PAPER: 99-11

Pressure Pulsing at the Reservoir Scale: A New IOR Approach

T. SPANOS
University of Alberta
B. DAVIDSON
E_2 Solutions Inc.
M. DUSSEAULT
University of Waterloo
D. SHAND
PRISM Inc.
M. SAMAROO
University of Waterloo

Abstract

Laboratory tests initiated in January 1997 demonstrated clearly that periodic, large-amplitude, low-frequency strain excitation of porous media leads to large flow enhancements. Based on these results, a new liquid flow enhancement technology for reservoirs was formulated, and a successful full-scale field experiment was executed in early 1999. Other field projects in 1999 through 2001 waterfloods in heavy oil cold production wells with sand influx confirmed the expectation that pressure pulsing, properly executed, increases oil production rate at low cost.

The first trial showed that periodic application of large amplitude, liquid-phase pressure pulses increased oil production rates, decreased water-oil ratio, and increased the percentage of sand produced, even without large-scale injection. Though experience to date is in heavy oil, the process is general and will work in all porous media that have interconnected pore space. Furthermore, the method works in single-phase and two-phase liquid saturated cases, although the presence of large amounts of free gas is detrimental.

Based on the field and laboratory work, and considering the nature of the physical processes, it appears likely that pressure pulsing will also help reduce coning and viscous fingering instabilities, help overcome capillary blockages, and result in more total oil recovery over time.

Introduction

In the oil industry, progress in production technologies is most commonly based on empirical discoveries, and only later followed by attempts to develop a consistent physical theory to explain, analyse, and predict field behaviour. This is the case for all processes, such as CHOPS (Cold Heavy Oil Production with Sand), SAGD (Steam Assisted Gravity Drainage), and so on. Often, a fully rigorous physical theory remains elusive (e.g., for oil-gas-water-sand slurry flow in CHOPS production), and practice is refined through empirical models, physical reasoning and trial and error. However, the results obtained from laboratory and field research and development in pressure pulsing over the past five years were initially predicted from a new, more rigorous physical theory for porous media flow.

The new theory[1] is a more complete system of equations for dynamic behaviour of interconnected multiphase porous media (matrix-liquid, including matrix-water-oil systems). It was developed by considering all relevant pore-scale physical processes (micro scale), followed by rigorous volume averaging to scale the physics up to the scale of a representative elementary volume (REV) that can statistically represent mesoscopic behaviour (cm scale). The theory is therefore consistent with the laws of thermodynamics in component phases at the pore scale, and leads to large-scale thermodynamic relationships (equations) in which porosity is found to play a fundamental thermodynamic role, similar to that of temperature in single-component systems. In other words, porosity must be treated as a basic thermodynamic variable in porous media[2]. Furthermore, induced dynamic variations in porosity are responsible for the observed flow rate enhancement effect. The physical theory also dictates the experiments required to determine the parameters that arise in the equations[3].

A slow dynamic wave called the porosity dilation (or porosity diffusion) wave is predicted[4]. This is a dynamically induced elastic (reversible) porosity change that moves at a velocity predicated by the elasticity of the matrix and the viscosity of the fluid. Because matrix elasticity is a function of effective stress and porosity, the wave propagates more effectively at greater depth, other factors being equal. If the porosity is zero, the porosity dilation wave cannot exist; its presence depends on the interaction and relative displacements of a liquid and a solid phase. This is not the case for existing theories: seismic wave theory treats the multiphase system as an averaged "solid" with no water flow, and diffusion theory treats the solid as immobile with no possibility for inertial effects. (Note that if the liquid phase is largely immobilized, such as by silica surface adsorption of water in smectitic clay shales, the wave will be suppressed)[5].

Are there potential uses of this effect for oil production? Properly executed in appropriate reservoir conditions, more oil can be induced to flow more rapidly to wells. The dynamic energy that is introduced can also suppress (though not eliminate) various viscous instabilities, including fundamental viscous fingering and coning. Also, in the case of CHOPS technology, where sand influx is desirable, fewer blockages and higher flow rates can be expected because of the pore-scale dynamic effects. Thus, greater sweep efficiency and higher production rates can be expected through application of the right kind of pulsing energy.

Dynamic EOR Methods

During the 1970s in Russia, earthquakes were observed to affect fluid levels in petroleum reservoirs[6]. Fluid levels were reported to increase, leading to enhanced flow from the reservoir. It was also observed that water/oil ratios change during an earthquake swarm: wells with initially large water/oil ratios were observed to have lower post-earthquake swarm water/oil ratios and vice-versa in wells with initially low water/oil ratios. Earthquakes and explosions have also been known to affect

PEER REVIEWED PAPER ("REVIEW AND PUBLICATION PROCESS" CAN BE FOUND ON OUR WEB SITE)

underground fluid levels (water table and oil reservoir levels) in some areas(7). Clearly, fluid flow is affected by dynamic phenomena. These observations led to the concept of seismic excitation as a flow enhancement method for fluids in (underground) porous media.

Seismic excitation involves applying relatively small-strain excitation, either at the surface above the reservoir, or underground within the reservoir. For surface excitation, even using large motive sources, induced dynamic strains within the reservoir are no larger than 10^{-10} to 10^{-6} because of amplitude attenuation with depth and energy adsorbtion factors (frictional energy dissipation as heat), geometric spreading, and practical limitations in the characteristics of the seismic source, particularly deep in boreholes. Thus, very high-energy surface sources (e.g., a dozen coupled Vibro-seis™ devices) are needed to apply sufficient energy to the reservoir(8).

In downhole approaches, it is challenging to induce large strains without casing damage, and the restrictive casing diameter exacerbates the difficulties. For example, excitation at 1,000 m depth through displacement of the fluid at the surface in a 177.8 mm (7 in.) casing requires acceleration of ~25 m^3 of liquid. Even setting aside the issue of casing system compliance that filters out energy, the impulse required to generate a sharp rise time at depth would explode the casing at the surface. Introduction of large amplitude vibrations through mechanical means deep in a well is also problematic: tools are restricted in diameter 152.4 mm (~6 in.) and provision of sudden electrical or hydraulic energy is difficult.

In addition, we now understand that the low strains generated by non-earthquake seismic excitation make it unlikely that enough strain energy would be generated to substantially affect flow rates. Sharp strains exceeding 10^{-2} appear necessary.

Pressure Pulse Flow Enhancement

The physical theory that has been developed(9) qualitatively predicts liquid flow rate enhancement arising from pressure impulses that generate elastic porosity dilation waves. Depending on the boundary conditions, the excitation characteristics, and the state of the medium, a synergetic build-up of internal pressure within the pores of the medium takes place during the porosity dilation wave generation.

Conceptually, the porosity dilation wave may be viewed as a tsunami-type displacement wave with a long period, low frequency, and high amplitude, rather than as a strain wave with short period, high frequency, and low amplitude, such as a P- or an S-wave. This tsunami-type wave causes pore-scale fluid transport, and arises only when appropriate frequency excitation is applied to a deformable porous medium saturated with a viscous liquid.

To more clearly understand the porosity dilation wave, a direct analogy may be made with a tsunami ("tidal wave") in the open ocean. If a sudden, sharp strain is generated in water (e.g., an explosion), most of the energy is converted to a compressional wave (P-wave) moving through the water at ~1.5 km/s. However, if a sudden large displacement is generated, such as during an earthquake or underwater volcanic eruption, a displacement wave is set up that travels much slower than the P-wave. An earthquake offshore Japan will generate a tidal wave (tsunami) that will arrive at Port Alberni, British Columbia, about 12 – 14 hours after the event, but the P-wave that travelled through the ocean at 1.5 km/s took less than an hour to travel the same distance. The velocity of the tsunami (displacement wave) in the open ocean is predicated by the incompressible limit of water subjected to dynamic displacement.

Similarly, the porosity dilation wave velocity is predicated by the incompressible limit of the pore liquids, and travels at about $^1/_{20th}$ to $^1/_{30th}$ the velocity of body strain waves. Because it arrives so late in a wave train and is of very long wave length, it has not been consistently identified and studied by geophysicists. It should have a velocity of about 40 – 100 m/s in typical sandstones, compared to a P-wave velocity of 2.5 – 4.5 km/s.

In addition to the porosity diffusion theory(3, 9) leading to postulate the existence of porosity dilation waves, new empirical models describing the propagation of seismic waves in liquid-saturated porous media have also been constructed, based on the same theory(10-12). The establishment of the theory, expressed by a set of differential equations [Reference (9) contains a full treatment], led to an extensive series of laboratory experiments, ongoing since early 1997(13).

Various means of seismic and non-seismic excitation were applied to instrumented sand packs containing one or more liquid phases (i.e., a single phase, or a wetting phase and a different non-wetting phase). Experiments were all carried out with a constant head controlled by a large liquid reservoir, schematically represented in Figure 1. Tests were repeated with different wetting conditions and liquid phases of different viscosities, with the objective of obtaining systematic, repeatable flow enhancements of the mobile phase(14). In some experiments, the matrix was immobilized by virtue of the confinement of the system; in other experiments, the solid matrix was allowed to flow, simulating CHOPS(15), although there was no gas dissolved in the oil phase.

All experiments showed that pressure pulsing, under the right conditions, had the potential to produce systematic and repeatable fluid flow rate enhancements (in isolated cases in heavy oil up to ten fold). The amount of enhancement depends on many factors, but amplitude, frequency content of the impulse, physical parameters and boundary conditions all play a part. Other experiments with internal high-frequency (30 – 60 Hz) small-strain devices showed that small-strain seismic excitations at typical seismic frequencies had only a marginal effect on flow rate.

