Real-time completion monitoring of deepwater wells: Part II - Active and passive surveillance

Andrey Bakulin, formerly Shell International E &P Inc, presently WesternGeco/Schlumberger; Alexander Sidorov, Boris Kashtan, Dmitry Alexandrov, St. Petersburg State University; Mikko Jaaskelainen, formerly Shell International E & P Inc, presently SensorTran.*

Summary

We present results of Real-Time Completion Monitoring (RTCM) with acoustic waves on a full-scale model of a cased deepwater well with sand-screened completion. First, we describe the results of active surveillance with a controlled source. Using permanent fiber-optic sensors and observing changes in tube-wave signatures we detect changes in permeability along the completion. We prove that such measurements can be conducted while the well is flowing and show that continuous surveillance also allows monitoring technological processes such as gravel packing. Then we describe the first results of passive listening that allows locating flowing perforations and speculate on the possibility of detecting flow velocity. Finally, we outline a possible path to implement RTCM technology.

Introduction

Deepwater production increasingly relies on a few precious wells that are complex and expensive. Success is critically dependent on our ability to understand and manage these wells particularly at the sandface. These wells are filled with expensive "jewelry" like sand control and production allocation systems that aim at maximizing production and minimizing risk. While this smart equipment can mitigate many anticipated dangers, it easily can fail when something less expected happens. For example, repairing a sand control system failed due to plugging can cost US$30-40 million. Costs of lost production due to long-term well impairment can be much higher. Lower than expected production is often referred to as "well underperformance" (Wong et al, 2003) and can be caused by various impairments: a plugged sand screen, contaminated gravel sand, clogged perforations, damaged formation around the wellbore or larger-scale compartmentalization. While 4D seismic can address large-scale compartmentalization, it has no resolution to address near-well issues. Scarce downhole data from pressure and temperature gauges also cannot unambiguously characterize the impairment. This limits mitigation opportunities and prevents us from finding more effective drawdown strategies for high-rate high-ultimate-recovery deepwater wells. We strongly believe that geophysical surveillance in boreholes has a big role to play in identifying sources of well impairment and optimizing production. Here we describe one possible avenue - Real-Time Completion Monitoring (RTCM) – that utilizes acoustic signals in the fluid column to monitor changes in permeability along the completion. In essence, this is a miniaturized 4D seismic in a well. Bakulin et al (2008a,b) introduced the concept and presented modeling and initial experiments without gravel sand. Here we illustrate capabilities of acoustic surveillance through a series of full-scale laboratory tests with a more realistic gravel-packed completion, prove that measurements can be done while the well is flowing and outline capabilities of passive surveillance.

Evaluating permeability with acoustic waves

At low frequencies acoustic signals in a fluid-filled borehole are mainly carried by tube or Stoneley waves. Inside the fluid column the tube wave mainly consists of a piston-like motion. When fluid is compressed, it attempts to expand radially and pushes against the formation or casing. When the borehole wall is permeable, then the tube wave can move the fluid through and this leads to a slowdown in velocity and an increase in attenuation (Figure 1a). Currently these principles are employed in estimating near-wellbore permeability from an open-hole acoustic logging (Tang and Cheng, 2004). Conceptually similar principles may be extended to deepwater production wells with sand-

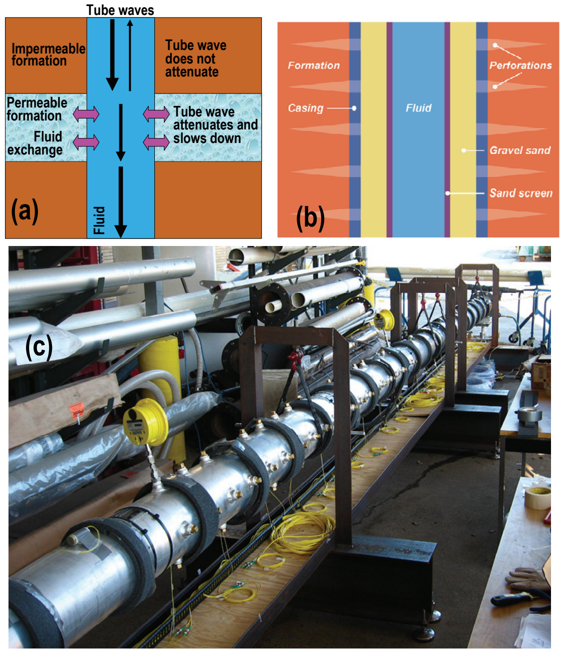

Figure 1: (a) Tube wave attenuates and slows down when it encounters permeable interval that can exchange fluids between borehole and formation. (b) Schematic cross-section of a cased deepwater well with sand-screened completion. (c) Photograph of the full-scale laboratory model of completed horizontal well.

