Review of Existing Methods for Interpretation of Shut-in Pressure from Hydraulic Fracturing Tests

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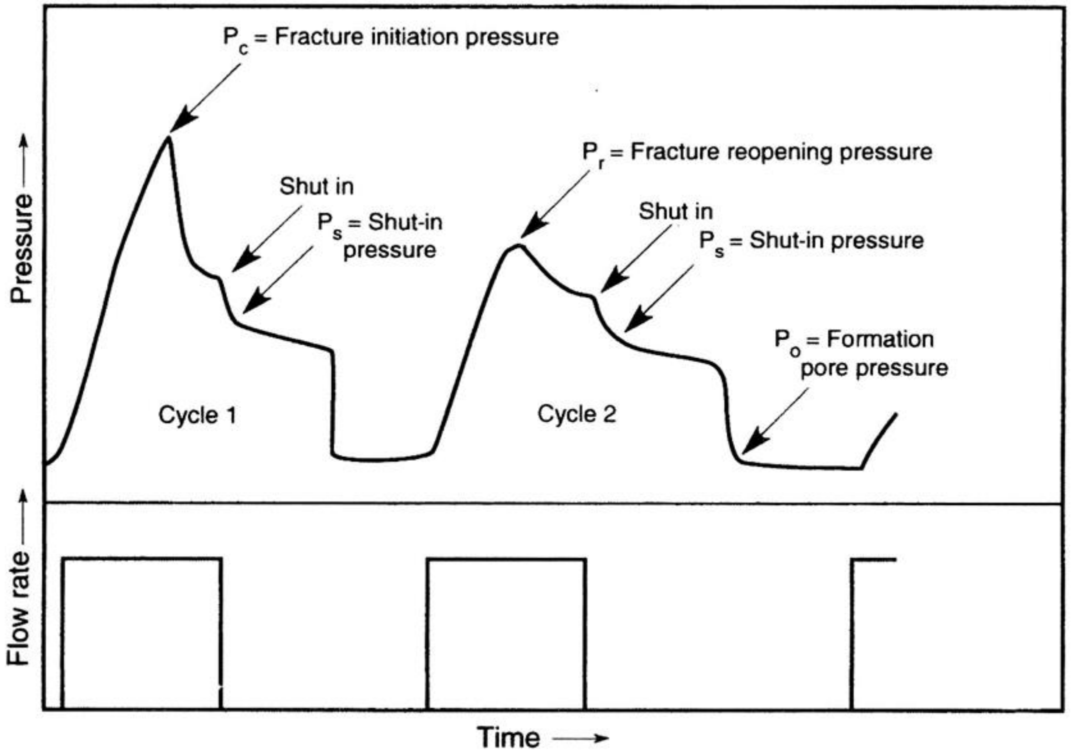
Introduction

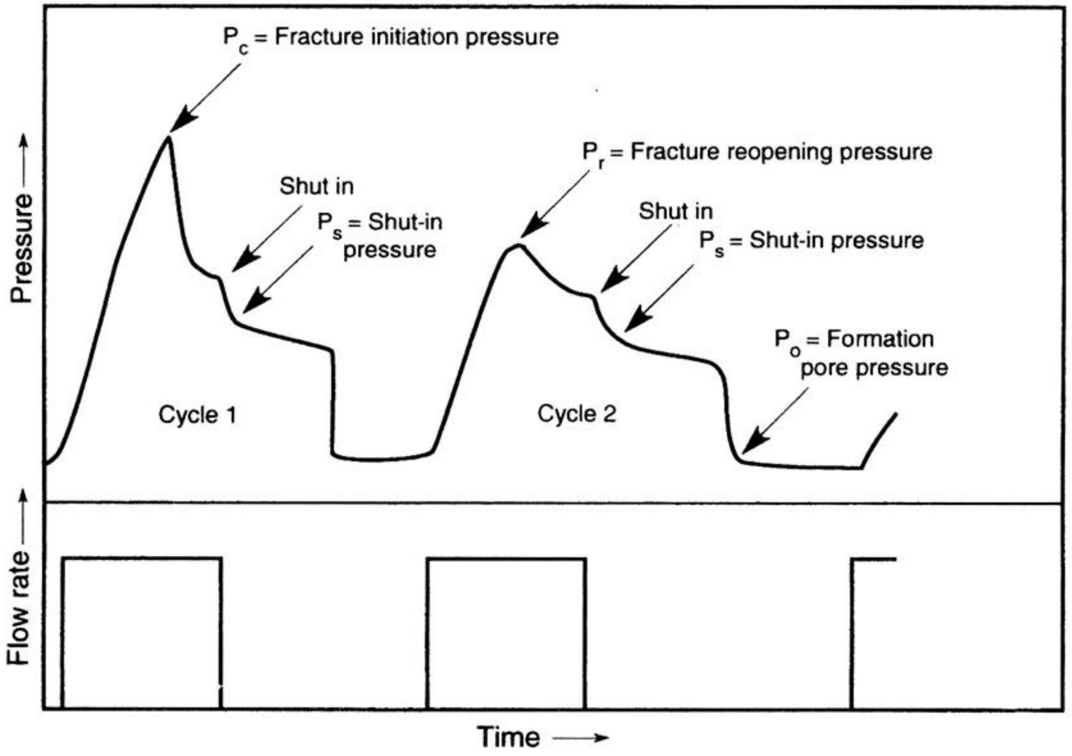
- Hydraulic fracturing measures the state of stress in-situ in boreholes by applying pressure along a section of a borehole.
- In hydraulic fracturing tests, the shut-in pressure is assumed to be equal to the minimum principal stress.
- The minimum principal stress is an important parameter in the design of underground openings and excavations.
- The shut-in pressure is **indistinct** in situations where leak-off is not negligible.
- Several methods are proposed to deal with indistinct shut-in pressure.

