Fast and Reliable Estimates of Low Permeabilities by the Full-Immersion Pressure-Pulse Decay

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U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

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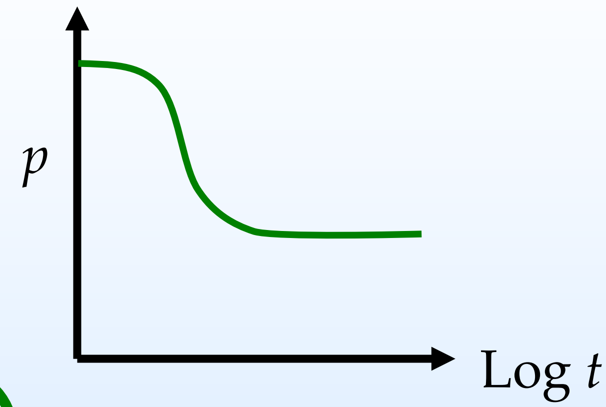
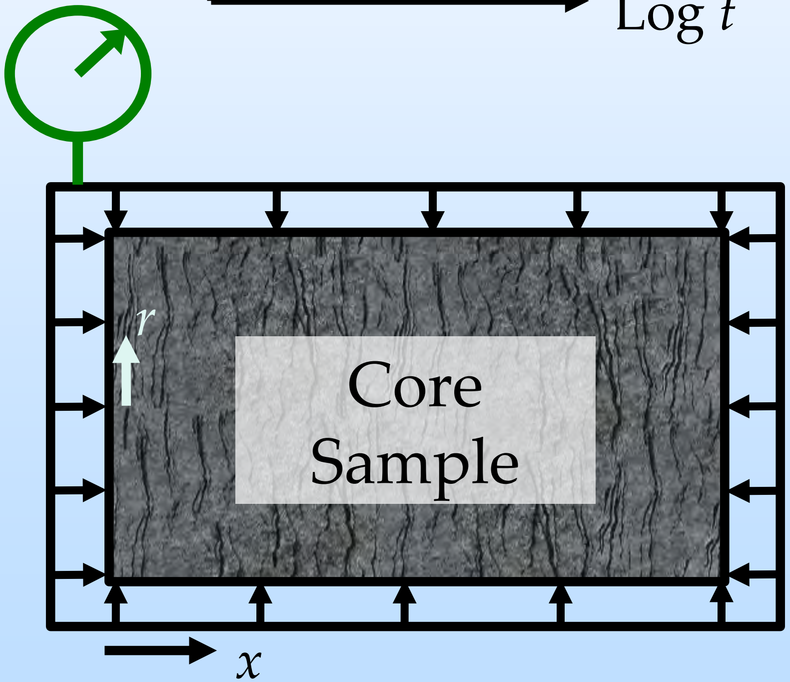
Presentation Outline

- Introduce Full Immersion Pressure-Pulse Decay
  - Unique solution
  - Range of applicability
- Experimental design
- Comparison to traditional measurements
- Future work

Full-Immersion Pressure-Pulse Decay

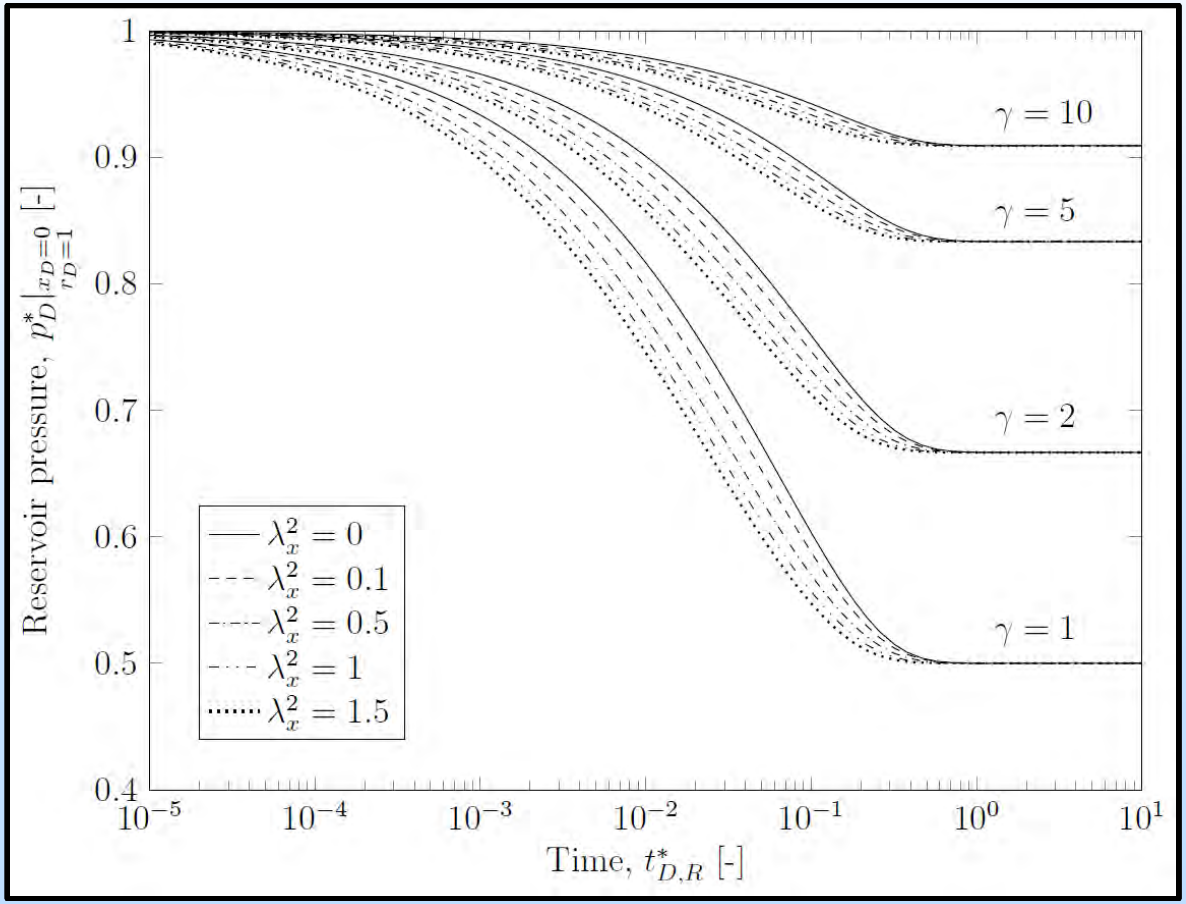
- Apply pressure disturbance to entire outer surface area.
- Sample cut perpendicular to bedding.
- Assume uniform but distinct permeabilities in radial (horizontal) and axial (vertical) directions.
- Numerical simulation to predict pressure response; Inverse model to infer porosity and permeabilities
- Simultaneously determine both permeabilities from a single test!





