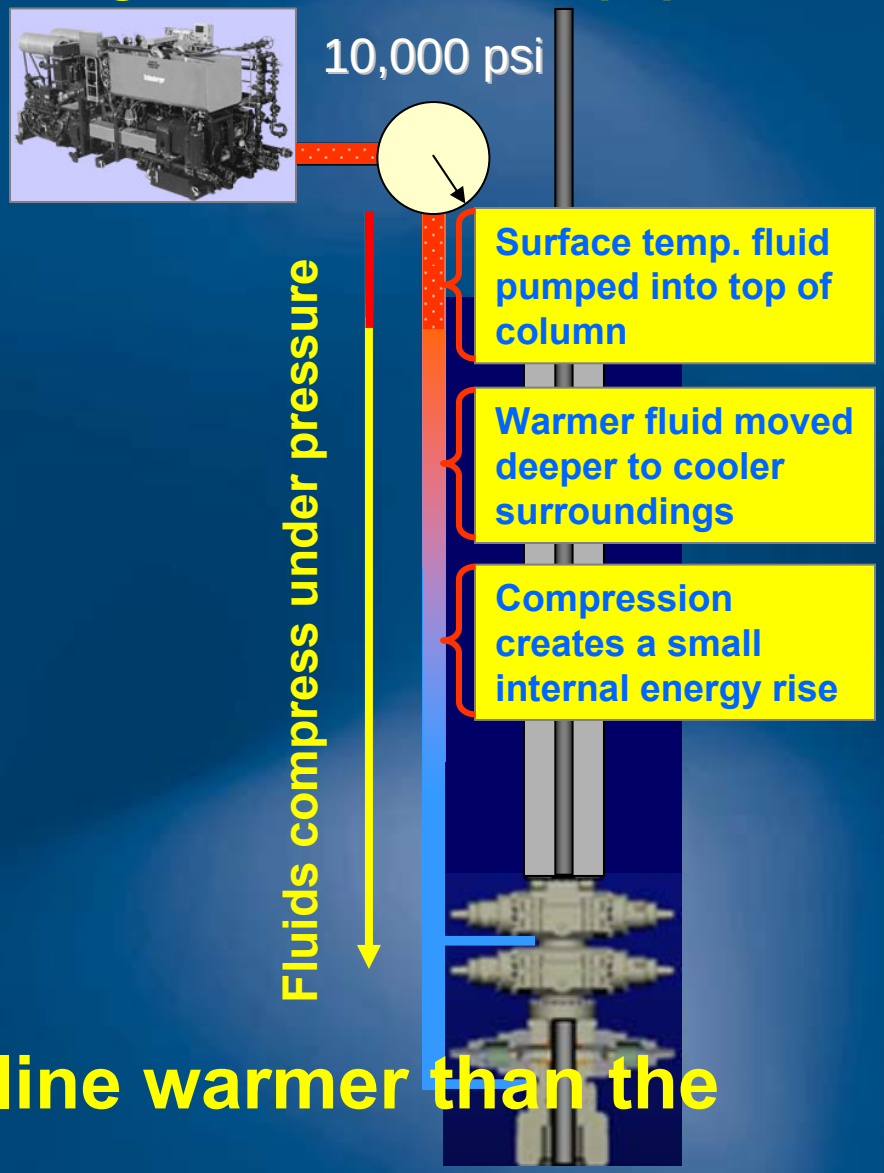
Initially, kill line temp. is same as water temp. profile:



Pumping-in to raise the pressure changes the kill line temp. profile:



Q: Why is the kill / choke line warmer than the water?

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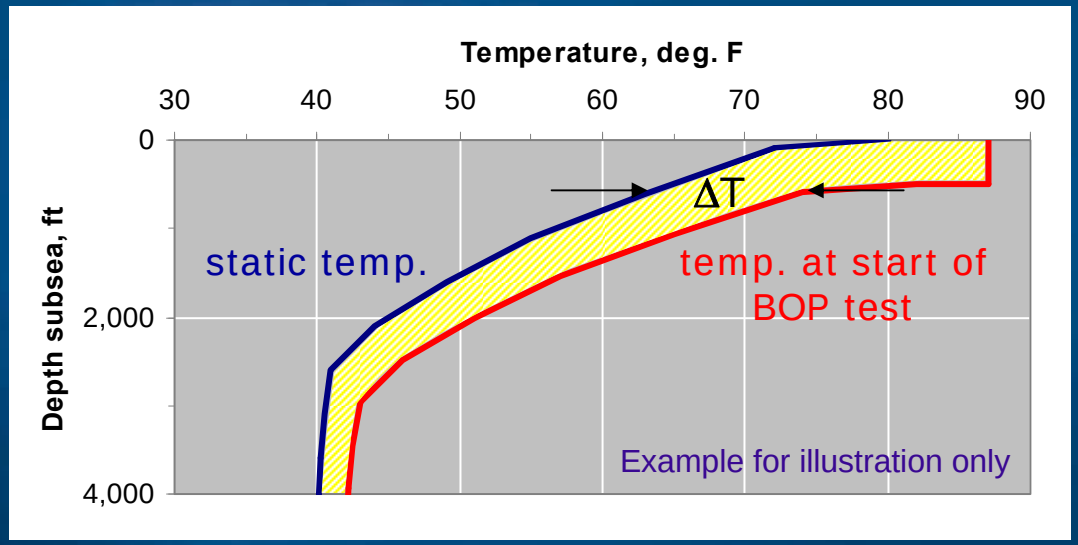
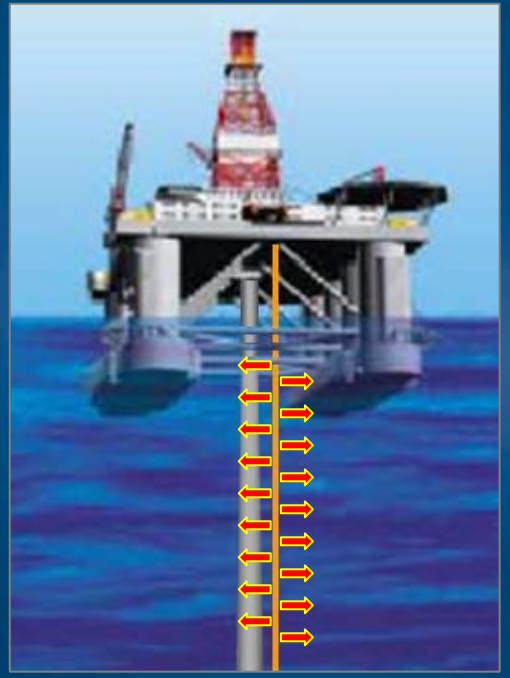
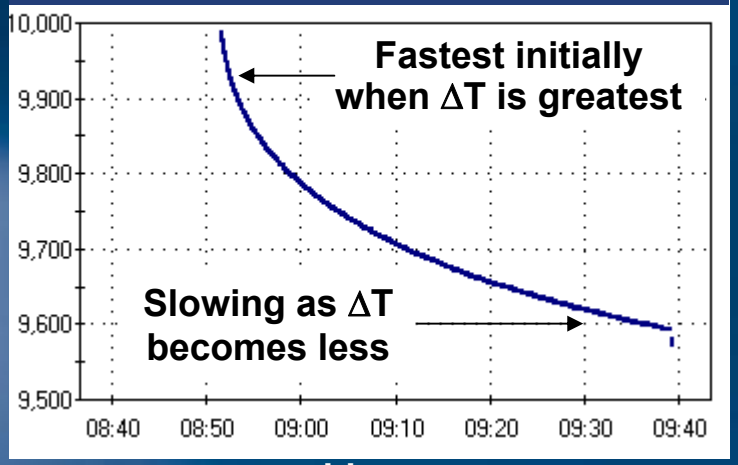
Pump-in alters the kill line temp. profile:

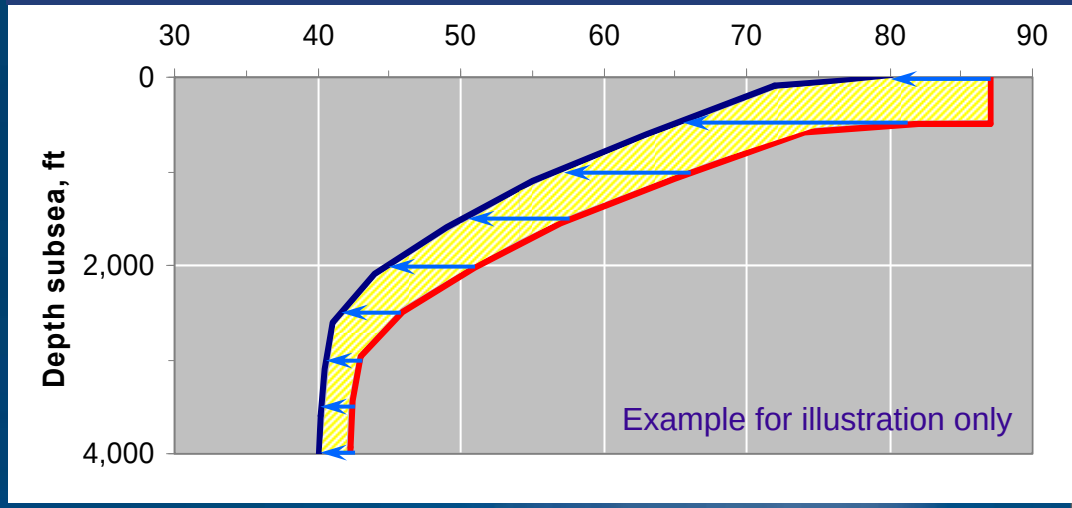




Shut-in pressures decline as the fluids cool:



Heat flows from higher to lower T. Kill line fluids cool as they lose heat.



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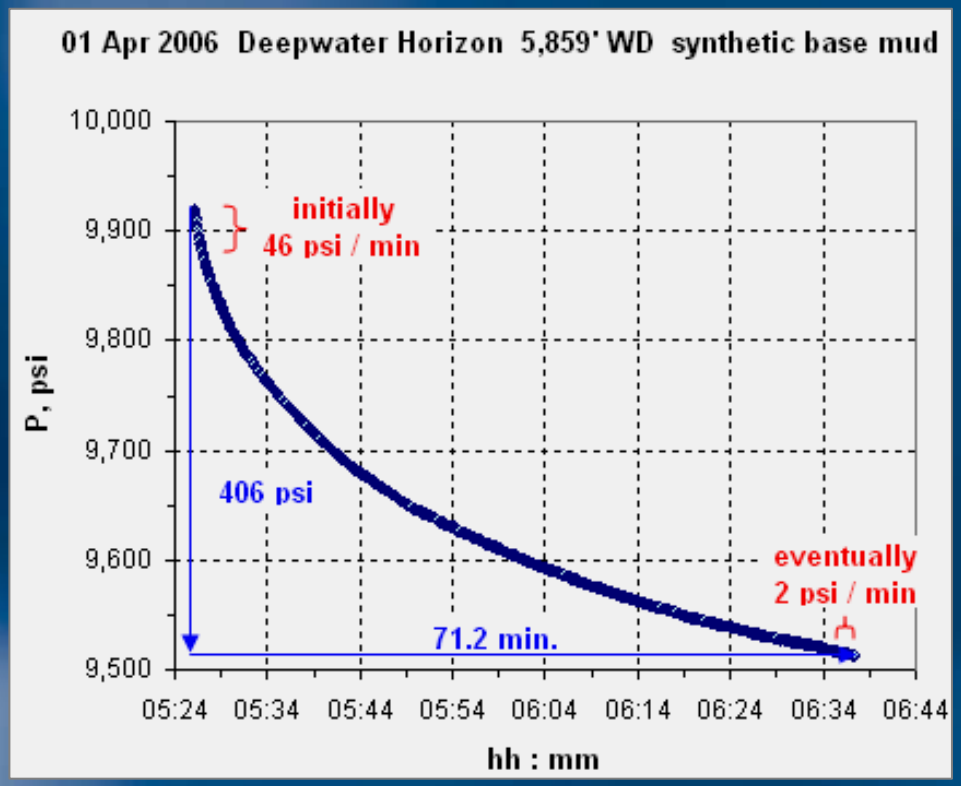
Influence of Synthetic Base Mud

Tests with SBM last longer.



SBM vs. WBM properties

▲ Compressibility
pump 50% more volume to reach test pressure

▲ Heat of Compression
3X more internal energy heat-up than water

▼ Heat Capacity
loses heat 50% slower than water

Deeper water, higher test pressures, larger choke/kill ID – contribute to longer tests with any fluid.

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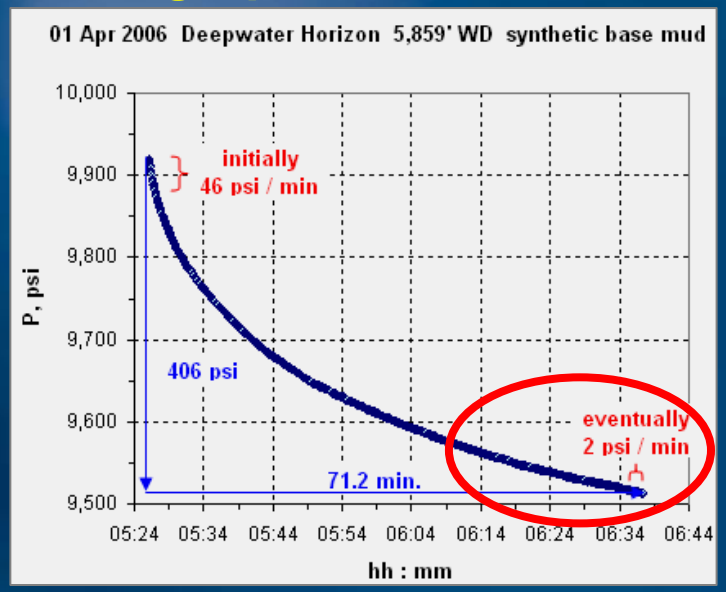
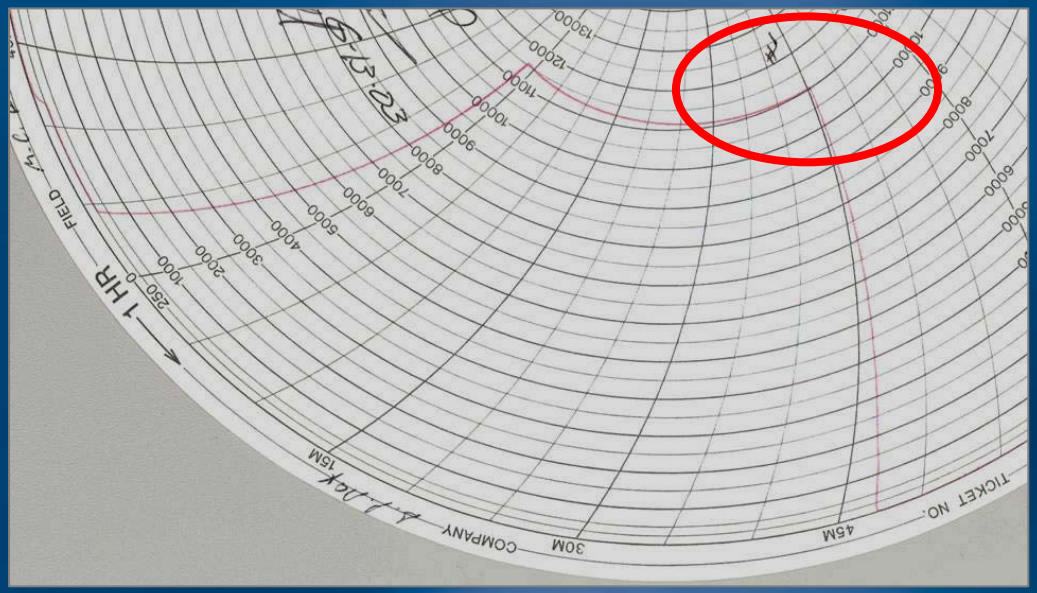
Chart Resolution

Small pressure declines visible when graphed on this scale



appear stable when viewed on chart recorder scale.



- Chart resolution (ability to detect pressure changes) is 3–4 psi/min.
- The decline rate at end of most subsea BOP tests is 3-4 psi/min.
- We end tests when pressures look stable for 5 min. on a chart.
- “Each test must hold the required pressure for 5 minutes.”