$$\begin{cases} P_c = \dfrac{T + 3S_h - S_H - 2\eta P_0}{1 + \beta - 2\eta} \\ S_h = P_s \\ T = P_c - P_r \end{cases}$$



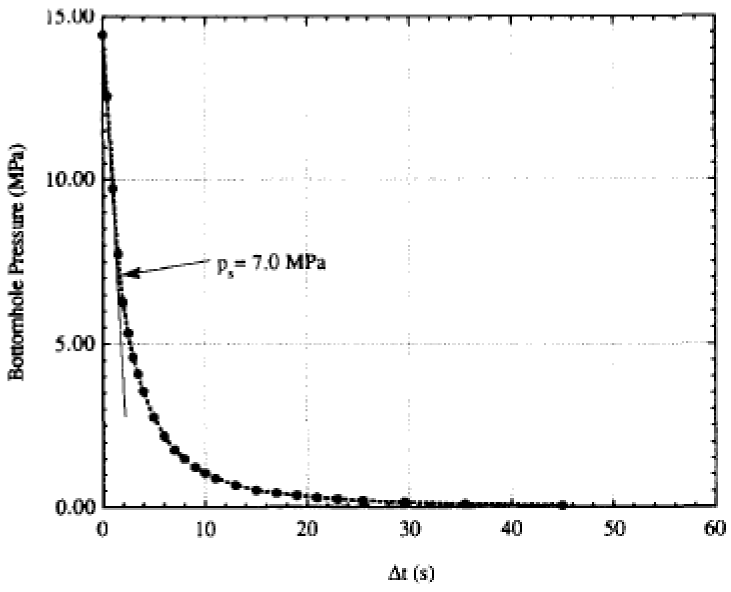
Interpretation Methods

- Inflection point method
- p_w vs $log(t + \Delta t)/\Delta t$ Method
- p_w vs $log\ \Delta t$ Method
- Muskat Method - $log(p_w - p_a)$ vs Δt
- $log\ p_w$ vs $\log t$ Method
- dp_w/dt vs p_w Method
- p_w vs $\sqrt{\Delta t}$ Method
- Maximum Curvature Method
- Tangent Intersection Method
- $P - Q$ Method
- Exponential Pressure Decay Method
- Bilinear Pressure Decay Rate Method



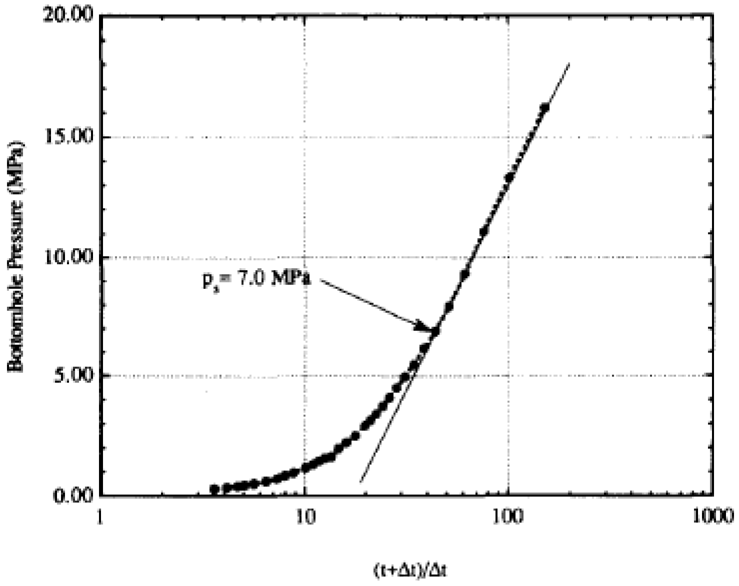
Inflection Point Method

- Also called *tangential divergence method.*
- A simple graphical technique proposed by Gronseth and Kry (1981) and Gronseth (1982).
- Interpretation involves drawing a tangent line to the pressure-time record immediately after shut-in.
- The shut-in pressure is defined as the pressure at which the pressure-time record departs from the tangent line.
- Suggested to interpret low-rate hydraulic fracturing data (< 50 l/min).
- Always results in a high shut-in pressure, especially for a low stress.



