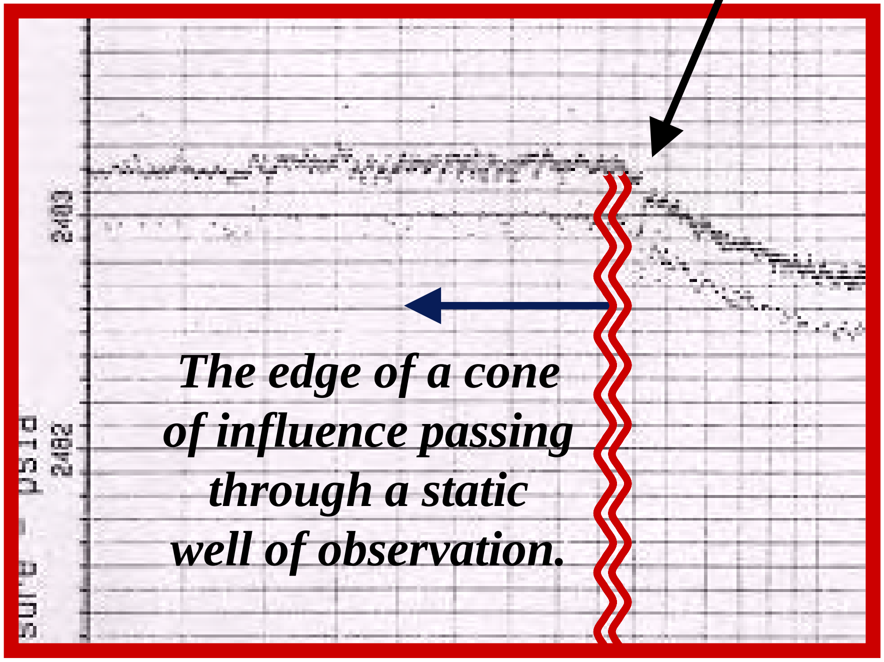
WAVEX®

Reservoir Dimensioning™

Technology Protected Under
U.S. Patent No. 6,041,017
Canadian Patent No. 2,263,466
European Patent No. EP 0 916 102 B1



SHOCKWAVE

The edge of a cone of influence passing through a static well of observation.

PRESSURE TRANSIENT ANALYSIS USING

"Capillary Shockwave Front Theory"

DR. FRED L. GOLDSBERRY, P.E., PRESIDENT

OFFICE: *(281) 397-7010*
CELL: *(832) 524-0810*
HOME: *(281) 893-7118*
E-MAIL: *wavex@sbcglobal.net*

WAVEX®, INC.
15314 Wilkshire Court
Houston, Texas 77069
www.wavexcorp.com

Bubble
Petroporokinekinetics©
Theory

WAVEX®

Reservoir Dimensioning

Catch the Wave

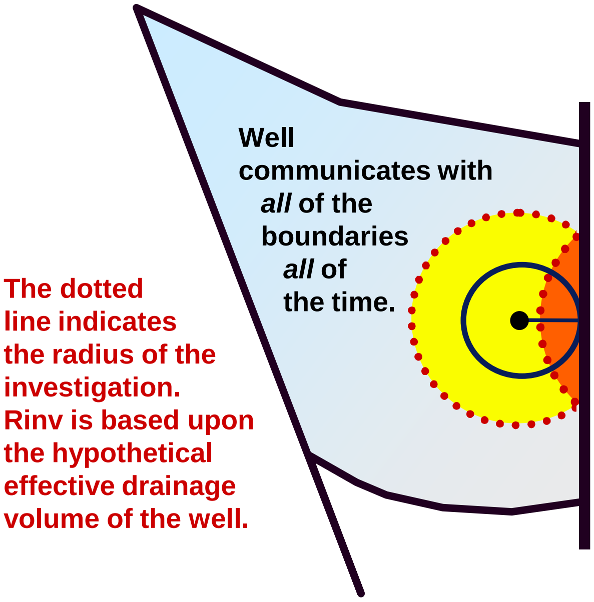
"BUBBLE THEORY™", or "Petroporokinekinetics©", is a proprietary method developed by **WAVEX®, Inc.** for pressure transient analysis of flow through porous media. The "Bubble" is an expanding "energy bubble" contained in the capillary shockwave front; the shockwave front exists at the "Radius of Investigation". Bubble Theory™ uses a model based upon boundary layer theory, wave mechanics, and thin film theory. The **WAVEX®** model was developed to explain discrete phenomena observed in pressure transient data.

WAVEX®, Inc. ***processes and analyses pressure data much like geophysical data.*** Our method is used to confirm reservoir geometry and volumes with unprecedented accuracy. We can also confirm the actual connectivity of 3D seismic map interpretations of a reservoir.

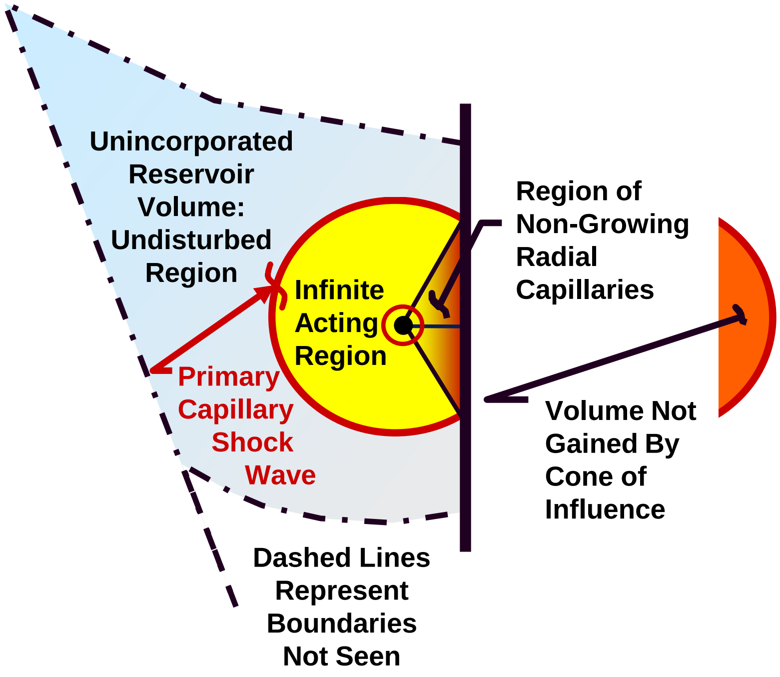
The traditional pressure transient analysis method yields a solution for distance to the first limit that is foreshortened by 62%. ◆Bubble Theory™ predicts correct distances to ***each*** limit! The **WAVEX®** method is used in conjunction with electric log data, core data, reservoir fluid composition data and constant pressure rate flow data to describe the fluids in place in the reservoir. ◆***Why develop an undersized uneconomic reservoir?*** ◆**WAVEX®** ***can book reserves sooner by confirming geologic maps limit by limit.*** ◆**WAVEX®** ***can directly confirm the hydrocarbon volumes in place.***

Time for analysis after assembling the basic data is approximately one week. The cost for an analysis is determined by time, the number of wells, and number of pressure curves per well. **WAVEX®, Inc.** caps charges even though serial drawdowns and buildups may be analyzed. Time above this cap is considered to be R&D. We are looking for ***cost effective results***. Check with us for current rates.

Traditional Diffusion Model



WAVEX® Model



PRESSURE-TRANSIENT 3D IMAGING

Shockwave model reduces risk

A new well testing method calibrates the seismic reservoir image at a fraction of the cost

AUTHOR

Fred Goldsberry is president of WaveX Inc.

Reservoir imaging adds value to an oil and gas property. A new pressure analysis method generates reservoir dimensions, limit distances and point-of-contact shapes from a family of slow-moving capillary shockwave fronts as they pass through the reservoir at slow diffusive speeds. A byproduct of the process is a running integration of fluid volume in place as the test progresses. This integrated volume can be used to develop information as to relative limit positions. This is made possible by the recognition of capillary bundles as physically constraining conduits of flow growing from the well and terminating in a step pressure shock front that acts as a moving boundary. Using these naturally occurring wave fronts can enhance the traditional use of pressure transient analysis as an evaluation tool. Capillary shockwave front imaging also can be performed throughout the life of a gas well to monitor the movement of a gas/water contact. If the relative position of one of four identified limits changes in a gas well with regard to the other three, it is probably a moving gas/water contact, since the fixed boundary limits will remain the same. A gas well can be retested with every operational shut-in to monitor each limit individually.

Technical summary

A shockwave front exists coincident with the traditional radius of investigation = $2(\eta t)^{1/2}$. It becomes the boundary condition for the cone of influence during the transient phase.

The capillary forces that give rise to the shockwave also constrain flow through radial capillary pathways that have finite strength. An example of the bounding shockwave is shown in Figure 1. Many attempts were made to reconcile this data using different simulators. The breakthrough came with the recognition that capillary pressure was playing a major role in limiting the rate of growth of the cone of influence. This led to a constrained capillary model.

The combination of radial pathways and the shockwave boundary condition produce discrete responses at the wellbore that are the result of First and Second Law requirements for Joule-Thomson hydraulic power dissipation through heat generation. When a section of the shock front encounters a change in permeability, the system responds by creating a secondary drawdown region within the original cone of influence. It is this secondary cone behind its own secondary shockwave that indicates the presence of a limit. Limits are encountered individually as the test progresses. The increased rate of pressure decay at the wellbore signals a limit has been encountered. The intensity of the change in pressure decay signals the shape of the limit at the point of contact relative to a straight line. Each limit can be described by distance from the well and by a bent line shape of known angular displacement. This allows point-by-point comparison of features on a geologic map. All pressure-transient analysis is based upon the homogeneous property assumption. The assumption is that the more heterogeneous a formation is, the more likely it will behave in a homogeneous manner. The shockwave overlay example was generated by limits that represented a shift from 500 md rock to 25 md rock. Better stated, all pressure analysis is a view of the reservoir relative to the cylindrical volume of the reservoir material around the well investigated during the midtime or infinitely acting radial flow period. Major anomalies appear as distortions in the growth process. Leaking or nonsealing faults and shale islands have characteristic responses when viewed from the perspective of the advancing shockwave.

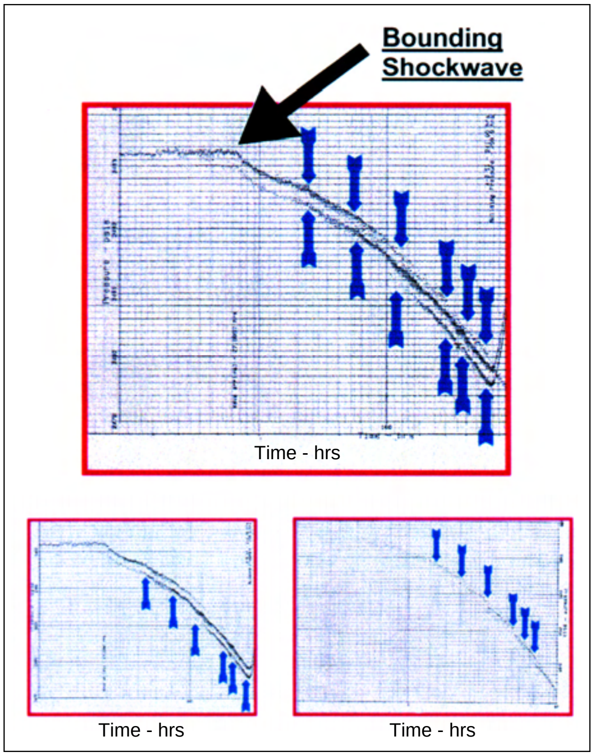


Figure 1.Constant flow rate test from two points of observation.

To reduce the capillary model to the traditional diffusion potential model, one only has to declare that all initiating pressures have broken down. A new physical model is traditionally placed in blind trials for evaluation. Every well test should be treated as an experiment. This requires that a best-fit geometric shape be developed without reference to a map. The blind geometric information can be compared with the geologic map to confirm its dimensional details both geometric and volumetric. Where the test and map differ, a reassessment of both studies can be focused upon the geologic aspect in question. For example, if a "blind" point-by-point assessment agrees on three out of four mapped limits, the efforts of the geologic engineering team can be focused upon the item in question. Often a question is raised as to whether a seismic feature is sealing. A transient test may be used to determine whether something changes at the

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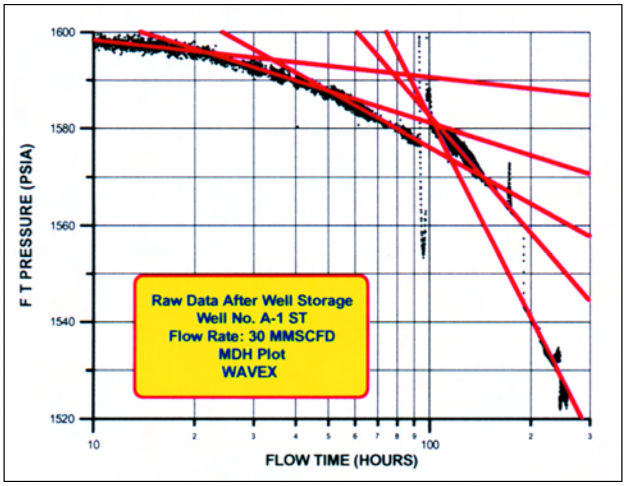

Figure 2. Well A-1 drawdown example.

radius of investigation for the feature in question. If the shock front passes through the feature with no corresponding response, it may not be material to the reservoir model. If reservoir continuity is in question, the use of overlapping tests may be used in lieu of a longer running interference test or an additional delineation well. In the case of transient reservoir models, each must be judged against a geologic and geophysical map and a track record of "blind" predictions.

Reservoir imaging

The use of 3D seismic has grown dramatically. This has resulted in much improved exploratory discovery ratios. However, as in all technologies, the new plateau of seismic technology is better than the old but remains imperfect. A comparable process that can explore the reservoir laterally from a wellbore is an excellent complementary technique.

Capillary shockwave fronts propagate from the wellbore when flow is initiated or a major rate change is imposed. These fronts are composed of many radial capillary pathways that grow coincident with the traditional radius of investigation. The small initiating capillary breakdown pressure that exists at each pore throat produces this physical phenomenon. The core laboratories have measured these pressure steps in the form of entry pressure and Haines' Jumps since their discovery in the 1940s. They have not been incorporated into transient reservoir models until now.

When these capillary ray clusters strike a reservoir boundary, they act in unison to provide specific information about that portion of the reservoir boundary. The capillary structure of the expanding cone of influence restricts the response of the system to reservoir limits in a radial isotropic manner. Fluid momentum stabilizes the cone of influence. When the cone encounters a limit, a secondary depletion region is formed around the wellbore to maintain the balances required by fluid momentum and the laws of thermodynamics. Because the system is composed of capillaries, each capillary acts much like a ray of light – a ray of light goes straight out and reflects off a boundary, while amplitude and frequency are factors of the boundary and its angle. A shape for each boundary contact can be developed to assemble an energy image of the reservoir that compares well with 3D seismic but at a fraction of the acquisition and interpretation cost.

In a process called pressure logging, the shock front capillary wave passes through the reservoir as Mother Nature's means for initiating flow. It is important to differentiate a capillary shock front from a sound wave. Sound causes the reservoir fluid and formation to vibrate. The shock front produces actual depletion. That is, the reservoir fluid moves from pore space to pore space, creating actual pressure decline. This pressure depletion wave is used to assess the reservoir volume, distance to limits and the point-of-contact energy equivalent shapes of those limits just as we would pull a resistivity logging tool across the face of a pay section to define its characteristics. This process is just as important as electric logging in early assessment of reserves. When a well is placed on production, it is possible to provide volume and reservoir dimensions that can be used to book reserves much faster than waiting for the production history to develop. In many cases, 2 days to 1 week of pressure data can tell the story. Small reservoirs test faster than large ones. The test duration is controlled by the volume required to assure a positive investment outcome or to confirm key limits on the geologic map.

The outermost or primary capillary shockwave propagates in a manner coincident with the traditional radius of investigation. As the capillary shockwave encounters an order of magnitude decrease in fluid mobility, the cone of influence responds within the constraints of the system of capillaries of which it is composed. Normally, a choke is used at the wellhead to maintain constant flow rate. The loss of growth at a sealing boundary results in the formation of a secondary cone of influence bound by its own secondary capillary shockwave discontinuity boundary. The new cone maintains constant flow by making up the flow loss from the nongrowing capillaries. The secondary boundary grows at a velocity commensurate with the growth of the outer or primary capillary shockwave boundary.

Testing method

The drawdown test conducted on a fixed choke bean is the preferred testing method. For wells already on production, a buildup followed by a drawdown provides two datasets that can be compared for pressure derivative shifts and singularities of the same set of reservoir limits or fluid mobility changes. Every time a well is shut in, then placed back on production, is an opportunity to test a well either from the surface or with a downhole pressure bomb. Wells producing substantial liquids should always be tested with a downhole gauge. Dry gas wells or wells that produce less than 150 bbl of total liquid per million standard cubic feet and flow enough to assure fluid unloading, are candidates for surface measurements. Resolution, accuracy and stability of the pressure recording instrument are essential to good testing practice. Mechanical bombs are best applied to low-permeability systems. The preference for smooth, reasonably constant-rate testing has to do with the fact that every time a rate is changed abruptly, a new primary shockwave front is propagated into the reservoir. Smooth flow rate drift in the range of +10% is desirable.

Observation of a cone of influence

A unique experimental opportunity presented itself in 1987 to observe the

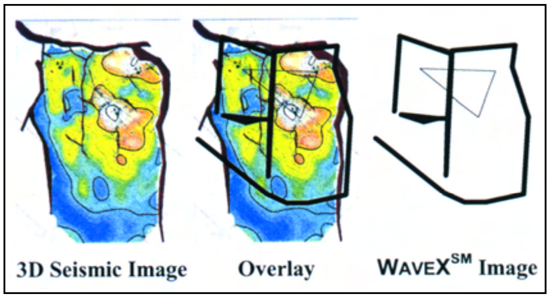

Figure 3. Seismic confirmation example.

growth of a cone of influence from the vantage point of the wellbore of the producing well and two offset wells at 2,000ft and 4,000ft distance. The data plot in Figure 1 depicts the pressure response in the static observation well at a distance of 2,000ft. The producing well was completed in a 500 md sandstone and flowing dry gas at 17 MMscf/d. The time scale originates at the same time the producing well was opened to flow. The observation well was not affected by the offset producing well for the first 28 hours of flow. The double image plot is due to a thermistor cycling between temperature outputs by 0.1ºF. The pressure response begins, not asymptotically as we expect from traditional diffusion theory assumptions, but as a step pressure drop followed by a small half sine wave dynamic. Several pressure step discontinuities were followed by abrupt changes in the semilog slope. Two different wells, two different gauges, very smooth and constant flow, plus a long delay in pressure communication through an extremely permeable reservoir result in the same pattern of pressure anomalies. A third pressure gauge used in a surface readout mode on wireline was placed in a third well 4,000ft from the producer. The surface readout electronic pressure gauge recorded no change in pressure for 104 hours after the producer was opened to flow. A similar pressure step event occurred at that time followed by a sustained drawdown.

The plots were printed upon transparency material. The arrows were placed to note the small step anomalies in the data. The next step is to overlay the two transparencies and scan the resulting overlay.

The propagation of the wave front is solely a function of the hydraulic diffusivity during the midtime region until reservoir closure. As the cone of influence and its bounding shockwave strike the limit, a secondary region forms within the first to make up the production shortfall caused by the limit. The key to the model is an energy solution to a complex network mass of growing capillaries. Radial momentum stabilizes the cone of influence, resulting in a flow system that begins as pure radial flow and continues during the growth phase as radial flow. The well in this case becomes analogous to a lens gathering and focusing light. This is why the point of contact image or its energy equivalent shape can be reproduced (Figure 2).

Note that the pressure data in the semilog plot of Figure 2 is composed of straight-line segments. These features are generally eliminated from pressure data by functional smoothing, filtering and parsing before history matching to a fixed boundary field diffusion model. In this case, we propose to derive limit-specific information from them.

Figure 3 is a simple overlay of the image with the well positioning triangle. It is used to locate the outline over the seismic image. The image is the result of a different geophysical measurement system. This study was produced as a crosscheck to the 3D seismic image for less than 5 on the dollar, including data acquisition.

Capillary stream tubes are not just theoretical devices but represent the physical structural elements of a producing reservoir that allow us to see much more of the reservoir than is promised by conventional diffusion models. Instead of smoothing the discontinuities from pressure data, it is profitable to look for them and process pressure data directly for the information contained therein. Limit-by-limit confirmation from a constant rate flow test offers an independent means for confirming geologic maps. Systematic analysis of several well tests can lead in some cases to blind energy maps. ■

ENERGY IMAGING

Pressure analysis explains seismic

A new capillary shock-wave model enhances the accuracy of 3-D seismic interpretation.

AUTHOR

Fred L. Goldsberry, wavex@wt.net, is president of WaveX Inc. in Houston, Texas. **Mark A. Janik** is a reservoir engineer at Southwestern Energy Production Co. **Daniel R. Zebrowski** is a geophysicist at Southwestern Energy Production Co.

A year ago, a new wave mechanics approach to pressure-transient analysis called WaveX was introduced.[1] This pressure analysis method generated reservoir dimensions, limit shapes and images from a family of capillary shock-wave fronts as they passed through the reservoir at slow diffusive speeds. A new case study illustrates the economic effectiveness of combining traditional material balance reservoir engineering with geophysics and WaveX pressure-transient imaging.

The problem

A new well has been successfully drilled and completed on the basis of a prospect generated with 3-D seismic data and traditional material balance calculations on offset wells. The target was a higher amplitude seismic event associated with gas sands that apparently never were drained by offset wells. The hydrocarbon-bearing sands and seismic amplitudes are discontinuous, making the generation of net pay maps from 3-D seismic data extremely difficult. The initial performance of the well suggested that although it is "a keeper," it may not be as large as initially mapped. Many questions were associated with a geologic nonconformity that would impact reserves from the current well and a future development well. In fact, the economic viability of the second development well was in question.

The solution approach

Why did the property team elect to conduct a pressure analysis test? Producing this well while monitoring flowing tubing pressure at a constant rate controlled by a fixed choke would give the exploration team tangible results while generating cash flow to the project. They expected to learn:

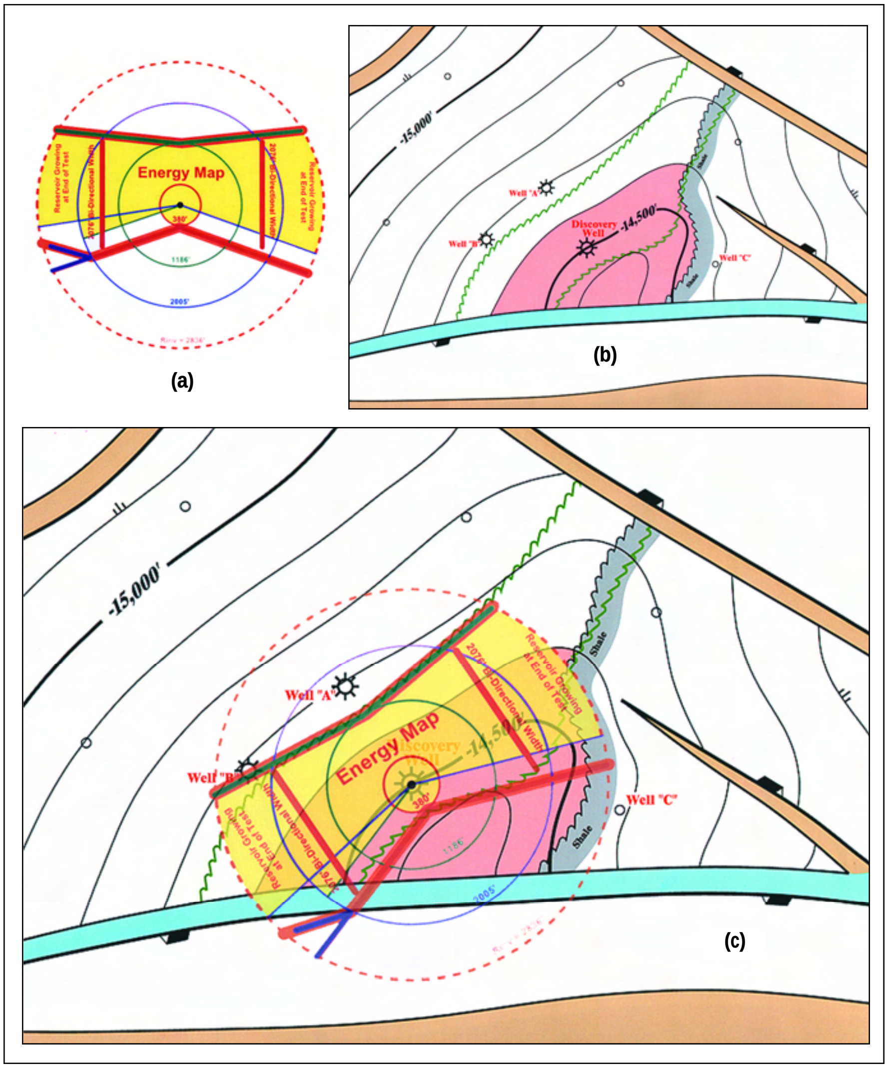

Figura 1.The energy map of pressure-transient boundaries (a) was compared to the structural map (b),and the overlay (c) showed that the field was smaller than the original interpretation.A second development well was not drilled.

