TECHNOLOGY BRIEF

# Pressure Pulsing: The Ups and Downs of Starting a New Technology

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When technology based on new science is started, there can be a lot of skepticism, which is a healthy reaction. The skepticism encountered by PE-TECH as pressure pulsing is gradually introduced has been partly overcome, but only in the Canadian heavy oil industry. Here are some typical remarks we have encountered over the last three years, accompanied by our responses.

"This is not predicted by Darcy's Law." *This is quite correct since Darcy's Law is a static law and cannot handle inertial effects. For example, look at how Darcy's Law is fudged to handle turbulent flow.*

"Well, it works in heavy oil, but it won't in light oil." Or, "Our reservoirs are different." *Physics is physics; it will work in all liquid-saturated systems, but will have to be optimized in individual cases.*

"We don't need this because we use horizontal wells." *It can be used in many different configurations, and can help horizontal wells just as it does vertical and inclined wells.*

"It's not the pulsing, it's a relative permeability effect (or permeability increase or viscosity decrease, etc.)." *Nope, we've proven otherwise, although in the case of highly viscous oils of large molecular weight, there may be an additive effect of viscosity reduction.*

"It won't work in consolidated rocks." *We're confident of field success; limited laboratory tests indicate that it does indeed work, but we have a lot more testing to do.*

"Sounds like Cold Fusion to me." *Frankly, we were pretty startled ourselves at how large the effect is, but you can do the experiments yourself.*

"Come back when you have some real field data." *We have. We're here.*

## History

Pressure pulsing is an emerging technology. Its roots go back several decades; as a rigorous theory, it goes back about 15 years. Russian engineers noticed decades ago that large earthquakes often caused changes in oil well behaviour, usually a short-term rate increase. This was variously ascribed to compaction, shaking loose of particles blocking pore throats, or changes in permeability, viscosity, and capillary entry pressure. However, attempts to use seismic excitation have, to our knowledge, met with failure in China, Canada, and the United States. Senior engineers from western oil companies have examined claims that mechanical vibrations are being used successfully, they appear unconvinced, even after site visits. Also, the numerous articles in the Russian literature, mainly by geophysicists, tend to be mathematically opaque, unfathomable in terms of physical processes, based on debatable premises, or without sufficient clear and unequivocal information to allow evaluation.

Nevertheless, published Russian data appear convincing, and R&D programs are active in Alberta, USA, and other areas, albeit without much apparent success. We believe we know why: seismic excitation is the wrong type of impulse, of insufficient amplitude, and applied at the wrong place.

Pressure pulsing experiments in the laboratory started only in January 1997; in the field, it was first tried in June 1998. PE-TECH conducted the first commercial applications in workover mode in September 1998, and in full field-wide rate enhancement mode in June 1999. These are early days and pressure pulsing has a long way to go, but signs are good that it will soon help a lot of operators. It has good potential for other applications, although the focus is on oil production at present.

## The Science Behind Pressure Pulse Flow Enhancement

About 15 years ago, Tim Spanos at the University of Alberta finished the initial development of a rigorous theory of porous media mechanics. Previous simplifications and assumptions were examined, found wanting, and corrected; resulting in a theory that is more thermodynamically sound than either Darcy theory for non-dynamic flow, or Biot-Gassmann theory for wave propagation. For example, Spanos found that porosity in porous media plays a fundamental role; to be rigorous, it must be treated as a thermodynamic state variable, similar to pressure and temperature, and not as a dynamically invariant quantity. (Other aspects were discussed in the *JCPT*, December 1999 issue.)

By 1995, this theory was known to predict some phenomena that were not "conventional" in any sense. Perhaps the most important of these is the existence of a new body wave in porous media. This deserves a bit of an explanation. Consider a solid isotropic mass without porosity: the two known body waves are the compressional and shear waves respectively. Now consider a liquid-saturated porous medium. If the pressure in a small region is suddenly pulsed, local porosity dilation occurs, and this transits the deformable medium as a porosity dilation (or porosity diffusion) wave. Incidentally, the reason we use the term diffusion is that there are diffusion terms ($\partial p/\partial t$) as well as wave terms ($\partial^2 p/\partial t^2$) in the equations.

