

Pressure Pulsing at the Reservoir Scale: A New IOR Approach¹

JTJ (Tim) Spanos, Porous Media Research Institute, University of Alberta, Edmonton

Brett C. Davidson, PE-TECH Inc, Lloydminster Alberta

Maurice B. Dusseault, Porous Media Research Institute, University of Waterloo, Waterloo

Mohendra Samaroo, Formerly, Graduate Student, University of Waterloo, Waterloo

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ABSTRACT

An extensive series of laboratory tests on going since January 1997 demonstrate unequivocally that large-amplitude periodic excitation of porous media experiencing flow leads to large flow enhancements. These are not small improvements in rate, but are as large as a factor of 2 to 4. Based on these results, a new technical approach to enhancing fluid flow in reservoirs was formulated, and a full-scale field experiment in Alberta was initiated in December 1998.

The field trial successfully showed that periodic application of large amplitude excitation to a porous medium experiencing pressure gradient-driven fluid flow increased oil production rates, decreased produced fluid water content, and increased the percentage of sand produced.

The scope of potential applications to the extraction of conventional and heavy oils using primary and enhanced recovery methods is substantial. As well, PE-TECH's novel technology will stabilize viscosity-graded liquid floods, provide longer production times during cold flow production of heavy oils, and so on.

INTRODUCTION

The laboratory and field results obtained from our research and development over the past two years were predicted by the physical theory. Using volume averaging in conjunction with basic physical arguments, we have constructed a complete system of equations for low-frequency wave propagation. This system of equations has been shown to be consistent with the laws of thermodynamics in the component phases at the pore scale. They also yield large-scale thermodynamic relationships in which porosity is found to play a fundamental role, similar to that of temperature in single component systems. In other words, it has been proven that porosity is a basic thermodynamic variable, and that

induced variations in porosity are responsible for the flow rate enhancement effect. The physical theory dictates the experiments required determining the parameters that arise in the equations.

What are the potential consequences of this process for oil production? Properly executed in appropriate reservoir conditions, more oil can be induced to flow more rapidly to oil wells. Also, in the case of cold flow with sand production in heavy oils, fewer blockages and higher fluid rates can be expected.

NON-CONVENTIONAL EOR METHODS

During the 1970's, in Russia, earthquakes were observed to have affected the fluid levels in petroleum reservoirs¹. In most cases, the fluid levels were reported to have increased, leading to enhanced flow from the reservoir. It has also been observed that the water/oil ratio during an earthquake swarm may change¹. 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 underground fluid levels (water table and oil reservoir levels) in some areas². These observations led to the concept of seismic excitation enhancing the flow of (underground) fluids in porous media.

The concept of seismic excitation involves applying small strain excitation, of magnitude 10^{-10} to 10^{-6} , either at the surface above the reservoir, or underground within the reservoir. However, because of the high rates of amplitude attenuation and geometric spreading associated with the application of surface excitation, very high-energy sources would be necessary to apply sufficient energy to the reservoir³. In addition, according to the same authors, the low strains that are generated by seismic excitation makes it unlikely that enough strain energy would be generated to substantially affect fluid flows.

PRESSURE PULSE FLOW ENHANCEMENT

The physical theory used here predicts the concept of flow enhancement through pressure pulses. Conceptually, this prediction is based upon the existence of a tsunami-type (long period, low frequency, high-amplitude) wave within a viscous fluid-saturated porous media subjected to appropriate large-strain excitation. This wave should give rise to a synergetic build-up of internal pressure within the pores of the media, under conditions of constant hydraulic head. In addition to development of the porosity diffusion theory new empirical models describing the propagation of seismic waves in fluid-saturated porous media have also been constructed⁴.

The foundation of the theory led to an extensive series of laboratory experiments on-going since early 1997. In these experiments, various means of seismic and non-seismic excitation were applied to instrumented sand packs containing one or more fluid phases (i.e. a single phase, or a wetting phase and a more mobile non-wetting phase). The experiments were repeated with wetting and (constant head) mobile phases of varying viscosities and wettabilities, with the objective of obtaining systematic, repeatable flow enhancements of the mobile phase. In some experiments, the matrix was immobile, in others, the solid matrix was allowed to flow, simulating cold production (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 of up to several thousand percent.