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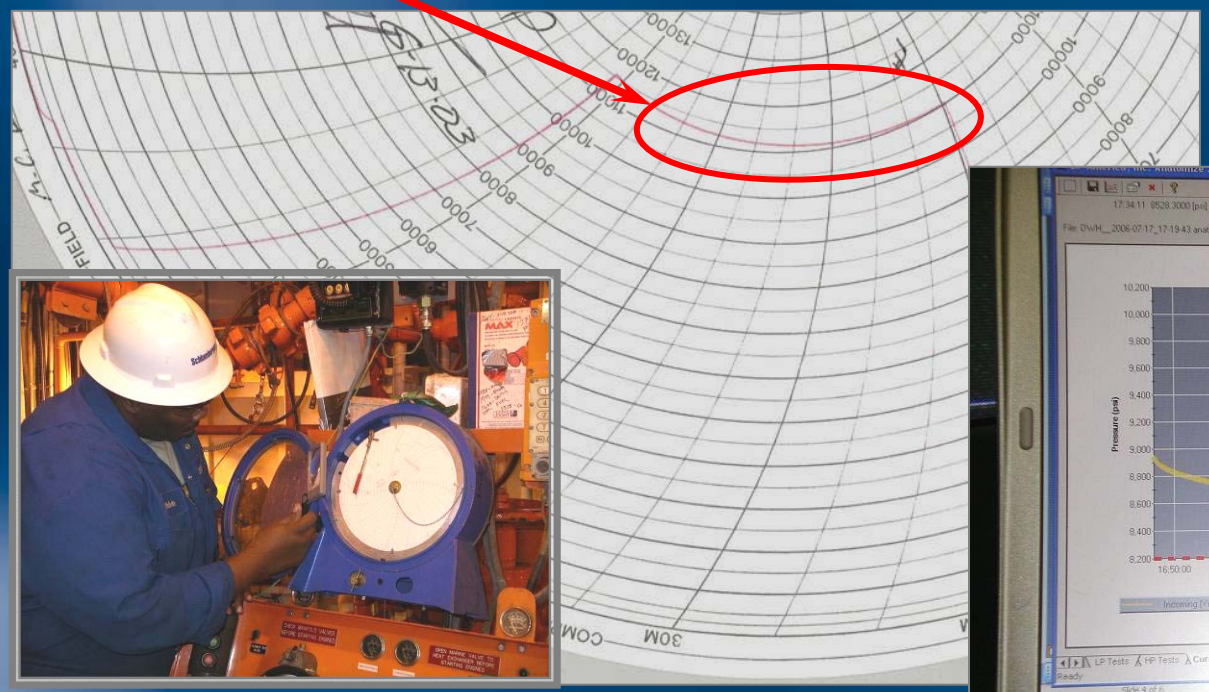
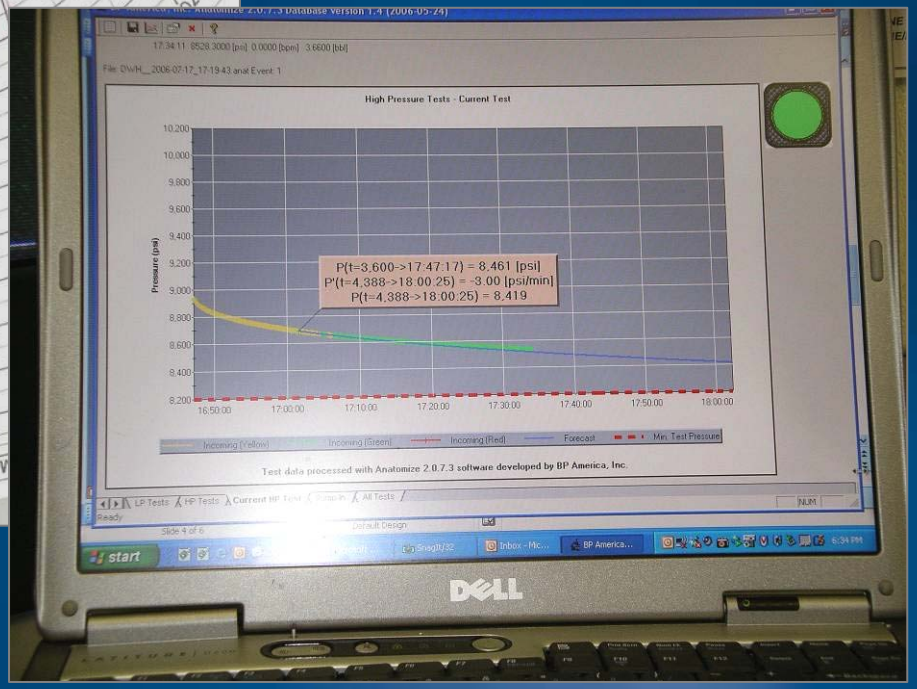
Digital Interpretation

The goal is to help the pump operator do this safely, accurately and more efficiently



with the help of this:



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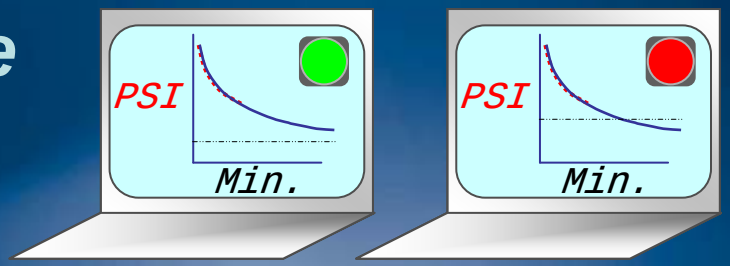
Digital Algorithm

Predicts the pressure at which a test done by chart method is likely to be ended and interpreted , i.e., the '*stable pressure*' where decline rate = -3 psi/min

so when implemented in Digital Software

a computer predicts if the *stable pressure* is above or below the required pressure (like chart method).



If greater, the test is POSITIVE.

If not, the test is NEGATIVE.

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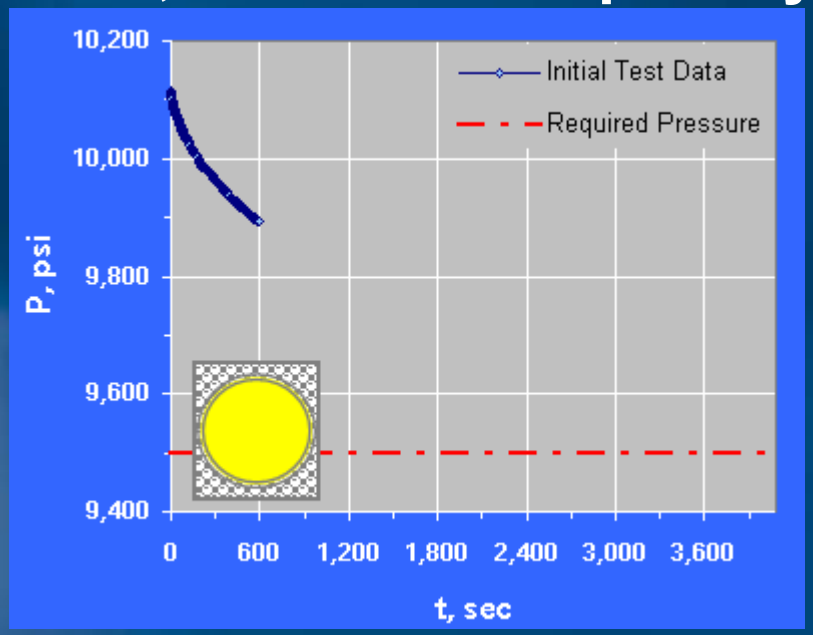
Digital Algorithm

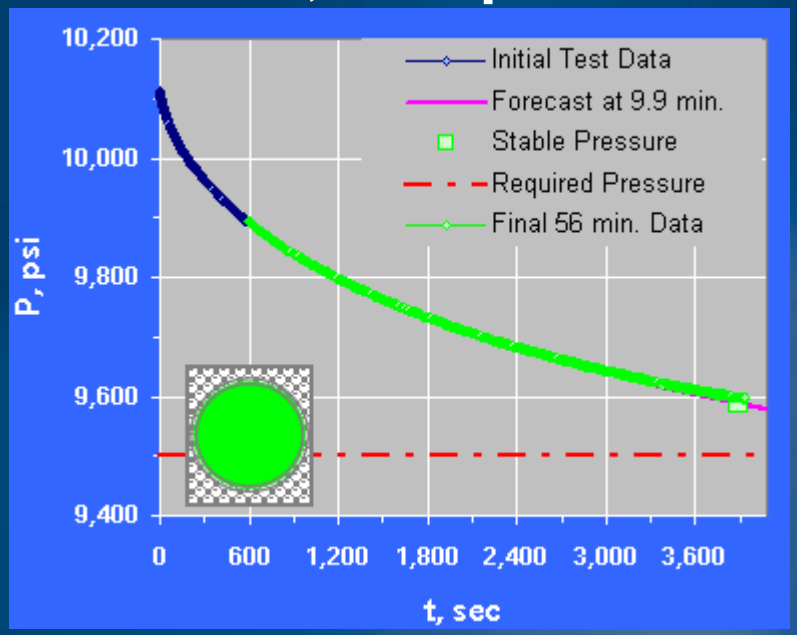
1. Fit an appropriate mathematical function with good predictive ability to the early pressure data.

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

2. Extrapolate pressure trend, predict *stable pressure*.
3. Test for confidence in forecast.

If NO, add data & repeat cycle. If YES, interpret test.





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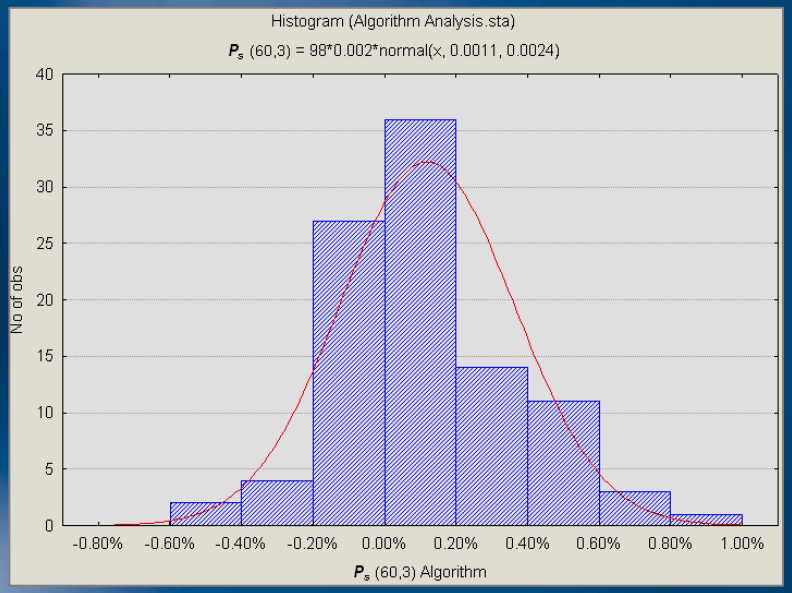
Prediction Accuracy

- Study group of 98 high-pressure subsea BOP tests.
- All tests held shut-in to decline rates ≤ 3 psi/min.
- Quantified algorithm pressure prediction accuracy.



- Near-normal errors distribution
- Mean error = 0.11% ± 0.05% 95% of the time
- Error range = -0.62% to 0.75% 99.5% of the time

- Digital Algorithm shown to be highly accurate.
- On par with accuracies of the instrumentation.

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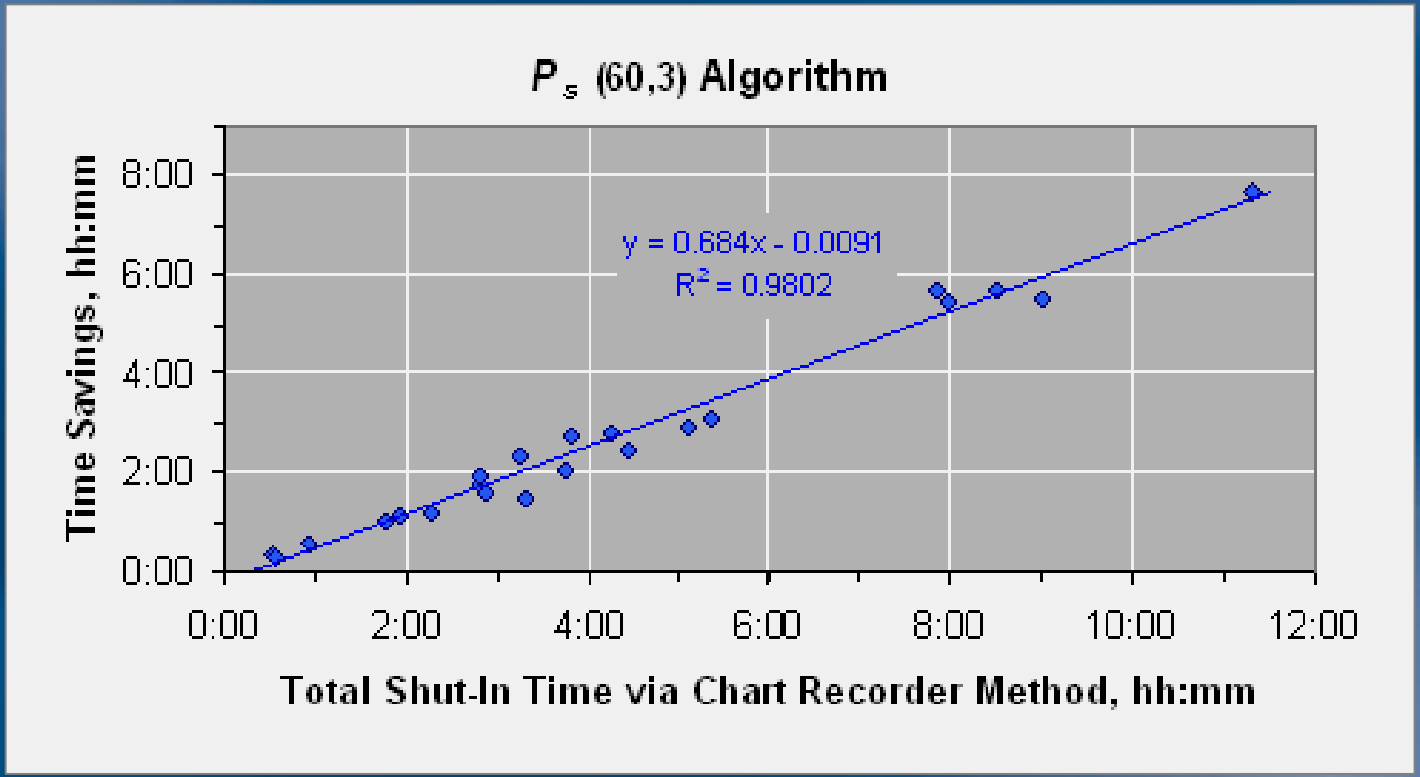
Potential Time Savings

- **Digital** interpretation can reduce the required shut-in time by 68%.



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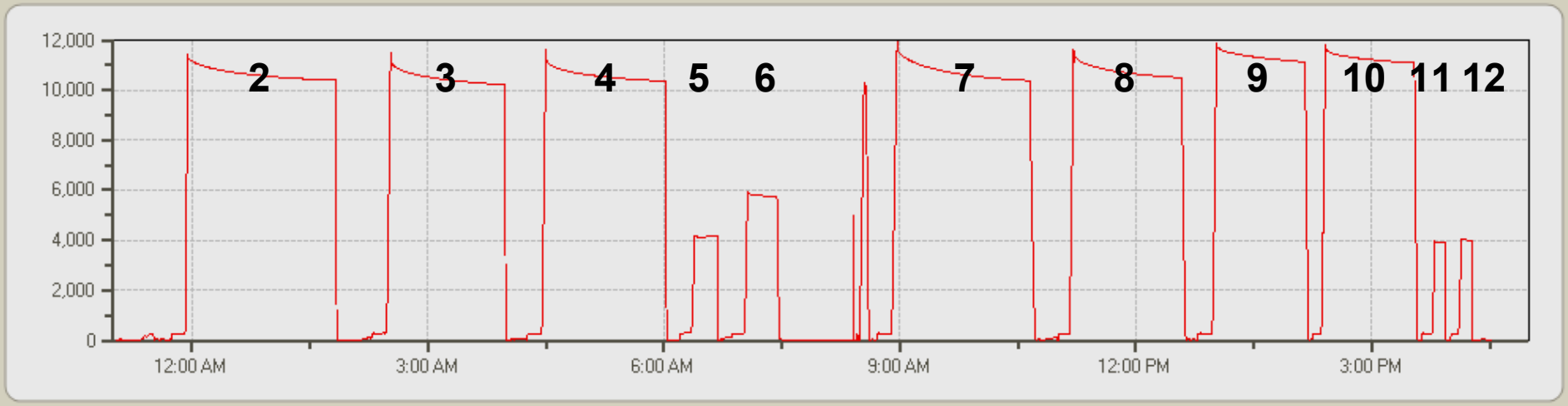
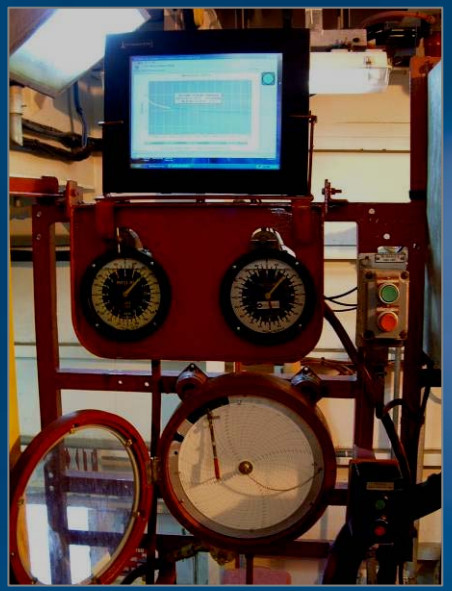
Deepwater Horizon 29 Sep 2007

11 of 12 subsea tests recorded & analyzed with Digital BOP software :



Digital BOP software run concurrent to chart method since July 2006.



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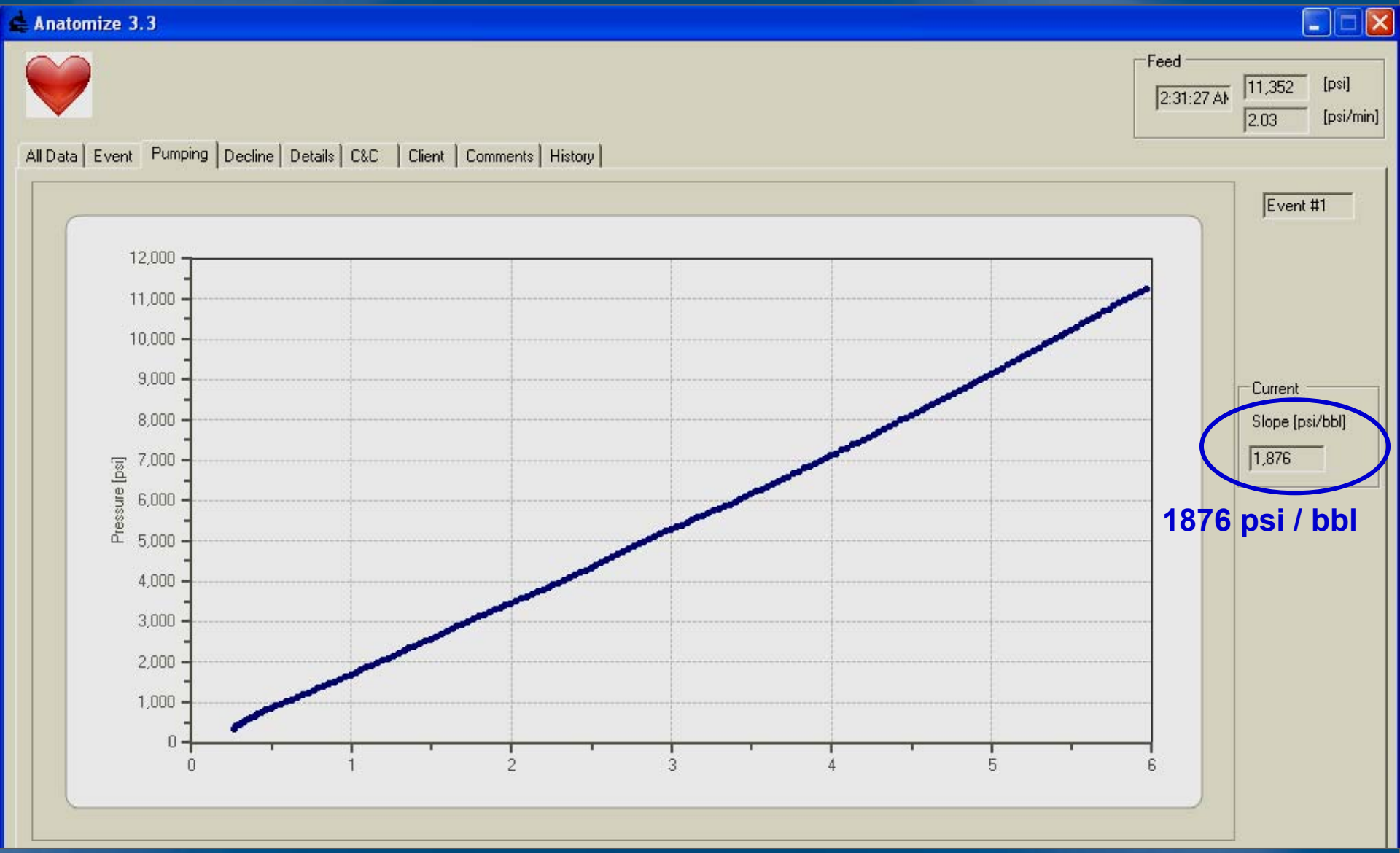
Deepwater Horizon 29 Sep 2007 **2:31 AM**
Subsea test #3 **pumping**