If this wave exists, why has it not been observed before now? The reason is complex. Biot-Gassmann theory does not predict its existence; therefore it was not sought. Furthermore, because it is an exceptionally slow wave, ~1/20th the velocity of the compressional and shear waves, it lies far down a seismic wave train, and is likely to be ascribed to internal reflections or something else.

We have measured this wave in the laboratory, and there is evidence of it in nature. In the 1964 Alaska earthquake, many water wells in the Great Plains showed a sudden change in head the day after the earthquake, long after all known body and surface waves had passed. Some wells experienced increased flow rate, in others, the water temporarily turned murky. We believe these and similar events to be evidence of the porosity dilation wave. It may even be that the porosity dilation wave can help trigger sympathetic earthquakes.

Why is this wave so slow? Its velocity is related to the dynamic frequency at which the pore liquid begins to behave incompressibly. We know that at significantly slow impulses, liquids behave incompressibly (as in Darcy flow); at fast impulses (acoustic sources), liquids can transmit a compressional wave. Somewhere in between lies the excitation where the liquid begins to behave incompressibly, and a porosity dilation wave is the result. Its velocity depends on the compressibility of the phases, the stresses and density, and the viscosity of the liquid.

It is now clear why seismic approaches are doomed to failure or to poor efficiency. If the excitation energy is all seismic it will not generate large porosity dilation waves. If the excitation is applied from the surface, most of the energy will be lost in transit to depth, and some valuable energy may be filtered out. Also, it is very expensive to get high amplitudes at depth within seismic sources (how deep is your reservoir and just how many huge vibroseis trucks can you afford?). Once the physical implications of the theory became clear, it became evident that excitation had to be within the reservoir, the amplitude had to be large, and the frequency content had to be low (and could also potentially be optimized for individual cases). When we realized this in late 1997, it was obvious that down-hole pressure pulsing was the optimum approach. Now, we had a field method to try.

## Introduction of Pressure Pulsing to the Canadian Heavy Oil Industry

PE-TECH took the idea and visited a number of oil and service companies in Canada and the USA in late 1997 – early 1998, and was met with skepticism, disbelief, and especially disinterest. In February 1998 we decided to build and test our own field devices. A few workovers were done with a modest pulsing device in June 1998, on wells that had not produced for some time; results were encouraging. Since the first commercial workover was done in September 1998, about 50 more have been done in ten different heavy oil fields in Alberta and Saskatchewan. The most important lesson learned is that careful screening is required; seriously depleted reservoirs with a lot of free gas are likely to be poor candidates. Today, based on a careful assessment, we are as likely to say no as to say yes to a workover request. The second important lesson is that the amplitude of the excitation is important; big impulses are disproportionately better than small impulses. Accordingly, we have built bigger tools, and are now on version four. The third lesson is to try to keep costs low; to this end, we are finalizing several new designs (i.e., coil tubing, pump-to-surface hybrid) to reduce service rig costs in prolonged workovers. The fourth lesson is that no matter how good the data on a well and how careful our analysis of its history and geology, we will encounter surprises.

The first field-wide pulsing project was done largely at our own expense in December 1998 to February 1999, on a field that was not an optimal candidate due to high extraction ratios and free gas. Despite being a distressingly poor candidate and some technical difficulties, after 10.5