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 unclear⁵. The mechanisms of this phenomenon were unclear 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. Seismic energy creates dynamic changes in the porosity of the porous media fluid, while fluid viscosity is an important factor in determining the dynamic behavior of the contained fluid under seismically induced stress. The interactions and deformations between the fluid and solid matrix in the porous media also

result in a porosity diffusion wave, a slow strain wave that is not predicted by conventional seismic equations.

Porosity diffusion refers to a spreading front of porosity that accompanies a traveling pulse of pressure generated within a fluid saturated porous media. It is the physical process responsible for the increase in fluid levels within the earth associated with seismic events such as earthquakes. Prediction of the porosity diffusion wave velocity and characteristics requires a physically correct and representative model of wave propagation within a deformable fluid saturated porous medium. A summary of the associated theory underlying the porosity diffusion wave 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 predicts the existence of one P (neglecting thermal effects) and one S wave (i.e. one compressional and one shear wave), it does not allow for attenuation and the waves are non-dispersive. Attenuation is usually compensated for in this single-continuum model by allowing the wave number to become a complex. 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.

A brief synopsis of the two major applicable theories of wave propagation in fluid filled porous media will be given in the following sections. These two theories are the conventional (Biot) wave propagation theory and the pore recent multi-component (de la Cruz-Spanos) theory. Introduction to these two theories is necessary in order for the reader to understand the foundations of the porosity diffusion wave and the associated physical phenomena.

BIOT-GAUSSMAN POROUS MEDIA MODEL

The Biot and Gaussman models 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 the viscous dissipation associated with attenuation of seismic energy within the fluid-filled pores of the media. These models also assume that the state of energy within a porous

(multi-phase) medium can be represented by a single energy potential eliminating porosity as an independent dynamic variable.

de la CRUZ-SPANOS POROUS MEDIA MODEL

The de la Cruz and Spanos model utilizes volume averaging in conjunction with physical arguments to construct the macroscopic continuum equations that describe wave propagation in a fluid-filled porous medium. This model includes:

- Porosity as a dynamic variable which plays a fundamental role in both the thermomechanics and thermodynamics of the porous medium.
- Thermomechanical coupling (first-order heating of the phases from compression and expansion of the phases due to heating and cooling or due to pressure changes). This theory is developed by imposing the microscopic boundary conditions of no slip, continuity of stress and continuity of heat flux to the following equations:
 - Equations of motion for a fluid;
 - Equation of motion for an elastic solid;
 - Continuity equation for a fluid;
 - Continuity equation for a solid;
 - The solid heat equation; and,
 - The fluid heat equation

Assuming a porous medium composed of pores of random size and orientation, but macroscopically homogeneous and isotropic enabled the use of volume averaging principles for specific parameters. By assuming a plane wave solution the resulting dispersion relations for S and P waves have been constructed. This resulted in four P waves and two S waves, whose phase velocities and attenuation are frequency dependent.

The resulting model consists of coupled, first order macroscopic equations which describe wave propagation in

porous media saturated with a single viscous compressible fluid. These equations are:

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

Equation 1

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

Equation 2

$$\rho_s c_v^s \frac{\partial \bar{T}_s}{\partial t} = T_0 K_s \alpha_s \left[\frac{1}{1-\eta_0} \frac{\partial \eta}{\partial t} - \frac{\partial \nabla \cdot \bar{\mathbf{u}}_s}{\partial t} \right] + \kappa_s \nabla^2 \bar{T}_s + \frac{\gamma}{1-\eta_0} (\bar{T}_f - \bar{T}_s)$$

Equation 3

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

Equation 4

$$\frac{\partial \eta}{\partial t} = \delta_s \nabla \cdot \bar{\mathbf{v}}_s - \delta_f \nabla \cdot \bar{\mathbf{v}}_f \quad \text{Equation 5}$$

Where:

- c_p^f is the specific heat, at constant pressure, of the fluid (i)
- c_v^s is the specific heat, at constant volume, of the solid (i)
- f is frequency
- k is wave number
- K is permeability (ii)