screen completions. These wells contain multiple permeable layers (sand screen, gravel sand, perforated casing, formation) as shown in Figure 1b. In unimpaired wells fluid can freely flow from the reservoir through all of these layers inside the borehole. However reduction of permeability in any of these layers (impairment) may greatly reduce the fluid flow. Low-frequency tube waves can conduct instant pressure testing and therefore indicate whether fluid communication is blocked, thus providing valuable information about impairment location and strength. While this sounds conceptually similar to the open-hole case, the quantitative interpretation is quite different because wells with sand screens support two tube waves and their permeability dependence is more complicated. Initial experiments and modeling (Bakulin et al, 2008a,b) confirmed our ability to identify sand-screen plugging in completions without gravel packs. Here we present more realistic experiments with gravel-packed completions and examine other completion scenarios beyond screen plugging.

Experimental setup

A photo of the full-scale laboratory setup of a completed horizontal well is shown in Figure 1c. On the outside it consists of 30 ft aluminum outer pipe (casing) with perforations while the inside has a sand screen (Figure 2b) and gravel pack. Acoustic measurements are performed with 24 fiber-optic sensors (Figure 2a) wrapped around the outer pipe (casing) as described by Bakulin et al (2008a). On the outside of the pipe, the tube or "breathing" waves have mainly radial motion. Minute expansion or contraction of the pipe volume is reliably picked up by 10 m of the wrapped sensing fiber. A wire-wrapped sand screen (Figure 2b,c) is placed inside the casing and consists of an aluminum base pipe with perforations and a plastic wire-wrap with 0.008" gaps (Figure 2b). To model plugged sand screens, we used the same but unperforated aluminum base pipe (Figure 2c). The annulus between casing and screen is packed with gravel sand (Figure 2d). An acoustic source (Figure 1e) is placed inside the screen.

Detecting sand-screen plugging

One typical impairment mechanism that can restrict deepwater well production is plugging of sand screens. Figure 3 compares responses for open to flow wire-wrapped screen and completely plugged screen modeled as a blank pipe. The top of the plot contains a visual display picturing a sand-screen assembly placed inside the casing. Plugged sections are shown in blue solid color while open sections are depicted in a dashed pattern. Yellow strips around the sand screen indicate that the completion is gravel-packed. Permeability of the wire-wrapped screen is estimated at ~ 250-1000D, whereas permeability of the blank pipe is zero. Plugged screens support tube-wave signals with small attenuation, whereas open screen have huge attenuation (Figure 3a,b). Despite high attenuation signal processing shows that velocity of the fast tube wave signal is greatly reduced in open screen (Figure 3c,d). Therefore we conclude that decreased velocities and large attenuation of the fast tube wave characterize open screens. We stress that examples of plugged and open screens represent the end members with very large and vanishing permeability, whereas partial plugging will manifest itself as an intermediate permeability, thus generating velocity and attenuation intermediate between the two extremes. Relatively large differences between signatures of plugged and open screens suggest that we are likely to be able to distinguish various levels of partial plugging or intermediate permeability of sand screens.

