Relative Permeability in Reactive Carbonate Rock

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Research Scientist
Research and Innovation Center

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NATIONAL ENERGY TECHNOLOGY LABORATORY

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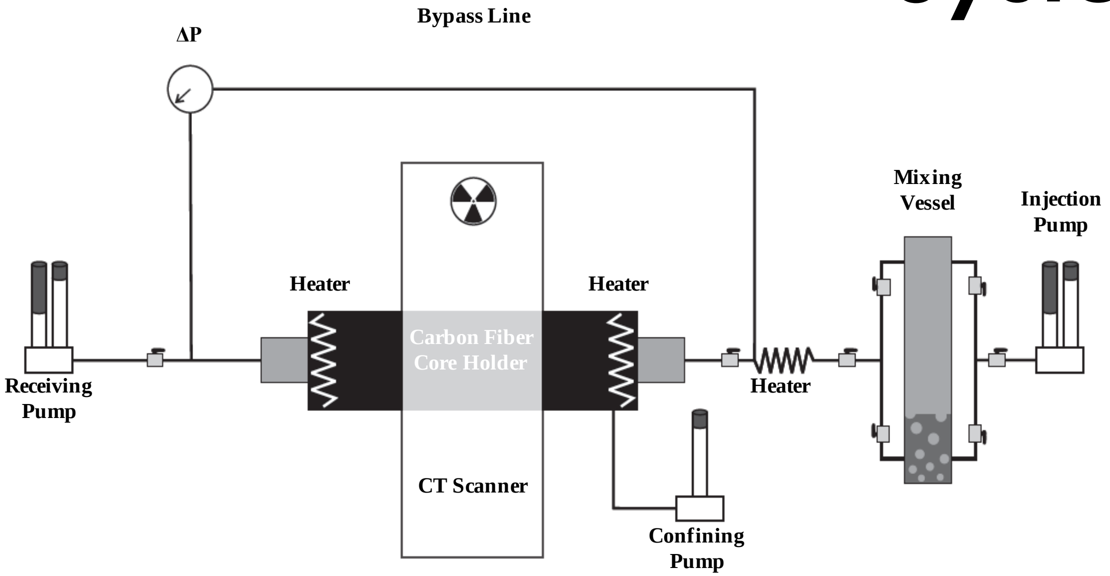
Background

- **Relative Permeability (*k_r*):** the ratio of the effective permeability of a single fluid in a fluid mixture through a rock to the absolute permeability (*k*) of that fluid alone.
- **Unsteady State *k_r*:** Injection of one fluid into a rock core completely saturated with another fluid.
- **Characterization of fluid behavior and interaction in GCS reservoirs is essential to understanding long term safety and storage efficacy**
  - k_r is one of the fundamental parameters used to populate simulations to predict fluid migration and behavior
  - While k_r has been largely characterized and parameterized in traditional 'unreactive' geologic reservoirs, carbonates are largely uncharacterized due to their reactive nature
    - Carbonates are highly reactive with even weak acids, such as carbonic acid, which readily dissolves the mineral constituents and increases permeability & porosity
  - Carbonate reservoirs are readily available and often have appreciable permeability/porosity (re petroleum in the Arabian Peninsula and drinking water aquifers)

System Design



Schematic of experimental system flow through system inside of medical computed tomography scanner.

Experimental Conditions

Temperature: 63.3 °C
Brine Composition (By weight %): 5% KI, 3% KCl
Pore Pressure: 9.65 Mpa
Overburden Pressure: 13.79 MPa

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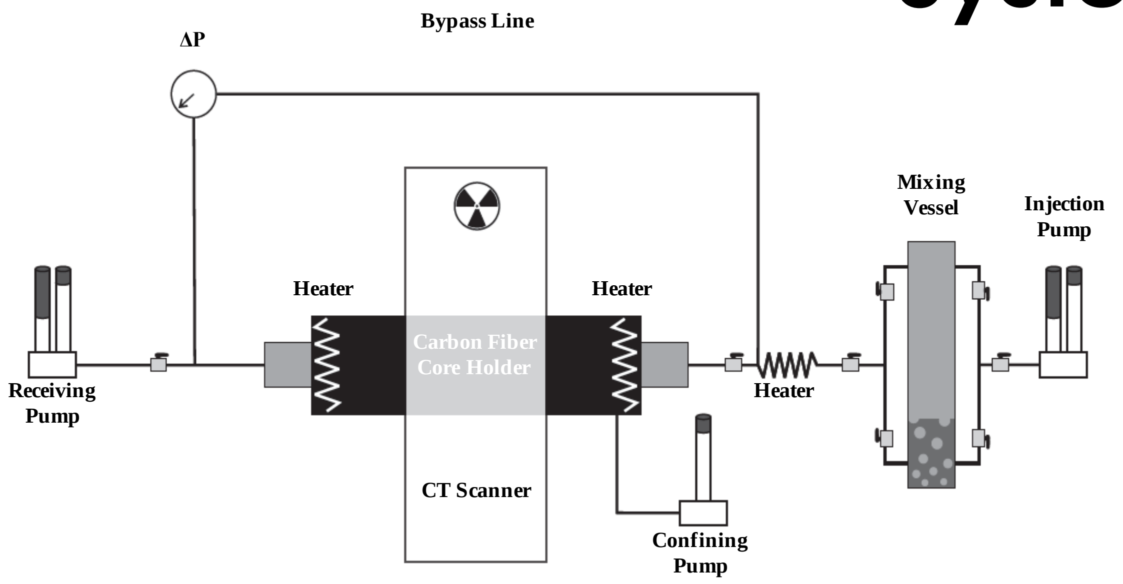

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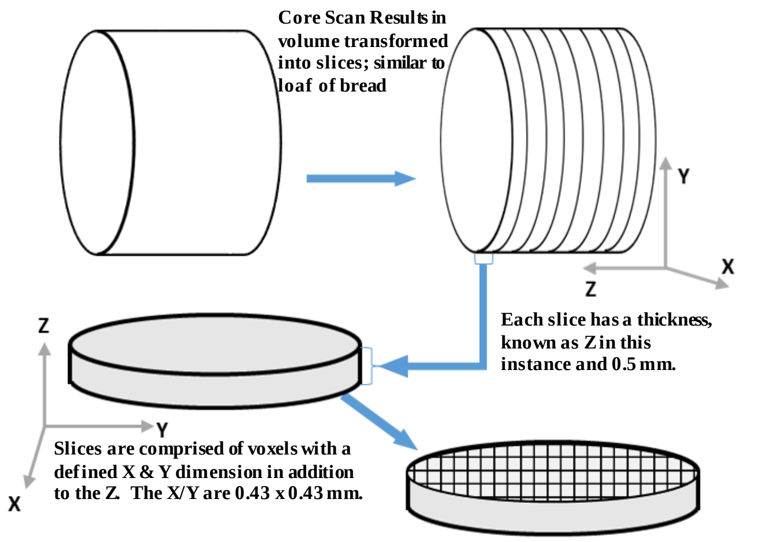

Schematic of CT scan within CT system illustrating data configuration.

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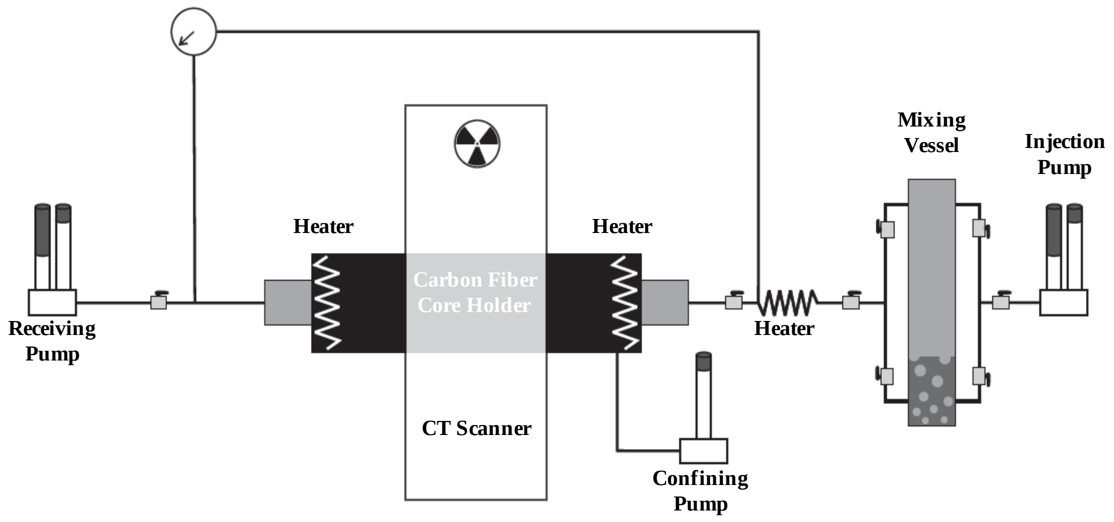