- K_f is bulk modulus of the fluid (i)
- K_s is bulk modulus of the solid (i)
- K_d is bulk modulus of drained material
- K_u is bulk modulus of undrained material
- $\bar{\mathbf{u}}_s$ is the macroscopic solid displacement vector
- $\bar{\mathbf{u}}_f$ is the macroscopic fluid displacement vector
- $\bar{\mathbf{v}}_f$ is the macroscopic fluid velocity vector
- $\bar{\mathbf{v}}_s$ is the macroscopic solid velocity vector
- V is averaging volume
- T_s is macroscopic temperature in the solid
- T_f is the macroscopic temperature in the fluid
- T_0 is the ambient temperature of the porous medium (ii)
- α_f is the thermal expansion coefficient for the fluid (i)
- α_s is the thermal expansion coefficient for the solid (i)
- δ_s is the solid dilation factor (ii)
- δ_f is the fluid dilation factor (ii)
- η_0 is the static porosity
- η is the dynamic porosity
- γ is the surface coefficient of heat transfer (ii)
- κ is the effective thermal conductivity across solid-fluid interfaces
- κ_f is the thermal conductivity of the fluid (i)

- κ_s is the thermal conductivity of the solid (i)
- μ_f is the viscosity of the fluid (i)
- μ_s is the shear modulus of the solid (i)
- ρ_s is density of the solid (i)
- ρ_f is density of the fluid (i)
- ρ_{12} is the induced mass coefficient (ii)
- ξ_f is the bulk viscosity of the fluid

Equations 1 and 2 represent the forces acting on macroscopic elements of the interacting continua while equations 3 and 4 represent the heat flow in the coupled continua. Equation 5 represents the dynamic interaction between relative proportions of solid and fluid constituents and the porosity during a transient compression in the volume element.

These equations include both microscopic and macroscopic parameters. Microscopic parameters are those which are solely dependent on the solid phase or solely on the 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) above. The variables in equations 1 to 5 are η , $\bar{\mathbf{u}}_s$, $\bar{\mathbf{u}}_f$, T_s and T_f , since $\bar{\mathbf{v}}_s$ and $\bar{\mathbf{v}}_f$ are simply the time derivatives of $\bar{\mathbf{u}}_s$ and $\bar{\mathbf{u}}_f$.

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 generally an easily determined quantity and is

a constant. This property can easily be determined 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 and is easily determined for single-phase fluid flow. In the case of a well-connected porous medium with no macroscopic structures, the permeability parameter (K) represents relative first-order velocities between the fluid and the solid continua, and 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, subject to the frequency-wavelength constraints imposed by 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 and for quasi-static processes can be determined from the undrained bulk modulus and a drained bulk modulus.

The Porosity Diffusion Wave: The de la Cruz-Spanos porous media model was simplified by neglecting all inertial terms and considering the fluid to be essentially incompressible⁵. The incompressibility of the fluid constraint is satisfied if the velocity of flow of the liquid is much less than the velocity of sound in the fluid. These equations were further manipulated to yield⁵:

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

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

Equation 6

Where M_{ik} is the seismic moment tensor

D is the porosity diffusion coefficient

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

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

This equation represents the dynamic porosity as a function of the seismic moment applied to a fluid saturated porous media.

The above expressions were further analyzed to derive an expression for the pressure regime within a fluid saturated porous medium subjected to a quasi-static stress⁶. 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 $\mathbf{r} = (x, 0, z)$

$$\rho_f(x, z; t) \approx \frac{\mu_s b S}{10\pi\eta_0 (Dt)^{3/2}} \frac{n_x n_z}{\sqrt{\pi/p^2 + 2/3} \rho^3}$$

Equation 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. They concluded that this expression shows that a pulse of pressure propagates from a fracture source and the maximum value of this pressure travels as $r_m \propto \sqrt{Dt}$ and decreases in amplitude as $(Dt)^{-3/2}$. The traveling pulse

increases pore pressure for a brief time within the fluid filled pores of the porous media and causes pore dilation, leaving behind a permanent (plastic) change in porosity. This results in a diffusional front that causes a variation in porosity to spread from the point of failure. The change in porosity can be positive or negative, depending on the direction of the two basic vectors of the fracture source: \mathbf{b} and \mathbf{n} . Over time, this failure leads to 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 traveling pulse of pressure and a spreading front of porosity may also cause secondary fractures, aftershocks and lead to the interaction of earthquakes⁵.

More recently the dynamic limit of incompressible fluid motions has been studied. In this case one obtains a tsunami like wave which is predicted to move at speeds of approximately 10 m/s in heavy oil reservoirs. 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.