Figure 2 shows the results from a typical experiment using single-phase glycerine (viscosity, μ ~ 700 cP) in a 35% porosity thin

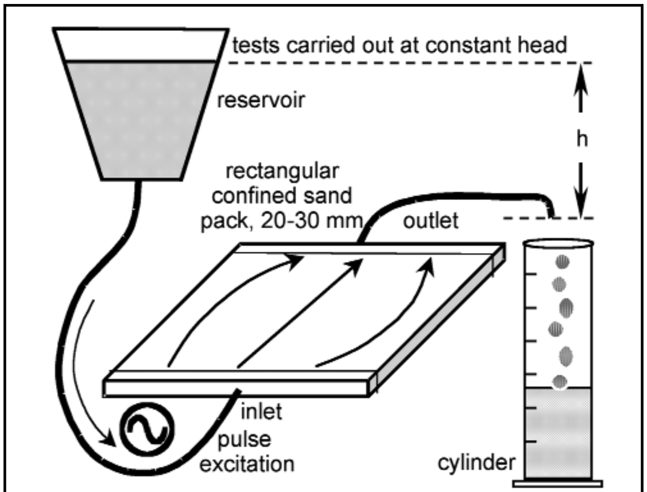


FIGURE 1: Simple experimental pulse apparatus.

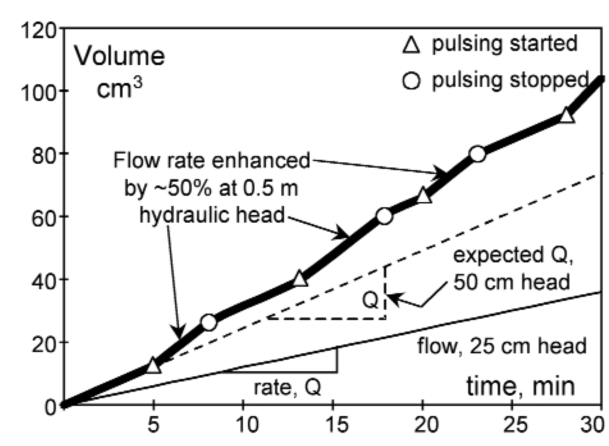


FIGURE 2: Laboratory flow enhancement experiment.

rectangular sand pack. The external pressure head was constant for the entire test. To assess flow behaviour, an initial change in the pressure head under static conditions from 0.25 to 0.5 m was applied; this simply doubled the steady-state flow rate, as expected from Darcy considerations. Applying pulsing to the upstream side increased the flow rate by about 50%, and when pulsing was stopped, the system reverted to the expected Darcian static flow rate in all cases. No peristaltic pumping effect was imposed on the system: only repeated sudden impulses applied to the inlet tube to allow a pressure jump to generate the porosity dilation wave.

These results, as well as results from over 150 tests since the initial ones, lead to these conclusions:

1. Appropriately applied dynamic excitation with the right frequency content and magnitude increases flow rate in porous media;
2. There is no change in basic static permeability associated with this effect because the simulation sands are clean, dense, and rigidly held in place;
3. The flow enhancement occurs in single-phase liquid flow. (A relative permeability explanation is therefore out of the question.);
4. There are clear transient build-up and decay periods in flow rate as pulsing is periodically stopped and restarted;
5. There are concomitant internal changes in pressure distribution, despite the fact that the macroscopic external heads remain constant;
6. The presence of free gas suppresses the flow enhancement effect; and,
7. The effect occurs for all liquids and permeabilities, but of course the lower the intrinsic static permeability the slower the flow rate.

The Seismicity-Fluid Flux Relationship

Fluid flux in deformable fluid-saturated porous media has long been associated with seismic events, although the mechanisms responsible for such a phenomenon have remained unclear[6, 7]. The mechanisms of this phenomenon were unclear in large part because the theoretical models used to examine seismic wave propagation and its effects on porous media are not founded on a self-consistent physical theory (i.e., one that simultaneously satisfies all the physical conservation laws, thermodynamic relationships, and the boundary conditions).

Excitation involving mean effective stress changes, no matter how small, must create dynamic changes in the porosity of a porous medium, and these porosity changes must interact with the saturating fluid through compressibility effects and flow. At the pore scale, a dynamic porosity change causes fluids to move into and out of the pore space. Thus, fluid viscosity is an important factor in determining the dynamic behaviour of the system. The interactions and deformations between the fluid and solid matrix constitute a case of dynamic stress-flow coupling, and can result in a porosity dilation wave, a slow displacement wave not predicted by conventional seismic equations.

Porosity dilation refers to a propagating front of porosity variation that accompanies a travelling pressure pulse generated within a liquid-saturated porous medium. This is the physical process responsible for the increase in liquid head within the earth associated with seismic events such as earthquakes[4, 6, 7]. Prediction of the porosity dilation wave velocity and characteristics requires a physically correct and representative model of wave propagation within a deformable, liquid-saturated porous medium. A summary of the theory underlying the porosity dilation wave effect is presented in the following sections.

The wave equation for elastic solids is the simplest model of wave propagation in a porous medium. Although this model (neglecting thermal effects) predicts the existence of one P- and one S-wave (i.e., one compressional and one shear wave), it does not allow for attenuation and the waves are non-dispersive (not to be confused with geometric spreading). Attenuation is usually empirically accommodated by allowing the wave number to become a complex function, and by determining attenuation values empirically through testing and field calibration. However, oil reservoirs contain multiple fluid phases and are not well represented by a single continuum model. Multi-phase porous media are better represented by multi-component systems.

The two major applicable theories of wave propagation in liquid-saturated porous media are the conventional Biot-Gassmann wave propagation theory and the more recent, multi-component de la Cruz-Spanos theory. Some discussion may permit the reader to understand the different aspects of these theories, the porosity dilation wave effect, and associated physical phenomena.

Biot-Gassmann Porous Media Model

The Biot[16, 17] and Gassmann[18] theories were the first models of wave propagation in porous media to consider two coupled and interacting continua. Both of these models, however, neglected to take into account viscous energy dissipation associated with attenuation of seismic energy within the pores of the medium. These models also assume that the state of energy within a porous (multi-phase) medium can be represented by a single energy potential, thereby eliminating porosity as an independent dynamic variable. The assumption of a single energy potential was based on the seemingly rational assumption that a single value could express the instantaneous energy state in a porous medium REV. In fact, N contiguous interpenetrating phases with different mechanical properties require N potentials, linked by physical limits and the laws of conservation.

These limitations mean that the Biot-Gassmann formulation cannot predict the existence of the elastic porosity dilation wave. Furthermore, if only a single energy potential exists, phenomena such as two-phase countercurrent flow are beyond the predictive capability of such a model. Finally, we note that the Biot-Gassmann model contains only second-order differential terms in time, and thus cannot incorporate diffusion effects, even if these are potentially important in certain frequency ranges.

At the other extreme, Darcy-based theories only include first-order time differentials; therefore, they can be used only for diffusive processes, and cannot be used to analyse or predict any process that has inertial (accelerative) components, such as porosity dilation wave generation and propagation. This is a vital point: the flow enhancement observed in our work cannot be predicted by Darcy diffusion theory.

Figure 3 is an attempt to qualitatively show the limitations of these theories over a wide range of frequencies. At very low frequencies, Darcy models are reasonable approximations; at very high frequencies, Biot-Gassmann models, empirically calibrated, are widely used. For a range of about three orders of magnitude between these limits, both diffusion and inertial effects must therefore be of first-order importance, and a more complete, coupled model is needed.

de la Cruz-Spanos Porous Media Theory

The de la Cruz and Spanos theory utilizes volume averaging in conjunction with physical arguments to construct macroscopic continuum equations that describe wave propagation in a fluid-filled porous medium. The major attributes of the theory are listed here.

1. Porosity is a dynamic variable (and it plays a fundamental role in both the thermomechanics and thermodynamics of any porous medium);
2. Rigorous first-order thermomechanical coupling is included (first-order heating from phase compression and expansion due to heating and cooling or pressure changes is included explicitly);
3. The theory is developed by imposing the microscopic boundary conditions of no slip, continuity of stress and continuity of heat flux to the following equations:

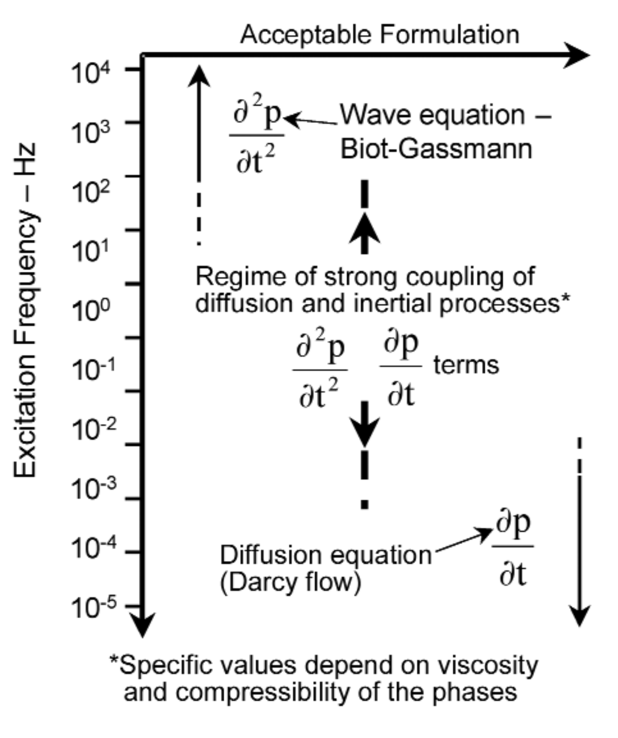


FIGURE 3: Frequency and process regimes.

- Equations of motion for a fluid (liquid)(i)(1);
- Equation of motion for an elastic solid;
- Continuity equation for a fluid (liquid);
- Continuity equation for a solid;
- The solid heat equation; and,
- The fluid (liquid) heat equation.

Assuming a porous medium composed of pores of random size and orientation, but macroscopically homogeneous and isotropic (the REV concept), the use of volume averaging principles for specific parameters may be introduced. By assuming a plane wave solution, dispersion relations for S- and P-waves are constructed. This results in predictions of four P-waves and two S-waves, whose phase velocities and attenuation are frequency dependent.