- distances from the well to the permeability limits;
- amount of gas explored by the test; and
- type of drive mechanism.

The operator had used shock-wave front pressure-transient analysis in the past to confirm geologic maps. Producing this well to sales while monitoring the flowing tubing pressure with a SPIDR has proven successful in generating independent reservoir dimensioning for gas reservoirs with fluid production less than 300 bbl/MMcf. The results of the analysis developed specific information on the distance from the well to the nearest reservoir boundary contacts. It also produced information as to the shape of each contact relative to a straight line. Because the transient model is based upon discrete finite capillary rays, it can provide information as to relative disposition of individual limits. It is possible to detect corners for intersecting faults and learn if any of the limits are nearly parallel to each other. Finally, the shock-wave model produces running integrals of the volume of gas in place as well as dimensional information for direct comparison with 3-

D seismic data.

The individual boundary contacts and angle of intersection computations then are assembled into an energy-equivalent image of the reservoir using the volume information to orient the boundaries with respect to each other – without making reference to a seismic map. This boundary contact drawing then can be overlaid onto a seismic image as an independent reference for interpretation.

Pressure testing and analysis

Data gathering is simple and cost-effective. The new well is placed on production on a fixed choke and pressures recorded as the gas is sold. The principal goal is to maintain a 2.5-1 pressure ratio across the choke.

This gas well was tested using a SPIDR surface-mounted pressure gauge and the associated downhole data conversion process. The best time to capture transient data is during the initial production period. No prior stabilizing buildup is required for the drawdown, hence there are no production delays or losses. The analysis was performed “blind,” with no prior geologic information for the analyst. The shock-wave front model builds the image from a sequence of abrupt energy shifts visible in the traditional semi-log plot. These events are caused by the growing capillary array from the well interacting with a permeability change. A traditional simulator model cannot replicate these singularity events. That is why historically it has been a common practice to “smooth out” test data numerically for the traditional iterative history-matching analysis process.

In contrast, the shock-wave front model sees limits as discrete events. A sealing limit is manifested as a sharp or singular shift in the derivative value on the semi-log pressure plot. Each boundary contact is described by the distance to the point of tangency and by the characteristic shape at the point of contact. A limit may be straight, concave to the well or convex. In Figure 1a, the red limit is the first contact, the green limit is the second contact, and the blue chevron represents a probable change in the direction of one of the limits. It has an insufficient energy shift to be a separate discrete limit. The area described in yellow is the energy integral for the test. Finally, from the linearity plot an equivalent bidirectional width for the parallel limits system can be calculated. This is depicted as two red bars an appropriate distance from the well. This squares nicely with the projections for limits 1 and 2 up and down the reservoir. An energy map that maintains all balances and dimensions is referred to as a “snap fit.” This means one representation is seen on a transparency. Of course, the transparency can be flipped over for the mirror-image case that in all instances is as legitimate as the first. It should be noted that the method does not imply direction but does recognize relative boundary placements. The pressure-transient analysis is complete. At this point it is taken to a meeting in the operator’s offices to compare with an as-yet-unseen geologic map.

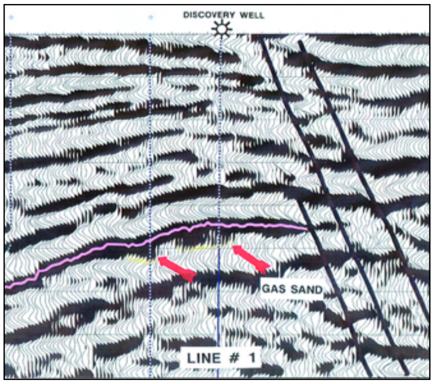

Figure 2.Higher amplitude events from the seismic were plotted on Figure 1b as green, squiggly lines, confirming the boundary. (Courtesy of Seitel Data)

Geology and geophysics

The prospect is a three-way, high-side closure on a large, regional down-to-the-south basin fault. The objective sands are within the Frio stratigraphic sequence. Existing well control demonstrates a sand pinch-out over the structure. An initial 3-D seismic-based structure map was constructed to drill this prospect (Figure 1b). In addition, a velocity anomaly was evident from the 3-D seismic data over the structure. Nearby well control allowed for the Frio sands to be directly tied to the 3-D seismic data via synthetic seismograms. No apparent gas-water contacts were evident from the initial interpretation of the 3-D seismic data. However, higher amplitude events were associated with the gas sands (Figure 2).

The initial discovery well found hydrocarbons within the objective sands. Correlation of the new sands to offset wells demonstrated that the new well encountered sands that were not present in offset wells. Obviously, the predrill sand maps needed to be corrected. Pressure-testing and analysis were completed and applied to the new interpretation. It was determined that we could demonstrate several sand lobes within the higher amplitude event on the 3-D seismic data.

A working meeting

The comparison of an independently generated energy image and a seismic image always has an element of suspense. But the key to successful exploration (exploration that involves making money) is based upon bringing as much data from as many independent sources and disciplines as possible together in order to reconcile differences. The business of exploration is to prioritize information and make unemotional judgments as to relative value. Profitable exploration is the assembly of information in order to reduce decision-making risk.

By placing the WaveX map over the structure map (Figure 1c), Boundary 2 seems to fit the distance and shape described in the geologic map. The blue fault appears to coincide with the distance of the blue anomaly or boundary shift. However, Limit 1 appears to cut across the middle of the reservoir. Initial well performance using traditional production plots and static material balances seemed to support a smaller picture from the standpoint of energy decline. A proposed offset well was discussed. A reduction in reservoir volume would be critical to the drilling decision for the second well. The nonconformity to the east was the principal uncertainty in the analysis.

The western reservoir boundary had been defined by a higher amplitude seismic event. A second higher amplitude event on the eastern side of the well had been noted but could not be structurally correlated with a boundary. The original western amplitude event had been ascribed to a gas-water contact. The transient test matched the boundary shape, casting doubt upon the gas-water contact interpretation. A quick traverse of the reservoir was made to plot the locus of both higher amplitude events. The amplitude reversals are shown in Figure 2, and the locus boundary is plotted over the map in Figure 1b as green lines. The next step was to again match the WaveX overlay to the geologic map in Figure 1c, which confirmed the geologic interpretation of a sand channel.

Increased certainty in defining a reservoir improves economics. Production performance, seismic and pressure-transient images enhance and complement each other. Team play and communication among the reservoir engineer, the pressure-test analyst and the geophysicist were essential in accurately defining this prospect. More importantly, a noncommercial well was not drilled. The money was applied to other ventures.

References

1. Goldsberry, F.: “Shockwave model reduces risk,” *Hart’ s E&P*, pp. 43-45, September 2000.

RESERVOIR IMAGING

Surface measurement aids imaging

Surface pressures are used to accurately and independently image a complex reservoir.

AUTHORS

Fred L. Goldsberry, *wavex@sbcglobal.net, is with Wavex Inc.;* ***Roger B. Knight*** *and* ***Ellen A. Rutherford*** *are with McMoRan Oil & Gas; and* ***Nathan Waldman*** *is with Data Retrieval Corp.*

A wave mechanic's approach to pressure transient analysis, based on a radial element capillary wave model, has been employed to produce simple 2-D images of reservoir boundaries and thus reservoir shape. This methodology could provide a method for independently corroborating seismically derived images of a reservoir at relatively low cost. In the gas well case history presented here, a "blind" test, using pressure data collected at the surface, has resulted in a reservoir image that closely matches the seismic interpretation.

Pressure transient energy imaging

The fundamental difference in this approach is a more complex model of the reservoir than that which the diffusivity model of conventional pressure transient analysis is based. Imagining the reservoir as a complex network of capillary stream tubes allows us to process discontinuities in pressure data more directly for the information contained in them, rather than smoothing them out to fit a simpler model.

Starting in the 1930s, when pressure transient technology was introduced by William Hurst, singular behavior or abrupt changes in pressure declines on semi-log plots were noted in data and directly related to reservoir boundaries (Hurst, 1968; Jones, 1957; Jones, 1961; Matthews, et al., 1967). The radius of investigation, based upon an effective drainage volume was recognized as an effective measure of distance to the permeability limit. Interference testing performed in the mid- to late-'80s with precision pressure gauges detected the pressure step associated with the boundary between the growing cone of influence and the remainder of the reservoir. Subsequent to the development of the physics of capillary-entry-pressure diffusion shockwave fronts, radial capillary models were developed that explained the singular behavior associated with the shockwave striking a boundary.

Traditional theory assumes capillary pressure is small and can be ignored, allowing us to use the diffusion equation with fixed boundaries. The capillary wave model recognizes the effects of capillary pressure and derives the velocity of a wave front. This velocity of the shockwave front, when integrated over time, produces the radius of investigation equation. The wave front acts as a boundary to the depletion volume of the cone of influence. When the pressure history is derived by basic integration of the energy equation, the result is the familiar relationship of the mid-time slope. The capillary model is fully developed in the references (Goldsberry, 1998, Goldsberry, 2000).

Under the capillary wave model, when flow is initiated or when a major rate change is imposed, capillary shockwave fronts propagate from the well bore. These fronts are composed of many radial capillary pathways that grow coincident with the traditional radius of investigation. The small initiating capillary breakdown pressure that exists at each pore throat produces this physical phenomenon. These pressure steps have been measured in core analysis labs, but never incorporated into transient models. Each capillary is analogous to a ray of light: a ray goes out and strikes a boundary and is reflected, and amplitude and frequency are factors of the boundary and its angle. When these capillary ray clusters strike a reservoir boundary, they act in unison to provide specific information about that boundary.

Recognition of a physical wave allows the use of the transient test as a means for "sideways logging" of the formation boundaries. The shockwave represents an expanding container that encompasses a growing volume of pressure depletion around the well bore as the well begins to flow. Initially, as the shockwave expands, the response is as though the well is in an infinitely large reservoir. When the cone of influence reaches a sealing boundary, the section of capillaries that strikes the limit stops growing, resulting in a reduction of flow to the well bore at the original pressure decay rate. A short fall in flow is made up by an abrupt increase in the rate of drawdown at the well bore. This compensates for the loss of growth of the cone of influence at the boundary.

All flow demands on the formation are constrained by the static capillary pressure differential required to initiate flow. Once a capillary pathway is established, it remains established until acted upon by a sufficiently large pressure difference to open the non-flowing pore throats that make up the wall of the capillary. These capillaries will eventually break down due to the asymmetry caused as boundaries are encountered. The capillaries as formed can withstand a sufficient pressure imbalance to sustain radial flow away from the well. Capillary memory sustains the flow paths to the well and serves to produce the

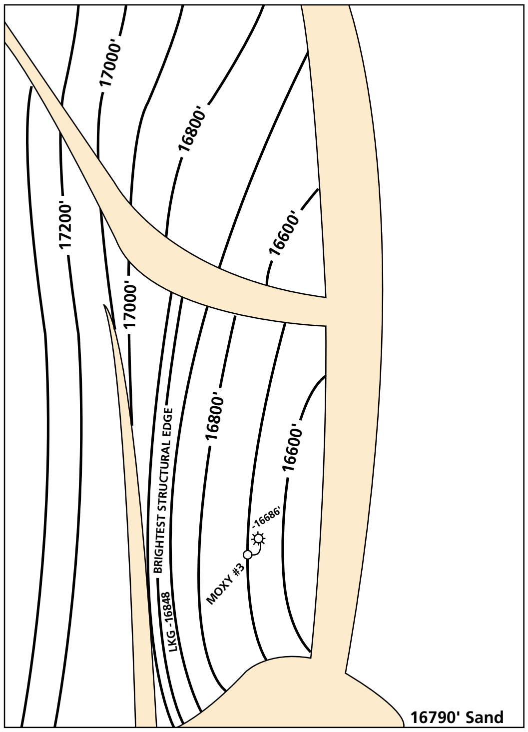

Figure 1. In this case history, the operator mapped the reservoir as a complex fault closure associated with a large bright spot.

abrupt increase in the semi-log derivative when a boundary change is encountered by the shockwave front.

The rate of increase in slope provides information to the radial capillary model that generates a "shape at point of contact" for the limit. In other words, each limit is defined both by distance from well and by angle of deviation from a straight line. In a reservoir with four sides, this means the analyst would detect four slope changes at four times, each related by distance from the well and shape.

However, direction is and will remain an unknown. But it is possible to develop a relative disposition of limits by using an energy model of the cone of influence with its secondary cones to account for the total energy of pressure decay. The relative disposition of the limits to each other is a function of their shape and some parameters from the radial capillary element model called "angles of splay." The limits can be arranged by holding the first limit at a fixed position, say, conventional map north, and then placing the other limits around the well so as to optimize fit to the computed energy growth pattern. In a 4-limit model, relative arrangements can be 1-2-3-4, 1-3-2-4, 1-2-4-3, and 2-1-4-3, etc. Other permutations are the mirror images of these.

Case history

In the case history presented here, the operator mapped the reservoir as a complex fault closure associated with a large bright spot (Figure 1). An independent test of the seismic-based map of the reservoir was carried out using our energy mapping methodology. Flowing tubing pressure and flow rate were measured with a high precision dual quartz gauge surface recorder while producing the well using minimal choke changes to sustain rate. During the test the well was producing at a constant rate of 11 MMcfd of 0.62 gravity gas and 363 b/d of 42°API condensate, with a bottomhole pressure in excess of 14,800 psia. The flow rate and flowing tubing pressure data were recorded and converted to downhole conditions by an independent contractor. The data were then analyzed along with a baseline petrophysical analysis derived from openhole electric logs. The reservoir transient pressure analysis was performed "blind" to the existing geologic interpretation, for a wholly independent comparison.

An image was developed from five indicated boundary contacts (or changes), calculating in-place volume integrals as a guide to reservoir shape. Computed angle-of-intersection calculations showed that although four boundaries were contacted, the angle factors indicated a rectangular arrangement with the system growing beyond one projected corner. Later, a fifth boundary change appeared that was consistent with a gas/water contact. Finally, the need for a major rate change ended the test.

The heavy green line in Figure 2 shows the best energy fit arrangement for the boundaries and their projections. The leak was associated with the fourth boundary. This map was developed solely from surface pressure and flow data measurements combined with information on fluid composition and the operator's analysis of pay properties.

An overlay of the geologic map derived from seismic with an inverted overlay of the energy map reveals that although the exact location of the gap on side four is not seen, the four limit shapes, a gap in one boundary and a gas/water contact beyond the gap were all recognized (Figure 3).

The gas in-place reserve calculations from the test indicated 26 BCF at the time of the fourth boundary and 34 BCF at the time of the gas/water contact. Beyond the gas water contact, the test is measuring the energy contribution of both gas and water. These values were consistent with the operator's integrated map volumes and a third-party reservoir engineer's in-place reserves for this region of the reservoir. The mapped reservoir extended beyond the radius of investigation of the test.

Pressure measurement

It should be noted that variations in the accuracy of porosity, fluid mobility, pay count, water saturation, compressibility and the downhole pressure conversion will all contribute to the energy map's deviation from the true reservoir shape. The

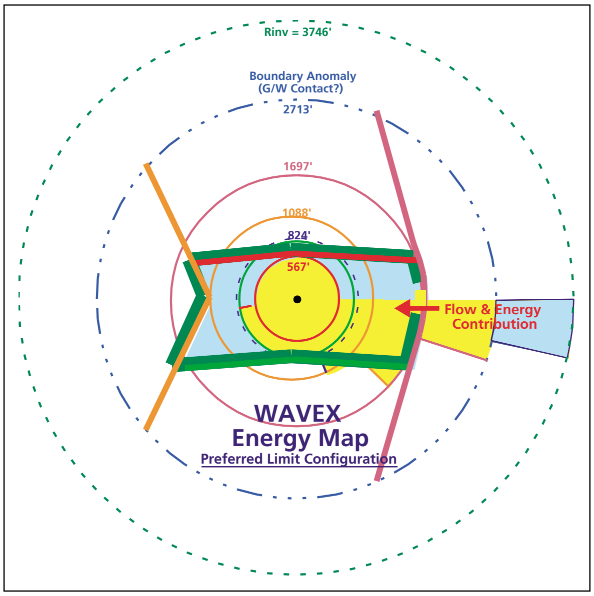

Figure 2. The heavy green line shows the best energy fit arrangement for the boundaries and their projections.

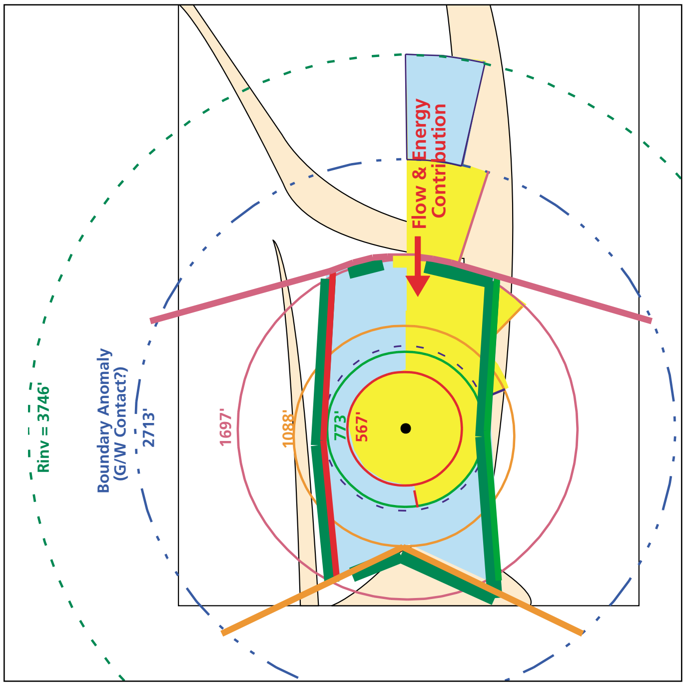

Figure 3. An overlay of the geologic map derived from seismic with an inverted overlay of the energy map reveals that although the exact location of the gap on side four is not seen, the four limit shapes, a gap in one boundary and a gas/water contact beyond the gap were all recognized.

accuracy of the map is directly related to the accuracy of the bottomhole pressure data. The gauge has to be stable enough to conduct a drawdown test of 1,200 hours duration. This degree of gauge stability was necessary to compute the rate of energy growth that pointed out the opening to and characteristics of a gas/water contact. Only then was it possible to map the reservoir and assess its volume. The key to transient analysis of this type is the ability to see the relative pressure changes with a gauge that is accurate and stable over time.

The map is also dependent upon an accurate pay count and petrophysical analysis. The reservoir engineers must provide "on the mark" petrophysical information from electric logs for this process to succeed.

Potential for applications

The potential applications of this methodology are significant. Essentially, it provides a means for obtaining an independent assessment of reservoir shape and size from simple surface measurements, without the need for wireline pressure measurements. Wireline-free testing has many advantages: tools and equipment are not subject to loss or damage; data collection is simple; pressure and flow rate are measured feet apart rather than miles apart; and the cost of wireline operations is eliminated. Since transient analysis is based largely upon relative pressure rather than absolute pressure, the inaccuracies introduced by measuring from the surface and computing the bottom hole values generally relate to compressibility computations and small differences in well skin calculations. The conversion technology has evolved from essentially dry gas wells to gas wells producing up to 300 barrels per million cubic feet of combined condensate and water. Some single-phase oil wells can be modeled under specific circumstances.

In locations such as offshore jackets and caissons, the opportunity to avoid costs associated with wireline equipment and jackup boat charges strongly favors a surface gauge approach. The key to surface measurements is transducer quality and the technology level of the algorithm used to convert surface data to bottomhole.

Good well testing also involves a fixed choke or a close approximation of constant rate flow. Downhole measurements often are made from locations well above the completion. If there is a fluctuating fluid level or change in flow regime below the downhole gauge, there is little or no advantage for the downhole measurement. If the well is hot, the reservoir engineer often is asked to analyze data that is an artifact of a slow thermal gauge failure rather than an accurate reflection of the well. Often, the only practical way to test a well that is hotter than 410°F is from the surface.

We should recognize also that long-range testing is practical only in the drawdown mode. Boundary information cannot be gleaned beyond the radius of investigation, and a large radius of investigation takes time. Surface measurements during the initial production drawdown allow the operator to do more testing for less money. The total cost of producing an energy map is less than the cost of a good production log.

In this case history, and in others presented earlier (Goldsberry, 2000, 2001), the operators developed confidence in the property by tackling the confirmation problem from two independent geophysical processes and arriving at the same answer. The reservoir information obtained in this manner is either generally correct or there are massive and compensating errors in both independent imaging techniques. E&P

Acknowledgement

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References

Goldsberry, F., "Shockwave model reduces risk," *Hart's E&P*, September, 2000, pp. 43-45.

Goldsberry, F., "Pressure analysis explains seismic," *Hart's E&P*, November, 2001. pp. 35-36.

Goldsberry, F. L., "Reservoir Conformance Developments – Capillary Shockwaves in Porous Media", 1998- Fourth International Conference on Reservoir Conformance, Houston, Aug. 12.

Goldsberry, F. L., "Method for Producing Images of Reservoir Boundaries," U.S. Patent No. 6,041,017, U.S. Patent Journal, U. S. Patent Office, Washington D.C., March, 2000.

Hurst, W., "SPE 2461 – Radius of Drainage Formula - A Technical Note", SPE of AIME, November, 1968.

Jones, Park J., "Drawdown Exploration Reservoir Limit, Well and Formation Evaluation" Technical Paper No. 824-G AIME, April 1957.

Jones, Park J., "Reservoir Limit Tests on Gas Wells", SPE Gas Technology Symposium, Tyler, Texas, July 17, 1961, p. 219.

Matthews, C. S. and Russell, D. G., "Pressure Buildup and Flow Tests in Wells", Henry L. Doherty Series Monograph Volume 1, SPE of AIME, New York, 1967, pp.87, 94-95.

SPE Paper Number 77700

Capillary Shockwave Front Blind Imaging of Reservoir Limits: A Case Study

Fred L. Goldsberry, **WAVEX®**, Inc. and Kevin C. Anderegg, Devon Energy Corporation

This paper was prepared for presentation at the SPE Annual Technical Conference and Exhibition held in San Antonio, Texas, 29 September–2 October 2002.

Abstract

Reservoir boundary information is gleaned from a steady-flowrate-drawdown test and/or a subsequent buildup following the steady flow period. Singularities are observed to be present in virtually all transient pressure data that can provide direct information about the limits around a well. Multiple limits can be detected discretely and described by distance from the well and angular shape at the point of contact. The input information required is pressure data acquired while flowing on a fixed choke, petrophysical properties from cores and electric logs, and fluid production rates and compositions during the flow period.(2)

Reservoir limits can be assembled into an energy equivalent image based upon cone of influence energy growth behind a bounding initiating capillary pressure shockwave front. The resulting image can then be compared with a seismic data based map or a geologic map. Volume integrals for gas inplace can provide an early physical measurement for reserve accounting purposes.(4,5,6,8)

A variety of boundary contact shapes were assembled into a “blind” energy map that was later confirmed by seismic imaging. A direct overlay comparison of the “blind” energy image and a 3D seismic map is presented. The limit information will be compared with the seismic image to confirm it point by point.