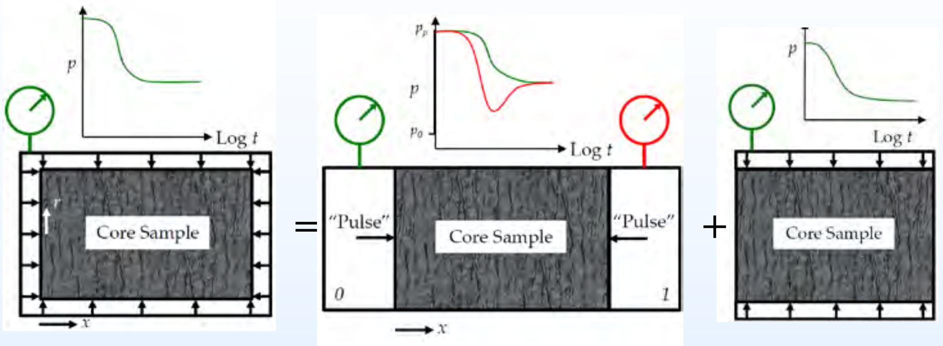
Full-Immersion PPD: Parametric study

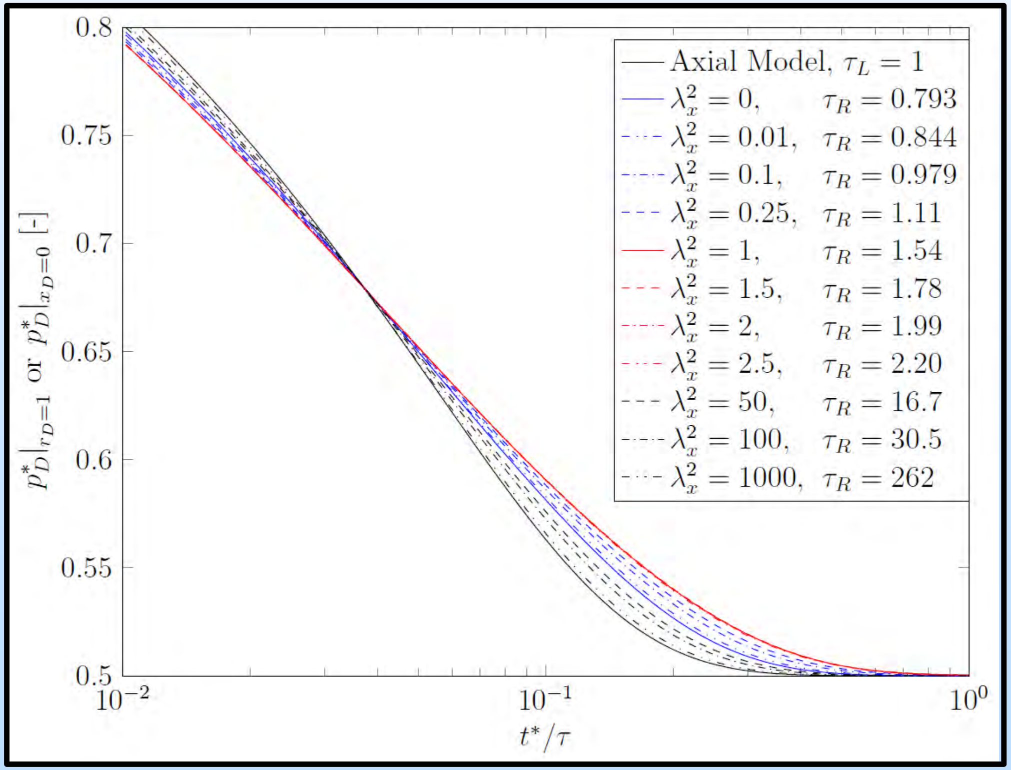
- τ_R: Time constant, inversely proportional to radial permeability k_r
- $\lambda_x^2 \equiv \frac{k_x}{k_r}\left(\frac{D}{L}\right)^2$
- γ: ratio of reservoir volume to pore volume, inversely proportional to porosity ϕ



Full-Immersion PPD: Unique solution?