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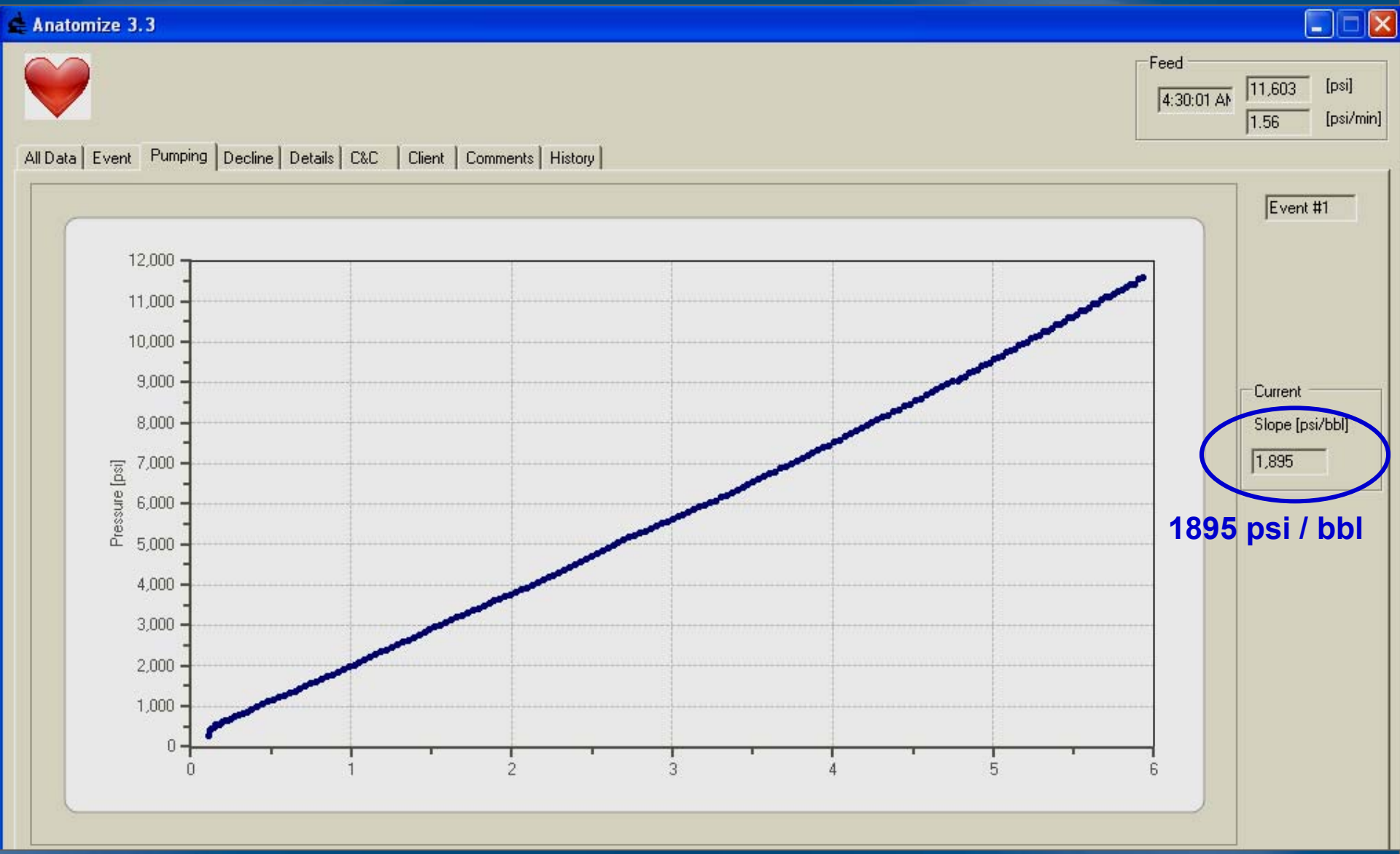
Deepwater Horizon 29 Sep 2007
Subsea test #4

4:30 AM
pumping



1895 psi / bbl

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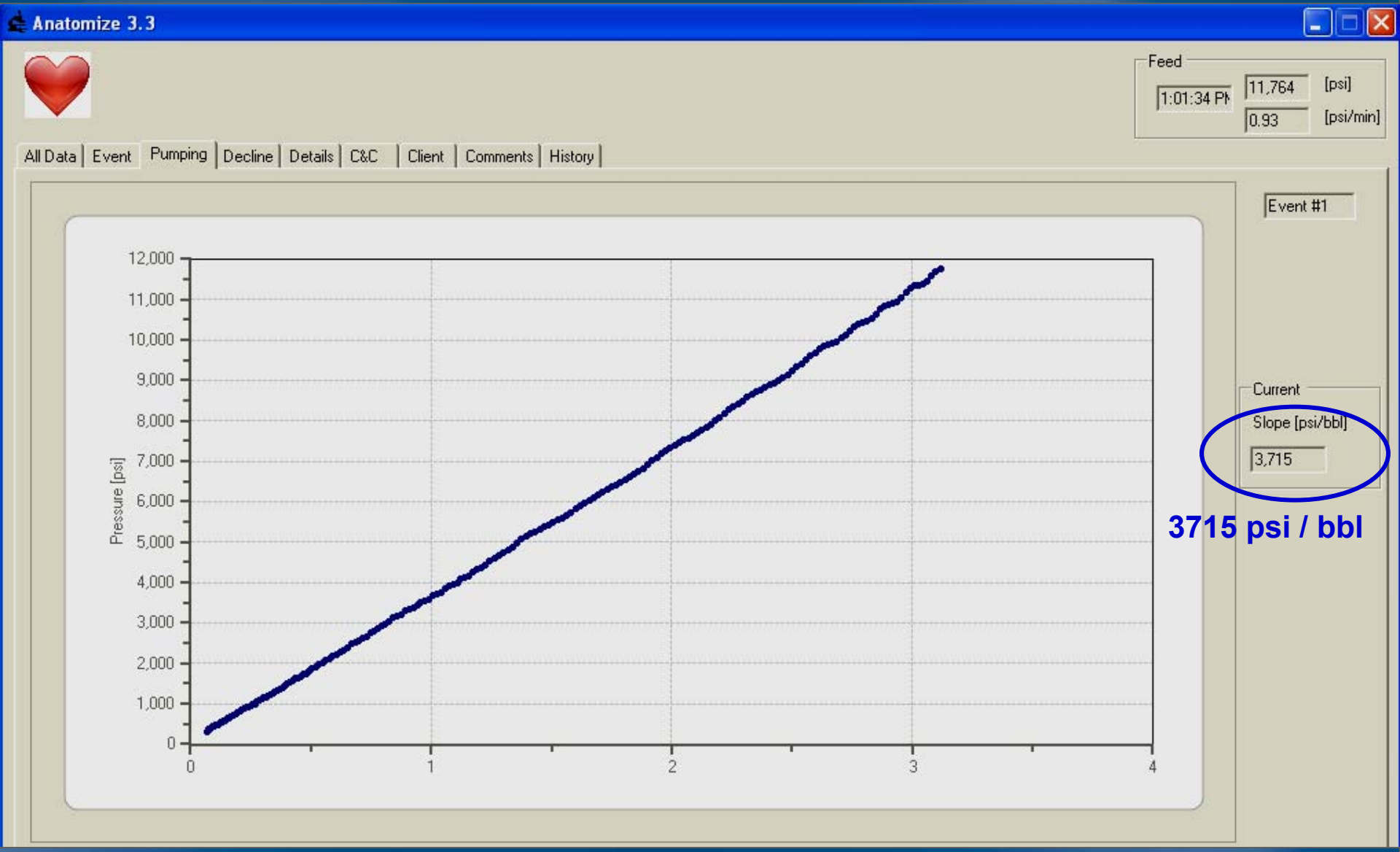
Deepwater Horizon 29 Sep 2007 **1:01 PM**
Subsea test #9 **pumping**



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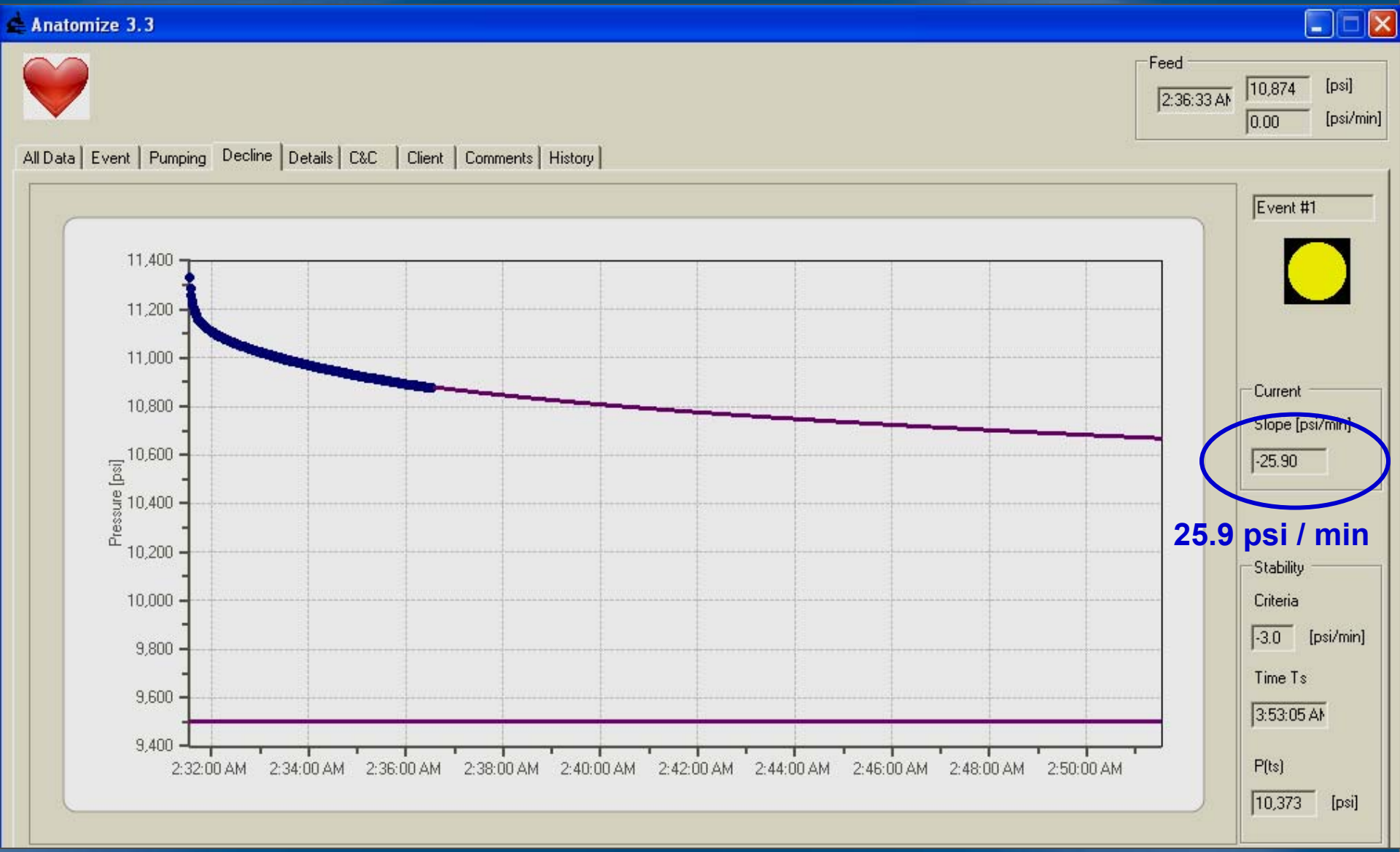
Deepwater Horizon 29 Sep 2007
Subsea test #3

2:36 AM
shut-in

5.0 min
since shut-in



25.9 psi / min

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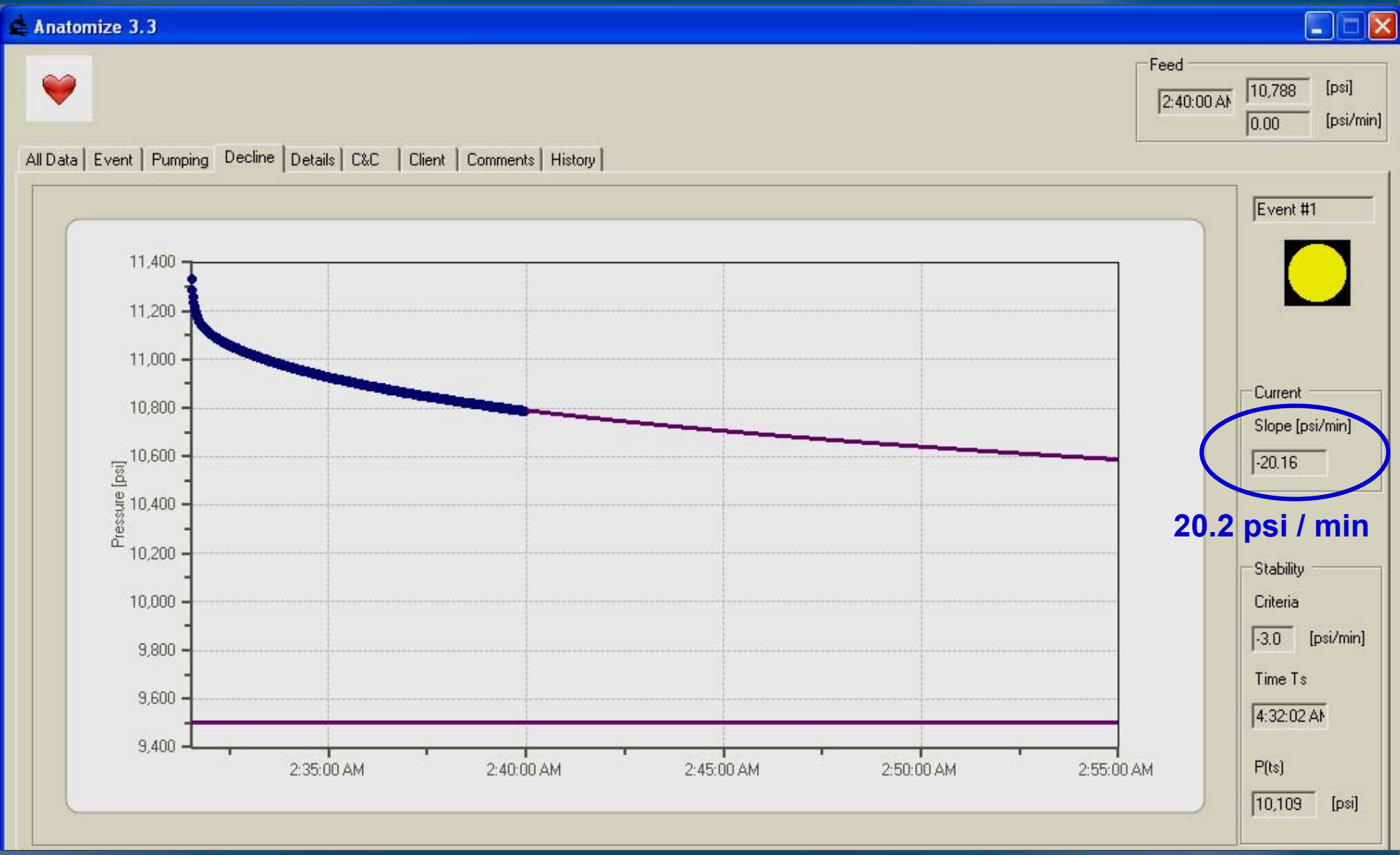
Deepwater Horizon 29 Sep 2007
Subsea test #3

2:40 AM
shut-in

8.4 min
since shut-in



20.2 psi / min

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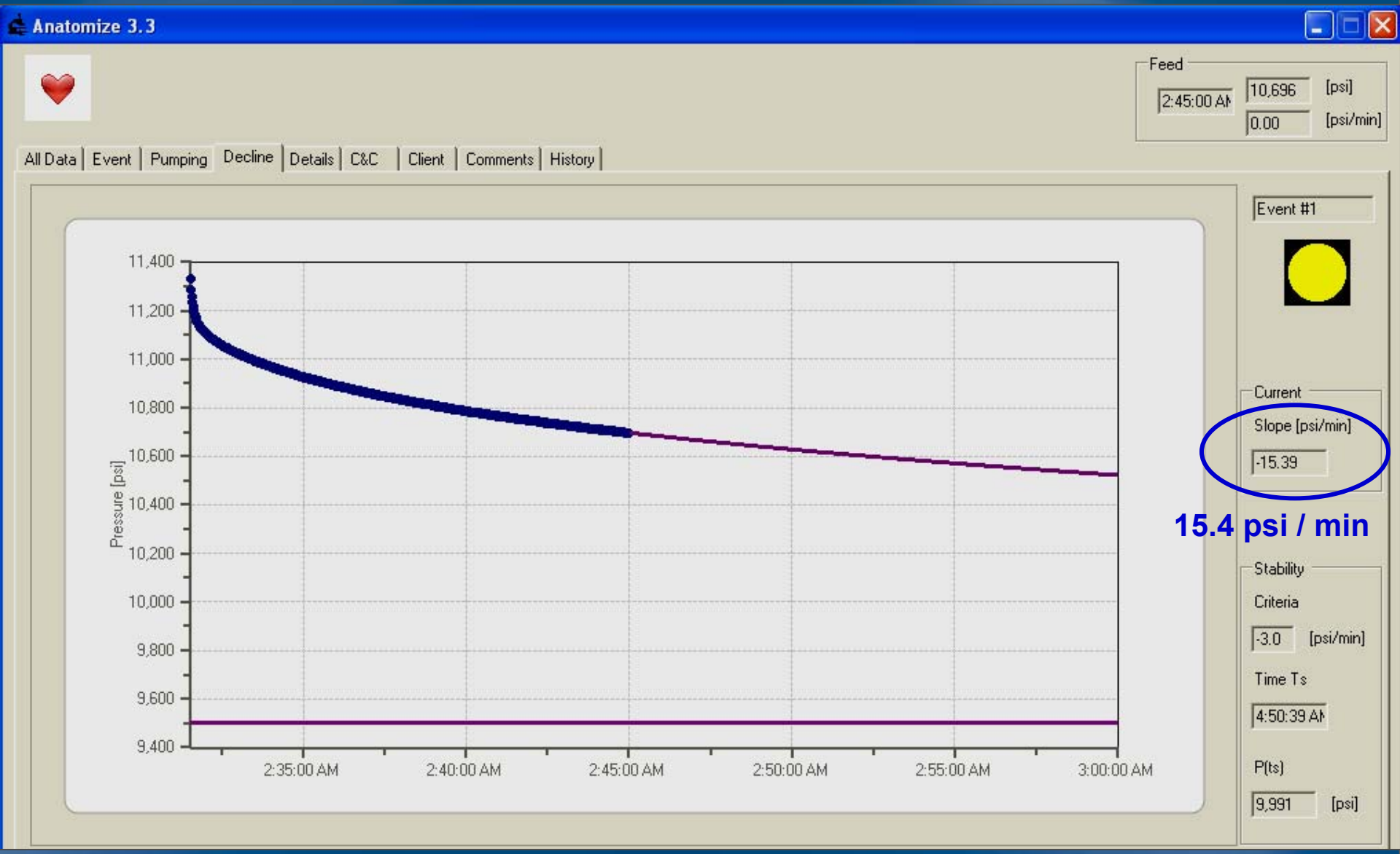
Deepwater Horizon 29 Sep 2007
Subsea test #3