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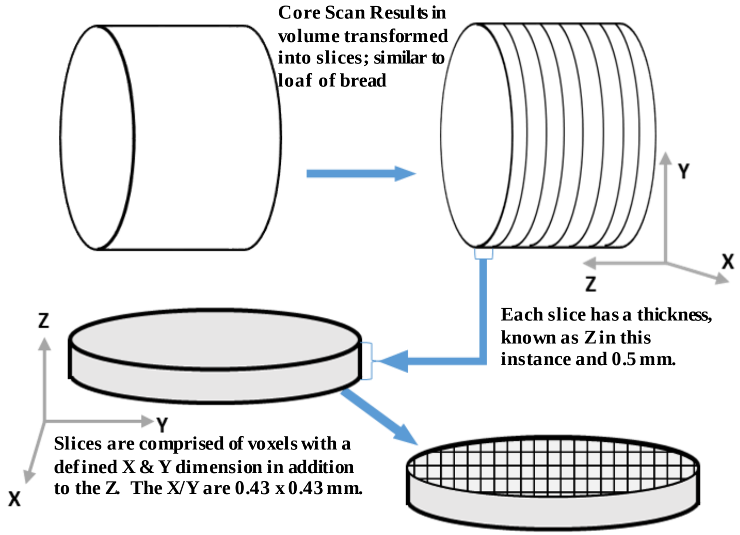

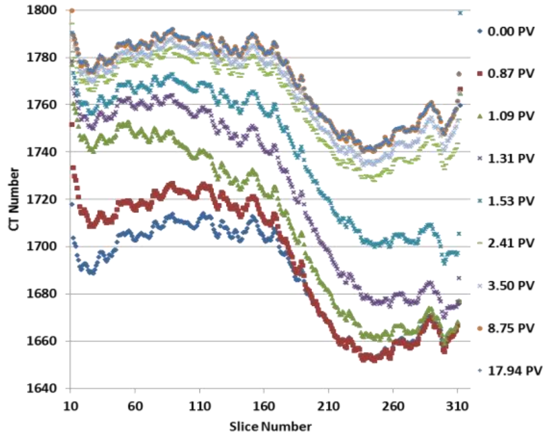

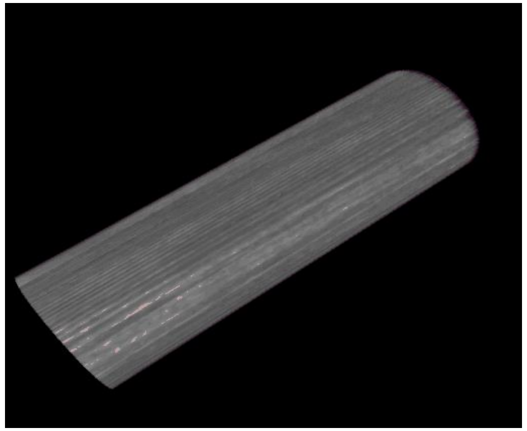

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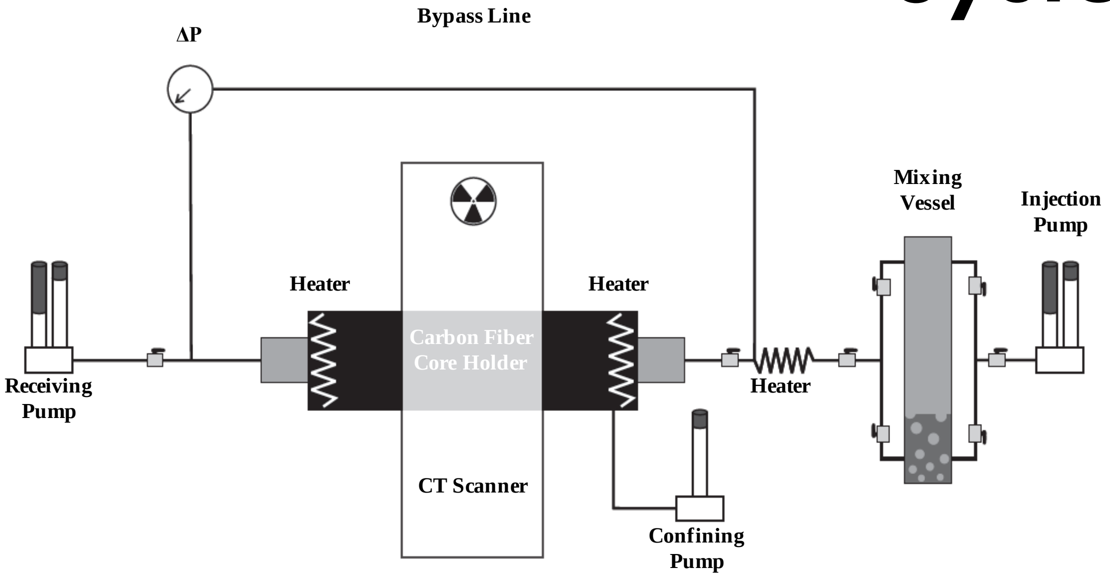

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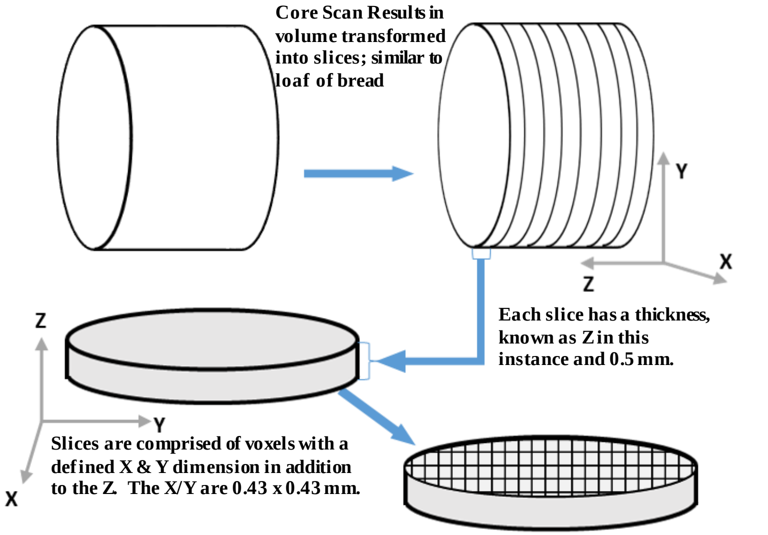

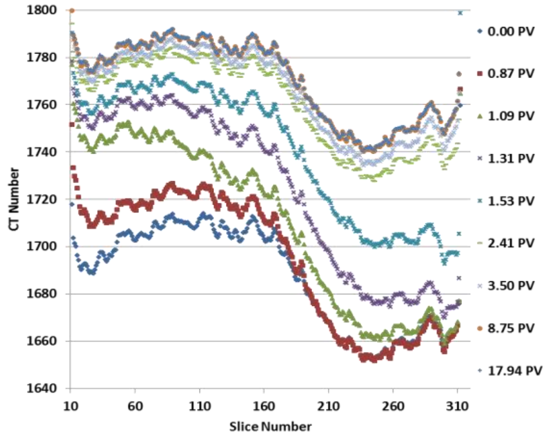

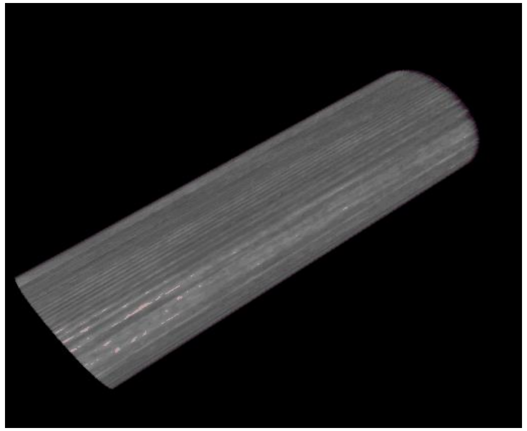

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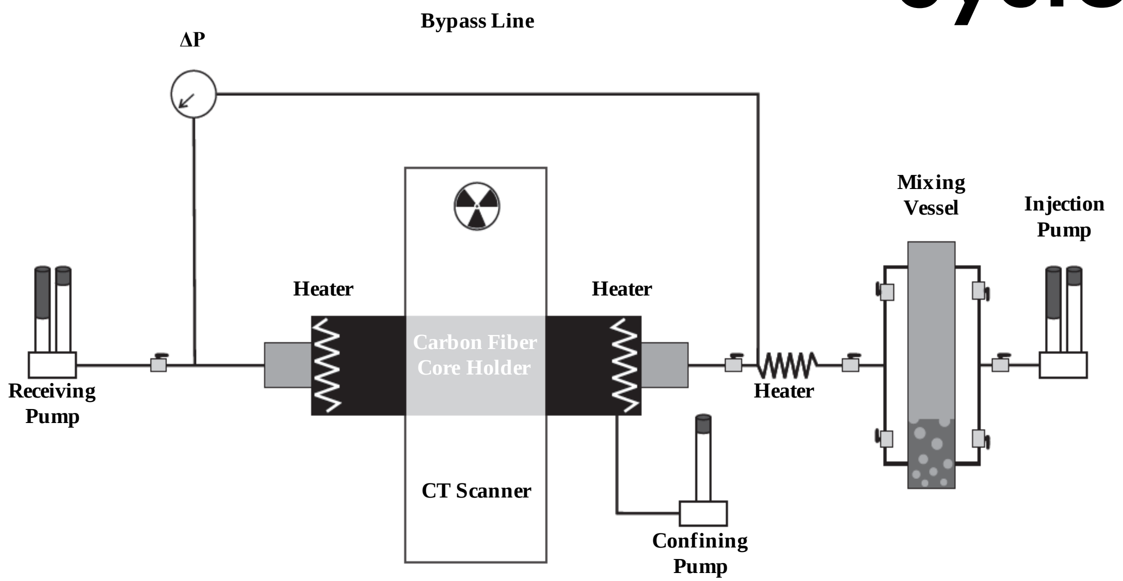