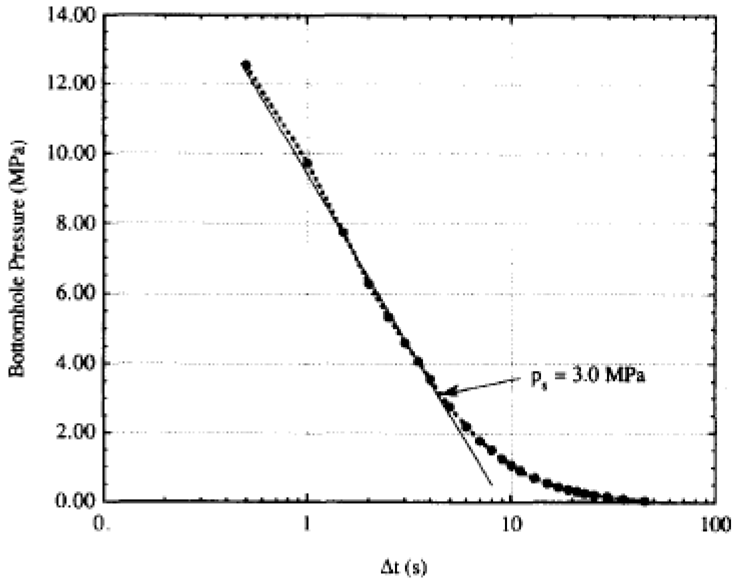
p_w vs $log(t + \Delta t)/\Delta t$ Method

- p_w – Bottomhole pressure , t – Time of injection and $\Delta\mathbf{t}$ – Time since shut-in.
- Suggested by McLennan and Roegiers (1981).
- The inflection point in the plot of p_w vs $log(t + \Delta t)/\Delta t$ represents the shut-in pressure.
- Produces a slightly high shut-in pressure.



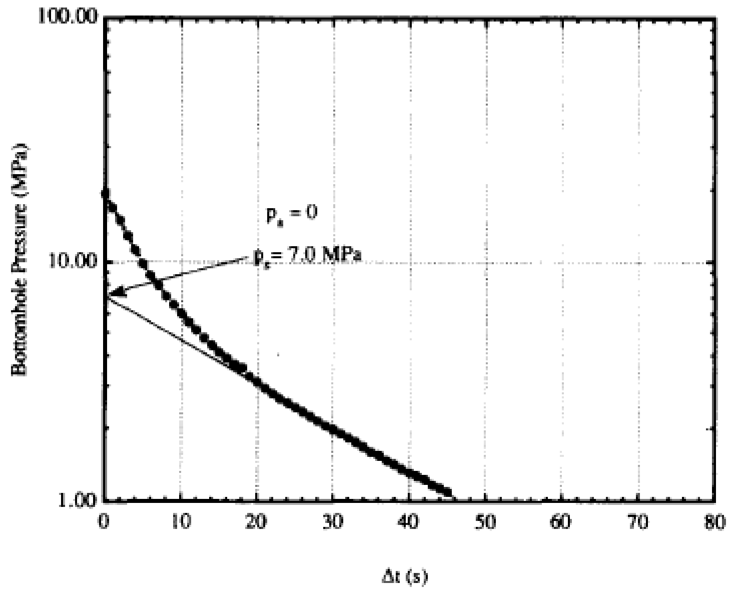
p_w vs $log\ \Delta t$ Method

- $\boldsymbol{p_w}$ – Bottomhole pressure and $\boldsymbol{\Delta t}$ – Time since shut-in.
- Suggested by Doe and Hustrulid (1981).
- A plot of $\boldsymbol{p_w}$ vs $\boldsymbol{\Delta t}$ for the period immediately following the first breakdown used where the shut-in pressure corresponds to a break in the slope of the plot.
- Recommended for interpreting hydraulic fracturing under slow pumping cycles.