This new transient pressure analysis method is based upon a real capillary network growing from the well bore. Flow into the well bore is restricted to radial flow and confined to the real capillary flow paths by initial capillary pressure.(2) The cone of influence is bounded by an associated capillary shockwave front that restricts its growth. The bounding initiating capillary pressure shockwave front is the physical phenomenon that exists at the radius of investigation.(1,7,10) The capillary networks give rise to secondary pressure singularities when a boundary is encountered. The method extends traditional analysis to the realm of wave mechanics(8,9,11) and allows direct data processing. The solution is based upon an energy model that solves for boundary geometry directly from flow and buildup data without the process of traditional iterative history matching. The boundary contacts can then be assembled into an image of the reservoir based upon relative disposition of individual limit contact.

The Problem

A single well reservoir had been successfully drilled in the Eugene Island Area and was being produced by Well No. B-13ST. This particular single well reservoir was identified as an attractive testing candidate for the operator because of its multi-faceted structure and questions regarding closure and water drive. The structural trap was composed of numerous splinter faults that held the possibility of discontinuous or leaky connection to another fault block. At issue was whether the reservoir trap was sealing up dip and how large a reserve base was represented by the fault closure. This other fault block would be an ideal candidate for a second well or future sidetrack of the existing well if it was indeed separate. Additionally, the operator was interested in increasing the booked reserves attributed to the well by confirming the reservoir limits indicated by the 3D seismic data.

The Solution

The operator has long owned and utilized a surface mount dual quartz transducer pressure recorder that has provided substantial quantities of data by recording long term initial drawdowns. Data acquisition is simple. Place the well on production on a fixed choke that is designed to produce the well at a moderate rate. This allows the completion to settle in before stressing it fully. This period may be brought to an end with an extended buildup test followed by another drawdown period. The result is that often the limits near the well are seen three times as data singularities and often the entire reservoir is explored during the first drawdown. In this case the initial drawdown was sufficient to define the reservoir boundaries. Figure 1 shows the drawdown data.

The startup was ramped up and held steady on a fixed choke for approximately 80 hours before control problems obscured the data. There are numerous shut-ins and some small rate changes that are associated with start up. The data in Figure 1 appear to be non-descript until replotted on a semi-log plot in Figure 2.

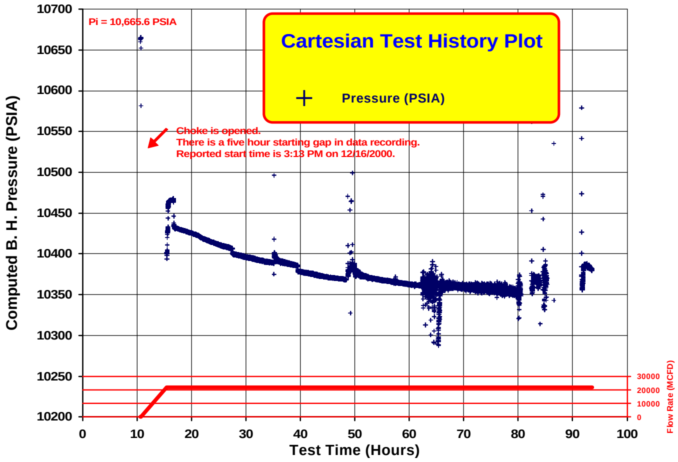


Figure 1. Cartesian Plot of Test History

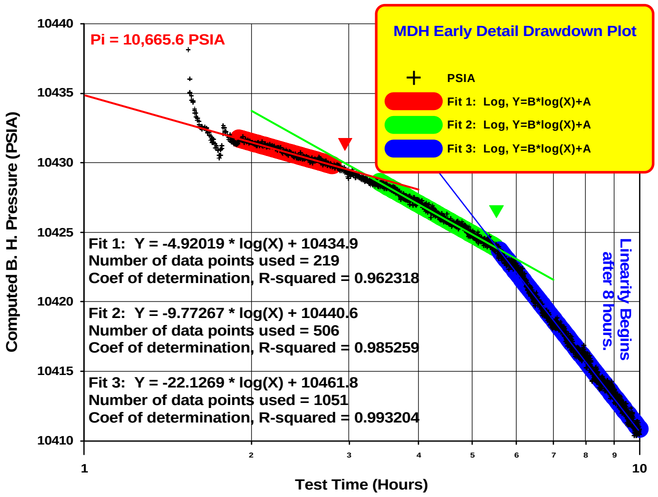


Figure 2. Semi-Log Plot of Drawdown Mid-Time and Late Region

Note that the expanded scale of Figure 2 reveals three straight-line sections. The sections are established as statistical fits of the data (natural log of time vs. pressure). The straight nature of the data over sections of the plot is the result of the response of a well under control of a fixed choke and the interaction of capillary flow paths encountering a reservoir limit. The slope increase is the response of the well to the failure of the cone to grow beyond the limit. This produces a natural reduction in the flow to the well, which results in an increase of drawdown to make up the difference in flow. The result is an immediate response to a limit that perpetuates with the test or until another limit is encountered. Figure 3 describes the capillary structure of the cone of influence during the drawdown when a limit is encountered. Each limit contact results in its own secondary cone of influence. The secondary boundaries are separated from each other by secondary capillary shockwave fronts that grow in proportional speed to the outer shockwave front. The outer shockwave front exists at the radius of investigation and functions as the boundary condition of the cone of influence.

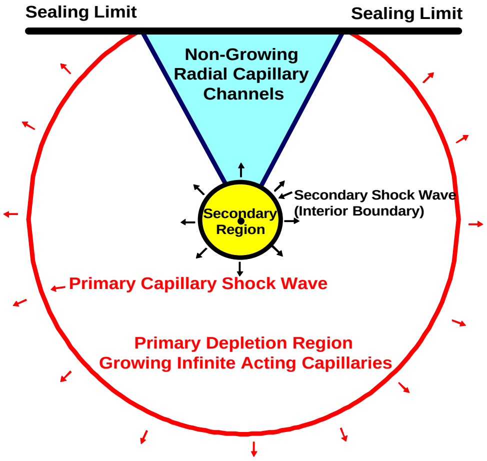


Figure 3. Cone of Influence Schematic Striking a Straight Limit

The fan of capillaries that has stopped growing represents a collection of fixed volume capillaries. All other capillaries continue to grow as though the reservoir was infinitely large. In times past, the mid-time region was described as infinite acting radial flow. The characteristic non-diffusive behavior has been recognized in transient well test data since the inception of well testing. Diffusion theory does not predict this behavior. Mirror image well theory was popularized in the 1950's but failed to provide an explanation for these observations. Widespread use of these singularities was in vogue until the advent of digital reservoir simulation. There have been numerous attempts over the years to use reflected waves and wave equivalents without the attendant physical explanation of why these occur or for that matter what they are. The scope of this paper is not intended to provide a full physical explanation but to provide a practical example of what may be accomplished. The solution method(2) is referenced for those interested in the physical theory and method. The semi-log slope is proportional to the energy decay rate in the section of the cone of influence being observed by the pressure gauge.

Further examination of the data at later times revealed a small energy shift and a final limit as detailed in Figures 4 and 5.

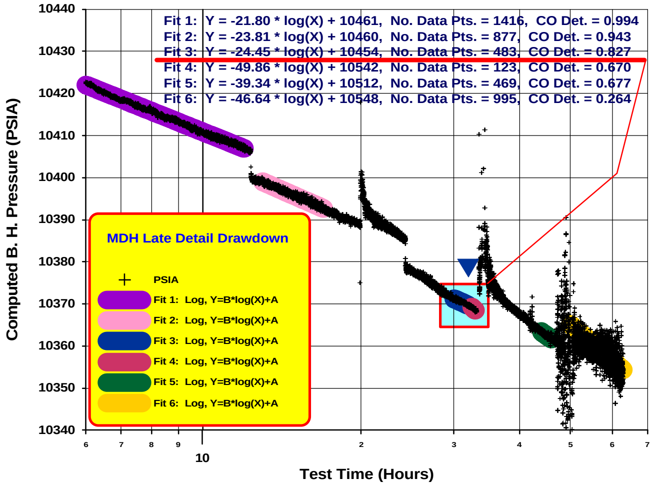


Figure 4. Limit 3 Position from Energy Shift

Note the limit shift marked by a blue triangle. The energy decay or slope calculation is approximately 22-24 psi/ln cycle before this point and consistently 39-49 psi/ln cycle thereafter. The energy shift must occur before 40 hours and after 30 hours. The best pick for the time at which this occurs is at approximately 32.8 hours as can be seen on Figure 5.

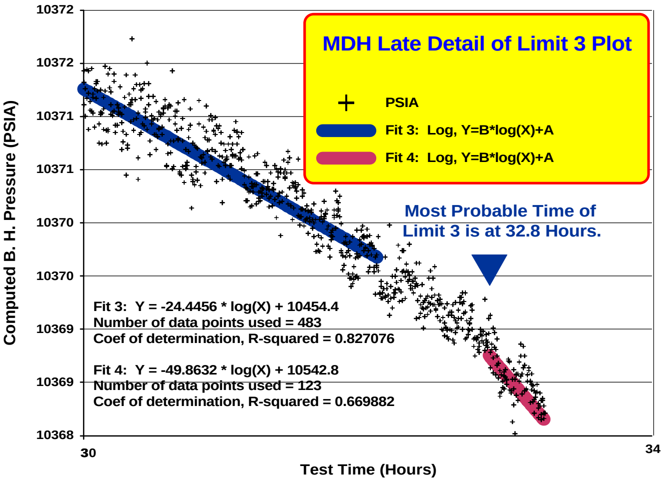


Figure 5. Limit 3 Detail

Each of these major limit events is input to the nested cone energy model. For each energy shift a characteristic shape at the point of contact is calculated. The time provides the radius of the capillary shockwave front from the well. The result is a limit diagram as shown in Figure 6. The energy growth is depicted in a polar plot that is shown in yellow.

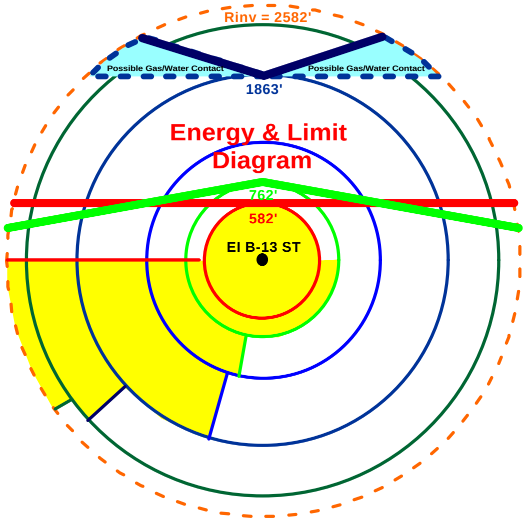


Figure 6. Limit and Energy Diagram

The limits are placed in a single direction from the well. This is because we do not know the direction and must arbitrarily assign a position to the first limit. The other limits will be placed relative to limit 1 around the energy diagram. The energy diagram is laid out to show the calculated angles of splay.

The options for relative limit position are several. The fact that a wedge of capillaries striking the limit defines each limit restricts the number of positions in which a limit may be placed. The relative relationships are 1-2-3-4 or 1-3-2-4 or 1-2-4-3. Once limit placements are made, a series of energy calculations are made to determine which configuration represents the best energy balance for the system through the end of the test. In this case the radius of investigation is boundary 4. In Figure 7 we begin with the placement of limits in a 1-2-3-4 rotation.

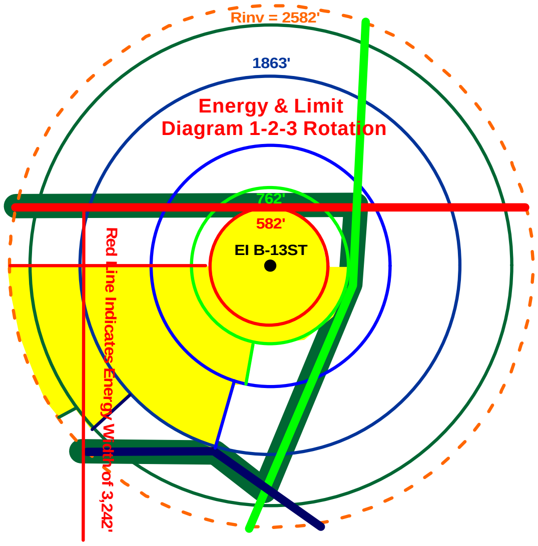


Figure 7. Limits Placed Around the Energy Diagram

Note that the linearity of the data as seen in Figure 8 suggests growth between parallel limits and then a splay in the system at about 50 hours. More importantly it suggests that the 1-2-3-4 limit rotation may not be the best choice.

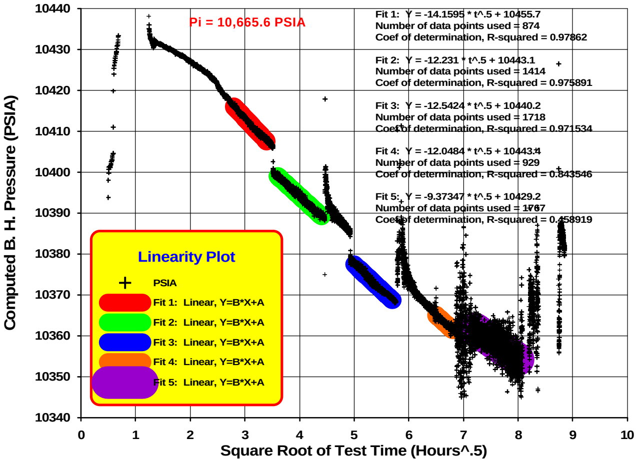


Figure 8. Linearity Plot

Now it is necessary to construct trial 2 around an energy diagram. Note that the energy diagram of Figure 9 can be split to provide another case, which involves limits 1 and 2 being opposites. Again, the limit width calculations at extended test time suggest a misfit on width calculations. Further, the projection of limit 2 in green is inconsistent with the energy diagram.

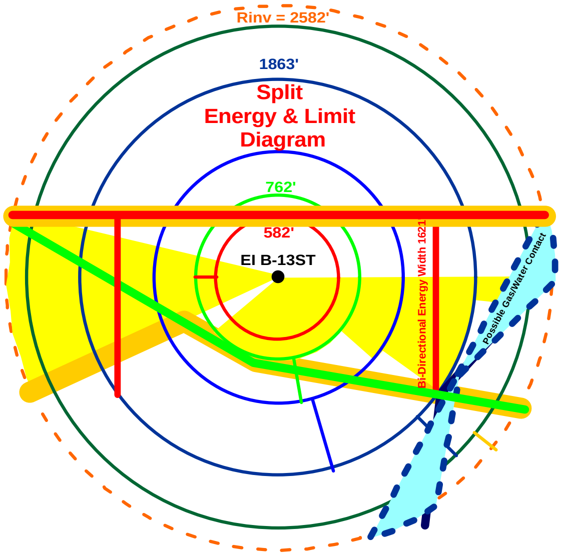


Figure 9. Limit 1 Opposite Limit 2 Bi-Directional Growth of the Cone of Influence

The next construction, in Figure 10, shows limits rotated in a 2-1-3 sequence around the energy diagram. Each image is displayed on a transparency and may be flipped over to see the mirror image. The mirror image or flip side is just as valid as the first. This method is indifferent to direction and is reflective only of the relative direction. This time the linearity calculation is used to fit limit 3 relative to limits 1 & 2 in order to produce the appropriate energy growth splay at the end of the test.

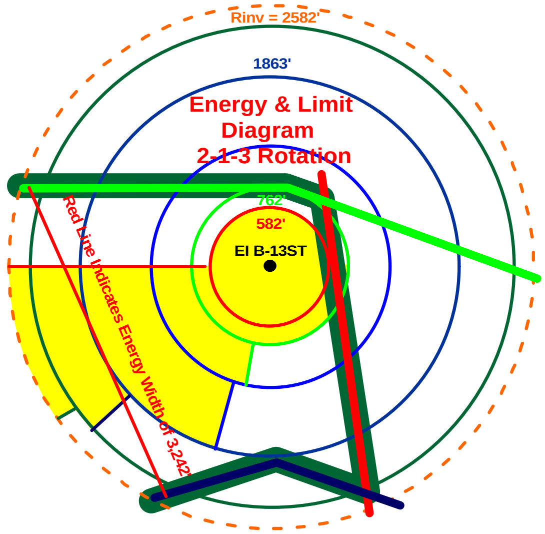


Figure 10. Final Relative Limit Configuration Case

Up to this point, it has not been necessary to refer to a geologic map. Inputs included pay count from an electric log and cores, fluid production rates and compositions, and finally high resolution and stability pressure data. The solution is the result of a proprietary nested cone radial capillary energy model**(2)**. This is accomplished from observing elastic energy growth. Figure 10 is a Blind Energy Image and Figure 11 is the Geologic/Geophysical Map.

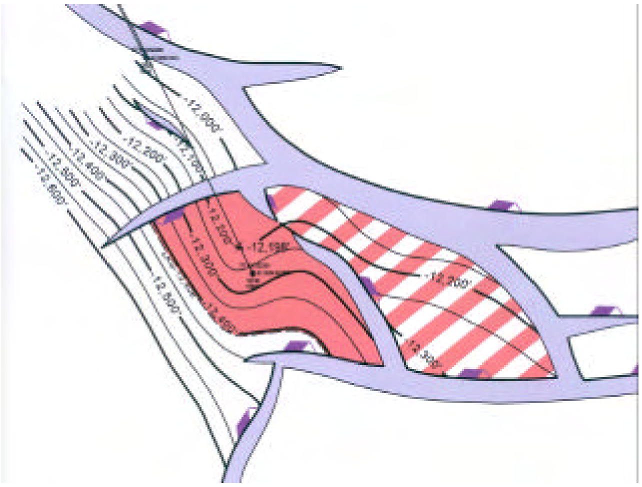


Figure 11. Geologic/Geophysical Map

The energy map is solely the result of the energy balance within and expanding cone of influence. The growth of the system is restricted by the initiating capillary pressure of each pore throat. The cone of influence is bounded by a moving wall of capillary breakdown pressure. This is a geophysical process independent of the traditional seismic measurement. Seismic images are produced soundwaves from the top down. Energy maps are produced by the radial growth of a shockwave front emanating from the wellbore. When two independent measurements produce images that bear many points of volumetric, angular, and dimensional similarity, there is a high probability that the maps are correct. This independence also suggests that the data acquisition and deconvolution of soundwaves and pressure singularities was accurate. Otherwise one must assume the geophysicist, the petrophysicist, and the pressure analyst have made equal and offsetting errors in their respective models and data processing.

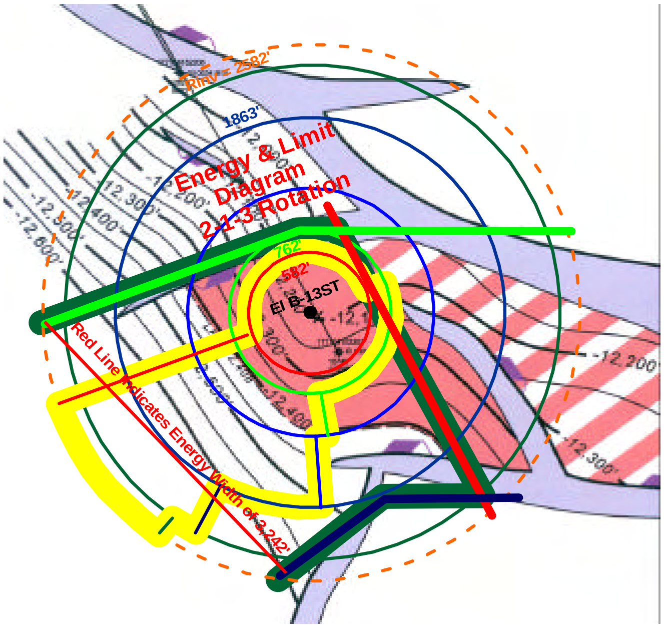


Figure 12. Map and Energy Image Overlay

Note the twelve points of comformance below and consider the ***value added*** to the certainty of the geologic picture.

1. **Distance to Limit 1**
2. **Shape of Limit 1**
3. **Distance to Limit 2**
4. **Shape of Limit 2**
5. **Distance to Limit 3**
6. **Shape of Limit 3**
7. **Corner of Limits 1 & 3**
8. **Corner of Limits 1 & 2**
9. **Response to the Spur Fault of Limit 3**
10. **Width of Reservoir at End of Test**
11. **Angle of Splay of Reservoir**
12. **Integral Volume for Gas Inplace**

Performance Confirms Results

The operator's two main objectives for the well test were to confirm the reservoir limits indicated by the 3D seismic data and to increase the proven reserves attributed to the well. The first limit indicated that the possible leaking fault to the east of the wellbore was sealing, leaving a separate fault block to the east as shown in Figure 12. Based on indications that the sand is thinning to the east, the separate fault block will be developed by a sidetrack of the B-13ST once it depletes.

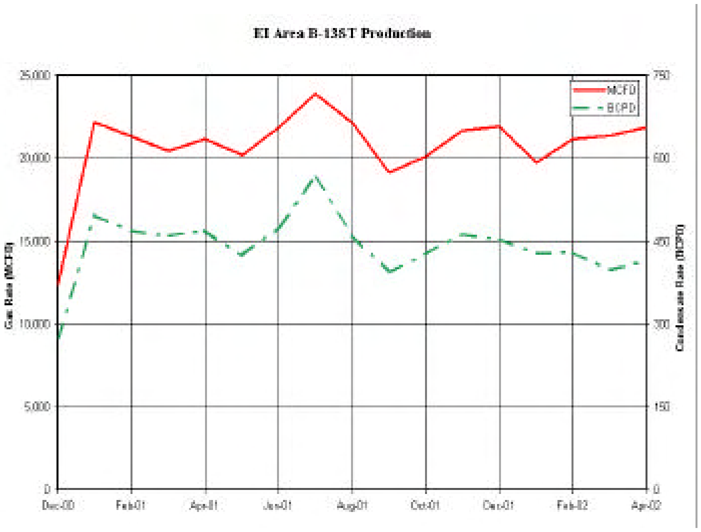


Figure 13. EI Area B-13ST Production History

Initial proven reserves in the B-13ST were based on a lowest known gas in the well. Based on geology and geophysics, a value for gas in place was computed based on the gas-water contact indicated from the 3D seismic survey. The integral volume for gas-in-place calculated from the test data agreed closely with the gas in place calculated using the geologic/geophysical data. ***Confirmation of the reservoir volume by energy imaging led to an increase in third party recognized proven recoverable reserves of 175%!***

To date the B-13ST has produced 11 BCF and 240 MBC. This represents 40 to 45% of the gas-in-place. Production has averaged 22 MMCFD and 450 BCPD for the life of the well as shown in Figure 13. ***A subsequent material balance study of the reservoir has confirmed the initial gas-in-place estimates.*** Table 1 lists each of the estimates for gas-in-place calculated for the reservoir along with the time from the date of first production required to arrive at the estimate.

Testing not only confirms seismic but also provides an early confirmation of reserves. ***When energy imaging is used as a blind crosscheck with seismic imaging, confidence levels are improved.*** Transient energy based volumetric dimensioning supports the operator's early economic decisions on the well and the property. Energy imaging can be used as a complement or a cost-effective alternative to tracking gas/ water contacts.(3)

Method of Calculation	Time to Estimate (From date of first production)	OGIP Estimate (BCF)
Volumetric Using Geology/Geophysics	0 Days	24.6
Pressure Transient Analysis	10 Days	27.2
Material Balance	16 Months	23.6

Table 1. Timing of Reserves Information

Prospects are drilled from seismic data. Seismic methods can be used to estimate volume when used in conjuction with formation evaluation and velocity electric logs that are available only after drilling. At this point the operator has a volumetric estimate based upon sound wave reflection.

After the discovery well is drilled, flow testing provides an energy growth picture by utilizing the integration of elastic energy as the cone of influence is formed and expands to encounter all of the boundaries of the reservoir. By using a ***bounding initiating capillary pressure shockwave model*** and its compliment of ***real radial capillary pathways***, it is possible to produce a second independent image and a reservoir volume at the outset of production. Traditional methods require a much longer pressure history to provide the same information. Pressure testing and shockwave front analysis is a faster way to achieve corroborating results.

The timing of recognition of reserves is important to most operators. Accounting practices require recognition of development costs as part of DD&A. Full reserves recognition including downdip gas typically lags development by as much as three to four years. Probablistic methods have been used to account for this lag. Well testing can be used to confirm 3D seismic based geologic maps allowing third-party engineers to accelerate deterministic SEC reserves by recognizing a “blind” energy test interpretation as other engineering information.

