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.

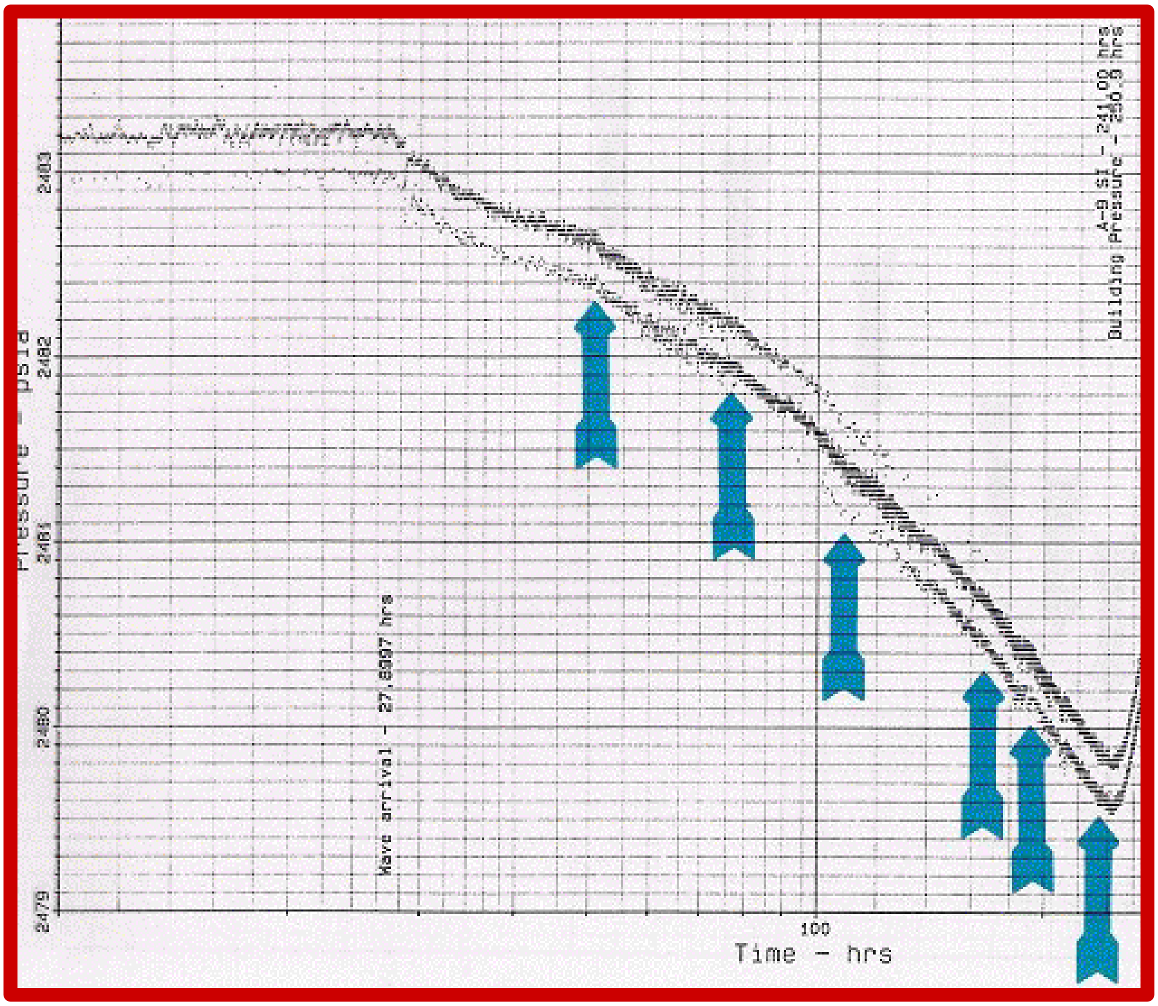

Figure 1 - A Single Well Drawdown Observed in a Static Well 2000' Away

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.***

