

Operational Considerations for Logging While Drilling Fluid Analysis Sampling and Testing in a Gas Reservoir in Asia Pacific*

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Abstract

An operator in Asia Pacific required a large sample volume from a gas reservoir for accurate non-hydrocarbon gas (NHCG) content analysis from two extended reach wells. The paper highlights the use of logging while drilling (LWD) fluid sampling and formation pressure testing to overcome numerous challenges including highly deviated wellbore, stuck pipe, oil-based mud (OBM) gas sampling issues, and prevention of geo-chemical adsorption.

The decision to utilize a LWD Fluid Sampler was established from several factors that reduced significant risks; because of the wells' deviated nature, traditional wireline fluid sampling would have required a pipe-conveyed logging mechanism. The mechanism would have added rig days to the project and increased the risk of a stuck pipe. To prevent geo-chemical adsorption, the storage tanks were manufactured with a specialized metallurgic design tested by applying a customer-requested coating to most of the tanks (and monitoring geo-chemical content differences). To prevent differential sticking, test sequences were limited to 140-minute intervals.

After two runs with two separate wells, 25 samples were acquired containing more than 20 liters of fluid. The reduced invasion profile, a result of LWD technology, caused the cleanup time to average only 40 minutes at each sample station. Furthermore, results showed only 8% OBM contamination, half the amount observed in offsets from wireline-produced fluid samples. Finally, because of the improved operation efficiency and sample quality, the customer estimates nearly \$10 million dollars in rig costs and millions more in reduced retrofitting costs were saved.

The paper highlights a major change in fluid sampling technology. Operators will no longer need to consider a well's deviation to collect fluid samples. The review of the two wells offers additional best practices and risk mitigation techniques for future LWD sampling projects. It also adds another LWD technology for providing consistent wireline equivalent data.

Background and Fluid Model

An operator in Asia Pacific required the collection of samples in a development field after results in nearby fields flagged potential concerns for high contamination levels with NHCG. This brings issues of environmental concern and equipment design/cost with it. No measurements were made on the initial wireline-acquired reservoir fluid samples in the exploration phase, which therefore presented the issue in the development phase where it was realized this information would now be invaluable to the future development of the field. A respective measurement was required to ascertain whether equipment design changes would be needed.

Due to the high-angle trajectory of the development wells, an LWD sampling service was deployed on two wells and configured to capture as many samples as possible to reduce the inevitable statistical variation of measurements. The LWD sampling service bottom hole assembly (BHA) was used to drill through the reservoir, the required rathole and collect the samples in the same run before being retrieved to surface immediately to secure the samples. Time is also an important factor when doing these contamination measurements and should be minimized to ensure a representative value.

Formation Pressure at the top reservoir was expected to be roughly 4,500 psi. With a mud density of 1.14 g/cm^3 , this will give approximately 4,900 psi considering the effect of equivalent circulating density (ECD). Applied was an oil based mud at an expected formation mobility varying between 1 and 500 mD/cP and approximately 70°C formation temperature. Two different reservoir fluids were expected, a gas with high methane content and formation water with a salinity above 80 g/L. An overview of the different fluids and the estimated sensor response is given below.

- Formation gas (in situ) with high methane content : density 0.19 g/cm^3 , sound speed $\gg 235 \text{ }\mu\text{s/ft}$, compressibility 0.002 1/bar, refractive index < 1.3
- Formation water: $> 80 \text{ g/l}$ Chlorides, density 1.04 g/cm^3 , viscosity 0.3 cP, sound speed $175 \text{ }\mu\text{s/ft}$, compressibility 0.0004 1/bar, refractive index 1.39
- OBM (nonaqueous), oil based, saturated salt water fraction, density 1.14 g/cm^3
- Mud filtrate: oil, density 0.85 g/cm^3 , viscosity 1-2 cP, sound speed $180 \text{ }\mu\text{s/ft}$, compressibility 0.0004 1/bar, refractive index ≈ 1.41

The target of this operation was to obtain formation pressure and mobility data, perform a pump out of formation fluid, observe the fluid ID trend and obtain up to 16 low contamination samples of formation gas in two dedicated runs to determine the content of potential dangerous substances. Therefore, the contamination level needs to be as low as possible. The objective of both runs was the following:

- Obtain 16 high quality downhole fluid samples to be analyzed, 12 single-phase tanks sealed with a special coating and four uncoated Co-Ni-alloy chambers.
- Minimize filtrate contamination of the samples.
- Verify successful acquisition of samples prior to sending any bottles to shore for processing.
- At least four samples should be processed offshore.

- Secondary to fluid sampling objectives, evaluate the different contents of dangerous substances between coated and uncoated tanks to assess the performance of the Co-Ni-alloy compared to the coated tanks.

Figure 1 shows the simulated clean-up trend from OBM mud-filtrate to methane gas. For a sufficient cleanliness approximately 50-liter clean-up volume are required whereas the pump should run as fast as possible. Due to an anticipated high mobility and consolidated formation, no pumping pressure restrictions are expected. During fluid ID of a gas sampling operation there is often much scattering seen on density, viscosity and sound speed measurements, most probably due to small droplets of oil filtrate clinging to the sensors.

Therefore, the compressibility and clean-up mobility derived from the pump system will give a better idea of cleanliness (Cartellieri, 2012). It's recommended to start the clean-up process with 10 or 15 cm³/sec and then increase to 20 or 25 cm³/sec as soon as the data indicates a good seal and no sanding, until the fluid response shows mainly gas. Once this is arrived, send a downlink to take the samples.

The best indicators for clean-up monitoring in immiscible fluids and gas are:

- Compressibility strongly increases due to more compressible gas.
- Mobility will increase due to much lower gas viscosity.
- Density will scatter with a rough dropping trend.
- Sound speed time higher but expected with a lot of scattering. As the gas oil ratio (GOR) is calculated from sound speed and density it will scatter as well (DiFoggio, 2011).
- Viscosity shows low but scattering values (not designed for conductive multiphase media).
- Optical Refractive Index shows a flat trend with some scatter as the window is coated with residual oil-filtrate.

Results and Discussion

Figure 2 shows the BHA setup for both runs. The LWD sampling tool was run with four tank carrier modules each of them handling four single phase tanks with a volume of up to 800 cm³ (Cartellieri, 2011). This gives in total 12.8 L reservoir fluid. The BHA includes a steering head for the drilling operation and a power and communication module. For resistivity measurement and to find the best spot, an advanced measurement while drilling tool (MWD) was applied.