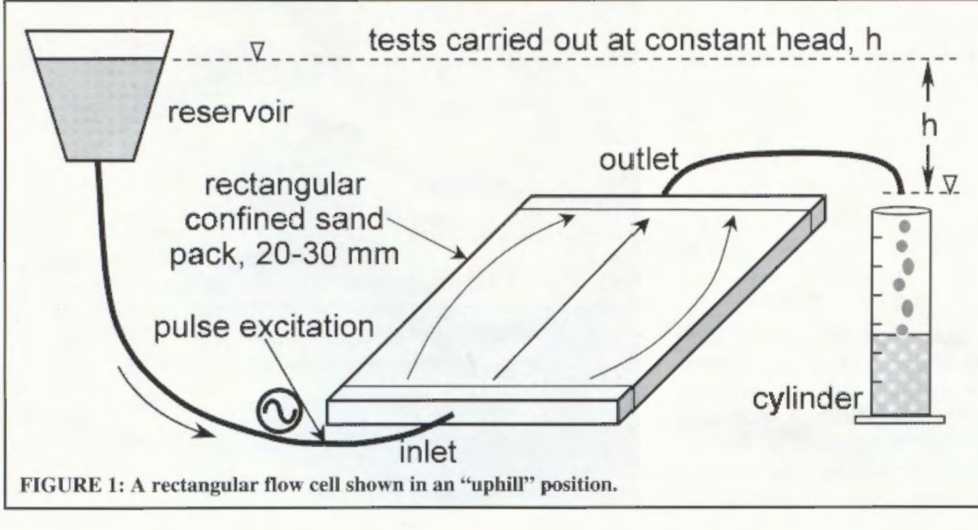



**FIGURE 1: A rectangular flow cell shown in an "uphill" position.**



Time = 139.2 s
Non-Pulsing

Time = 138.7 s
Pulsing

**FIGURE 2: Water displacement of a 35 cP oil-wet 34% porosity sand pack. Oil production on the right hand side is more than twice that on the left. Final OOIP production exceeded 90% with pulsing.**

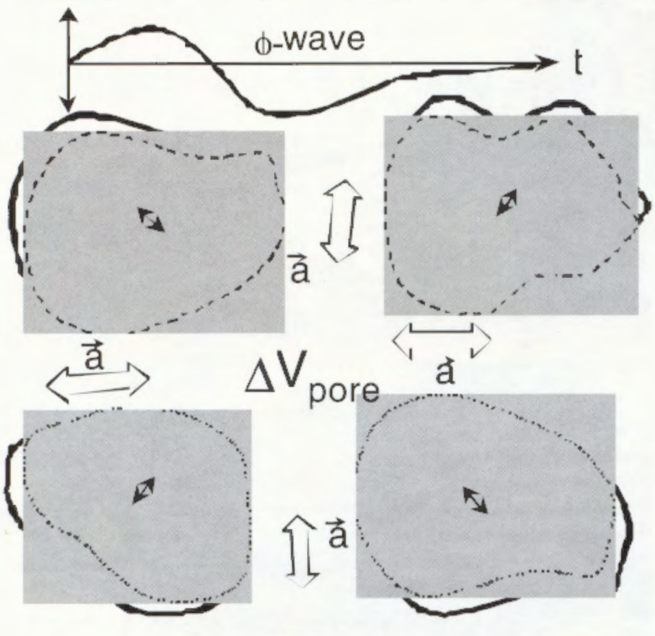
weeks, the field had ceased its precipitous production decline and production was even climbing slightly. The company was in the midst of a reorganization, the price of heavy oil was pathetic, and the time wasn't right to continue the experiment commercially.

Our second field-wide project was in the summer of 1999, and the third started in September 1999. The latter project is a waterflood in a 10,800 cP heavy oil reservoir experiencing severe production decline. Based on Darcy theory and static flow experiments, all textbooks and porous media engineers would strongly advise against waterflood attempts in such a reservoir. This year, we are looking forward to using pressure pulsing in less viscous oils, and in better candidates. Lessons we have learned are similar to those for workovers, and we also know we can change the pressure pulsing implementation (rate, volume, etc.) to achieve better results in specific cases. PE-TECH has a considerable distance to go, but as long as we can help companies increase revenue and book more reserves we can continue these developments.

Another important lesson we have learned is that simple clear demonstrations of the principles invoked are necessary. Accordingly, we use simple demonstrations to show that when a porous medium flowing at a constant head is excited appropriately, the flow rate increases. The apparatus is extremely simple (Figure 1), and the results are quite convincing (Figure 2). Similar experimental devices are now being used to explore environmental applications in aquifer clean up and mobilization of residual oil or gravity-segregated liquids. As soon as we have a clear experimental methodology for these cases, we intend to invite potential users to do the experiments themselves!

## What Does Pressure Pulsing Do?

Pressure pulsing generates porosity dilation waves. As the




**MECHANISMS:**

- Grains are physically linked
- Pores are in communication
- Porosity dilation wave
- Pore volume changes
- Fluid behaves
- Sloshes in and out of pores
- Acceleration forces at
- Improves liquid flow
- Overcomes capillarity
- Mobilizes trapped oil
- Re-connects oil ganglia

