Acoustic Surveillance of Production Impairment With Real-Time Completion Monitoring

Deepwater production is challenged by well-underperformance problems that are difficult to diagnose early and expensive to deal with later. Diagnosis is more difficult because of the reliance on few complex wells with sophisticated sand-control media. A nonintrusive surveillance method was developed to identify impairment in sand-screen completions by use of acoustic signals sent through the fluid column. The method relies on permanent acoustic sensors performing acoustic soundings at the start of production and then repeating these measurements during the life of the well.

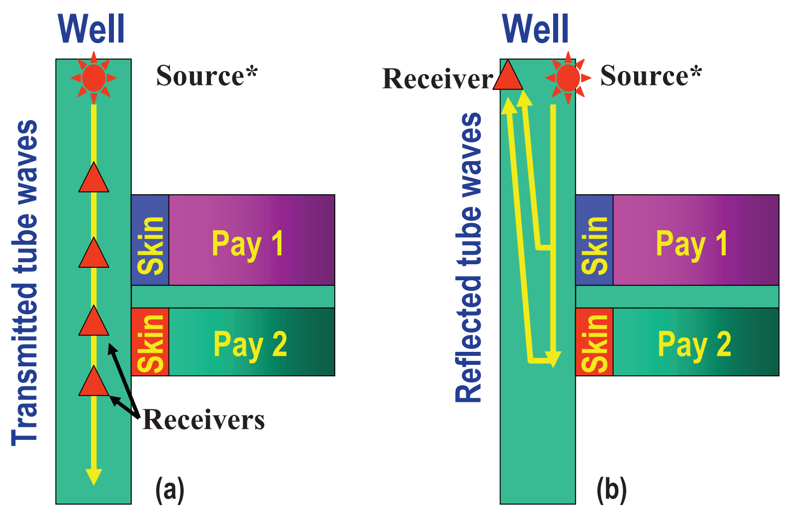

*Fig. 1—RTCM configurations: (a) "Repeated or permanent log" (transmission configuration) and (b) "Mini-4D seismic in a well" (reflection configuration). *Acoustic source may be eliminated when noise is used (section implementation).*

Introduction

Completion design is a large portion of the overall well cost, and much effort goes into designing completions correctly. During the production phase, little information is available to detect problems, optimize inflow, or prevent expensive workovers. Incomplete gravel packing, development of "hot spots" in screens, destabilization of the annular pack, fines migration, sand-screen plugging, near-wellbore damage, crossflow, differential depletion, compartmentalization, and compaction are extremely difficult to decipher with only a few permanent pressure and temperature gauges. Many problems can be identified by production logging, but it is costly and does not happen in real time.

The authors investigated underperforming wells in the Gulf of Mexico. Well-performance problems included large-scale reservoir issues, such as compartmentalization, as well as changes in local well skin with time that comprised completion, perforation, and near-wellbore effects. To distinguish between different scenarios of underperformance, more downhole data at various scales are needed that can characterize various components of the production system. The aim of this study was to develop a new method, real-time completion monitoring (RTCM), that can characterize permeability impairment of the sand screen, gravel, perforations, and the immediate near-wellbore space.

Principles

A tube, or Stoneley, wave is a fundamental axisymmetric mode that represents a piston-like motion of the fluid column restricted by the borehole wall. When tube waves encounter a permeable region, their signatures change because the radial motion of the fluid is no longer fully restricted by the borehole wall and part of the fluid can move into and out of the formation. This fluid communication at low frequencies implies that tube-wave velocity decreases and attenuation increases with increasing fluid mobility (permeability/viscosity). Boundaries between formations with different permeabilities also cause reflected tube waves.

It was concluded that tube waves are capable of indicating the presence or absence of fluid communication across the borehole wall inside a particular layer. If fluid communication is absent because of mudcake or lack of formation permeability, then no slowdown or attenuation is observed. If fluid communication exists, then slow-

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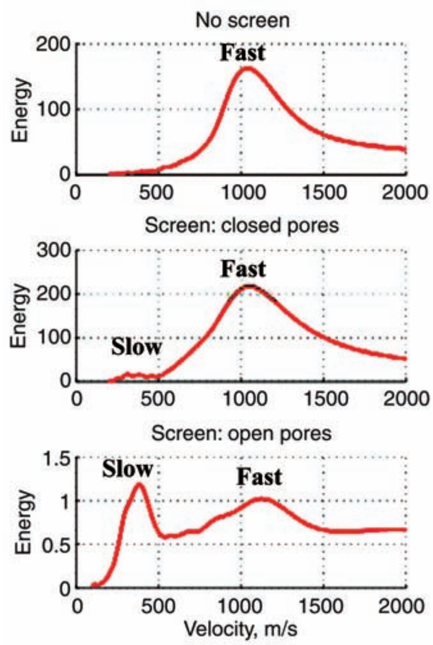

Fig. 2—Velocity spectra. Note that without a sand screen, only the fast tube wave exists. With a screen, fast and slow tube waves are recorded but the amplitude ratio is different.