First run

The BHA was picked up and run in hole until the open hole was reached. There a short reservoir section of 113 m was drilled at 50 m/hr to a measured depth of 3,491 m. At this point, the correlation showed a clear indication at which depths to take the samples. A short upwards relog was conducted to obtain an estimate of the pipe stretch from 3,480 m to 3,470 m MDRT where significant gamma ray readings on the log were investigated. The pipe stretch calculated from this back reamed interval was calculated to be 1m. This coincided with the measurements taken on the drill floor using a laser light to obtain the pipe stretch.

The first sampling depth was given at 3,455.75 m. Before samples could be acquired, a series of sticky tests was performed on the BHA, involving three separate tests over a 30-minute, 45-minute and 60-minute duration. A pressure test was conducted during each of the sticky tests to find a point with the highest mobility. No indication of differential sticking was observed during these tests, thus the sampling operation continued.

Table 1 shows the different pressure tests commenced during the first run. At station four and five, the tool continued after the pressure test with subsequent clean up. The initial clean up took approximately one hour. After that, a downlink was placed to start the sampling operation. Seven tanks were successfully filled before the two-hour maximum time limit of being stationary on the wall was reached. At this point, the pad was retracted, the tool moved and then placed back to the same depth again. Another five samples were taken again with an initial clean up of approximately one hour. Each tank filling process took approximately two minutes - including the downlink time to activate the sampling and a short period of cleanup after each sample, the total filling time for each tank was between 8 to 10 minutes before filling the next tank. The sampling was complete when 12 tanks were filled.

Figure 3 is illustrating the pressure test with subsequent clean up at station four – 3,456.75 m measured depth. The pressure test shows a nice repeatability of the three distinct formation pressures (Meister et al., 2003) with a calculated mobility of 15.4 mD/cP. The difference in the pressure readings is less than 0.3 psi.

The maximum drawdown of the pump during clean up was set to 120 bar at a pump speed of 10 cm³/s as a starting point. A downlink was sent after 25 minutes pump out to increase the pump speed to 25 cm³/s encountering the compression of the reservoir fluid this resulted in a maximum clean-up speed of 16 cm³/s on average.

The data from the acoustic transducer and the viscosity measurement from the tuning fork were not considered valid in the gas environment. The main indicators used to monitor clean-up were density, compressibility and mobility. At the 1-hour mark of being on station, the density and compressibility had stabilized but mobility was still increasing slightly. Nevertheless, the decision was made to start capturing samples bearing in mind that there was a 2-hour limit on station imposed by the drilling department. In total, seven tanks were filled before the 2-hour limit was reached on the wall for this first station.

The tool was moved and set to the same depth again. The pressure test conducted showed a mobility of 25.5 md/cp. It was decided to start the pump out at maximum speed right from the beginning. Again, the data from the acoustic transducer and the viscosity measurement from the tuning fork were not considered valid in the gas environment. The main indicators used to monitor cleanup were density (green in middle track), compressibility (red) and mobility (highlighted) (both in the top track of Figure 4). After 57 minutes of being on station, the density and compressibility had stabilized but mobility was still increasing. After discussions with the client, the decision was made to start capturing samples. In total, five tanks were filled on this final second station.

Figure 5 shows the same station with the data derived from the report based on the memory readings from the tool. Whereas the mobility is continuously increasing, the compressibility shows a very fast clean up from oil filtrate to gas. The absolute value 1×10^{-3} 1/bar for the

compressibility is in coincidence with the expected value for a dry gas. Viscosity readings are scattering a lot whereas the density shows a stable value of 0.3 g/cm^3 . Only when the pump stalled while filling the tanks and over-pressurization the density drops even more to nearly 0.2 g/cm^3 , the expected value of the formation gas. The sound speed measurement showed a flat trend with less than expected scattering at the lower limit of the measurement range indicated a dry gas. The temperature measurement showed in the beginning a very fast clean up trend and with needles the temperature increase while compressing the fluid during sampling.

The contamination measurements performed after the run indicated roughly 8% contamination level for the different samples on average ([Table 2](#)). The contamination seems to be more or less independent from the clean-up time and volume pumped. However, as the contamination is based on a very small condensate volume of around 15-20 ml the uncertainty is high. Contamination levels are always given in weight percent indicating a higher contamination in gas compared to liquid samples.

Second run

The LWD sampling assembly with four tank carriers was successfully surface tested and run in hole. The BHA was used to drill out the cement in the 9-5/8 inch shoetrack and the landing float collar (LFC). This process took between six and seven hours to complete, before the drilling of 118 m of new formation to perform the sampling operation commenced. The client allowed two 2-hour and 20-minute windows to perform sampling operations. To minimize contamination the client planned to have 90 minutes of clean-up time before sampling. Seven bottles were filled in the first 2-hour 20-minute window after 90 minutes of clean up and seven bottles were filled in the second 2-hour 20-minute window after 90 minutes clean- up. The clean-up on the second window showed a clean fluid after 60 minutes of pump out, but the client decided to follow the initial plan and start sampling after the full 90 minutes had passed.

The measured and sampling depth evaluated from significant gamma ray readings was 3,935.2 m for the first clean up and sampling station and 3,934.9 m for the second station. Again, two sticky tests were performed on the BHA, with 30-minute and 60-minute duration, both indicating no differential sticking. During this test, pressure tests were conducted to find the point with the highest mobility and to optimize clean-up speed. In total, six pressure tests were performed during the second run ([Table 3](#)).

Each tank filling operation took approximately two minutes. When including the downlink time to activate the sampling, and a short period of clean up after each sample, the total filling time for each tank was between seven to ten minutes before filling the next tank. The sampling was complete when 14 tanks were filled.

The pump out sequence was performed in the same way like during the first run. The clean-up limits were set to 120 bar delta pressure and $10 \text{ cm}^3/\text{s}$ pump speed in the beginning. After 20 minutes, a downlink was sent to increase the pump speed to $25 \text{ cm}^3/\text{s}$. This resulted in a maximum clean-up speed of $16 \text{ cm}^3/\text{s}$ on average.