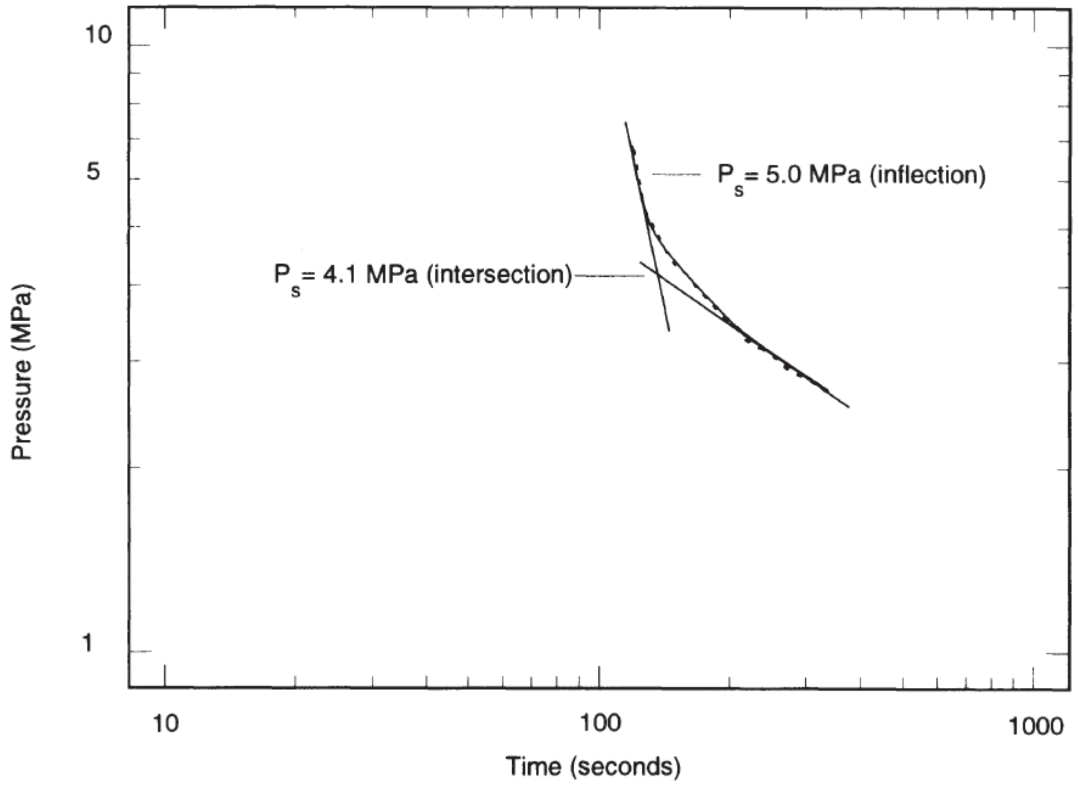
Muskat Method - $\log(p_w - p_a)$ vs Δt

- p_w – Bottomhole pressure, p_a – Asymptotic pressure and Δt – Time since shut-in.
- Proposed by Aamodt and Kuriyagawa (1981).
- Based on the presumption that the pressure after shut-in approaches some value asymptotically.
- A plot of $\log(p_w - p_a)$ vs Δt is made based on a trial value for p_a which is adjusted until the curve is best fitted by a straight line.
- The straight line is extrapolated back to the time of shut-in to get a pressure value, which is then added to p_a to get the shut-in pressure.
- Recommended for interpreting hydraulic fracturing under slow pumping cycles.



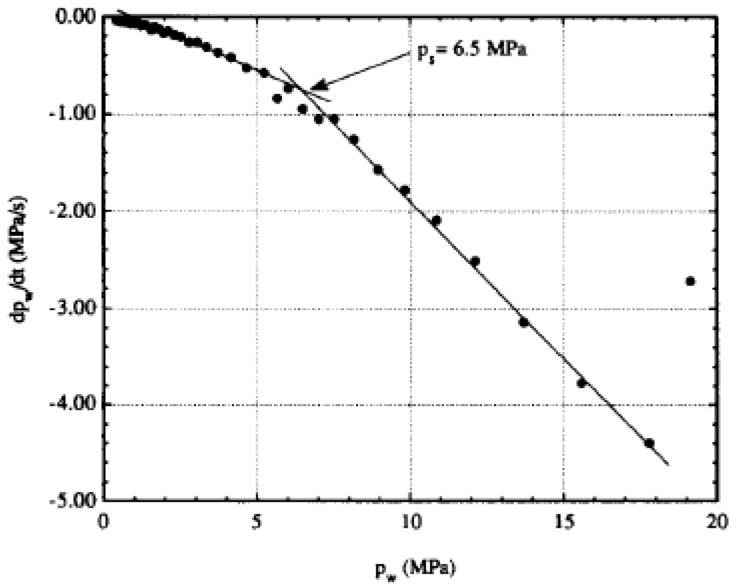
$log\ p_w$ vs $\log t$ Method

- p_w – Bottomhole pressure, t – Time since pumping.
- Zoback and Haimson (1982) proposed selecting the shut-in pressure from the plot of $log\ p_w$ vs $\log t$.
- The pressure versus time curve in this plot is bilinear where the shut-in pressure is the intersection of the bilinear lines.
- Produces few significant results.



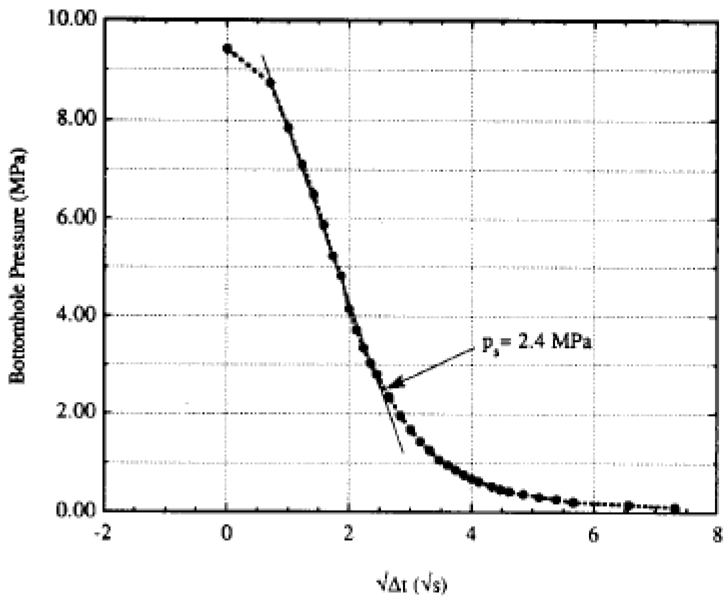
dp_w/dt vs p_w Method

- p_w – Bottomhole pressure, t – Time since pumping.
- Proposed by Tunbridge (1989)
- The curve in a dp_w/dt vs p_w plot is bilinear where the intersection of the two lines corresponds to the shut-in pressure.
- Provides a reasonable shut-in pressure for high stress but results in a high shut-in pressure under low stress.



