Development of a Ceramic Coaxial Cable Sensor-Based System for Long-Term Down Hole CO2 Sequestration Monitoring

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Title

Robust Ceramic Coaxial Cable Down-Hole Sensors for Long-Term In Situ Monitoring of Geologic CO2 Injection and Storage

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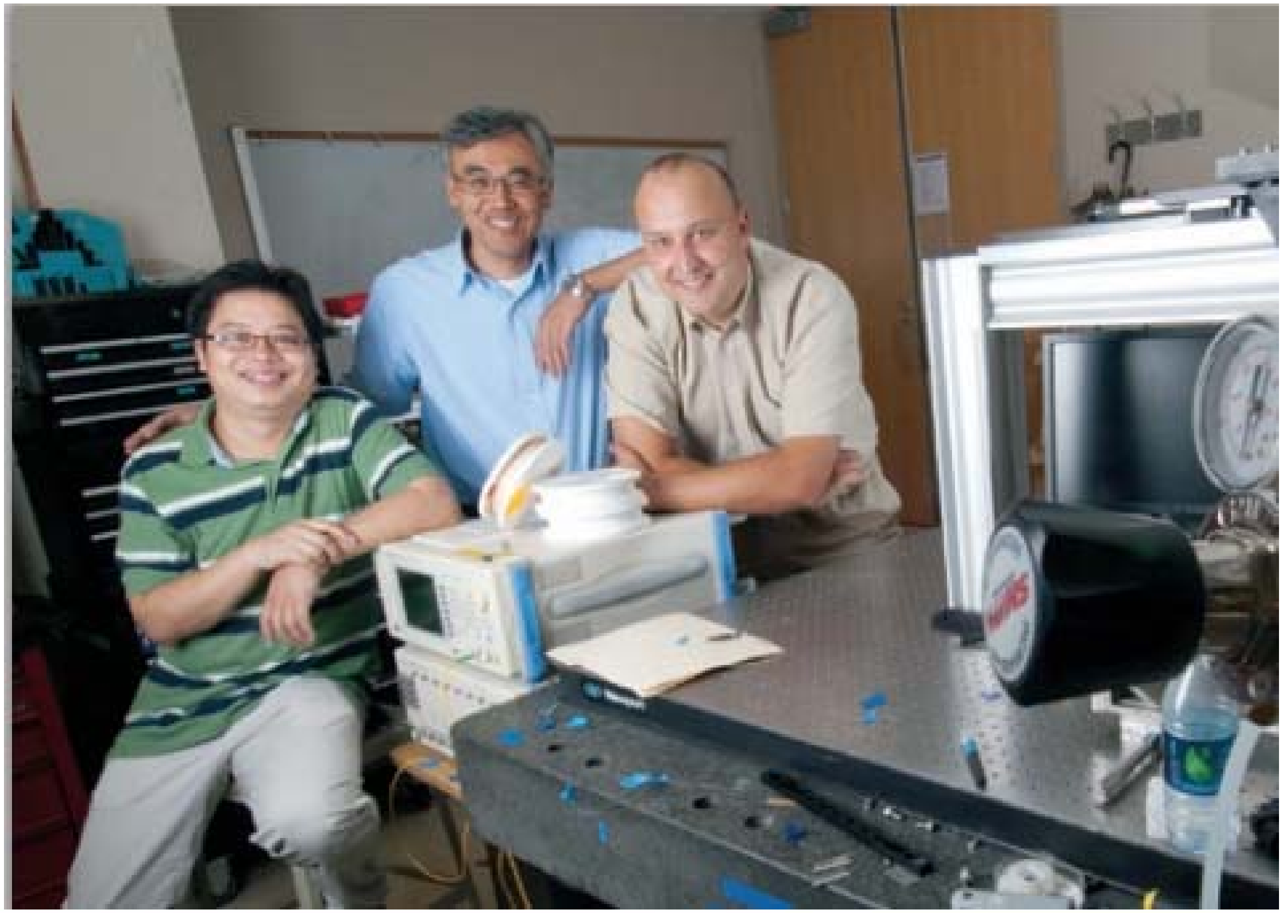
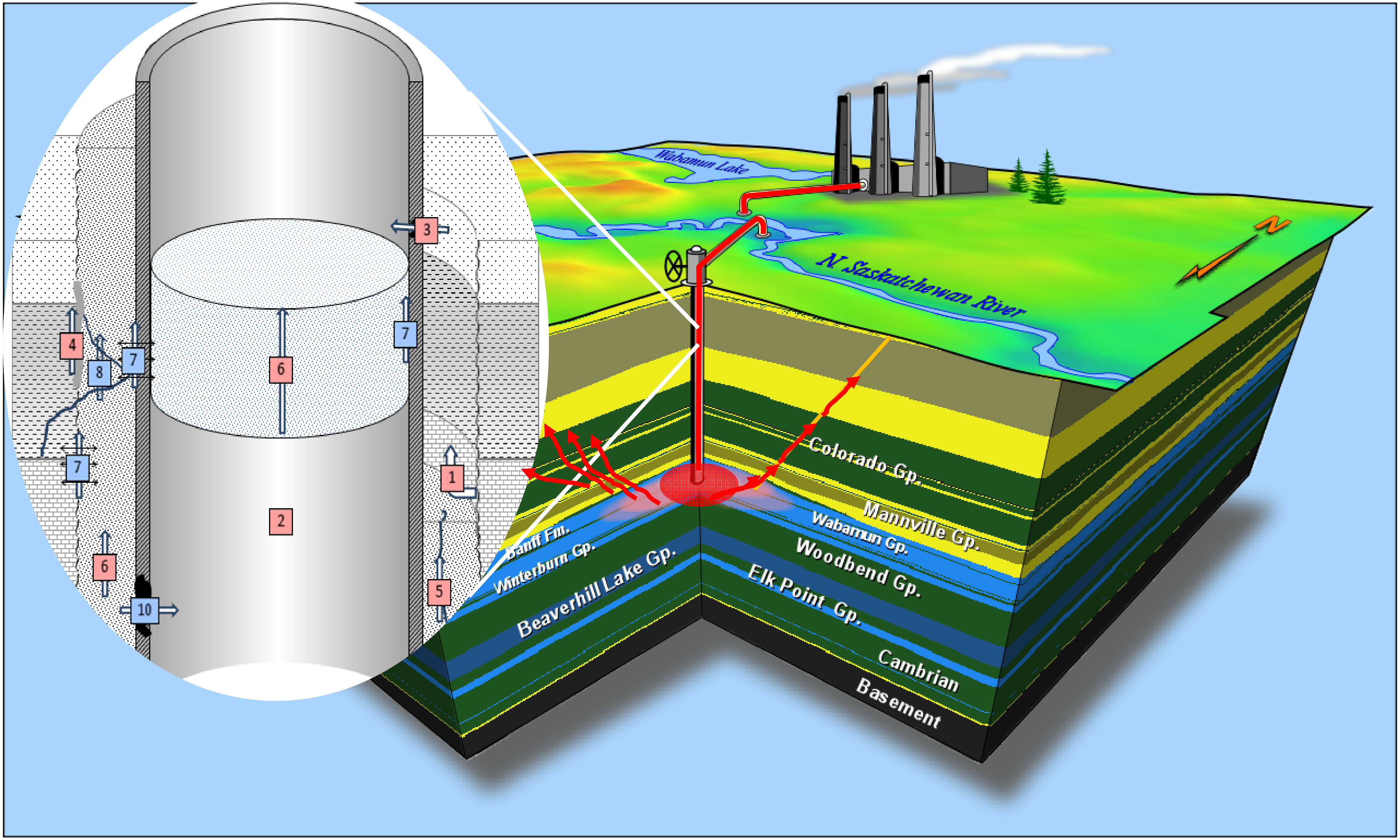


Outline

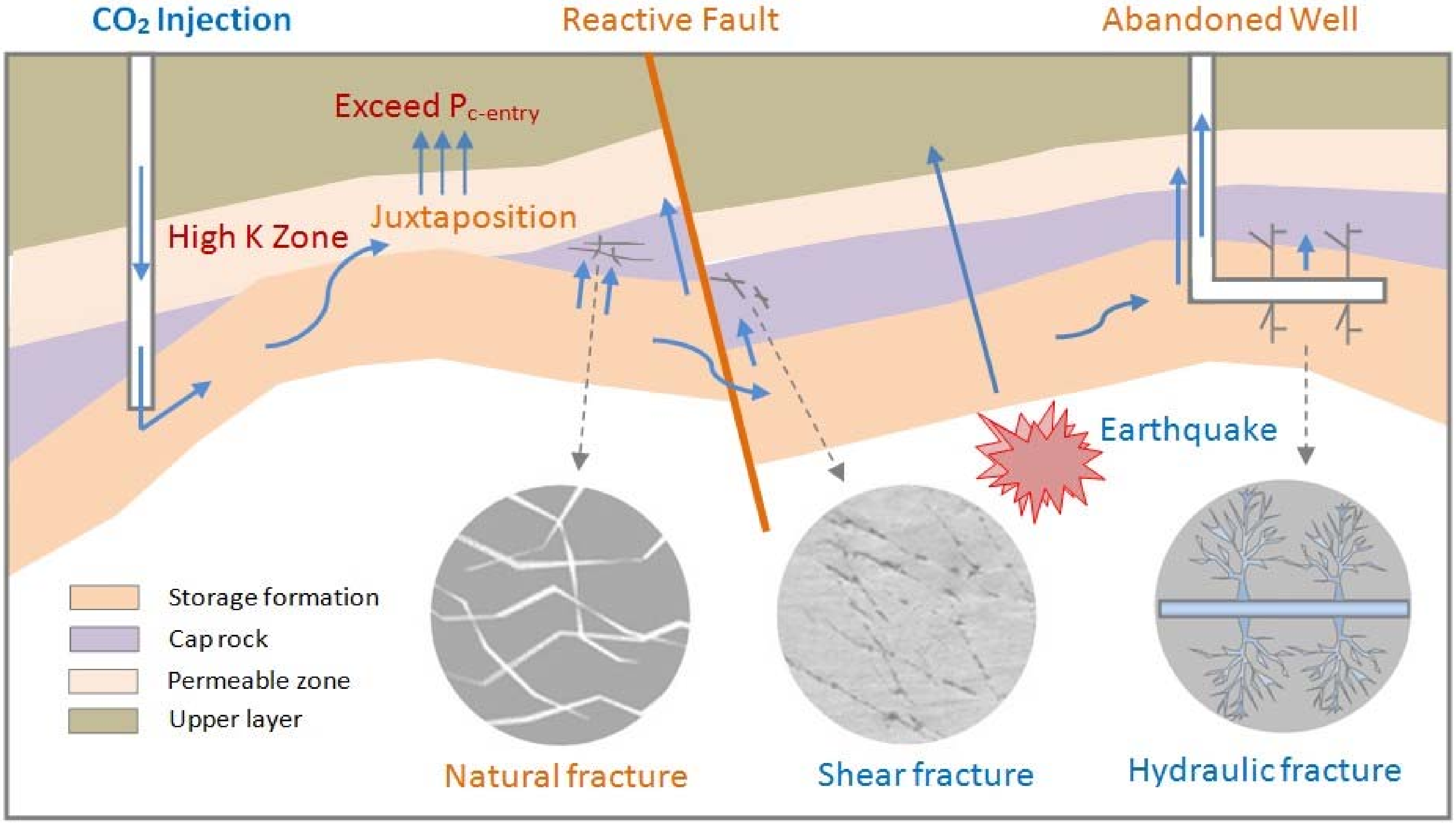
- Long term CO2 injection integrity monitoring – problem statement
- Main objective to demonstrate and develop a novel, robust, down hole sensing technology for in-situ monitoring
  - To reach the objective we need to develop robust ceramic coaxial cable sensors
  - and test the sensors at down hole conditions,
  - then integrate the sensor data with geological models.
- Summary

CO_2 Sequestration monitoring



Source: Wabamun CO_2 sequestration project - WASP

Potential leakage pathways of CO_2



Matrix
- Capillary entry pressure
- Seal permeability
- Pressure seals
- High permeability zones

Structural
- Flow on faults
- Flow on fractures
- Flow between permeable zones due to juxtapositions

Geomechanics
- Hydraulic fracturing
- Creation of shear fractures
- Earth quake release