The data from the acoustic transducer and the viscosity measurement again showed some scattering. Thus, the main indicators used to monitor clean-up were density, compressibility and mobility. At the 90-minute mark of being on station, the density and compressibility had stabilized

but mobility was still increasing slightly. Nevertheless, the decision was made to start capturing samples as per preplanned sampling strategy. In total, seven tanks were filled before the 2-hour 20 minute limit was reached on the well for this first station.

On station six at 3,934.86 m MD, the pressure test and the calculated mobility of 83.0 md/cp indicated a good spot to continue with clean up. It was decided to start the pump out at 25 cm³/s directly from the beginning. After 50 minutes of being on station, the density, compressibility and mobility had stabilized. However, the same strategy employed on the first station was applied to this second station. At the 90-minute mark, the filling process was initiated.

Figure 6 shows the pump out sequence at station six from the memory report. The pump was running at a constant speed, encountering the compressibility and the overbalance the red line in Figure 6 indicates the effective pump speed of approximately 16 cm³/s. In total nearly 120 L formation fluid were pumped in 130 minutes. The tank filling process can be easily detected as the pump speed goes down during over-pressurization of the sample. Again, seven tanks were filled on this final second station. This resulted in the filling of 14 tanks.

As discussed in the fluid model simulation the optical refractive index shows only a slightly decreasing trend with some scatter (Figure 7). The film on the optical window of the refractometer is dominated by residual oil-filtrate. However, the scattering towards the lower limit of the measurement range already indicates that there is gas in the flow line.

Even though the sound speed and density measurements are sometimes scattering the algorithm still calculates a valuable value for GOR of approximately 25,000 and even slightly higher during sampling. Figure 8 illustrates as an example the filling process of one sample from the memory report. The total process took less than 2 minutes with a total filling volume of 760 cm³ and a filling pressure of 9,400 psi.

From the samples taken during the second run no contamination measurements were performed. The measurements of the amount of NHCG in the reservoir showed a higher value than originally expected. Unfortunately, the measurements in the lab differed from the measurements performed offshore. Thus, the offshore analysis techniques appeared inadequate. Regarding the comparison of coated and uncoated tanks, the results were inconclusive, but this was not the main objective of the customer.

Conclusion

The LWD sampling service conducted successfully pressure testing, real-time fluid analysis and sampling in a high angle development well gathering in total 26 samples. The service was delivered without big issues and sets a new record for a LWD sampling service.

Even though the customer was concerned about differential sticking, no sticking event occurred during the whole operation. The given time limitation of 2 hours and 2 hours and 20 minutes respectively burdens the sampling operation. Due to the high automation and the well-trained personnel, it was still possible to deliver a high quantity of low contaminated samples.

The recent improvements made on the sensor readings in immiscible fluids shows valuable information and a good clean-up trend even under these difficult conditions. Besides compressibility and mobility derived from the pump system also the other sensors like density, GOR and refractive are now delivering a clear indication for the gas clean up.

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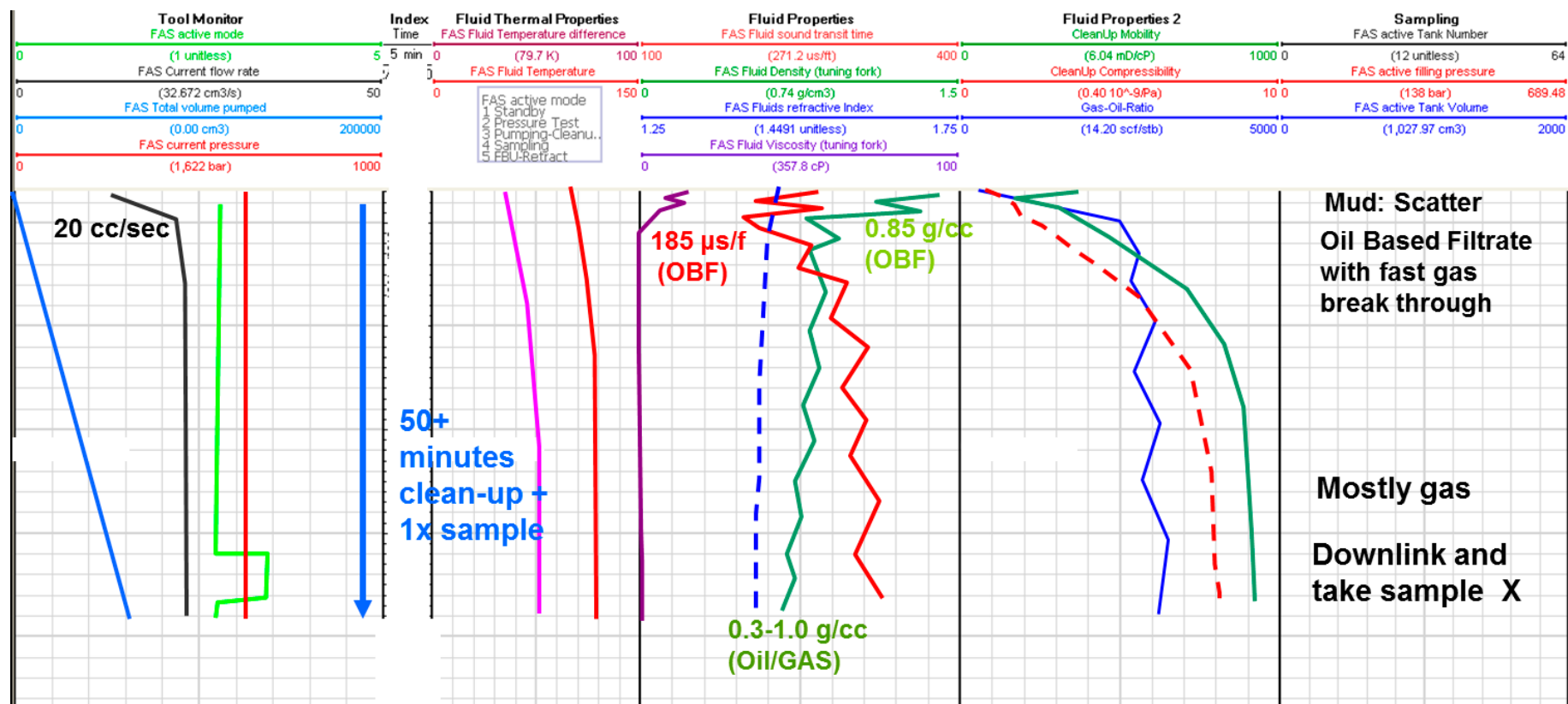


Figure 1. Simulated clean up from OBM mud-filtrate to methane gas.