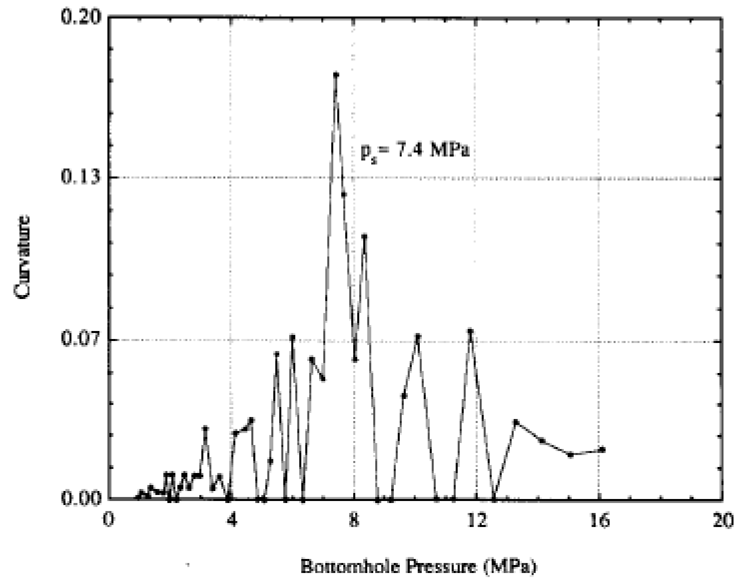
p_w vs $\sqrt{\Delta t}$ Method

- Fracture linear flow leads to a linear relationship between the pressure $\boldsymbol{p_w}$ and the square root of time $\sqrt{\boldsymbol{\Delta t}}$
- The fracture closes when the plot of $\boldsymbol{p_w}$ vs $\sqrt{\boldsymbol{\Delta t}}$ departs from a straight line
- The shut-in pressure is then the bottomhole pressure corresponding to the fracture closure.
- Sometimes produces a reasonable shut-in pressure.



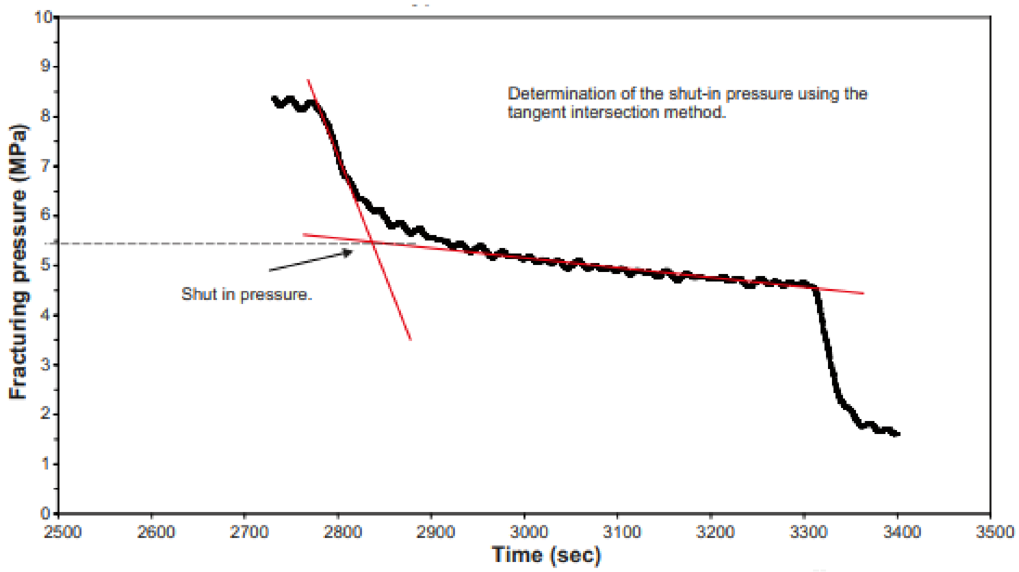
Maximum Curvature Method

- The shut-in pressure is considered as the bottomhole pressure at the point of maximum curvature.
- Often gives poor results despite an exact definition of the method.
- Noise in pressure data leads to large fluctuations in curvature, resulting in errors by producing false maximum curvature values.