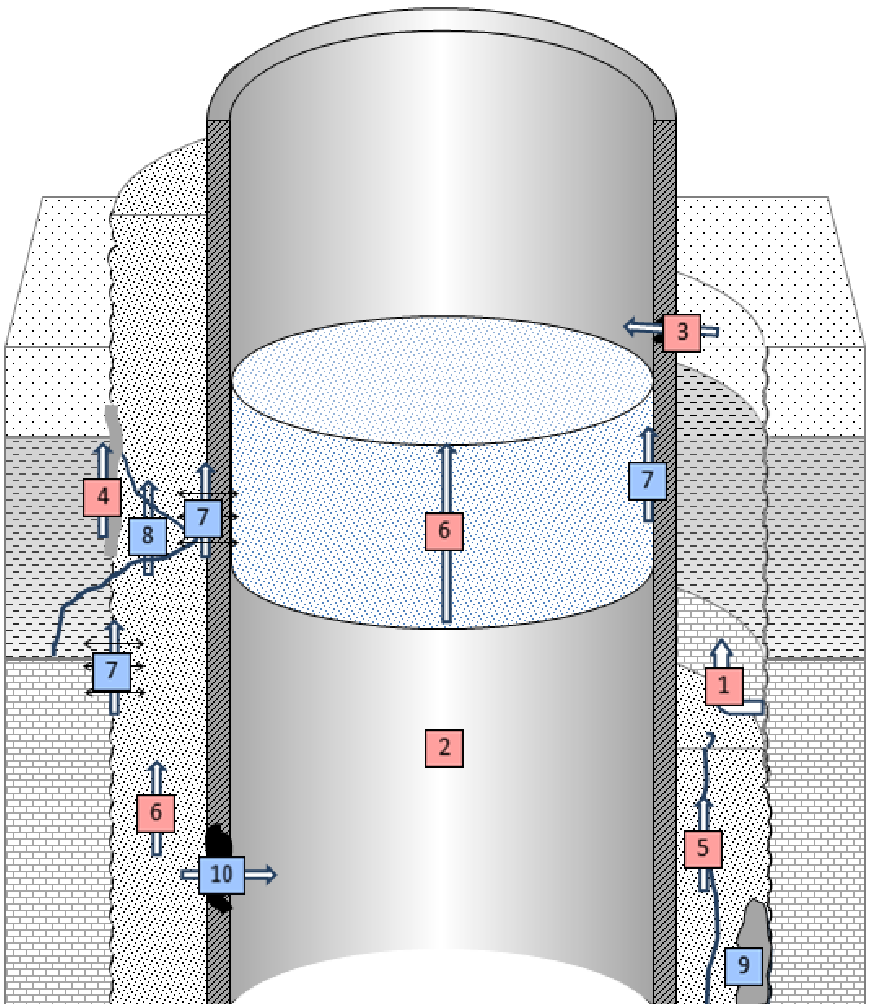
Wellbore Leakage

PRIMARY

1. Incomplete annular cementing job, doesn't reach seal layer
2. Lack of cement plug or permanent packer
3. Failure of the casing by burst or collapse
4. Poor bonding caused by mudcake
5. Channeling in the cement
6. Primary permeability in cement sheath or cement plug

SECONDARY

7. De-bonding due to tensile stress on casing-cement-formation boundaries
8. Fractures in cement and formation
9. Chemical dissolution and carbonation of cement
10. Wear or corrosion of the casing



Long term CO_2 injection integrity monitoring – problem statement

- **Background:**
  - Subsurface geologic formations offer a potential location for long-term storage of CO2.
  - Achieve the goal to account for 99% of the injected CO2 requires advanced monitoring technology to optimize the injection processes and forecast the fate of the injected CO2
- **Status:**
  - Due to the complexity, no single data type is sufficient by itself; different monitoring and characterization approaches are deemed to be necessary.
  - In situ down-hole monitoring of state parameters (e.g., pressure, temperature, etc.) provides critical and direct data points to validate the models, optimize the injection scheme, detect leakage and track the plume.
  - Current down-hole sensors are insufficient to meet the reliability and cost requirements.

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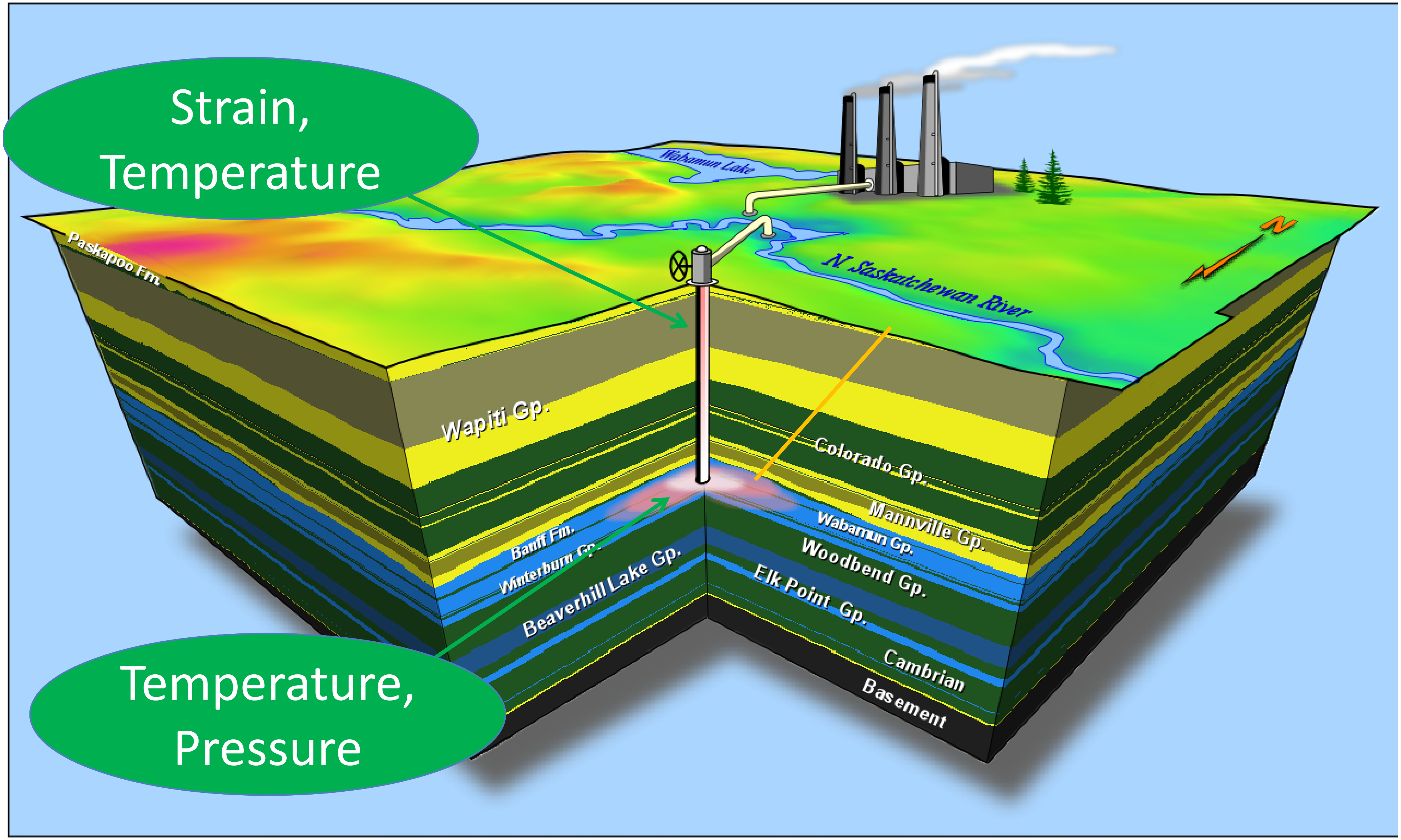
The goal is to develop a monitoring system combined for the wellbore and the reservoir



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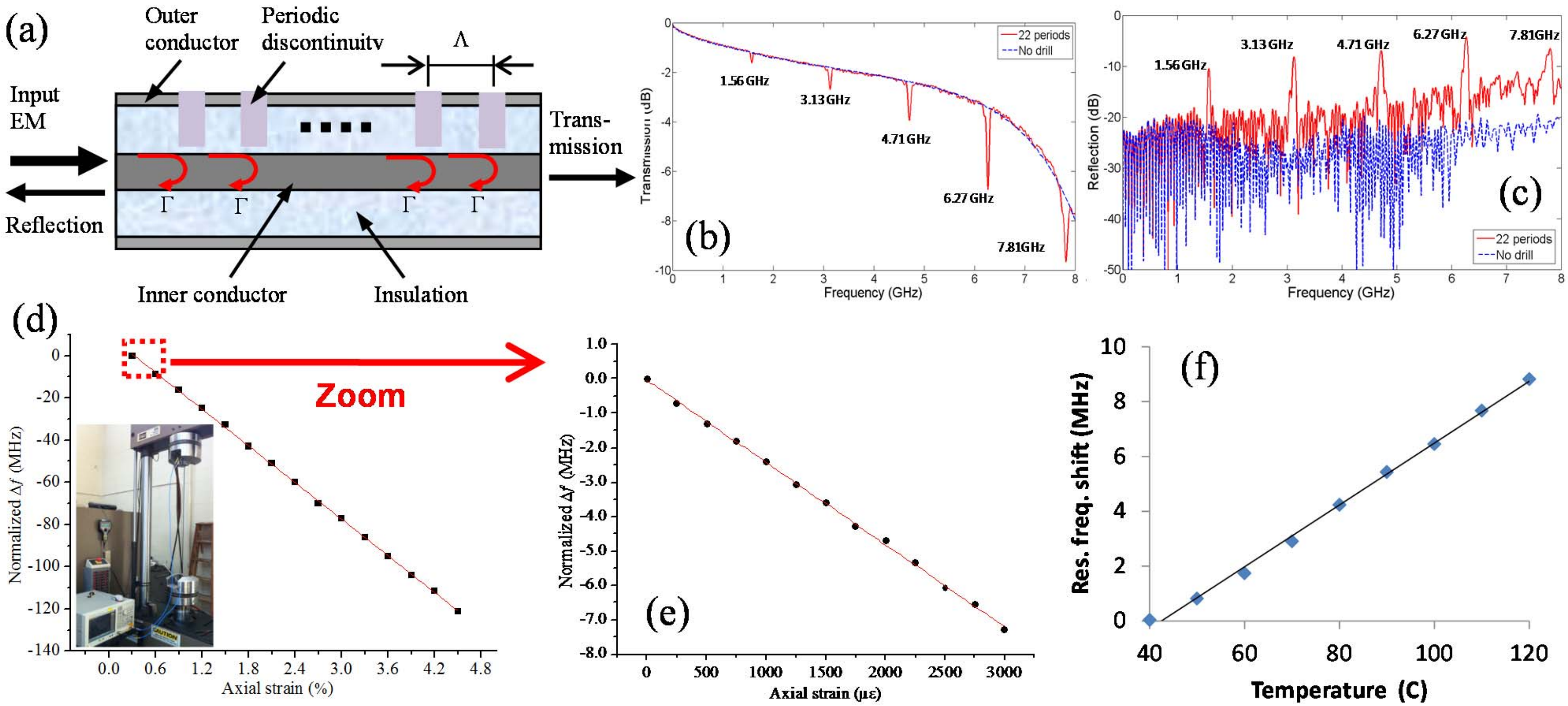
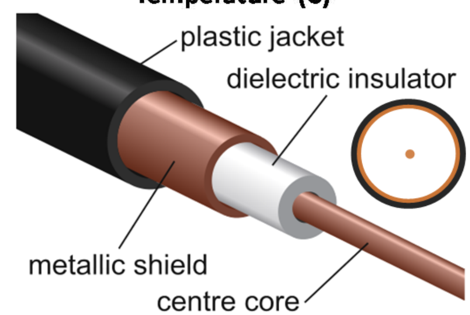
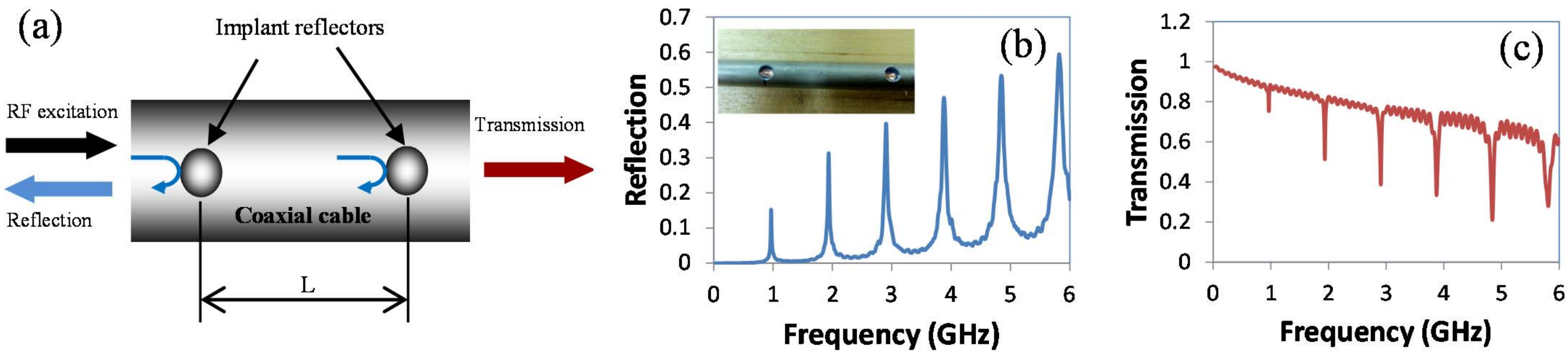
Coaxial cable Bragg grating