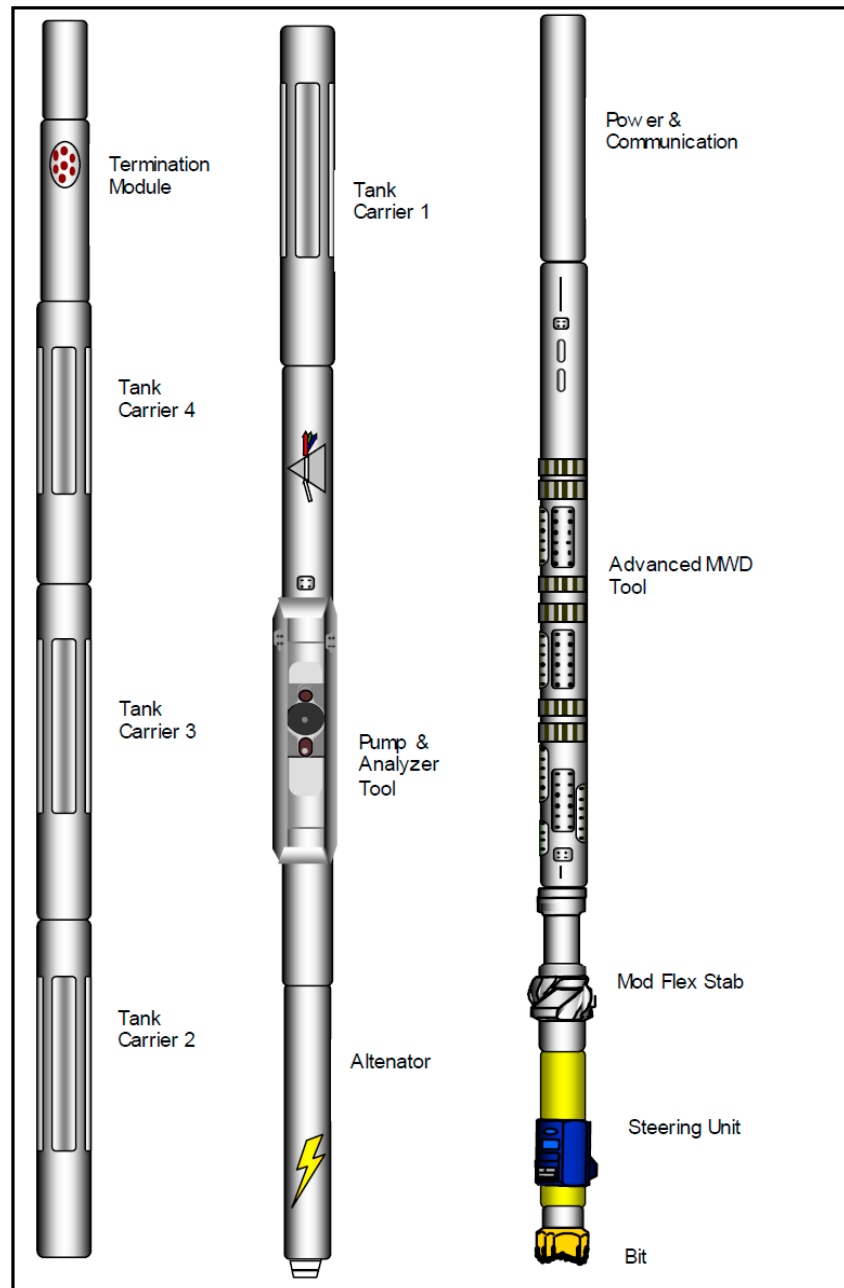


Figure 2. BHA sketch including the LWD sampling tool and four tank carrier modules.

Real-Time Pressure Test Summary

13 May 2013 20:11:00		Annular Pressure		Formation Tests			Best Test		Other		
Station #	5	Before	5144.286 psi		Pressure 1	Pressure 2	Pressure 3	Mobility	15.4 mD/dP	Test Time	0002:55
Sensor Depth (corrected)				Formation	4553.112 psi	4552.996 psi	4552.836 psi	Quality	7	Toolface	
MD	3456.75 m	EOD	EMW	Drawdown	4094.613 psi	4263.914 psi	4263.914 psi	Number	2	Time Since Drilled	9.28 h
TVD		1.27 g/cm3	1.12 g/cm3	Delta	1049.673 psi	880.372 psi	880.372 psi	Remarks / Comments			