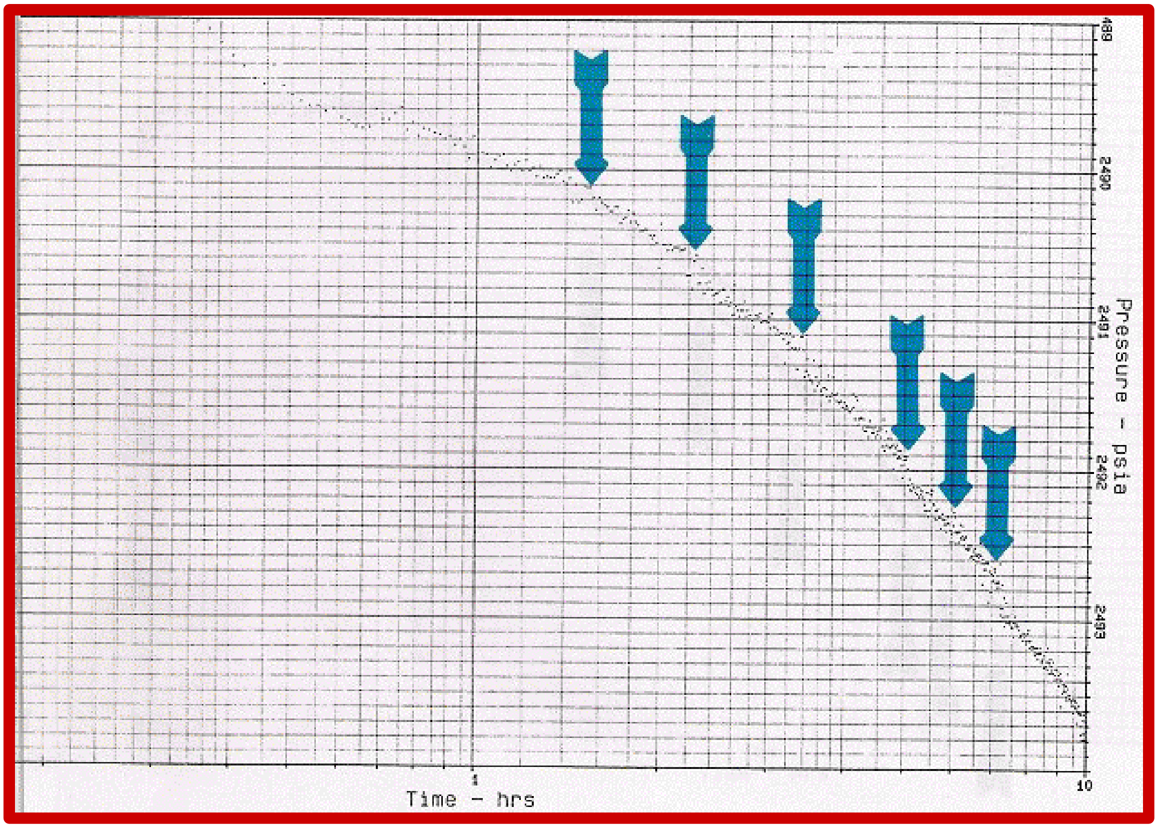

Figure 2 - Pressure Buildup in the Producing Well Plotted on an Inverted Scale

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.