Conclusion

The cone of influence is composed of a radiating capillary structure that responds to each major limit with a shift in decay energy. Figure 14 illustrates the pressure derivative singularities in a buildup followed by an interference cone of influence from an offset well. These are typical of limit responses.

For a relatively small investment in wellhead instrumentation and several days of analysis, it was possible to resolve several reservoir issues within a few days of startup rather waiting for production plots to mature over months and years. It was possible to resolve a geologic question using transient material balances integral to the shockwave front method rather than having to wait for substantial reservoir depletion to occur. ***The test is simple to execute. Install a dual quartz pressure gauge, flow the well on a fixed choke, and sell hydrocarbons.***

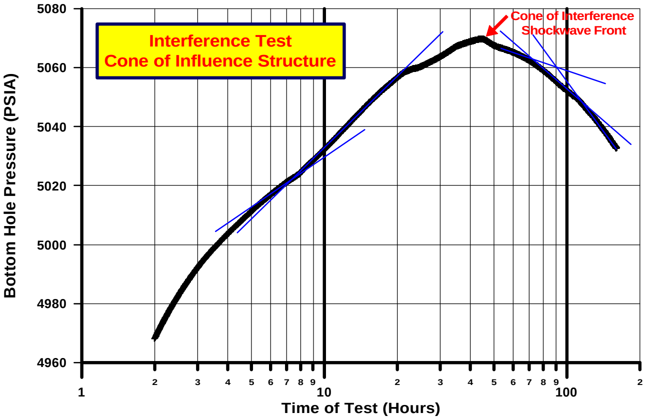


Figure 14. Data Singularities in an Interference Test

An early analysis for limits may impact future well interventions, add drilling locations, or in the case of a DST on a discovery, prevent setting a platform on an uneconomic reservoir. The more expensive the development of well locations, the more important testing can be to the operator’s bottom line. ***Accelerating the booking of reserves is just a part of using well testing to produce confirmation of reservoir volumes and dimensions or calibration of seismic images.***

References

1. Goldsberry, F. L., "Reservoir Conformance Developments – Capillary Shockwaves in Porous Media", 1998-*Fourth International Conference on Reservoir Conformance*, Houston, Aug. 1998.
2. Goldsberry, F. L., "Method for Producing Images of Reservoir Boundaries," U.S. Patent No. 6,041,017, U.S. Patent Journal, U. S. Patent Office, Washington D.C., Mar. 2000.
3. Goldsberry, F. L., Holland, J. T., Gross, W. E., Salzman, D. L., and Wildenstein, R. C., SPE 71456 “Reservoir Conformance: Tracking Gas/Water Contacts via Capillary Shockwave Fronts,” ATCE 2001, New Orleans, Oct. 2001.
4. Hurst W., Clark, J. D., and Brauer, E. B., "The Skin Effect in Producing Wells", 42nd Annual Fall Meeting, SPE of AIME, Houston, Oct. 1967.
5. Hurst, W., Haynie, O. K., and Walker, R. N., "SPE 145 Some Problems in Pressure Buildup", SPE of AIME, Dallas, Oct. 1961.
6. Hurst, W., “Unsteady Flow of Fluids in Oil Reservoirs,” Physics 5, January 1934.
7. Hurst, W., "SPE 2461 – Radius of Drainage Formula - A Technical Note", SPE of AIME, Nov. 1968.
8. Jones, Park J., “Drawdown Exploration Reservoir Limit, Well and Formation Evaluation” Technical Paper No. 824-G AIME, April 1957.
9. Jones, Park J., "Reservoir Limit Tests on Gas Wells", *SPE Gas Technology Symposium*, Tyler, Texas, July 17, 1961, p. 219.
10. Matthews, C. S. and Russell, D. G., "Pressure Buildup and Flow Tests in Wells", Henry L. Doherty Series Monograph Volume 1, SPE of AIME, New York, 1967, pp.87, 94-95.
11. Rowan, G., "SPE 918-G Wave Theory and Free Surfaces…A study of the Motion of Oil Reservoir Fluids", SPE of AIME, Oct. 1957.

SPE 71456

Reservoir Conformance: Tracking Gas/Water Contacts via Capillary Shockwave Fronts

Fred L. Goldsberry, WAVEX, Inc., Jeffrey T. Holland, Murphy Exploration & Production Co., William E. Gross, Chieftain International (U.S.) Inc., Rudy C. Wildenstein, Bellwether Exploration Co., and David L. Salzman, El Paso Energy Co.

This paper was prepared for presentation at the 2001 SPE Annual Technical Conference and Exhibition held in New Orleans, Louisiana, 30 September–3 October 2001.

Abstract

Much of the technology developed in the oil industry today is the result of cooperative engineering research efforts between operating companies with a problem and a technology developer with a potential solution. Often all parties discover the unexpected in the course of making physical measurements. In this case, the data captured showed the advancement in time of the limit singularity associated with a gas/water contact. The purpose of this paper is to share knowledge that may be useful to other operators, particularly those with permanent pressure gauge completions in oil and gas wells, or those operators who may use precision pressure gauges to monitor the flowing tubing pressure of a gas well.

The authors' companies have engaged in joint reservoir evaluation efforts to resolve rapidly declining production behavior in gas wells. The efforts were based upon pressure transient well evaluations utilizing the capillary shock front theory to map the gas cap at the time of the test. Two examples are presented that illustrate water contact boundary progression just prior to the onset of water production in each of the wells. The joint efforts have resulted in a better understanding of how to use operational shut-ins to monitor gas/water contacts from the inception of flow to the point of water encroachment. The goals of this effort are to see the end coming and perhaps delay the end in order to maximize well production. The secondary goal is to predict the end so as to avoid unnecessary post mortem efforts to repair a well that has watered-out.

The first case is a test of a deep well in Louisiana that was being evaluated for rapidly declining pressure and flow rate. The second well was offshore in the Gulf of Mexico that was being evaluated for geology and remaining reserves. The movement of the limit contacts over time is illustrated with a sequential limit mapping presentation. A second test is presented to show an overlay of two tests performed two weeks apart, just before the well watered out.

Introduction

Since the introduction of the first mechanical pressure gauge, pressure transient data has shown segmentation when plotted on a semi-log plot of pressure vs. $\log_{10}$ t. This led to early observations of specific abrupt changes in slope that were best described as mirror image wells or offset wells that appear to "turn on" when the boundary is contacted by the cone of influence. Often these singularity slope changes were noted as abrupt or "turning on a single data point." This was originally ascribed to friction in mechanical gauges. The advent of accurate electronic pressure gauges eliminated the argument for gauge friction and led to an investigation for other causes.

There were other problems noted by Professor Park Jones in the mid-1960's relating to the correlation of distance to the first boundary as observed and theoretically calculated. Where the interference or fault boundary was known with reasonable certainty through fault cuts in the well or interference patterns, the correct calculated distance was computed using the radius of investigation equation. Jones(6) published several papers that noted that the theoretical superposition derived distance solution for the doubling of semi-log slope at the first limit differed substantially from the observed distance. The first monograph by Russell and Matthews(7) contains both relationships but cites the radius of investigation more often in the text. About that time, Jones was pursuing volumetric calculations for a possible solution to the problem. These efforts ceased upon his death in 1967. Don Clark and Bill Hurst(3,4, and 5) made the principal author of this paper aware of this area of uncertainty and Jones' work in the early 1980's. About the same time as Jones, Rowan(8) was pursuing an investigation of surface wave mechanics as a possible explanation for routine observations in test data that were not explained by potential flow theory. Capillary shockwave theory is an extension of those earlier lines of reasoning.

Interference test data acquired in the late 1980's revealed that the segmented pattern is propagated from a producing well during the transient phase of a well test. This result is at variance with the traditional diffusion model, which mathematically cannot produce discontinuities in the solution. This led to work on the basic mechanics of capillary flow initiation, which produced the shockwave front model(1,2) used for this analysis. The shockwave is formed as flow is initiated. It is the mechanism that breaks down the initiating capillary pressure at succeeding pore throats allowing the depletion region around the well bore to expand to the reservoir limits.

A model for transient flow was developed that included this shockwave front and the capillary memory induced by the initiating capillary pressure. This is another way of describing the overcoming of the initiating shear stress. Fluid inertia was also included in the model. The result was a radial capillary model based upon fluid memory to the direction of flow. An energy solution was developed for the individual segments that allow limits to be detected and evaluated individually. From that came a limit by limit energy mapping technique that has been routinely applied to reservoirs for the past six years.

A consistent observation made over the years is that the pattern of slope shifts for each individual well is repeatable. In gas reservoirs we often see the gas/water contact as a discrete limit. In some cases, it has been possible to determine which limit is the water contact through detailed analysis of the irregularities in the semi-log slope shift. The principal use of the technology is to produce an image of the reservoir, which can be overlaid on the 3D seismic image to independently confirm the geologic geometry of a reservoir. Often when a well is behaving differently than the seismic image would suggest, it is possible to investigate the reservoir geometry independently in order to diagnose the possible problem. The pressure transient views the reservoir from the inside out, from the well to each of the boundaries. Many times, depositional problems such as braided channels can be described by pressure responses that are too small to be defined seismically.

In the year 2000, two tests were conducted and evaluated to assess strange behavior in producing wells. In each case, pressure transients two to three weeks apart saw a change in the slope shift pattern. Following these events one well began to produce water and the other watered out completely. The purpose of this paper is to share a practical method for monitoring the movement of gas/water contacts using spaced pressure transient measurements.

Case 1 – Deep Louisiana Test

The subject was a newly completed well that was showing signs of possible accreting skin damage or restricted reservoir size. The test was designed to take advantage of an operational shut-in. This would allow the well to be stabilized, then to be flowed for two-weeks to assess the reservoir for permeability, skin, and limits. Following the drawdown, a four-day buildup was planned to confirm limit contact times.

The results initially appeared to be inconsistent. It is not unusual for a buildup to suffer derivative suppression when compared with the drawdown. This is the result of a cone of influence continuing to grow behind the original shock front while the pressure in the region immediately around the well is building. Horner analysis overcomes this problem for very short duration DST's. The energy map developed from the drawdown is more likely to be the correctly scaled image. The ΔP plots for the drawdown and buildup will overlay about one third of the time.

It was clear that a limit had occurred at 0.45 hours and that two more had occurred during a data collection gap between 9 and 21 hours. The before and after slopes projected to a point at 16 hours. This would have been a single limit of 110° of curvature or almost a right angle. The system became linear after this point. The data is shown in Figure 1 with the limits marked by triangles. The resulting energy map is shown in Figure 2. The presence of a limit often looks like a small choke change followed by a doubling of the semi log derivative when no choke change has actually occurred. The buildup was analyzed independently, then compared to the drawdown test.

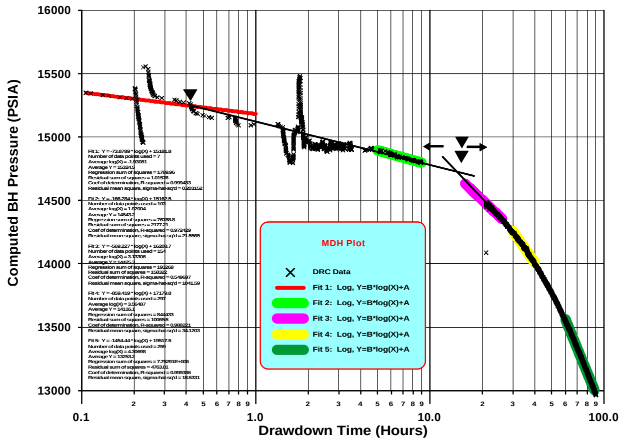


Figure 1. Drawdown Data with Limits Marked

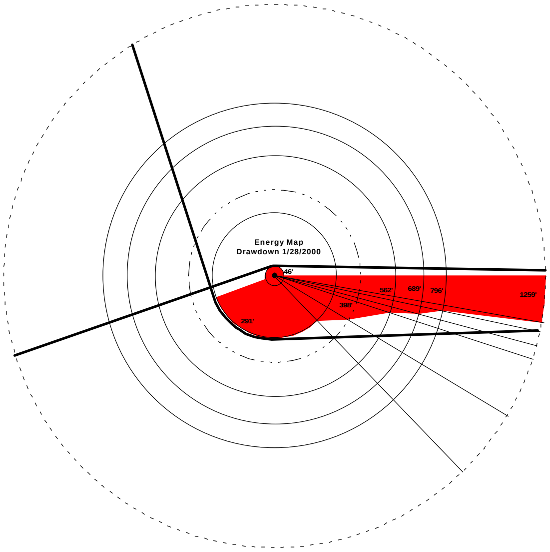


Figure 2. Energy Map Derived from Drawdown

The buildup of Figure 3 indicated a larger permeability that further suggested the reservoir was growing at the end of the test. The buildup repeated the limit at 0.42 hours and also showed a second clear limit contact at 0.9 hours. There was a pressure anomaly shown in the buildup that would be consistent with a small non-sealing fault. The derivative slope recovers its original value before 10 hours indicating the non-sealing nature of the resistance to flow anomaly.

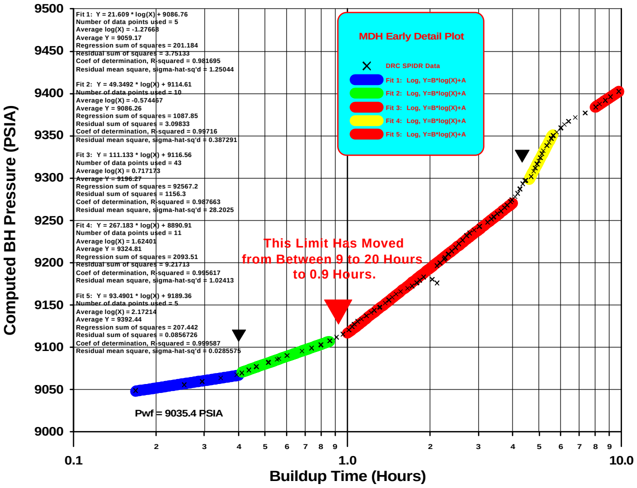


Figure 3. Early Buildup MDH Plot Detail

The data continue on Figure 4, which indicated a clear limit contact at 16 hours. But this is a straight limit not a corner. This data was mapped without correcting for the derivative slope suppression as a quick look at what was occurring. This is presented below in Figure 5. Both tests map as parallel limit systems but the maps show different near well limit configurations. These findings were communicated to the operators and partners.

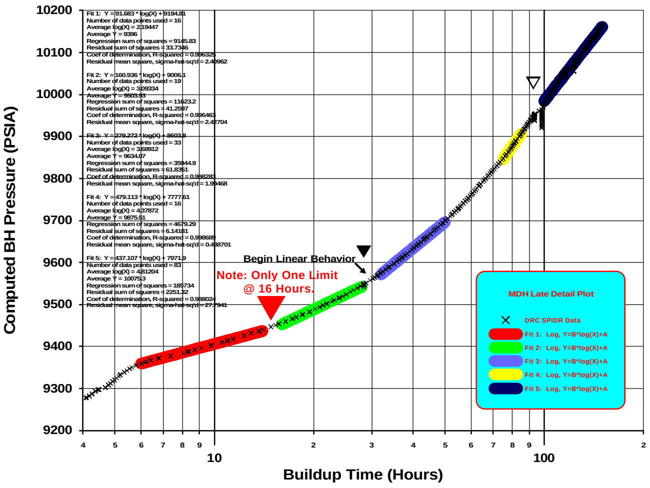


Figure 4. Buildup MDH Plot Detail after 10 Hours

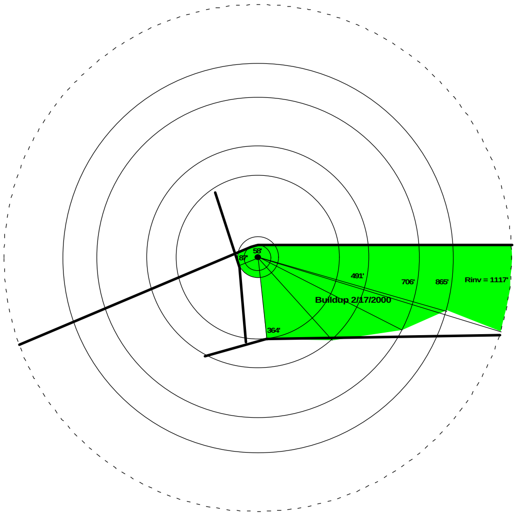


Figure 5. Energy Image Based upon Buildup

The response was a production plot from the operator, which showed that the well had just begun to increase water production immediately prior to the buildup. The water rate then increased after the well was placed back on production. Figure 6 shows the overlay of the two maps. From this it is clear that one of the limits had moved relative to all of the others. If the buildup map is shrunk to the same dimensions of the drawdown map, the change would be more pronounced.

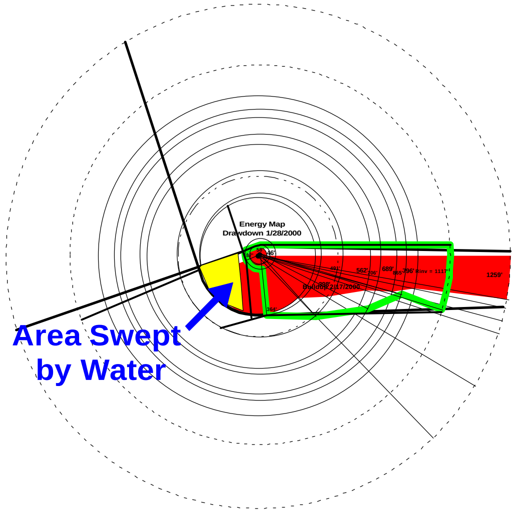


Figure 6. Overlay of Energy Maps

In spite of the discontinuous nature of the drawdown data, it is clear that a limit moved from somewhere in the 9 to 21 hour range to the 0.9-hour range. Had we acquired initial drawdown data it is reasonable to assume that this contact may have moved a considerable distance over the prior 4 months. Our timing involved a significant stroke of luck to be in the right place at the right time to see this dramatic change. In larger and broader reservoirs, we would expect to observe movement over longer periods of time. In a water drive reservoir with an expected life of say 5 years, one would expect annual or semi annual buildups to show relative movement of a gas/water contact. The subject well continues to produce water. It apparently is a very long parallel limits system as it rebuilds toward original pressure repeatedly only to follow the same repetitive transient when on production. Figure 7 represents an overview of the entire test sequence. It is a picture that summarizes the events better than words.

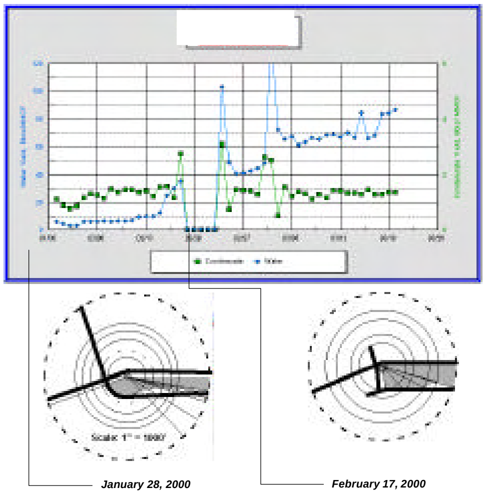


Figure 7. Production Summary in Pictures

Case 2 - Comparison of Two Succeeding Buildups

The second example required no mapping exercise. We knew the result before the report was written. The second test was offshore in the Gulf of Mexico. This test had a different objective in that the mapping exercise was to confirm the reservoir geology of a mature field to assess whether any gas was being left behind. Five wells were tested producing a high degree of conformance to the map. The last well of the series presented a surprise. A buildup test was conducted for reservoir limits, then the well-placed on production for three weeks. Just before the pressure gauge was to be removed from the tree, a final shut-in of the well occurred for four days. The gauge was returned with a note that it had watered out during shut-in and was now dead. Figure 8. Shows the ΔP Vs Log_{10} t plot for the first buildup with the second ΔP Vs Log_{10} t curve just prior to watering out.

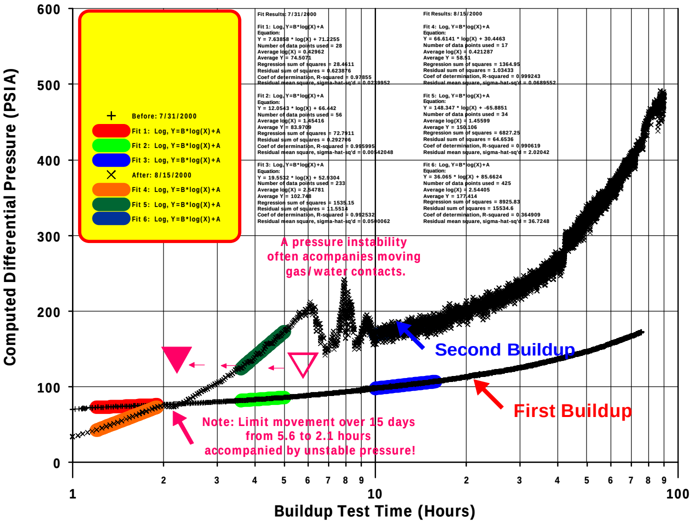


Figure 8. Direct Overlay of Sequential Buildup Tests

The purpose served by this plot is to demonstrate that a process as simple as overlaying successive data sets from a series of buildups or drawdowns can produce an early warning that something is moving toward the well.

Conclusion

The options here are quite broad. In dealing with water production, we often have different situations that require different operational responses. Water coning involves restricting flow to optimize water disposal costs or perhaps to minimize water production. Many companies operate with a view to increase flowrate in gas reservoirs in order to outrun water. In some cases distortion of an approaching gas/water contact may mean reducing flowrate to prevent fingering as an agent of premature completion failure.

As artificial intelligence progresses in downhole applications, it will be possible to expect a smart well completion to measure its reservoir limits during each operational shut-in and respond appropriately by restricting flow or by opening the choke automatically. It may be programmed to provide an alarm and diagnostic to the production engineer.

A final image is presented in Figure 8. This is an image of a shock front passing through a static observation well. Pressure depletion begins in a reservoir only when fluid begins to flow from a pore. For this to happen, the initial stress at the pore throat must be overcome to initiate flow from the pore. The breakdown of this small initial fluid shear stress in successive pore throats is a slow process. It represents a moving barrier to depletion or better said, ***"a moving reservoir boundary."***

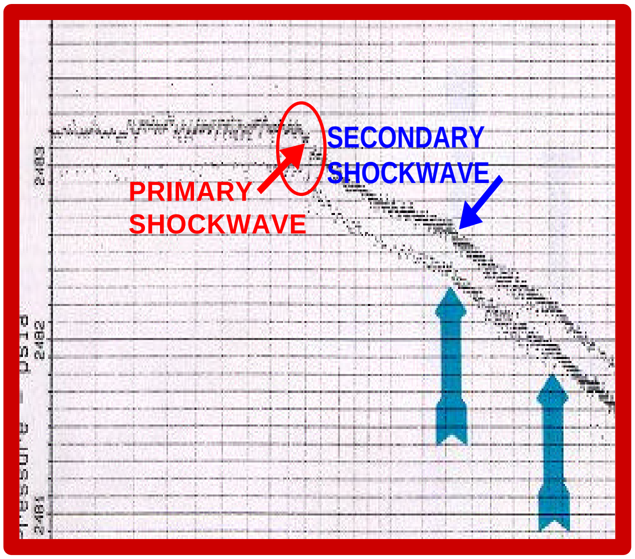


Figure 9. Primary Capillary Pressure Shockwave *Located at $R_{inv} = 2(ht)^{1/2}$ (Reference 1)*

These pressures produce an induced radial anisotropy that leads to the necessary formation of secondary capillary shockwave fronts as the moving boundary encounters the actual sealing boundaries or water boundaries of the reservoir. It is the formation of these secondary depletion regions around the well bore that provides the basis for discrete limit detection and dimensioning. ***This small capillary pressure step is the physical event that exists at the radius of investigation.*** By using this diffusion wave, it is possible to track gas/water contacts using successive shut-in and flow periods.