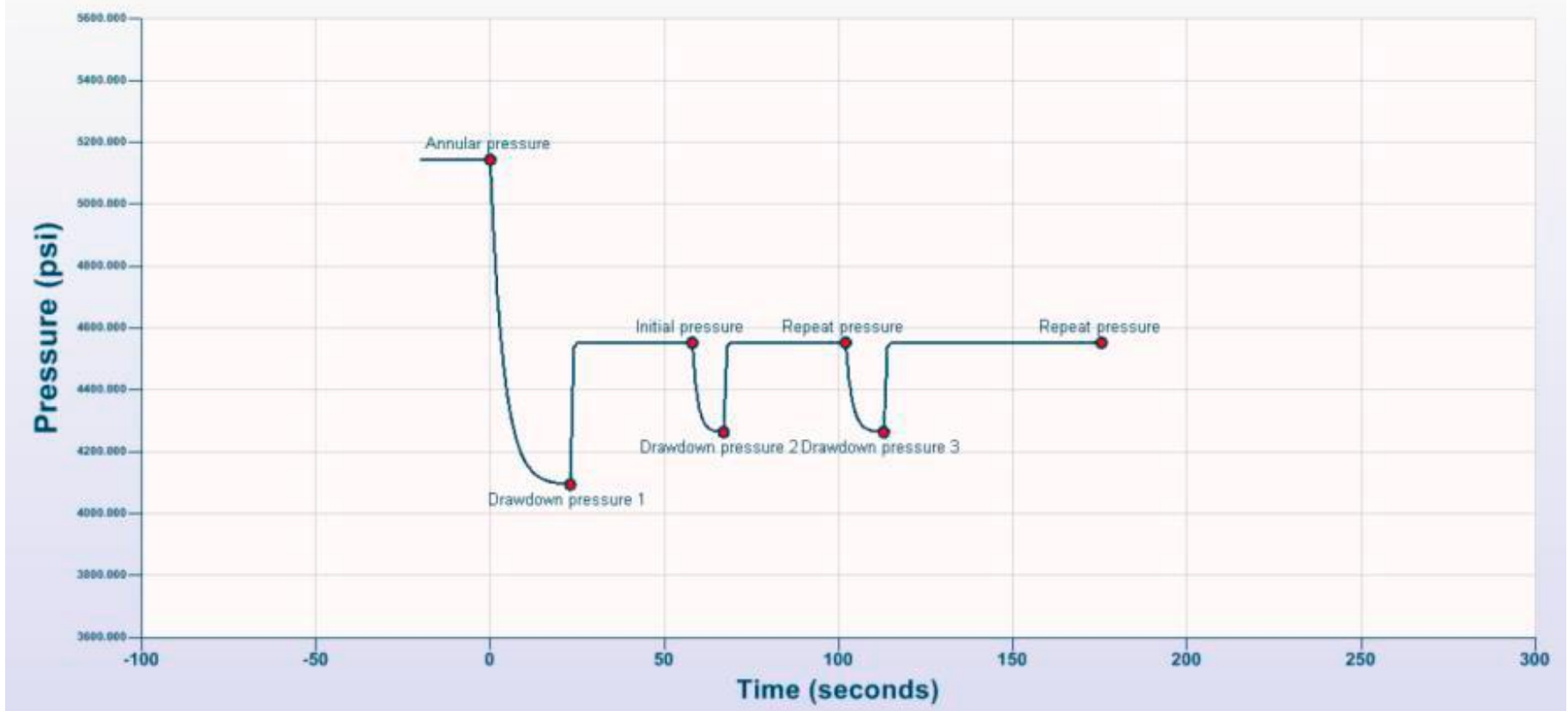


Figure 3. Pressure test station four with subsequent clean up.

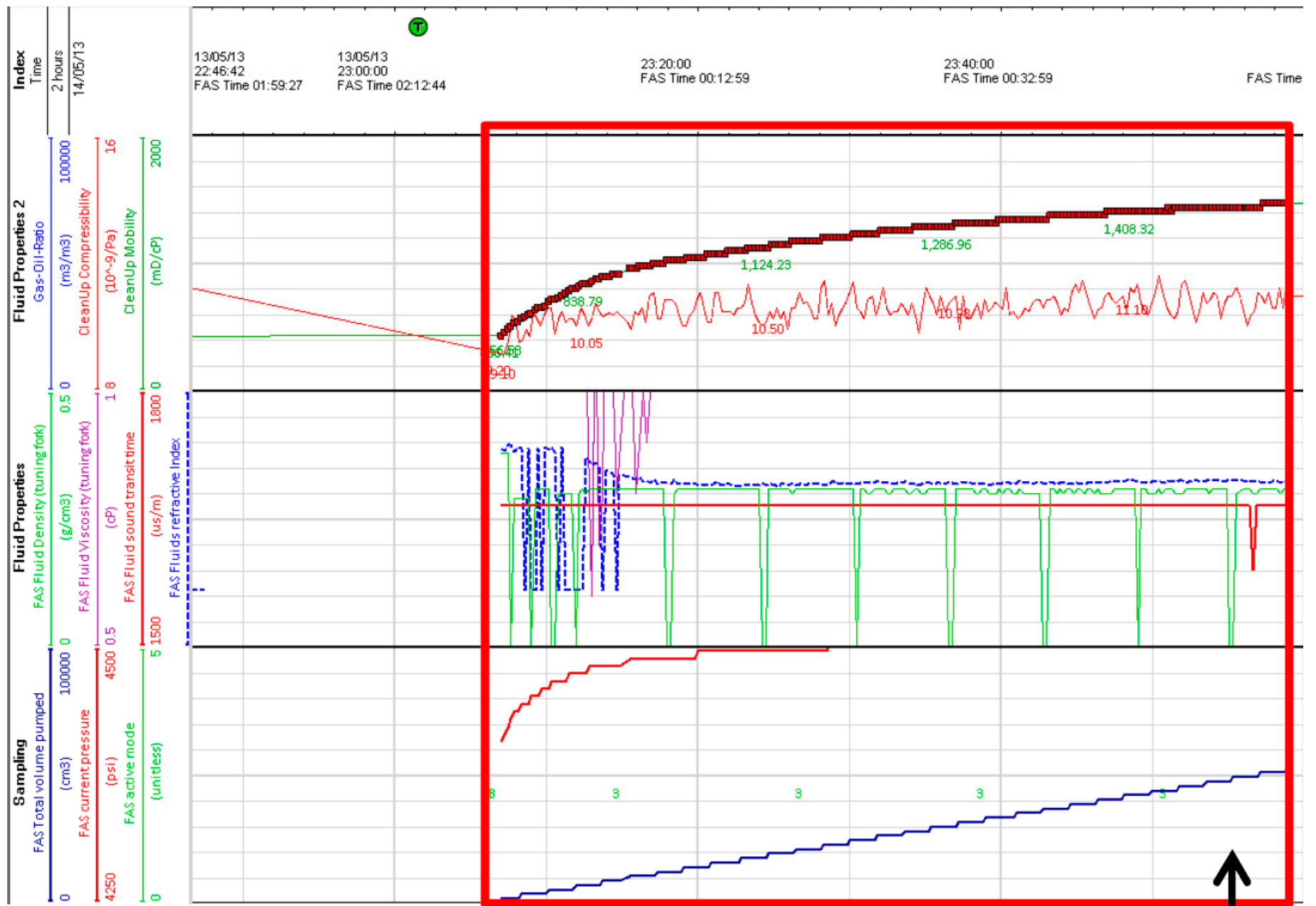


Figure 4. Clean-up station five in the real time display.