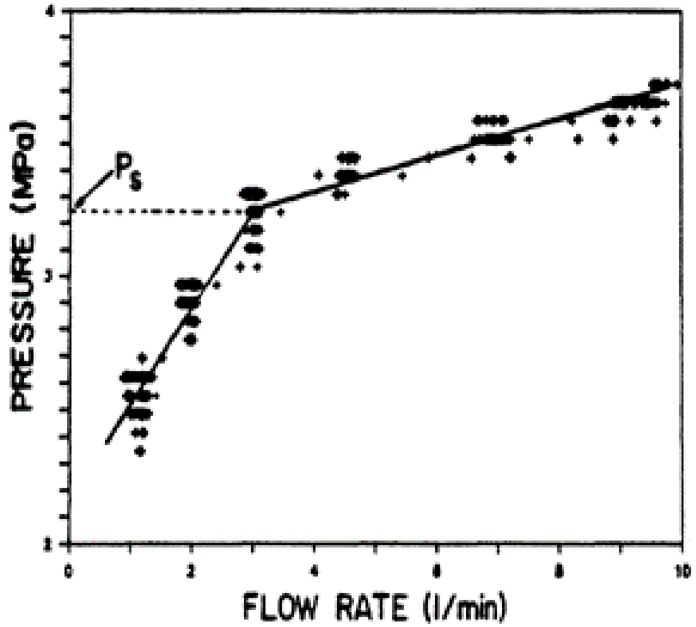
Tangent Intersection Method

- Utilizes the pressure versus time curve
- Proposed by Enever and Chopra (1986)
- The shut-in pressure is represented by the point of intersection between the tangent to the pressure curve immediately after pump shut-off and that to the late stable section of the pressure curve



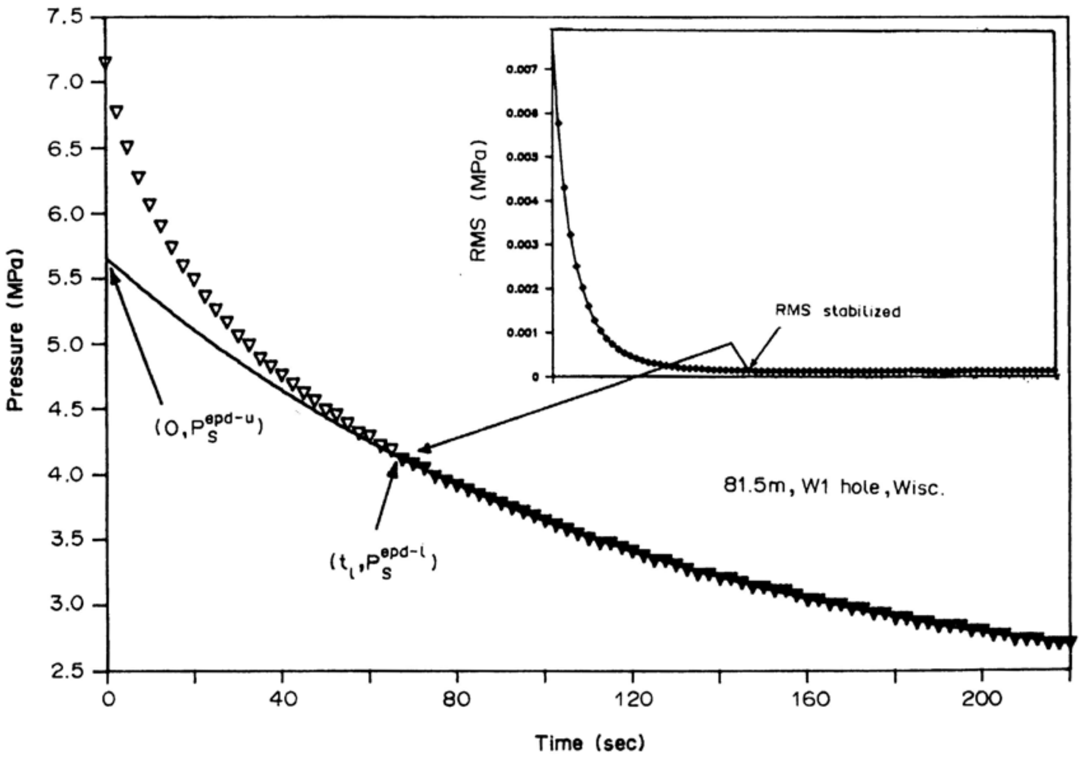
$P - Q$ Method

- The pumping pressure at a constant flow rate usually stabilizes for cycles subsequent to the breakdown cycle.
- The shut-in pressure can be determined by plotting the varios flow rates against the stable pumping pressures.
- Method works best when all data are taken from a single cycle.



Exponential Pressure Decay Method

- Proposed by Lee and Haimson (1989).
- The pressure at the test section of the drill hole decays after the pump is shut-off.
- It is assumed that after the hydrofracture closes, the pressure-time curve follows an exponential relation.