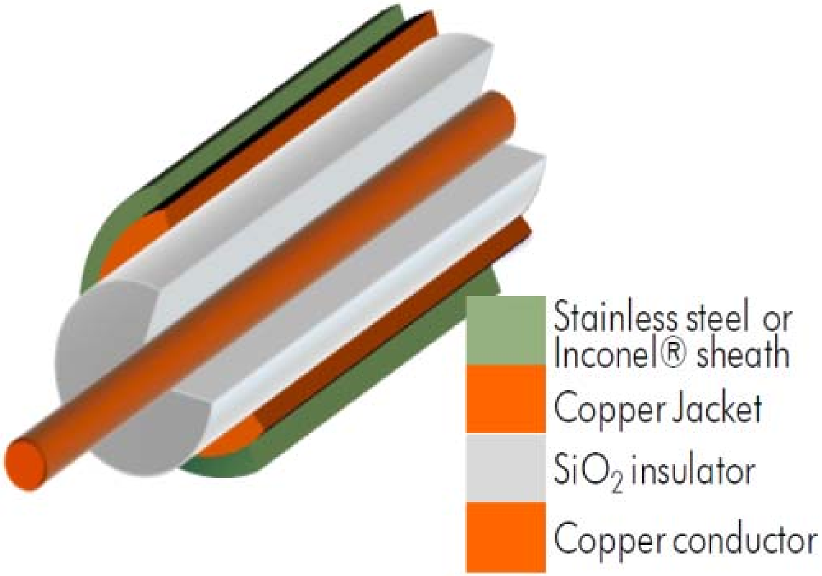
- A new concept inspired by fiber Bragg grating
- Demonstrated for temperature and strain sensing

Coaxial cable Fabry-Perot interferometer



- Another microwave sensor device inspired by the fiber optic Fabry-Perot interferometer
- Demonstrated for temperature and strain sensing with good sensitivity

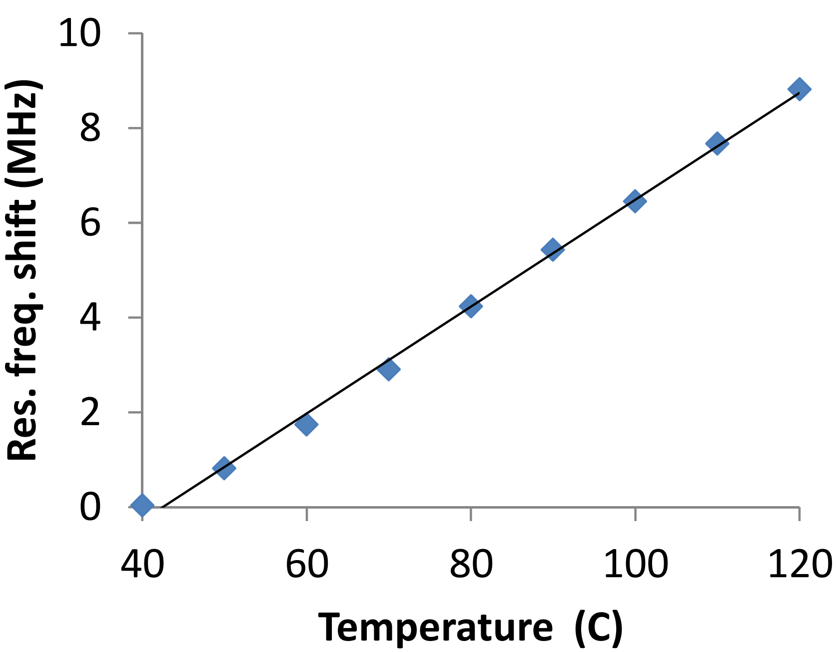
Ceramic coaxial cable



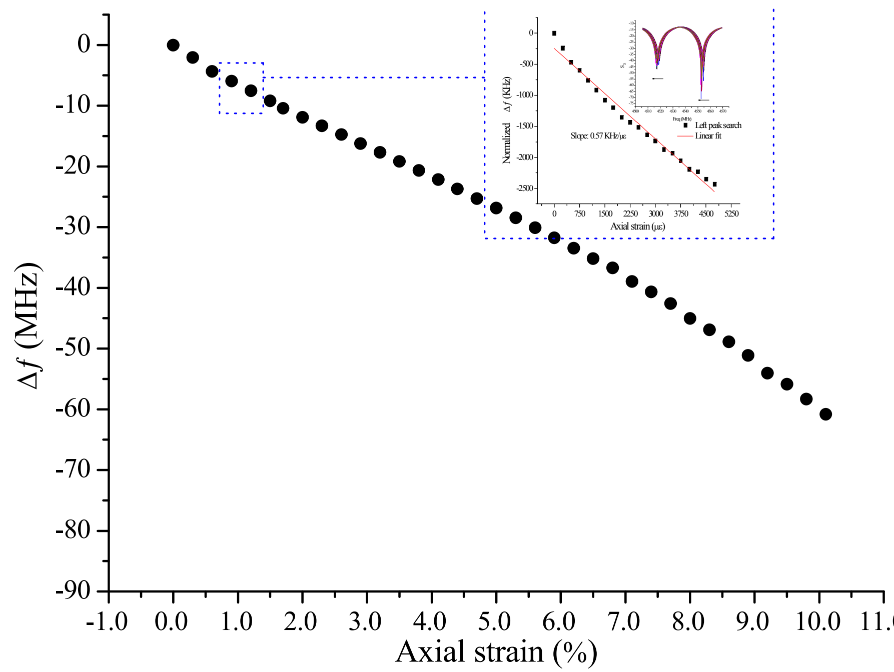
- Made by using various ceramic materials as the insulation layer
- Can operate at high temperatures up to 1000°C and high pressures up to 10,000 psi
- Operate in the frequency range up to 20 GHz
- Have a very small attenuation of 0.08 dB/m that allows the signal to be transmitted over a long distance
- Have the necessary flexibility for deployment

Temperature and large strain measurement sensors developed and tested

Temperature Measurement

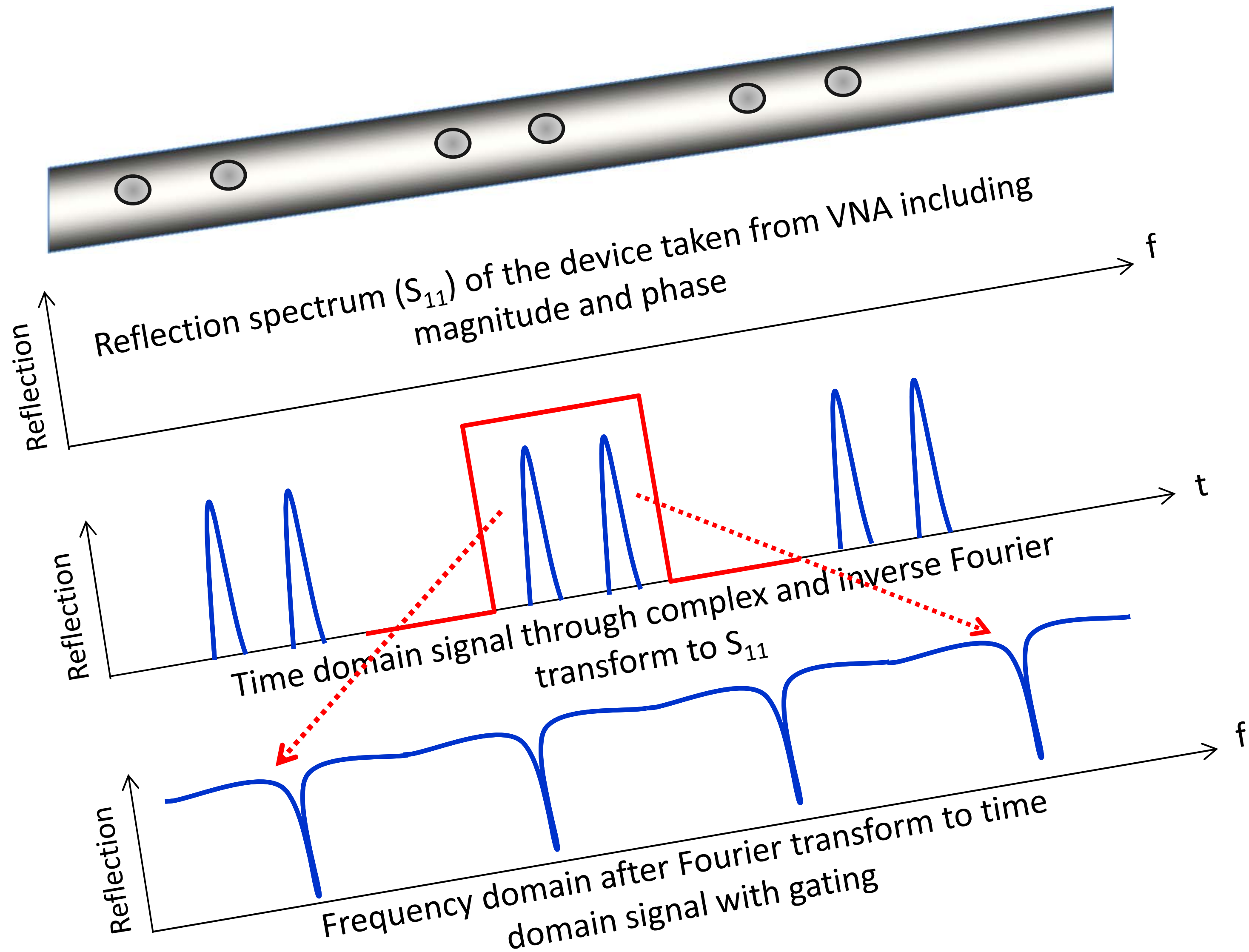


Large Strain Measurement



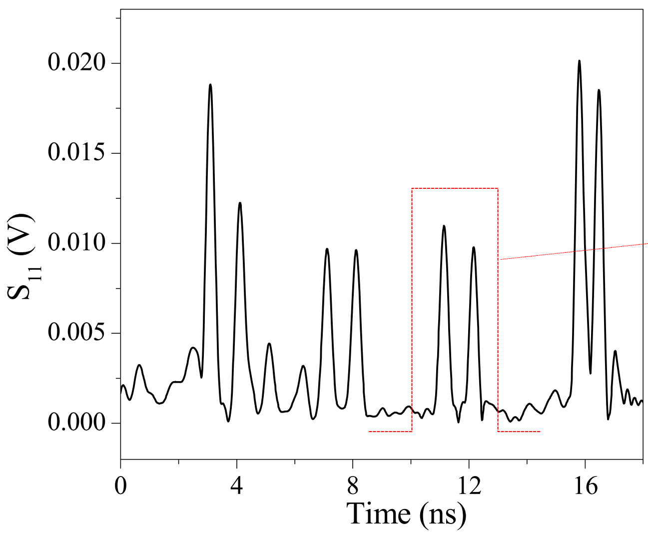
- **Linear and fast responses**
- **Large strain measurement (>10%) with high sensitivity (~με)**