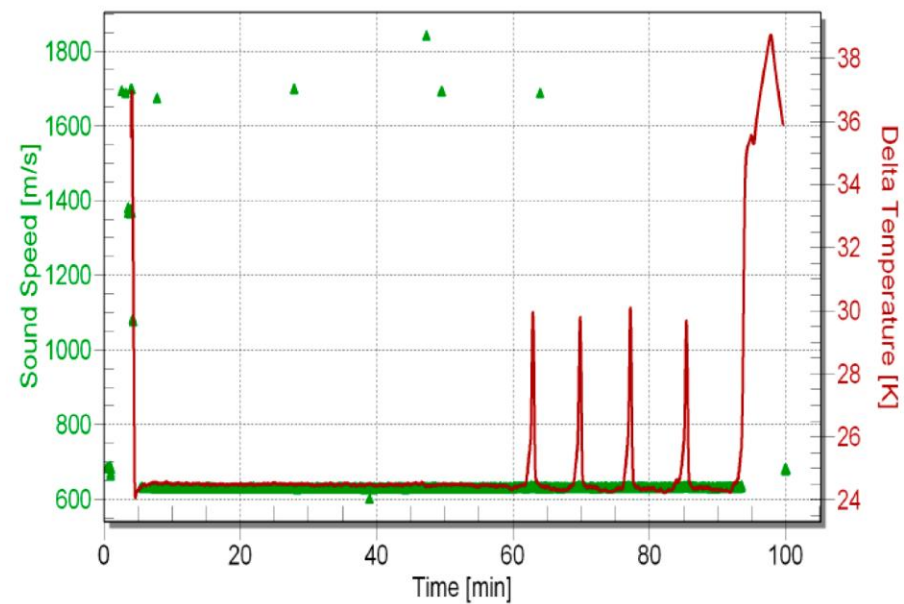
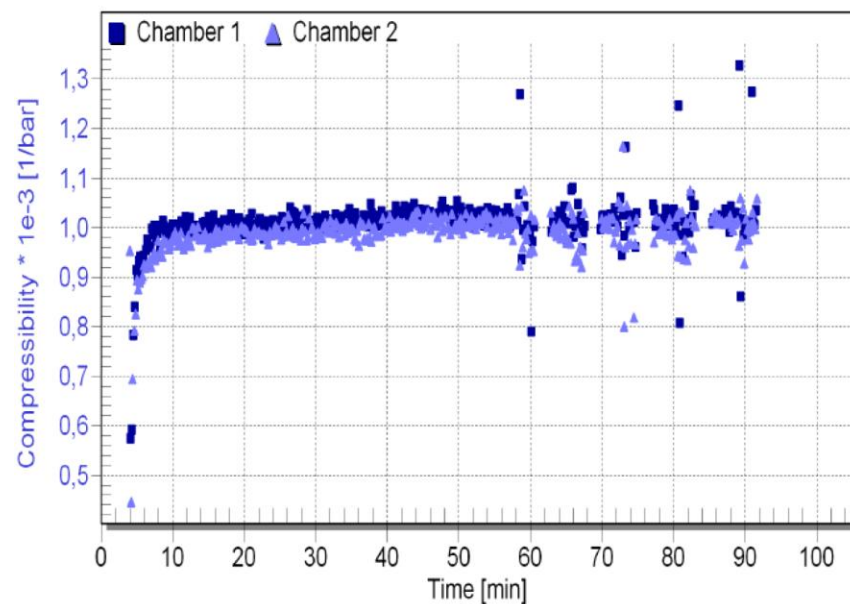
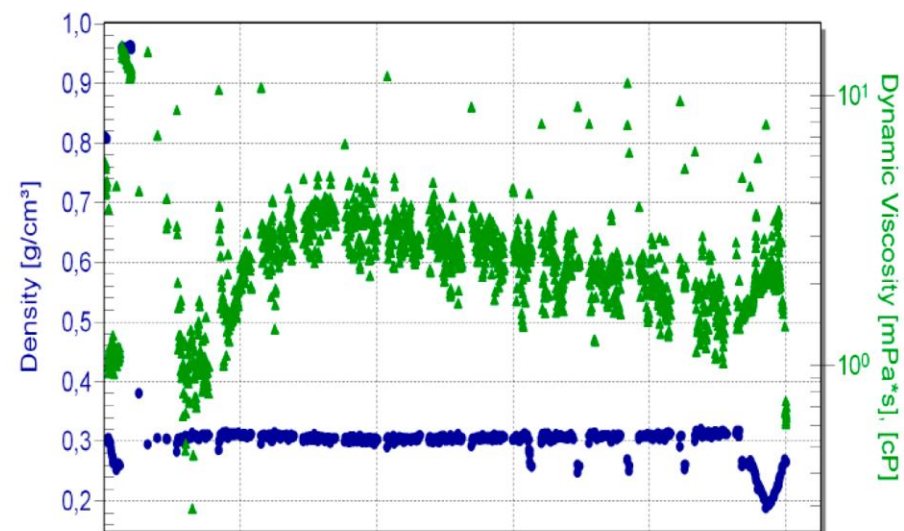
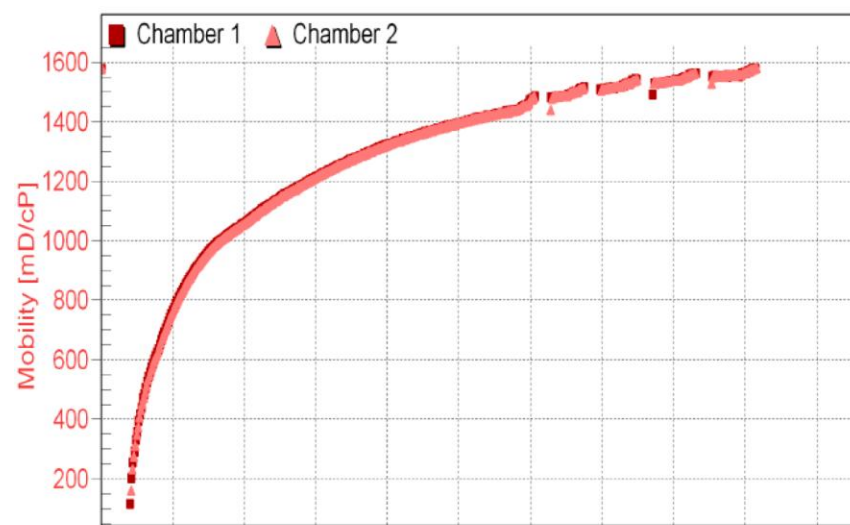


Figure 5. Clean up and sensor response at station five from the tool memory.