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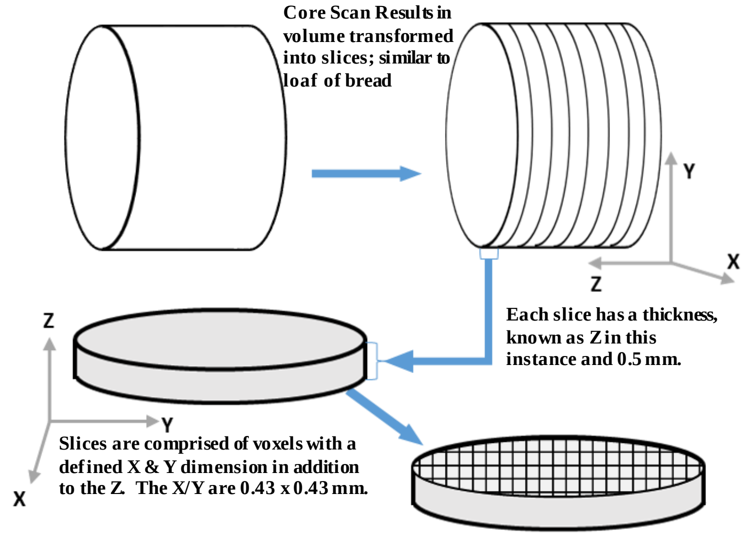

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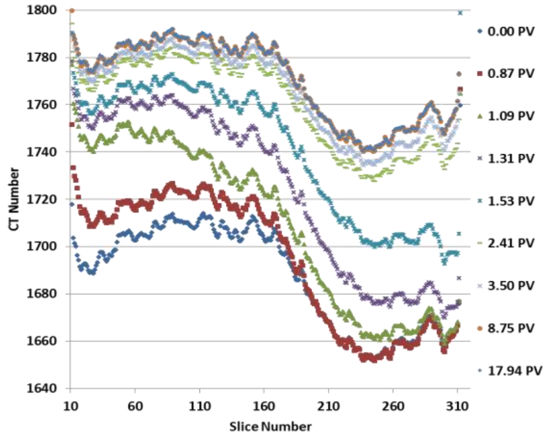

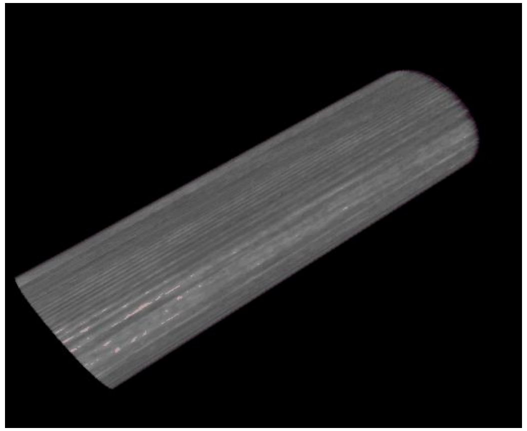

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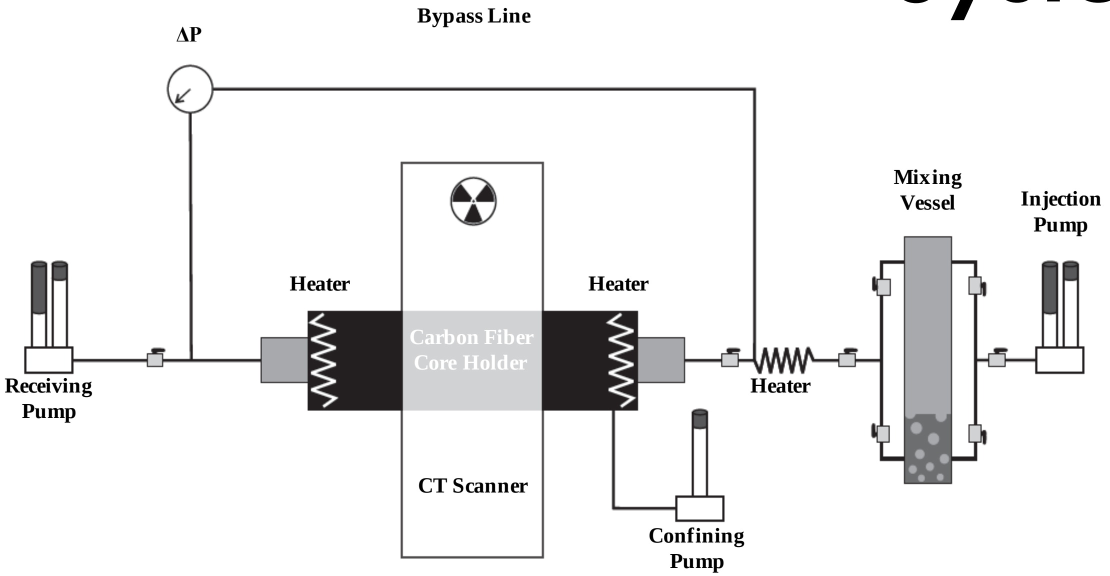

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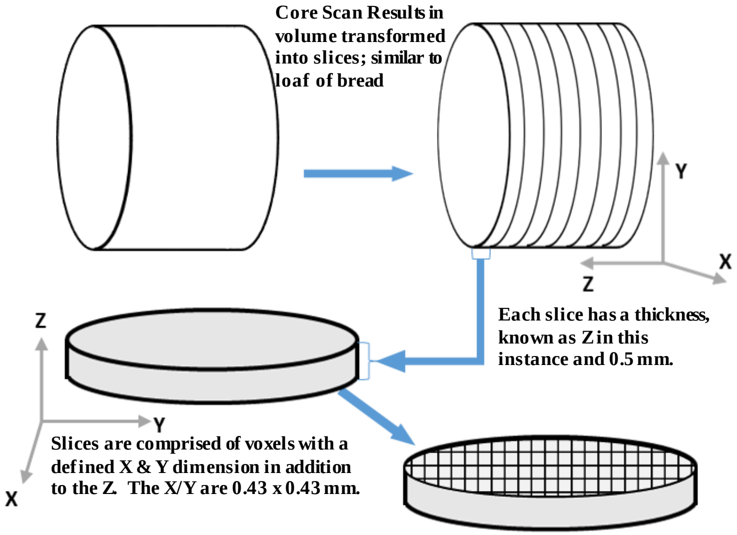

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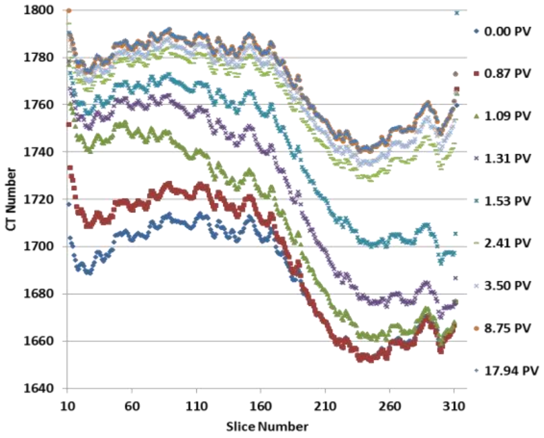

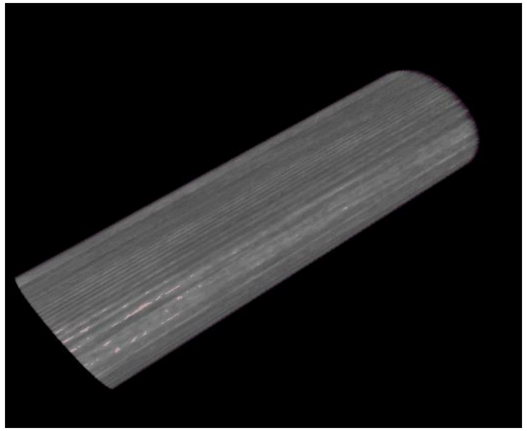

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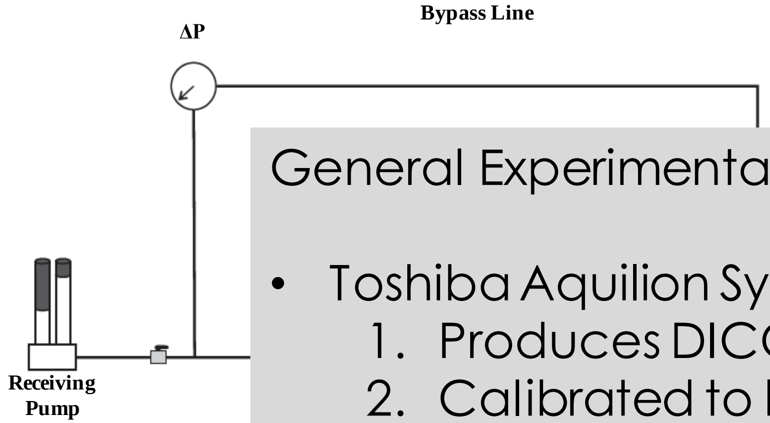

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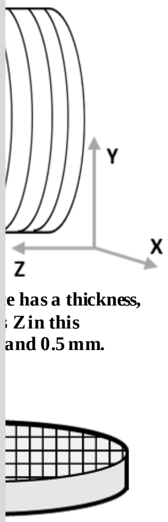
General Experimental Standards & Limits

- Toshiba Aquilion System
    1. Produces DICOM image format in 16-bit grayscale
    2. Calibrated to known standards relative to HU
    3. 8-slice fan beam helical scanner
    4. Scans < 10 seconds at 10-20 second intervals
    5. Resolution at 0.43x0.43x0.5 mm
- Flow System
    1. Carbon Fiber Hassler style core holder
    2. Buna-N sleeves for confining membrane
    3. Teledyne ISCO 500 HP pumps for pressure/injection
    4. Rosemount DP gauges (3051CD)
    5. Clamshell heaters to apply heat to both coil and core holder



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data configuration.