The mathematical realization of these physical considerations, combined with rigorous scaling, results in a set of coupled, macroscopic differential equations that describe both wave propagation and diffusion in porous media saturated with viscous, compressible fluids. For the case of a single saturating fluid, these equations are:

$$\rho_s \frac{\partial^2}{\partial t^2}\bar{u}_s = K_s\nabla\left(\nabla.\bar{u}_s\right) - \frac{K_s}{1-\eta_0} + \frac{\mu_f\eta_0^2}{\left(1-\eta_0\right)K}\frac{\partial}{\partial t}\left(\bar{u}_f - \bar{u}_s\right) - \frac{\rho_{12}}{\left(1-\eta_0\right)}\frac{\partial^2}{\partial t^2}\left(\bar{u}_f - \bar{u}_s\right) + \mu_s\left[\nabla^2 u_s + 1/3\nabla\left(\nabla.\bar{u}_s\right)\right] - K_s\alpha_s\nabla\bar{T}_s \quad \text{......................(1)}$$

$$\rho_f \frac{\partial^2}{\partial t^2}\bar{u}_f = K_f\nabla\left(\nabla.\bar{u}_f\right) + \frac{K_f}{1-\eta_0}\nabla\eta - \frac{\mu_f\eta_0}{K}\frac{\partial}{\partial t}\left(\bar{u}_f - \bar{u}_s\right) + \nabla\left[\frac{\xi_f\partial\eta}{\eta_0\partial t}\right] + \frac{\rho_{12}\partial^2}{\eta_0\partial t^2}\left(\bar{u}_f - \bar{u}_s\right) + \left[\mu_f\nabla^2\frac{\partial}{\partial t}u_f + \left(\xi_f + 1/3\mu_f\right)\nabla\left(\nabla.\frac{\partial}{\partial t}\bar{u}_f\right)\right] - K_f\alpha_f\nabla\bar{T}_f \quad \text{...........................(2)}$$

$$\rho_s c_v^s\frac{\partial\bar{T}_s}{\partial t} = T_0K_s\alpha_s\left[\frac{1}{1-\eta_0}\frac{\partial\eta}{\partial t} - \frac{\partial\nabla.\bar{u}_s}{\partial t}\right] + \kappa_s\nabla^2\bar{T}_s + \frac{\gamma}{1-\eta_0}\left(\bar{T}_f - \bar{T}_s\right) \quad \text{..............................(3)}$$

$$\left(\rho_f c_p^f - T_0\alpha_f^2K_f\right)\frac{\partial\bar{T}_f}{\partial t} = -T_0\alpha_fK_f\frac{\partial}{\partial t}\left[\nabla.\bar{u}_f + \frac{1}{\eta_0}\frac{\partial\eta}{\partial t}\right] + \kappa_f\nabla^2\bar{T}_f - \frac{\gamma}{\eta_0}\left(\bar{T}_f - \bar{T}_s\right) \quad \text{.........................(4)}$$

$$\frac{\partial\eta}{\partial t} = \delta_s\nabla.\bar{v}_s - \delta_t\nabla.\bar{v}_f \quad \text{..(5)}$$

where:

c_p^f = specific heat, at constant pressure, of the fluid (i)
c_v^s = specific heat, at constant volume, of the solid (i)
f = frequency
k = wave number
K = permeability (ii)
K_f = bulk modulus of the fluid (i)
K_s = bulk modulus of the solid (i)
K_d = the bulk modulus of the drained system
K_u = the bulk modulus of the undrained system
$\bar{u}_s$ = the macroscopic solid displacement vector
$\bar{u}_f$ = the macroscopic fluid displacement vector
$\bar{v}_f$ = the macroscopic fluid velocity vector
$\bar{v}_s$ = the macroscopic solid velocity vector
V = the averaging volume
T_s = the macroscopic temperature in the solid
T_f = the macroscopic temperature in the fluid
T_0 = the ambient temperature of the medium (ii)
α_f = the thermal expansion coefficient for the fluid (i)
α_s = the thermal expansion coefficient for the solid (i)
δ_s = the solid dilation factor (ii)
δ_f = the fluid dilation factor (ii)
η_0 = the static porosity
η = the dynamic porosity
γ = the surface coefficient of heat transfer (ii)
κ = the effective thermal conductivity across solid-fluid interfaces in the porous medium
κ_f = the thermal conductivity of the fluid (i)
κ_s = the thermal conductivity of the solid (i)
μ_f = the viscosity of the fluid (i)
μ_s = the shear modulus of the solid (i)
ρ_s = density of the solid (i)
ρ_f = density of the fluid (i)
ρ_{12} = the induced mass coefficient (ii)
ξ_f = the bulk viscosity of the fluid

Equations (1) and (2) represent the forces acting on macroscopic elements of the interacting continua (the solid and the liquid phases each constitute a connected continuum) whereas Equations (3) and (4) represent the heat flow in the coupled continua. Equation (5) is extremely basic, but fundamentally important; it represents the dynamic interaction between relative proportions of solid and fluid constituents and the porosity during a transient compression in the volume element. Simply stated, this last equation is an explicit statement of the porosity diffusion rate arising from solid and liquid fluxes.

These equations include both microscopic and macroscopic parameters. Microscopic parameters are those that are solely dependent on the solid phase or fluid phase (indicated by (i) in the list above). These can be easily determined for simple systems. Macroscopic parameters, however, result from the volume averaging process and these are denoted by (ii) in the symbol list above. The variables in Equations (1) to (5) are η, $\bar{u}_s$, $\bar{u}_f$, T_s and T_f, whereas $\bar{\boldsymbol{v}}_s$ and $\bar{\boldsymbol{v}}_f$ are simply the time derivatives of $\bar{u}_s$ and $\bar{u}_f$.

The equations show how porosity η must be treated as a fundamental thermodynamic variable, similar to pressure and temperature, in order to satisfy all the laws of continuity. This makes sense: in defining the thermodynamic state of a porous medium, temperature, stress and pressure are insufficient (i.e., incomplete),

i) Although the theory is general, we specify "liquids," because the dynamic enhancement effects are massively suppressed by the presence of free gas.

the porosity plays a direct role and must be included to thermodynamically specify the system uniquely.

In these equations, both first- and second-order time differential terms are present, therefore both diffusion processes and inertial (acceleration) processes are explicitly included. This allows direct coupling in the range where both inertial and diffusion effects are of first-order importance (see Figure 3). However, it should be remembered that the new theory is general and is applicable over a wide range of excitation frequencies.

The importance and characteristics of the microscopic parameters of porous media are well described in continuum mechanics and thermodynamics literature and will not be described here. A brief description of the main macroscopic properties is given below.

Dynamic Porosity

The static porosity (η_0) of a porous medium is a constant and is an easily determined quantity as long as a sample of the porous medium is available. The dynamic porosity (η), however, is a variable and it represents the first-order change in the static porosity when the porous medium is subject to a transient compression.

Permeability

Darcy permeability quantifies the ability of the porous medium to transmit fluids in the absence of inertial effects and is easily determined for single-phase fluid flow. In the case of a well-connected homogeneous porous medium, the permeability (K) represents relative first-order velocities between the fluid and the solid continua, and in these equations is equivalent to the Darcy permeability. This permeability parameter represents the net effect of all interactions across all fluid-solid surfaces within the volume element.

Induced Mass Coefficient

This coefficient has its origins in the relative accelerations that occur during wave propagation. It appears in Equations (1) and (2) and accounts for inertial coupling between the phases (note that all phases are, in principle, of different densities). This parameter is frequency independent, and is subject to the frequency-wavelength constraints imposed by the physical basis of the de la Cruz-Spanos theory.

The Solid and Fluid Dilation Factors

Equation (5) states that a change in porosity within a volume element is equal to the difference in the product of the solid dilation factor with the macroscopic change in volume of the solid, and the fluid compliance factor with the macroscopic change in volume of the solid. A macroscopic change in the volume of a phase can be caused by dilation of the constituent or the net flux of the constituent into or out of the volume element. The physical measurements of these two dilation factors are straightforward; for quasi-static processes they can be determined from the undrained and drained bulk moduli.

The Porosity Dilation Wave

The de la Cruz-Spanos porous media model was simplified by considering the fluid to be essentially incompressible. A fluid incompressibility assumption is acceptable if the velocity of liquid flow is much less than the sonic velocity in the fluid, and this is clearly the case for all porous media flow.

To introduce the effect of a strong displacement impulse into the model, these equations were further manipulated to yield[4]:

$$\eta(r,t) = \eta_0 - \left(1 - \frac{K_d}{K_s}\right)\frac{M_{ik}}{K_d + 4\mu_s/3}$$

$$*\left\{\frac{r_i r_k}{r^5}\frac{2}{\pi^{3/2}}\int_{r/2\sqrt{Dt}}^{\infty} dy y^4 e^{-y^2} - \frac{\delta_{ik}}{r^3}\frac{1}{\pi^{3/2}}\int_{r/2\sqrt{Dt}}^{\infty} dy y^2 e^{-y^2}\right\}$$

Where: M_{ik} = the seismic moment tensor arising from an impulse such as a pressure pulse or an earthquake, D = the porosity diffusion coefficient

$$D = \frac{k}{\mu_f}\frac{K_s(1-\eta_0)\left[K_d + (4\mu_s/3)\right]}{\eta_0\left[\eta_0 K_s + (1-\eta_0)(K_s - K_d)\right]}$$

and

$$y^2 = \frac{r^2}{4}D(t-t') \quad \text{......(6)}$$

This equation represents the dynamic porosity as a function of the seismic moment that is applied to the porous medium. This expression is valid for a pure shear fracture with slip in the x-direction and normal to the plane of slip in the z-direction, and at a point with coordinates **r** = (x,0,z). (Other impulse shapes will require other initial conditions.)