References

1. Goldsberry, F. L., "Reservoir Conformance Developments – Capillary Shockwaves in Porous Media", 1998-*Fourth International Conference on Reservoir Conformance*, Houston, Aug. 12.
2. Goldsberry, F. L., "Method for Producing Images of Reservoir Boundaries," U.S. Patent No. 6,041,017, U.S. Patent Journal, U. S. Patent Office, Washington D.C., Mar. 2000.
3. Hurst W., Clark, J. D., and Brauer, E. B., "The Skin Effect in Producing Wells", 42nd Annual Fall Meeting, SPE of AIME, Houston, Oct. 1967.
4. Hurst, W., Haynie, O. K., and Walker, R. N., "SPE 145 Some Problems in Pressure Buildup", SPE of AIME, Dallas, Oct. 1961.
5. Hurst, W., "SPE 2461 – Radius of Drainage Formula - A Technical Note", SPE of AIME, Nov. 1968.
6. Jones, P., "Reservoir Limit Tests on Gas Wells", *SPE Gas Technology Symposium*, Tyler, Texas, July 17, 1961, p. 219.
7. Matthews, C. S. and Russell, D. G., "Pressure Buildup and Flow Tests in Wells", Henry L. Doherty Series Monograph Volume 1, SPE of AIME, New York, 1967, pp.87, 94-95.
8. Rowan, G., "SPE 918-G Wave Theory and Free Surfaces…A study of the Motion of Oil Reservoir Fluids", SPE of AIME, Oct. 1957.

Reservoir Conformance Developments - Capillary Shockwaves in Porous Media

Prepared for the 4th International Conference on Reservoir Conformance August 12, 1998
Profile Control
Water and Gas Shut Off
by

Fred L. Goldsberry, P. E.
President,
WAVEX^{SM}, Inc.
5625 FM 1960 West, Suite 405
Houston, Texas 77069
Wavex@WT.net
281-397-7010

Have you ever seen something in pressure transient data that you could not explain?

Summary

In 1987, an early model Panex memory pressure gauge was placed in an observation well. It captured the passing of the edge of a cone of influence from the **only well producing** in that reservoir or on the platform. The observation well was at a distance of 2000' in the same channel sand as the producer. The gauge recorded no pressure activity or decline for 28 hours, then exhibited a step change in pressure followed by a steep decline. The subsequent buildup recording in the producing well revealed a series of step pressure responses accompanied by slope changes. Flow throughout the test was steady. When the semi log plots of these disturbances were overlaid, they matched. These abrupt changes in slope were correlated to known geophysical discontinuities. The data confirmed previous observations by the author that a cone of influence contains measurable pressure perturbations or shock waves that separate regions of constant hydraulic fluid power dissipation. The outermost or **Primary Capillary Shockwave** propagates in a manner that is coincident with the traditional radius of investigation. This paper is confined to a description of the **Primary Capillary Shockwave** that is the basis for a more complete transient model developed by **WAVEX**^{SM}, Inc. to describe the expansion of the cone of influence as it initiates flow through porous media.

$$\textbf{Radius of Investigation} = 2\,(\eta * t)^{1/2}$$

Introduction

As the capillary shockwave encounters an order of magnitude decrease in fluid mobility, the cone of influence responds within the constraints of the system of capillaries of which it is composed. Normally, a choke is used at the well head to maintain constant flow rate. The loss of growth at a sealing boundary results in the formation of a secondary cone of influence bounded by its own **Secondary Capillary Shockwave** discontinuity boundary. The new cone maintains constant flow by making up the flow loss from the non-growing capillaries. The secondary boundary grows at a velocity commensurate with the growth of the outer or **Primary Capillary Shockwave** boundary. The system of radiating capillaries observes the laws of thermodynamics; that is, it observes the **First Law: Conservation of Energy** throughout the capillary system and the **Second Law: Distribution of Thermal Energy Generation** as hydraulic energy is dissipated by fluid moving through the capillaries to the producing well. The radiating system of capillaries maintains stability through two mechanisms: fluid momentum and electronic membranes across each pore throat along the established radial streamlines. The system maintains radial stability so long as some portion of the primary wave is advancing. Each limit encountered results in a regeneration of the cone of influence.

The cone of influence is composed of **kinematic** capillary shockwaves bounding regions of **kinetic** energy dissipation passing through **porous rock**. This area of engineering physics is properly named ***Petroporokinekinetics*** but is now commonly referred to as **"Bubble Theory"**. The method began as **wave exploration** hence the Service and Trade Mark name **WAVEX.** The scope of this paper will be to derive the **Primary Capillary Shockwave** velocity equation and develop the easily recognized relationship for permeability using a wave mechanics based approach and an energy solution.

Observation of a Cone of Influence

A unique experimental opportunity presented itself about ten years ago to observe the growth of a cone of influence from the vantage point of the well bore of the producing well and two offset wells at 2000 ft. and 4000 ft. distance. The following data plot depicts the pressure response in the static observation well at a distance of 2000 ft. The time scale originates at the same time that the producing well was opened to flow. The double image plot is due to a thermistor cycling between temperature outputs by .1 degree Fahrenheit. The relative value of each pressure point is accurate to less that .01 psia. The pressure plot was remarkable at the time for several reasons. The pressure response begins not asymptotically as we expect from traditional diffusion theory assumptions, but as a step pressure drop followed by a small half sine wave dynamic. The plot demonstrates what appears to be a well storage effect 2000 feet into the formation. The pressure plot assumes constant a semi log derivative slope before experiencing another step pressure drop and an associated slope increase. And so on.

The observation well was not affected by the offset producing well for the first 28 hours of flow. The producing well was completed in a half Darcy sandstone and flowing dry gas at 17 Mmscfd. In this instance it was deemed prudent to fall back on that tried and true method of explaining the unexplainable; that is, to blame the pressure instrument. Subsequent re-calibration determined that the instrument "saw what it saw". The step changes were real, as were the changes in the semi log plot slopes. This pattern was atypical of any failure mode known to the instrument manufacturer. Step pressure changes associated with semi log slope shifts were then noted as common occurrences in pressure transient data.

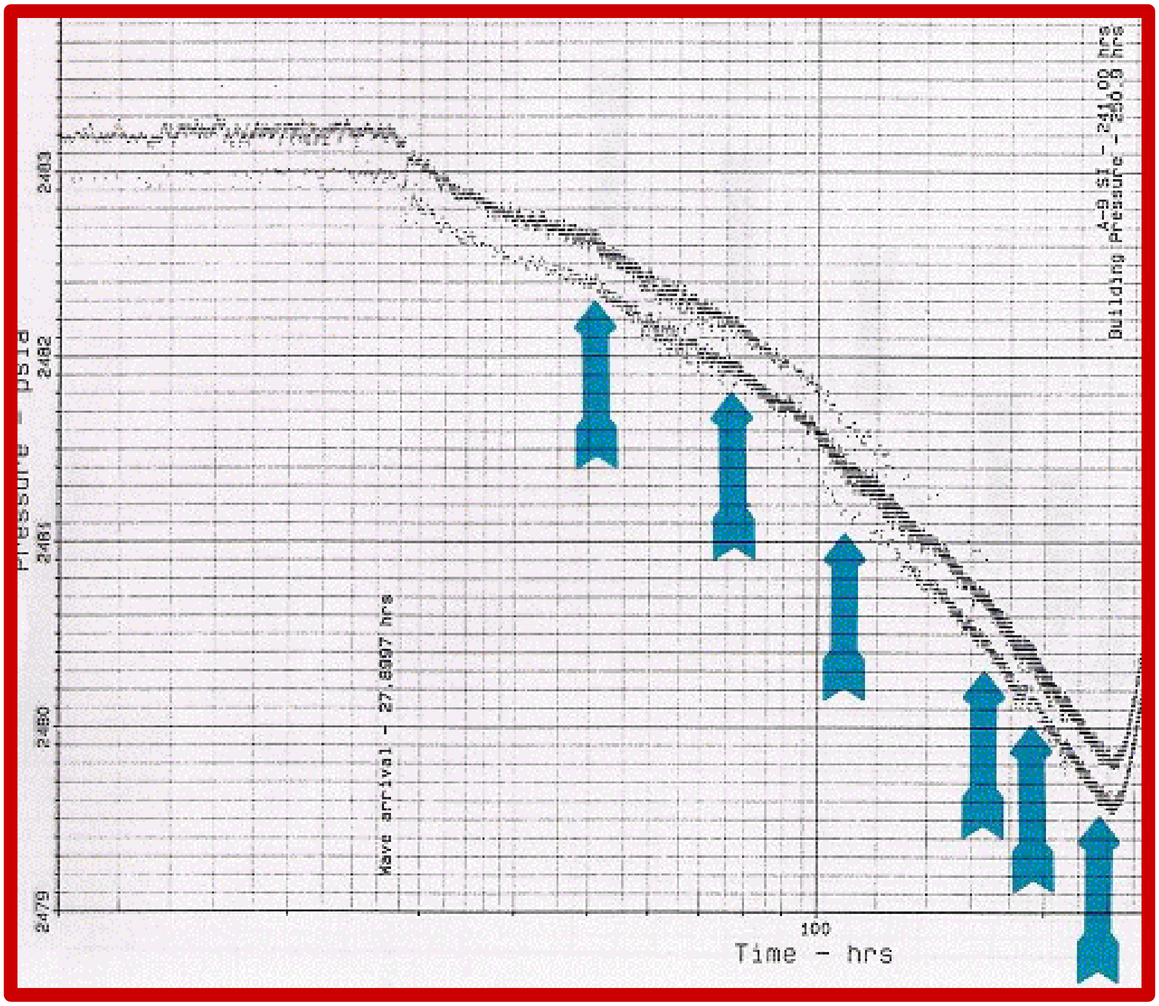


Figure 1 - A Single Well Drawdown Observed in a Static Well 2000' Away

A second instrument had been placed in the producing well. It recorded a strange set of unusual step pressure pulses and semi log slope changes beginning about one hour after shut-in. Examination of this instrument found it to be in calibration and operating within specifications. The plot of the buildup data has been made on an inverted pressure scale so that the ***drawdown in the observation well*** and the ***buildup in the producing well*** may be ***overlaid.***

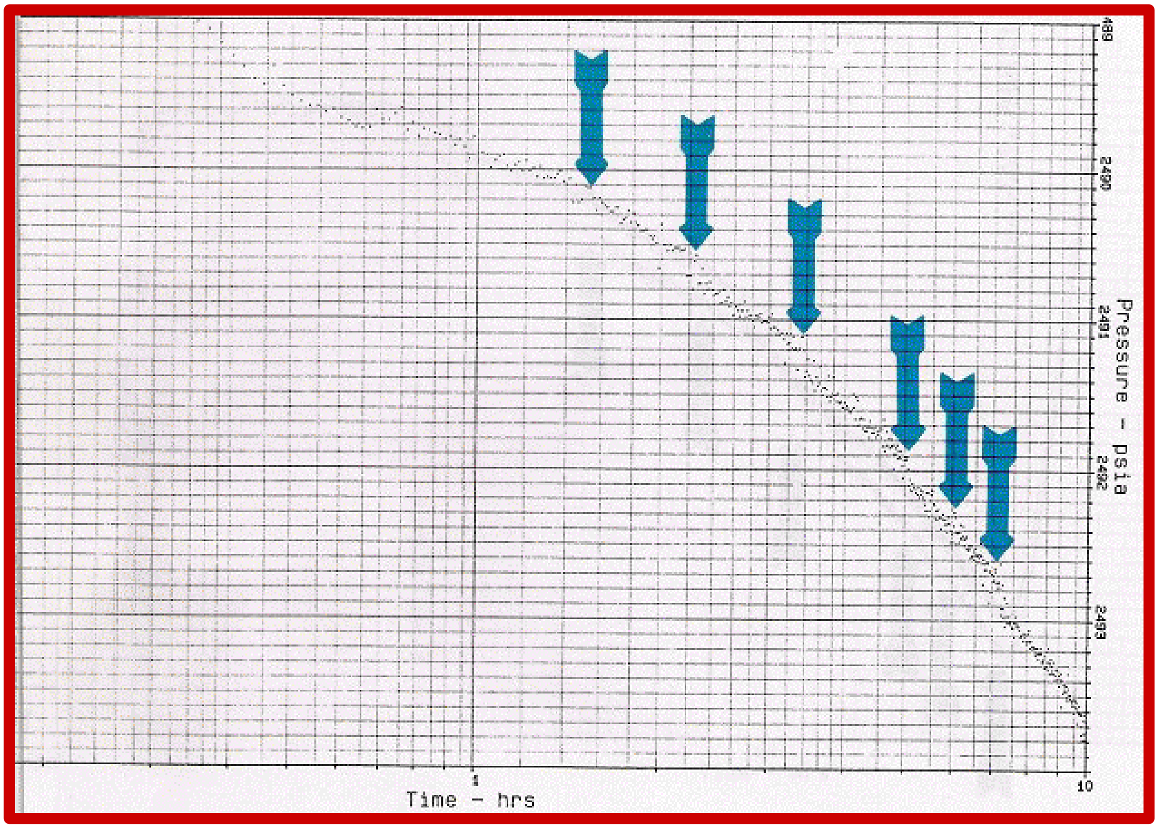


Figure 2 - Pressure Buildup in the Producing Well Plotted on an Inverted Scale

The plots were printed upon transparency material. The blue arrows were placed to note the small step anomalies in the data. The next step is to overlay the two transparencies and scan the resulting overlay.

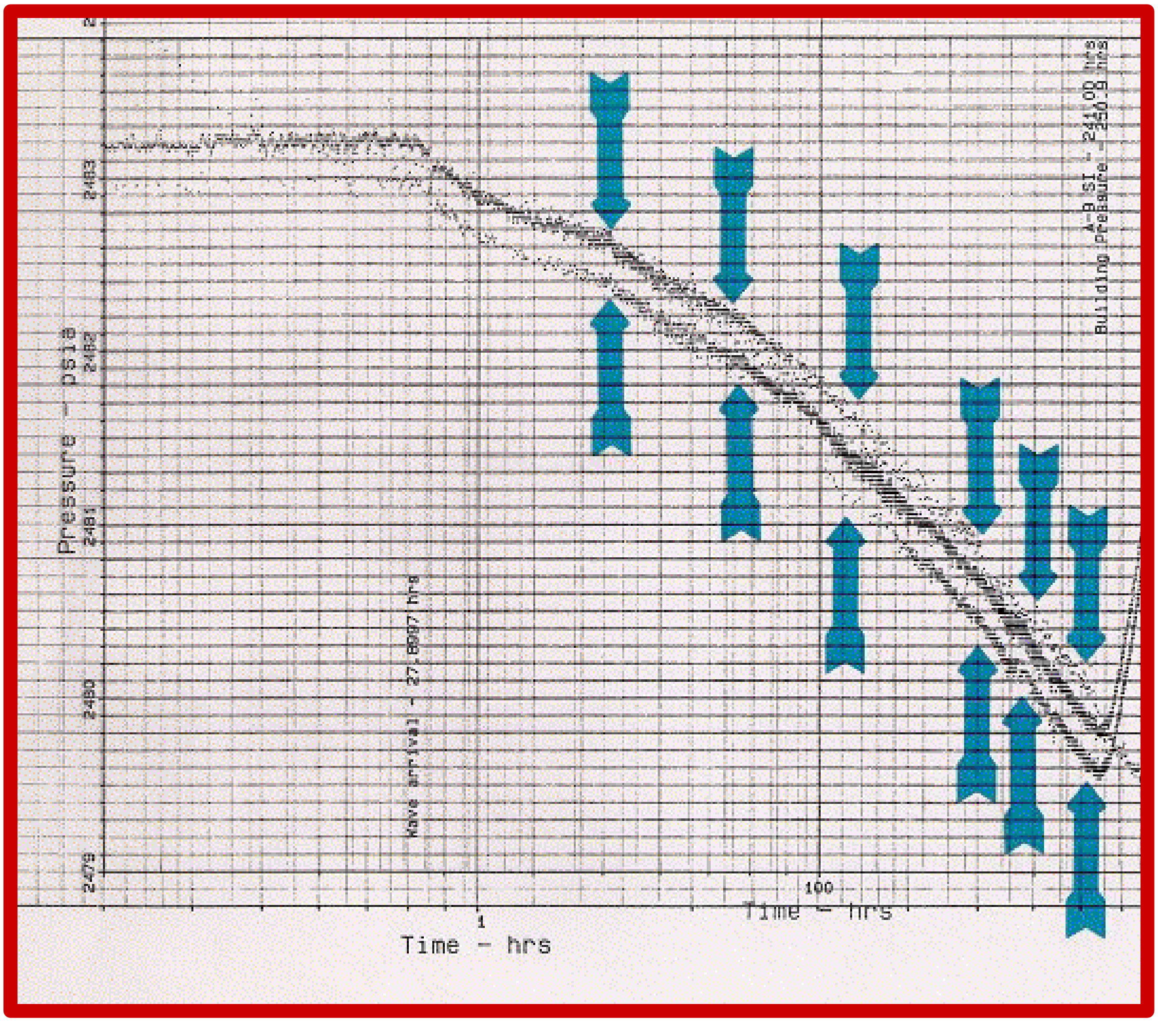


Figure 3 - Transparencies Overlaid

These plots contain a large number of striking coincidences. Two different wells, two different gauges, very smooth and constant flow, plus a long delay in pressure communication through an extremely permeable reservoir result in the same pattern of pressure anomalies. To compound matters further, a third pressure gauge used in a surface readout mode on wireline was placed in a third well located 4000 feet from the producer. The SRO gauge recorded no change in pressure for half a day after being placed on bottom. Prior to the passage of a step pressure shift followed by a pressure decline, the only observation was that of electrical noise. The appearance of the step was later correlated to approximately 104 hours after the producer was opened to flow. The SRO gauge observed the pressure response for a half day before it was pulled. The test had demonstrated reservoir continuity and had met its objective. The data plots contained more questions than answers. Thus, being unexplainable to the author, these plots were consigned to the bottom of a file cabinet drawer for the next two years. A decade ago these plots were retrieved to become one of many pressure data and geophysical map sets from different sources that became part of the road map for **"Bubble Theory"** development. This paper will be confined to a basic derivation for the properties of the first shockwave or the edge of the cone of influence. It will be referred to as the **Primary Capillary Shockwave.**

Theory

The only time a reservoir is truly at steady state is when it is at original pressure before production. **Darcy's Law is a steady state relationship** that measures the resistance of a bulk fluid flow through porous media. Reservoir fluid in place is a stable mass cohering to itself and adhering to the formation through electronic forces. These forces are stronger across small distances than large ones. The fluid stress required to initiate flow through porous media will be greater across the pore throats than the pores of the formation itself. Polar molecules will be in electrostatic alignment with the formation and each other. Surface tension is a manifestation of the cohesion of a fluid for itself in terms of energy per unit area that must be applied to penetrate the fluid body. The dimensional units for surface tension then simplify to force per unit length. This convention has always been more convenient for teaching and working fluid droplet and bubble foam problems without having to explain the Principle of Virtual Work. ***Electronic forces exist throughout the fluid volume, not just at a free surface.***

Before the fluid can flow from a pore, the electronic forces at the pore throat must be overcome. The electronic membrane static differential pressure must be overcome before fluid flows from the pore. As the pressure in the pore depletes, the next pore throat electronic membrane is stressed until it too ruptures, propagating the cycle.

Deplete…rupture…deplete…rupture...deplete...rupture and so on as the capillary grows. An example is the head of foam on a soda. The bubbles at the surface break exposing the next layer and so on. Welcome to "Bubble Theory".

The rupturing of a bubble could best be described as a shock. A pattern or front of bubbles is a wave. In thermodynamics, it is common practice to describe certain classes of energy events as shock waves. Adiabatic shockwaves such as those that govern the behavior of every oil field choke are described in terms of conditions before and after, not during the shock wave event.   The rupture of the bubble front can be described as a before and after event or shock. The conditions across the shockwave element *(face pressure, fluid incorporation per unit area, and fluid flux away from the wave)* can be described as a steady state process. The coordinate system used is tied to the stream element as it incorporates new active reservoir volume. The element recognizes time-volume flux as a simplified version of a moving coordinate system. The cone of influence system is measured with respect to its shockwave edge.

The Bubble rupture plane advances against a constant pressure boundary condition. As pores open, active elastic flowing fluid mass is added to the cone of influence. In order to deplete the pressure in the leading pore throats, fluid must flow away from the rupture front. As this is a steady process insofar as our wave front of ΔA is concerned; Darcy's Law may be applied without the simplifying assumptions. The rupture front element is actually the head of a real physical stream tube. It grows at steady state conditions and reckons time-distance in terms of incorporated fluid volume. The sides of the element are theoretical and physical stream functions. The membranes along the streamlines define a physical capillary wall. Each capillary propagates radially outward along the path of least resistance while fluid begins to flow radially inward to the producing well. ***Porous reservoir formations have a mechanical memory of the direction of flow.***

Rupture fronts have been measured in the core laboratory as Haines' Jumps since their discovery in the 1940's. Classic reservoir mechanics developed by Hurst and others in the 1930's was never modified to incorporate these basic factors of physical fluid flow through cores. This paper represents an effort to include a discrete flow initiation pressure in the porous media flow model.

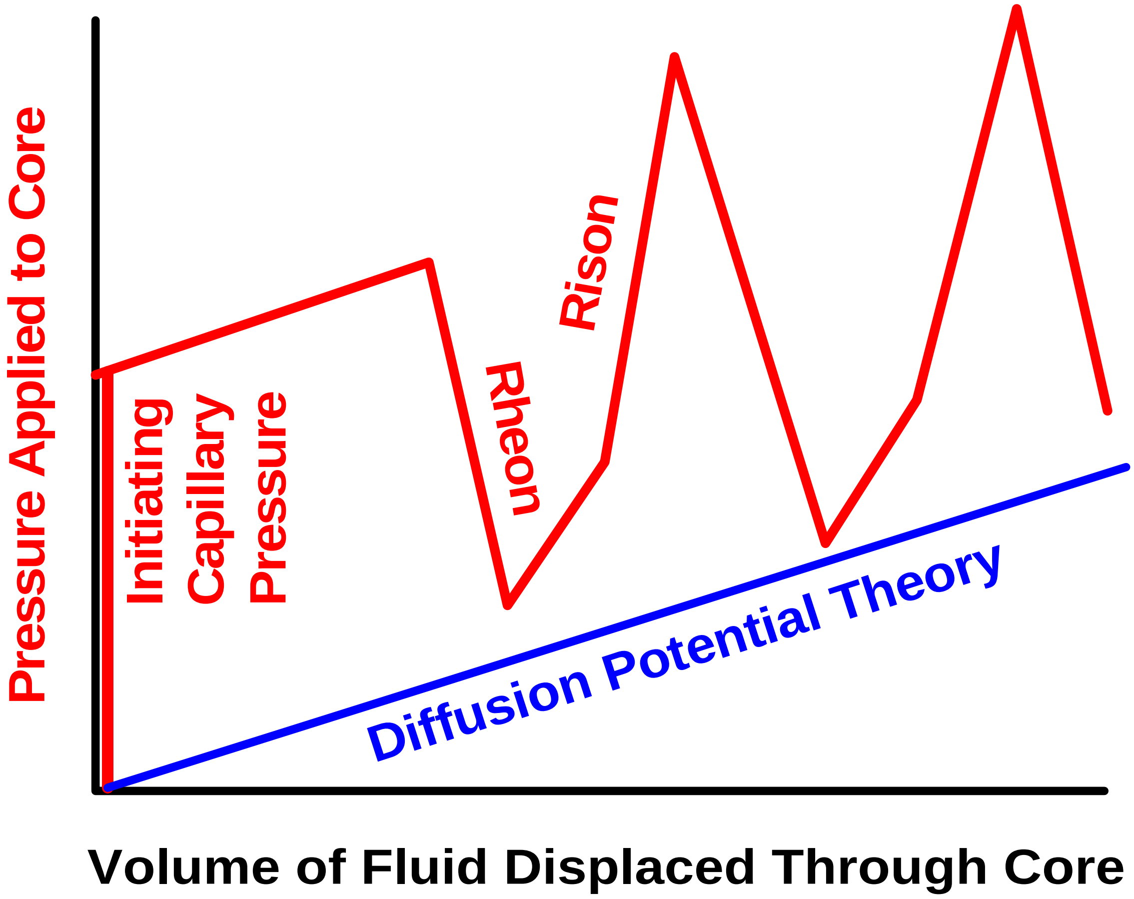


Figure 4 - Haines' Jumps Laboratory Measurements of Flow Through Porous Media

Let us consider the basic moving boundary element of the cone of influence.