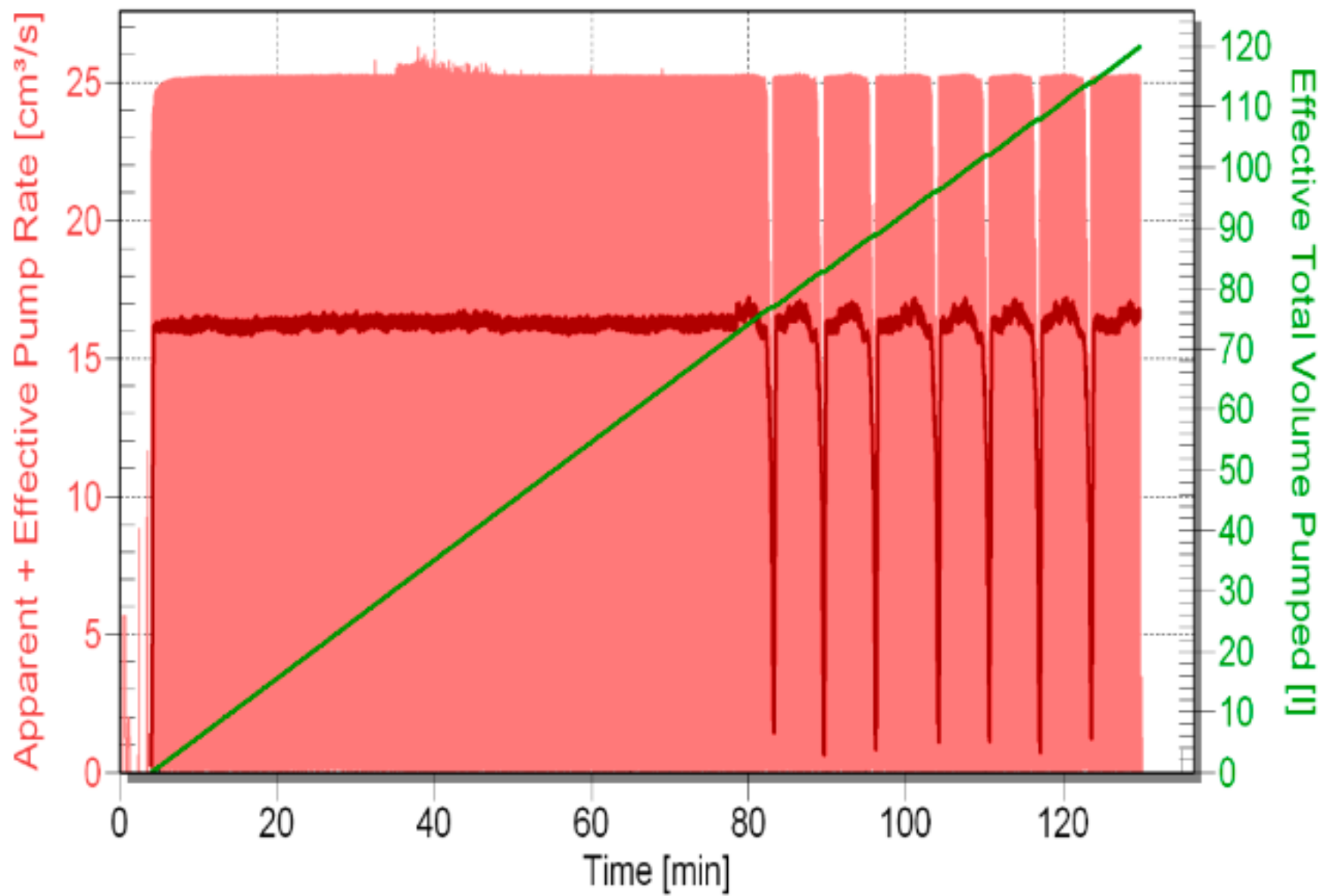


Figure 6. Pump out at station six from the memory report.

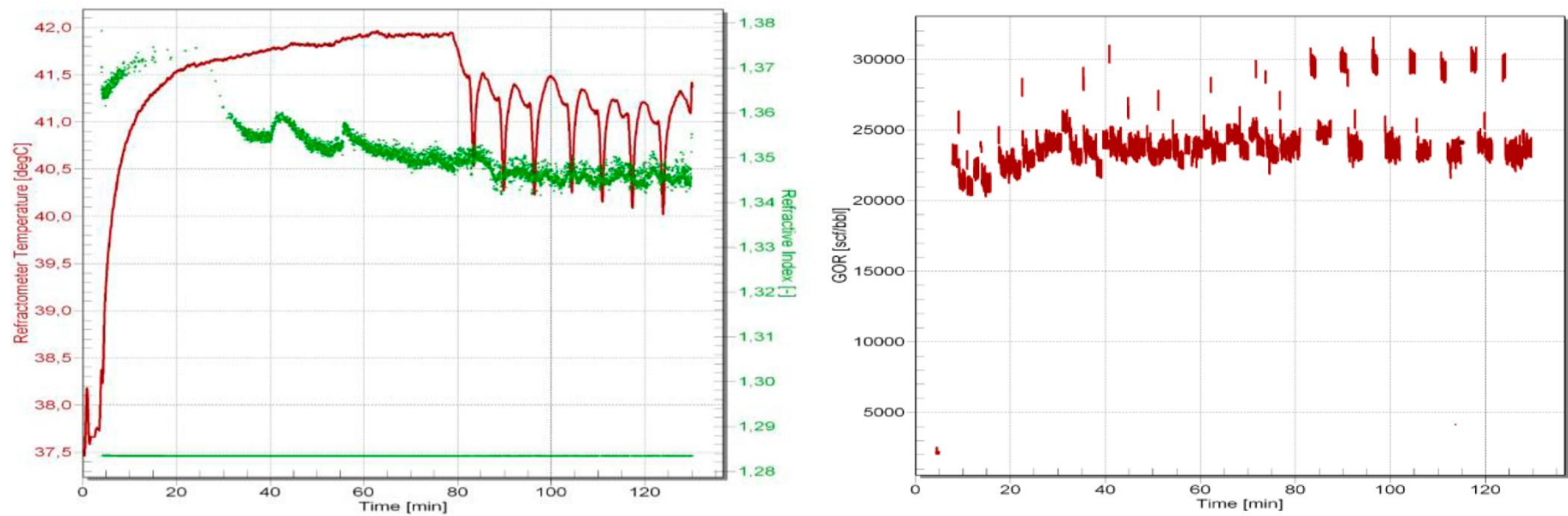


Figure 7. Refractive index and gas oil ratio at station six.