CT Number

I, 3% KCl

Slice Number

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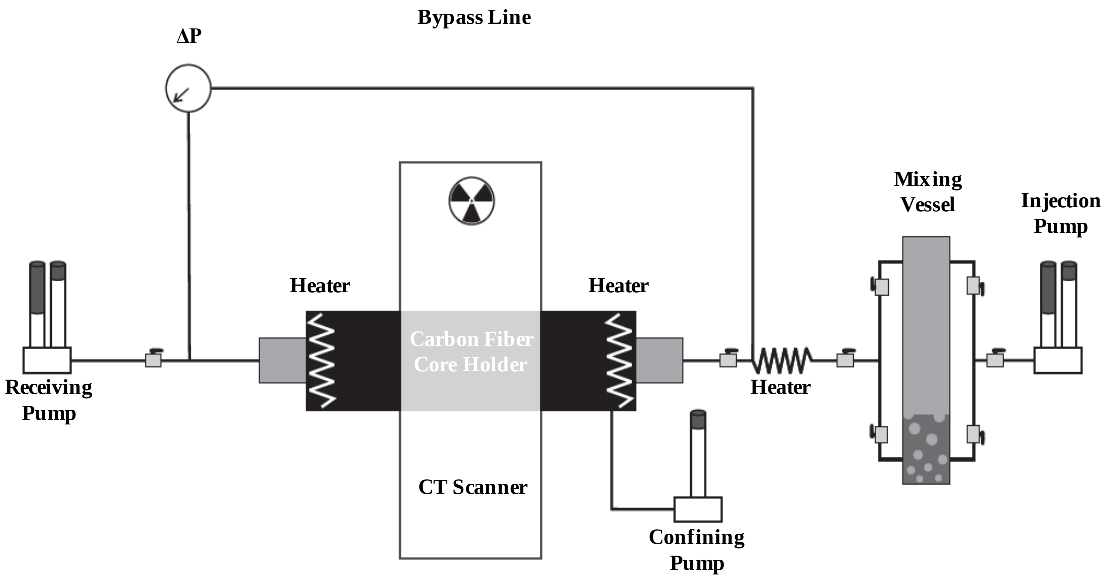

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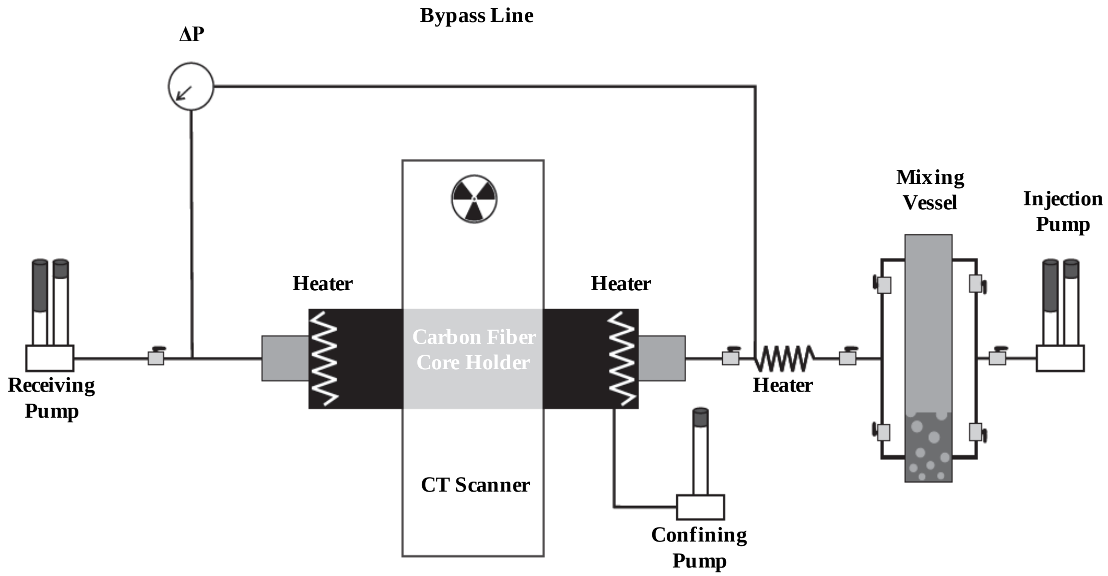

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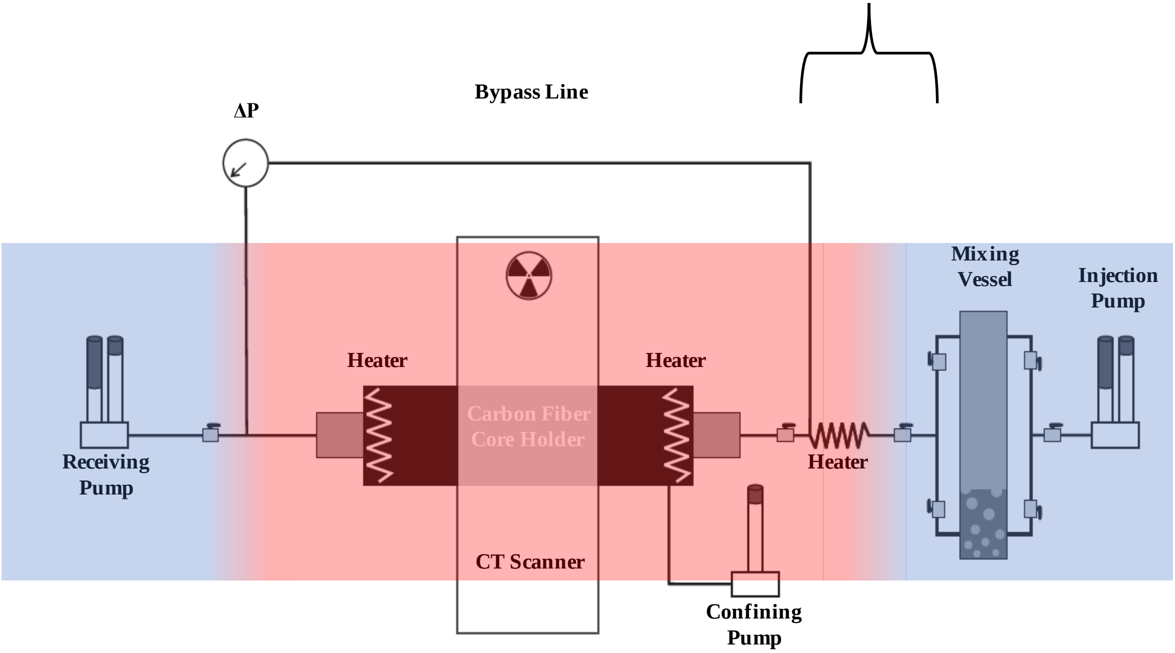