FIELD TRIAL

Since pressure pulsing had proven to be a success at a laboratory scale, the next logical step was to investigate the effects of field-scale heterogeneities, geometric spreading and attenuation on porosity diffusion in a heavy oil reservoir. The apparent success of the workover method based on pressure pulsing (see companion article), combined with theoretical considerations that predicted beneficial effects at the reservoir scale for continuous pulsing, a field project was planned. The technology group at Wascana Energy Inc. agreed to participate in the field trial. The field trial envisaged the application of long-term pressure pulse stimulation to the center well in a pseudo five-spot pattern, while monitoring downhole microseismic, pressure and fluid production data from all wells on a section.

The main requirements for the location of this field trial was that the reservoir should still be reasonably intact, not having been subjected to thermal methods, or chemically conditioned or altered in a way that would introduce a number of unknown variables in the experiment. Also, to be considered a candidate reservoir certain criteria had to be met.

These included not massively depleted, low free gas content, reasonably high permeability, and the pulse and monitoring 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 to allow unimpeded migration of pressure effects between wells.

Had there been a history of excessive sand production from the pulsing well, it would have generated a large yielded zone that could potentially result in very high attenuation of the pressure pulses within that yielded region due to high dissipate effects. This would result 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 lead to the pulsation energy being used to compress gas, resulting in low energy transfer rates to the liquid phase around the wellbore and, consequently, a delay in 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 gas shock absorber. In this case, continued liquid injection and pulsing would have to continue until such time that the formation pressure gradually started to increase, at which time the free phase gas content would progressively dissolve. Under such conditions pressure pulsing related effects would not be seen at monitoring wells until the free phase gas has been substantially driven back into solution (re-dissolved in the oil phase). While driving gas back into solution might eventually provide enhanced gas (foamy oil) drive during post-pulsing production, elimination of gas-related effects would increase the probable detection of beneficial pressure pulsing effects at monitoring wells within a shorter time frame.

Taking into consideration these prerequisites and the options available Wascana Energy chose a mature field

location for field-scale experiment. The location consisted of nineteen 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.

RESERVOIR SETTING OF THE SECTION

The wells within this Section exploit mainly the Sparky Sands, while some wells are also perforated in the Lloydminster and Cummings Sands. A geological interpretation from well logs of the setting of the Sparky Reservoir in Section indicates that the geologic attitude of the reservoir is relatively flat within the Section. The average thickness of the Sparky Sands range from a maximum of about 7-metres at the location of pulse well to a minimum of about 1-metres on the eastern and southern regions of the section. Sand pinch-out conditions in the eastern and southern extremities of the Section are suggested by the thickness trend of the Sparky sands within this region. Original in-situ oil saturation in the Sparky Sands within the Section averages 90%.

PULSE GENERATION

Since the pulse tool designed for workovers (see companion paper) was designed for short-term pulsing, a long-term field trial required an automated design. The chosen design was hydraulically operated and analogous in operation to a submersible variable displacement pump. The downhole assembly of this tool was comprised of a stationary section attached to the end of the production tubing and a moveable section attached to the (pump rotor) rods. The stationary section was composed of a polished barrel with fluid inlet and outlet ports and a waterproof compartment containing an instrumentation package, on the lower end. A mechanically operated gas release valve was incorporated into the top section of this unit. This gas relief valve was mechanically opened during the upstroke stage of the pulse tool and this allowed any gas accumulated in the pulse barrel to escape. (Gas trapped within the pulse barrel of the tool would dampen the pulse stroke and absorb energy without transferring the energy to the fluid.)

The moving section of the downhole assembly consisted of a boronized piston, designed to travel inside the polished

barrel, and attached to the pump rotor rods. The uphole assembly of the pulse tool consisted of a hydraulic cylinder (designed to lift and dampen or stop the fall of the rod and barrel assembly) and a hydraulic pump to provide fluid pressure to operate the mechanism. A Temposonics programmable limit switch interfaced with an LVDT controlled the pulse tool. The programmable limit switch controlled rod travel length within the hydraulic cylinder as well as the various solenoid valves, which regulated and guided the hydraulics required for safe and effective operation of the pulsing mechanism. The rate of rise and fall of the pulse tool could also be controlled by the adjustment of the control valves.

The pulse tool had a piston diameter of 6.985 cm and a maximum safe travel-distance of 157.48 cm, generating an effective fluid displacement of 0.006032 m³/stroke (6 liters/stroke).