- Radial flow (solid blue) model cannot match axial flow model (solid black).
- Under favorable conditions (remaining blue), each permeability provides unique signature effect on pressure trace.
- Under unfavorable conditions (red), they cannot be distinguished.

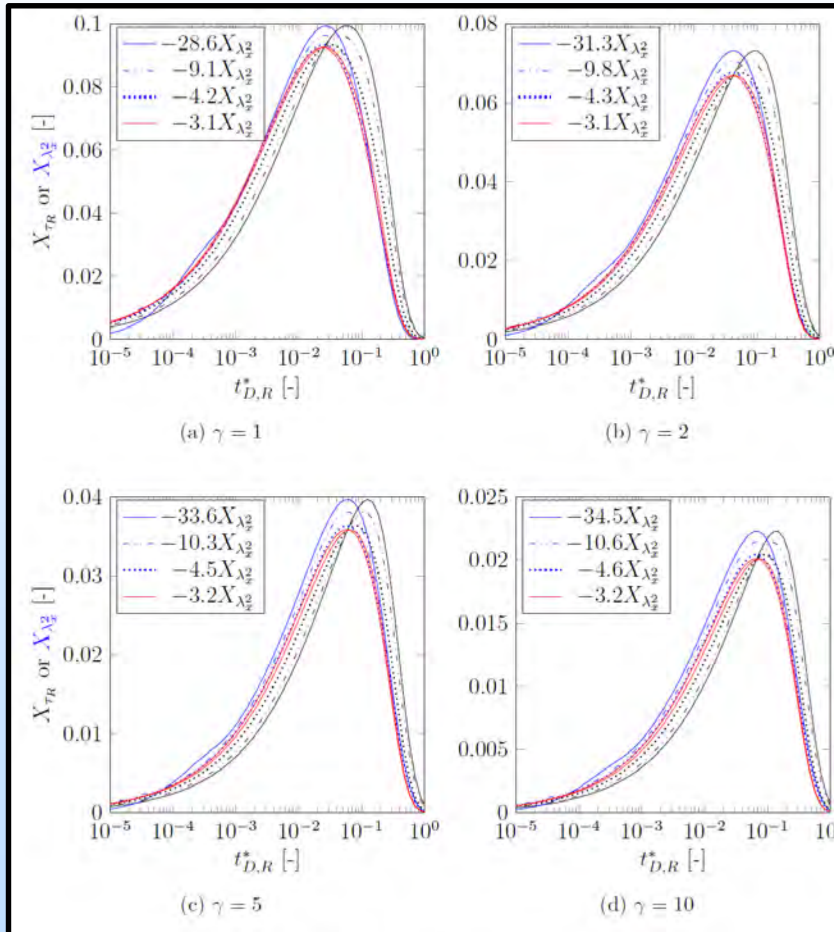




Full-Immersion PPD: Permeability Correlation

- $X_\beta \equiv \beta \frac{\partial p_D^*}{\partial \beta}$, scaled sensitivity coefficient
  - γ (dependent on porosity)
  - τ_R (dependent on porosity and radial permeability)
  - λ_x^2 (dependent on radial and axial permeabilities and dimensions)