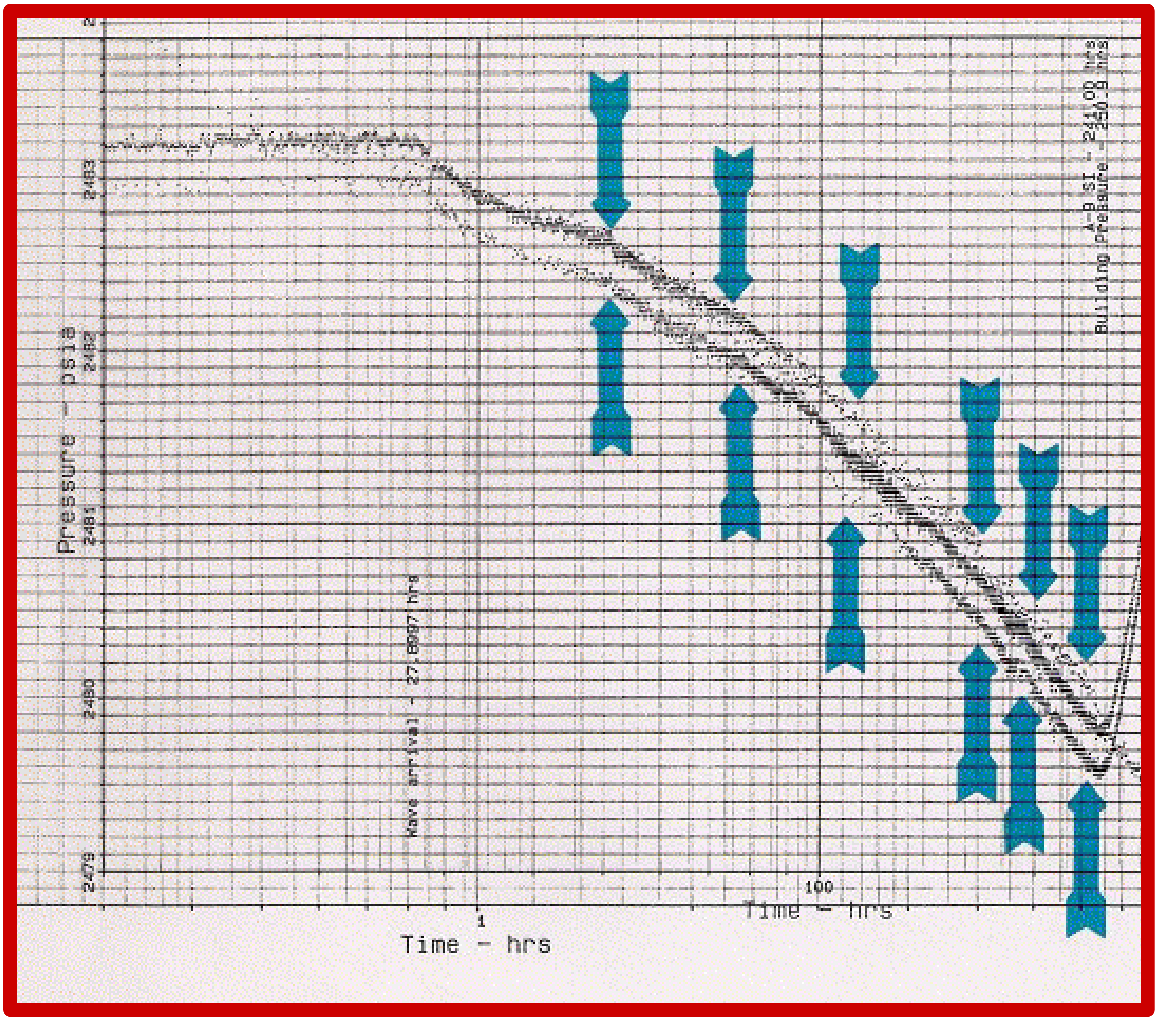

Figure 3 - Transparencies Overlaid

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.