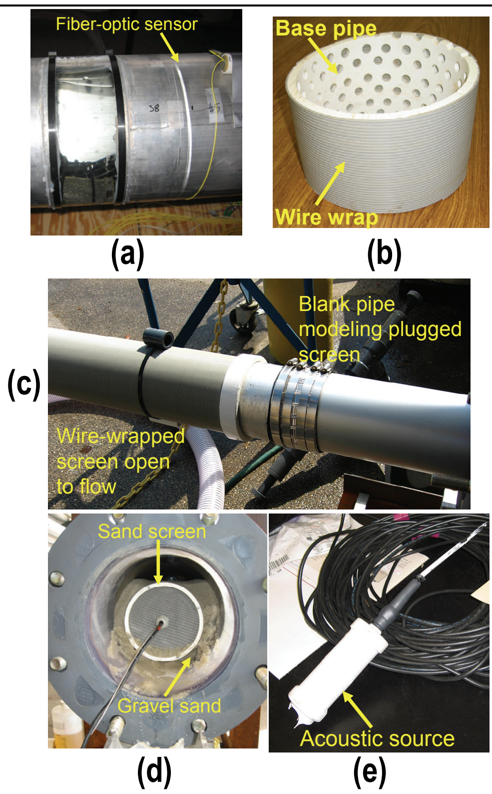

Figure 2: Components of experimental setup: (a) fiber-optic "on the pipe" acoustic sensor; glass windows were inserted every 5 ft to observe the gravel packing process; (b) cross-section of the screen showing wire wrap and base pipe (although plastic base pipe is shown, aluminum one was actually used in the experiment); (c) wire-wrapped sand screen and blank pipe; (d) gravel-packed annulus; (e) piezoelectric acoustic source.

Figure 4 shows a simulated wireline survey conducted with a moving source in a model where the left part of the screen is open and the right one is plugged. Acoustic data can be easily interpreted by visual inspection and the location of

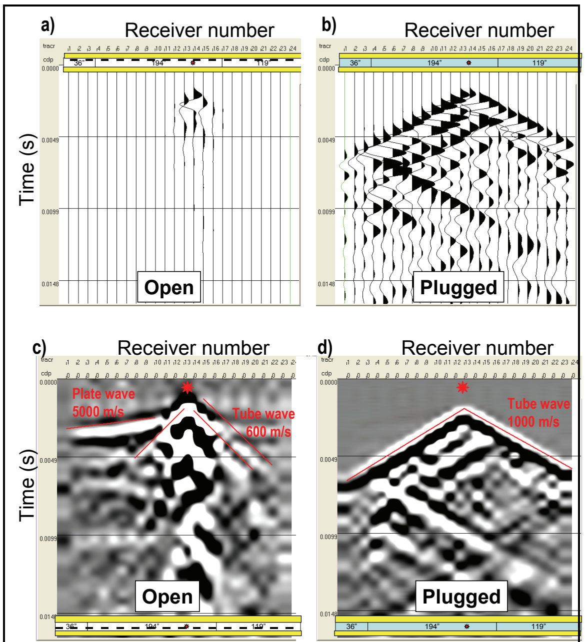

Figure 3: Acoustic response of open to flow sand screen (a) and unperforated base pipe (b) modeling a plugged screen. Both displays are shown with equal magnification. Notice the greatly increased attenuation of the tube-wave signal in the open screen. These displays suggest large difference in acoustic signatures of open and plugged screens that should be easily detectable. Figures (c) and (d) show the same data as (a) and (b) but with with variable density display and larger magnification. Notice the slower velocity of tube-wave signals in open screen compared to the plugged one. Again a large difference in velocity (~40%) suggests that not only we can distinguish open and plugged but also we should be able to detect any partial plugging.

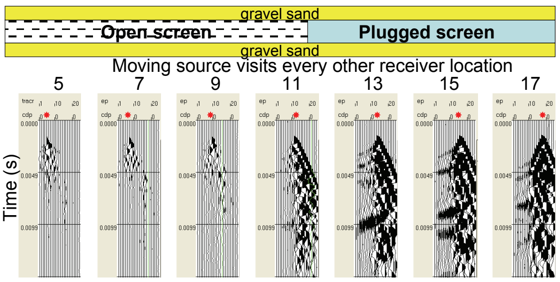

Figure 4: Simulated wireline survey with a source moving from sensor location 5 to 17 with the increment of 76 cm in the gravel packed completion with an open-plugged interface. Note that the location of the open-plugged interface (between receivers 11 and 12) is easily found by tracking attenuation and velocity attributes.

the open-plugged interface is identified between sensor locations 11 and 12. When the source is in the plugged section, we observe a fast tube wave velocity of ~ 1000 m/s and small attenuation, whereas the highly permeably open screen reduces this velocity to ~ 600 m/s and leads to extremely high attenuation. We conclude that plugged intervals of sand screens can be reliably identified using tube-wave signatures.