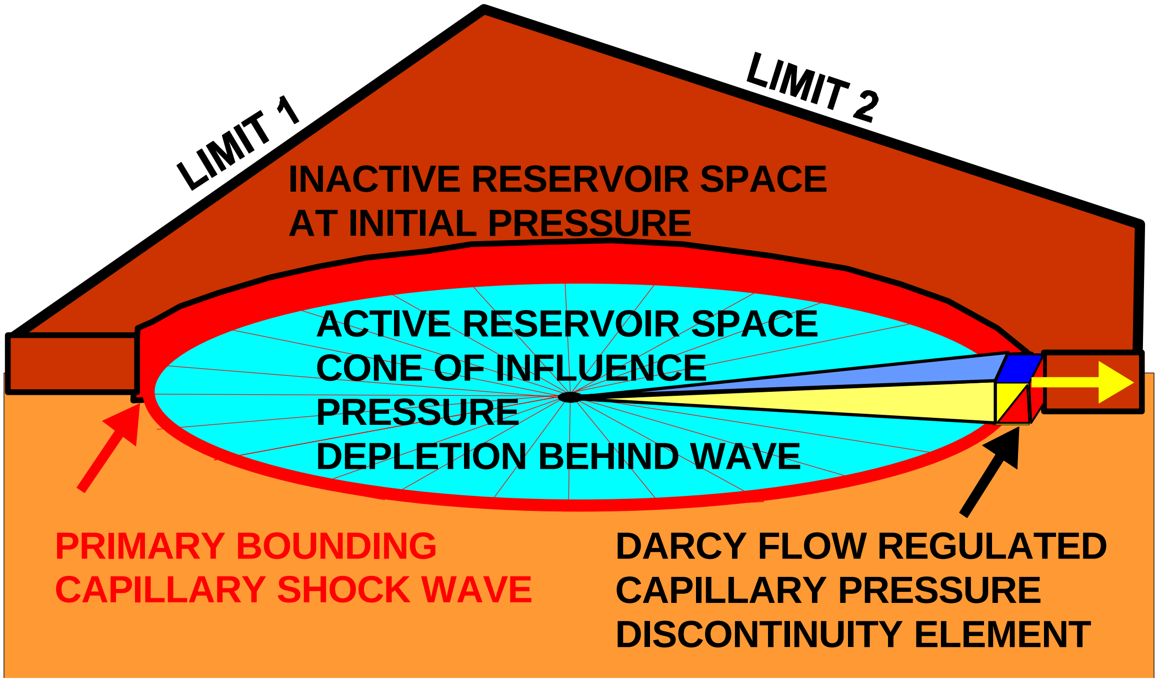


Figure 5 - Infinite Acting Radial Growth Cone of Influence and Element

The element has the sole function of incorporating the static reservoir volume that exists outside the shockwave front into the active cone of influence. There is no flow through the sides of the element. The front is the bubble rupture plane and the back face accommodates Darcy flow back to the well. The shockwave depletes the reservoir pressure by ΔP_c and then moves on until it can propagate no farther. Three basic principles of physics govern the Capillary Shockwave: Continuity, Energy Conservation, and Darcy's Law resistance to flow.

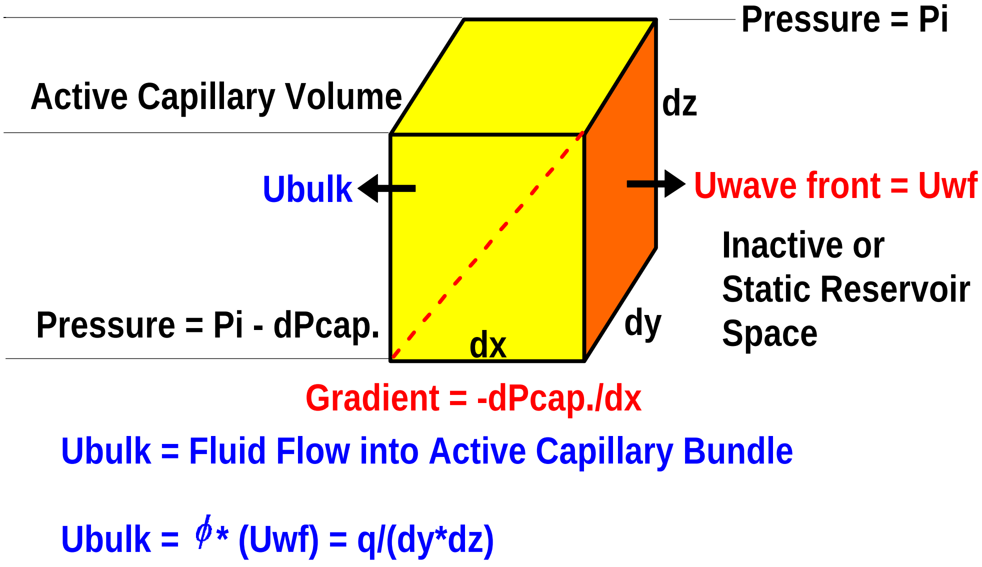


Figure 6 - The Shockwave Element: Steady State Constant Flux Streamtube Head

First, let us consider the fact that we do not know the value of ΔP_c. Also the effective length of the element is not known, although one could assume it bears some relationship to actual pore length. For this example it is sufficient to recognize the system as the head element in a bundle of real bubble membrane defined capillaries.

Continuity of fluid and formation flow into the element and fluid from the element based upon shockwave front velocity:

$$q\ /\ AREA_{\text{Element Face}} = U_{\text{Bulk}} = \phi * U_{\text{Wave Front}}$$

Darcy's Law:

$$U_{\text{Bulk}} = (-k/\mu) * dP/dx$$

The compressibility form of the **Energy Equation**:

$$dP_c/dV = -1/(C_t * V)$$

The **Energy Equation** rewritten in terms of constant flux per unit area and time:

$$dP_c/dx = -1/(t*C_t*U_{wf}) \;,$$

Where, $U_{wf} = q/(\phi*\Delta A)$, $dV = \phi*\Delta x*\Delta A$, and $V = q*t$

Restating Darcy's Law above and eliminating the term dPc/dx by substitution of the Energy Equation based equivalent:

$$\phi*U_{wf} \;=\; (-k/\mu)*dP_C/dx \;=\; (-\,k/\mu)*(-1/(t*C_t*U_{wf}))$$

Rearranging the terms to solve for the capillary shockwave front velocity:

$$U_{wf}^{2} \;=\; k/(\phi*\mu*C_t*t) \;=\; \eta\;/\;t$$

And Solving for U_{wf}:

$$U_{wf} \;=\; (\eta\;/\;t)^{1/2}$$

It is of interest to note that the capillary entry pressure does not appear in the final wave front equation. It does appear as part of the pressure depletion and in tight reservoirs does control the ultimate limits to which the cone of influence can grow. We know from observation of actual well tests that the propagation of the disturbance is independent of well flow rate. Classic diffusion theory predicts this outcome as well. It is sufficient for the entry pressure, Pc, to exist. In high gradient or low gradient situations the propagation of the wave front is solely a function of the hydraulic diffusivity and the volume of the stream tube capillary bundle activated by the shock front. The volume is interchangeable with apparent time or volume divided by flow through the front face of the shock element

Finally, by integrating the wave front velocity from **0** time to **t**, the position of the wave front from its source is derived. It appears that the capillary shockwave position with time coincides with the classic radius of investigation. The radius of investigation was assumed to be the equivalent of a hypothetical expanding cylindrical volume at semi steady state conditions. The ***Capillary Shockwave is a real physical phenomenon*** that forms an actual expanding volume of connected fluid around a well. The reservoir outside this volume is not a part of the depletion energy of the well.

$$L = \int_0^t U_{wf}\, dt = \int_0^t (\eta/t)^{1/2}\, dt = 2(\eta t)^{1/2}$$

Let us examine the traditional case of a vertical well drilled between two horizontal sealing plane boundaries. We can calculate the active fluid volume as:

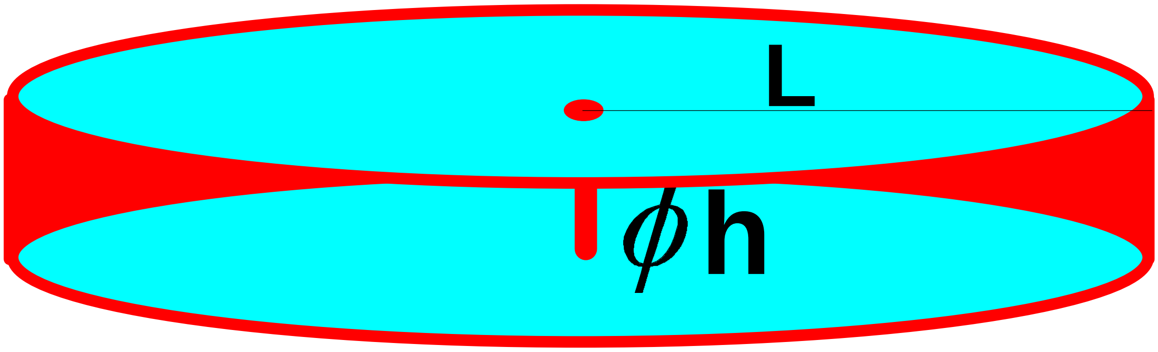


Figure 7 - Cylindrical Volume Around Well

$$\text{ACTIVE VOLUME} = \phi\, h\, \pi\, L^2 = \phi h 4\pi\eta\, t$$

Returning to the energy equation for a closed system observing the second Law of Thermodynamics:

$$dP/dt = q/(Ct^*\text{VOLUME})$$

By substituting the active volume incorporated by the shockwave over time and ***integrating for pressure with respect to time from a reference point at a radius of one hour*** (*traditional convention to avoid the singularity of Log 0*) ***to time t:***

$$P_i - \Delta P_c - P(r_{obs},t) = \int_{t_{obs}}^{t} -\{dP/dt\}dt = \int_{t_{obs}}^{t} \{q/(C_t \phi h 4\pi\eta t)\}dt$$

Where, $t_{obs} = t_{observation} = r^2_{observation}/(4\eta)$

Note that the pressure at any given point of observation does not change until that point is incorporated by the primary shock wave. That is, $P(t) = P_i$ from $0 \leq t \prec t_{obs}$. At the time of the shockwave wave passage at $t = t_{obs}$, $P(t) = P_i - \Delta P_c$. After the passage of the wave front at $r_{observation}$ then:

$$P_i - P(r_{obs},t) - \Delta P_c = \{q/(\phi h C_t 4\pi\eta)\} \; ln\,(t/t_{obs})$$

Where, $t \geq t_{obs}$

By replacing hydraulic diffusivity with its constituent terms and canceling, the radial flow equation for the semi log slope M_1 emerges. This is one of the most recognizable and universally respected traditional relationships in pressure transient analysis. However, it was derived by following a different solution approach. The shockwave solution did not require the concept of critical inertial damping to write a field differential equation because the Primary Capillary Shockwave is the only physical phenomena in the reservoir that acts at steady state. Because the Primary Capillary Shockwave moves several orders of magnitude slower than fluid in the capillaries, a lumped second law based energy solution is appropriate. Field observations bear these assumptions out. Consequently there are no error functions to calculate or Bessel's functions terms to drop to arrive at this basic relationship.

$$P_i - P(r_{obs},t) - \Delta P_c = \{q\mu/(4\pi kh)\} \; ln\,(t/t_{obs})$$

By using first principles, it is possible to derive the radius of investigation and the relationship for permeability from the semi log pressure plot slope without cumbersome solutions to differential equations or by ignoring capillary entry pressure as being small and inconsequential. Capillary entry pressure is a small discrete initial stress that provides a stabilizing control function for the reservoir similar to the flight control provided by the fletching on an arrow. Capillary entry pressure guides the ever increasing fluid momentum of the expanding cone of influence. It provides the formation with flow memory.

The kinematic properties of bounding capillary shockwave result in an accurate measurement tool. Because the wave is slow moving and bounds a radially confined system, it is possible to measure ***accurate distances*** to individual reservoir limits and to determine basic information about the ***shape of each limit*** at its point of contact with the shockwave. This solution also represents an answer to the questions raised in numerous papers by Park Jones of the University of Houston in the 1960's. Jones recognized during many years of field experiments that the proper distance to a known interference limit was given by the radius of investigation equation $\mathbf{2(\eta t)^{1/2}}$ while the slope intercept method derived from superposition of infinite diffusion fields yielded a coefficient of **.749** instead of **2.** The diffusion solution predicts a long smooth continuous transition between semi log slopes in infinite reservoirs. For actual bounded reservoirs, diffusion solutions do not exhibit discernible faceting or semi log straight sections after the first limit. As pressure gauges improved, the semi log slope shift became sharper and sharper. As seismic data and processing have improved, the resulting images when correlated with test data support the radius of investigation coefficient distance to the limit. ***Capillary Shockwave Theory explains Jones' field observations.***

The Capillary Shockwave presents a solution that is based upon an expanding volume model rather than the relaxation model of a fixed boundary field. The pore throat flow initiation pressure represents a confining mechanism for flow between capillaries as well as an outer shockwave boundary. Once each capillary is opened, the diffusion process holds along the opened capillary pathway. The growth of capillaries is much slower than the communication of pressure and subsequent redistribution of mass within the capillary. For practical engineering purposes, each capillary is assumed to be at near semi steady state as it grows. As each capillary reaches a sealing boundary and can no longer grow, it produces less fluid to the well bore. If flow demand from the well is relatively constant, the well is constrained to produce fluid in the only way it can, by increasing flow from all capillaries. This increased flow requirement initiates a **Secondary Capillary Shockwave** that proceeds outward from the well. The derivation of the mechanics of this model and its supporting pressure data will be reserved for another time.

Summary

A physical solution for the properties of the shockwave front observed in actual field data describes a phenomena that regulates growth of the cone of influence. Perhaps the best description for this technology is ***"The Path Not Taken."*** In this case the entrance to the path lay hidden in the 1930's. Haines did his work on core displacement a decade later, after the fixed field diffusion solution path was well established. Fixed field diffusion potential theory appeared to work well for long term semi steady state reservoir depletion. Transient flow has been more problematic. As accurate and stable electronic pressure gauges came to market and were applied to testing, more questions about early transients were raised than answered. It is the path between radial flow and semi steady state that has been a subject of frustration and speculation for many analysts. The **Capillary Shock Wave** is an energy event of constant intensity with a velocity that is inversely proportional to the square of the distance from the source. The discovery of its presence will change our perception of transient flow and provide a tool for measurement.

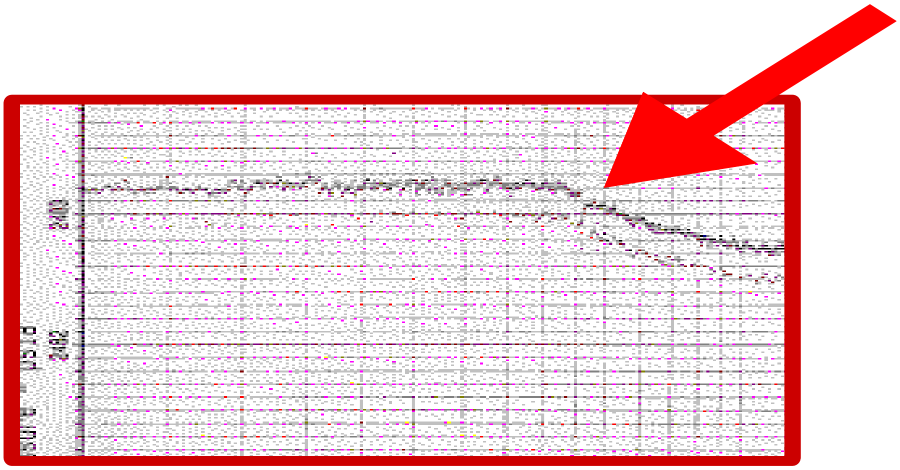


Figure 8 - The Primary Capillary Shockwave

The ***Fixed Field Diffusion Model*** and the ***Capillary Shockwave Model agree in radial flow and at semi steady state, but follow different pressure histories between the two conditions.*** The **WAVEX^{SM} Technology Model** produces ***more information and more accurate information*** to correlate geophysical images**.** Performance at predicting a reservoir's geometry as defined by 3D seismic images will in the end determine the best model for reservoir dimensioning. Each new pressure transient contains old familiar events and something novel. Each new event is a learning experience that tests our concepts of nature. Each answer leads to more questions. Let us close this introduction to the **WAVEX^{SM} "Bubble Theory"** with the question that opened it. ***Have you ever seen something in pressure transient data that you could not explain?***

"Catch the Wave"

Interference Testing Applied to Proved Undeveloped Well Locations

By Fred Goldsberry

Presented at the Forty Sixth Annual Meeting of
The Society of Petroleum Evaluation Engineers
The Homestead Resort, Virginia
June 9-10, 2008

Summary

- A reservoir is a creature of capillary forces.
- Capillary forces must be broken down one pore throat at a time.
- This process is performed by a wave that restricts the areas and volumes being drained as surely as sealing boundaries until it reaches the sealing boundaries.
- The wave propagates as a function of hydraulic diffusivity and the time of initiation. It is predictable.
- The passage of this wave is distinct and easily recognizable but it does not look like the picture in the textbook.
- The capillary wave can be used to make money in spite of the SEC but could best be used to reduce uncertainty in reservoir continuity thereby increasing the accuracy of reserve reports.

Introduction

Reservoir continuity is one of the most critical aspects of property evaluation that Evaluation Engineers encounter. Interference testing is a simple procedure to establish reservoir continuity. Traditionally this has been underutilized because the application of the technique and test results have been inconclusive. The difficulty in the application of interference testing has to do with knowing ***what to look for*** in pressure data and ***when to look for it.***

Capillary Forces

There are physical reasons that account for historical frustrations with the method. First, the evaluator is seeking information about the propagation of pressure depletion in a reservoir that is composed of billions and trillions of pores that represent physical containers of the fluids that are produced. These fluids are locked in place by formidable electronic forces that manifest themselves as true physical barriers to fluid movement. These are generally refered to as capillary forces. This is the same mechanism that produces wetting of surfaces by water and oil or produces the strength of thin films such as soap bubbles. These are associated with phase changes because the affects of electronic forces at the interface surfaces can be seen. ***Whether their influences can be seen or not, these forces exist.***

The act of initiating production is to apply enough pressure differential to serially break down the structural barrier imposed at each pore throat. The flow of oil or gas is produced by breaking the electronic barrier at each pore throat and maintaining the opening with continuous flow from pore to pore. The process is one of serial opening followed by production from pore to pore until reaching the wellbore. At each pore throat, the entry pressure must be broken and enough depletion of that pore passed out of the pore to open the next pore throat. This is a slow and tortuous process that requires substantial time.

Cone of Influence

The cone of influence is a pressure depletion region around each well that is surrounded by an advancing wall of static capillary forces. As the pores open serially to allow flow to the wellbore, the volume of the cone of influence slowly begins to expand the volume of the reservoir being drained. Think of these as small magnetic doors to each pore. This is manifested to a pressure gauge as the passage of a step drop in capillary pressure. It will appear in time sequence to a remote pressure gauge as a step drop in pressure followed a rapid decay of pressure. **Figure 1** is such a pressure step viewed by a gauge in an offset well to the only producing well in a new reservoir that was at initial pressure. Note that the pressure is stable at initial pressure before the wave arrival. The bounding capillary shockwave is represented by the apparent gap in the data as pointed out by the red arrow in **Figure 1.**

It should be noted that had the recording of pressure been stopped at 24 hours, the test would have indicated no communication. This would have been the case if the system had been modeled by a traditional potential flow diffusion simulator. Most interference tests are terminated before the capillary interference wave has had time to reach the static offset well. This capillary wave represents the pressure boundary of the cone of influence. The blue arrows point to higher order capillary waves that were produced earlier by the primary wave reaching boundaries. In other words, this is the transient history of the offset producing well from a remote location. For the purposes of this technical note, focus on the bounding wave alone.

Figure 2 shows a simple image of the radial flow system with an element that represents the breakdown of capillary entry pressure and the bundle of capillary elements that connect it to the wellbore. Think of the element as **PacMan®** literally eating his way through the formation. This is his first nephew **PoreBoy™**. **PoreBoy™** exists between the initial capillary pressure and the cone of influence. He must reduce the pressure at his front face sufficiently to rupture the static pore entry shear stresses, then pass enough fluid through his body length of ΔX before he can advance to the next collection of pore throats.

At this juncture, to make this a technical note one must produce a derivation. **Figure 3** shows an element on which an energy balance needs to be performed and related to the stream of capillaries reaching back to the wellbore of the producing well.

The model involves balancing Darcy flow through the element with the pressure depletion of the element then performing an energy balance between the trailing capillary stream bundle and the element to calculate the velocity of the element.

- **Constant Pressure on Leading Edge Face of Element**
- **Darcy Flow From Element**
- **Energy Balance Between Shockwave Element, and its Capillary Stream Tube Volume**
- **Addition of Expanding Fluid Mass and Its Elastic Energy to the Cone of Influence**

Fluid Growth of Cone

The next step is to create an equation and work to eliminate the $\Delta P/\Delta X$ term from the energy balance and rearrange to calculate the speed of the element as U_{wf}. Wave velocity is reduced with time, it is not constant. The location of the element, or simply stated, the length of the capillary trail from the well, is what is of interest. The last step is to integrate the velocity over time to achieve the effective length of the trail of capillaries. These equations are shown in **Table 1.**

HOLD IT. ATTENTION! Note that the equation in Table 1 is the classic radius of investigation equation or drainage radius. The radius of investigation is the location of a diffusion wave that is passing through the reservoir and acting as a means for connecting the reservoir pore by pore to the well. This equation also indicates how long one must wait to see interference. This wave moves at a very slow pace. If one does not wait long enough, interference will not be detected in an offset well. Note also that the distance is solely a function of hydraulic diffusivity and time from initiation. Flowing a well at a higher rate will not speed up the process. The capillary shockwave is the physical phenomenon that exists at the radius of investigation. One cannot detect any boundaries that exist beyond the radius of investigation.

In few cases is there an undisturbed reservoir to begin the test. What does one look for?

Note the changing scales until the tell-tale peak is exposed. During the buildup, fluid is flowing toward the well that is building up. Then there is a stable period where static capillary forces re-establish. Then the interfering well cone of influence begins to pass through the observation well breaking the static pressure, and initiating flow in the opposite direction. These are completely separate events! This is the signature of interference. Note that it takes a quality pressure gauge to see all of the detail. The difference between the stair-steps of points is the resolution of the pressure gauge. This was a dual quartz gauge capable of 0.01 psi resolution. The preceding example is a Permian basin well with an offset well 1440 feet away. The following example was off the Coast of Africa and proved interference from a well 8500 feet away. The third example represents two other wells sequentially interfering with the well being tested.

All of the well tests in **Figures 4 and 5** received bearing the same question **"What in the #%@* is this?"** When two wells are interfering and one is shut in, the producing well's cone of influence begins approximately half way in between. The time required for interference to appear in the shut-in well will be approximately 3/4ths of the wave transit time because of the "head start." This rule applies to a homogeneous reservoir, but changes in thickness and permeability can be handled as well.

It should be noted that if the first test is questioned, one could do this process again and again and expect to see the same detail in the results.

Two Well Testing

If two wells begin producing at the same time, the shockwave fronts will meet at the same time. This method requires only 1/4th the time. That is an advantage if you have control of both wells and do not have to see the wave passage. The response in both wells would be a doubling of natural log pressure derivative at the same point in time. It is my opinion that the wave passage is a more compelling case when presenting evidence to outside parties.

The beauty of interference testing is that you can calculate the permeability and hence hydraulic diffusivity at each well during the early part of the flow, then measure the effective or mean hydraulic diffusivity by the time of the wave passage from the well of generation to the well of observation. Rate changes are not going to affect the arrival time but will be seen in the pressure profile behind the wave. ***The wave moves as a function of the properties at the wave front.*** All that this testing requires is a recording pressure gauge with an accurate clock. Please note that the hydraulic diffusivity is the coefficient of the diffusivity equation used in all reservoir modeling. This is a critical piece of information that can be developed directly from the test with a simple calculation.

The method of execution can go something like this: Gauges are placed in each of two suspected interfering wells. Each well is opened on a fixed choke to create a short drawdown and buildup. Next one well is turned on. The other well is observed for arrival of the capillary shockwave front. While waiting, the short tests are analyzed for permeability and the hydraulic diffusivity for each well is computed. The average of these values is used to estimate the transit time of the wave. If the wave arrives on schedule or within a reasonable tolerance of say + or – 10%, it is reasonable to assume that the wave passed through the reservoir unabated. Hence there appears to be a clear path between wells. At issue is how many locations are located on that clear path.