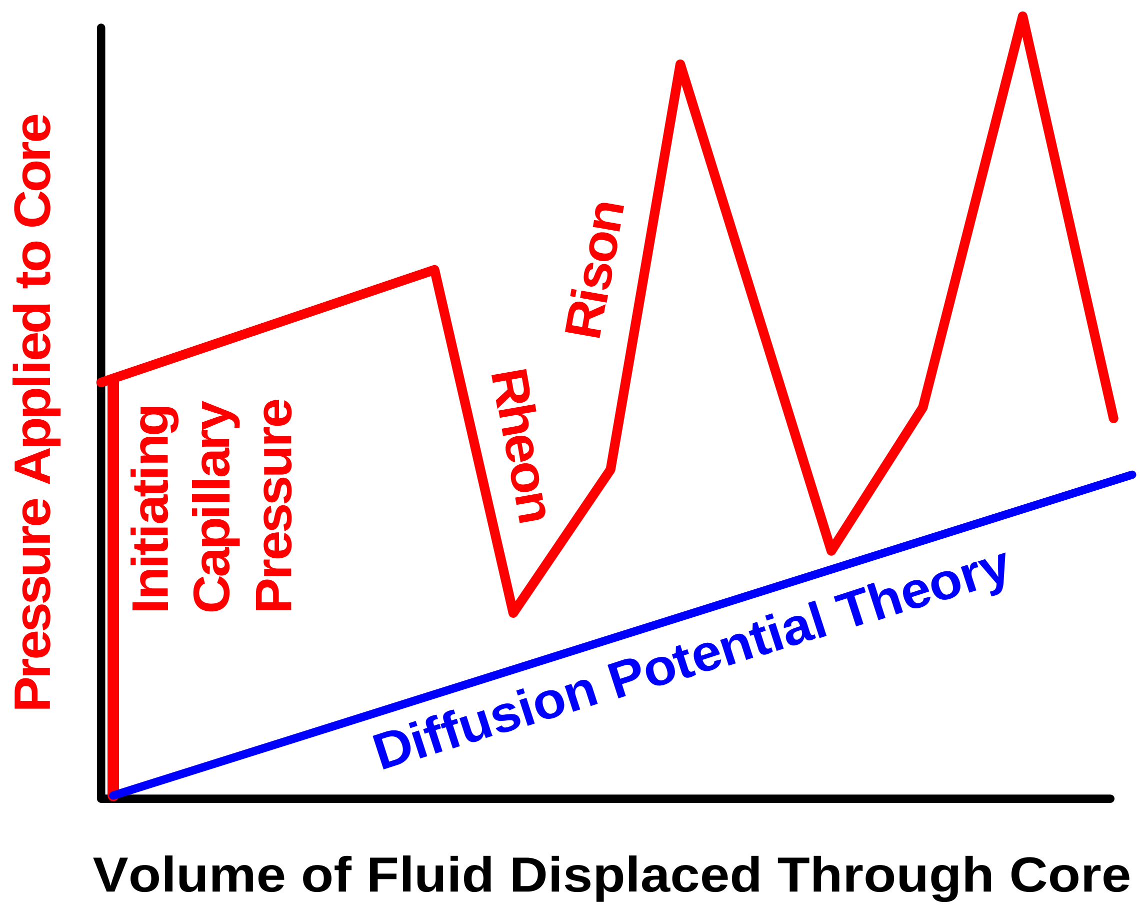

Figure 4 - Haines' Jumps Laboratory Measurements of Flow Through Porous Media

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

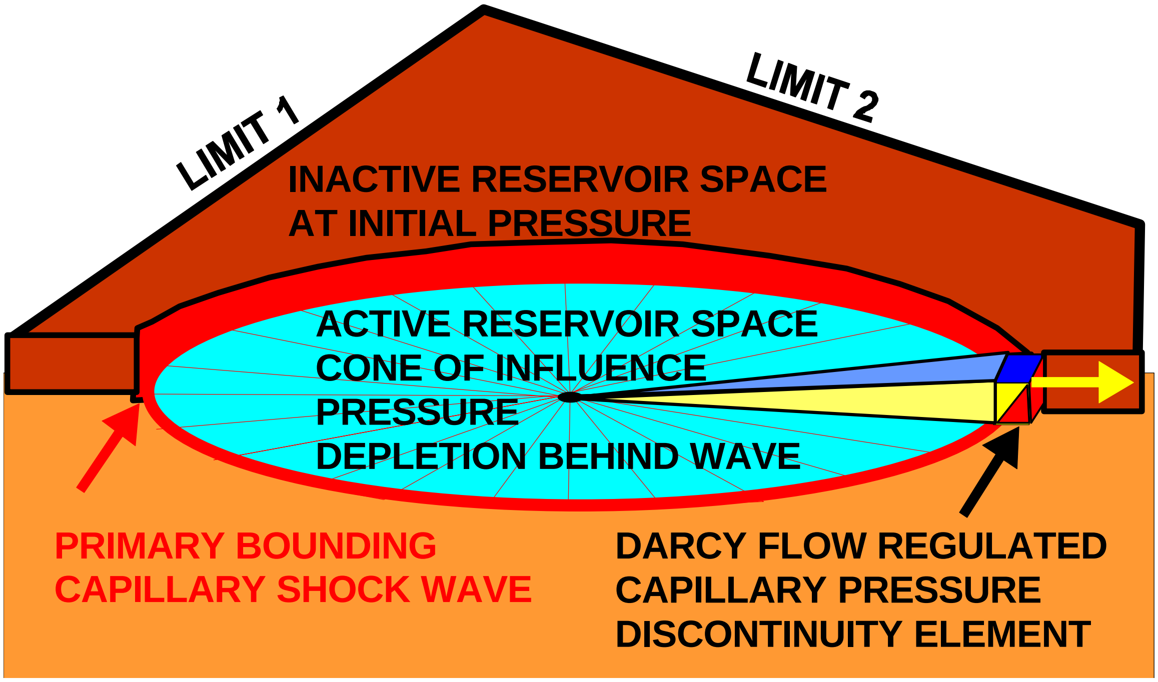

Figure 5 - Infinite Acting Radial Growth Cone of Influence and Element

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.