These expressions were further analysed to derive an expression for the pressure regime within a porous medium subjected to quasi-static stress:

$$\rho_f(x,z,t) \approx \frac{\mu_s bS}{10\pi\eta_0(Dt)^{3/2}}\frac{n_x n_z}{\sqrt{\pi/p^2} + 2/3\rho^3} \quad \text{......(7)}$$

Where $\rho^2 = \frac{x^2+z^2}{4Dt}$ and n_x and n_y are direction cosines from the source to the observing point. This corresponds to a sudden excitation corresponding to short-term slip across a planar surface, such as in an earthquake or microseismic tremor.

This expression leads to the conclusion that a pulse of pressure propagates from a sudden fracture source. The maximum value of this pressure travels as $r_m \infty \sqrt{Dt}$ and decreases in amplitude as $(DT)^{-3/2}$. The traveling pulse increases pore pressure for a brief time within liquid-filled pores, and causes transient pore dilation in an elastic medium. It may also trigger some compaction or dilation in a granular medium, leaving behind a permanent (plastic) change in porosity. This must result in a diffusional front that causes a variation in porosity to spread from the point of shear slip. The change in porosity can be positive or negative, depending on the direction of the two basic vectors of the fracture source: **b** and **n**. Over time, a plasticity process leads to a static change in porosity, which decays with distance from the source to the point of observation as r^{-3}. It has also been noted that a travelling pulse of pressure and a spreading front of porosity may also trigger secondary fractures, aftershocks and lead to the interaction of earthquakes[7, 8].

More recently, the dynamic limit of incompressible fluid motions has been studied. To understand what this means, consider a liquid that is excited by compression at a certain frequency[ii]. At low frequencies, ~10^{-4} Hz and lower, the liquid does not strain, it merely behaves incompressibly and displaces; this is a basic premise of Darcy theory. On the other hand, at high (seismic) excitation frequencies, ~10^2 Hz and higher, no large displacements arise, only strains. It becomes apparent that somewhere in the intermediate range the liquid undergoes a transition between compressible and incompressible behaviour. This limit is of great interest.

ii) In the range of practical excitation frequencies, gases cannot behave incompressibly, therefore this discussion is limited to liquids.

At a critical excitation frequency one obtains a tsunami-like wave that moves at about 10 m/s in the laboratory in glycerine filled sand packs at low stress (<1 MPa), and 100 m/s in water filled sand packs. This wave is symbiotically coupled to the quasi-static porosity diffusion process, which traps the mechanical energy of successive pulses, resulting in an increased reservoir pressure in a flowing system.

Field Trial

Pressure pulsing flow enhancement was first proven at a laboratory scale, and the next logical step was to investigate the effects of large-scale heterogenities, geometric spreading, and attenuation on porosity diffusion in a real reservoir. The best laboratory in this case is the field.

The decision to do a full-scale field trial was provoked by the apparent success of a workover method based on pressure pulsing[19], combined with theoretical considerations that predicted beneficial effects at the reservoir scale for continuous pulsing. The technology group at Wascana Energy Inc. (now Nexen Inc.), Calgary agreed to participate in the field trial by providing a field site and field support. The trial consisted of long-term continuous application of pressure pulse stimulation to the centre well in a pseudo five-spot pattern, while monitoring downhole microseismic, pressure and fluid production data from all surrounding wells (about one section in area), comprising 13 production wells in total.

The main requirements for the field trial were that the reservoir should still be reasonably intact, not having been subjected to thermal methods, chemically conditioned, or altered in a way that would introduce a number of unknown variables in the experiment. Also, to be considered a suitable candidate reservoir, certain other criteria had to be met. These included low free gas content, a reasonably high permeability (given the high oil viscosity), and the pulse and monitoring/producing wells had to be perforated in the same geologic zone. In addition, the geologic zone in which these wells were located and perforated had to be reasonably homogeneous without any significant permeability barriers or discontinuities between them, so as to allow unimpeded migration of pressure effects between wells. Finally, it would be best if the reservoir were not massively depleted before implementing pressure pulsing.

Had there been a history of excessive sand production from the pulsing well, or massive depletion of the pulsing well, it would have generated a large unsaturated yielded zone that could have caused excessively high pulse attenuation within that region. This would have resulted in retarded or impeded propagation of induced pressure pulses into the intact formation beyond the yielded zone, and consequently little or no effect might have been generated in the peripheral monitoring and production wells.

High gas content in the region around the well to be pulsed would have led to the dynamic energy being used simply to compress the gas, resulting in low energy transfer rates to the liquid phase around the wellbore and, consequently, a delay or elimination of pulse transmission. Free formation gas could be expected to absorb the pressure pulses and attenuate the pulse energy in a manner analogous to the action of a shock absorber on an automobile. In this case, continued liquid injection and pulsing would have to continue until gas saturation were reduced so that the formation pressure gradually could increase, so that the free gas content would progressively dissolve. Under such conditions, pressure pulsing related effects would not be seen at monitoring wells until the free gas was substantially driven back into solution (re-dissolved in the oil phase).

Taking into consideration these prerequisites and the options available, Wascana Energy chose Morgan Field, 30 km NW of Lloydminster, for the field-scale experiment. The location consisted of nineteen mature production wells exploiting the Sparky or the Lloydminster zones of the Upper Mannville Group. Of these nineteen wells, however, only thirteen were operational during the field trial. The reservoir state for the full-scale experiment was far from ideal: free gas was present near the pulsing well, the reservoir was in an advanced state of depletion, and substantial quantities of sand had been produced from most of the wells in the section. The experiment proceeded nonetheless with the logic that a success under such conditions would be confirmation that pressure pulsing would be far more effective in better reservoirs. Besides, no operator was willing to expose a functioning asset to a completely new EOR approach, so the experiment had to proceed in the depleted, disturbed reservoir available.

Reservoir Setting

The wells within the section exploit mainly the Cretaceous Sparky Sands; some are also perforated in the Lloydminster and Cummings Sands. A geological interpretation from well logs of the setting of the Sparky Reservoir in the section indicates that the reservoir is quite flat, with no significant structure, at a depth of about 580 m. Because of stratigraphic thinning, the average thickness ranges from a maximum of about 7 m at the location of pulse well to a minimum of about 1 m on the eastern and southern boundaries of the section. Original in situ oil saturation in the Sparky Sands within the section averaged 90%, and the "live" oil viscosity (i.e., with gas in solution) was reported to be approximately 10,600 cP.

The reservoir is a typical Mannville Group unconsolidated sandstone, likely fluvial in nature. These reservoirs have sands of 29 – 31% porosity, without significant intrinsic cohesion. Oil production is based on the CHOPS method[20] where sand is allowed to enter the production well along with the reservoir fluids. Sanding massively enhances oil production rate and resource recovery, compared to methods that exclude sand. Sand production rate is generally a few per cent of the gross fluids, but this results in hundreds of cubic metres of sand per well over a period of a few years. Thus, each well is surrounded by a large volume, yielded, high-porosity, highly compressible region of remolded sand that usually has some free gas in the interstices.

Despite the presence of free gas as interstitial bubbles, a general continuous gas phase apparently does not develop in these viscous oil sands, as it does in light oil reservoirs. The well selected for the pressure pulsing was producing about 3 m^3/d at the time of the project, and historical evidence suggested that there was free interstitial gas in the remolded sand around the well.

Pulse Generation

Since the pulse tool developed for workovers[21] was designed for short-term pulsing (5 – 30 hours), a long-term field trial required an automated design that could operate continuously for weeks. The tool used is a hydraulically operated, computer-controlled pulser, analogous in operation to a submersible variable displacement pump. The downhole assembly consisted of a stationary section attached to the end of the production tubing and a moveable section attached to sucker rods. The tool was designed to be installed in 177.8 mm (7 in.) casing. It has fluid bypass valves, limit switches, and other electronic control devices that help tailor the pulse to the desired shape.

The surface assembly consisted of a hydraulic system, a power skid and a control shack, shown in Figure 4. This first pulse tool (1999) was designed to have an effective fluid displacement of 6 litres/stroke, and it was operated at six to eight strokes per minute for 10.5 weeks. Provision was made to add fluid to the well through the pulsing tool if desired. Each pulse consisted of a rapid expulsion of the liquid through the perforations, followed by a recharge back-stroke. The recharge liquid was dominantly backflow from the formation itself, therefore the pressure pulsing action involved little pumping or fluid displacement. Rather, the pulsed fluid was > 95% reservoir fluid recharge; only a small amount of reservoir-compatible fluids were fed into the tool from uphole, and only when necessary. This was done deliberately to demonstrate that it is the dynamic energy associated with the transit of a porosity dilation wave that was causing enhanced flow, rather than an induced pressure front from massive injection.

The pulse tool operated trouble free for the entire project period

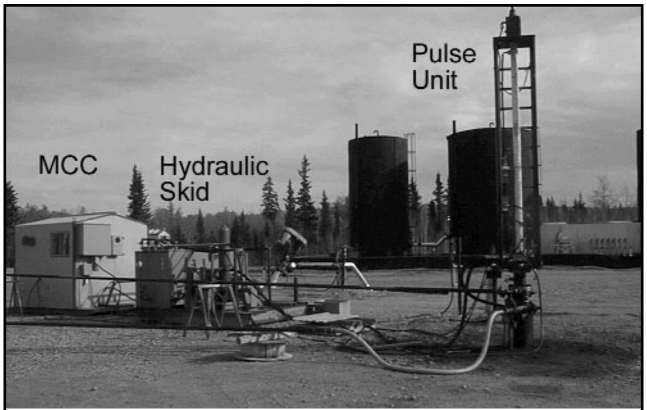


FIGURE 4: Initial well head assembly pulse tool (1999).

FIGURE 5: Current well head assembly pulse tool (2002).

without maintenance. The sand content of this fluid moving into and out of the tool, estimated at a few per cent, generated no visible wear during the 10.5 week period.