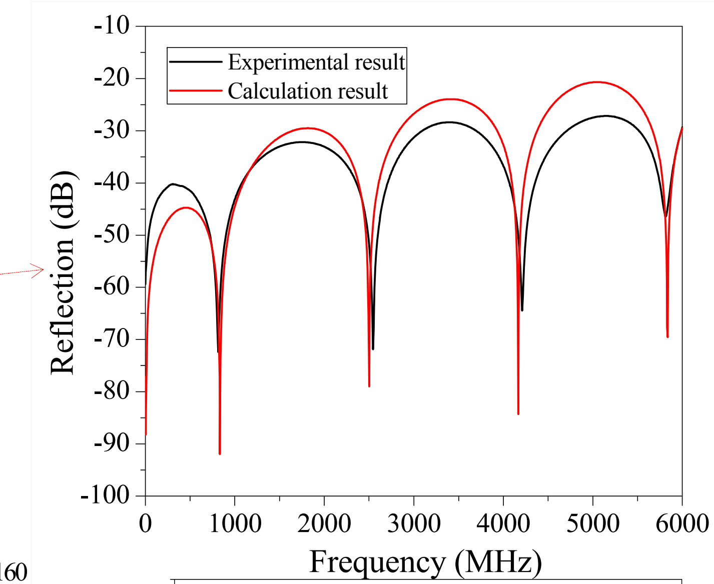
Distributed sensing concept

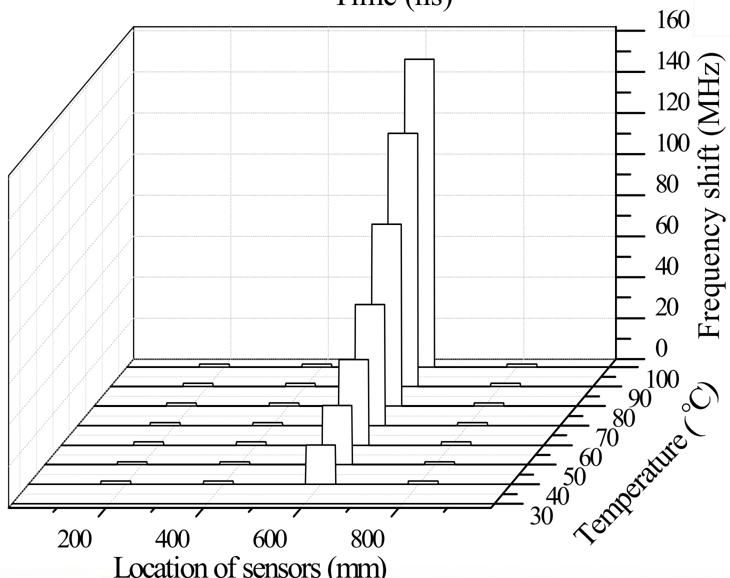


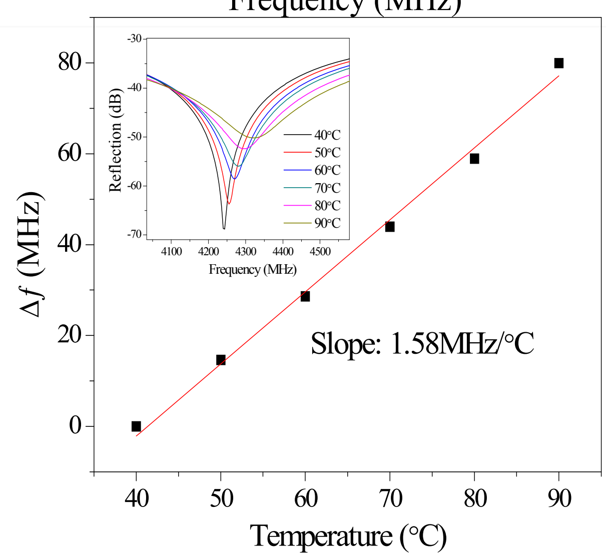
Distributed sensors proof of concept

Isolate and reconstruct an FPI measurement from a series FPIs



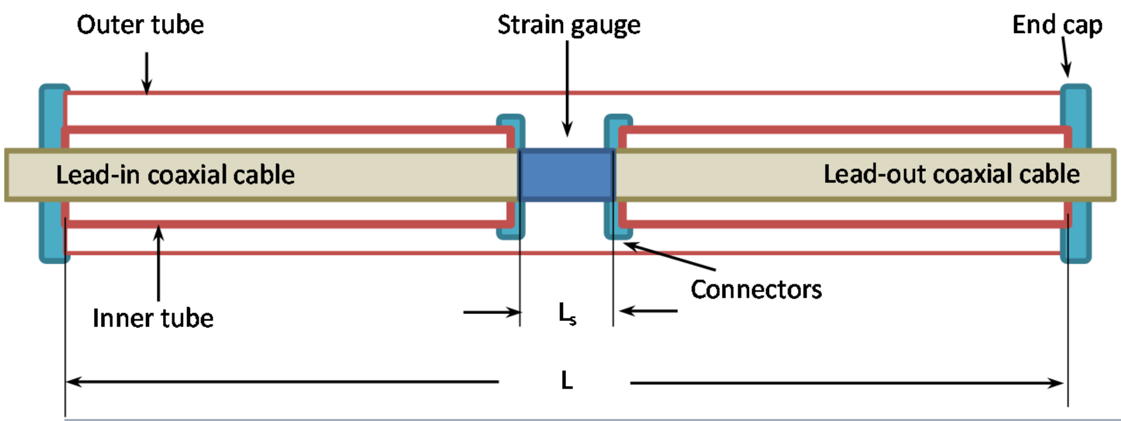


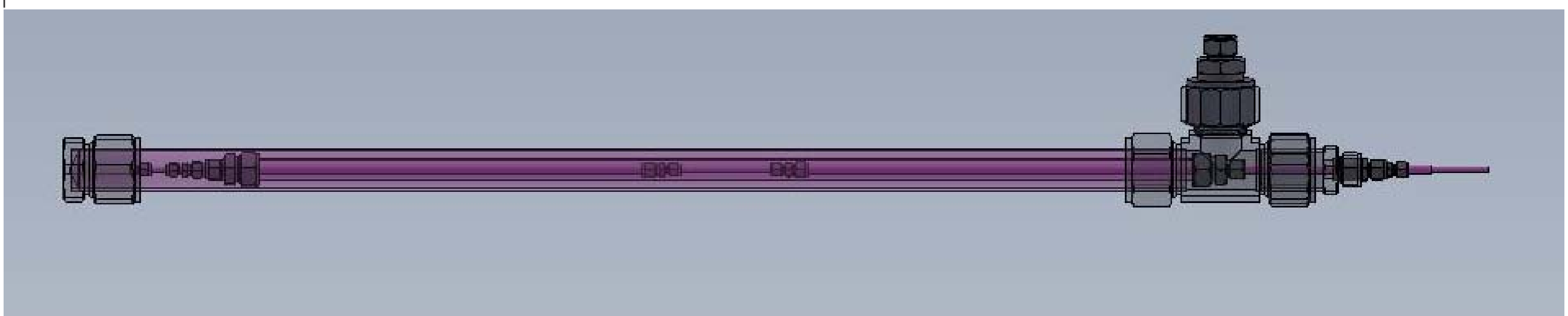




Demo on distributed sensing (video)

Pressure sensor design





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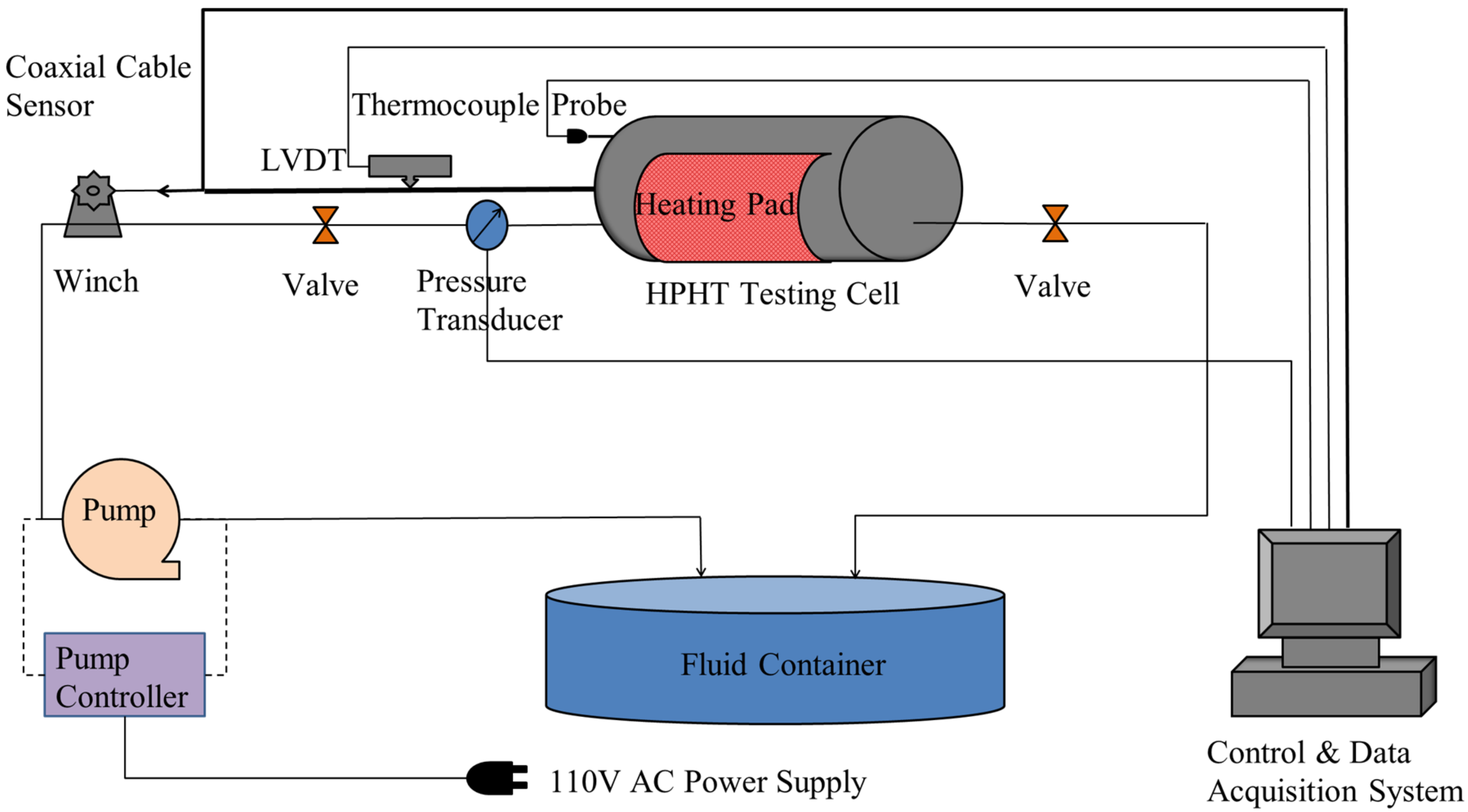
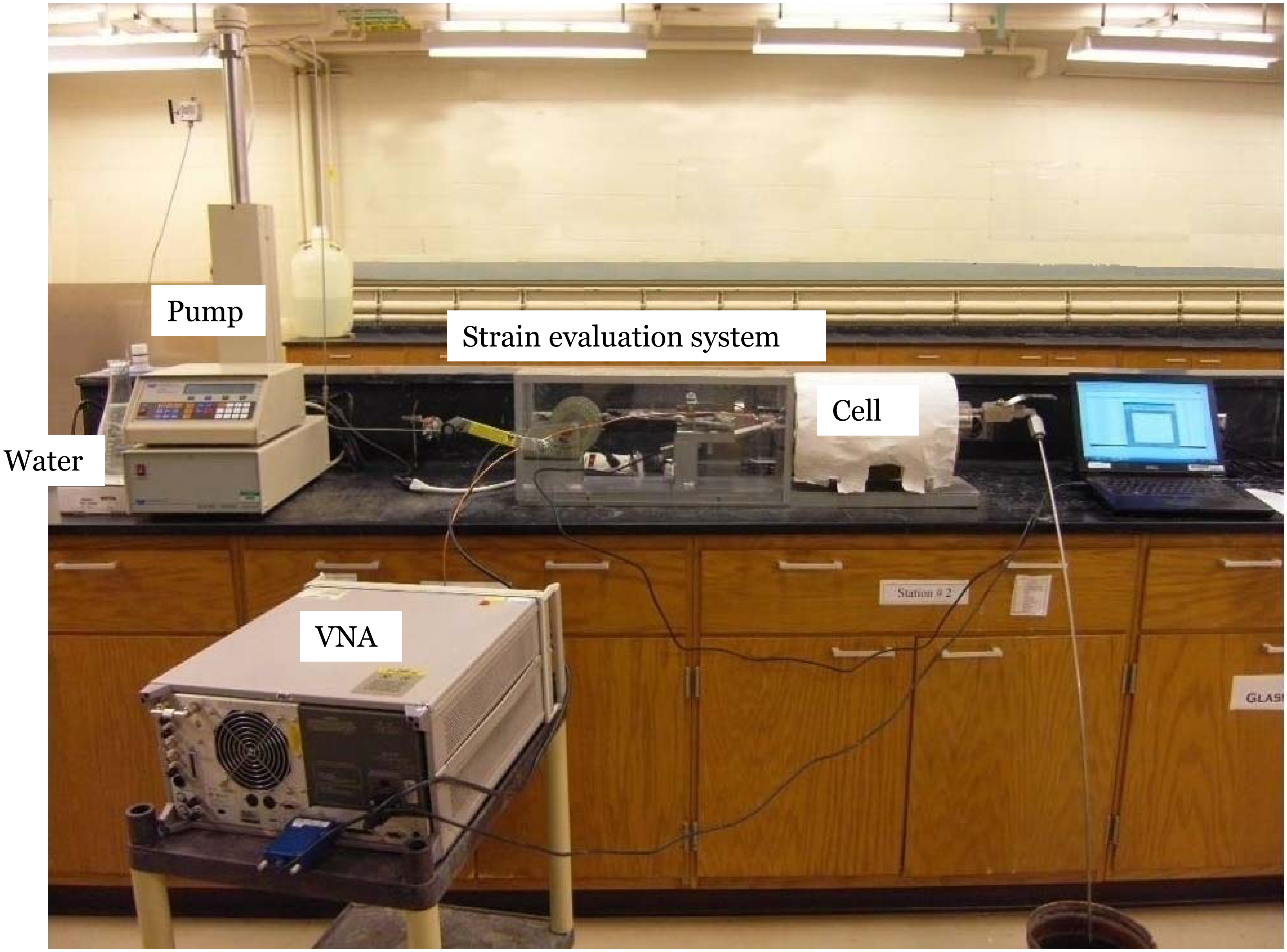
Strain, temperature, pressure, with flow sensor testing system