MONITORING

Monitoring during the period of the field trial consisted of the collection of production-related data, downhole pressure and microseismic data from two functional monitoring sites and data from the pulse well. Production related data was comprised of the following:

- 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 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 triggers of magnitude above the average background noise and continuous eight-minute averages of the background noise. 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 was 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. Applicability 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 essentially operating under similar conditions to those prevalent during the test period. Re-perforation of the wells, seasonal environmental changes, changes in the (regulated) casing gas pressure and changes in pump rotational speeds are some of the factors that directly influence the quantity and composition of fluid produced from the well. Changes in any of these factors would change the amount of fluid being produced from the well. Thus, in order to obtain an unbiased comparison, the immediate pre-pulsing production period for a well is used as the background for that well. A comparison of the post-pulsing period for each well to that well's production history was also made. However, the historical water cuts and daily gas vent rates (produced by Wascana) are taken at irregular intervals ranging from monthly to every two to three months. It was observed that the monthly averages recorded in the production history are actually interpolated from the previous measurements or estimates, and thus may not be representative of the actual production history of the well.

Where applicable, baseline (pre-pulsing) production-related data trends are determined by fitting logarithmic trendlines to the data generated during both the pre-pulsing and post-pulsing periods.

Since oil is a finite natural resource, natural long-term oil production tends to decrease unless new reserves are tapped or other fluid drive mechanisms are provided within the reservoir (i.e. the introduction of new energy). Wells that have been on production for an extended period would show this trend,

especially in the shallow low-pressure reservoirs that are typical of the heavy oil industry. Long-term oil production therefore would thus show a decreasing trend. In the case of reservoirs containing water below or above the oil pool, reduction of the in-situ oil saturation and various coning and fingering phenomena would increase water flow rates to the well over time. Consequently, a progressively increasing water-content of the produced fluid over the production history of the production well would be observed. While initial sand-rates could be as high as 30%-40% of the initial liquid volume, steady state sand production ranges to a maximum of about 10% (0.25 to 10%, depending on oil viscosity) unless interrupted by a⁷.

Relevant background total-fluid production for the wells in the Section consisted of fluid production for each well during the period where all the known production was essentially the same as that of the test period. However, since this is an impossible task, two baselines were chosen. These are the production history for the wells from the date of their last re-completion or significant change (in the physical layout that would affect their ability to produce fluid), and the immediate pre-pulsing two-month period. This period is considered since it enabled the collection of additional field production data, monitoring of the field operational variables and principally because it portrayed the (current background) production trend of the wells immediately prior to the initiation of the reservoir-scale pulsing experiment. Consideration of this immediate pre-pulsing background trend of the wells is important for determination of the pre-pulsing background status of the wells. Since the reservoir is dynamic, and tends to follow the natural (expected) trends outlined above, this background period is considered reasonable. These data are used for comparative purposes, since uncertainties about the production methodologies, environmental variables and the natural reservoir tendencies eliminate use of the historical data.

Background BS&W data used were derived from Wascana Energy's records. Base sediment and water composition (BS&W) is the generic name attributed to the total percentage of both water (both free and emulsified)

and sand contained in the produced fluid. Some of this data is obtained from truck transportation tickets. These records quantify volumes of water, oil or sand removed from the stock tank. However, the stock tank is a 120-m³ vessel with fluid withdrawal taps at intervals corresponding to approximately 30-m³ 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 generates inconsistencies in the BS&W cuts generated therefrom, since the stock tank acts as a buffer zone and no records are maintained of the opening and closing inventories of the fluid composition within the tank.

Wherever possible, logarithmic trendlines have been fitted to all of the data obtained. This was done in order to identify the dominant trend in the data being analyzed, since most of the data obtained is semi-chaotic. The logarithmic trendlines are logarithmic averages of the production data over time and are considered adequate representations of the data generated since they provide an unbiased estimate of the production trends. The dominant trends existing in the data collected during the pre-pulsing period were plotted separately and the equations for the trendlines determined. This was also done for the data generated during the post-pulsing period. These equations were then used to plot the production trend for the duration of the field experiment.

The production and workover history for each well was also obtained and this information was used to plot the monthly production history 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 (by a simple arithmetic average) and used to update the production history of the well to include the pulsing period.