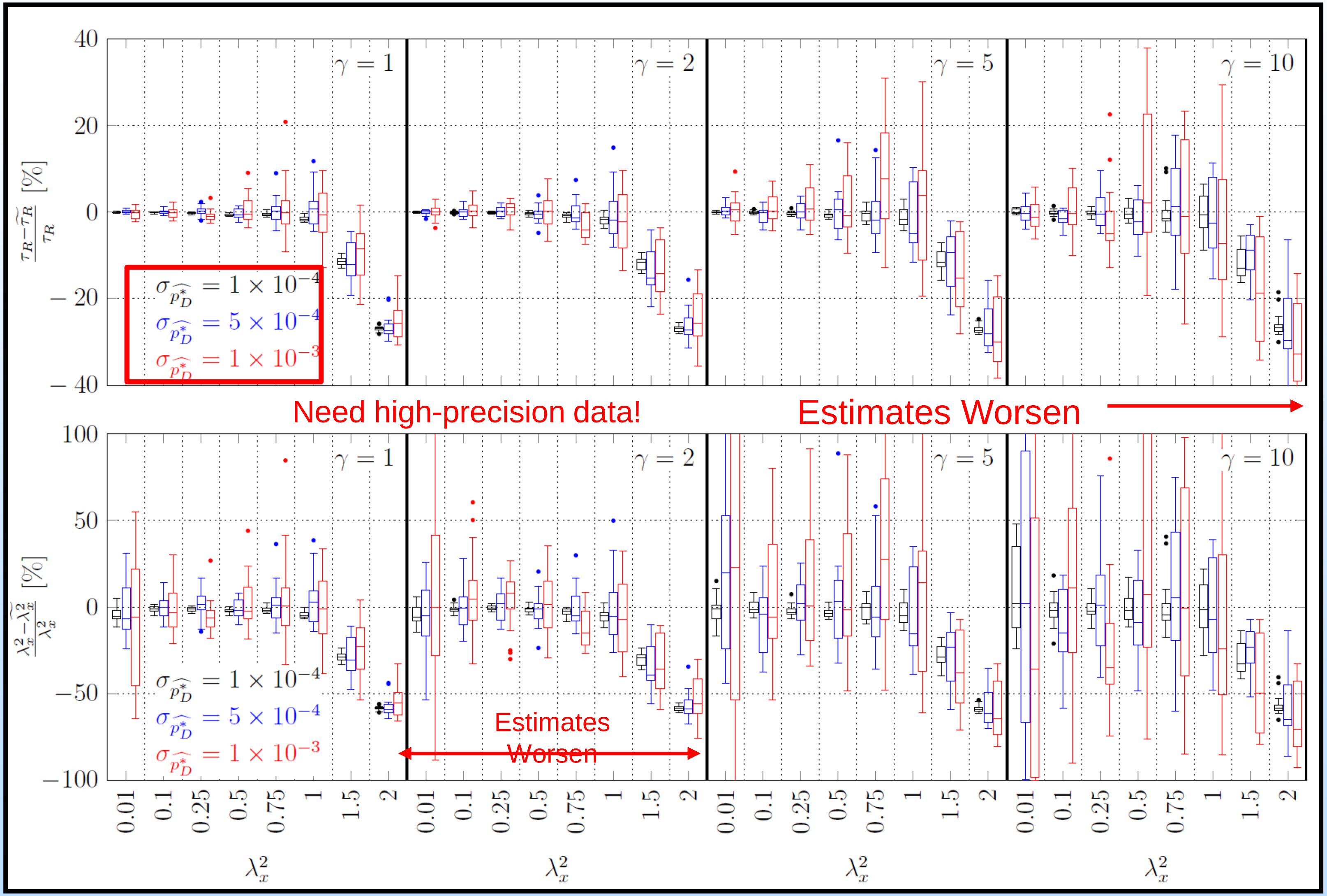
- When too low (solid blue/black), axial permeability doesn't influence result enough.
- When too high (red), axial permeability is correlated with radial permeability.
- "Uniqueness window"
- Inversion strategy: see how much data deviate from radial-flow model.



(a) $\gamma = 1$ (b) $\gamma = 2$ (c) $\gamma = 5$ (d) $\gamma = 10$

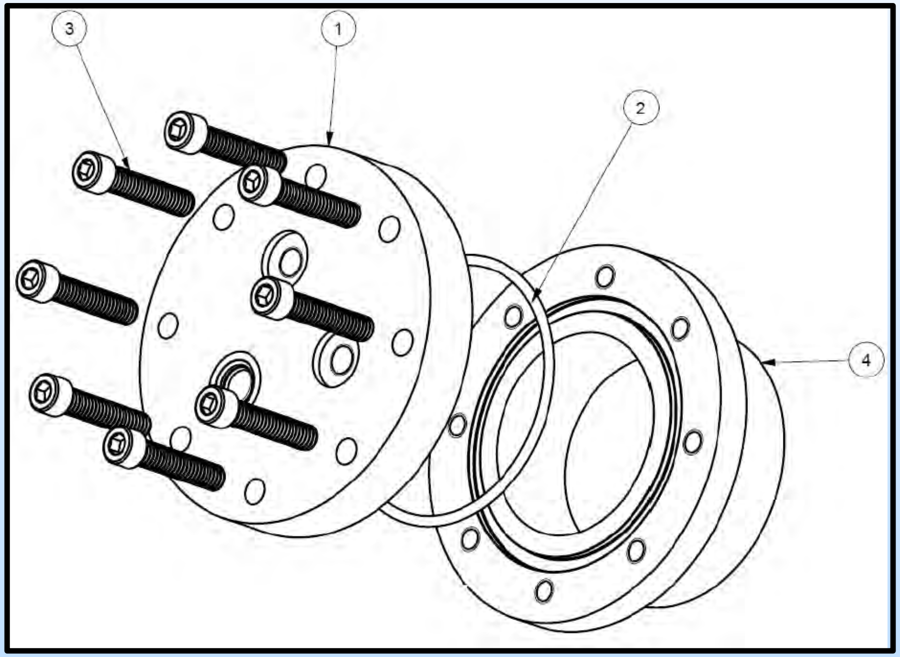
— $\lambda_x^2 = 0.01$, - · - $\lambda_x^2 = 0.1$, ····· $\lambda_x^2 = 0.5$, — $\lambda_x^2 = 1.0$

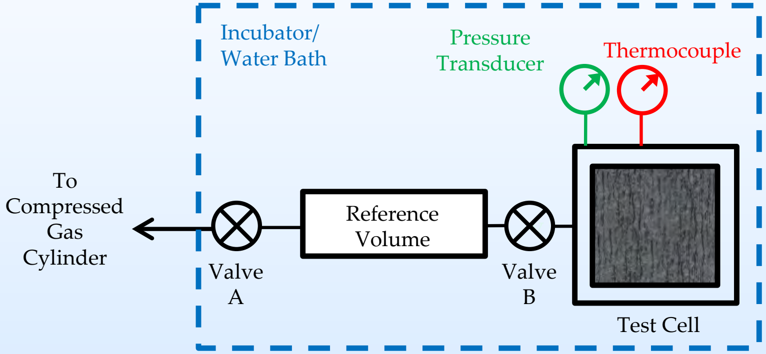
Full-Immersion PPD: Monte-Carlo Analyses