The current well head assembly (2002) is more compact and robust; it is a braced square truss shape about 3 m long and 50 cm diameter sitting vertically on the wellhead, linked to the control and motive systems (Figure 5). It has a much larger displacement volume, and is more effective in generating large-amplitude porosity dilation waves because the downstroke can be sharper, and strokes can be more frequent (up to 15 strokes per minute). This version was used for six months in 2001 on another site in Saskatchewan, reported in more detail elsewhere[22] and discussed below.

Monitoring

Project monitoring consisted of the collection of production-related data, downhole pressure and microseismic data from two functional monitoring wells (two others malfunctioned soon after start-up), and data from the pulse well. Production-related data consisted of:

- Daily total fluid production from each individual well in the section;
- Daily casing-gas and pump flowline pressures from each well in the section;
- Fluid composition (water and sand) cuts and casing gas volumetric vent rates on each monitoring well (this was done on every fourth day); and,
- Regular annulus fluid level shots on all wells (taken approximately once per week).

Downhole data collection consisted of the absolute bottomhole pressures in two monitoring wells, measured at five-minute intervals, and microseismic data. The microseismic data consisted of received seismic triggers of magnitude above the average background noise, as well as regular continuous eight-minute averages to determine the background noise magnitude and spectral characteristics[iii][4]. Data collected from the pulse well consisted of continuous fluid level shots taken every 20 minutes, hydraulic lift and braking pressures from the hydraulic drive unit, and upstroke and downstroke reach and duration, collected on a per-stroke basis. The pulse well operational data was averaged over half-hour periods and only those averages were recorded.

Data Collection and Analysis

Data were separated into background, pre-pulsing and post-pulsing periods for comparative analysis. The production histories of the wells were also used as a basis for background comparison and for the determination of pre-pulsing trends, where applicable. The use of production histories as a basis for the determination of background trends for comparative purposes was limited to the period during which the wells were operating under similar conditions to those prevalent during the test period.

Obtaining a Production Baseline

During operation of a heavy oil well using CHOPS, re-perforation of the wells, seasonal environmental changes, changes in the casing gas pressure, and changes in pump rotation speeds are among factors that can directly influence produced fluid rate and composition. For unbiased comparisons, an accurate production history was needed for the immediate pre-pulsing production period for each well. This was also to be used to extrapolate what the production would have been had pulsing not been implemented. Obtaining this baseline datum proved far more challenging than anticipated.

Historical water cuts and daily gas vent rates are generally taken at irregular intervals ranging from weekly to every two to three months (regulatory policy requires monthly reports of oil and water production, giving average rates in the month). It was observed that the monthly averages recorded in the production history often were extrapolations from previous measurements, interpolated figures from sparse measurements, or visual or conjectural estimates. Sand cuts are taken irregularly as well, and the repeating of a particular value indicates that the operator usually assumed that the sand production rate was constant. (Detailed data collection shows wide sand rate fluctuations on a minute-by-minute basis, as well as a day-by-day basis)[23]. Thus, data points were infrequent and perhaps not representative of the actual well history. Short of a long-term, statistical, multi-reservoir correlative study, there is no way of resolving this uncertainty.

Wells that had experienced some intervention in the months prior to the project were particularly difficult to baseline because they had not yet stabilized to give a history that could be easily extrapolated. Nevertheless, whenever possible, pre-pulsing production-related data trends were determined by fitting logarithmic trendlines.

Validity of Production Extrapolations

How valid is an extrapolation from a historical baseline in a Canadian heavy oil well? Undoubtedly less so than for conventional oil, but on average, certain principles can be assumed.

Natural long-term oil production tends to decrease monotonically unless new drive mechanisms are provided; thus, oil rate declines unless a new technology is implemented that introduces additional energy in the form of pressure or heat. Decline rate in the shallow low-pressure reservoirs typical of Canadian heavy oil fields can be quite high, and well behaviour, even in a single reservoir, can be variable.

CHOPS wells usually show some form of a depletion curve that is different from conventional oil wells[24]. In CHOPS reservoirs with mobile water, reduction of oil saturation plus various

iii) Space limitations do not permit exposition of the seismic data.

coning and fingering phenomena increase water flow rates to the well over time. Sand rates in mature CHOPS wells may be as high as 30 – 40% initially, and tend to approach values of 1 – 5%, depending on oil viscosity, unless interrupted by a blockage or a loss of connection to the reservoir drive energy[25]. In CHOPS wells experiencing rapid oil rate decline, there is invariably a large decline in the sand influx rate. In other words, when the sand stops, so does the oil production.

Relevant background total-fluid production for each well used in the field tests consisted of fluid production history during the period where all the known production was essentially the same as that of the test period. However, determining precise histories was impossible because of a lack of detailed data and changes in well operation. Therefore, two baselines were chosen. These are the production history for the wells from the date of their last re-completion or significant operational change that would affect their ability to produce fluid, as well as the two-month period immediately preceding the pulsing project. The instantaneous background production rate and trend of each well immediately prior to initiating pulsing was extrapolated from the historical data. Since the reservoir production rate evolves dynamically and tends to follow the natural (expected) trends outlined above, this background period is considered sufficient, particularly since a number of wells were being used for project evaluation. This approach allowed the success of the project to be evaluated rationally, despite the difficulties discussed and the concern about the data quality.

Background oil, water, and solids content data were derived from Wascana Energy's records. Base sediment and water composition (BS&W) is the generic name for the total percentage of water (both free and emulsified) and sand in the produced fluid. Some data are obtained from truck transportation tickets that record volumes of water, oil, or sand removed from the stock tank at the well site. However, the stock tank is a 120 m^3 vessel with fluid withdrawal taps at intervals corresponding to approximately 30 m^3 of contained fluid. Fluid is only removed from the tank when a single-phase fluid occupies one volumetric interval (i.e., the same fluid can be withdrawn from two consecutive taps). This arrangement means there were inconsistencies in the BS&W cuts generated, since the stock tank acts as a buffer and no records are maintained of the opening and closing inventories of the fluid composition within the tank. If a well is a slow producer, it may be weeks between withdrawals, and even longer for sand cleaning.

Wherever possible, logarithmic trendlines were fitted to the data obtained. This was done to identify dominant trends in the data being analysed, since most of the data obtained is semi-chaotic. A logarithmic trendline is a logarithmic average of production history and is considered to be an adequate representation, as it is an unbiased estimate of the trends. The dominant data trends determined from the pre-pulsing period were plotted separately, and the equations for the trendlines then determined. This was also done for data generated during the post-pulsing period. The equations were then used to plot the production trends for the duration of the field experiment.

The long-term production and workover history for each well was also obtained and used to plot monthly production rates for each well within the section, commencing from the date of the last re-completion. Monthly production and oil cut rates for each well, for the duration of the pulse experiment, were determined and used to update the production history of the well to include the pulsing period.

Results From the First Field Trial

The generation of a porosity-diffusion wave in a fluid-saturated porous medium results in radial propagation of that wave into the medium, until attenuation effects consume the dynamic energy. Attenuation magnitude in the reservoir around the pulsing well was unknown, the size of the disturbed zone was unknown, and thus the possible extent of the radial zone of influence that would develop during the pressure pulsing was also unknown. It was important for sufficient energy to transit well beyond the immediate pulse well environment into the more distant reservoir where it could facilitate fluid flow. Even if only the near wellbore region was affected strongly by the pulsing, it was hoped that the pressure enhancement would positively affect the productivity of offset wells.

Based on laboratory experiments, observations in wells adjacent to workover sites using pressure pulsing, and a bit of guesswork, we believed that constant pulsing would generate regular, periodic porosity-dilation waves that would eventually influence not only the region around the pulse well, but would gradually migrate outward. The original estimate was that the closest offset wells would see clear evidence of pulsing through an increase in fluids production rate or a change in annular pressure within four to six weeks.

The estimate was supported by the data; effects started to be noticed on offset wells in about 4 – 5 weeks. For example, one of the wells that had been producing less than 1% sand suddenly jumped to more than 10% sand (estimated), causing surface problems and down-hole plugging. A workover on this well was needed. At the end of 10.5 weeks of pulsing, there were clear effects on 11 of 13 wells; the two that showed no effect were also the most distant. (Remember that the pressure effect diffuses out into the reservoir, so it is rate-limited by the viscosity and the permeability.)

Over the duration of the field trial, significant changes in cumulative oil production and BS&W were seen. Overall, oil production on the 13 wells increased by about 37%, and water cuts were lowered in some cases by over 20%. Prior to pressure pulse stimulation at the field scale it was postulated that, given the history and age of the wells, a 30% to 40% increase in oil production rate in the near off-set wells would be observed. The results therefore were quite satisfying.

Sand cuts increased from an average of 0.5 – 1% to between 4 – 10%. Increase in sand cuts is probably caused by increased fluid gradient (i.e., increased hydrodynamic drag) across the boundary between intact rock and liquefied sand, combined with dynamic shaking of grain assemblages. Both processes should increase sand destabilization within the reservoir. The close link between sand rates and oil rates in cold heavy oil production is well known, and the increased sanding rates that accompanied the increased oil rates was expected.

Observation Well 1

The production history of this well indicated that oil rates and oil cuts are highly variable and cyclical, and periodically this well showed no oil production. Pre-pulsing oil production rates for November 1998 showed a decreasing trend. However, oil rates during and after pulsing showed an increasing trend. The oil production rate for February 1999 was the highest the well had ever experienced in the eight years of its productive history.

The pre- and post-pulsing fluid production trends for Well 1 show that total pre-pulsing fluid production for this well was declining at a rate of approximately 0.041 m^3/day. Pre-pulsing BS&W show that this was increasing at a rate of approximately 0.031%/day, roughly similar to the declining oil cuts observed. Post-pulsing total fluid-production rates, however, show an increasing trend of approximately 0.041 m^3/day, which is the same value as the pre-pulsing trend, but at an increasing rate (i.e., mirror image of the pre-production trend). The post-pulsing BS&W trend shows a decrease of approximately 0.125% per day. This is shown in Figure 6. Production declines had been clearly reversed by the pulsing.