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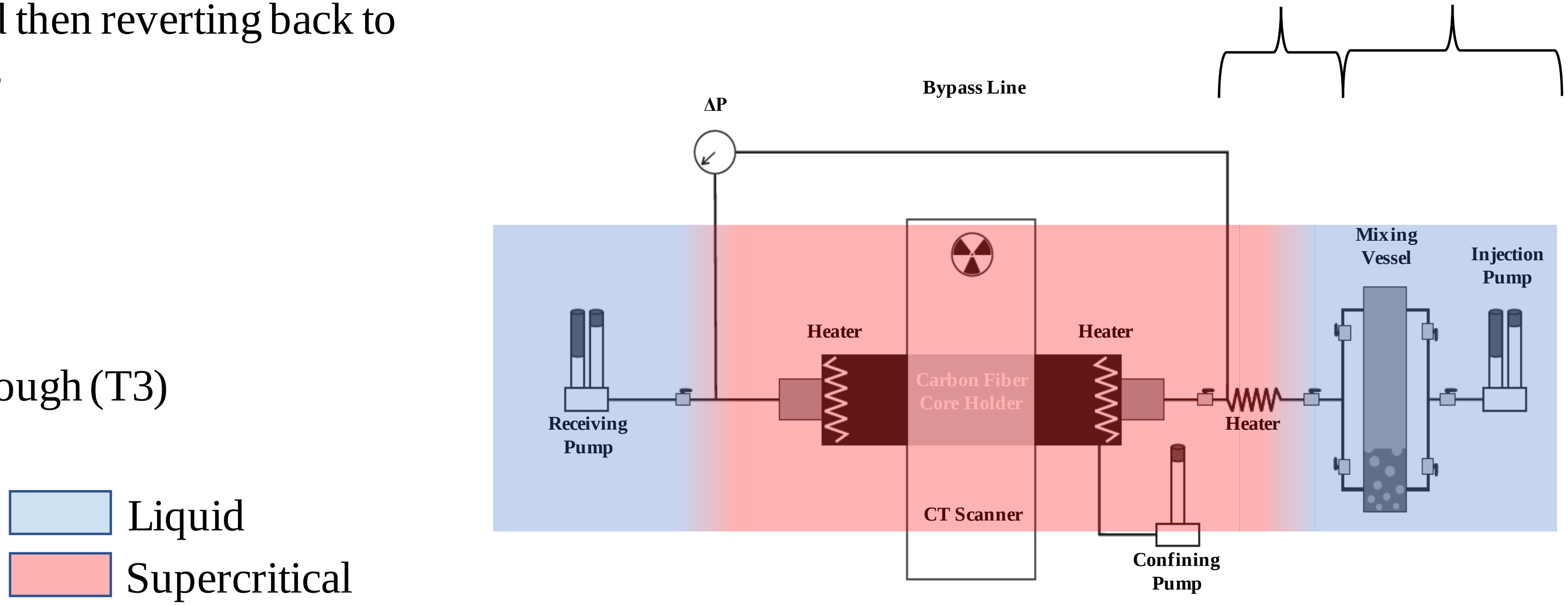

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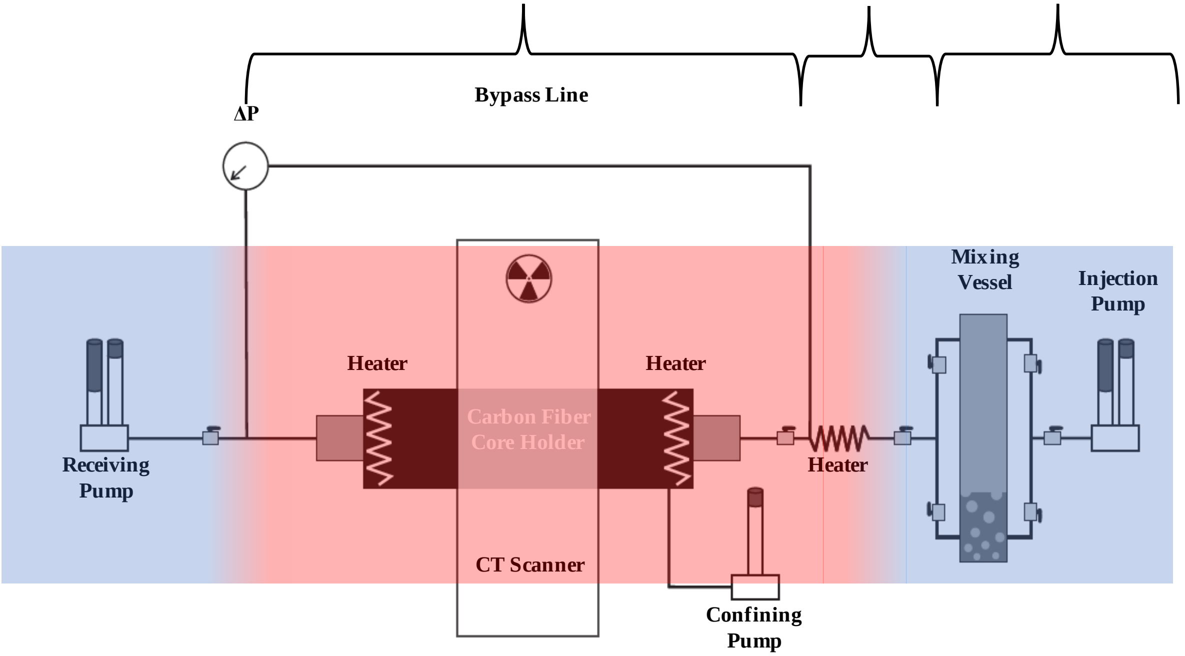

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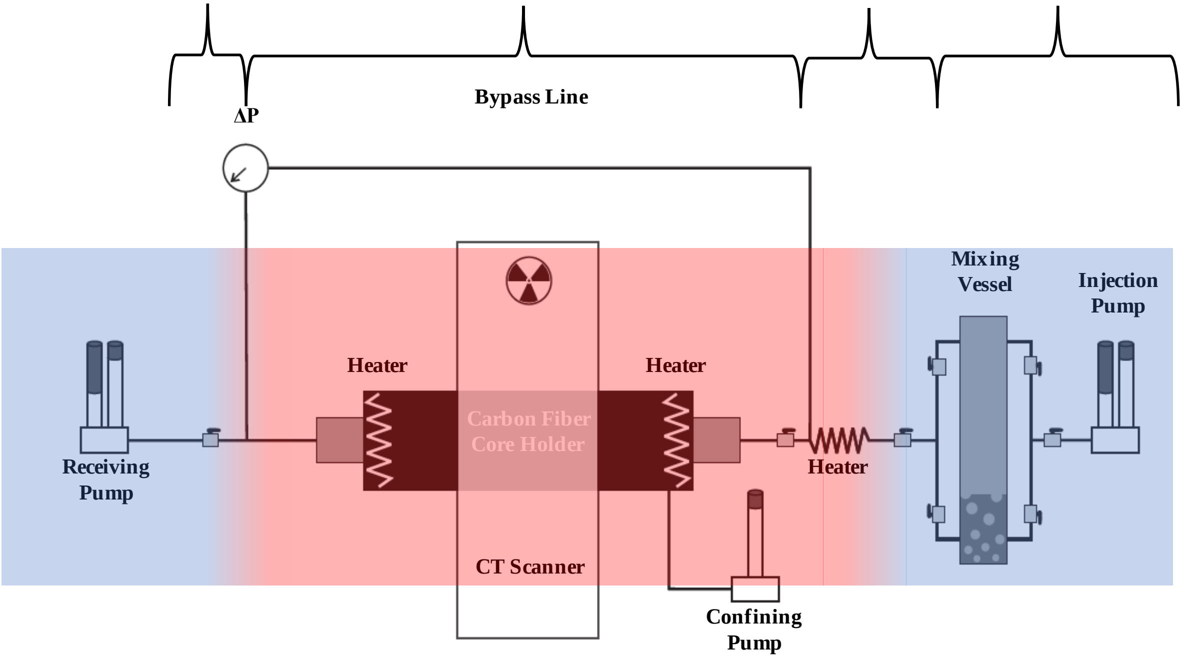

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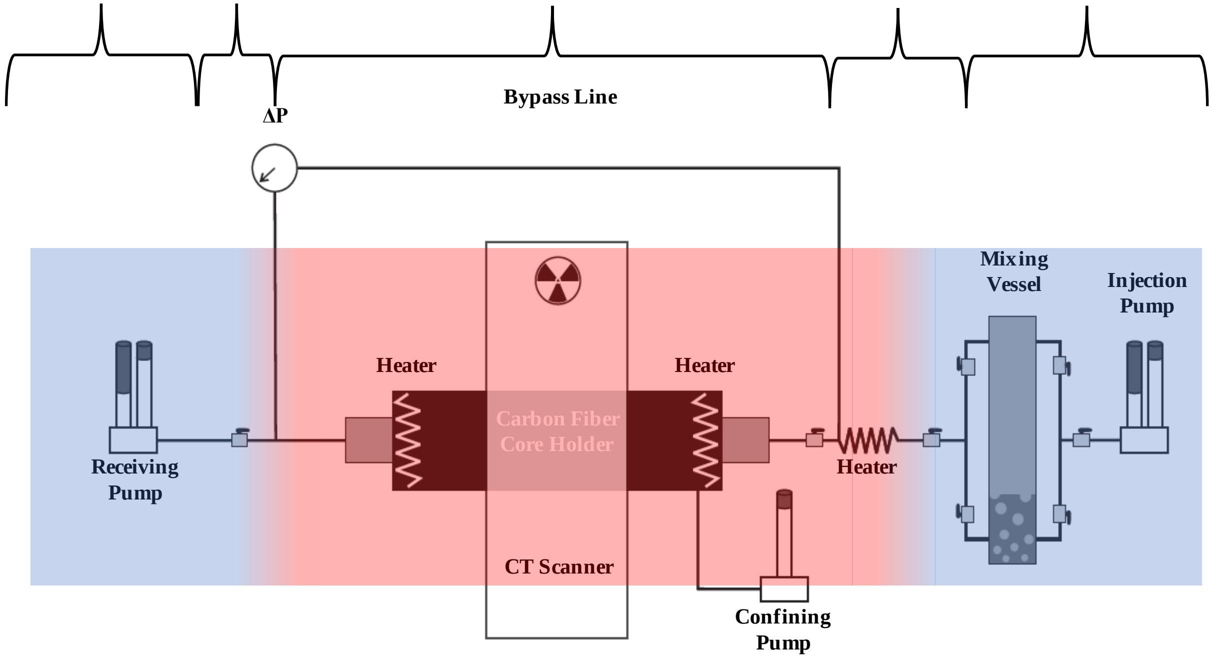