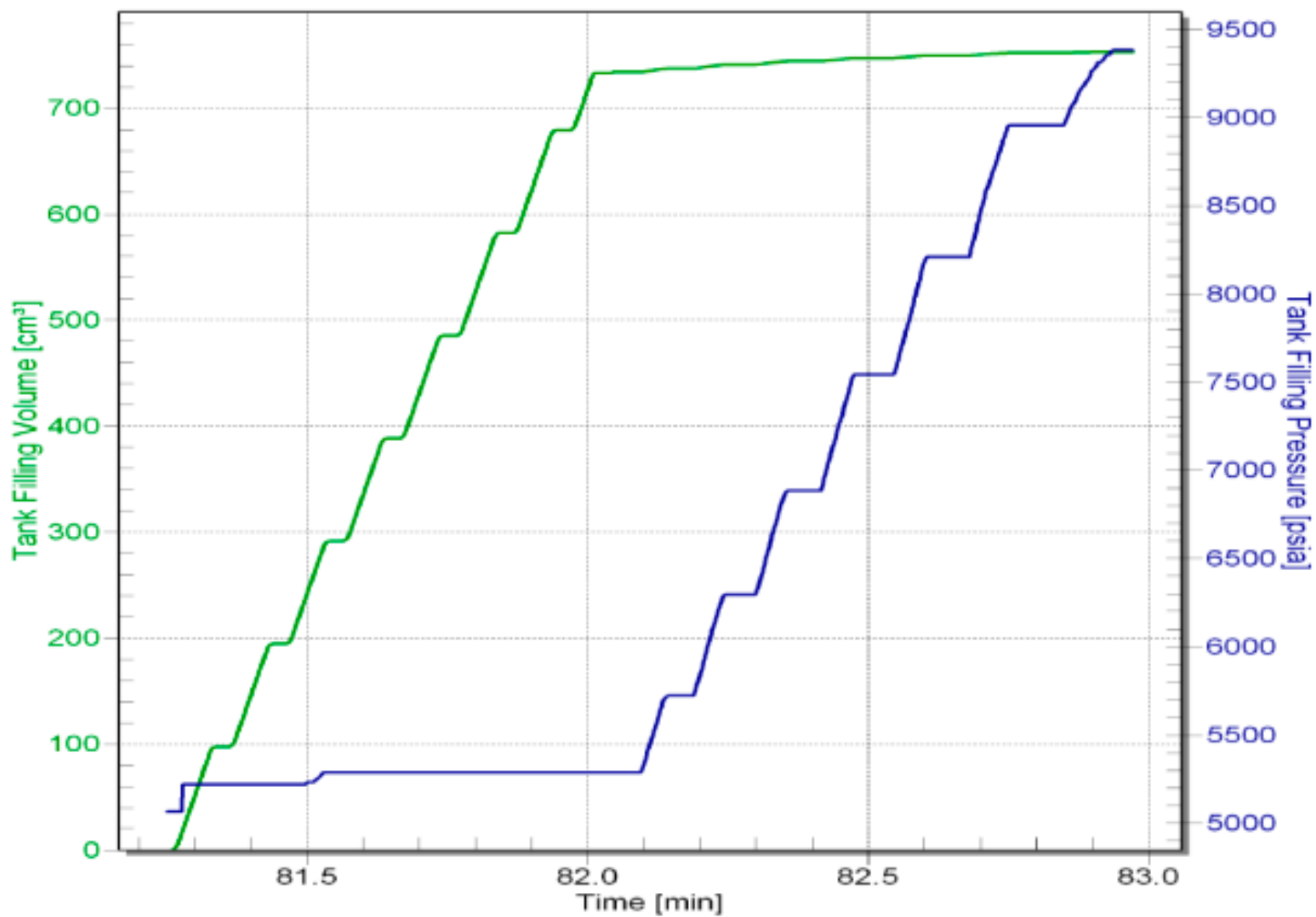


Figure 8. First sample at station six.

Station #	Date DD.MM.YY	Time HH:MM:SS	MD [m]	TVDSS [m]	APresA [bar]	FPres1 [bar]	FPres2 [bar]	FPres3 [bar]	Mob1 [mD/cP]	Mob2 [mD/cP]	Mob3 [mD/cP]
1	13.05.13	17:17:29	3456.9	2824.4	351.7	313.9	313.9	313.9	28.0	81.3	123.7
2	13.05.13	18:09:25	3456.4	2824.2	351.7	313.9	313.9	313.9	11.9	23.1	33.6
3	13.05.13	19:19:09	3455.8	2824.3	351.6	313.9	313.9	313.9	33.3	57.6	91.2
4	13.05.13	20:41:51	3456.8	2824.4	351.8	313.9	313.9	313.9	10.9	15.4	25.3
5	13.05.13	23:01:28	3456.8	2824.4	350.6	313.9	313.9	313.9	25.5	36.1	52.4

Table 1. Pressure test stations.

Volume pumped	Time on the wall	Contamination level
<i>[cm³]</i>	<i>[min]</i>	<i>[%]</i>
63281,3	80	6%
89648,4	109	8%
70312,5	71	8%
77343,8	79	7%

Table 2. Contamination results of four samples from the first run.

Station #	Date DD.MM.YY	Time HH:MM:SS	MD [m]	TVD [m]	APresA [psi]	FPres1 [psi]	FPres2 [psi]	FPres3 [psi]	Mob1 [mD/cP]	Mob2 [mD/cP]	Mob3 [mD/cP]
1	10.06.13	06:27:36	3935.0	2827.6	5081.6	4553.6	4553.5	4553.5	162.0	214.7	244.2
2	10.06.13	07:14:05	3935.4	2827.7	5080.3	4553.7	4553.6	4553.6	735.1	1769.2	2279.0
3	10.06.13	08:32:48	3935.6	2827.7	5076.4	5102.0	5101.3	5101.4	1290.3	219.5	172.6
4	10.06.13	09:25:44	3935.2	2827.7	5057.5	4553.8	4553.8	4553.7	45.5	71.8	113.1
5	10.06.13	12:12:16	3936.0	2827.8	5059.6	4554.0	4554.0	4550.5	12.5	12.2	13.1
6	10.06.13	12:45:51	3934.9	2827.6	5050.9	4553.6	4553.6	4553.3	51.0	83.0	100.3

Table 3. Pressure test stations second run.