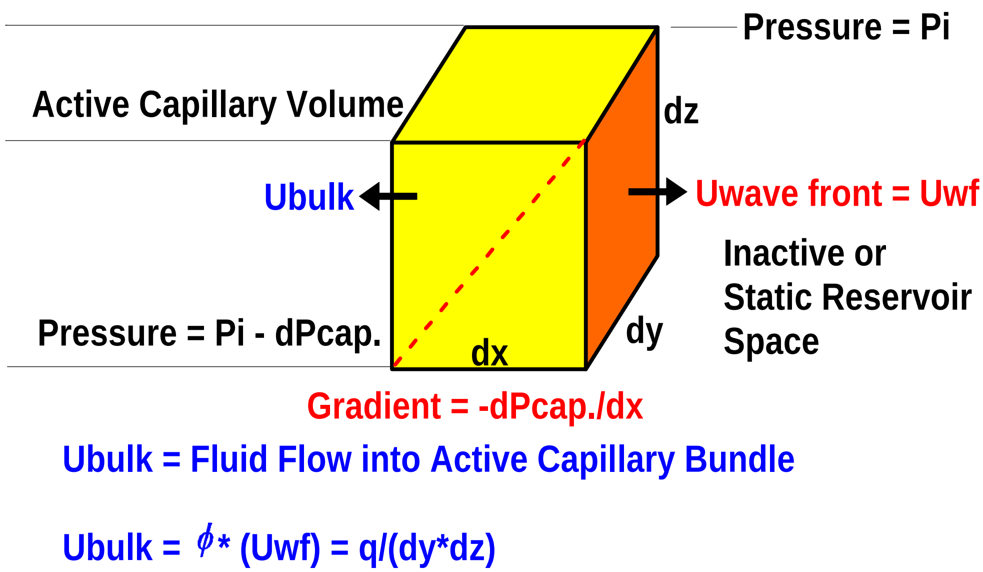

Figure 6 - The Shockwave Element: Steady State Constant Flux Streamtube Head

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:

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

Darcy's Law:

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

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:

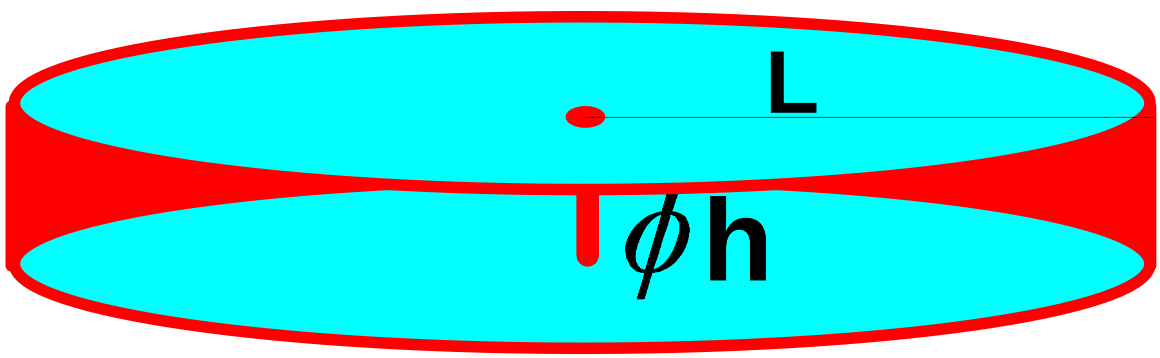

Figure 7 - Cylindrical Volume Around Well

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

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.

<u>Summary</u>

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. An example of limit by limit data processing is offered in the narrative accompanying this paper. Cone regeneration physics will be left for another time. The description of the wave and pressure data to support its existence are sufficient for this writing. 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.

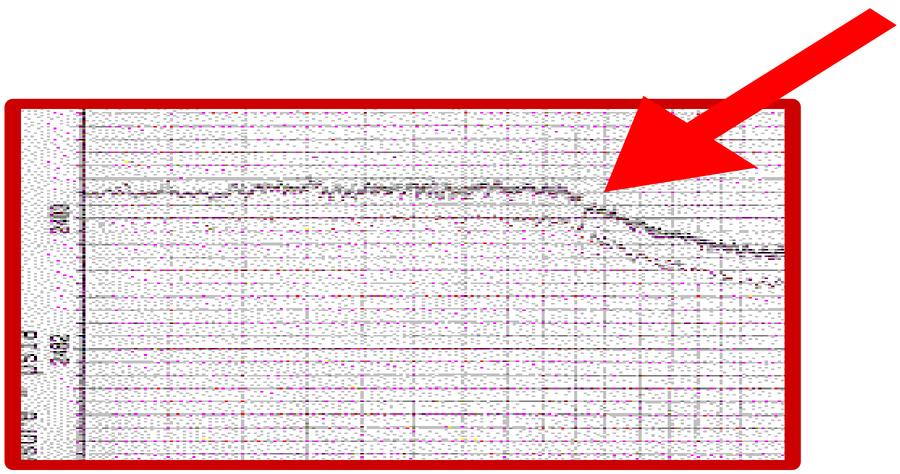

Figure 8 - The Primary Capillary Shockwave

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"