RESULTS

As stated, the generation of a porosity-diffusion wave in a fluid saturated porous medium would result in radial propagation of that wave into the medium, until attenuation effects consume all of its energy. However, since the magnitude of the attenuation effects of the reservoir was unknown, the extent of the radial zone of influence of applied pressure pulsing period was also unknown. We maintained

that constant pressure pulsing would generate regular, periodic porosity-diffusion waves that would influence not only the instrumented monitoring within the pseudo five-spot pattern, but also all other wells within the same producing zone on the Section.

This hypothesis was supported by the data. Over the duration of the field trial significant changes in cumulative oil production, and base sediments and water were seen. Overall, oil production on the Section increased by about 37%, and water cuts were lowered in some cases by over 20%. Sand cuts increase from an average of 0.5-1% to between 4-10%. This is probably an indication of increased fluid gradient across the intact reservoir-crumbling sand boundary, increasing the sand destabilization mechanisms within the reservoir and is likely to be one of the mechanisms responsible for increased production within the Section. It should be noted that prior to pressure pulse stimulation at the field scale it was postulated that given the history and age of the wells, and the device used to generate pulses, a 30% to 40% increase in oil production would be observed. The results therefore were quite satisfying.

Pre-pulsing and post-pulsing trendlines for selected observation wells are presented in below.

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 shows no production. Pre-pulsing oil production rates for November 98 showed a decreasing trend. However, post-pulsing oil rates showed an increasing trend, and the oil production rate for February 1999 was the highest the well has ever experienced in the past eight years of its productive history.

The pre and post-pulsing fluid production trends for this well show that total pre-pulsing fluid production for this well was declining at a rate of approximately 0.041 m³/day. Pre-pulsing BS&W show that this was increasing at a rate of approximately 0.031%/day, which equates to the declining oil cuts observed. Post-pulsing total fluid-production rates, however, show an increasing trend of

approximately 0.041 m³/day, which is the same value as the pre-pulsing trend, but of 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% /day. This is shown in Figure 1.

Observation Well 2

A review of the pre-pulsing and post-pulsing total fluid production rates for this well indicated that the pre-pulsing fluid production was decreasing at a rate of approximately 0.01 m³/day. Conversely, the post-pulsing fluid production rate was the mirror image of that trend increasing at approximately 0.01 m³/day. This represented a complete reversal of the pre-pulsing production trend. Comparison of the post-pulsing oil cuts and oil production 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. This is shown in Figure 2. Oil production and oil cut rates decreased by approximately 20% during early February 1999. However, the data considered for February-99 consists 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 the monitoring wells). This average is then used to derive oil cut for the well.

Observation Well 3

The pre-pulsing total fluid production trends for this well show that pre-pulsing total fluid production was decreasing at an average rate of 0.074 m³/day. Post-pulsing total fluid production showed a negligible decrease of approximately 0.005 m³/day. Pre-pulsing BS&W cuts based on truck tickets, were 19% while post-pulsing production rate increased to approximately 41.5%. The reasons for the increase in post-pulsing BS&W are uncertain. The pre and post-production data comparison plots for this well are shown in Figure 3.

Observation Well 4

The pre-pulsing fluid production rate for this well shows a decreasing fluid production trend of approximately 0.033

m³/day. Post-pulsing total fluid production shows a stabilization of production at about 0.003 m³/day. The pre-pulsing BS&W cut based on truck tickets, were approximately 26%. The post-pulsing BS&W cut for December 1998 based on truck tickets, 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 December 1998 and January 1999 are uncertain, the approximate commencement or rate of decrease of the BS&W is unknown. This well also sanded in for four days in January 1999 resulting in a workover and the 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. This is shown in Figure 4.

CLOSURE

Pressure pulse flow enhancement has been shown to enhance oil production on a reservoir scale. The main mechanisms for this production increase seem to be the reconnection of oil isolated ganglia, increase of the fluid gradient across the sand destabilization zone and a decrease in water content of the produced fluid (i.e. increase in oil cuts).

The results generated from this field trial and our continuing research could dramatically change production in heavy and light oil deposits. Future installations are the subject of discussion with several oil production companies at the time of writing. On-going laboratory experiments and theoretical considerations, indicate that this approach will suppress viscous fingering and can be used as a means of stabilizing waterfloods to reduce coning and early breakthrough.