down and attenuation are observed. Similarly, in a reflection configuration, increased fluid communication leads to a larger reflection. RTCM extends ideas of openhole Stoneley-wave logging to wells with sand-screen completions, typical for deep water. These wells have additional layers between the formation and borehole fluid such as sand screen, gravel pack, or casing. The sand screen and gravel pack prevent migration of reservoir sand into the wellbore and maintain the integrity of the reservoir around the wellbore. This more complex model has one essential similarity to the simple openhole model: For a flowing well, there must be fluid communication across all layers of the completion. Lack of fluid communication in any intermediate layer (screen or perforations) will disconnect the flow of reservoir fluid into the borehole. The aim of this study was to analyze the effect of broken fluid communication across the sand screen (or perforations) through the signatures of tube waves.

RTCM Concept

Fig. 1 depicts the conceptual design of the RTCM method. There are two RTCM configurations: "repeated or permanent log" (transmission) and "mini-4D seismic in a well" (reflection). In both cases, changes in acoustic signatures of tube waves over time were detected and permeability changes along the completion were inferred. In transmission configuration, velocity and attenuation of the tube waves are measured along the completion, which requires having sensors along the entire sandface (Fig. 1a). In reflection configuration, sensors are required only above the completion to analyze the change in reflected arrivals from permeability interfaces (Fig. 1b). The depth of the change can be determined by analyzing the arrival times, just as with reflection seismic.

Such measurements can be performed while the well is flowing or during brief shut-in periods. This method can provide valuable information about the well's in-flow potential in real time. Such information would enable the following.

- Detecting changes in permeability in and around the well (thus, the in-flow potential) in real time
- Identifying the well structure responsible for any problems (e.g., screen or perforation)
- Helping design best practices for producing the wells without damaging them
- Early alerting of problems before they become acute, enabling repairs with less effort, rather than major problems developing and intervention being unavoidable
- Helping characterize crossflow and differential depletion in wells with multiple commingled producing intervals

Full-Scale Laboratory Test

The horizontal flow loop at Shell's Bellaire Technology Center was used for experimental measurements. The full-length paper details a full-scale laboratory test of the RTCM concept for a particular scenario in which permeability impairment is caused by sand-screen plugging in a completion without gravel pack.

The intent of RTCM is to distinguish completion scenarios by use of tube-wave signatures. "Open" and "closed" denote two extreme cases of the presence or absence, respectively, of full fluid communication. "Partial" fluid communication should manifest itself with intermediate signatures between these two bounds. Examined signatures include propagation velocity and attenuation of tube waves and transmission and reflection amplitudes from interfaces of two contacting media.

The first conclusion was immediate: In the absence of a screen, there was only one (fast) tube wave, having a velocity of 1050 m/s. When an impermeable inner pipe was added (closed pores), a slow tube wave appeared, and the fast tube wave became more attenuated because of high absorption in the screen. With the slotted inner pipe (open pores), the fluid on both sides of the screen communicated,

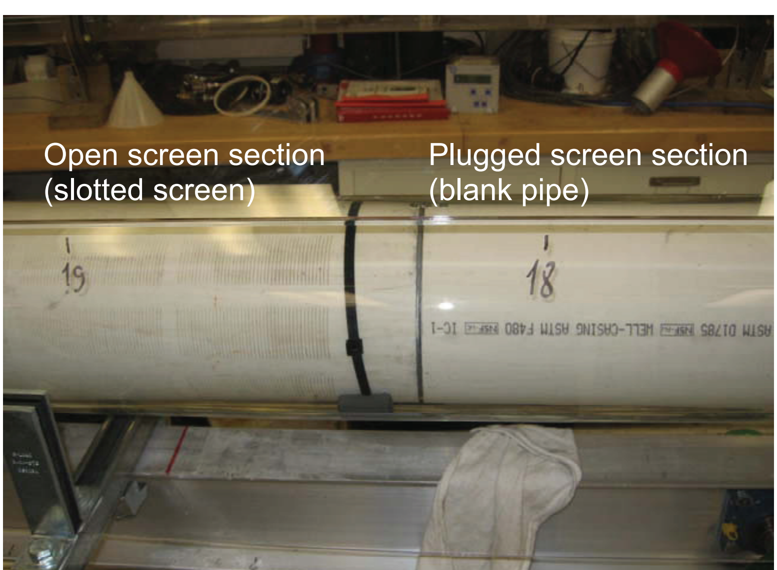

Fig. 3—Test-apparatus interface between open (left) and plugged (right) screen sections.