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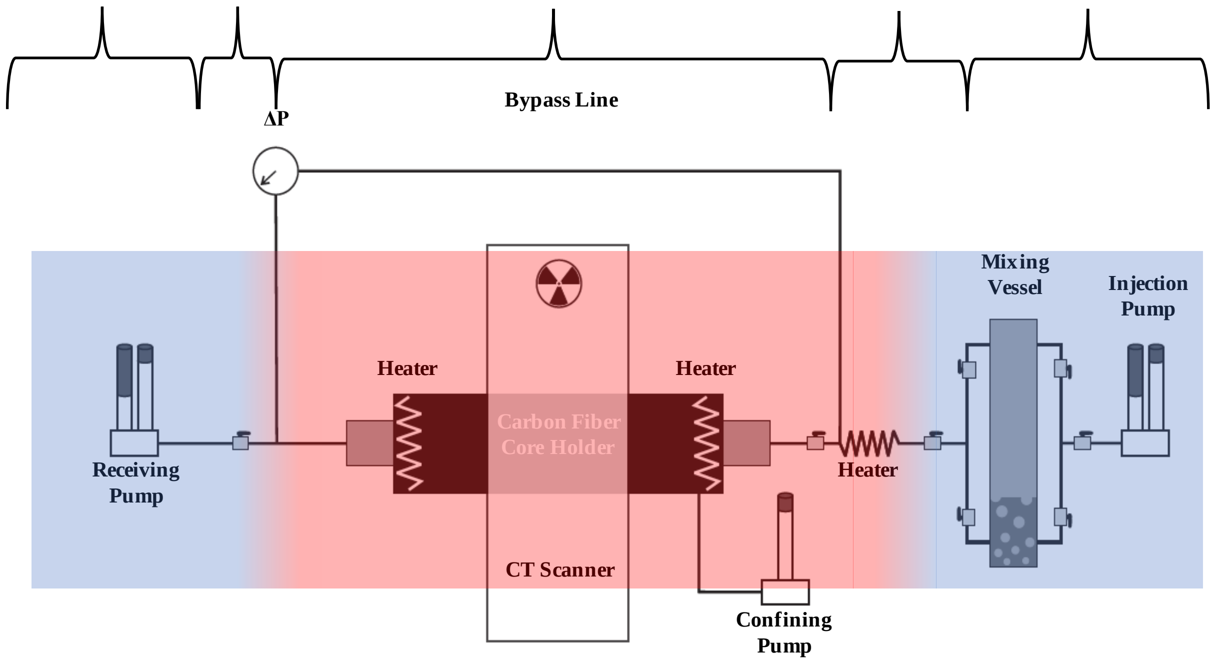

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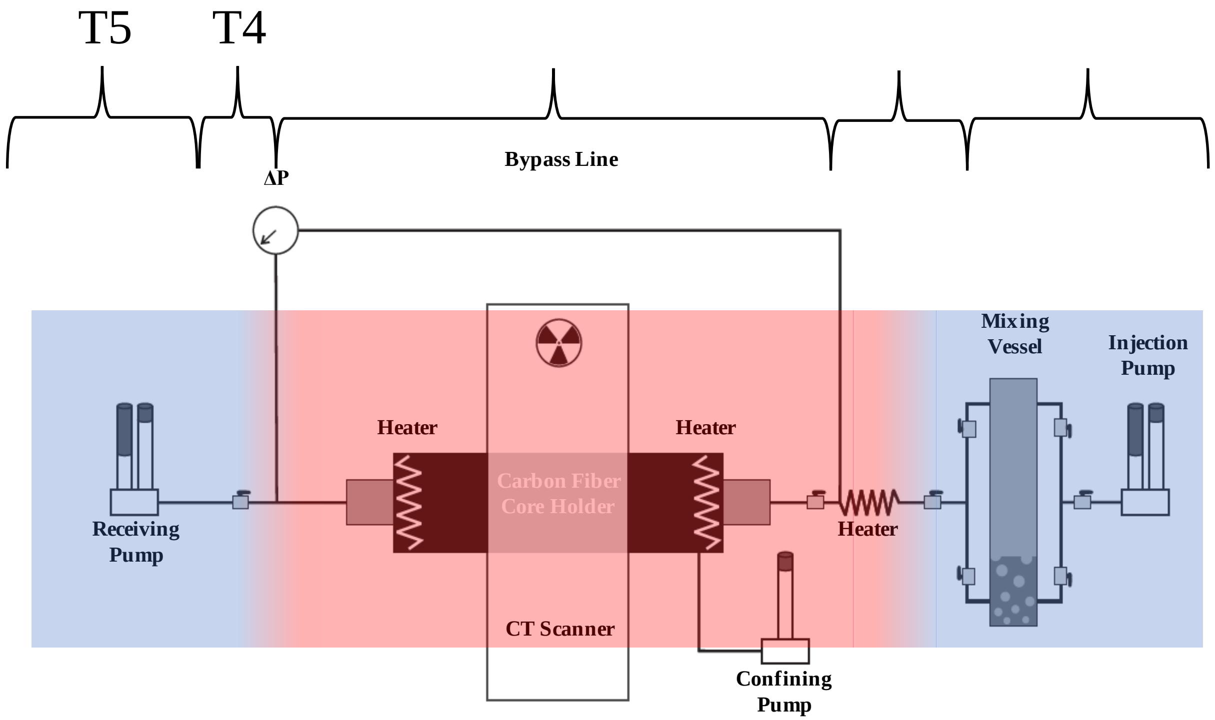

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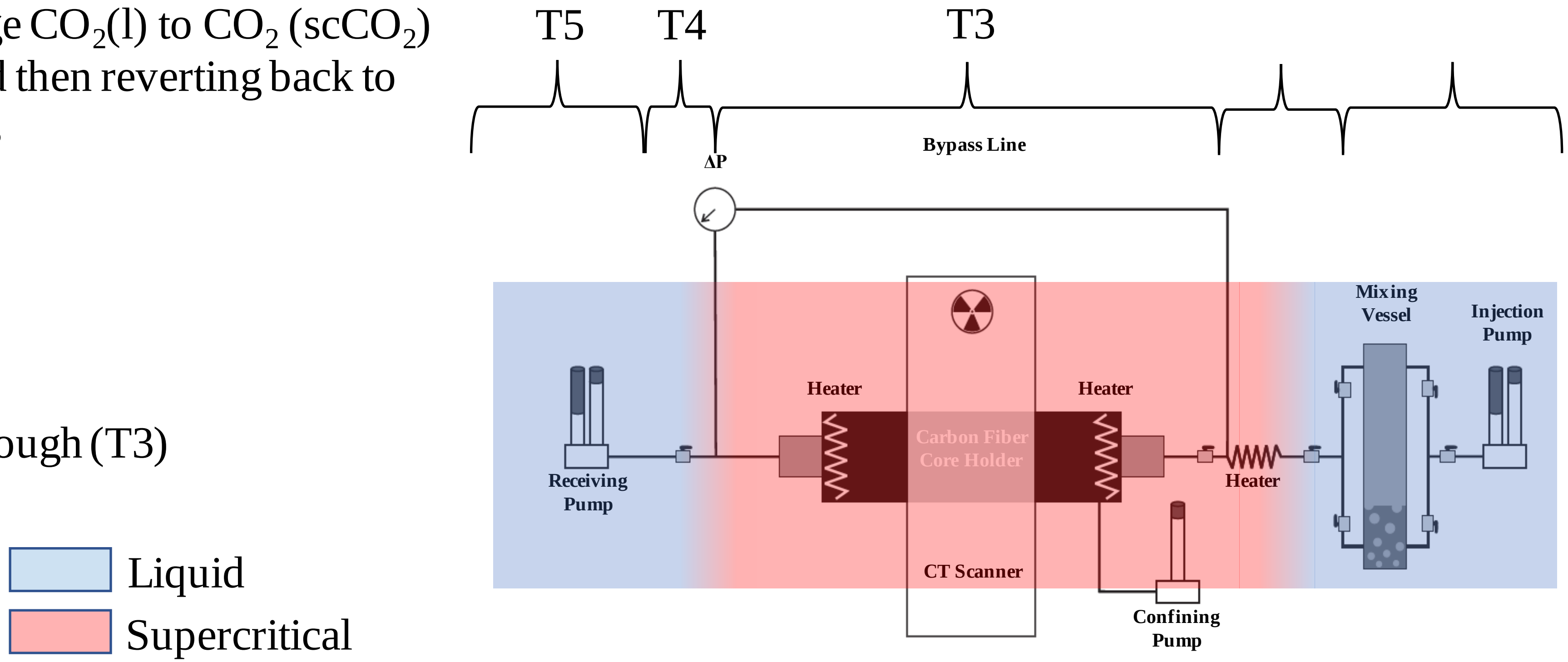