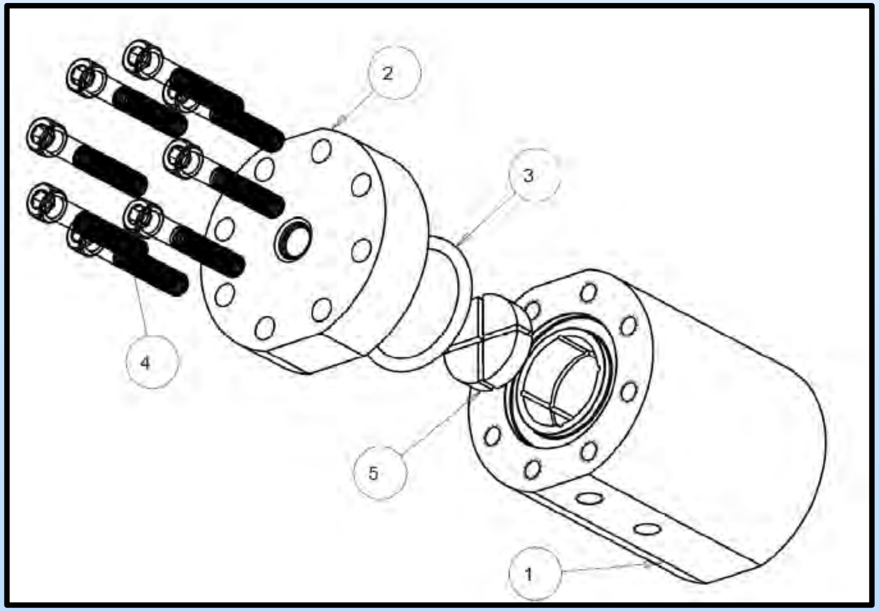


Full-Immersion PPD: Experimental Apparatus

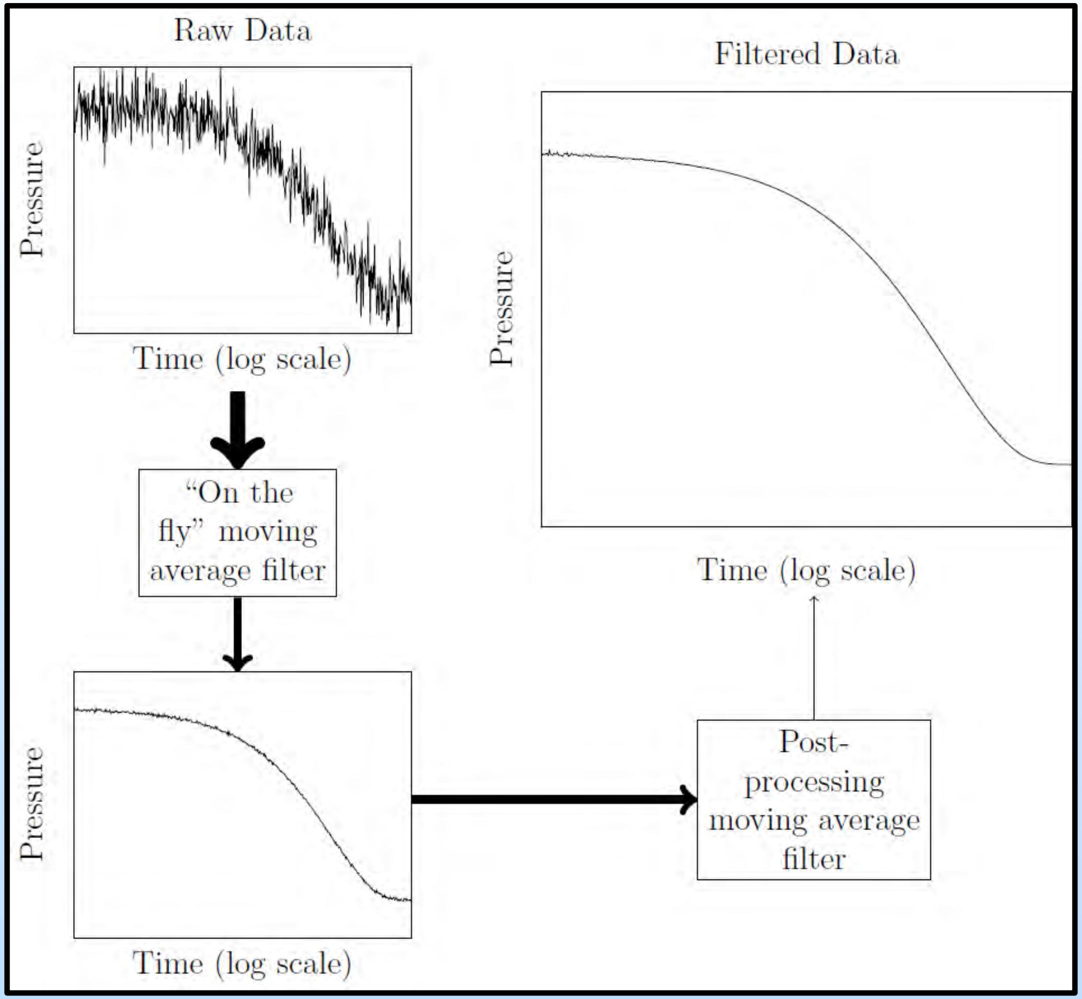
2″ D, 1″ L samples:

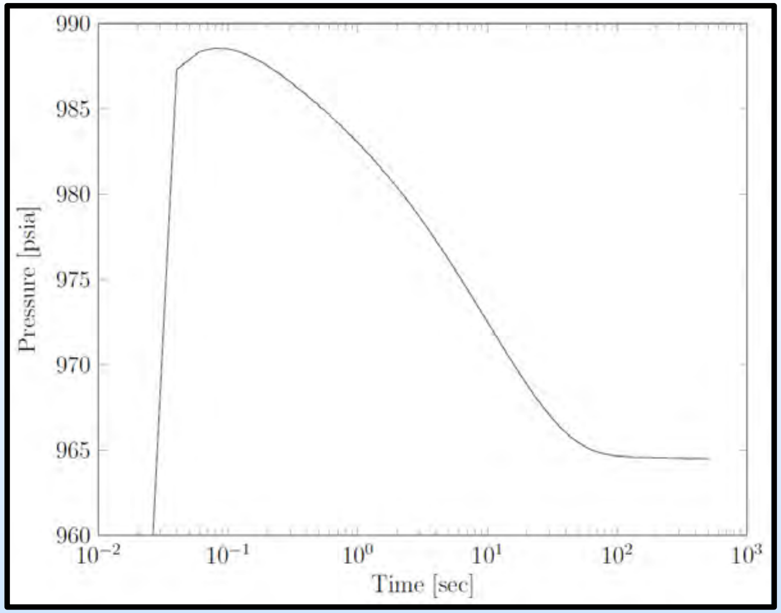






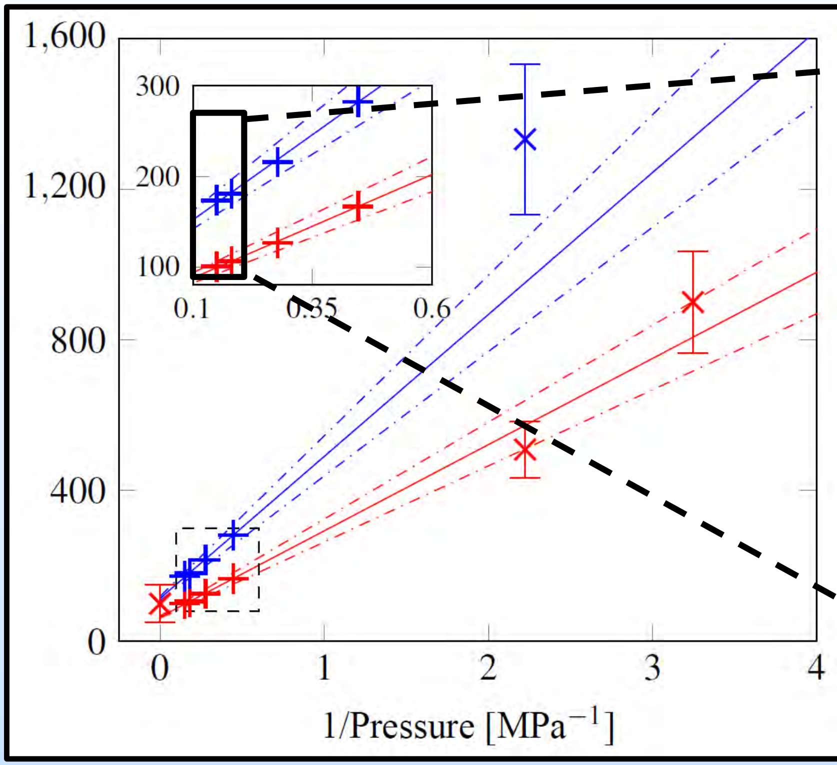
Full-Immersion PPD: Data Acquisition and Reduction Algorithm





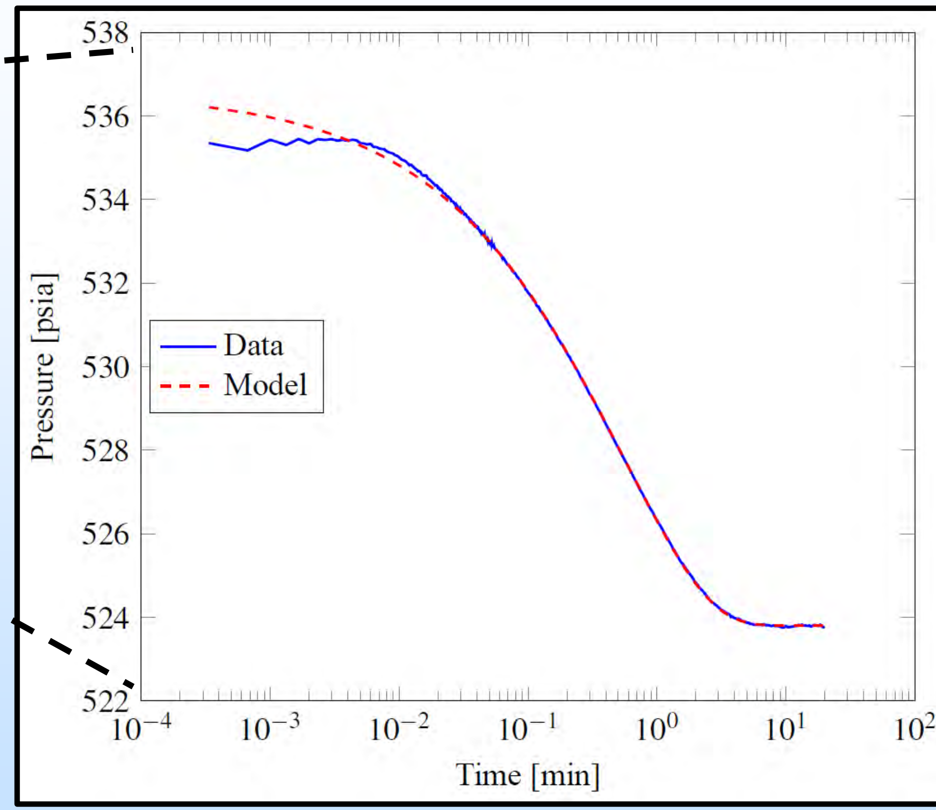
Data trace from sample having estimated radial and axial *k* of 544 and 85 nD, respectively, and an estimated ϕ of 9.5%.