Pressure pulse flow enhancement also holds potential in other areas including aquifer clean-up, groundwater extraction, fluidized bed reactors in the chemical industry, and slurry pipeline flow.

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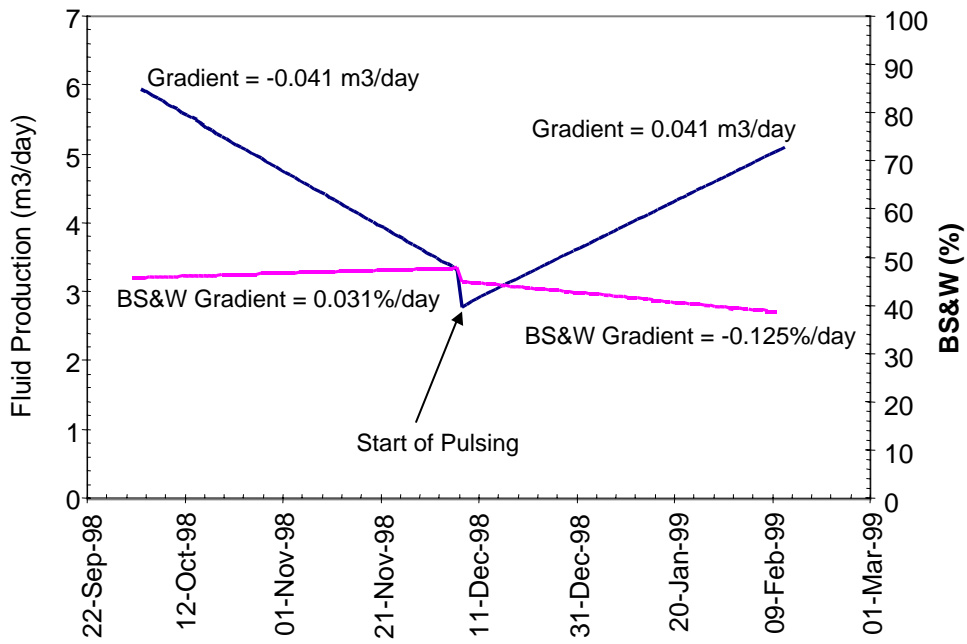


Figure 1: Pre and Post Pulsing Production and BS&W Trendlines for Observation Well 1

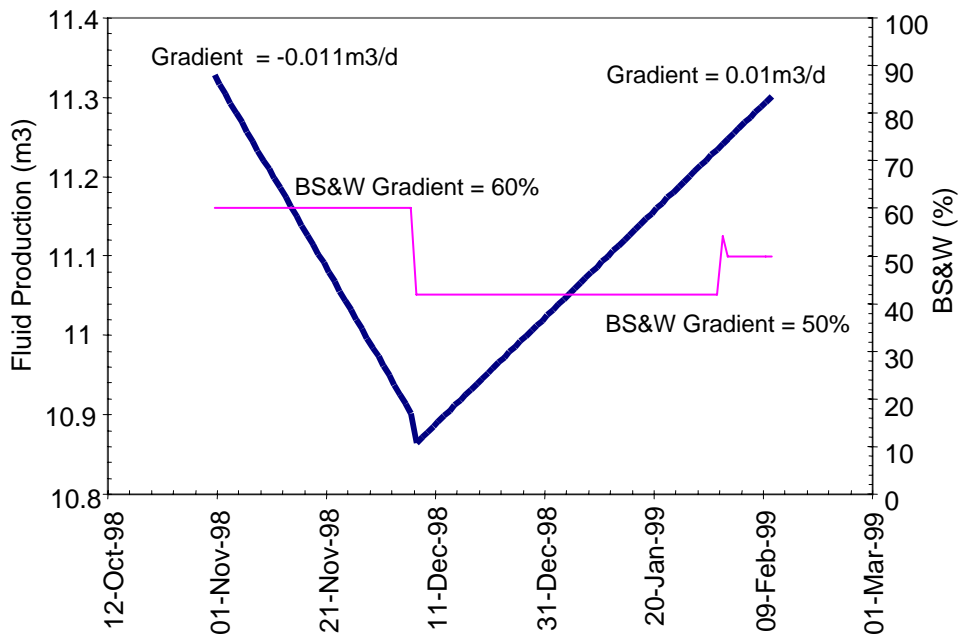


Figure 2: Pre and Post Pulsing Production and BS&W Trendlines for Observation Well 2