Observation Well 2

A review of the pre-pulsing and post-pulsing total fluid production rates for Well 2 indicated that the pre-pulsing fluid production was decreasing at a rate of approximately 0.01 m^3/day. The post-pulsing fluid production rate showed an increasing trend of about 0.01 m^3/day; again, a reversal of the pre-pulsing production trend. Comparison of the post-pulsing oil cuts and oil production

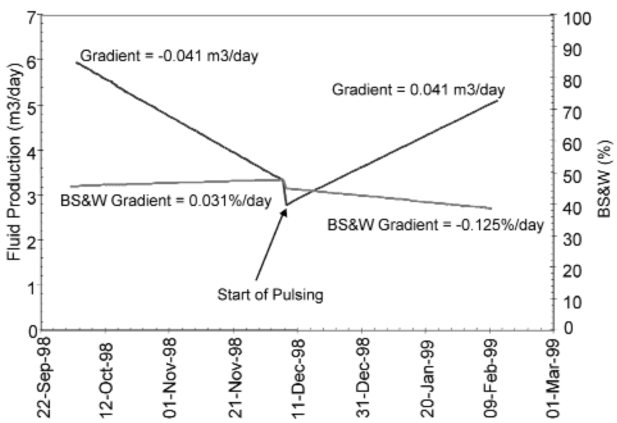


FIGURE 6: Pre- and post-pulsing production and BS&W trendlines for Observation Well 1.

rates with the historical production shows that the December 1998 and January 1999 production rates were 6% higher than highest oil rate ever recorded by the well since re-perforation. This production increase was also the largest sustained post re-completion increase ever experienced by this well, and is shown in Figure 7. Oil production and oil cut rates decreased by approximately 20% during early February 1999. However, the data considered for February 1999 consist of only two discrete samples of BS&W cuts taken in early February. In most cases ten BS&W samples are taken and a trendline average fitted to these values to arrive at a monthly BS&W for each monitoring well. This average is then used to derive oil cut for the well.

Observation Well 3

The pre-pulsing total fluid production trends for Well 3 show that pre-pulsing total fluid production was decreasing at an average rate of 0.074 m^3/day. Post-pulsing total fluid production showed a negligible decrease of approximately 0.005 m^3/day. Pre-pulsing BS&W cuts, based on truck tickets, were 19% while post-pulsing production rate increased to approximately 41.5%. The pre and post-production data comparison plots for this well are shown in Figure 8.

Observation Well 4

The pre-pulsing fluid production rate for this well shows a decreasing fluid production trend of approximately 0.033 m^3/day. Post-pulsing total fluid production showed a stabilization of production. The pre-pulsing BS&W cuts based on truck tickets were approximately 26%. The post-pulsing BS&W cut for early December 1998 was recorded at approximately 26.9%. The measured post-pulsing BS&W cut for February 1999, obtained from wellhead samples, was 14%. Since wellhead samples from this well were obtained for February 1999, and the BS&W cut for late December 1998 and January 1999 are uncertain, the approximate

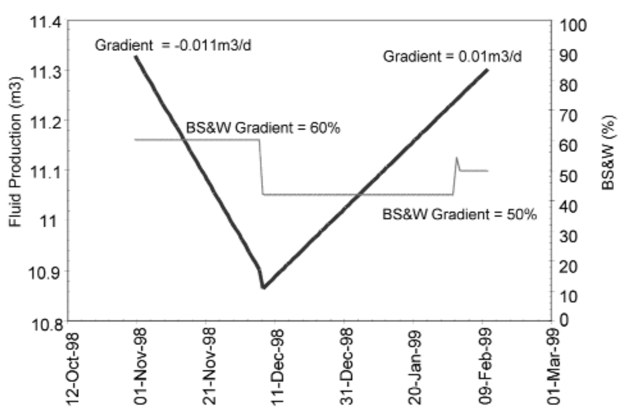


FIGURE 7: Pre- and post-pulsing production and BS&W trendlines for Observation Well 2.

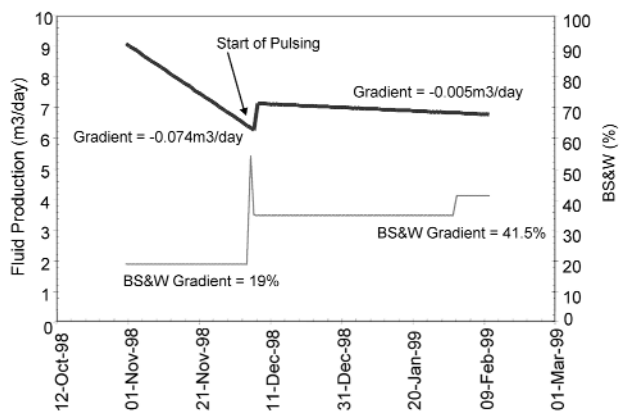


FIGURE 8: Pre- and post-pulsing production and BS&W trendlines for Observation Well 3.

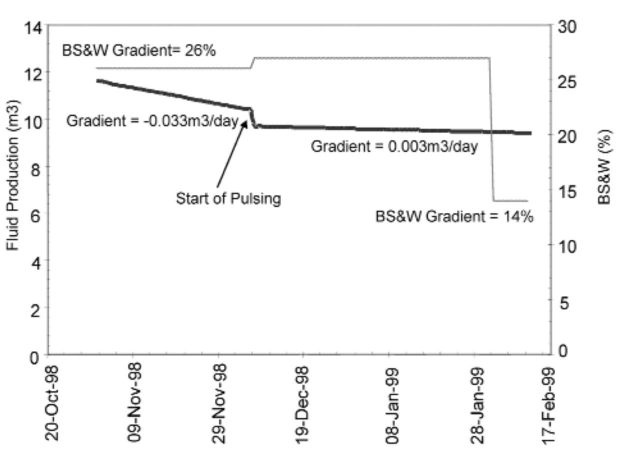


FIGURE 9: Pre- and post-pulsing production and BS&W trendlines for Observation Well 4.

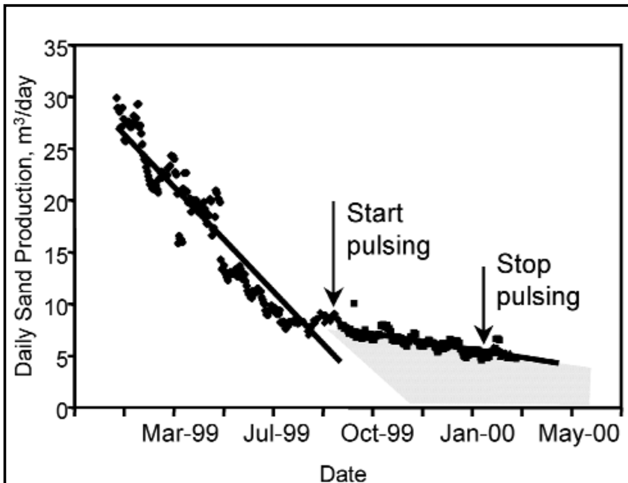


FIGURE 10

commencement or rate of decrease of the BS&W is unknown. This well also sanded in for four days in January 1999, requiring a workover and loss of four days of production.

The production history for this well shows a straight-line decreasing trend for both oil cuts and oil production rates. Post-pulsing oil production rates show a stabilization of oil cuts, while there is an average increase of approximately 16% in February 1999, shown in Figure 9.

After the 10.5 weeks of pulsing was finished, the operating company decided to place the pulsing well back on production. From being a well that was producing 3 m^3/d before it was shut-in, it went to 12 – 15 m^3/d, then settled down after a few months to 7 m^3/d, about equal to the best producers (historically) in the section. During the pressure pulsing, a total of about 31 m^3 of oil had been placed into the pulsing well, so this was recovered in about three days of post-pulsing production, plus the extra oil produced for many months thereafter.

Other Field Trials

No detailed economic analysis was performed for this first field project because of unavailability of OPEX data. However, two subsequent projects in similar reservoirs in Alberta and Saskatchewan, done on a commercial basis, were clear economic successes, netting back substantial additional profits for the operating companies, after all costs had been met. If the same commercial charges had been used on the experimental site, estimates show that the incremental oil produced at the price at the time would have generated a small net profit. For the first field trial of a new technology under particularly difficult reservoir conditions, this is a promising result.

The second and third pressure pulse stimulation trials were water floods in heavy oil reservoirs (one 1,600 cP, the other 10,300 cP). In both cases, the decline rate of wells surrounding the excitation well slowed, and the projects were economical, generating profits. Figure 10 shows the change in decline rate of oil production for one of the cases. Pulsing extended the life of the field, and the beneficial effect lasted long after pulsing stopped (more months than are shown). The shaded area is considered as additional production, and the pulsing well also produced additional oil when placed on production. In fact, over a period of almost five months, the pulsed well produced over $CDN150,000.00 worth of oil, similar to the costs of the entire pulsing project.

Lone Rock, Saskatchewan

The third case that will be discussed is in the Lone Rock, Saskatchewan field (30 km SE of Lloydminster), a highly depleted viscous (~10,000 cP in situ with depleted gas) heavy oil reservoir in the Sparky sand (ϕ ~ 30%), that was shut-in since 1970. In March 2001, pulse excitation in a single well (see Figure 11) was implemented along with water flooding in the same well. This project was established with the intent of improving waterflood well injectivity and increasing the well reservoir pressure, as part of a much larger field redevelopment scheme.