2:45 AM
shut-in

13.4 min
since shut-in



15.4 psi / min

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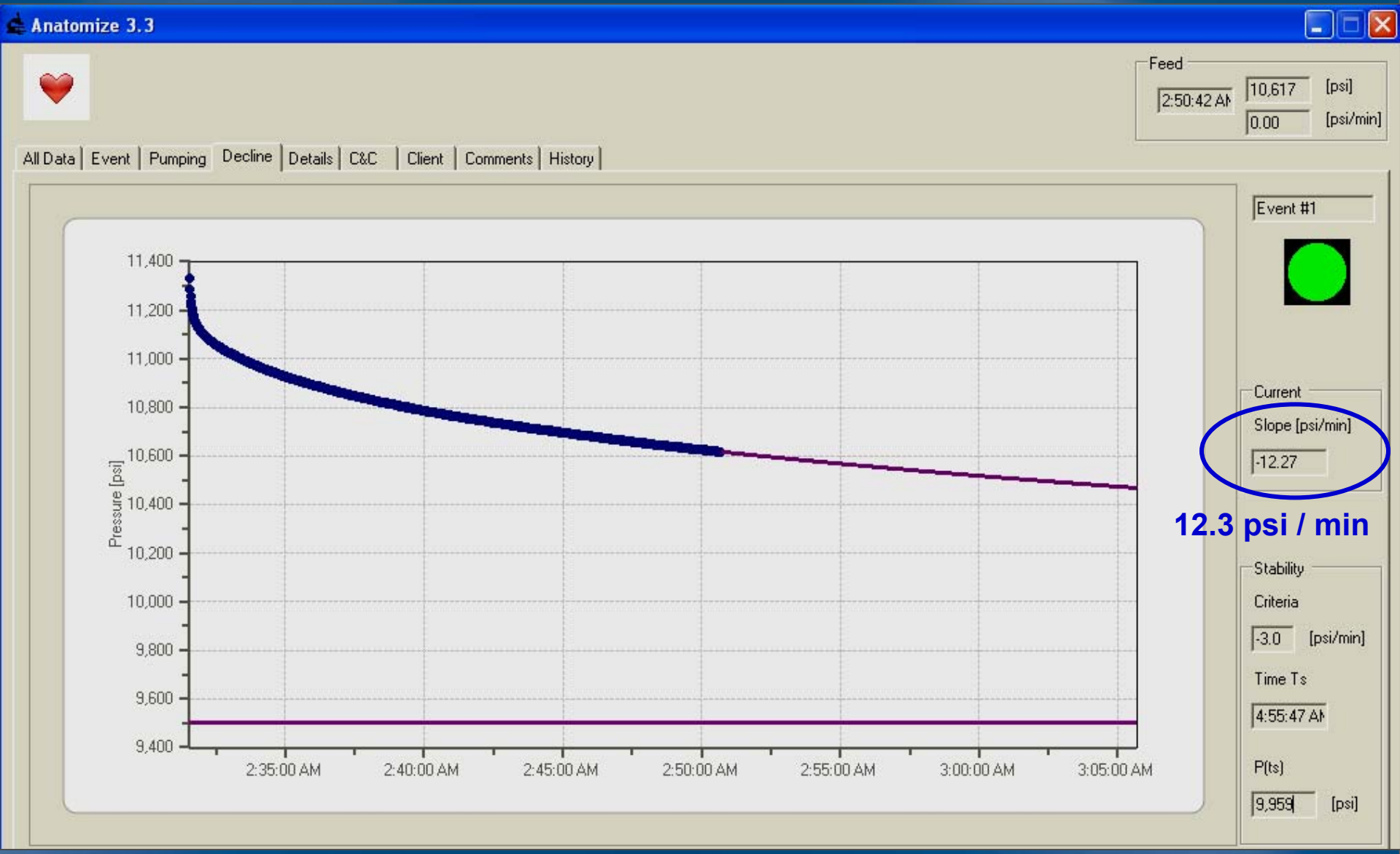
Deepwater Horizon 29 Sep 2007
Subsea test #3

2:50 AM
shut-in

19.1 min
since shut-in

0.1 min
since light



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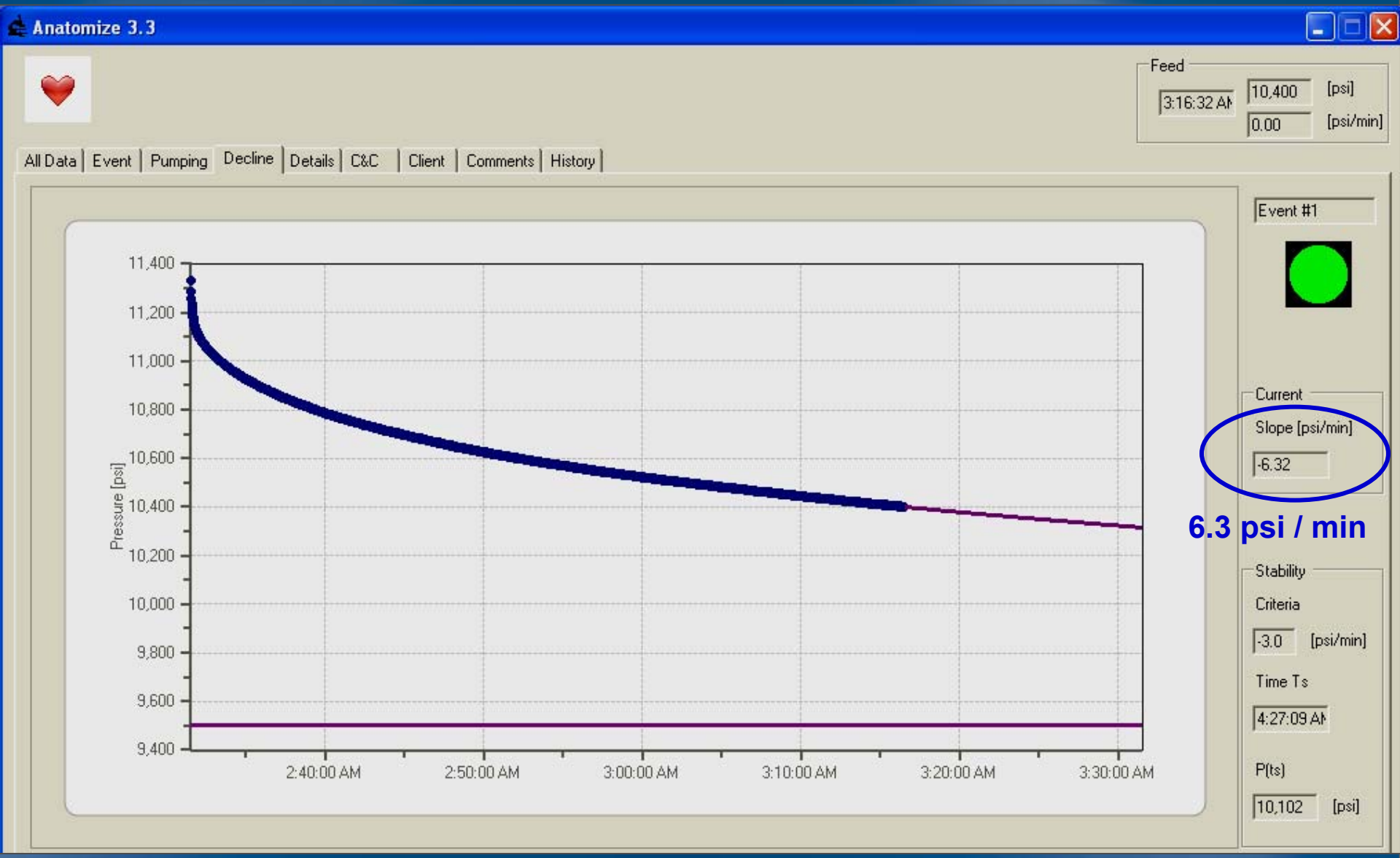
Deepwater Horizon 29 Sep 2007
Subsea test #3

3:16 AM
shut-in

45.0 min
since shut-in

26.0 min
since light



6.3 psi / min

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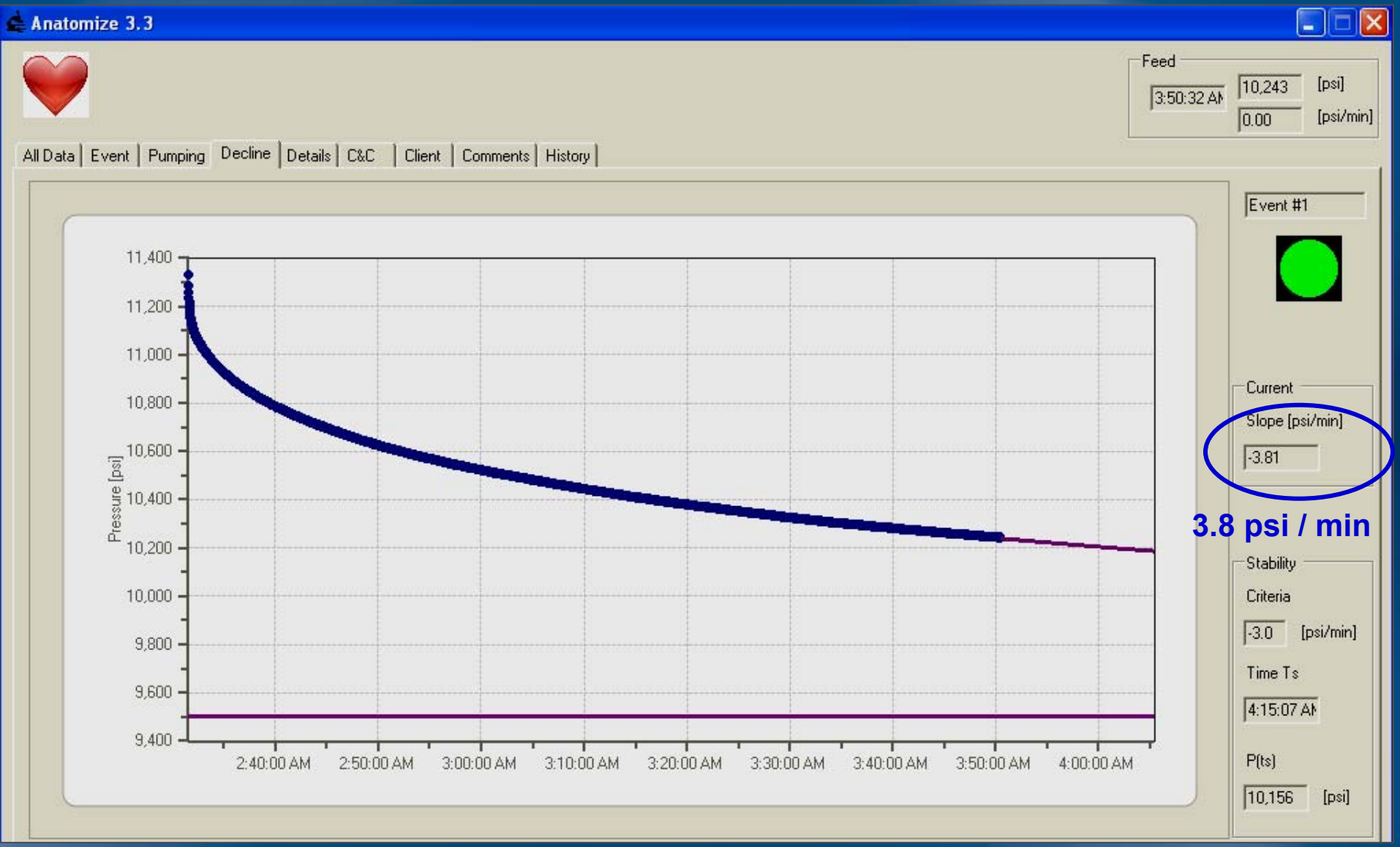
Deepwater Horizon 29 Sep 2007
Subsea test #3

3:50 AM
shut-in

79.0 min
since shut-in

60.0 min
since light



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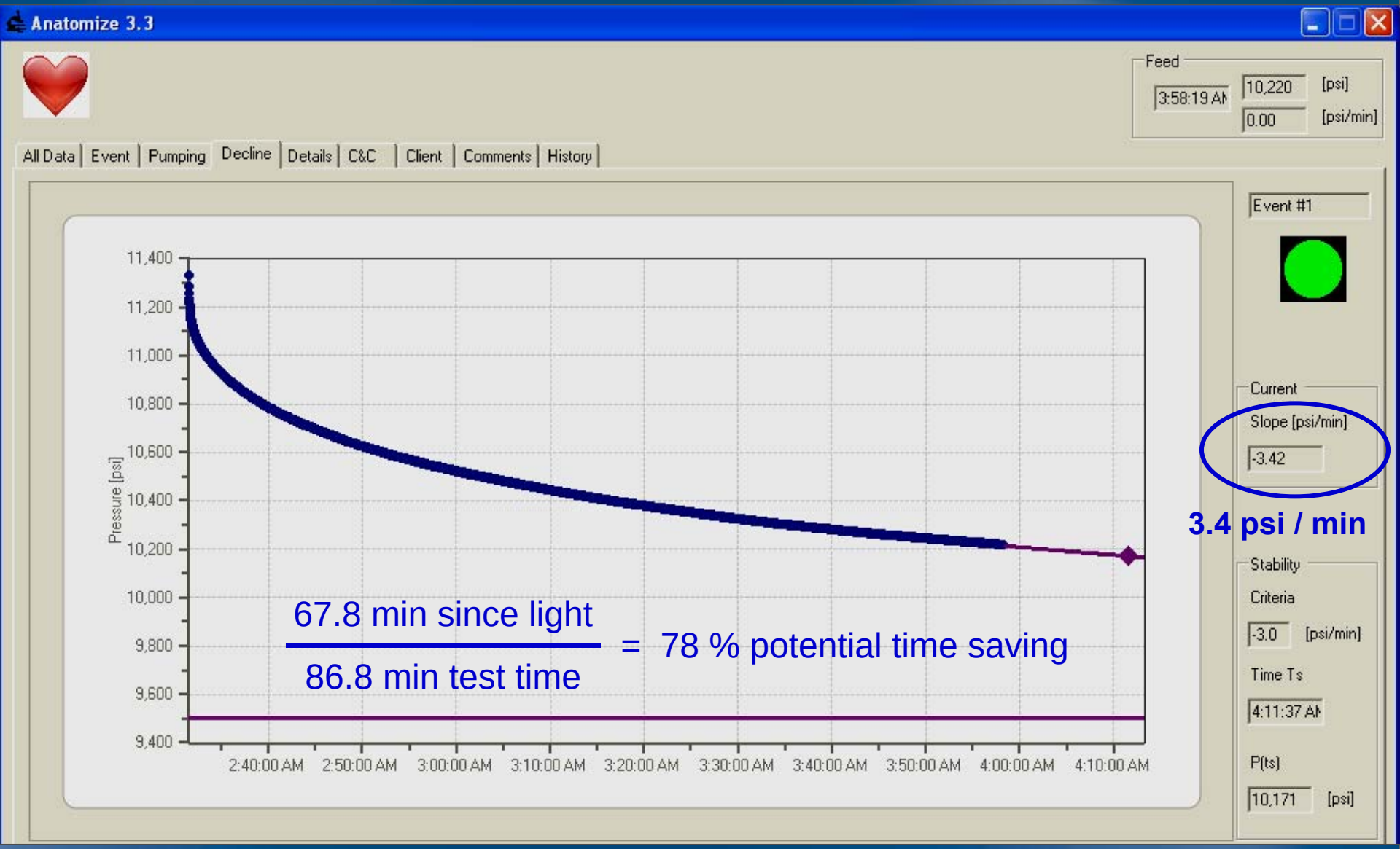
Deepwater Horizon 29 Sep 2007
Subsea test #3