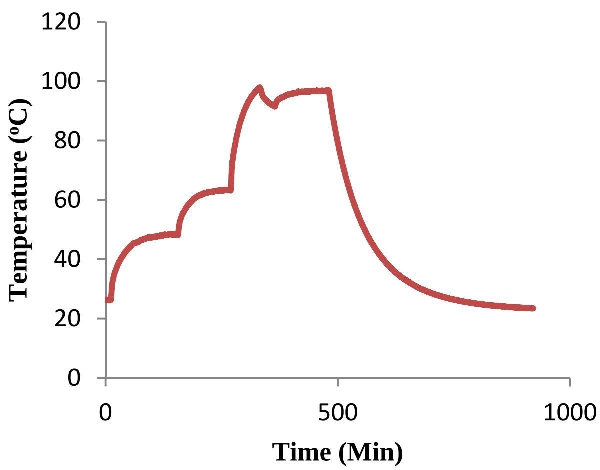
Schematic of HPHT Sensor Testing System

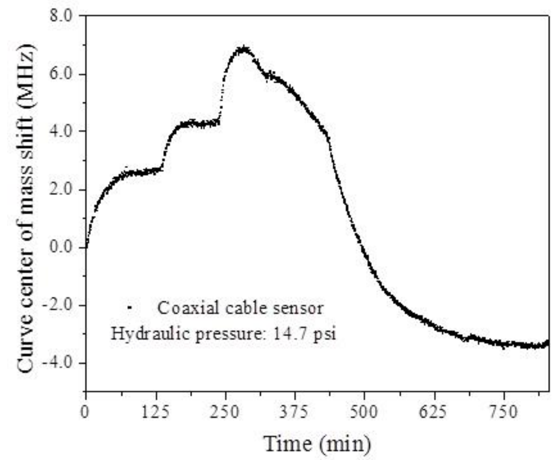
Results

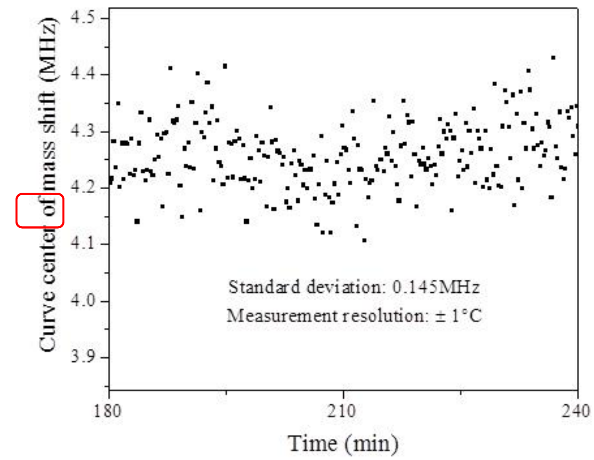


Temperature sensor results under pressure

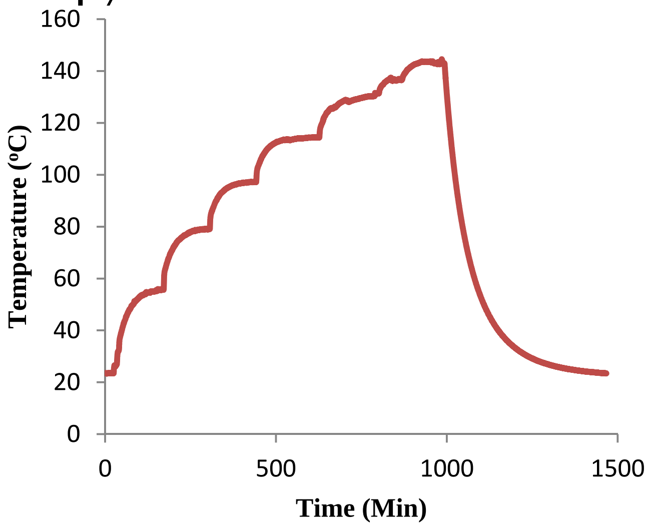
Atmospheric Pressure (14.7 PSI)

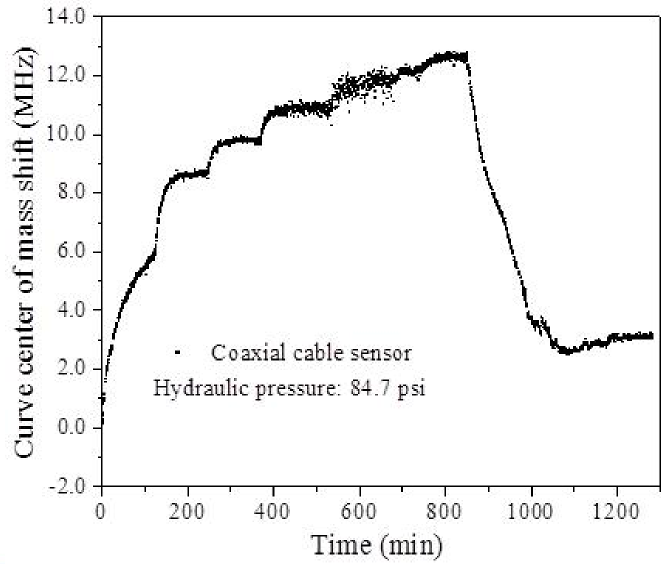






84.7 PSI Mass Center Method





Constant measurement resolution of ±1℃

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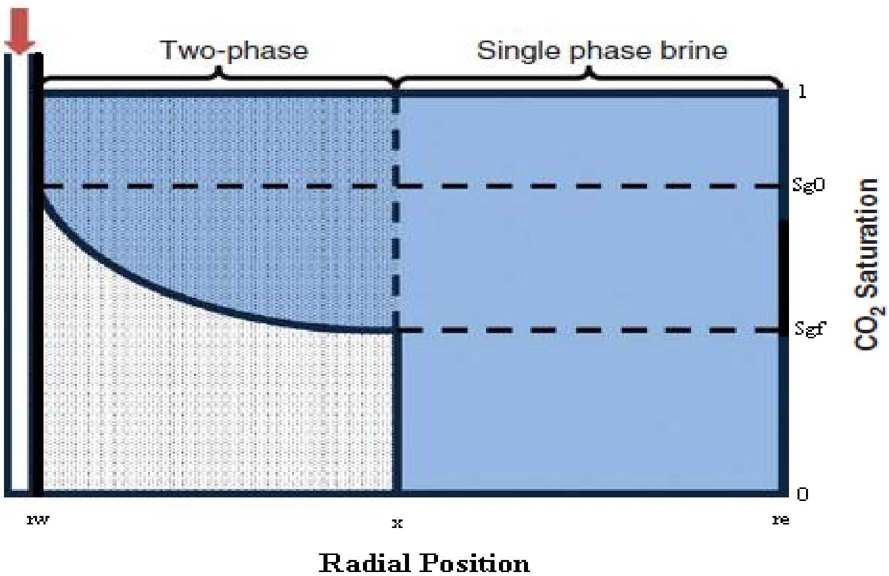
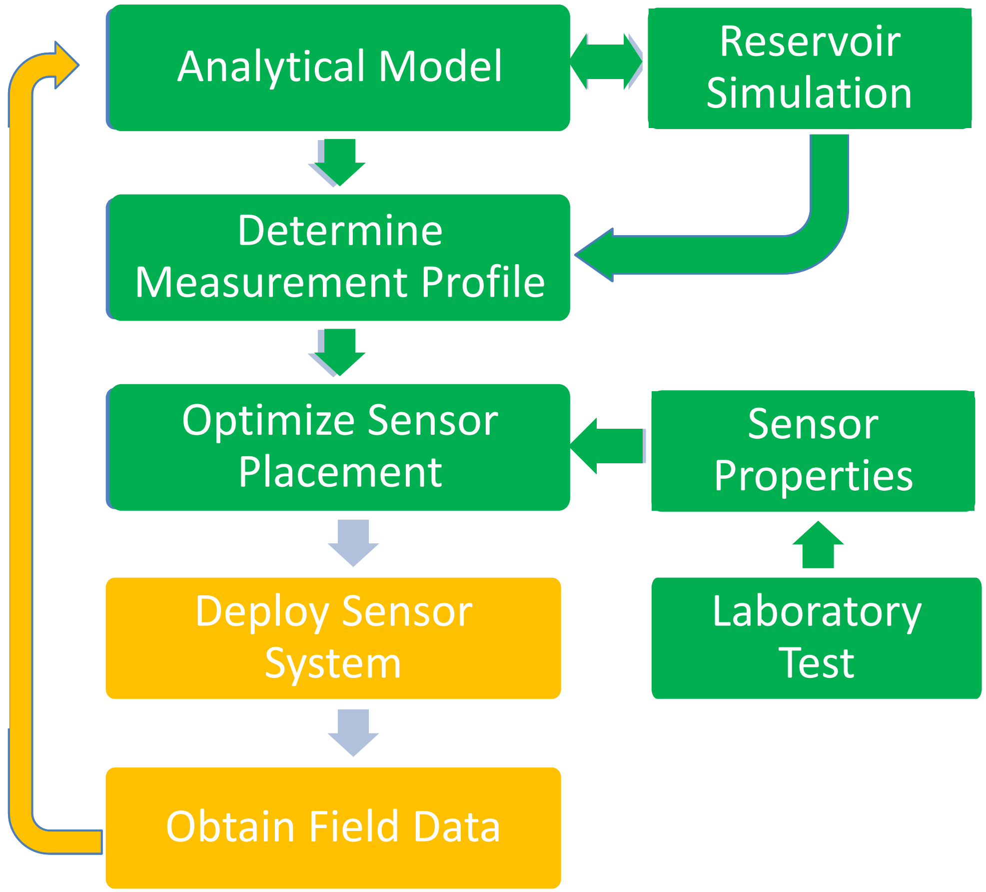
CO2 injection monitoring

Injection model



work flow



CO2 injection Modelling → Pressure profile → Optimize sensor placement → Deploy system → Deploy sensor system → Obtain field data

Analytical Pressure Solutions

Studies	Pressure Results	Flow Regimes	Boundary Conditions
Nordbotten et al. 2005	BHP	Steady State	Closed
Mathias et al. 2009; 2011	BHP	IARF and SS	Infinite and Closed
Economides et al. 2010	BHP	Steady State	Closed
Burton et al. 2008	BHP	Steady State	Constant Pressure
Azizi and Cinar 2013	BHP	IARF and SS	All Three
This study	Pressure Profile in Aquifer Scale	IARF, PSS and SS	All Three

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Diffusivity Equation

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r} = \frac{\phi \mu c}{0.0002637k}\frac{\partial p}{\partial t}$$

Infinite Acting Radius Flow (IARF)

$$p_{(r,t)} = p_i + \frac{70.6 q\mu}{kh}\left[Ei\left(\frac{-948\phi\mu c_t r^2}{kt}\right)\right]$$

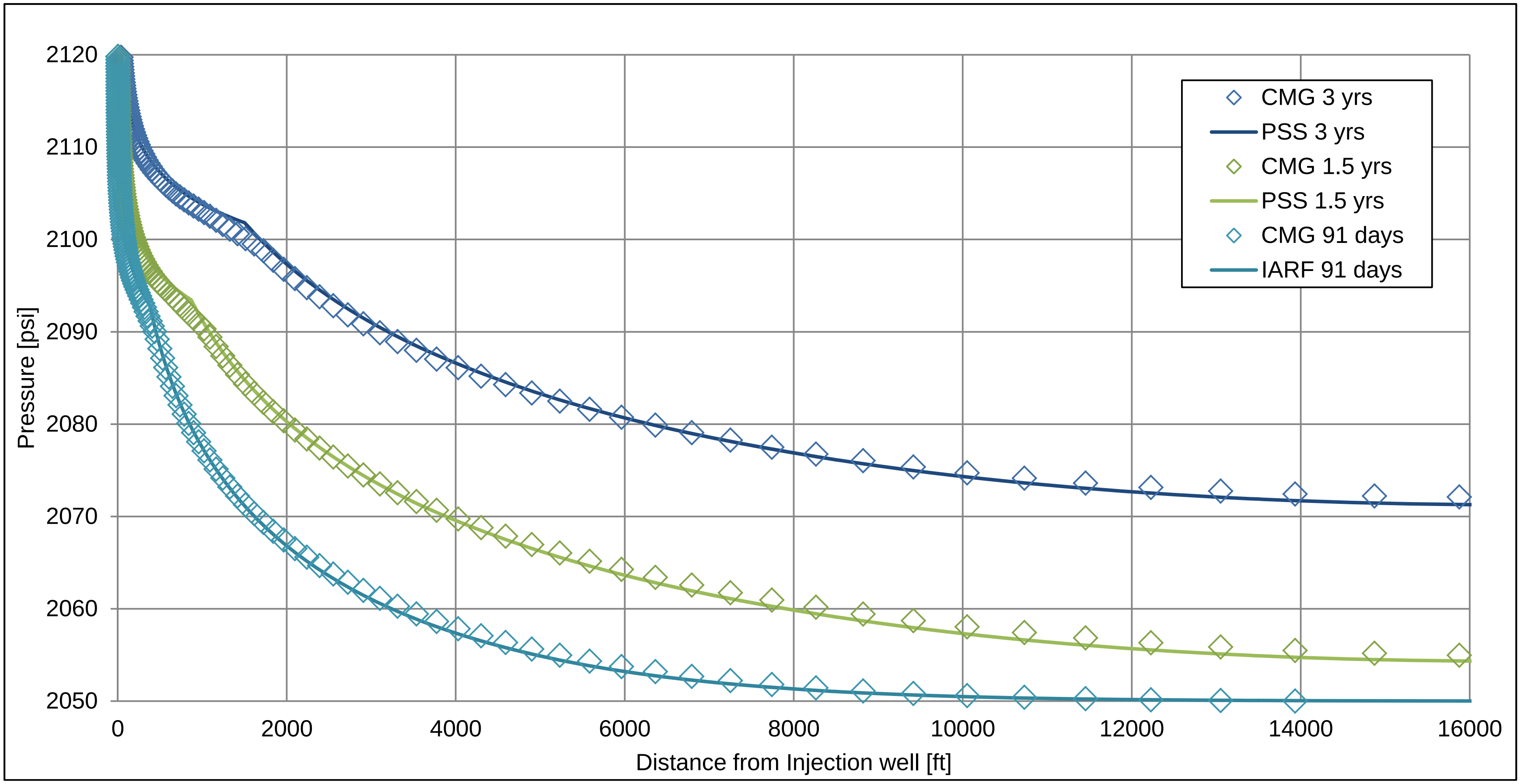
Pseudo-Steady State Flow (PSS)