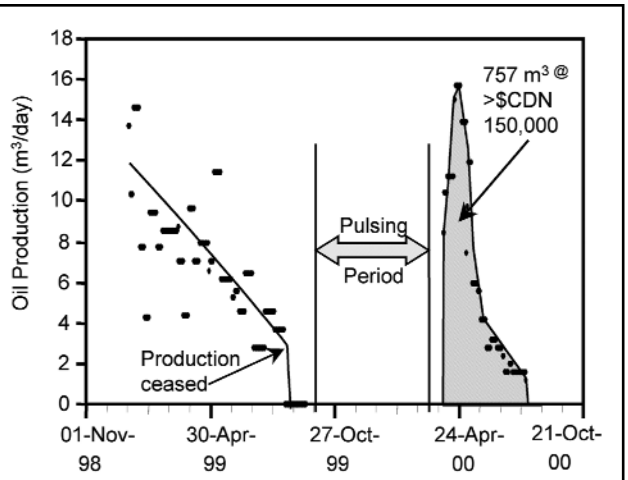


FIGURE 11: Oil production for the pulsed well after the field trial.

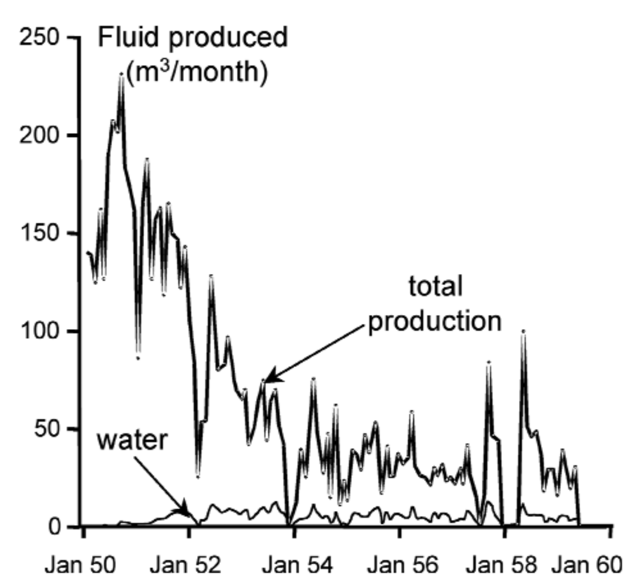


FIGURE 12: CFS pulse well history.

CFS Pulse Well History

The pulsed well was drilled at the end of 1949. The fluid production history for this well is shown in Figure 12. It was shut-in in 1959 after cumulative production of 7,443 m^3 of fluid, of which 585 m^3 was water.

In 1959, the well was changed to a water injector, lasting until November 1970, with a total of ~180,000 m^3 of water injected in a series of four water injection episodes (Table 1). There is no record of any pressure build-up during these episodes. In March 2001, the injector was reactivated and water was injected using a bottom-hole pulsing device that ran for 6 months at a rate of approximately 15 strokes per minute. A total of 39,000 m^3 of water was injected. Monthly data are shown in Table 2.

Pulsed Injection Well Details

Water injection using pulsing was tested for six months,

TABLE 1: Long-term injection well history.

Period	Average Injection m^3/mo	Total Injected Water – m^3
Feb 60 – Sep 61	1,850	37,000
Aug 63 – Nov 64	3,420	54,700
Jul 67 – Oct 68	3,830	61,200
Dec 68 – Apr 70	1,583	26,900
Apr 01 – Sep 01	6,334	39,000

TABLE 2: Injection well pulsed injection period.

Month	Max Inject. Rates (m^3/day)	Min Inject. Rates (m^3/day)	Monthly Injection Rate (m^3/month)
April-01	304	76	6,540
May-01	330	14	5,679
June-01	335	137	7,378
July-01	344	129	7,421
August-01	297	80	6,346
September-01	354	0	4,641

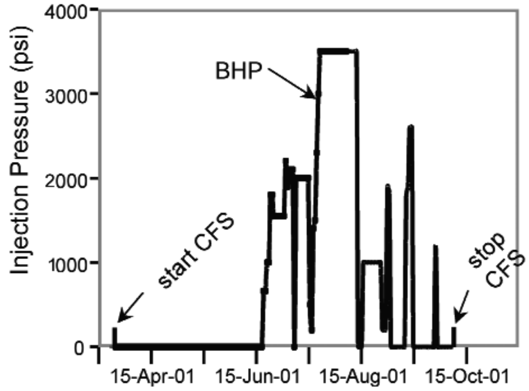


FIGURE 13: Surface injection pressure for CFS injection well.

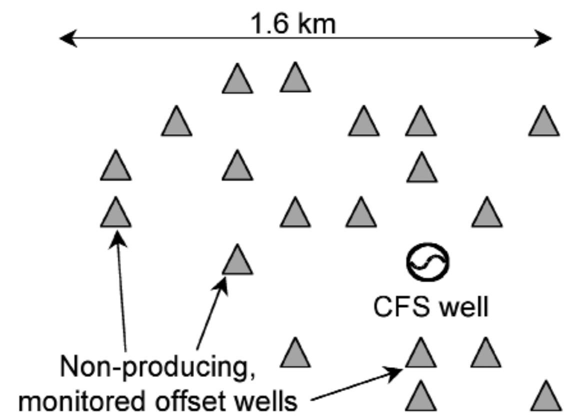


FIGURE 14: Wells drilled in the Lone Rock area.

between April and September 2001. (The rate for September is low because of intermittent injection during this period.) The pulsing device was specifically designed for this project and the long run-time bodes well for future implementation. The overall average of 6,334 m^3/mo was sustained with only one three-day shutdown for mechanical reasons (hydraulic seals). During the study, there were several occasions when the water volume supplied was insufficient to allow for a full day of pulsing.

Apparently, pulsing during injection increased the injectivity of this well by a factor of two, showing that pulsing also has interesting applications in increasing the capacity of injection wells.

Injection Pressure

Surface injection pressure for the CFS injection well are presented in Figure 13. An increase in injection pressure at the wellhead was noticed on June 20, 2001, after ~19,500 m^3 of pulsed injection H_2O over three months. Larger fluid volumes could have been injected during the first three months had greater volumes of water been available.

Injection pressures reached a plateau at 3,500 psi one month after initial pressurization was noted. This is the maximum injection pressure, and perhaps hydraulic fracture was taking place in the formation on each pulse. This means that less energy was available for the generation of porosity dilation waves, but this was probably compensated for by the overall increase in energy input.

Offset Well Behaviour

Wells in this field were drilled on a 4 hectare (10 acre) spacing (Figure 14). Except for one producer, the surrounding offset wells were shut in at the time of pulsing, although currently (early 2003) some of them are being rehabilitated. Annulus fluid levels were collected with an acoustic fluid level device that has an accuracy of about 10 m, and the results showed a small average head increase of ~6 m (~56 kPa) that was rising at the time excitation was ceased at about 10 kPa per month (remember that this was a severely depleted field with a bottom-hole pressure less than 300 kPa, even in wells that had been shut in for 40 years). Although this value is less than had been hoped, it is a 17% increase in pressure in the massively depleted reservoir, suggesting that pulsing effects are propagating a great distance from the excitation well. In such reservoirs, because of the huge viscosity contrast between the natural and the injected fluids, intense channeling and viscous fingering usually occurs, and some wells are affected by injection while others are not. With pulsing, it appears that a more general and homogeneous pressure increase can be achieved around the injection well (which includes better conformance, less by-passing of water fingers).

Success or Not?

Until more wells are placed on production and the history is collected for some time, it is impossible to determine whether the pulsing increased the oil production rate in the offset wells in which pressure increases were observed. This should be possible in several years time, once more wells have been rehabilitated, but even in this case it will be contentious to attribute improvements to the pulsing, to the recompletion and workover procedures, to the effects of water injection alone, or to the new lifting technology (PC pumps instead of reciprocating pumps). However, theory and previous experience show that pulsing dynamic stimulation is most effective when there is a substantial gradient of pressure, and in the absence of such a gradient, flow rate improvements are impossible to evaluate. Thus, the issue of whether pulsing improved (or will improve) oil rates must remain unresolved in the Lone Rock case.

However, the original goal was to increase the injectivity of the water injection well, which was achieved. In fact, the oil company acknowledges that pulsing the water injection well has achieved:

- Injectivity levels that could not be achieved in previous episodes;
- A modest but widespread increase in fluid pressure; and,
- A homogeneous increase in pressure in surrounding wells, rather than intense channelling of injected liquids.

The excitation system, consisting of an electrically-driven hydraulic pump actuating a mechanical-hydraulic stroking device at the well bottom by lifting the entire tubing string, worked for six months with only one mechanical problem.

Lone Rock is an unusual case. It has had an exceptionally long history of exploitation, and the initial pore pressures have been drawn down to the point where only 200 – 300 kPa BHP is acting, even though > 90% of the original oil is still in the reservoir. Low shut-in pressure is not recovered if the wells are left static. In some wells that were abandoned decades ago, the pressure on reopening was the same as the pressure at shut-in. This indicates no natural recharge and almost complete depletion. Also, communication with any non-depleted regions of solution gas is so slow that it cannot be achieved in engineering time scales. Thus, the non-thermal production options seem limited to waterflood while trying to reactivate gravity drive effects and communication with extant pressure, using pulsing to aid and enhance flow.

We optimistically believe, based on our other experiences in heavy oil in high porosity sands, that economically successful revitalization of production from Lone Rock can be achieved with excitation wells, and would recommend that a number of wells be placed on excitation, perhaps a ratio of one in eight, so that no producing well is farther from an excitation/injection well by more than two well spacings.

Closure

Pressure pulsing in three heavy oil field-wide stimulation trials has achieved economically interesting results in circumstances where other techniques had become ineffective. A reliable tool for the long-term application of frequency- and amplitude-tailored pulses to the liquid phase in a reservoir was developed and has proven reliable. The beneficial effects of pressure pulsing are largely related to the generation of long wavelength displacement waves (porosity dilation waves) that bring dynamic energy to the liquids at the pore scale, helping overcome barriers to flow and re-establish drive energy sources.