3:58 AM
test ended

86.8 min
since shut-in

67.8 min
since light



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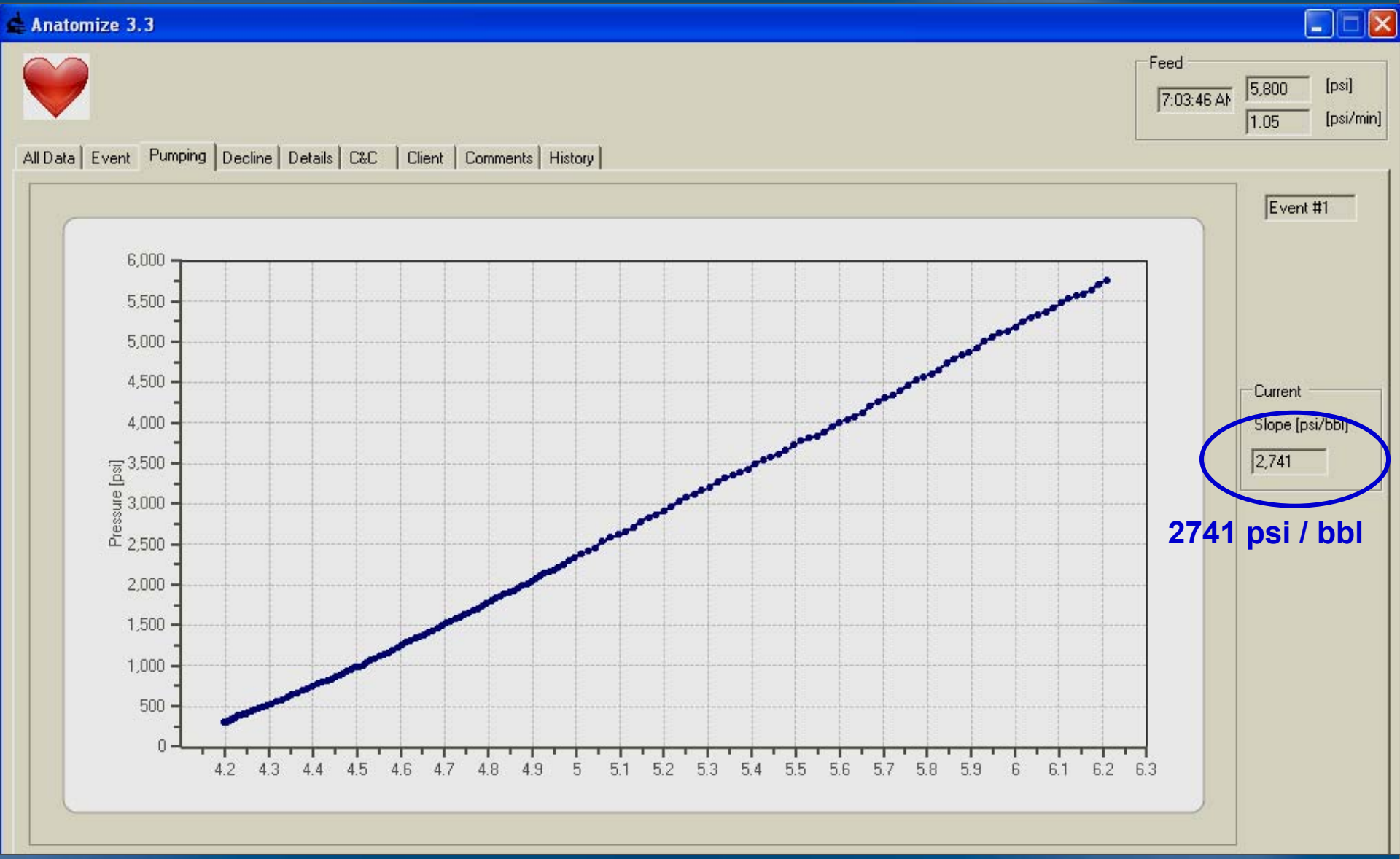
Deepwater Horizon 29 Sep 2007
Subsea test #6

7:03 AM
pumping



2741 psi / bbl

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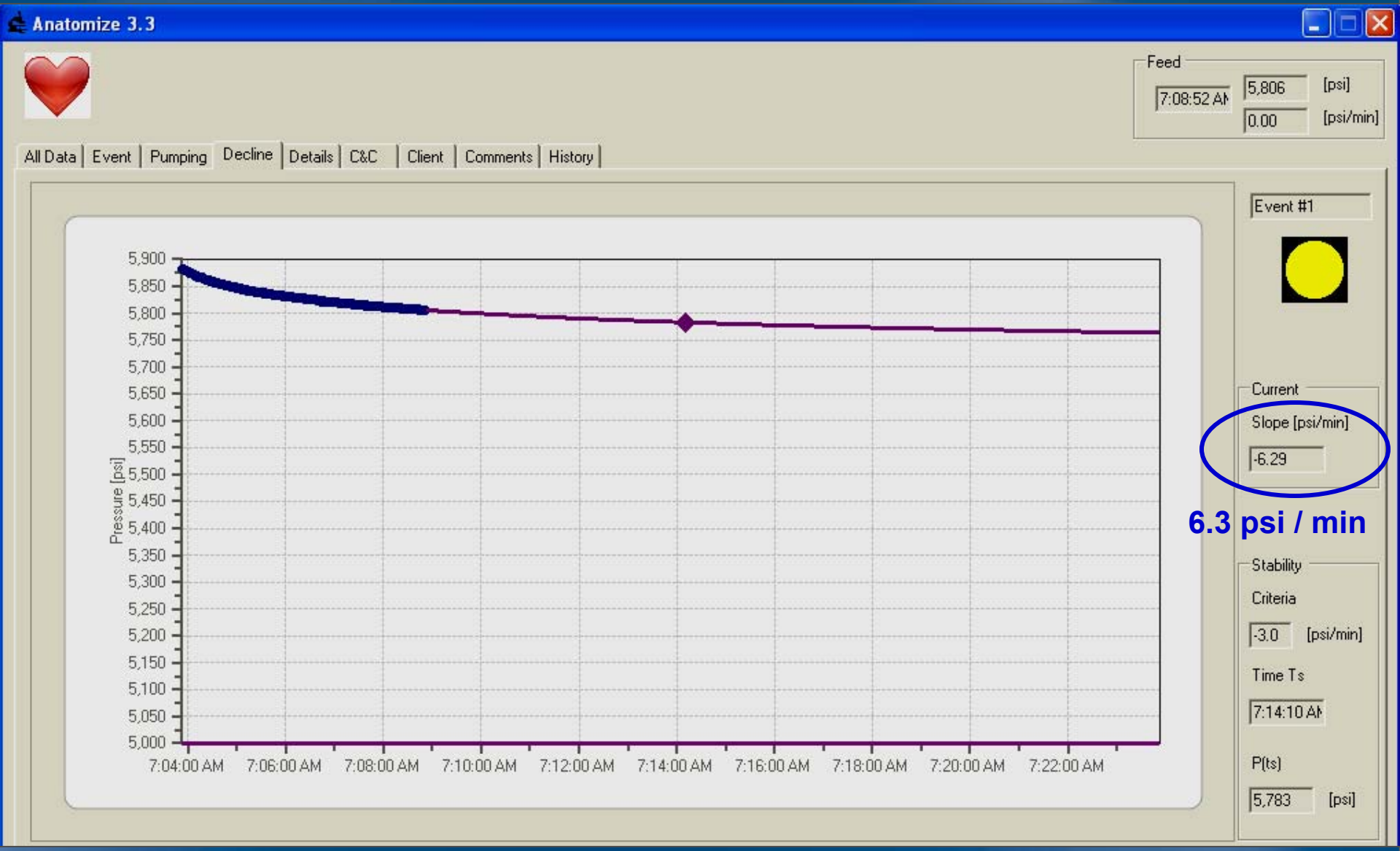
Deepwater Horizon 29 Sep 2007
Subsea test #6

7:09 AM
shut-in

5.0 min
since shut-in



6.3 psi / min

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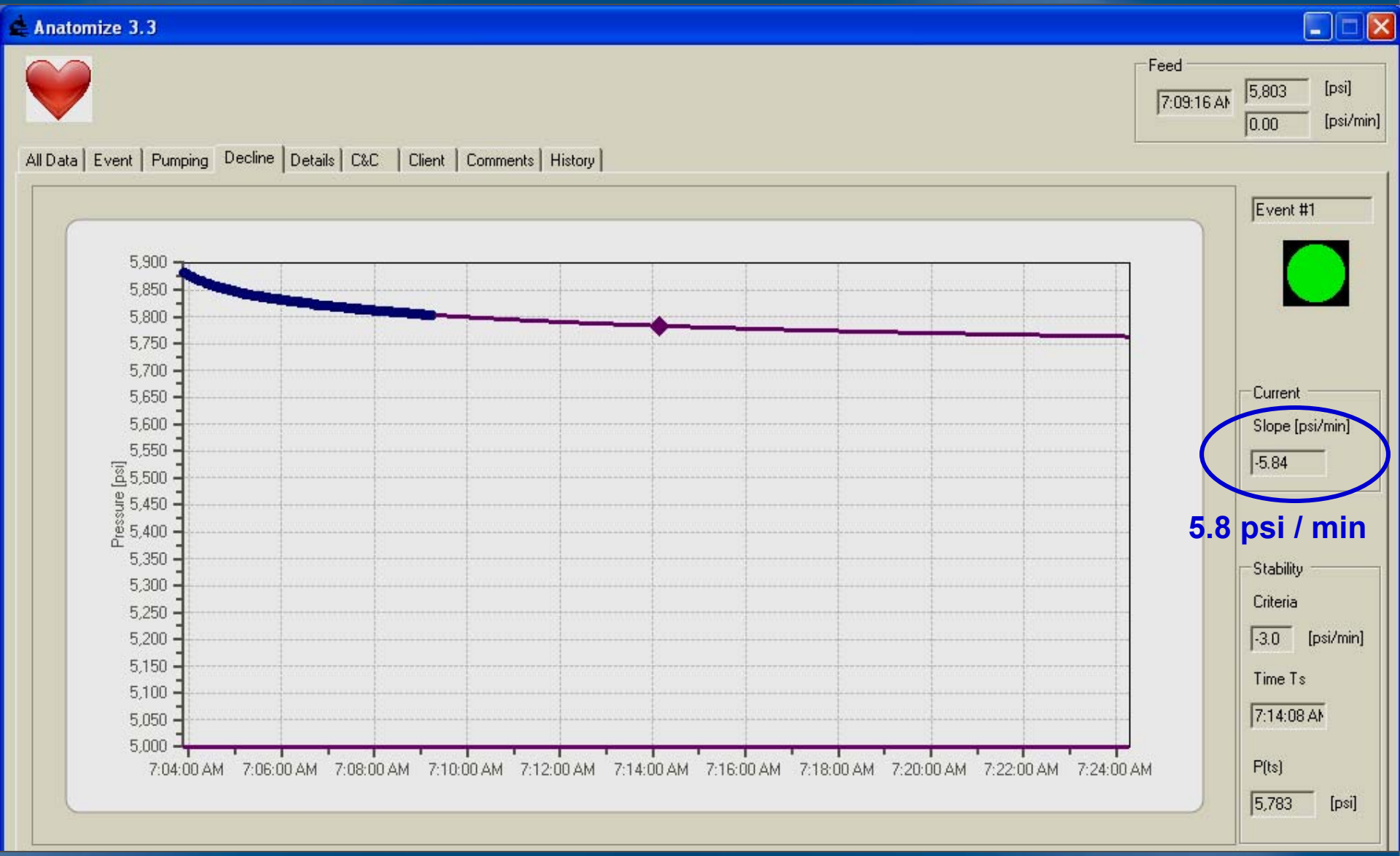
Deepwater Horizon 29 Sep 2007
Subsea test #6

7:09 AM
shut-in

5.4 min
since shut-in

0.0 min
since light



5.8 psi / min

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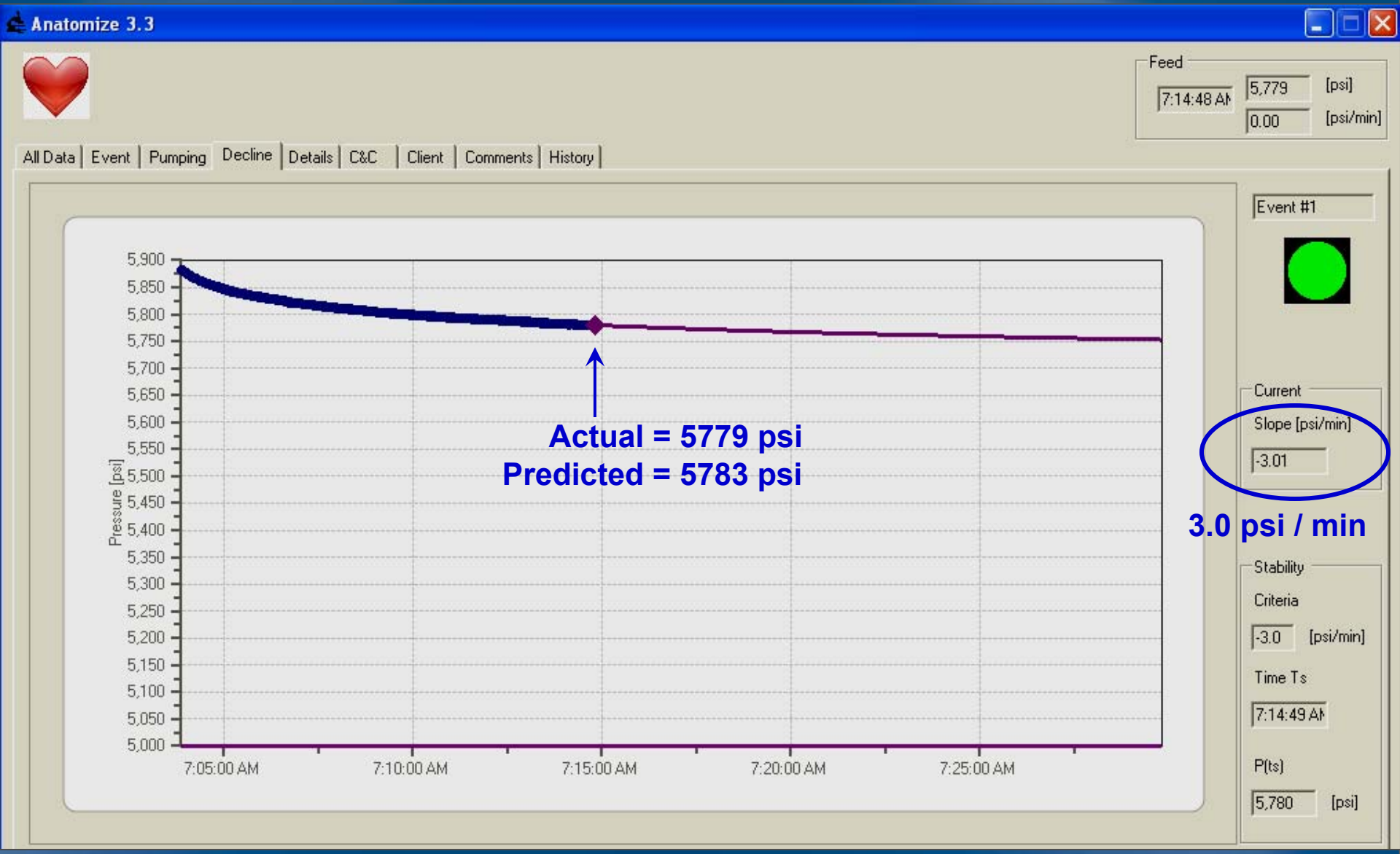
Deepwater Horizon 29 Sep 2007
Subsea test #6

7:15 AM
shut-in

10.9 min
since shut-in

5.5 min
since light



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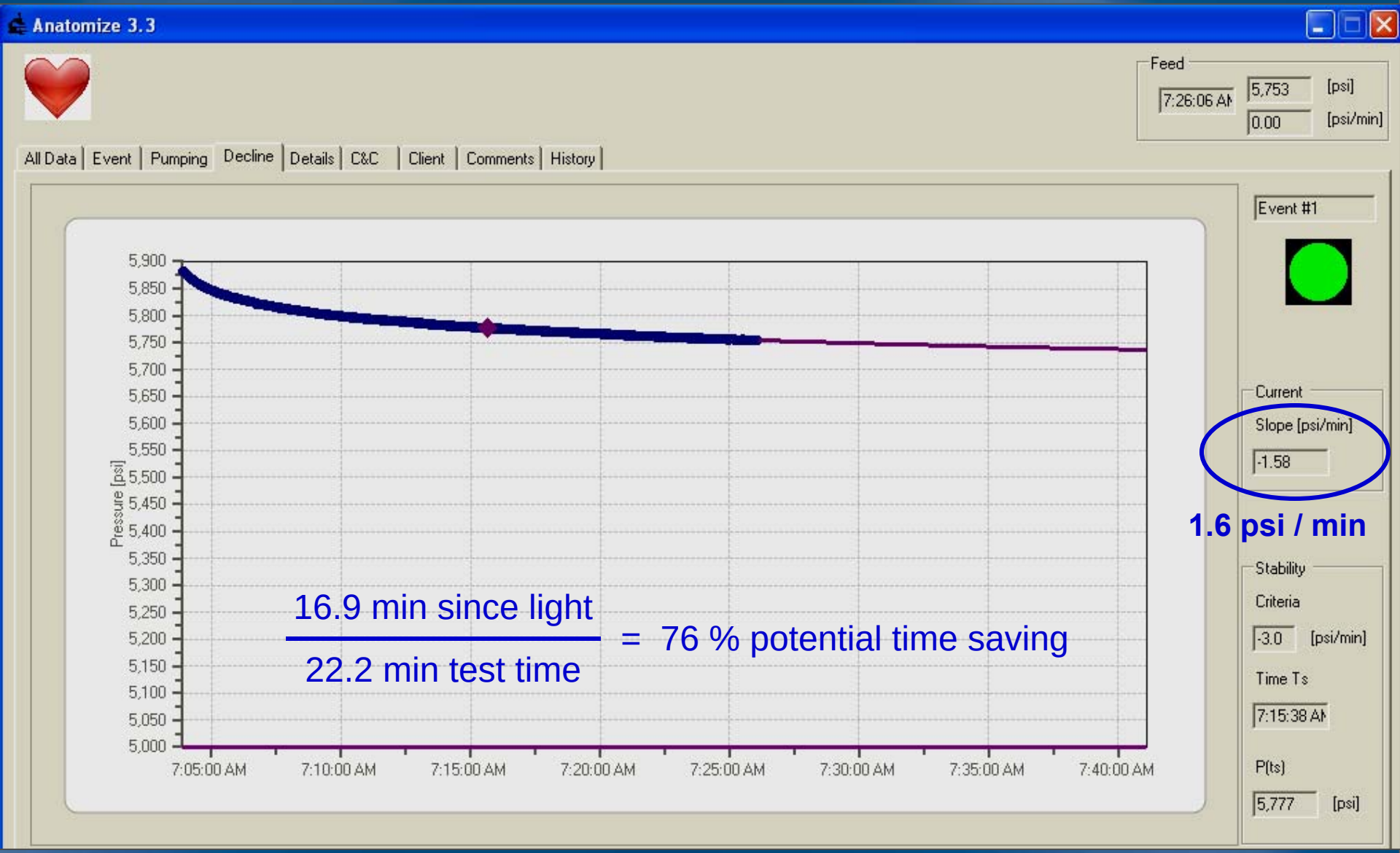
Deepwater Horizon 29 Sep 2007
Subsea test #6

7:26 AM
test ended

22.2 min
since shut-in

16.9 min
since light



$$\frac{\text{16.9 min since light}}{\text{22.2 min test time}} = \text{76 \% potential time saving}$$