Full-Immersion PPD: Experimental Comparisons



$k_r = k_{\infty,r}\left(1 + \frac{b_r}{p_{\text{ref}}}\right)$, k_r confidence interval, × Weatherford k_r estimate, + UAB k_r estimate,

$k_x = k_{\infty,x}\left(1 + \frac{b_x}{p_{\text{ref}}}\right)$, k_x confidence interval × Weatherford k_x estimate, + UAB k_x estimate



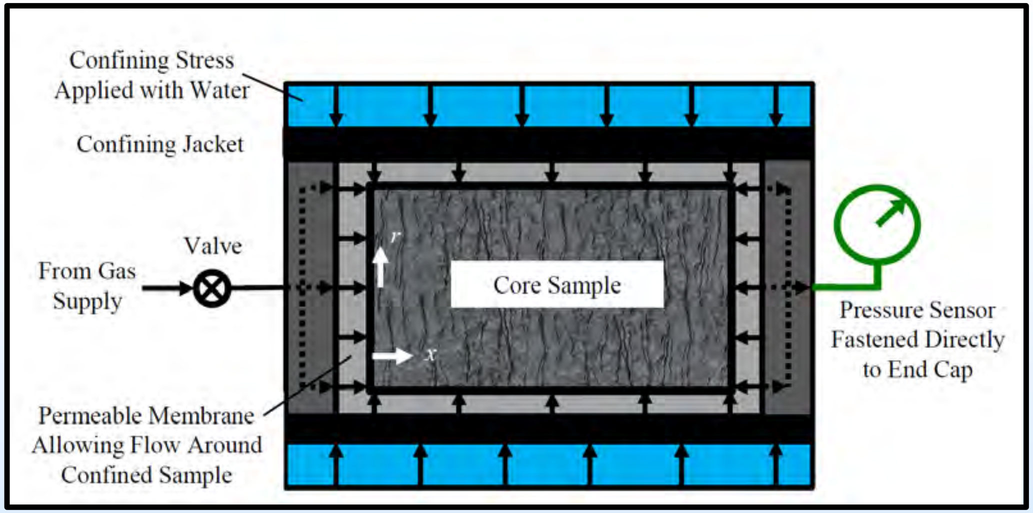
$\widehat{p_0}$ = 491.6 psia, $\widetilde{p_p}$ = 536.5 psia, $\widetilde{\phi}$= 8.5%,
$\widetilde{k_r}$ = 215.8 nd, $\widetilde{k_x}$ = 126.6 nd

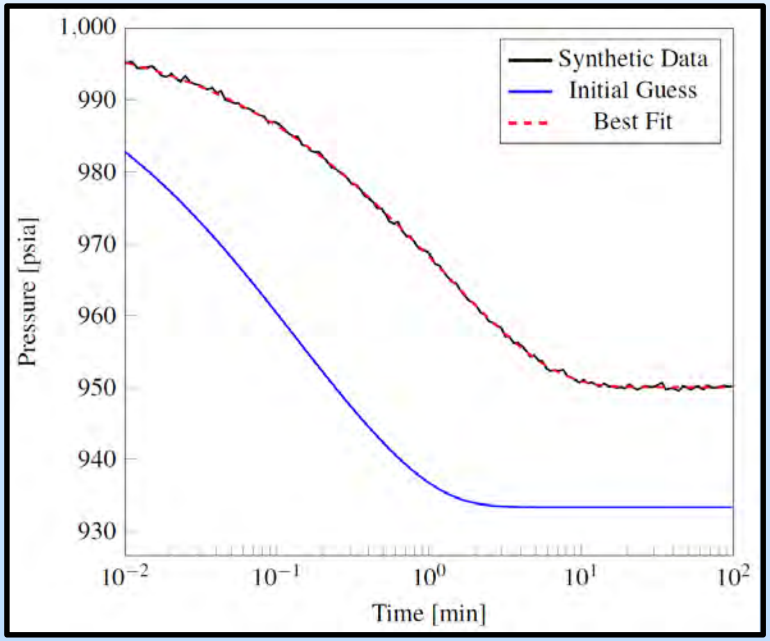
Permeabilities ~ 100s of nD

Tests complete in 5-20 minutes!