**FIGURE 3A: Acceleration of liquids and dynamic forces at pore throats .**

*Static pressure:*

$$d \cdot \frac{\partial p}{\partial l} = \Delta p_S$$

*Dynamic pressure:*

$$\frac{\vec{F}}{A} = \frac{m\vec{a}}{A} = \Delta p_D$$

A = throat area
F = new force
m = mass
a = acceleration

**Breakthrough when:**

$$\Delta p_S + \Delta p_D > \gamma/2r$$

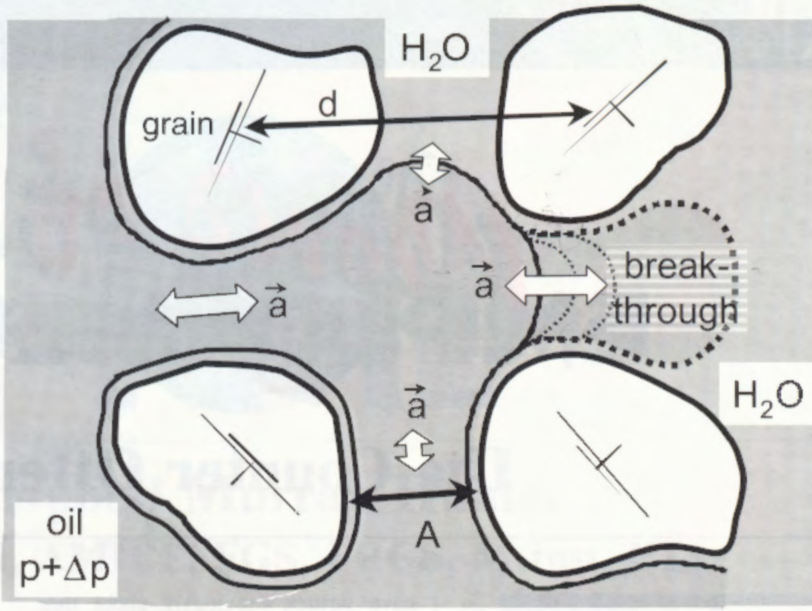



**FIGURE 3B: Dynamic Forces can Overcome Static Capillary Resistance. This leads to beneficial effects on liquid flow.**

wave passes a point in a porous permeable medium, porosity changes cause the liquid to rush into, then out of the pores that are dilating. Even though the volume changes involved are small, the porosity dilation wave velocity is high enough so that the local accelerations at pore throats are quite large. This has beneficial effects on many aspects of fluid flow, including fines mobilization and mechanical skin removal, reconnection of isolated bodies of oil, enhancement of flow rate that can lead to re-pressurization, and so on. For example, Figure 3a shows what we believe is happening at the pore scale, and Figure 3b shows how the input of additional energy through inertial effects (**F** = m**a**) can help overcome capillary blockages. The additional force brought to bear at the interface, added to the flow forces in the medium because of the existence of a pressure gradient, "pop" the interface through the restrictive throat. The oil that was trapped because of capillary forces can now be "reconnected" to the flow system. In some of our experiments with heavy oils (>1000 cP), we have displaced 70 – 80% of the oil from the cell in half the time that Darcy flow at the same head displaced 30% of the oil.

The benefits of pressure pulsing that have been proven in the field include higher flow rates, better waterflood efficiency, and mechanical skin removal during workovers. Also, chemicals can be placed with far less channelling, cold heavy oil production (CHOP) can be revitalized in many cases, and it appears that properly executed pulsing can even heal channels that have coned to water. The major limitation is that the presence of gas causes the porosity dilation wave to die out rapidly: the gas simply compresses instead of transmitting the energy onward.

## Future Applications in the Oil Industry

Pressure pulsing means that we have to rethink many widely accepted concepts. How do we define irreducible oil saturation if we can mobilize some or most of that oil through pulse excitation? How do we select candidates for waterflooding now that carefully applied pulsing has been shown to partially suppress viscous fingering and permeability heterogeneities? How do we view classic water coning predictions if coning can be delayed by pulsing? How do we make production rate predictions in cases of reservoir-wide pulse excitation? Can we now book new reserves because of the beneficial effects of pressure pulsing? If we had clear answers to these questions, they would be here, now, in print.

Only time will allow us to quantify the additional benefits to be found in pressure pulsing, but they appear to be real and substantial. Perhaps it will even open new dimensions in petroleum production; a mere 1% increase in recoverable reserves adds up to a lot more oil and a lot more revenue. Now, in early 2000, pressure pulsing is attracting more and more attention on the part of innovative engineers in oil companies; within a decade, we expect that it will become a valuable and widely known tool in the reservoir engineer's kit.