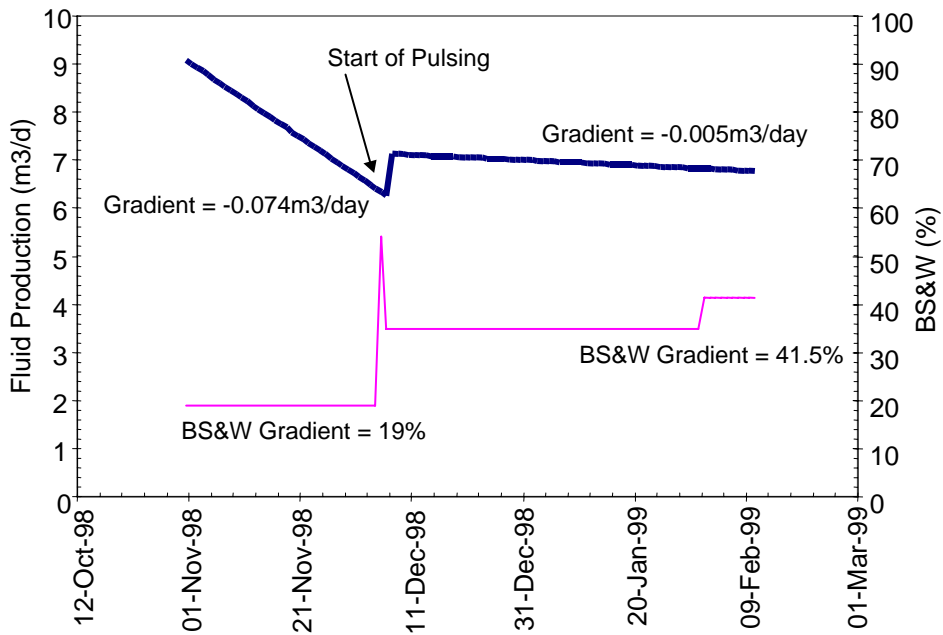


Figure 3: Pre and Post Pulsing Production and BS&W Trendlines for Observation Well 3

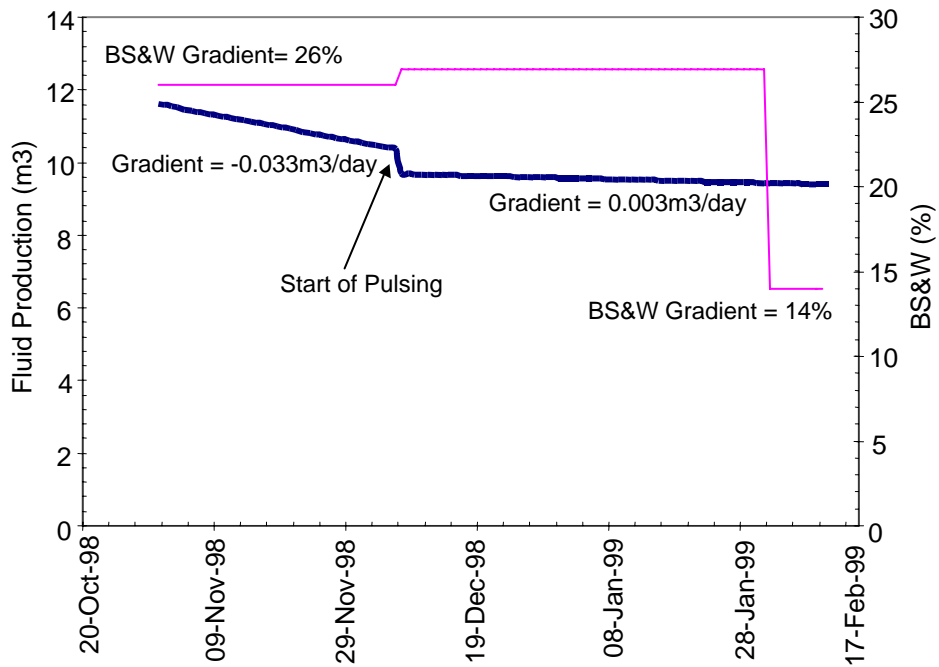


Figure 4: Pre and Post Pulsing Production and BS&W Trendlines for Observation Well 4