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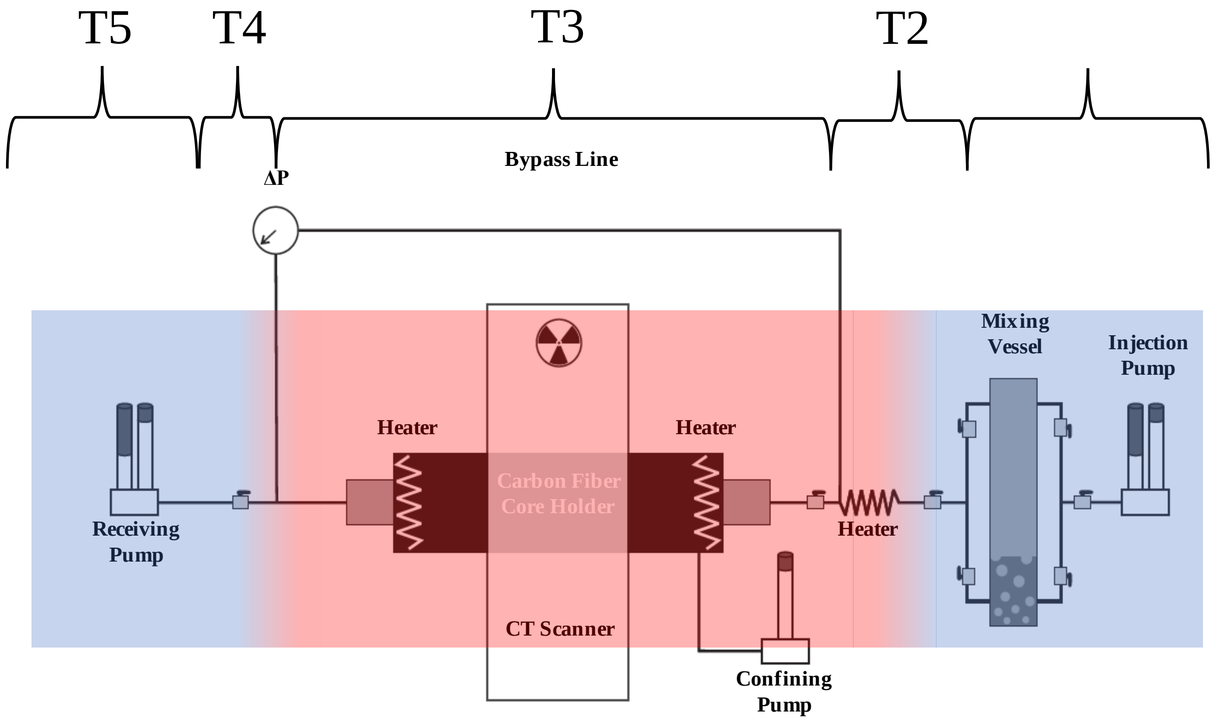

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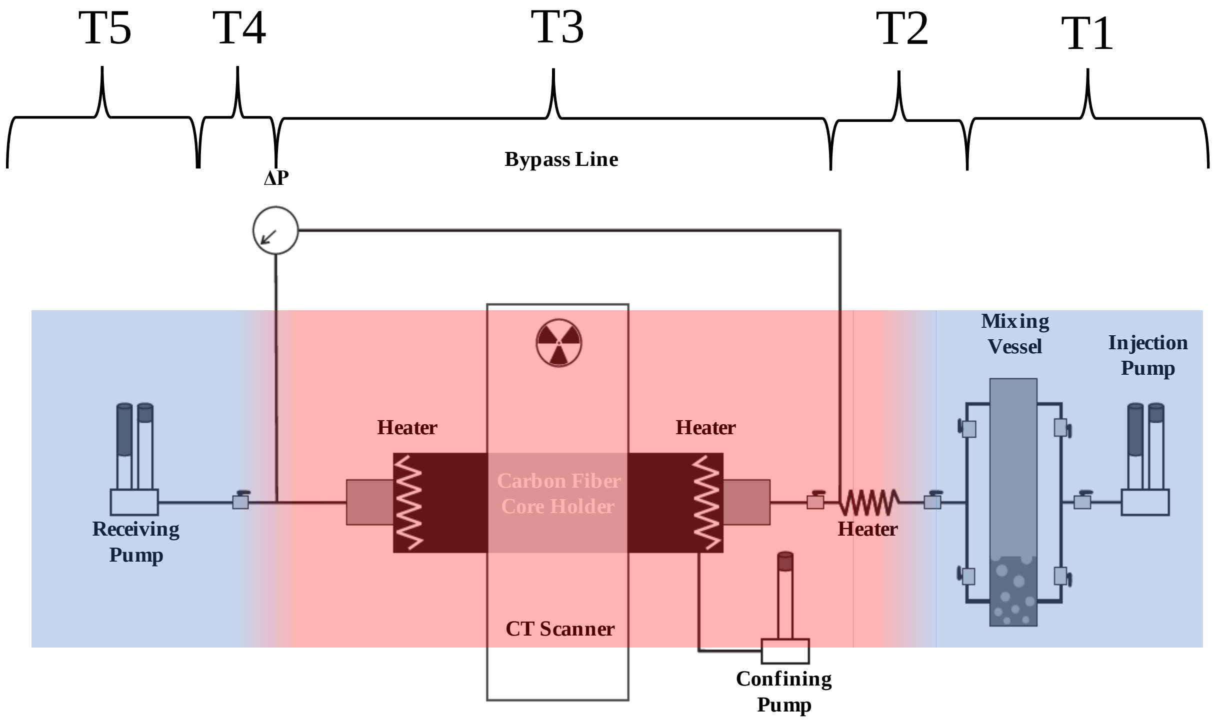

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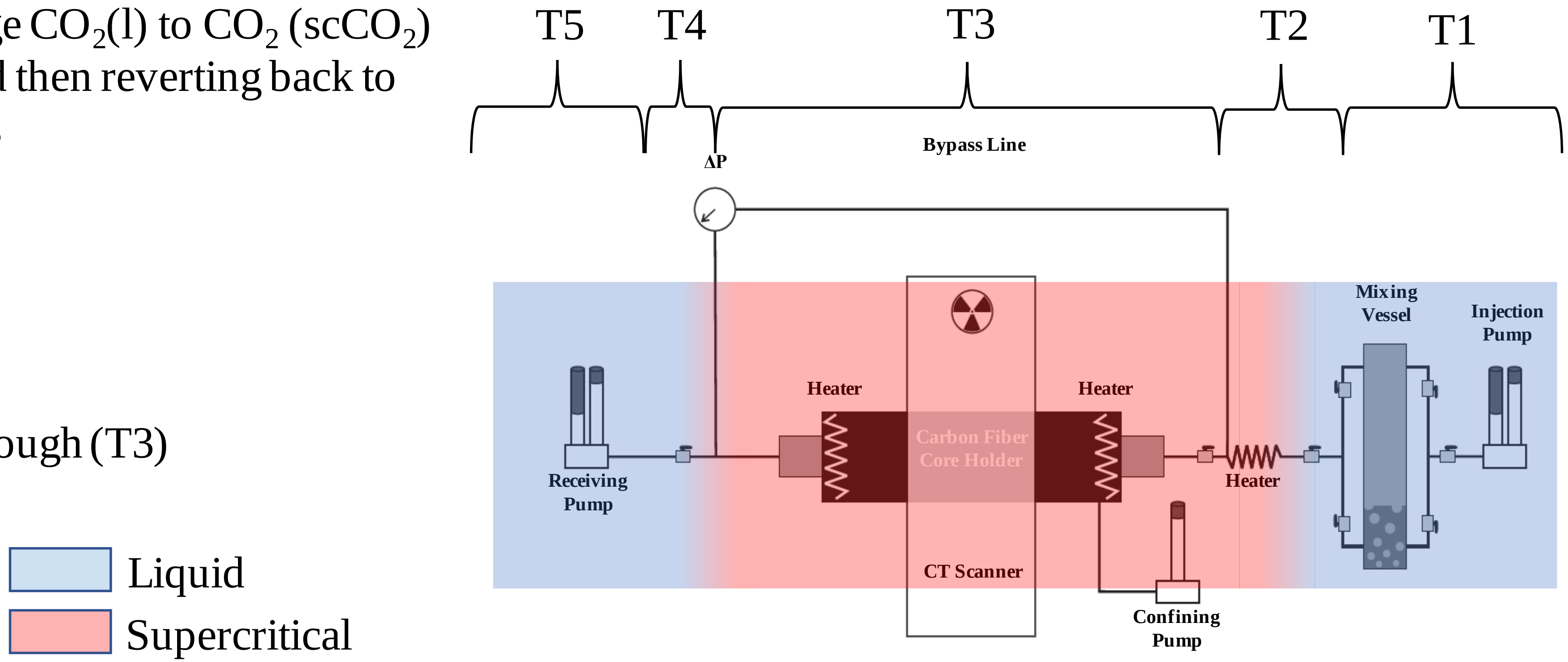