Detecting flowing perforations with passive listening

While active surveillance represents the main task, a permanent non-intrusive system gives opportunities for passive measurements detecting various flow conditions. We present a first attempt to detect flowing perforations based on passive acoustic data. Figure 5 shows several perforations connected to the water line via a manifold. The water line was chosen to simulate a static flow through the perforations. Water is injected through a single perforation at a time inside the completed well to simulate reservoir production.

Figure 6 reveals that a flowing perforation acts as a constant source of very low-frequency "noise" of about 0-50 Hz. This noise has a structure of ridges with peaks at the perforation location. Gysling et al (2005) describe similar "convective ridges" that are due to acoustic noise from vortices induced by turbulent fluid flow in pipes. They suggest that those vortices create coherent acoustic disturbances that can be tracked at a distance of about two pipe diameters. Therefore they use acoustic sensors with a fine spacing (~2/5 of the pipe diameter) to track these signals and thus estimate fluid flow velocity inside the pipe. Although in our case the sensor spacing is too coarse (about two pipe diameters), we can still claim that signal can be

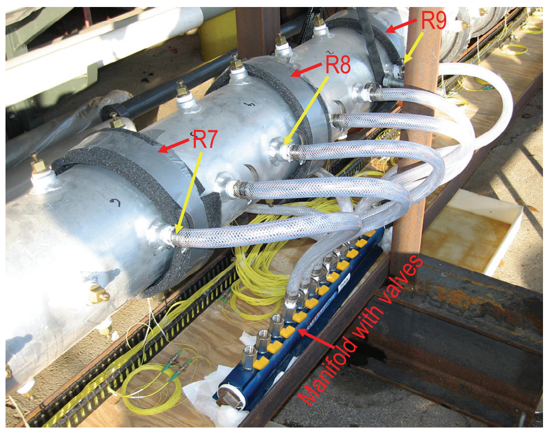

Figure 5: Picture of the setup with flowing perforations. Three fiber-optic receivers R7-R9 are shown with red arrows. Yellow arrows point to the nearby perforation that was used for flow. Water, injected through one perforation at a time, flows inside the completed well thus simulating reservoir production.

picked up at several neighboring sensors near a flowing perforation. The apparent slope of ridges on Figure 6 is around 20-50 m/s whereas estimated flow velocity through the perforation is less than 1 m/s (for a flow rate ~ 4-6 gallons per minute). It is likely that our large sensor spacing leads to severe aliasing and precludes us from estimating such small flow velocity. Nevertheless, we believe that the nature of observed ridges is certainly similar to those described by Gysling et al (2005) for flow in the pipes. Presence of gravel sand is likely to modify flow conditions and behavior of vortices considerably which should be a subject of future studies.

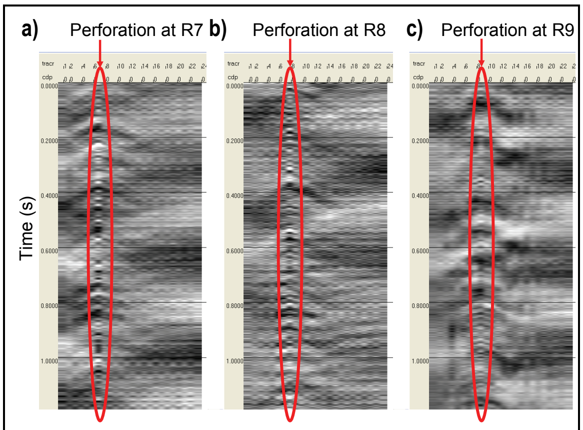

Figure 6: Acoustic responses of flowing perforations after simple pre-processing. Observe low-frequency ridge-like signals with the peaks located near perforations flowing at: a) next to receiver 7; b) next to receiver 8; c) next to receiver 9.

If only location of the flow is of interest, then the same data can be analyzed in a simpler fashion following ideas of "noise logging" (McKinley et al., 1973). Again the location of single flowing perforations is easily found from the strength of the acoustic noise level.