$$p_{(r,t)} = p_i + \frac{141.2 q\mu}{kh}\left[\ln\left(\frac{r_e}{r}\right) - \frac{3}{4} + \frac{r^2}{2r_e}\right] + \frac{5.615qt}{\pi r_e^2 h\phi}$$

Steady State Flow (SS)

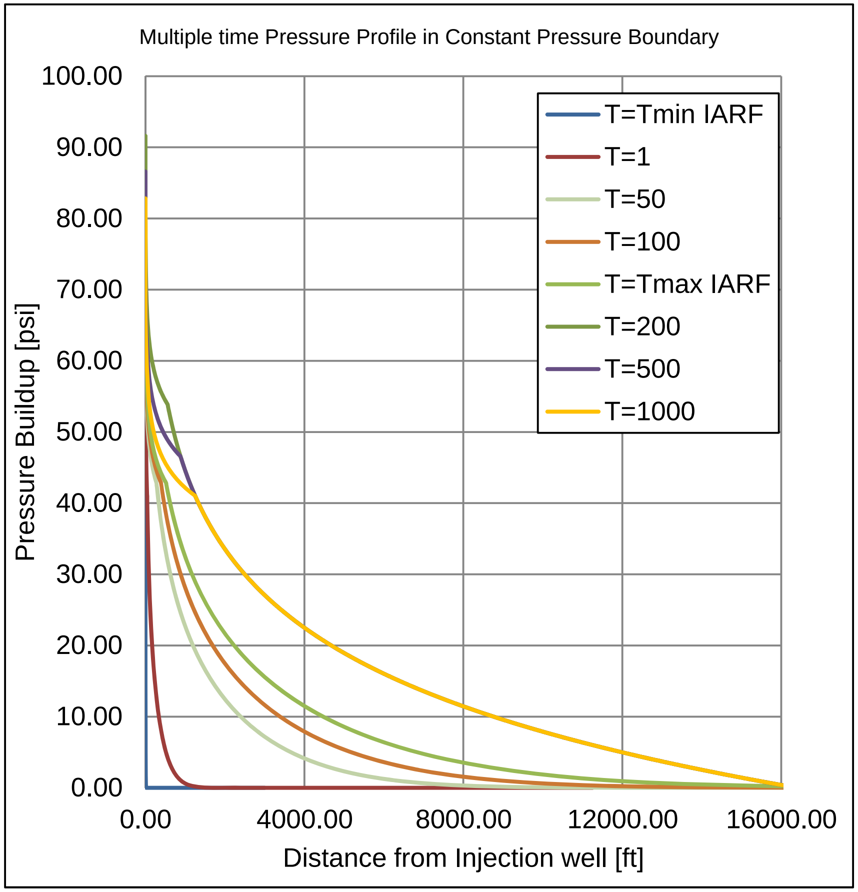
$$p_{(r,t)} = p_i + \frac{141.2 q\mu}{kh}\left[\ln\left(\frac{r_e}{r}\right)\right]$$

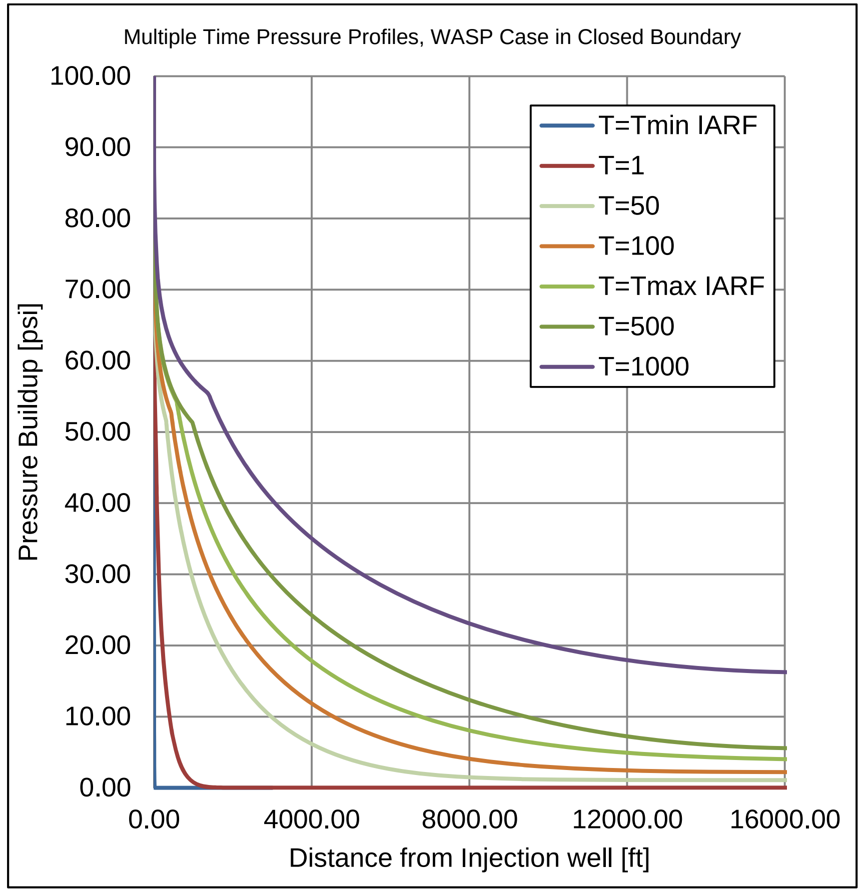
Analytical model and Reservoir simulation comparison



CO2 injection Modelling → **Pressure profile** → Optimize sensor placement → Deploy system → Deploy sensor system → Obtain field data

Pressure plume development over time





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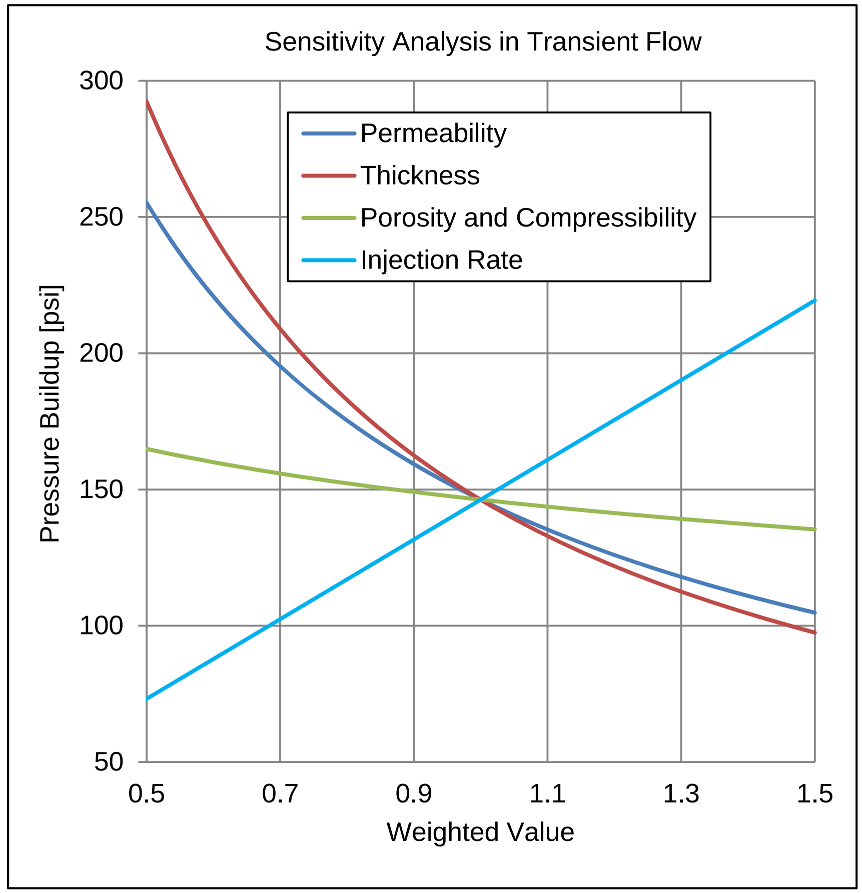
Sensitivity Matrix

- The (*i,j*)-entry of *J* represents a quantitative measure of how sensitive measurement s_i is to perturbations of parameter c_j.

$$J_t = \left(\frac{\partial s_{i,t}(c_t)}{\partial c_{j,t}} \right)_{i=1,\, j=1}^{M,K}$$

- Monitoring Location is 100 feet from injection well after injecting for 100 days

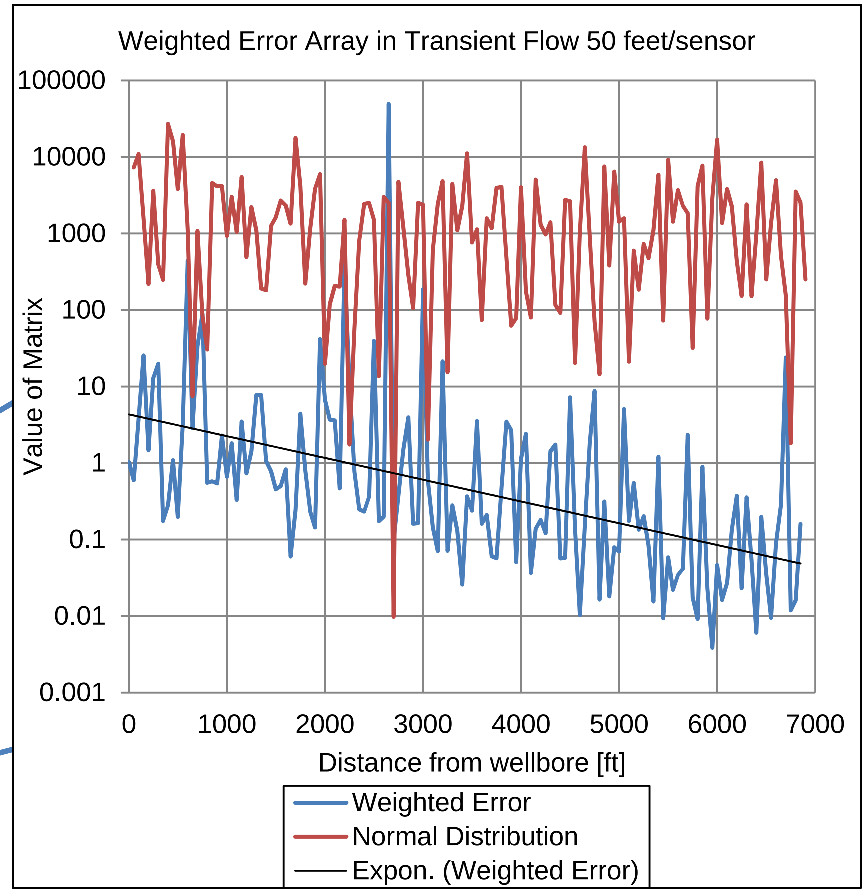


Source: Naevdal et al. 2001

Sensor ranking

- Sensitive responses from sensors to perturbations of aquifer parameters and the most precise sensor measurements lead to find the most valuable place to put the sensor.

$$Err_t = \sum_{i=1}^{K} \left(\frac{s_{i,t} - \hat{s}_{i,t}(c_t)}{\sigma_i} \right)^2$$