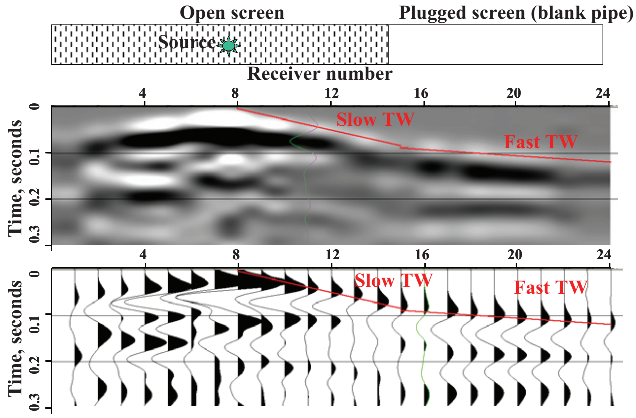

Fig. 4—Transmission at the open/plugged interface. Note excellent conversion of slow tube wave in open screen into fast tube wave in the plugged section. (TW=tube wave.)

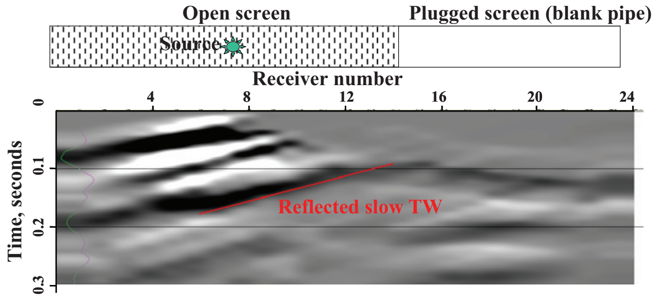

Fig. 5—Reflection from an open/plugged interface. Note strong reflected slow tube wave on a processed response after wavefield separation.

which led to high attenuation of both tube waves. Thus, a highly increased attenuation of both fast and slow tube waves was the first-order diagnostic for open screens, whereas reduced attenuation was characteristic for plugged screens. Thus, if plugging developed, a large signal was observed.

Additional diagnostics can be established by analyzing energy distribution as a function of frequency between these two cases. Because the experimental data were complicated by the presence of additional reflections at pipe joints, this analysis was performed by use of the slowness-frequency spectra. **Fig. 2** represents the averaged velocity spectrum over the entire frequency range. Both fast and slow tube waves, with approximately the same velocities of 1100 and 350 m/s, were present in the plugged and open cases. However, the slow wave was completely absent without a screen. In a plugged screen, the fast wave carried maximum energy in the frequency range of 300 to 600 Hz, close to the dominant frequency of the source, whereas lower and higher frequencies carry less energy. In contrast, the spectrum of the fast wave in an open screen was a large energy "hole" between 300 and 600 Hz where the fast wave was attenuated so strongly that even higher frequencies (600 to 900 Hz) carry more energy.

Reflection Configuration. The difference in velocity and attenuation between completions with open and plugged screens also led to reflections at the boundaries where properties change **(Fig. 3).**

Interface Plugged/Open. Consider a model in which two-thirds of the setup consists of a blank pipe (closed pores) and the remaining one-third is a slotted screen. At low frequencies, a source in the middle of the blank pipe excites both fast and slow waves. The fast wave becomes highly attenuated upon reaching the interface. The slow wave experiences a strong reflection. At higher frequencies, fast-wave reflections become more observable. Modeling showed qualitatively similar behavior but underestimated the amplitude of the slow wave in open pores.

Interface Open/Plugged. Wave propagation changed when the source was inside the open section. First, at low frequencies, the slow-tube-wave-dominating wave propagation in the open section converts into a fast wave in the plugged section **(Fig. 4).** The interference between the strongly attenuating fast and slow waves created the impression of a curved moveout around the source; however, the fast wave was excited by a late-arriving direct slow wave. Inspection of the unprocessed gather revealed the location of the open/plugged interface where it manifested as the change in the slope of the dominant events. Second, that same incident slow wave generated a strong reflection back into the open section **(Fig. 5)** that was larger than the earlier reflection from a pipe joint.

Gravel Pack: Numerical Modeling

In gravel-packed completions, the presence of a sand layer, with presumably small (but nonzero) shear rigidity, led to the existence of only a single (fast) tube wave. This effect simplified wave propagation. Thus, the presence of a second, slow tube wave may indicate completions with fluidized sand or lack of sand. Synthetic finite-difference seismograms showed that in the plugged section of the screen (closed pores) the tube wave had higher velocity (1020 m/s) and experienced very little attenuation. However, open pores allowed fluid communication between the liquid column inside the screen and pore fluid in the sand. As a result, a strong velocity slowdown (700 m/s) was observed along with dispersion and substantial attenuation. Thus, similar to openhole-logging methods, permeable and impermeable sections of the screen can be distinguished by examining velocity and attenuation. Slowdown in velocity and high attenuation are simple diagnostics of an open section, whereas speedup and little or no attenuation are characteristics of a plugged section.

Conclusions

A nonintrusive real-time technique was proposed that monitors changes in permeability along sand-screen completions by use of acoustic signals in the fluid column. Various impairment mechanisms can impede production. A full-scale laboratory test verified the method for a scenario in which impairment was caused by sand-screen plugging in a completion without a gravel pack. It was concluded that experimental monitoring of the tube-wave signatures over time can reveal plugging of the sand screen or its parts. **JPT**