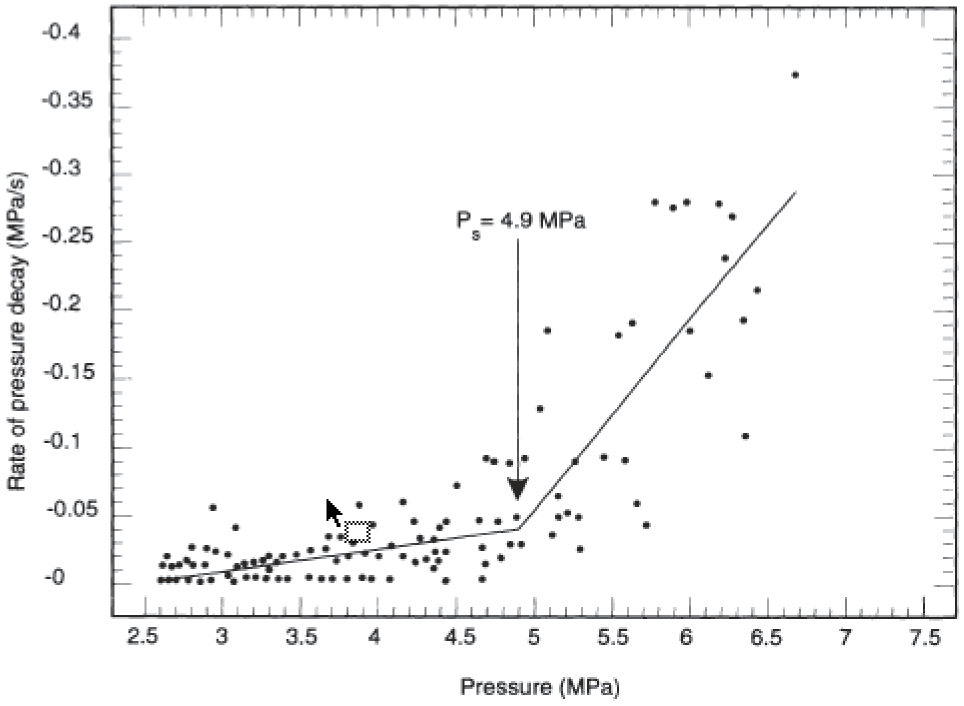
Bilinear Pressure Decay Rate Method

- Proposed by Turnbridge (1989).
- Turnbridge showed mathematically that the plot of rate of pressure decay versus pressure consists of two linear segments.

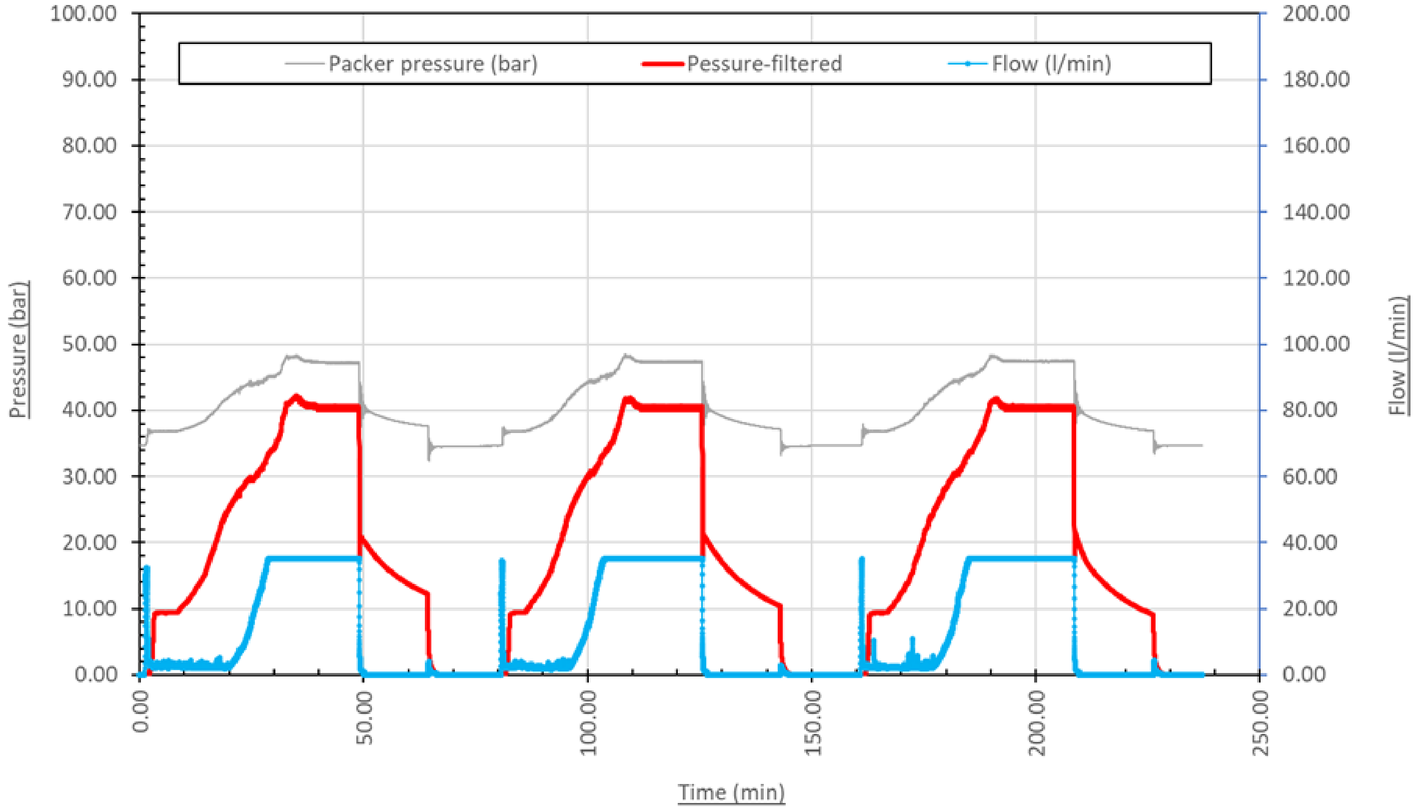
$$\frac{dP}{dt} = -a\, e^{at+b}, P \gg P_s$$