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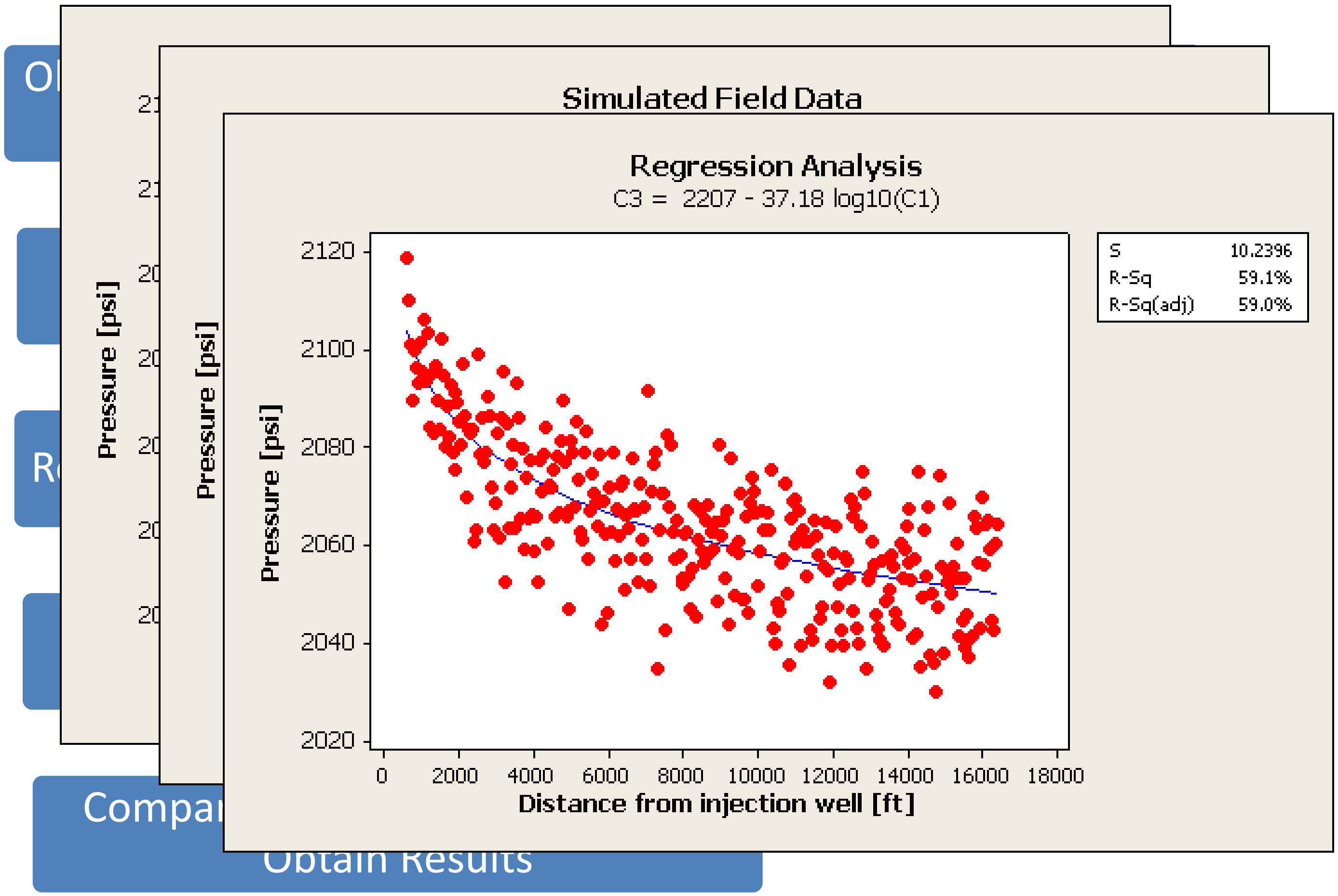
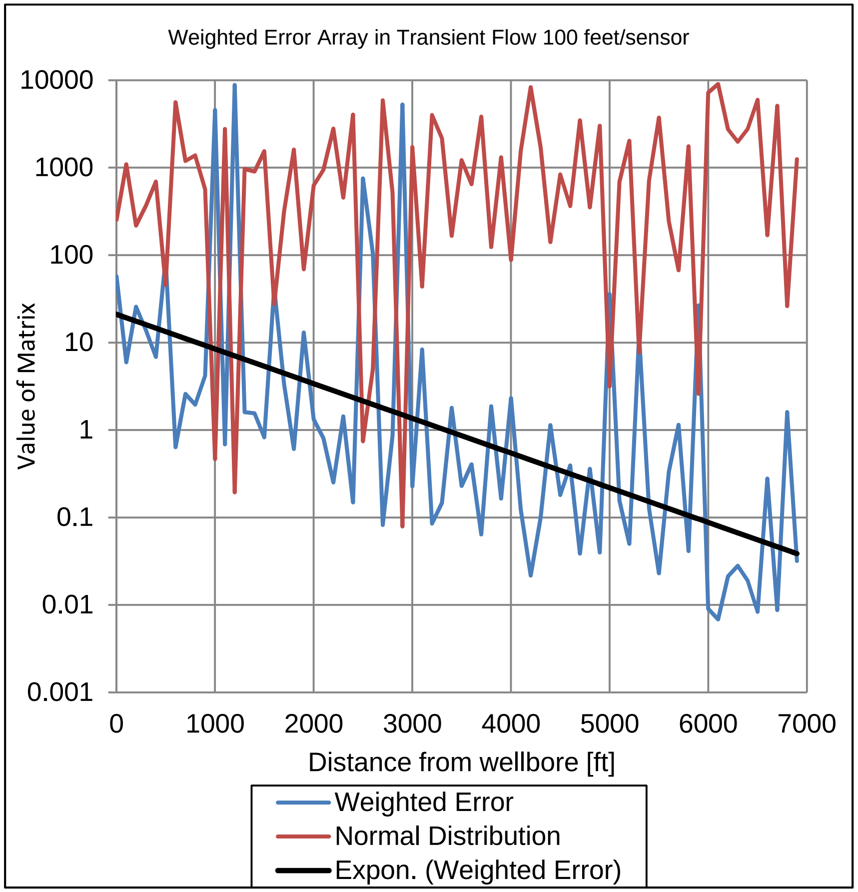
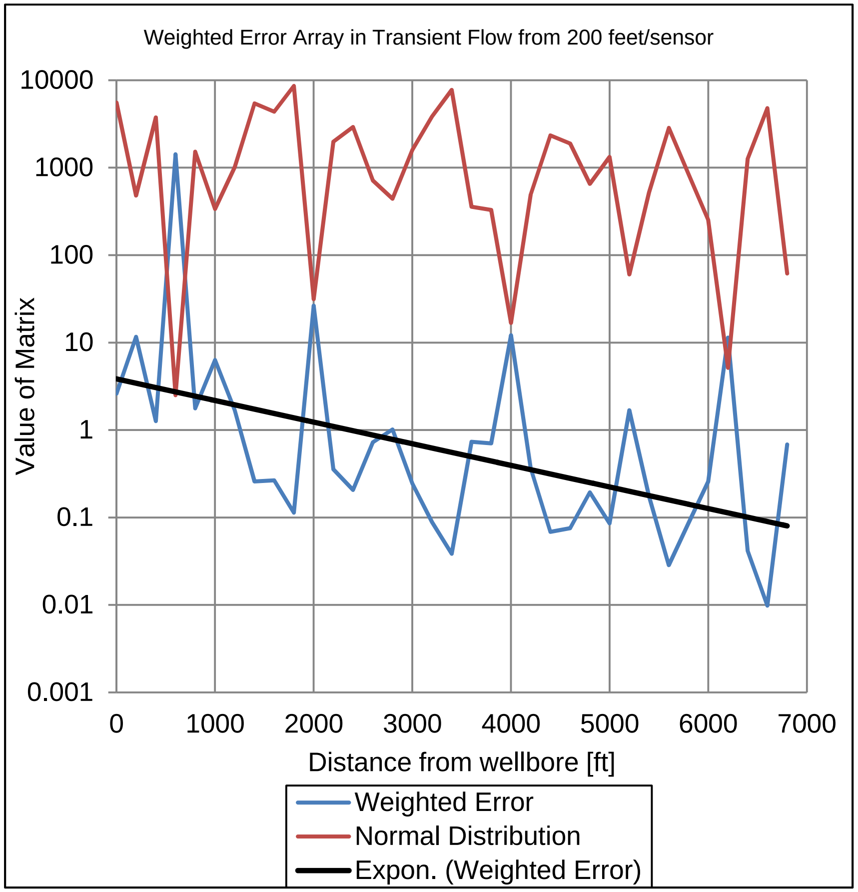


Weighted Error - Sensor Distribution





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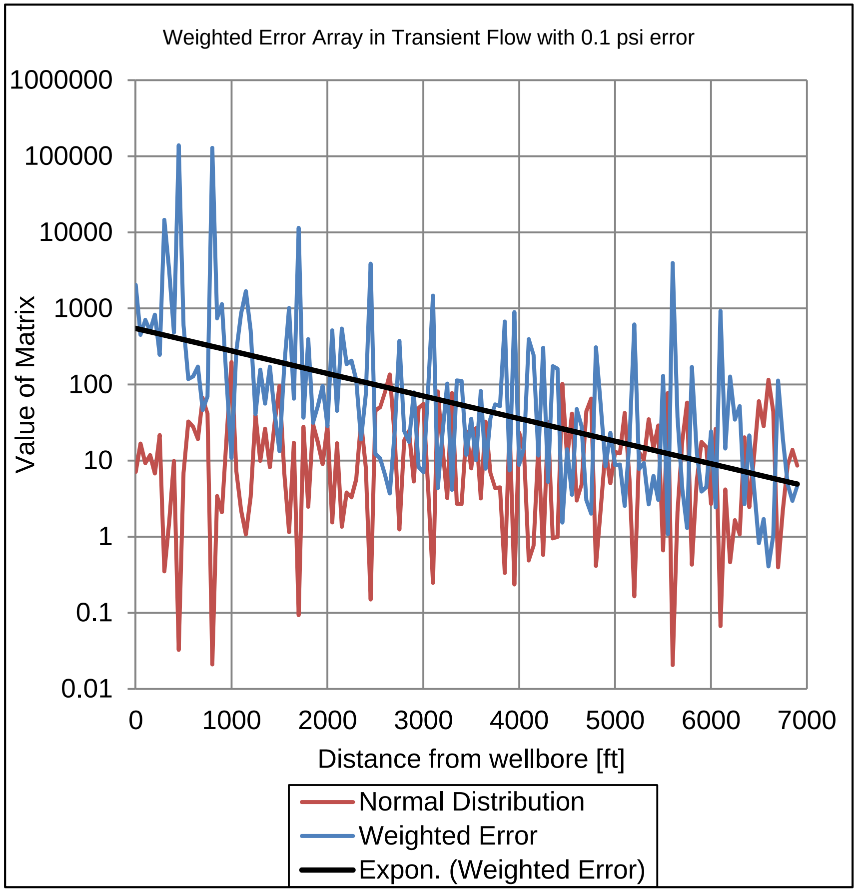
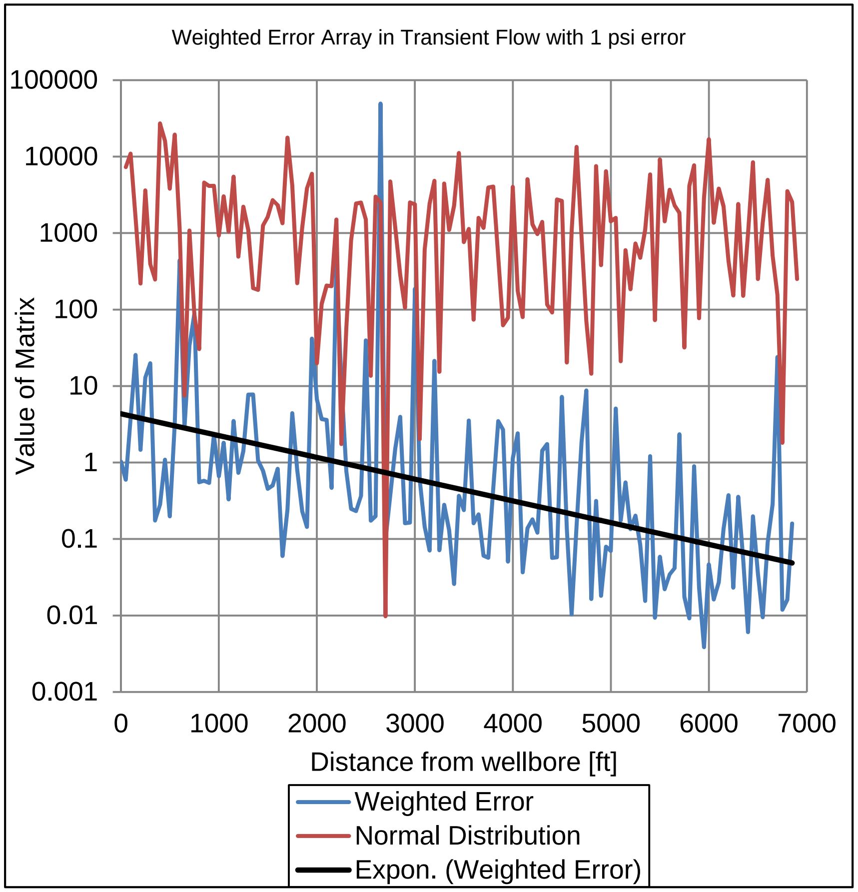
Weighted Error - Sensor accuracy