1.6 psi / min

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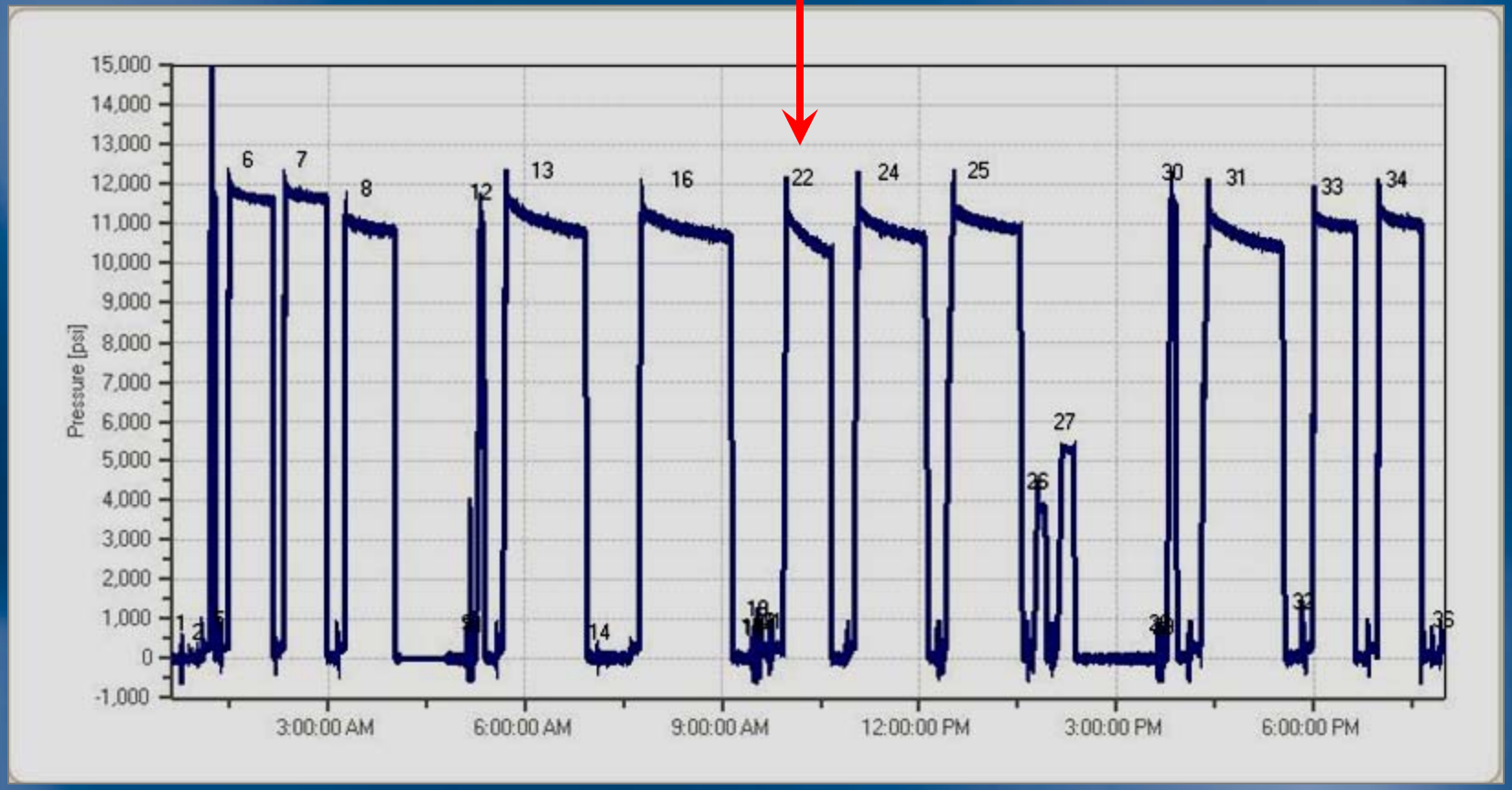
How About Leaks?

Deepwater Horizon 28 Aug 2007
Leak Example

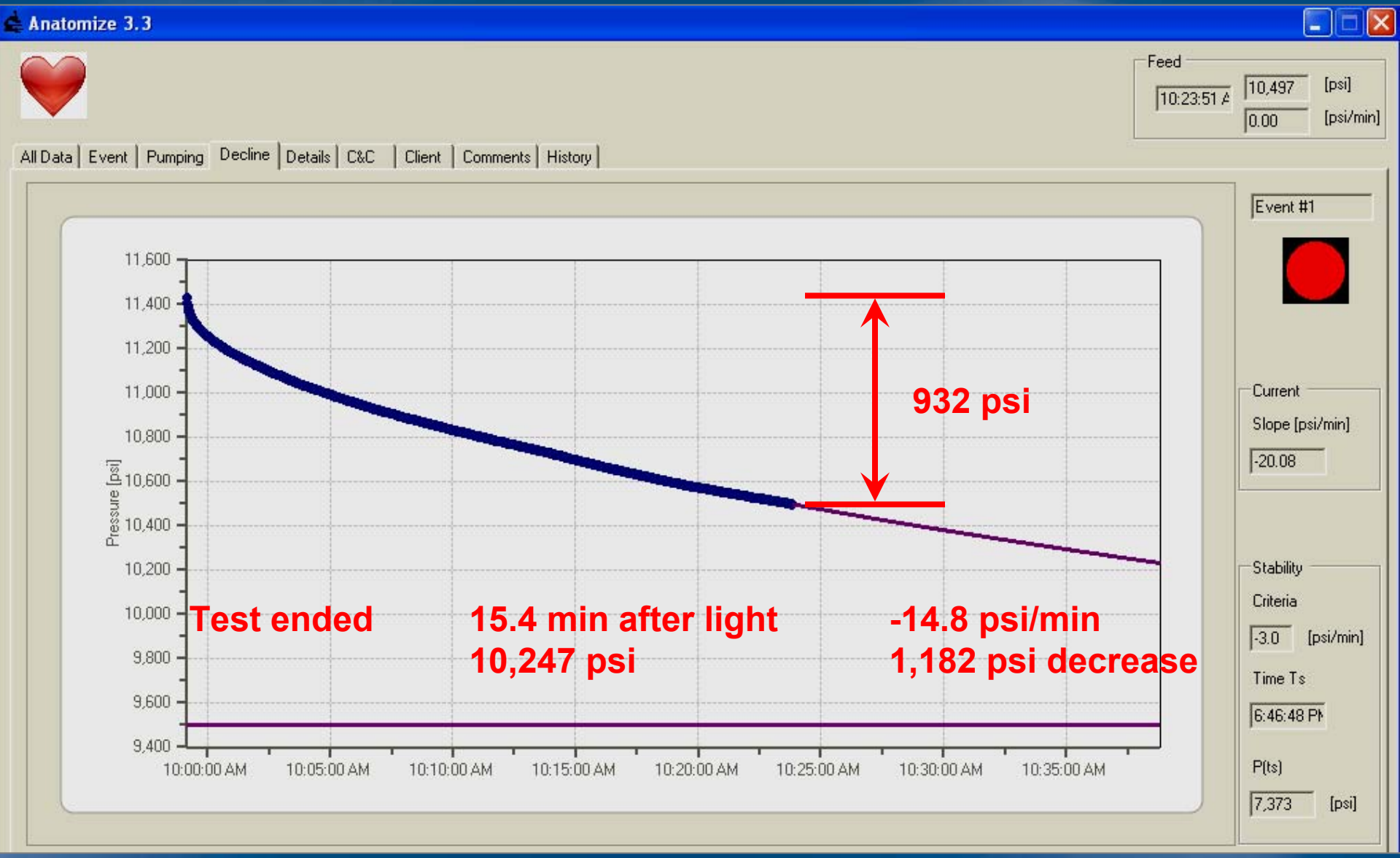


Deepwater Horizon 28 Aug 2007
Leak Example

10:24 AM
shut-in

24.7 min
since shut-in

0.2 min
since light

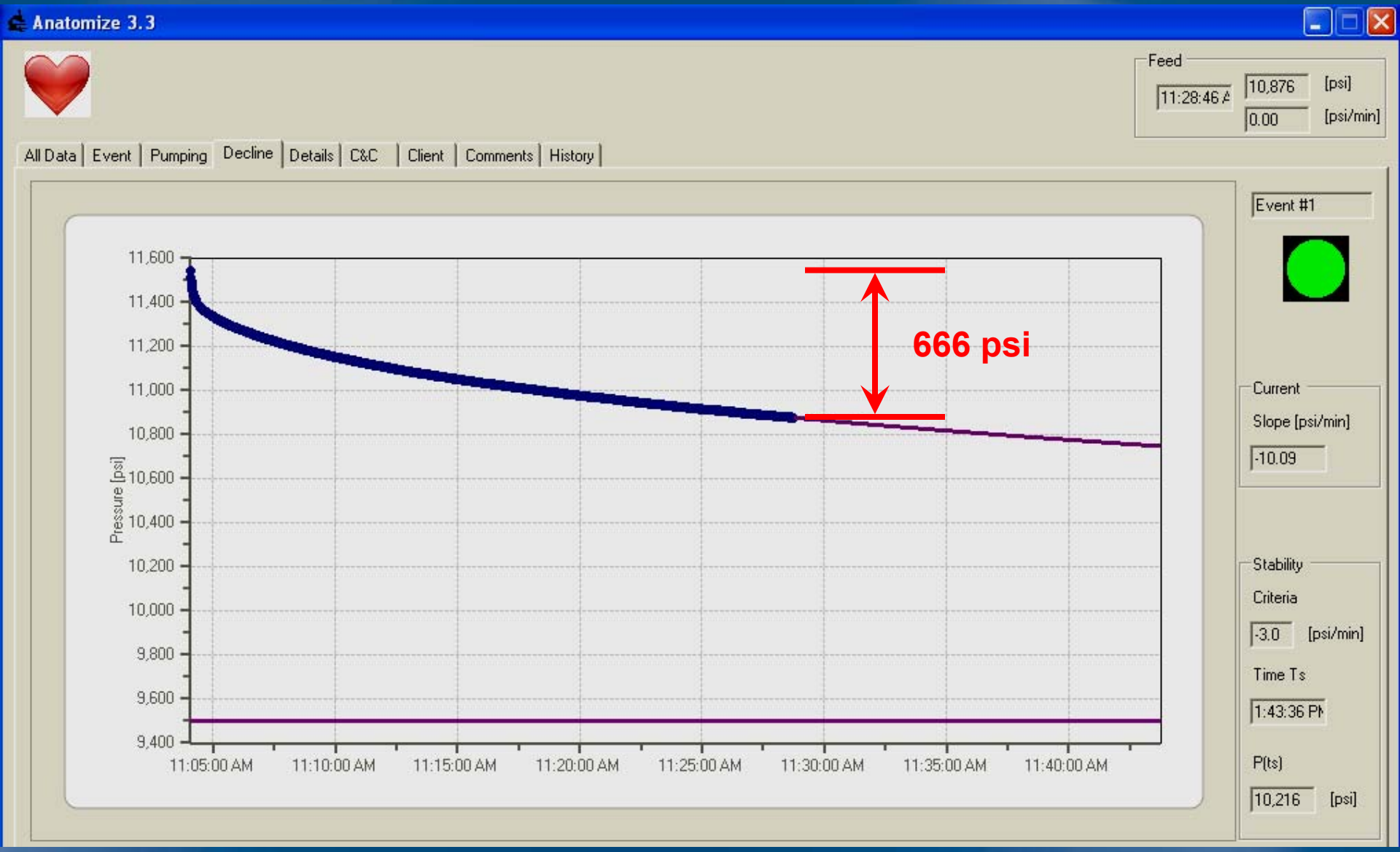


Deepwater Horizon 28 Aug 2007
Re-Test

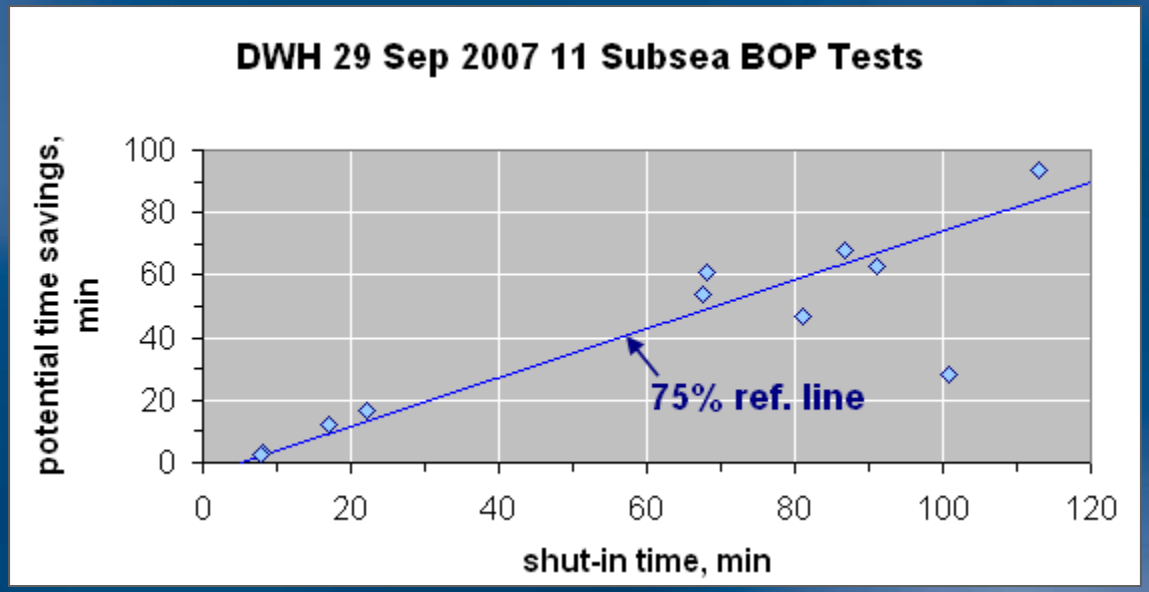
11:29 AM
shut-in

24.7 min
since shut-in

3.1 min
since light



Digital BOP can reduce shut-in time by 68% - 78% .



	11 tests	12 tests
Total shut-in time	11.1 hrs	12.7 hrs (est)
Potential savings	7.5 hrs	8.7 hrs (est)

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Digital BOP Software

- Also works for high pressure surface manifold tests.
- Generates a summary report of all tests.

Subsea

Test Started: 11:07:52 17Jul08
Test Ended: 11:07:45 18Jul08
Rig: TOI Deepwater Horizon
File Name: DWH__2008-07-17_11-14-35.anat

Software: 3.5.0.0
Well Name: MC 771 #1 Kodiak OCS-G-24017, 608174113400
Location: Kodiak: 28° 14' 46.888" N, 88° 48' 30.268" W
Operator: BP

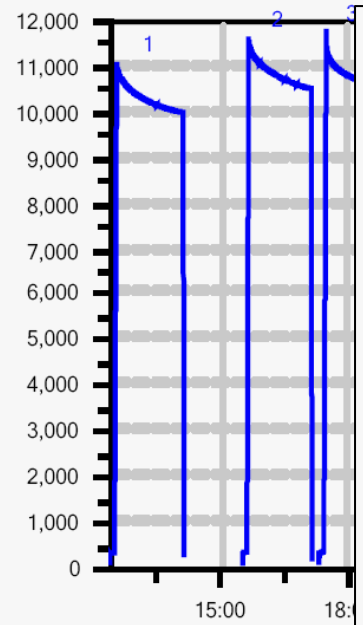
Subsea Engineer _____

Toolpusher _____

	Low Pressure				
Test No.	Start	End	Shut-in Time [min]	Target Pressure [psi]	Final Pressure [psi]
1	12:25:44 P	12:33:06 P	7.4	200	309
2	3:34:00 PM	3:39:34 PM	5.6	200	324
3	5:22:14 PM	5:27:45 PM	5.5	200	338
4	7:30:44 PM	7:42:07 PM	11.4	200	310
5	9:17:34 PM	9:28:55 PM	11.4	200	325
6	9:56:54 PM	10:03:05 P	6.2	200	265
7	11:43:36 P	11:51:58 P	8.4	200	277
8	1:41:20 AM	1:51:50 AM	10.5	200	372
9	3:25:57 AM	3:31:35 AM	5.6	200	371
10	4:31:03 AM	4:37:59 AM	6.9	200	440
11	5:33:12 AM	5:39:32 AM	6.3	200	349
12	5:56:31 AM	6:02:27 AM	5.9	200	330