Drill and perform interference tests with two more wells. How many PUD locations are added using the same logic?

It would appear that these PUD locations have many other undeveloped locations completely surrounded. Each of the interference tests will produce a transient from the perspective of each of the wells. That information can be turned into a single well transient analysis of the reservoir limits from four points of perspective, but stay with the current case.

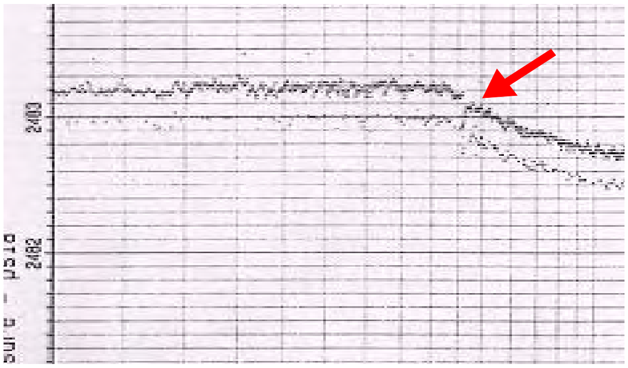
Could one make a more compelling case for proving undeveloped locations?

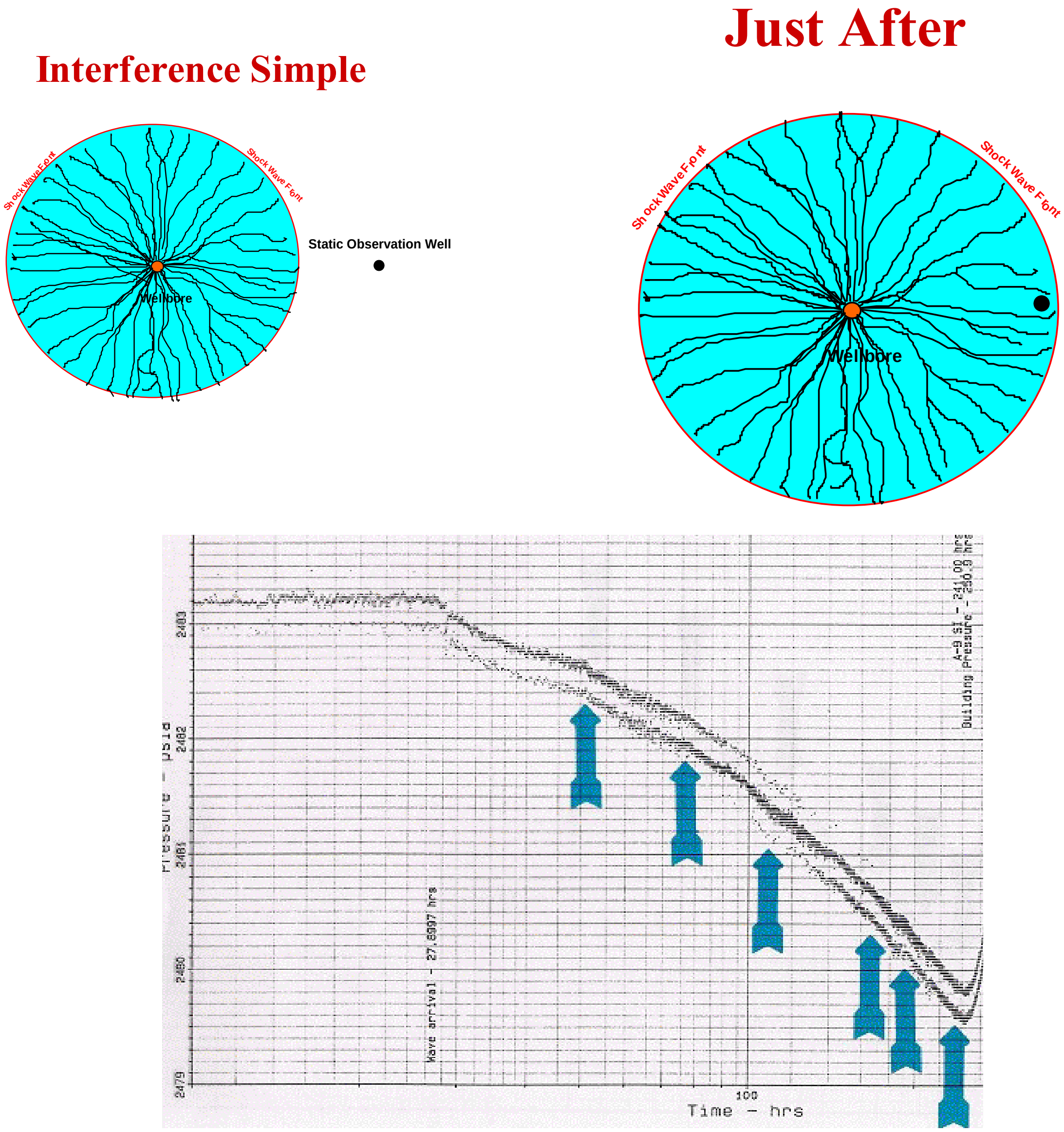
When there is a predictable and singularly observable wave why not use it?

Future Steps

It would appear that a sound approach to get this accepted by the SEC would be to present a case to them that involves an actual test with ample prior warning as to the intentions of the operator and the physics of the technique to be used. Develop a case for interference PUDs by testing; then prove it by drilling an interior location. This could reduce the number of drilled holes to produce PUD locations in the future. **Acceptance generally derives from use. Use involves the willing participation of all parties.** Acceptance is also based upon consistently making money with the technique by avoiding unnecessary or dry holes.

This is a necessary first step in the rehabilitation of interference testing as a means for evaluating reservoirs. The next and intermediate step is recognition of the clear radius method for dealing with water down-dip. Only then can the SEC be approached on the more sophisticated method of single well energy mapping to confirm seismic images.





Interference Simple

Just After

Fig. 1 - Capillary Shockwave Passing the Static Observation Well Initiated by Opening a Well 2000 Feet Away 27 Hours Earlier.

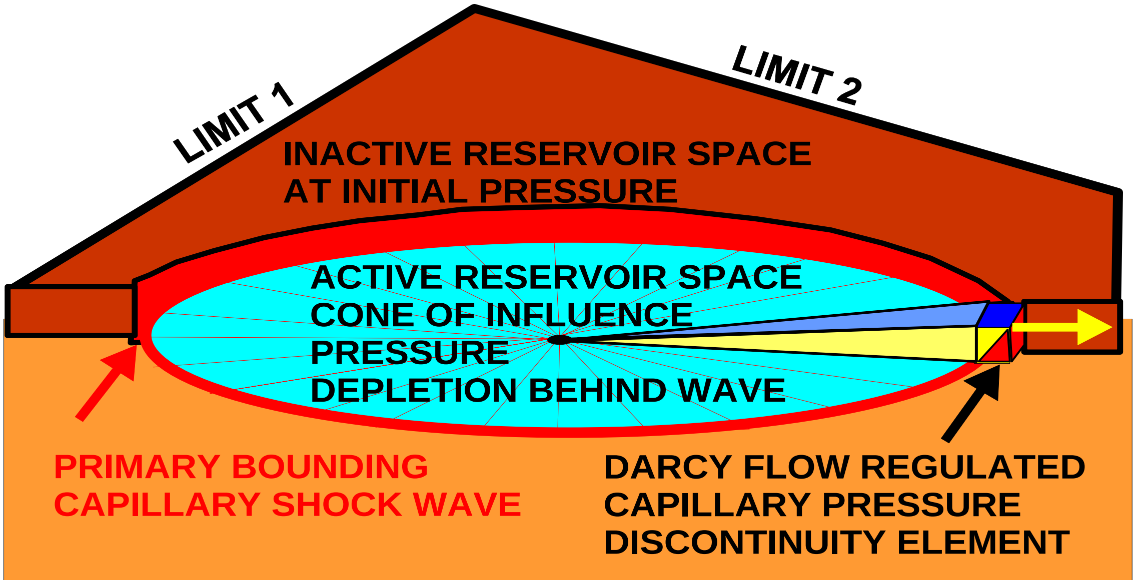


Fig. 2 - The Radial Capillary Structure of the Cone of Influence and the Bounding Capillary Shockwave Element.

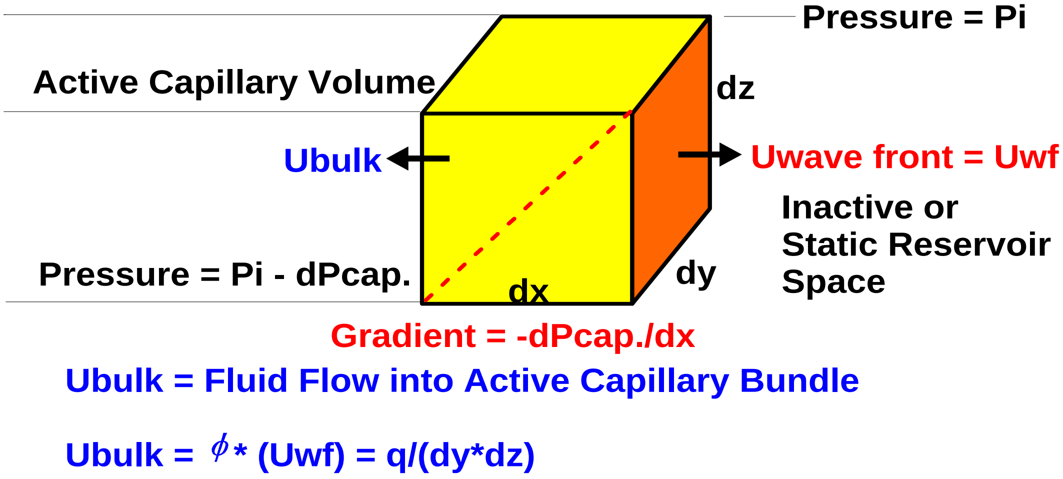


Fig. 3 - The Bounding Capillary Shockwave Element.

$$q \,/\, \text{Tube Area} = U_{Bulk} = \phi * U_{Wave\ Front}$$

Fluid Continuity… Darcy’s Law………Energy Equation

$$\phi * Uwf = -(k/\mu) * dPc/dx = -(k/\mu)*(-1/(t*Ct*Uwf)$$

$$Uwf = \sqrt{k/(\phi * \mu * t * Ct)} = \sqrt{\eta / t}$$

$$L = \int_0^t Uwf\, dt = \int_0^t \sqrt{\eta / t}\, dt = 2\sqrt{\eta\, t}$$

Table 1 - Equating Fluid Growth of Cone in Terms of Bulk Fluid Velocity.

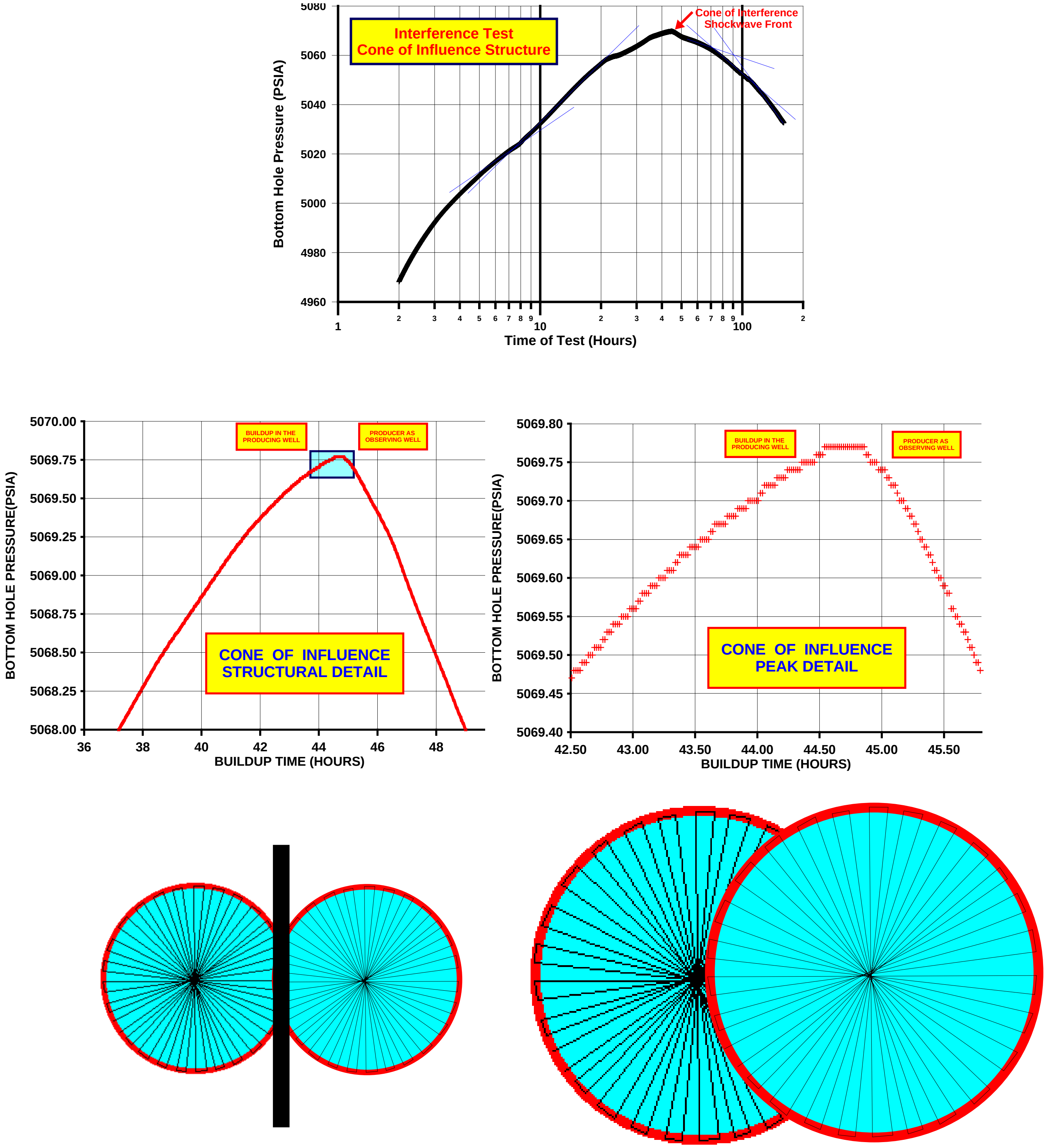


Fig. 4 - Sequential Zoom and Magnification of the Data at the Peak

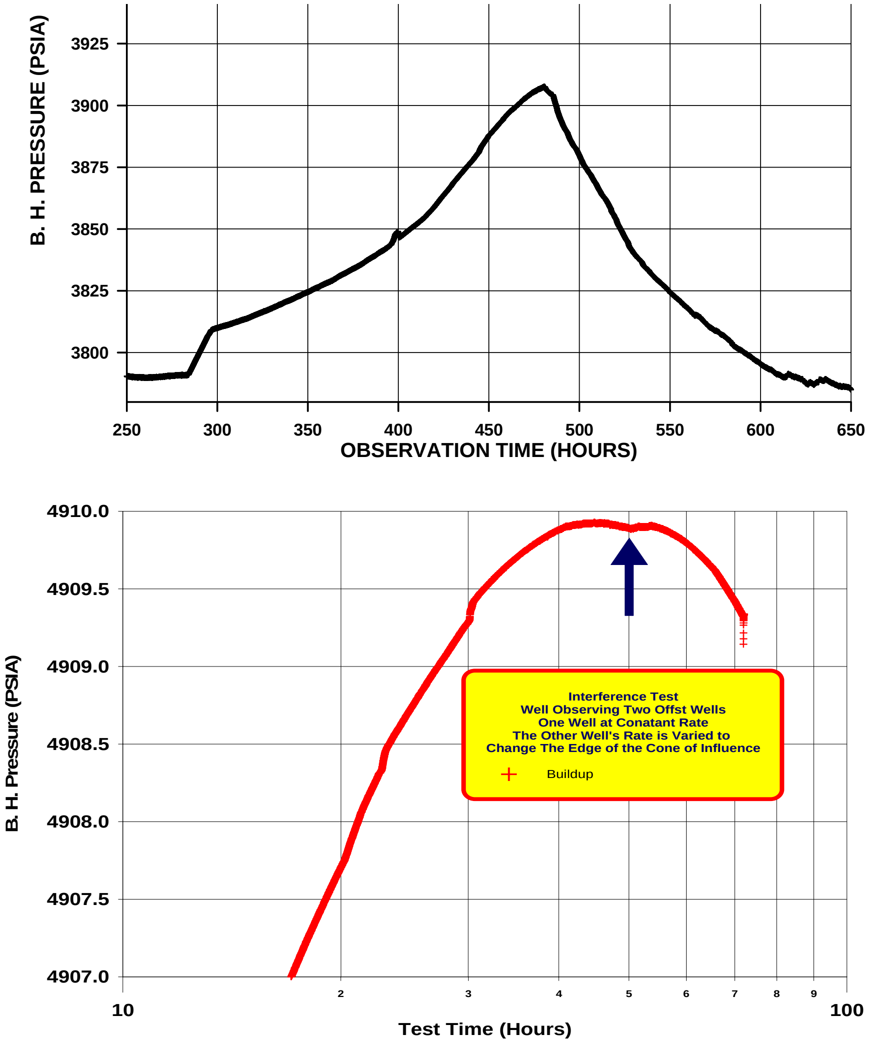
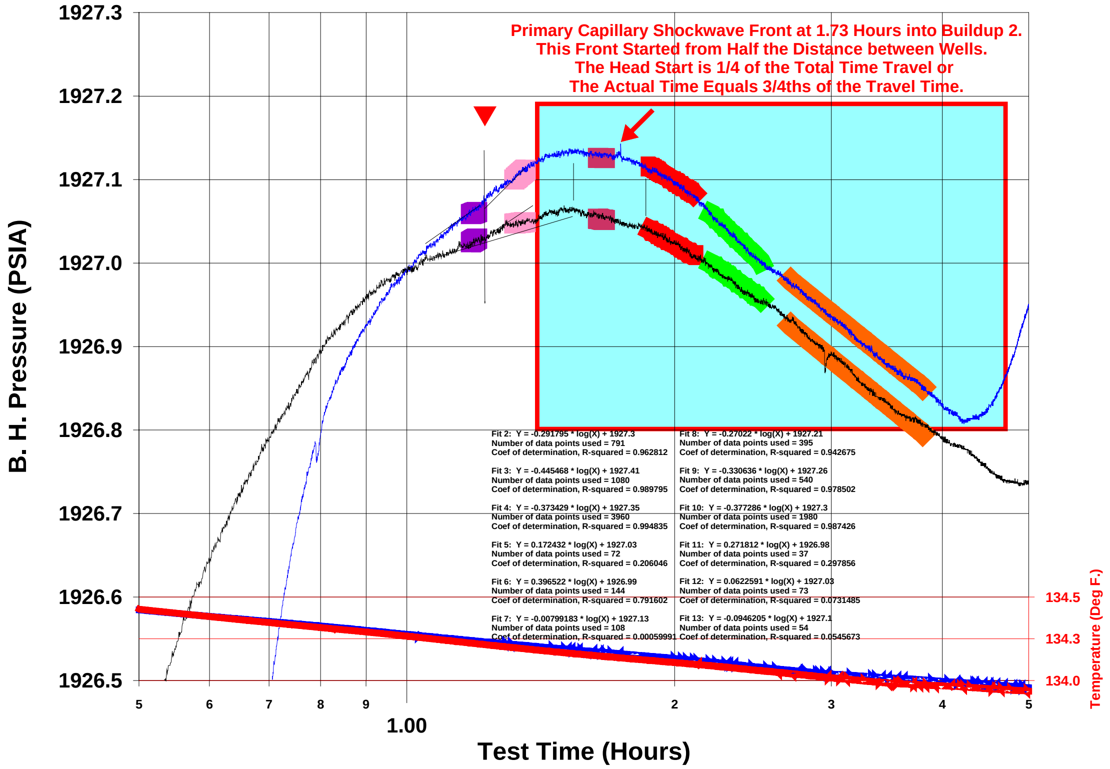


Fig. 5 - Second Buildup with Interference Above and a Buildup with Two Interfering Wells in Sequence



Primary Capillary Shockwave Front at 1.73 Hours into Buildup 2.
This Front Started from Half the Distance between Wells.
The Head Start is 1/4 of the Total Time Travel or
The Actual Time Equals 3/4ths of the Travel Time.

Fit 2: Y = -0.291795 * log(X) + 1927.3
Number of data points used = 791
Coef of determination, R-squared = 0.962812

Fit 3: Y = -0.445468 * log(X) + 1927.41
Number of data points used = 1080
Coef of determination, R-squared = 0.989795

Fit 4: Y = -0.373429 * log(X) + 1927.35
Number of data points used = 3960
Coef of determination, R-squared = 0.994835

Fit 5: Y = 0.172432 * log(X) + 1927.03
Number of data points used = 72
Coef of determination, R-squared = 0.206046

Fit 6: Y = 0.396522 * log(X) + 1926.99
Number of data points used = 144
Coef of determination, R-squared = 0.791602

Fit 7: Y = -0.00799183 * log(X) + 1927.13
Number of data points used = 108
Coef of determination, R-squared = 0.00059991

Fit 8: Y = -0.27022 * log(X) + 1927.21
Number of data points used = 395
Coef of determination, R-squared = 0.942675

Fit 9: Y = -0.330636 * log(X) + 1927.26
Number of data points used = 540
Coef of determination, R-squared = 0.978502

Fit 10: Y = -0.377286 * log(X) + 1927.3
Number of data points used = 1980
Coef of determination, R-squared = 0.987426

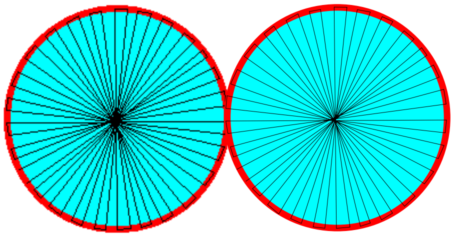
Fit 11: Y = 0.271812 * log(X) + 1926.98
Number of data points used = 37
Coef of determination, R-squared = 0.297856

Fit 12: Y = 0.0622591 * log(X) + 1927.03
Number of data points used = 73
Coef of determination, R-squared = 0.0731485

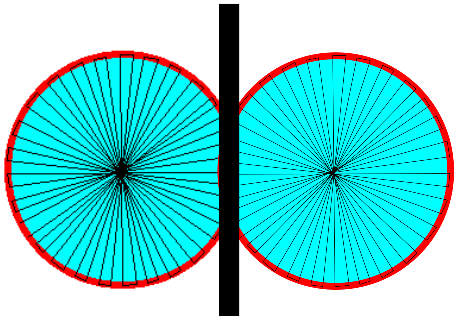
Fit 13: Y = -0.0946205 * log(X) + 1927.1
Number of data points used = 54
Coef of determination, R-squared = 0.0545673

Fig. 6 - Repeated Tests Bear the Same Fingerprints to a Surprising Level of Detail.