Next Steps: Tight Core Analysis Lab - FIPPD

- A mesh sleeve wraps the sample before confining it in the core holder.
- A pressure sensor is fastened directly into the end cap, minimizing dead volume.
- A test is initiated by rapidly opening and closing the valve just upstream of the sample.
- Preliminary simulations with liquids show faster tests than those with gas!
    - Dependent on product of viscosity and compressibility





Parameter	True Value	Initial Guess	Best Estimate
Porosity (%)	2.5	5.0	2.497
Horizontal Permeability (nd)	1.0	10.0	1.0
Vertical Permeability (nd)	0.1	0.01	0.0986

Accomplishments to Date

- A proof-of-concept apparatus has been built to perform these tests under unconfined conditions.
- Split-sampling analyses have been performed successfully with steady-state experiments performed independently at Weatherford Laboratories.
- The numerical simulation modeling anticipated experimental outcomes has been refined so that parameter estimates can be calculated in less than 1 minute.

Lessons Learned

- Finding a unique set of directional permeabilities from a single experiment is difficult but not impossible.
- In cases where a unique solution cannot be found from a single test (outside of the "uniqueness window"), a second set of data can be collected from a unidirectional experiment.
- Particularly regarding tests that may take a long time (a few hours or more) to complete, temperature stability and leak maintenance are key obstacles to overcome:
  - Temperature stability: The device should sit within a temperature-controlled system (e.g., air or water bath) that maintains good temperature stability.
  - Leaks: The number of fittings connecting to the test chamber should be minimized and broken only when necessary.

Synergy Opportunities

- Relationship with industrial partners established
- Relationships with national labs under development

- The potential for this methodology to be used as a fast screening process of low permeability shales is high, and we'd be happy to assist in characterization of shales.

Project Summary

- The Full Immersion Pressure-Pulse Decay is a promising avenue for a quick and accurate assessment of low-permeability cores.
- Tests should now be performed in standard tri-axial core holders with confining stress.
- Additional factors (e.g, Knudsen diffusion, sorption, and microfractures) should be incorporated into future numerical simulations and accounted for in future experimental designs.

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Benefit to the Program

- Shales are often discussed in geologic circles, yet their properties are poorly described and understood. The inherent low permeability of shales makes understanding their flow characteristics non-trivial. A novel permeability measurement technique has been developed to rapidly and accurately measure shale properties.
- The ability to quickly determine the permeability of shales and other tight formations will reduce time and effort in the formation evaluation required to characterize these unconventional resources.

Project Overview
Goals and Objectives

- The primary impact of this research is better defined on how reservoir geomechanical processes contribute to the potential for long-term gas production from shale.
  - By developing an improved technique to measure shale permeability, that is faster than available techniques and comparable with accuracy, our aim is provide stakeholders with the ability to understand the flow of fluids through shale for improved production.
- Success will be measured by proof of concept experiments in the laboratory and through direct comparisons with traditional permeability measurements.
  - Further development of this technique to examine a wider range of conditions (i.e. fractured shales and multiphase flow properties) are long term success criteria.

Organization Chart

- Former NETL/ORISE, now IGWS: Michael Hannon
- NETL/RIC: Dustin Crandall
- NETL/ORISE: Yael Tucker

NOTE: With Mikey taking a job with IGWS survey at the end of July, the dates on this plan are likely to change. The details of these changes are still being worked out.

Gantt Chart

Timeline Overview – Sub-Task 2.1.2

Low Permeability Shale Measurements

Milestones

1. Compare and contrast traditional pulse decay with high resolution steady state gas permeability measurements. (Completed - December 2017)
2. Peer reviewed manuscript of modification to high-resolution steady-state permeability measurements with low downstream pressure submitted to journal. (September 2018)
3. Assemble a bench scale full immersion pulse decay device and shakedown apparatus. Compare/contrast measurements to traditional pulse decay. (December 2018)
4. Develop a full immersion pulse decay permeability technique for fractured shales. Examine this technique numerically to confirm measurements can be obtained, and perform shakedown on experimental prototypes. (June 2019)
5. Commercialization of full immersion pulse decay technique with external partner. (December 2019)

Go / No-Go

September 2019 - Test full immersion pulse decay permeability technique for fractured shales experimentally and show match numerical expectations. If successful continue towards commercialization with partners.

Impact

Key Accomplishments/Deliverables	Value Delivered
2017: Numerical simulations and preliminary experimental measurements have shown that the full immersion pulse decay technique (patent pending) is able to measure shale permeability faster than any other reliable method on the market. Discussions with industry and applications for technology commercialization funds are underway.	• Shale permeability measurements that are accurate, can be obtained efficiently, and with a process that is openly described will provide greater confidence in measurements for stakeholders and regulators that need to quantify carbon storage seal integrity.

Chart Key

\# TRL Score | Go / No-Go Timeframe | Project Completion | Milestone

Bibliography

Hannon, M.J., 2017, Fast and Reliable Estimates of Low Permeabilities by the Full-Immersion Pressure-Pulse Decay. Unconventional Resources Technology Conference, Austin, Texas, 24-26 July 2017: pp. 673-692.

- Patents

**PCT/US2016/031502, Publication Date: 11 October 2016

U.S. Patent Filed November 2017

- Publications in preparation:

Hannon, M.J. (in preparation) Fast and accurate core analysis by the Pressure-Pulse Decay: Part 1-Theory. SPEREE.

Hannon, M.J. (in preparation) Fast and accurate core analysis by the Pressure-Pulse Decay: Part 2-Demonstration. SPEREE

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