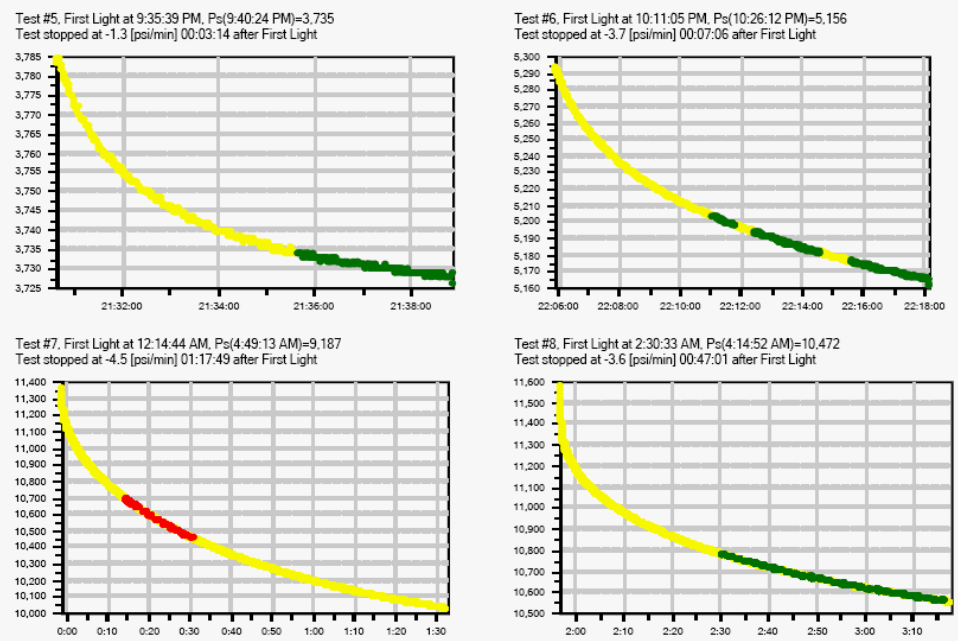
DWH__2008-07-17_11-14-35.anat

Subsea



DWH__2008-07-17_11-14-35.anat

Subsea



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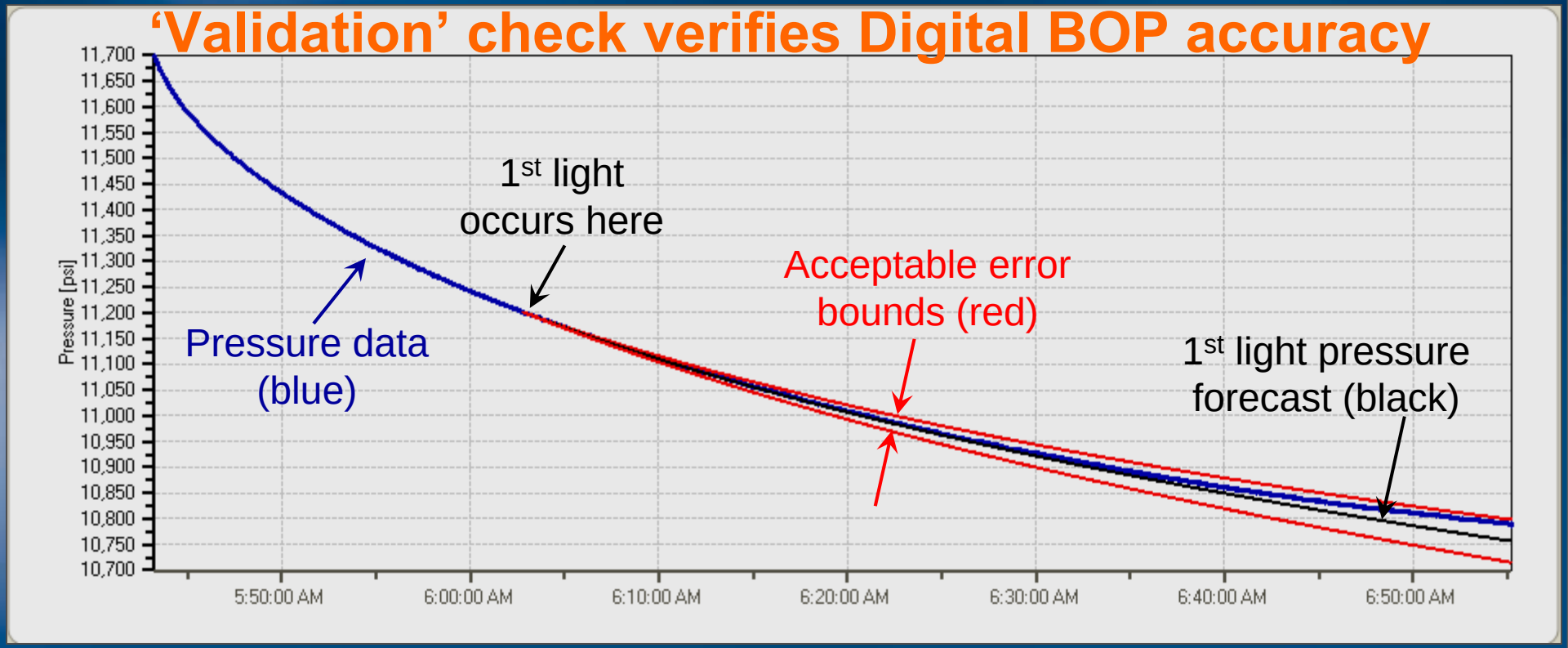
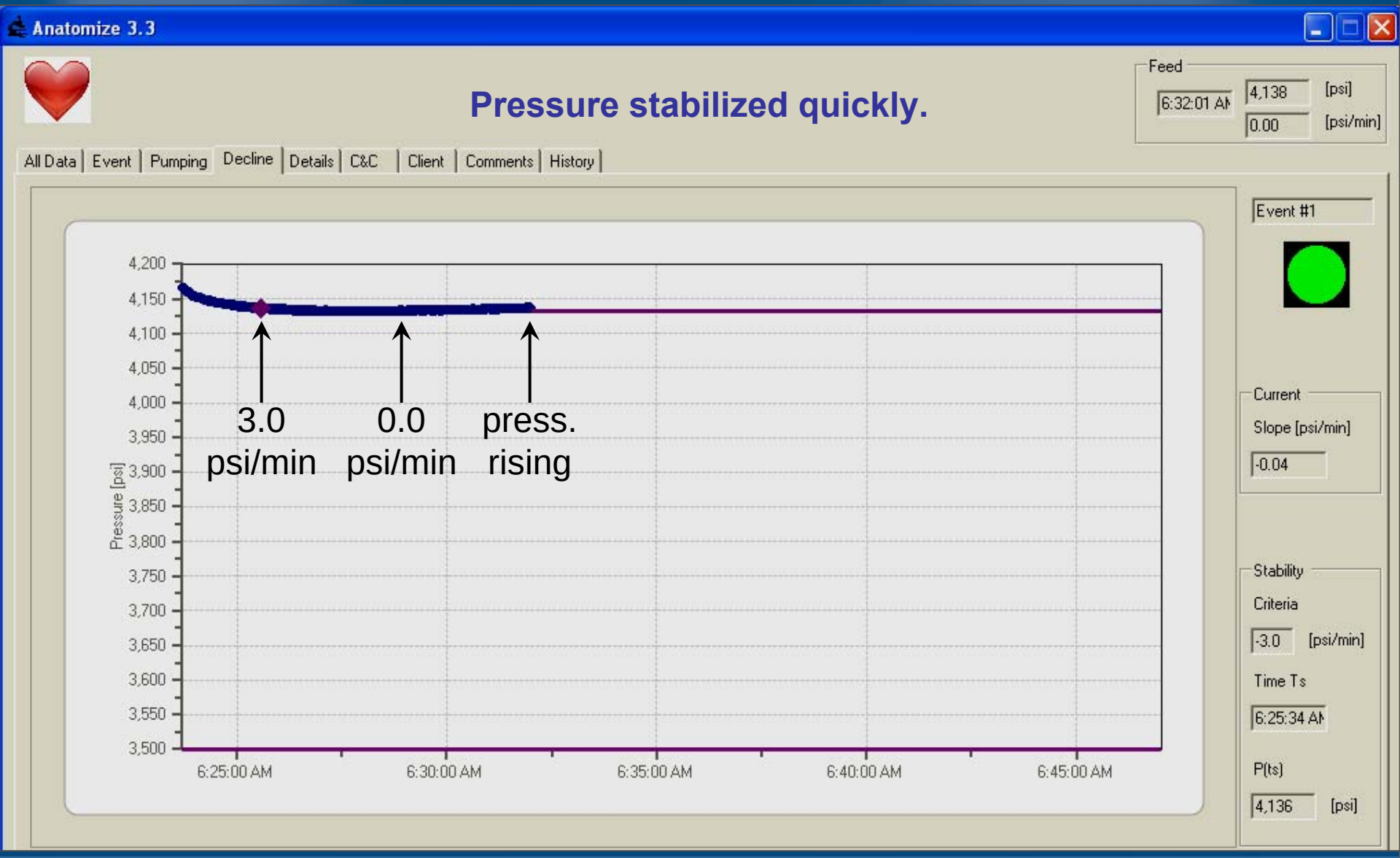
Digital BOP Status

- MMS-accepted under present regulations, June 2008.
- BP must familiarize each district Chief Inspector.
- Approvals to be granted well-by-well via APD.
- 1st test of a series to be done by chart method.
- If Digital BOP valid on 1st test, then okay to use.



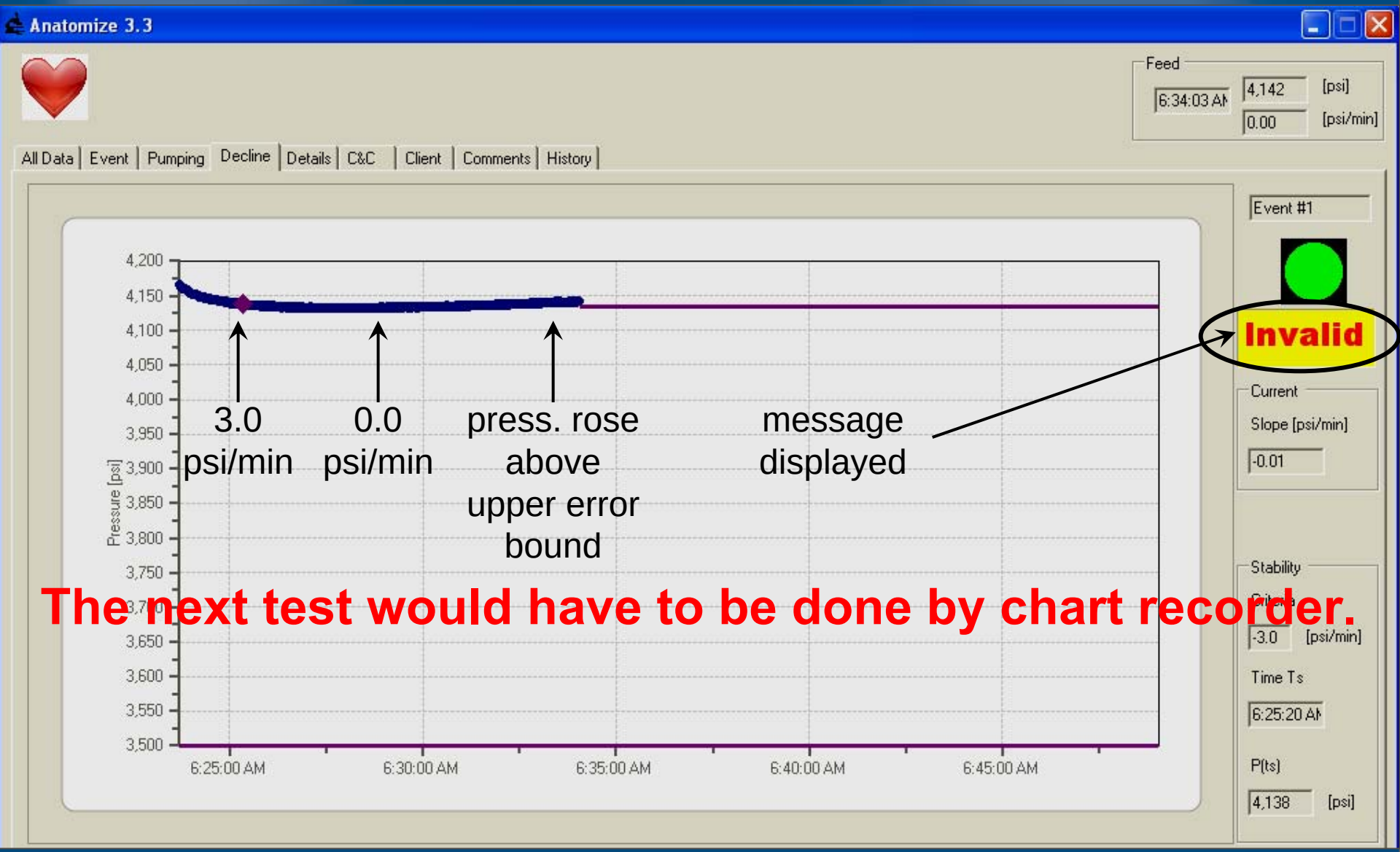
Validation is always being checked.

Example where a forecast became invalid:



Validation is always being checked.

Example where a forecast became invalid:



The next test would have to be done by chart recorder.

6 Rules of Use

1. 1st test – done 'long way' to validate software
2. Validation – if valid, software can then be used
3. Invalidation – what to do next
4. Green lights – basis for ending tests
5. Red lights – what to do next
6. Documentation – requirements

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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.

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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.

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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).

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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”.

In the absence of a definitive software interpretation, i.e., the software displays a yellow "light", it will be permissible to 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.

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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.

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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.

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Software-Generated Report page 1

Subsea

Test Started: 11:07:52 17Jul08
Test Ended: 11:07:45 18Jul08
Rig: TOI Deepwater Horizon
File Name: DWH__2008-07-17_11-14-35.anat

Software: 3.5.0.0
Well Name: MC 771 #1 Kodiak OCS-G-24017, 608174113400
Location: Kodiak: 28° 14' 46.888" N, 88° 48' 30.268" W
Operator: BP

Subsea Engineer _____ Operator _____

Toolpusher _____ OIM _____

	Low Pressure					High Pressure						Digital Analysis		
Test No.	Start	End	Shut-in Time [min]	Target Pressure [psi]	Final Pressure [psi]	Start	End	Shut-in Time [min]	Target Pressure [psi]	Initial Pressure [psi]	Final Pressure [psi]	Stable Pressure [psi]	Target Time [min]	Final Status
1	12:25:44 P	12:33:06 P	7.4	200	309	12:36:26 P	2:09:57 PM	93.5	10,000	10,974	9,956	9,893	6,695.2	Bad
2	3:34:00 PM	3:39:34 PM	5.6	200	324	3:42:08 PM	5:10:00 PM	87.9	10,000	11,537	10,476	10,237	9,046.6	
3	5:22:14 PM	5:27:45 PM	5.5	200	338	5:31:24 PM	6:48:02 PM	76.6	10,000	11,538	10,532	10,453	5,931.2	
4	7:30:44 PM	7:42:07 PM	11.4	200	310	7:47:20 PM	8:51:55 PM	64.6	10,000	11,416	10,292	10,016	8,129.9	
5	9:17:34 PM	9:28:55 PM	11.4	200	325	9:30:39 PM	9:38:53 PM	8.2	3,500	3,784	3,726	3,735	285.1	Good
6	9:56:54 PM	10:03:05 P	6.2	200	265	10:05:55 P	10:18:11 P	12.3	5,000	5,291	5,163	5,156	907.3	Good
7	11:43:36 P	11:51:58 P	8.4	200	277	11:59:07 P	1:32:33 AM	93.4	10,000	11,362	10,031	9,859	8,304.9	
8	1:41:20 AM	1:51:50 AM	10.5	200	372	1:57:03 AM	3:17:34 AM	80.5	10,000	11,582	10,551	10,473	6,250.1	
9	3:25:57 AM	3:31:35 AM	5.6	200	371	3:34:03 AM	4:17:27 AM	43.4	10,000	11,712	11,153	11,098	3,682.0	Good
10	4:31:03 AM	4:37:59 AM	6.9	200	440	4:40:12 AM	5:26:14 AM	46.0	10,000	11,653	11,013	10,918	4,382.5	Good
11	5:33:12 AM	5:39:32 AM	6.3	200	349	5:40:38 AM	5:49:50 AM	9.2	3,500	3,740	3,724	3,716	79.3	Good
12	5:56:31 AM	6:02:27 AM	5.9	200	330	6:03:21 AM	6:12:57 AM	9.6	3,500	3,786	3,747	3,755	249.2	Good

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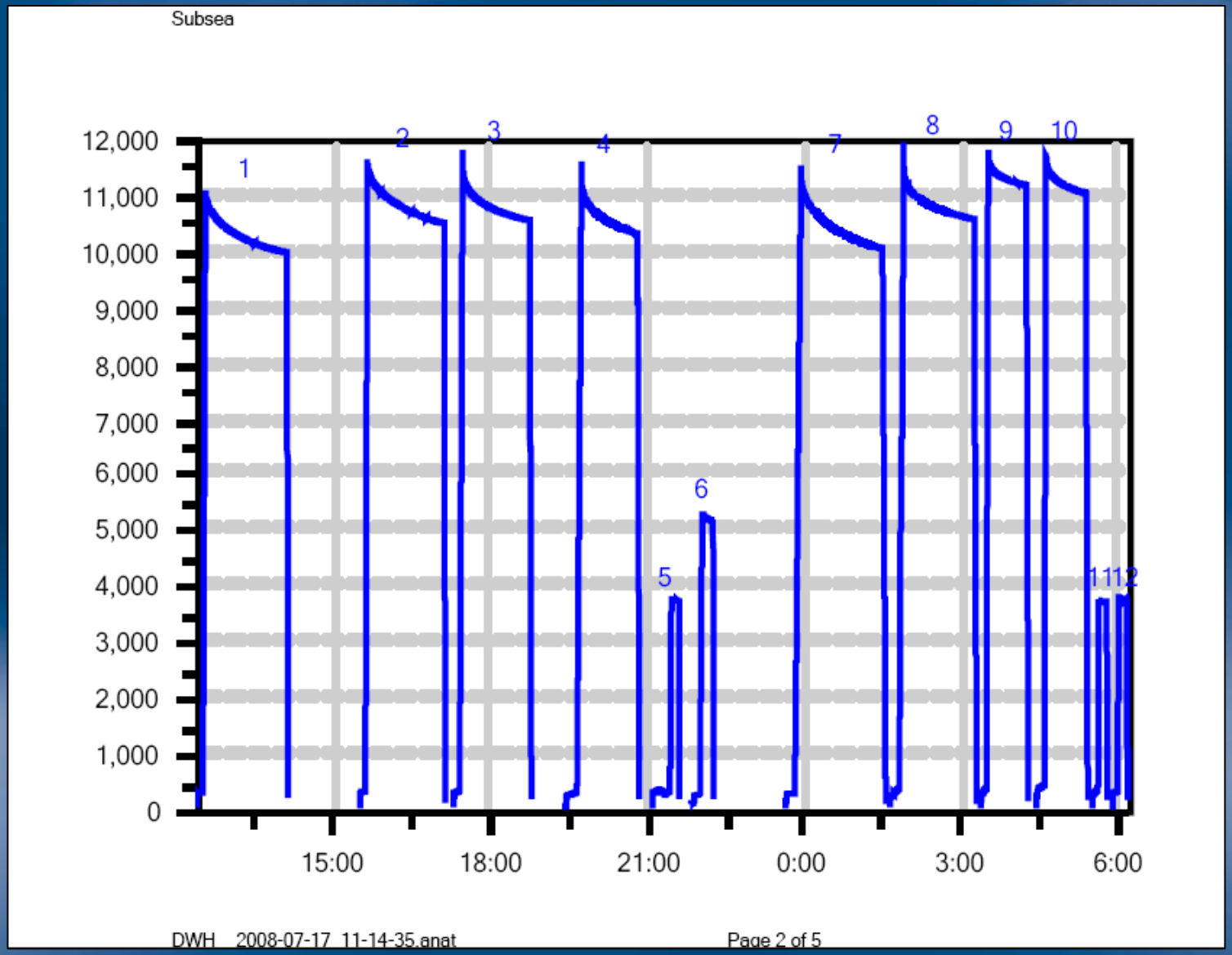
Software-Generated Report page 2