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Regression Analysis Example

$$p_{(r,t)} = p_i + \frac{141.2q\mu}{kh}\left[\ln\left(\frac{r_e}{r}\right)\right]$$

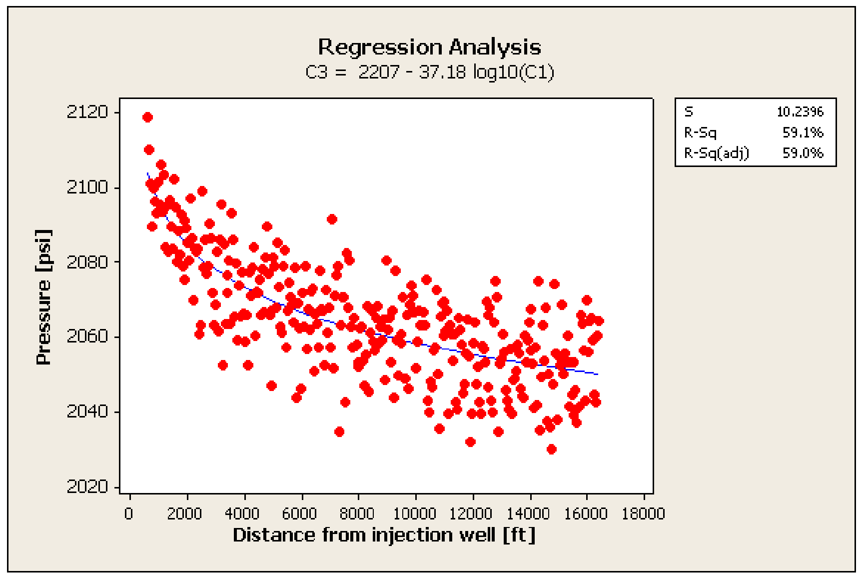
$$p_{(r)} = A - B\ln r$$

$$A = P_i + \frac{141.2q\mu}{kh}\ln(r_e)$$

$$B = \frac{141.2q\mu}{kh}$$

Sensor Error: 10 psi

Sensor Distance: 50 feet



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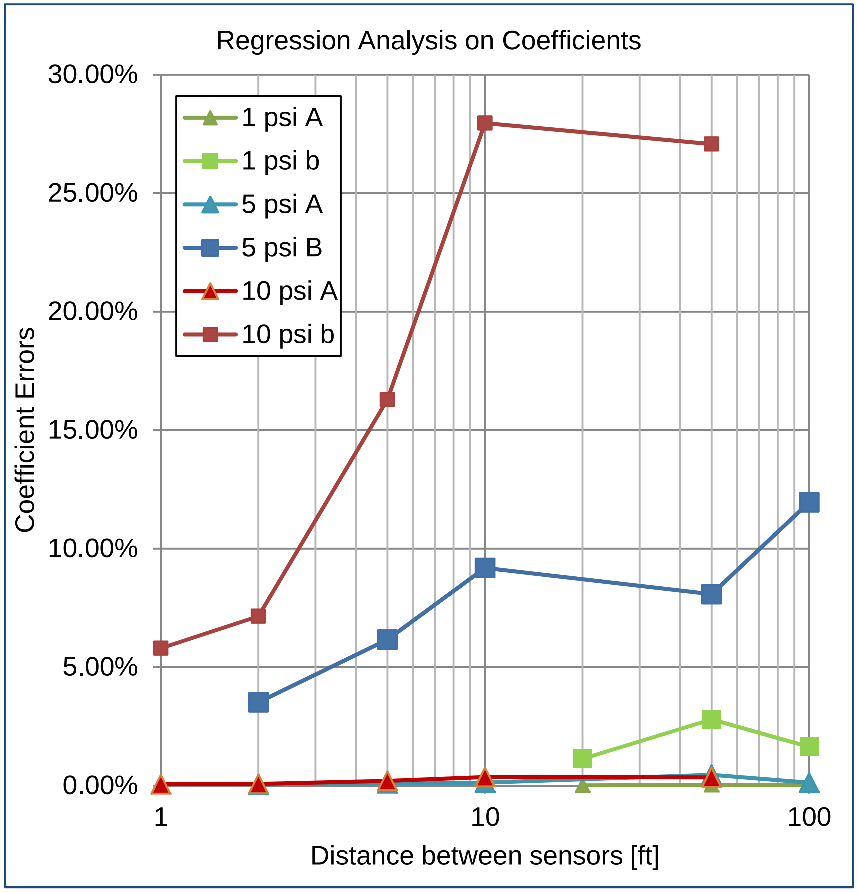
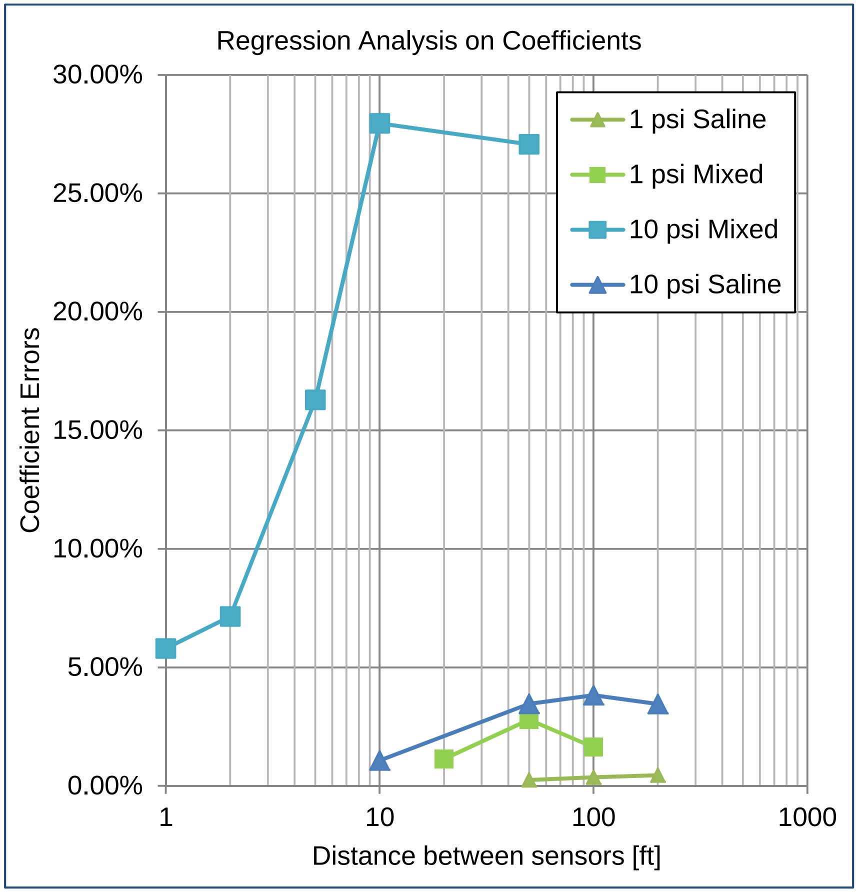
Optimization on Sensor System





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Summary

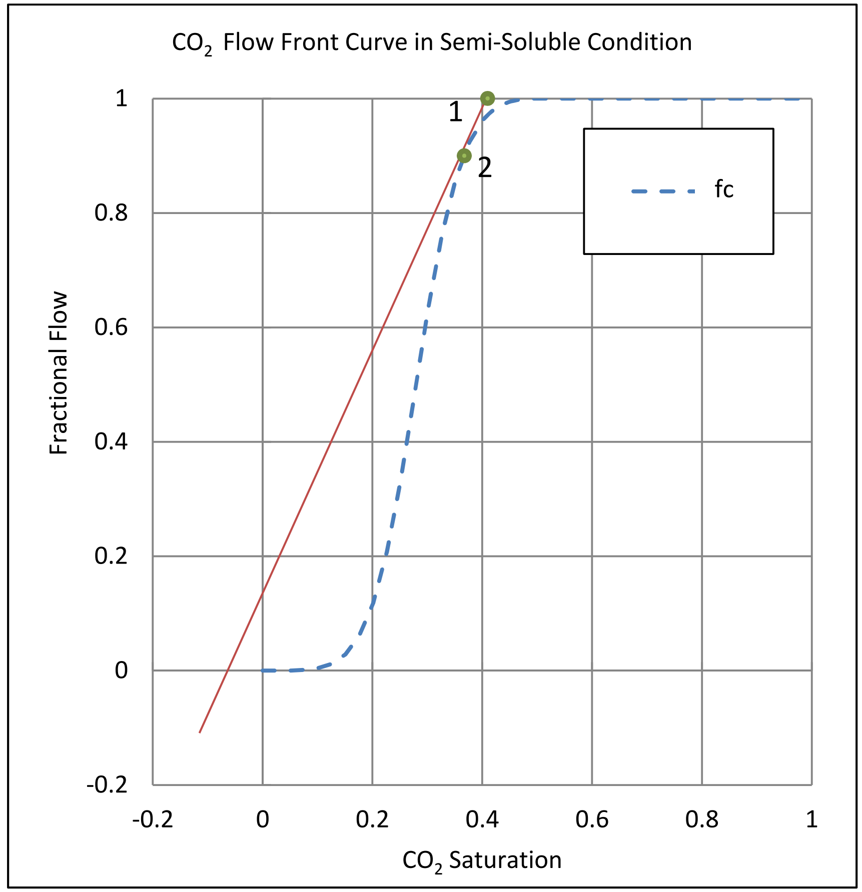
- Distributed strain and temperature rigid coaxial sensors for down hole conditions have been developed and are being tested at down-hole conditions
- The pressure sensor is developed and ready to be tested
- Distributed sensing concept using coaxial cable is validated
- An analytical model solving pressure distribution of CO_2 injection into a saline aquifer for any flow regime is developed and verified with reservoir simulations
- Permeability is determined to be the most dominant parameter affecting the pressure profile
- Sensor accuracy has a significant impact on sensor ranking and the CO_2-brine region needs denser sensor distribution than the saline region

OUT

Semi-Soluble Condition

$$x_{sg} = \sqrt{\frac{qt}{\phi 2\pi h}\left(\frac{df_g}{dS_g}\right)_{sg}}$$

$$x_{sg} = \sqrt{\frac{qt}{\phi 2\pi h}\left(\frac{df_g - \left(\frac{C_a}{C_a - C_g}\right)}{dS_g - \left(\frac{C_a}{C_a - C_g}\right)}\right)_{sg}}$$

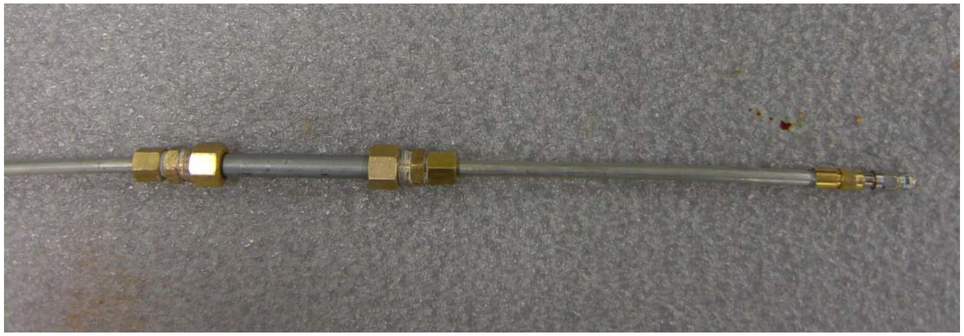


Source: Noh et al. 2007

Detailed objectives

- Develop robust CCCS for remote measurement of temperature, pressure, and strain in a high-temperature, high-pressure down-hole harsh environment.
- Develop high-performance sensor interrogation methodology and instrumentation with self-compensation capability for long-term, maintenance-free operation and dense-multiplexing capability for cost reduction.
- Integrate sensor data with the geological models for intelligent sensor deployment/installation, rational interpretation of the sensor outputs, improved accuracy of plume tracking, optimized CO_2 injection, and sensor-verified model prediction.
- Characterize the performance and demonstrate the critical functions of the developed sensors and instrumentation for down-hole applications in relevance to CO_2 sequestration monitoring.

Material testing on Preliminary Test on Coaxial Cable Pressure Sensor Model



Copper : 1000 psi collapse

Stainless Steel: 5000 psi 24 hours intact