Interference Limit Contact



Interference Boundary Formed



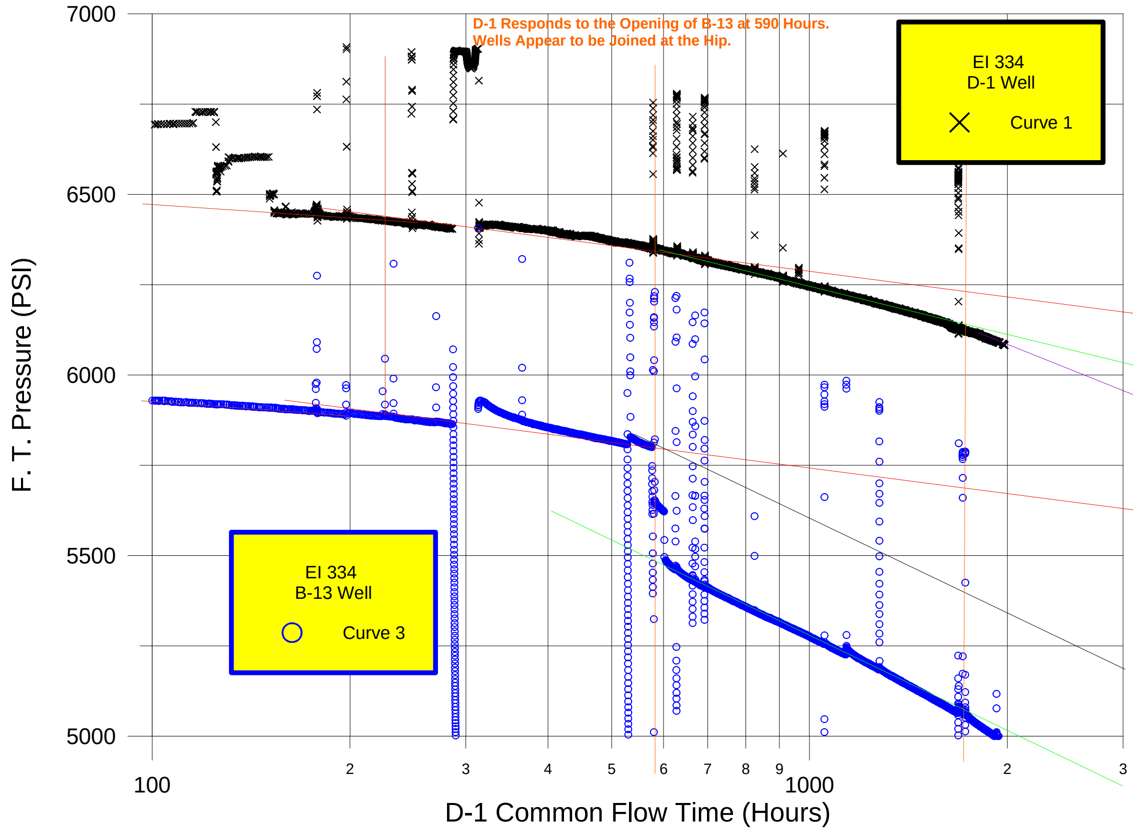


Fig. 7 - Two Well Test Configuration Requires Two Gauges

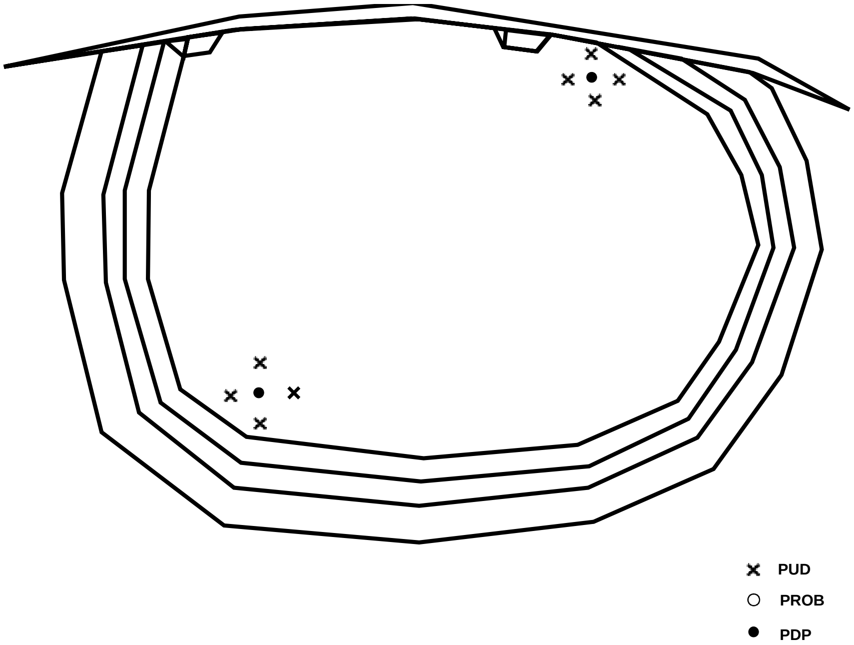


Fig. 8 - SEC PUD Locations Newly Discovered Reservoir Two Delineation Wells

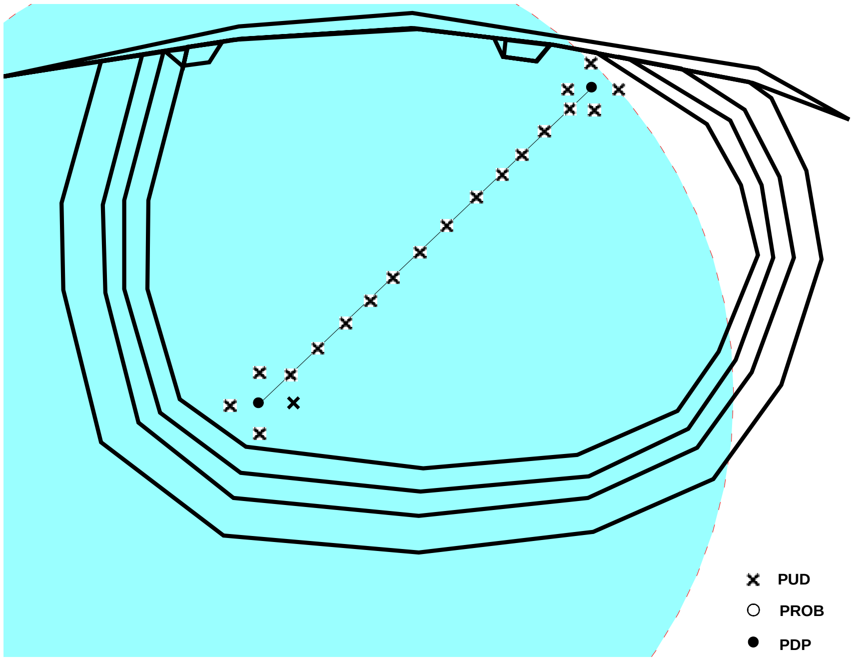


Fig. 9 - Proposed PUD Locations Based Upon Direct Passage of Capillary Shockwave Between Wells.

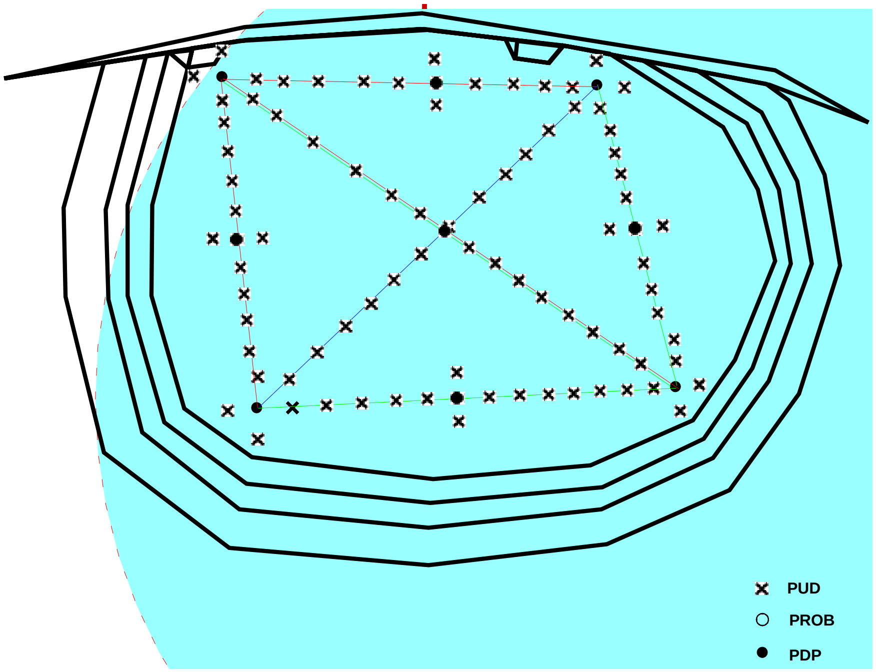


Fig. 10 - Proposed PUD Locations Based Upon Direct Passage of Capillary Shockwave Passed From Two More Delineation Wells.

50 Key IT Players in Energy, 2002

Energy based information technology requires great leaders, but also demands scientifically based technology providers.

33 individuals and a total of 52 companies were recognised in RaderEnergy's 2nd annual '50 Key Information Technology Players in Energy' 2002 global honours programme. The mission was to identify, recognise and honour the best and brightest individual technologies and technology-focused companies in the world, positioned at the forefront of information technology (IT) applications used throughout the global energy marketing chain – upstream, midstream, downstream and retail.

BY LINDA K. RADER

SchlumbergerSema was the global sponsor of the 2002, 50 Key IT Players in Energy, awards. Supporting organisations included Major Newswire and Bozell & Jacobs.

The honours are intended to recognise individuals who made contributions over the past 2 years to pioneering technological achievements in innovation, creativity, problem resolution and future solutions. They also honour corporations with leading technological solutions to industry or user problems, innovative applications for existing technology, and marketing/communications achievements or trade show/event programmes.

The collective work of those honoured encompasses a world of information technologies, including geospatial information systems (GIS), homeland security, electronic metering, data management, data- and text-mining, automation, workforce management, substation management systems, reservoir analysis, oilfield services, electronic trading and portfolio management systems.

Individuals and companies honoured herein work, operate, or are headquartered in multiple countries: Australia, Belgium, Canada, Germany, the Netherlands, South Africa, Sweden, Switzerland, the United Kingdom and the United States.

Operating in multiple countries can sometimes pose as great a challenge as developing and delivering leading-edge technical systems and services. "In the US, UK and Australia, it's every man (or woman) for themselves," said one honouree. If the person failed, he noted, often the entire product or company failed. "Europeans work more for consensus. One can see even greater differences in Scandinavia, where everything is done by consensus."

Individual honours categories are as follows: Dragon Slayer (best chaos-to-order solution), Leadership (executive/management), Outside-the-Box Thinker, Promising Rookie (less than two years in the field), and Mind-the-Gap (crossing chasms between users, industries or standards). Coincidentally, the latter category also straddles individual and corporate honourees.

Corporate/institutional honours categories are as follows: Best IT Solution or Problem Resolution, Best New Use of Existing Technology, and Best Advertising Campaign, Special Promotion or Educational Outreach. Among corporate honourees are Autodesk, Chevron Texaco Energy Research and Technology, ESRI, IBM, Intergraph Mapping & Geospatial Solutions, Itronix, KWI, MDSI Mobile Data Solutions, Inc., Memphis Light Gas and Water, Miner & Miner, Native Energy, Osmose Utility Services, Inc., PetroSkills/OGCI, Schlumberger, Siebel, Sight Informationssyteme GmbH, UBS, Vereinigte Wirtschaftsdienste GmbH, the World Business Council for Sustainable Development and the World Resource Institute.

A special category for Best Advertising, Special Promotion or Educational Outreach honoured six groups, including several companies involved in creative joint projects: IBM; UBS; the team of Intergraph Mapping and Geospatial Solutions and Intergraph Geospatial Users Community; the team of Native Energy, The Rolling Stones and MusicMasters; the group of ESRI, Sun Microsystems, the Library of Congress, the National Geographic Society, The Association of American Geographers, and the University Consortium for the Geological Survey; and the combination of Ben & Jerry's Homemade, Inc., the Dave Matthews Band, and SaveOurEnvironment.com (a collection of 19 global companies) that teamed to bring Internet-based awareness to the issue of global emissions.

The list of honourees for achievements attained by December 31, 2002, was announced earlier this spring. A panel of five judges, representing three nationalities and several organisations, reviewed the nominations and made their final decisions.

LINDA K. RADER is President of RaderEnergy.
For more information T: + 1 713 960 0001, raderenergy@att.net
or visit **www.keywomeninenergy.com**, under 'IT'.

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BRIAN PEACE, CEO AND CHAIRMAN, PEACE SOFTWARE, MIAMI, FLORIDA, USA, WWW.PEACE.COM. REASON: CORPORATE EXPANSION – CUSTOMER INFORMATION SYSTEMS (CIS)

Between 2000 and 2002, Peace Software grew from a small, relatively unknown customer information system (CIS) provider with 350,000 customers outside of the United States to a company supporting 3.5 million customers globally, signing contracts for an additional 10 million customers, growing revenue nearly 150%, and doubling employment. Brian Peace is known for employee recognition at key industry events and for a company-wide Tahiti conference in 2000. He initiated partnerships of action with strategic integration partners the size of IBM Global Services and PwC Consulting.

JAN SCHEURWATER, CHIEF EXECUTIVE OFFICER, TENSING•SKS LLC, A DIVISION OF TENSING SKS B.V., ZALTBOMMEL THE NETHERLANDS, WWW.TENSINGSKS.COM. REASON: LEADERSHIP AND DIRECTION

Jan Scheurwater is the founding member of Tensing•SKS (Spatial Knowledge Systems). He transitioned his government and geospatial information systems (GIS) industry experiences into high quality services. He showed exemplary foresight in determining many future (current) energy industry-specific requirements. He encourages employees to get involved in product management and team play. Tensing•SKS is known for its bi-directional SPY and alternate solution SPYder, its mobile field (GIS) solutions, and Field Vision, its customer relationship management (CRM) tool.

DOUG STAKER, VICE PRESIDENT, MOBILE AND NETWORK TELEMETRY SOLUTIONS, ITRON INC., SPOKANE, WASHINGTON, USA, WWW.ITRON.COM. REASON: ADVANCED METER TECHNOLOGY STRATEGY

By plugging into public networks and the web, and taking an open architecture approach to system design, Doug Staker and team are rewriting advanced metering technology business cases by delivering enterprise-wide value to utilities and utility customers. Old view of AMR: automates labour-intensive function, cuts costs, leaves dogs with only mail carrier to chase. New view of AMR: Strategic asset, real-time source of critical information, portal to customer.

CATEGORY: OUTSIDE-THE-BOX THINKER

INFORMATION TECHNOLOGY IS ONE OF THE AREAS OF BUSINESS THAT THRIVES, IN PART, BECAUSE OF PEOPLE WHO REFUSE TO ACCEPT THE STATUS QUO AND WILL DEDICATE THEMSELVES TO IMPROVEMENTS OR COMPLETE RECREATION.

LEE MARGARET AYERS, INDUSTRY MANAGER FOR POWER TRANSMISSION & DISTRIBUTION, OSISOFT INDUSTRY, SAMMAMISH, WASHINGTON, USA, WWW.OSISOFT.COM. REASON: PLUG-AND-PLAY TECHNOLOGY

Ayers makes it her goal to look for effective solutions that easily integrate GIS with SCADA and other real-time systems. In the last two years, her concentrated efforts surrounded a unique plug-and-play approach. Originally designed as a planning tool, OSIsoft and another company jointly developed the product, produced a prototype and implemented at a utility with excellent results. Operations now wants the solution that enables existing geospatial assets with real-time data.

NICOLINE BREDENKAMP-BOSHOFF, CHIEF ANALYST, ESKOM, TRANSMISSION, JOHANNESBURG, SOUTH AFRICA, WWW.ESKOM.CO.ZA. REASON: CROSS-BORDER TRADER PORTFOLIO

Spanning across eight African countries, from South Africa to the Democratic Republic of the Congo, Eskom's Transmission Trader portfolio (the Trader) covers cross-border trading. Since October 2001, Bredenkamp-Boshoff has spearheaded the creation of an integrated trading system to combine operational, invoicing, financial and management reporting aspects into a single system to increase efficiency and effectiveness and to reduce invoice preparation time. She utilises simple computerised tools to ensure continued operational applications of the bilateral agreements that facilitate successful trading.

MARTIN GELLERSTEDT, UNIVERSITY OF TROLLHÄTTAN/UDDEVALLA, UDDEVALLA SWEDEN, WWW.HTU.SE. REASON: DATA MINING INSTRUCTION

"We regard our students as information entrepreneurs," said Martin Gellerstedt, a statistician and 10-year teacher who leads courses in data mining, with specific programs like SPSS, Clementine, SAS, Enterprise Miner, etc. "I am interested in applied statistics and teach mainly students from the business or computer science field." In 2000, he started integrated courses and a special education programme, where courses in informatics, statistics, data mining and economy are integrated.

DR. FRED L. GOLDSBERRY, P.E., PRESIDENT, WAVEX, INC., HOUSTON, TEXAS, USA. REASON: RESERVOIR ANALYSIS TOOL PATENT

Dr. Fred Goldsberry applies information technology to a company's own reservoir formation technology. He received US, Canadian and European Community patents for WAVEX , a new technology for oil and gas reservoir analysis that describes the physical phenomena at the radius and uses it as an exploratory tool. The unique solution unique recognises capillary entry or threshold pressure. Rather than setting it to zero or smoothing out anomalies in a semi log graph, it highlights them and uses them as a valuable reservoir mapping tool.

JOINT HONOUR: PAUL, V. STERGIOU, SENIOR ENGINEER, CONSOLIDATED EDISON COMPANY OF NEW YORK, INC., NEW YORK, NEW YORK, USA; AND DAVID KALOKITIS, SCIENTIST, SARNOFF CORPORATION, PRINCETON, NEW JERSEY, USA, WWW.CONED.COM; WWW.SARNOFF.COM. REASON: GPS PHASE MATCHING SYSTEM

Together, this duo condensed a 72 hour basic substation operational process to four hours. Paul V. Stergiou and David Kalokitis married space-age technologies to solve a Thomas A. Edison-era application.

Fred L. Goldsberry, P.E.
15314 Wilkshire Court
Houston, Texas 77069
Office Phone: (281) 397-7010 Home: (281) 893-7118 Cell: (832) 524-0810
Registered Professional Engineer - Texas License No. 33923

EXPERIENCE

WAVEX®, Inc. (*A Registered Engineering Company in Texas #F-001670*)- Houston, Texas (1995-Present)
President- Developed "Bubble Theory" to Replicate Reservoir Geometry Using Wave Mechanics. (Patent)

ZAPATA EXPLORATION COMPANY - Houston, Texas (1983-1995)
Vice President *– Operations -Managed Offshore Exploration, Facilities Construction and Field Development Projects U.S. and U.K.*
UNITED STATES DEPARTMENT OF ENERGY - Houston, Texas (1976-83)
Director, Geopressure Projects Office *- Project and Science Program Management*
Program M*anager – Spent Unreprocessed Nuclear Fuel Handling, Packaging and Storage*
J. M. HUBER CORPORATION - Borger, Texas (1975-76)
Assistant Chief Engineer *for Carbon Division*
SOUTHWESTERN PUBLIC SERVICE COMPANY, TUCO,INC. - Amarillo, Texas (1973-75)
Supervising Engineer *–Drilling and Production, LPG, Natural Gas, Oil, and Coal Trading.*
LONE STAR GAS COMPANY, ENSERCH CORPORATION - Dallas, Texas (1971-73)
TEXAS RAILROAD COMMISSION - College Station, Texas (1970-71)
ROCKETDYNE, NORTH AMERICAN ROCKWELL - McGregor, Texas (1965-67)

EDUCATION

B. S. M. E. (Honors), M. S., Ph.D. - ***Continuum Mechanics*** - Texas A&M University – 1968,69 and 71
M. B. A. - ***Marketing/Management/Finance/International Business*** - University of St. Thomas - 1992

HONORARIA

Elected to the ***Board of Directors for The Society of Petroleum Evaluation Engineers*** - 2005-07
Named to International List of ***50 Key Information Technology Players in Energy*** Sponsored by ***Schlumberger Sema*** - 2002
Chairman 2002, Emerging and Peripheral Technology Committee- ***Society of Petroleum Engineers*** - 2001-03
Chairman, Houston Section - ***Society of Petroleum Evaluation Engineers*** - 1999
Inducted into the ***Texas A&M Mechanical Engineering Academy of Distinguished Graduates*** - 1996
Chairman, Geopressure Advisory Committee to the Idaho National Engineering Laboratory - 1988-93
Testified Before the ***U. S. House of Representatives*** - 1984
Technical Advisor to the European Community Committee on Energy, Brussels - 1982
Member of the Houston Engineer's Intersociety Committee on Critical Issues - 1981-83
Testified Before the ***Louisiana Legislature*** - 1981
Advisor to the ***Pacific Northwest States*** on Energy Matters - 1977-79
Member ***ANSI Z21.11 Standards Committee*** - 1971-73
Tau Beta Pi, Phi Kappa Phi, Phi Eta Sigma, Pi Tau Sigma - 1966-67

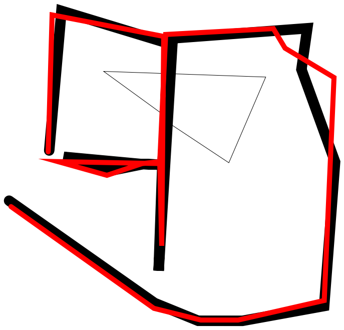
U. S. PATENTS - Eleven (Diverse Subjects)
The WAVEX® Technology is Patented in the U.S., Canada,
U.K., Germany, Italy, France and the Netherlands.

3D Seismic

Total Cost: ***>$500K***

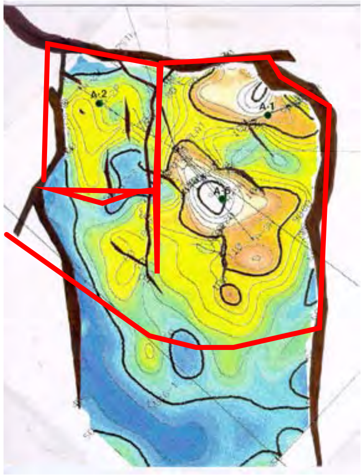
WaveX®

Total Cost: ***<$50K***



WaveX® Three Well Overlay

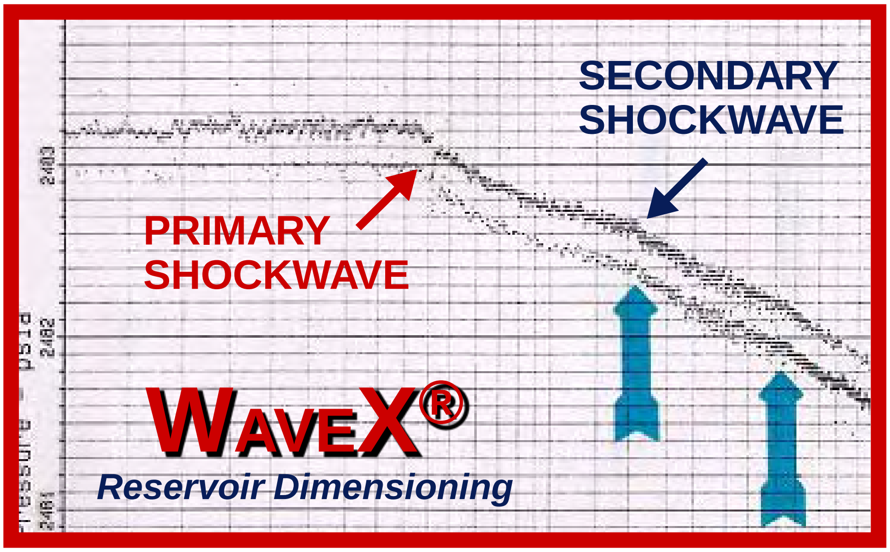
3D Seismic - WaveX® Alternate Overlay



WaveX® technology provides a cost effective solution to all of your pressure transient analysis requirements.

- The analysis process is streamlined to include only relevant first order pressure information.
- Proprietary **WaveX®** methods are used in the analysis, achieving greater accuracy through innovation.
- Simplified data formats are easy to read, yet cover all of the necessary data and parameters.

Thus, a superior result is achieved that is directly comparable to 3D Seismic images *for around one tenth of the cost.*



When the

Primary

Shockwave

Hits a Limit,

It Reproduces.

THE WAVEX DIFFERENCE

Traditional Method:

- Permeability
- Skin
- Semi Steady State
  Volume in Place

Bubble Theory:

- Permeability
- Skin
- Semi Steady State
  Volume in Place

Reservoir Dimensioning Information

By Diffusion Model:

- History Matching

***"What you get is
what you guess."***

Capillary Shockwave:

- Distance to Limit 1
- Curvature of Limit 1
- Distance to Limit 2
- Curvature of Limit 2
- Distance to Limit 3
- Curvature of Limit 3
- Distance to Limit 4
- Curvature of Limit 4
- Water Leg Measurement
- Channel Deposition
- Volume Proved
- Volume Mapped
- Confirm Electric Log Data
  - Porosity
  - Water Saturation
- Relative Disposition of Limits

For a Free Pre-Test Consultation, Call:

WAVEX®

www.wavexcorp.com

Dr. Fred L. Goldsberry, P.E., President

Office: *(281) 397-7010*
Cell: *(832) 524-0810*
Home: *(281) 893-7118*
E-mail: *wavex@sbcglobal.net*

WaveX®, Inc.
15314 Wilkshire Court
Houston, Texas 77069
drgoldsberry.com