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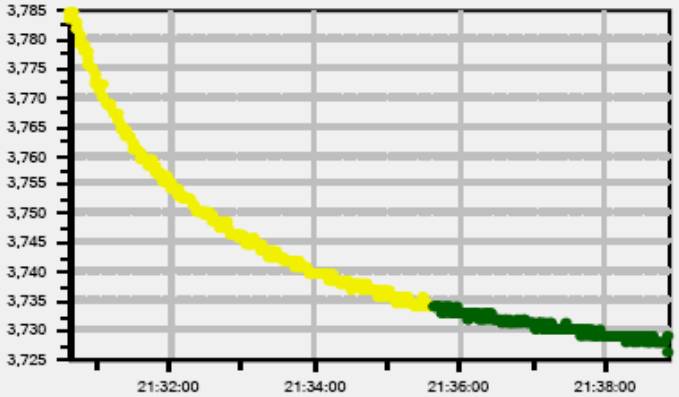
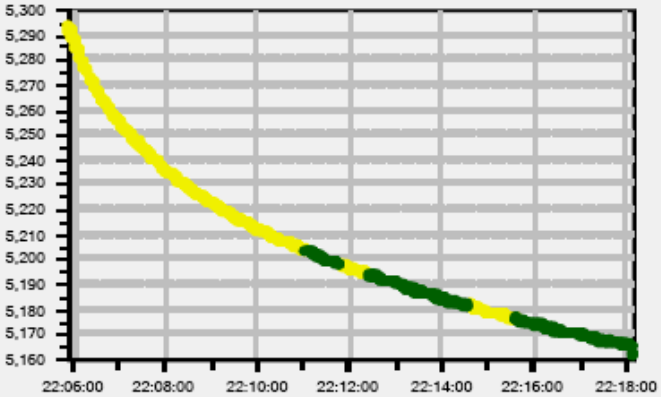
Software-Generated Report pages 3-end

Subsea

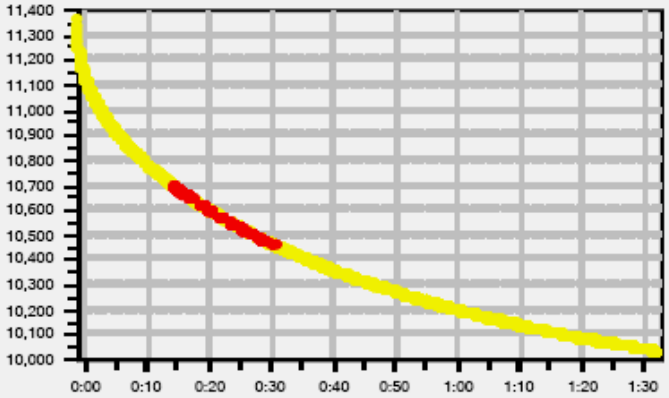
Test #5, First Light at 9:35:39 PM, Ps(9:40:24 PM)=3,735
Test stopped at -1.3 [psi/min] 00:03:14 after First Light



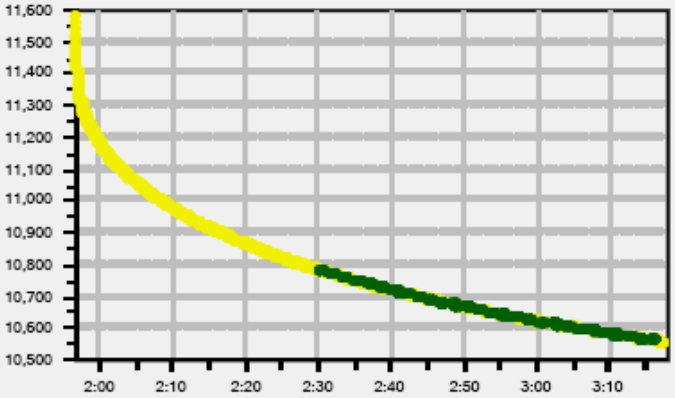
Test #6, First Light at 10:11:05 PM, Ps(10:26:12 PM)=5,156
Test stopped at -3.7 [psi/min] 00:07:06 after First Light



Test #7, First Light at 12:14:44 AM, Ps(4:49:13 AM)=9,187
Test stopped at -4.5 [psi/min] 01:17:49 after First Light



Test #8, First Light at 2:30:33 AM, Ps(4:14:52 AM)=10,472
Test stopped at -3.6 [psi/min] 00:47:01 after First Light



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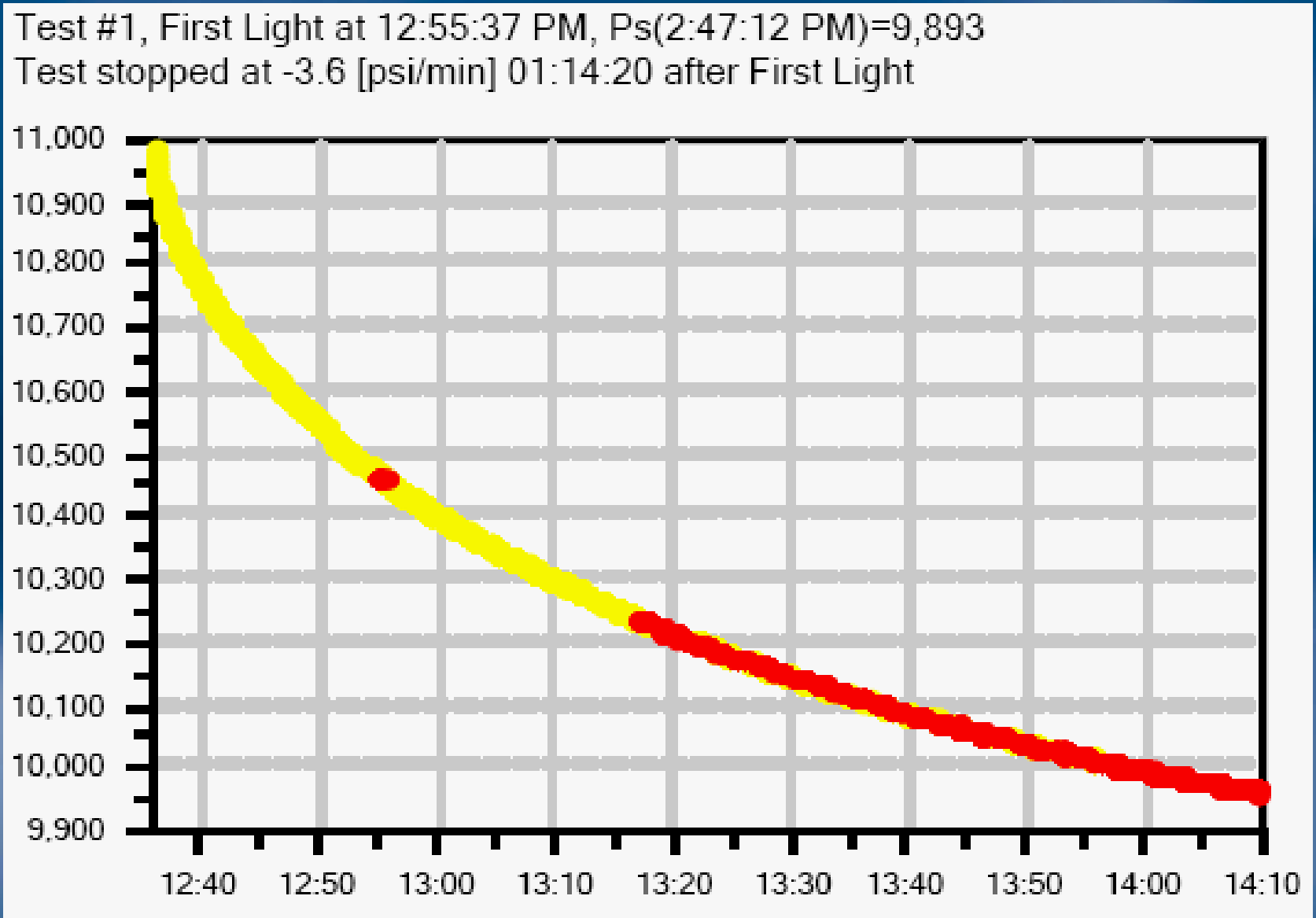
Software-Generated Report Example 1



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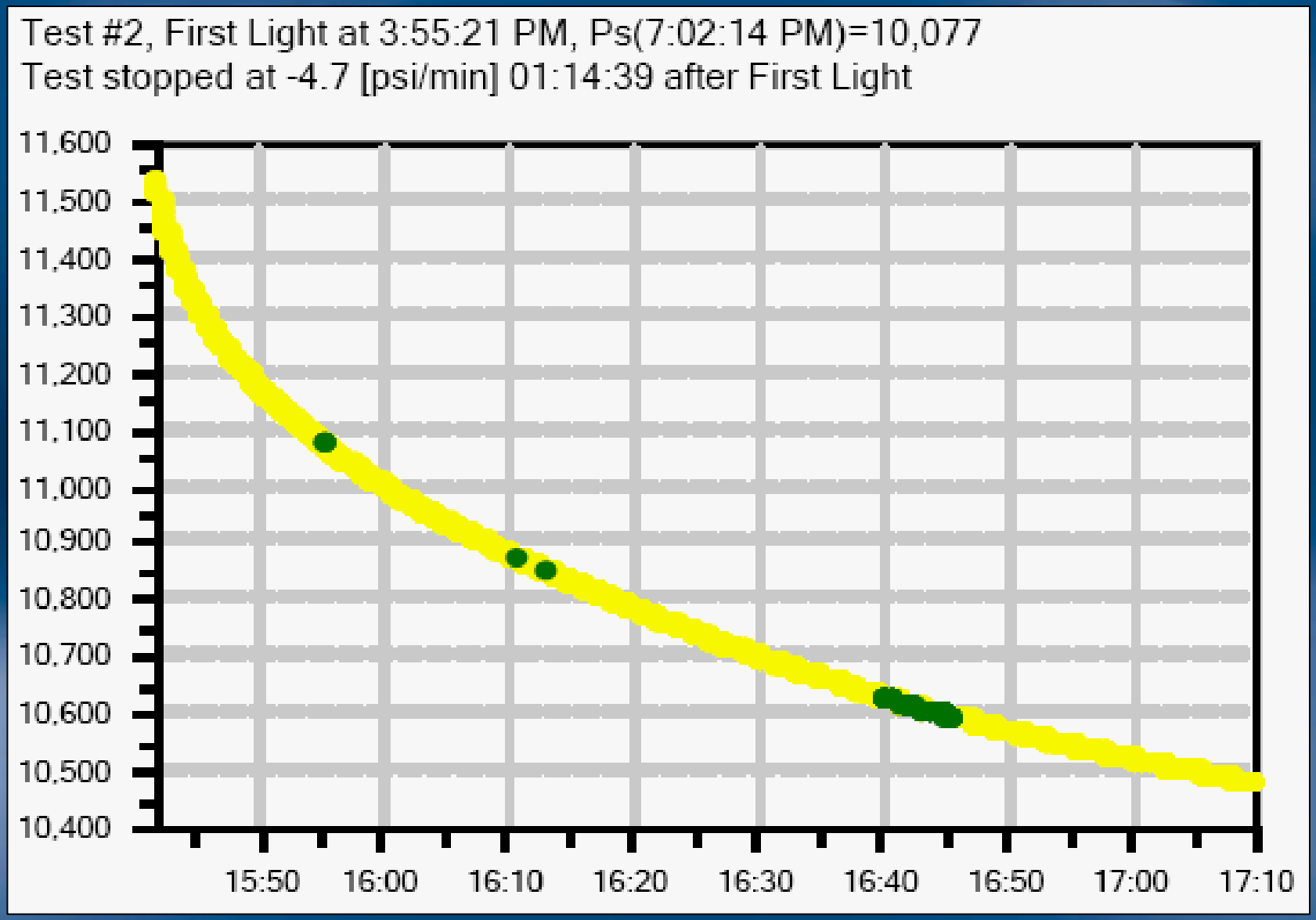
Software-Generated Report Example 2



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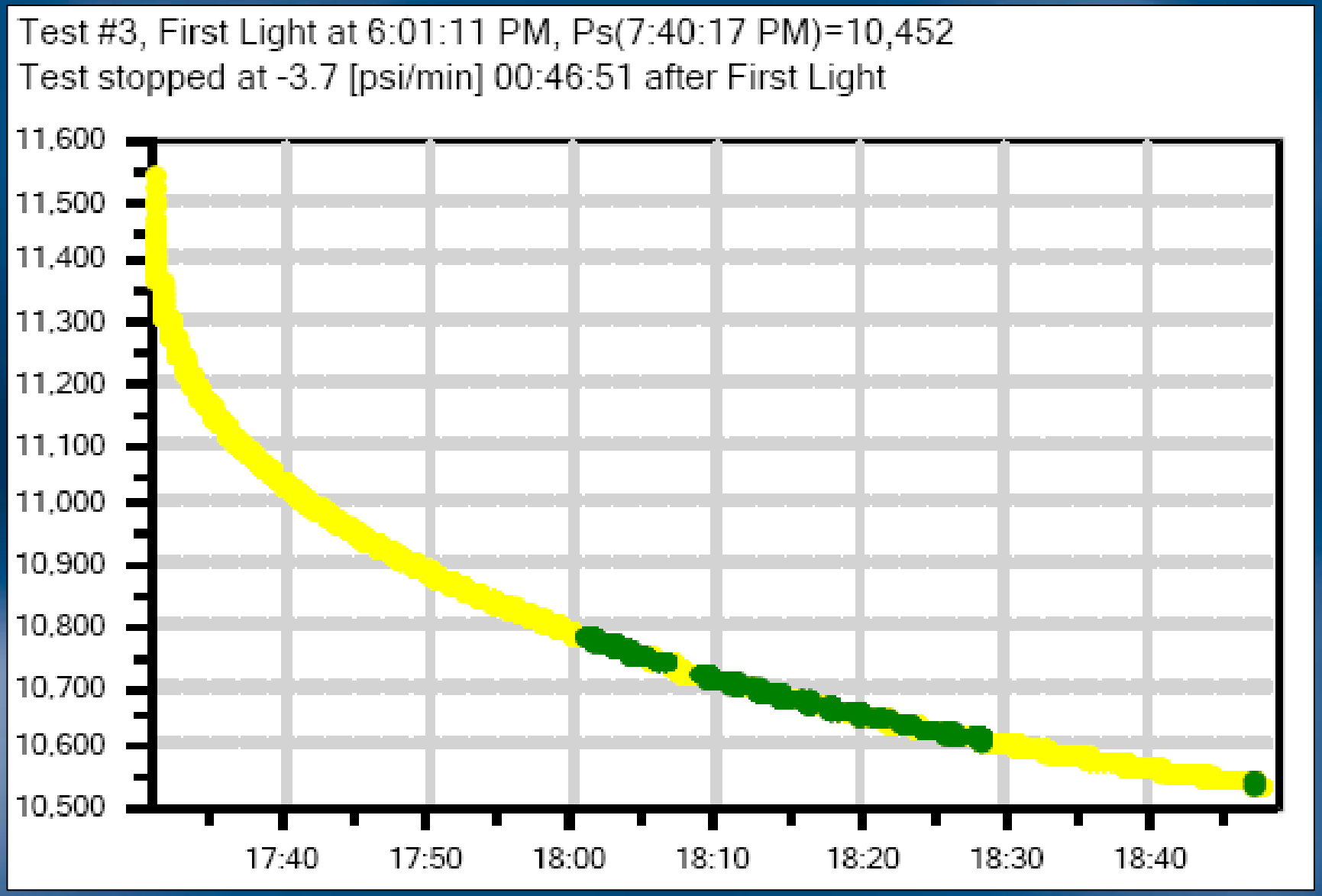
Software-Generated Report Example 3



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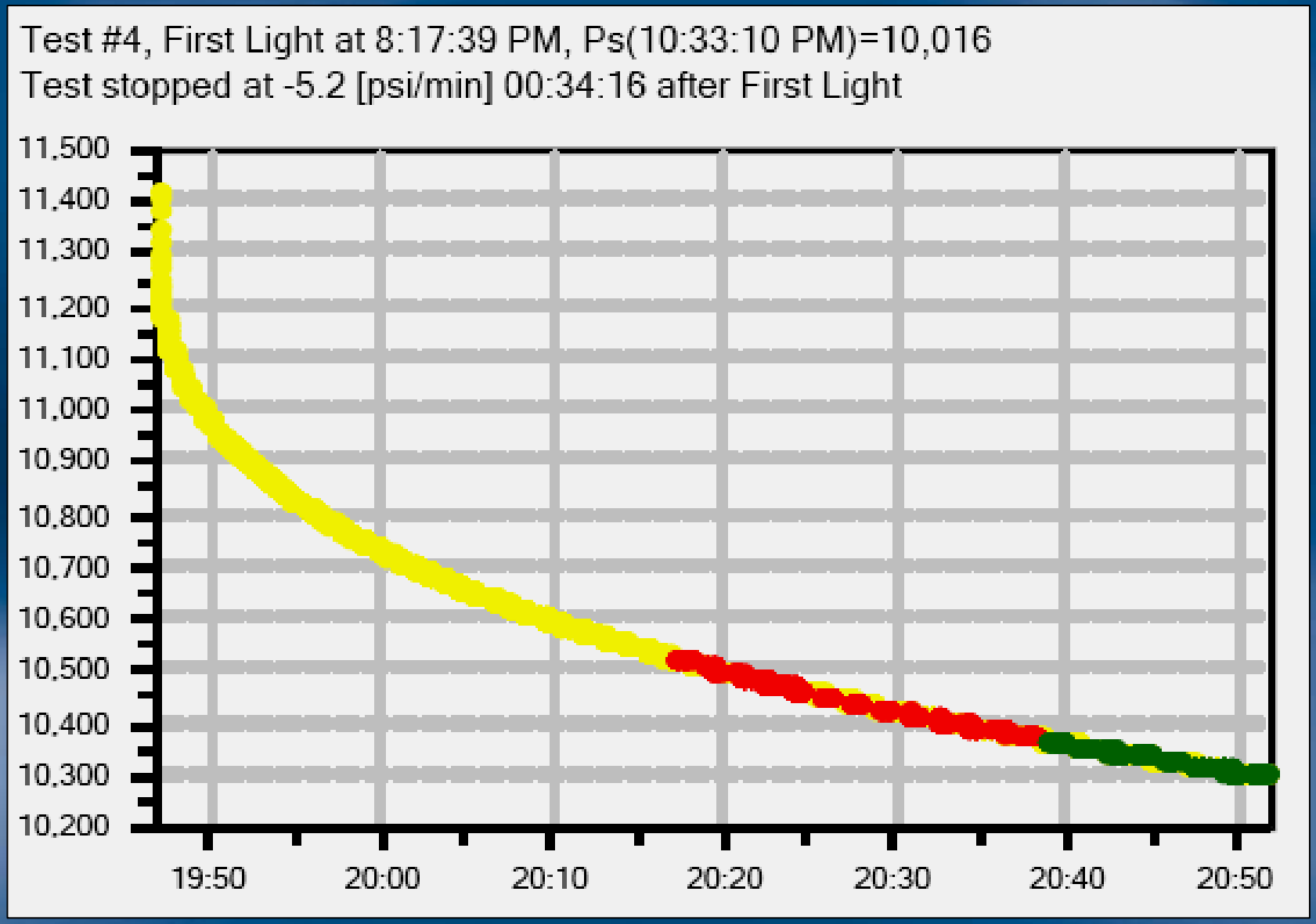
Software-Generated Report Example 4



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Conclusion

Questions / Discussion

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