The results generated from these field trials and our continuing research could dramatically change production in heavy and light oil deposits. On-going laboratory experiments and theoretical considerations indicate that this approach could suppress viscous fingering and can be used as a means of stabilizing waterfloods to reduce coning and early breakthrough. However, further work is required before these assumptions can be confirmed.

Acknowledgements

We thank Wascana Energy Inc. (now a division of NEXEN Inc.), including Richard Kerr, Shane Freeson (now with Husky Energy), and the operations group from the Morgan Battery for providing the opportunity and support to demonstrate this novel oil recovery technique. As well, we thank David Schwarz and Samir El-Sayed who were instrumental in the development of the field trial. We also thank the Alberta Oil Sands Technology and Research Authority (now the Alberta Energy Research Institute) for their support.

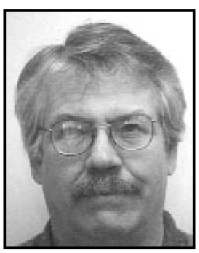
REFERENCES

1. DE LA CRUZ, V., SAHAY, P.N., and SPANOS, T.J.T., Thermodynamics of Porous Media; *Proceedings of the Royal Society of London, 443, pp. 247-255, 1993.*
2. SPANOS, T.J.T., UDEY, N., and DUSSEAULT, M.B., Completing Biot Theory; *proceedings 2nd Biot Conferrence on Poromechanics, Grenoble France, Balkema, Rotterdam, pp. 819-826, August 2002.*
3. HICKEY, C.J., SPANOS, T.J.T., and DE LA CRUZ, V., Deformation Parameters of Permeable Media; *Geophysical Journal International, 121, pp. 359-370, 1993.*
4. GEILIKMAN, M., SPANOS, T.J.T., and NYLAND, E., Porosity Diffusion in Fluid Saturated Porous Media; *Tectonophysics, 217, pp. 111-115, 1993.*
5. DOLINŠEK, J., BHARATAM, J., DUSSEAULT, M.B., and PINTAR, M.M., Two-Dimensional NMR Study of Surface Water Dynamics in Hydrated Silica Spheres; *Physical Review B, 58, pp. 7340-7346, November 1998.*
6. NIKOLAEVSKIY V.N., LUPUKHOV G.P., LIAO Y., and ECONOMIDES M.J., Residual Oil Recovery with Seismic Vibrations; *SPE Production and Facilities, pp. 89-95, May 1996.*
7. BERESNEV I.A. and JOHNSON P.A., Elastic Wave Stimulation of Oil Production—A Review of Methods and Results; *Geophysics, 59, pp. 1000-1017, 1992.*
8. DAVIDSON B.C., DUSSEAULT M.B., and SPANOS T.J.T., Comments on the Mechanisms Responsible for Pressure Pulse Enhancement of Fluid Flow in Oil Reservoirs; *PE-TECH Inc. Internal Document, 1997.*
9. SPANOS, T.J.T., The Thermophysics of Porous Media; *CRC Monographs and Surveys in Pure and Applied Mathematics, Chapman & Hall (Boca Raton), 2001.*
10. HICKEY, C.J., EASTWOOD, J.E., and SPANOS, T.J.T., Seismic Wave Propagation in Oil Sands; *AOSTRA Journal of Research, 7, 67, pp. 67-81, 1991.*
11. DE LA CRUZ, V. and SPANOS, T.J.T., Seismic Wave Propagation in a Porous Medium; *Geophysics, Vol. 50, No. 10, pp. 1556-1565, 1985.*
12. DE LA CRUZ, V. and SPANOS, T.J.T., Thermomechanical Coupling During Seismic Wave Propagation in a Porous Medium; *Journal of Geophysical Research, 94, pp. 637-642, 1989.*
13. WANG, J., DUSSEAULT, M.B., DAVIDSON, B.C., and SPANOS, T.J.T., Fluid Enhancement Under Liquid Pressure Pulsing at Low Frequency; *Proceedings of the 7th Unitar International Conference on Heavy Crude and Tar Sands, Beijing, People's Republic of China, October 1998.*
14. ZSCHUPPE, R., Pulse Flow Enhancement in Two-Phase Media; *M.Sc. Thesis, Department of Earth Sciences, University of Waterloo, 2001.*
15. DUSSEAULT, M.B., GEILIKMAN, M.B., and SPANOS, T.J.T., Mechanisms of Massive Sand Production in Heavy Oils; *Proceedings of the 7th Unitar International Conference on Heavy Oils and Tar Sands, Beijing, People's Republic of China, p. 14, 1998.*
16. BIOT, M.A., Theory of Propagation of Elastic Waves in a Fluid Saturated Porous Solid, I, Low-Frequency Range; *Journal Acoustical Society of America, Vol. 28, pp. 168-178, 1956a.*
17. BIOT, M.A., Theory of Propagation of Elastic Waves in a Fluid Saturated Porous Solid, II, Higher-Frequency Range; *Journal Acoustical Society of America, Vol. 28, pp. 179-191, 1956b.*
18. GASSMANN, F., Uber die elastizitat poroser medien; *Vierteljahresschrift d. Naturf. Ges. Zurich, 98, pp. 1-24, 1951.*
19. DUSSEAULT, M.B., SPANOS, T.J.T., and DAVIDSON, B.C., A Dynamic Pulsing Workover Approach for Wells; *proceedings of the 10th European Improved Oil Recovery Symposium, EAGE, Brighton, August 1999.*
20. DUSSEAULT, M.B. and EL-SAYED, S., CHOP—Cold Heavy Oil Production; *proceedings of the 10th European Improved Oil Recovery Symposium, EAGE, Brighton, August, 1999.*
21. DUSSEAULT, M.B., SHAND, D., and DAVIDSON, B.C., Pressure Pulse Workovers in Heavy Oil; *paper SPE 79033, proceedings of the SPE International Thermal Operations Conference and Heavy Oil Symposium, Calgary, AB, November 2002.*
22. DUSSEAULT, M.B., SHAND, D., MELING, T., SPANOS, T., and DAVIDSON, B.C., Field Applications of Pressure Pulsing in Porous Media; *Proceedings of the 2nd Biotechnology Conference on Poromechanics, Grenoble, France, Balkema, Rotterdam, pp. 639-645, 2002.*
23. Centre for Frontier Engineering Research (C-FER); *Sand Production and Management Project Report (Industry JRV); Edmonton, AB, 2 Volumes, 1994.*
24. DUSSEAULT, M.B. and EL-SAYED, S., Heavy Oil Well Production Enhancement by Encouraging Sand Influx; *paper SPE 59276, SPE/DOE Improved Oil Recovery Symposium, Tulsa, OK, 2000.*
25. DUSSEAULT, M.B., SPANOS, T.J.T., and DAVIDSON, B.C., A New Workover Tool—Applications in CHOP Wells; *Proceedings of the Petroleum Society's 50th Annual Technical Meeting, Calgary, AB, paper 99-77, p. 11, 1999.*

Authors' Biographies

Tim Spanos received his B.A. in mathematics and physics from the University of Lethbridge in 1971. He subsequently completed a M.Sc. at the University of Alberta in 1974 on black hole dynamics in general relativity. His Ph.D., 1977, was in geodynamics at the University of Alberta, where he began working on geophysical fluid dynamics. This led to an Alberta Oil Sands Technology and Research Authority (AOSTRA) Post-Doctoral fellowship and an AOSTRA Chair in Physics in 1980 at the University of Alberta. His work has led to the prediction and subsequent commercial use of porosity waves. This theory, as well as his work on the seismic theory for porous media, multiphase flow in porous media and the thermodynamics of porous media, are summarized in the recently published book entitled *The Thermophysics of Porous Materials* published by CRC press in their Monographs and Surveys in the Pure and Applied Mathematics series.

Brett Davidson has over 15 years experience in the area of applied research and development, and commercialization. For the past five years Mr. Davidson has been the president and CEO of PE-TECH Inc. (now E_2 Solutions Inc.) bringing the novel fluid flow technology "Pressure Pulsing" to market. Prior to PE-TECH, Mr. Davidson founded and managed a consulting company that provided technical services in the civil, environmental, and geotechnical disciplines with specific concern regarding salt rock mechanics. In addition, Mr. Davidson holds a technologists diploma in geotechnical engineering and is certified by the Ontario Association of Certified Engineering Technicians and Technologists.



Maurice Dusseault is a professor of geological engineering in the Earth Sciences Department, University of Waterloo, Waterloo, Ontario. Mr. Dusseault spent three years as a roughneck and drilling mud technician, prior to completing a B.Sc. (1971) and Ph.D. (1977). In 1977, he was awarded a five-year research chair at the University of Alberta funded by the Alberta Oil Sands Technology and Research Authority. In 1982, Professor Dusseault became chairman of the Geological Engineering Program at the University of Waterloo, and was also director of the Porous Media Research Institute from 1995 to 2000. He carries out research in petroleum geomechanics, new production methods, and deep waste disposal. He has co-authored two textbooks and over 350 professional articles in conferences and journals, and also works with industry as a consultant and as an instructor in a series of short courses that he has developed.

Darrell Shand trained as a geologist at the University of Waterloo. Darrell has worked in the Porous Media Research Institute at the University of Waterloo conducting research for hydraulic fracture in soft weak rock, development of harsh environment cements, shale stability, and pressure pulse technology. Darrell also has surveyed the transgression and regression of glacial lake shorelines in Northern and Southern Ontario for sand and gravel exploitation, as well as historical quaternary mapping. Currently with Prism, his duties include field implementation of monitoring instrumentation, data analysis, as well as design and implementation of improved recovery technologies for both the oil and environmental sectors.

Mahendra Samaroo received his B.Sc. in earth science from the University of Waterloo in 1999 while on leave from The Ministry of Natural Resources in Guyana. He currently works for a TRX consulting in Caracas, Venezuela.