$$\frac{dP}{dt} = -c\, e^{ct+d}, P \ll P_s$$

- The intersection of the two lines gives an estimate of the shut-in pressure.
- Most popular and most reliable method for the determination of the shut-in pressure (Amadei and Stephansson (1997)).



Comparison of Methods



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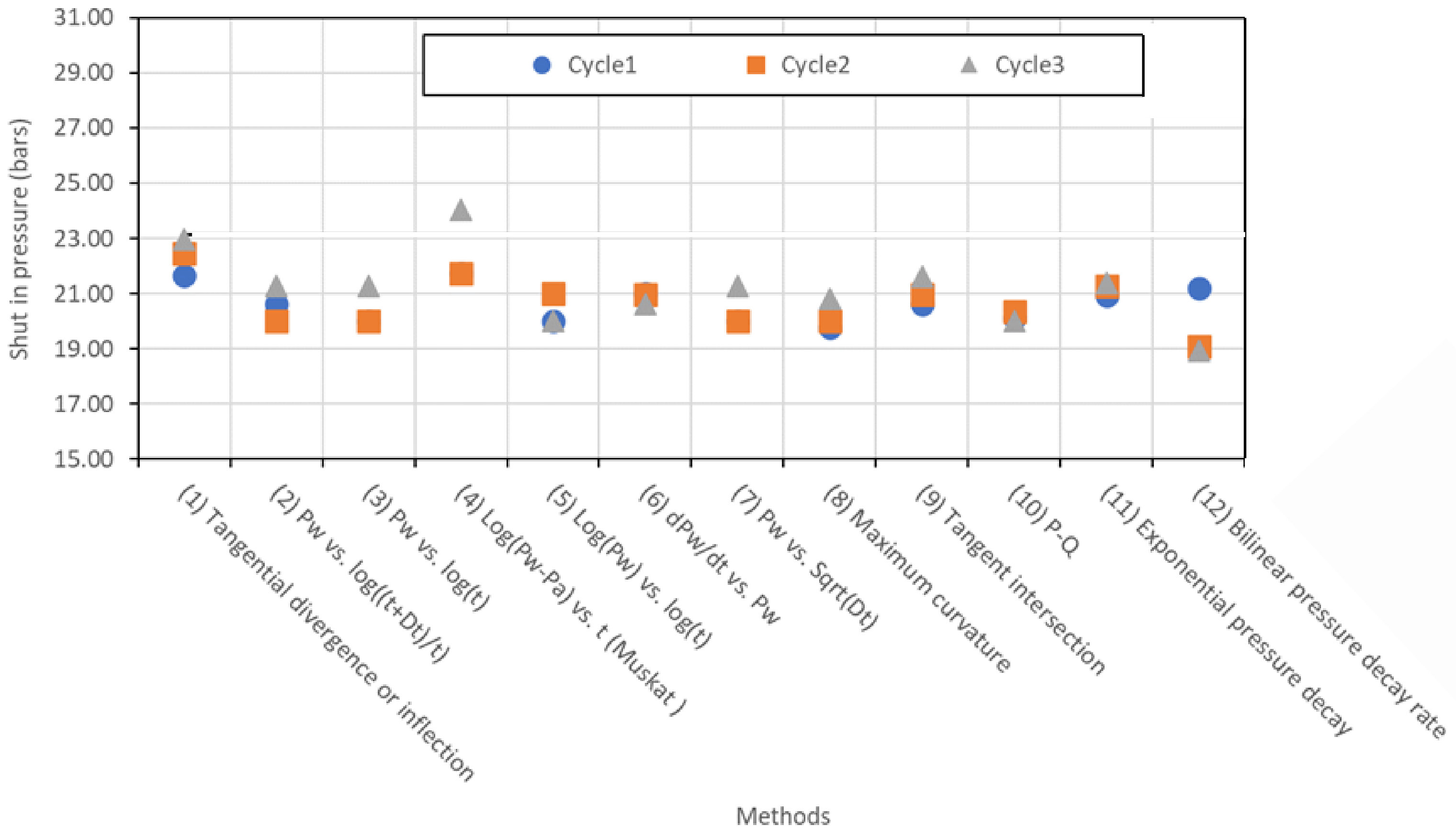

Summary

- Most of the existing shut-in pressure interpretation methods are subjective.
- Some existing interpretation methods do not produce reliable results in cases where the data are more sparse.
- Statistical analysis of hydraulic fracturing field data enhances the objectivity of determining the shut-in pressure.

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