Path to deployment

In the short term, the best chance to apply this technology is to utilize wireline acoustic logging. Slim acoustic tools with low-frequency monopole sources and receivers that go inside the screen can be easily manufactured. The disadvantage of the production logging approach is that it is not a real-time 4D measurement. It requires downhole access and possible shut in of the well. The latter two concerns may preclude applications to subsea and other wells with high intervention costs. In addition, repeatability between time-lapse logging runs may be an issue.

The longer-term solution is represented by a permanent downhole system that can be achieved for instance with fiber-optic sensors and passive noise source as suggested by Bakulin et al (2008a). A permanent system is desirable because access to complex deepwater or subsea wells is diminishing whereas intervention costs are increasing. In addition, the permanent system has these important advantages over the wireline option:

- it provides real-time information
- there is no well shut in required and thus no lost production incurred
- it allows monitoring gravel packing and other technological processes
- it enables passive measurements characterizing flow, open perforations, cross-flow and sand production.

To illustrate the last point we refer to work by Bakulin and Korneev (2007) who showed that direction of cross-flow between two commingled reservoirs can be estimated from repeated acoustic measurements. In essence, the acoustic monitoring method is like a permanently installed "stethoscope & sonograph" at the chest of the patient (sandface of the reservoir). The sonograph constantly conducts an active "health check" of the well, whereas the stethoscope passively listens to "sneezing and coughing" of the reservoir. We expect to detect many other conditions that we can not dream of right now. Early detection and proper diagnostics follow as a natural outcome of permanent monitoring, so that proper treatment (workover) can be delivered before issues get out of hand. Permanent monitoring can also serve as an additional insurance to safeguard expensive completions and sand control "jewelries" as well as the borehole itself.

Summary and outlook

Just like 4D seismic revolutionized our ability to manage reservoir production, real-time completion monitoring has the potential to revolutionize our ability to manage deepwater wells by understanding evolution of flow, drawdown and impairment in real time. We have presented results of full-scale laboratory tests proving this potential. Further progress could be achieved by performing field trials with available acoustic logging tools run inside sand screens. In 4D seismic, various fluid flow scenarios are used to predict seismic response and then benchmarked against real measurement. Similarly, in completion monitoring we could model possible production technology scenarios, and predict their acoustic signatures. These signatures could then be benchmarked against actual downhole RTCM measurements. While quantitative inversions may or may not be achievable, such closing-the-loop methodology of 4D seismic proved of superior value to reservoir management. We have no doubt that acoustic in-well monitoring following same methodology would lead to substantial progress in managing deepwater wells.

Acknowledgements

We thank our Shell colleagues Jim Kielty, Dave Stewart, Jack Boyles, Keith Love and Ken Wilson for their hard work in creating the experimental setup and assisting with the laboratory experiment. We are thankful to PGS fiber-optic team for assistance.

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2009 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Bakulin, A., and V. Korneev, 2007, Acoustic signatures of crossflow behind casing: Downhole monitoring experiment at Teapot Dome: 76th Annual International Meeting, SEG, Expanded Abstracts, 298–302.

Bakulin, A., A. Sidorov, B. Kashtan, and M. Jaaskelainen, 2008a, Real-time completion monitoring with acoustic waves: Geophysics, **73**, no. 1, E15–E33.

———, 2008b, Real-time completion monitoring of deepwater wells: Part 1——Modeling and first experiments: 78th Annual International Meeting, SEG, Expanded Abstracts, 2726–2729

Gysling, D., D. Loose, and A. van der Spek, 2005, Clamp-on, SONAR-based volumetric flow rate and gas volume fraction measurement for industrial applications: Proceedings of the 13th International Conference on Flow Measurement, FLOMEKO.

McKinley, R. M., F. M. Bower, and R.C. Rumble, 1973, The structure and interpretation of noise behind the casing: Journal of Petroleum Technology, 329–338.

Tang, X. M. and A. Cheng, 2004, Quantitative borehole acoustic methods: Elsevier.

Wong, G. K., P. S. Fair, K. F. Bland, and R. S. Sherwood, 2003, Balancing act: Gulf of Mexico sand control completions, peak rate versus risk of sand control failure: Annual Technical Conference and Exhibition, Society of Petroleum Engineers, Paper 84497.