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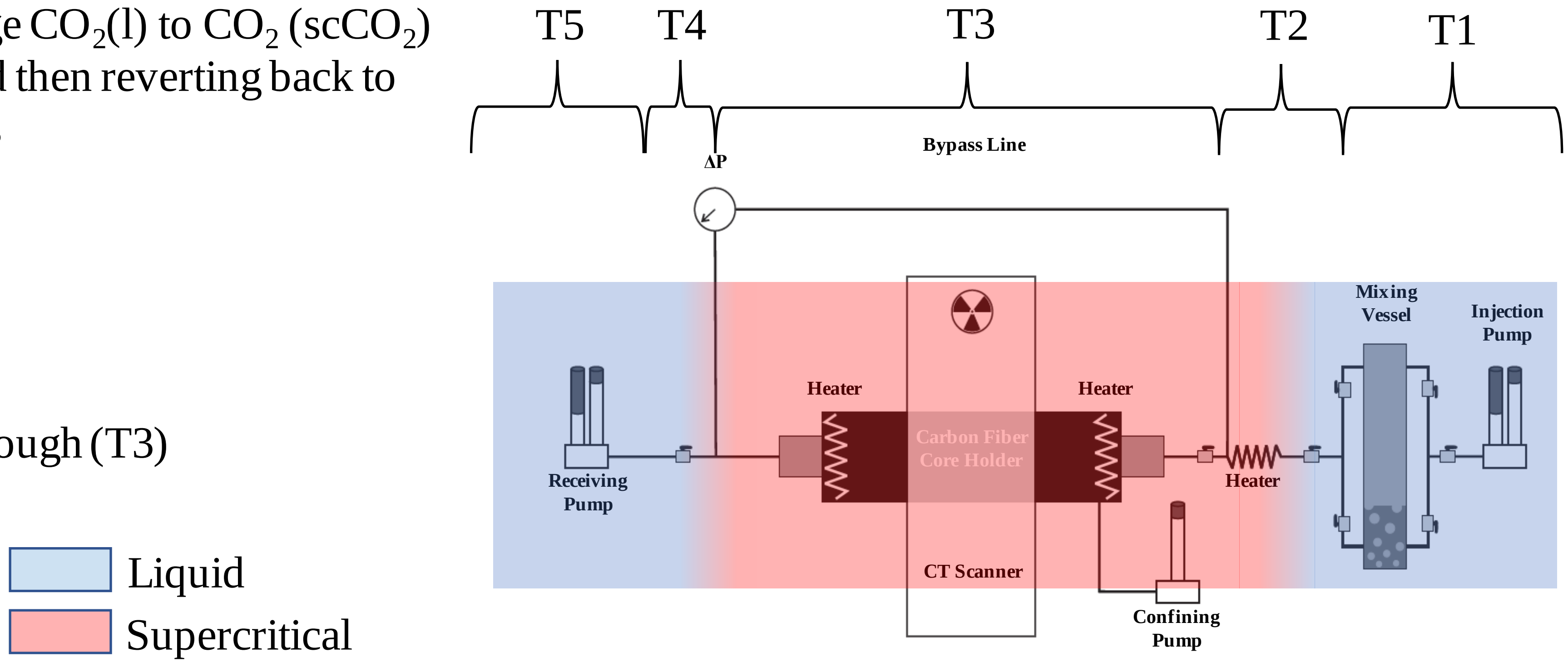

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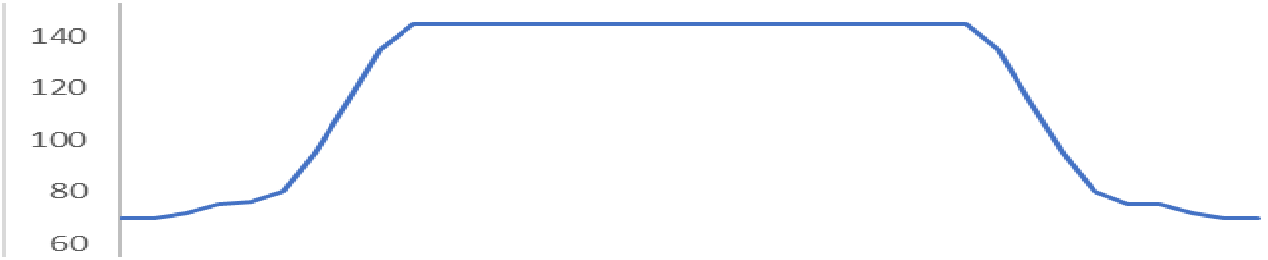

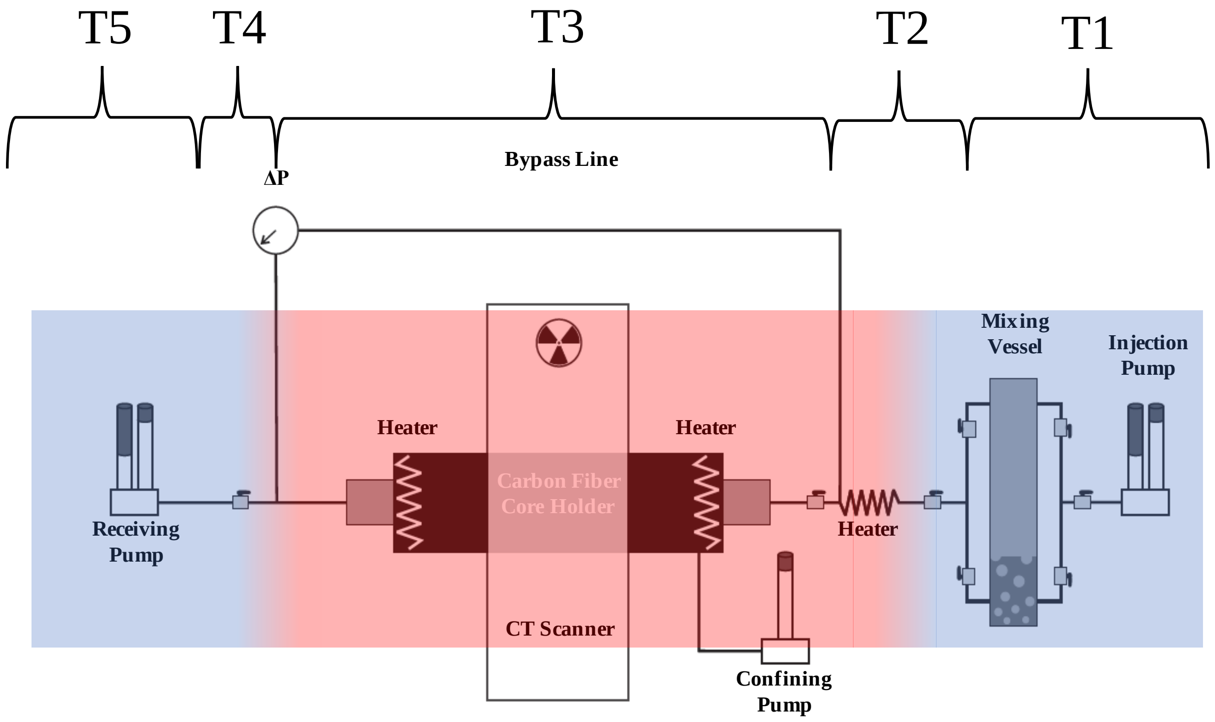

Liquid

Supercritical

Schematic of experimental system flow through system inside of medical computed tomography scanner.

Phase Change Implications for Flow Rate

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- When going from liquid to supercritical, the CO_2 effective Z increases (Peng & Robinson, 1976).

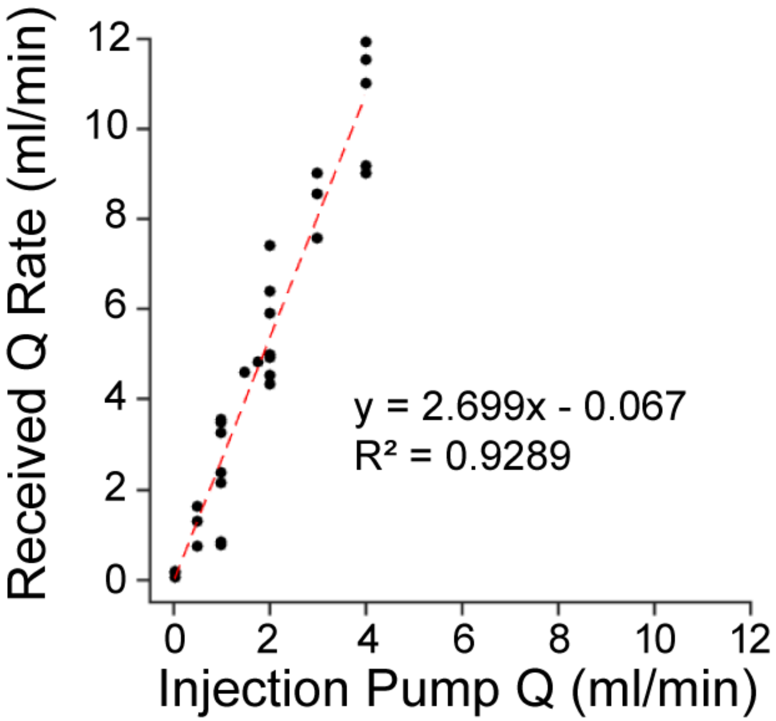
T=70F………Z=0.214
T=145.9F…..Z=0.585

The backpressure pump maintains a constant pressure = the fluid can expand via:

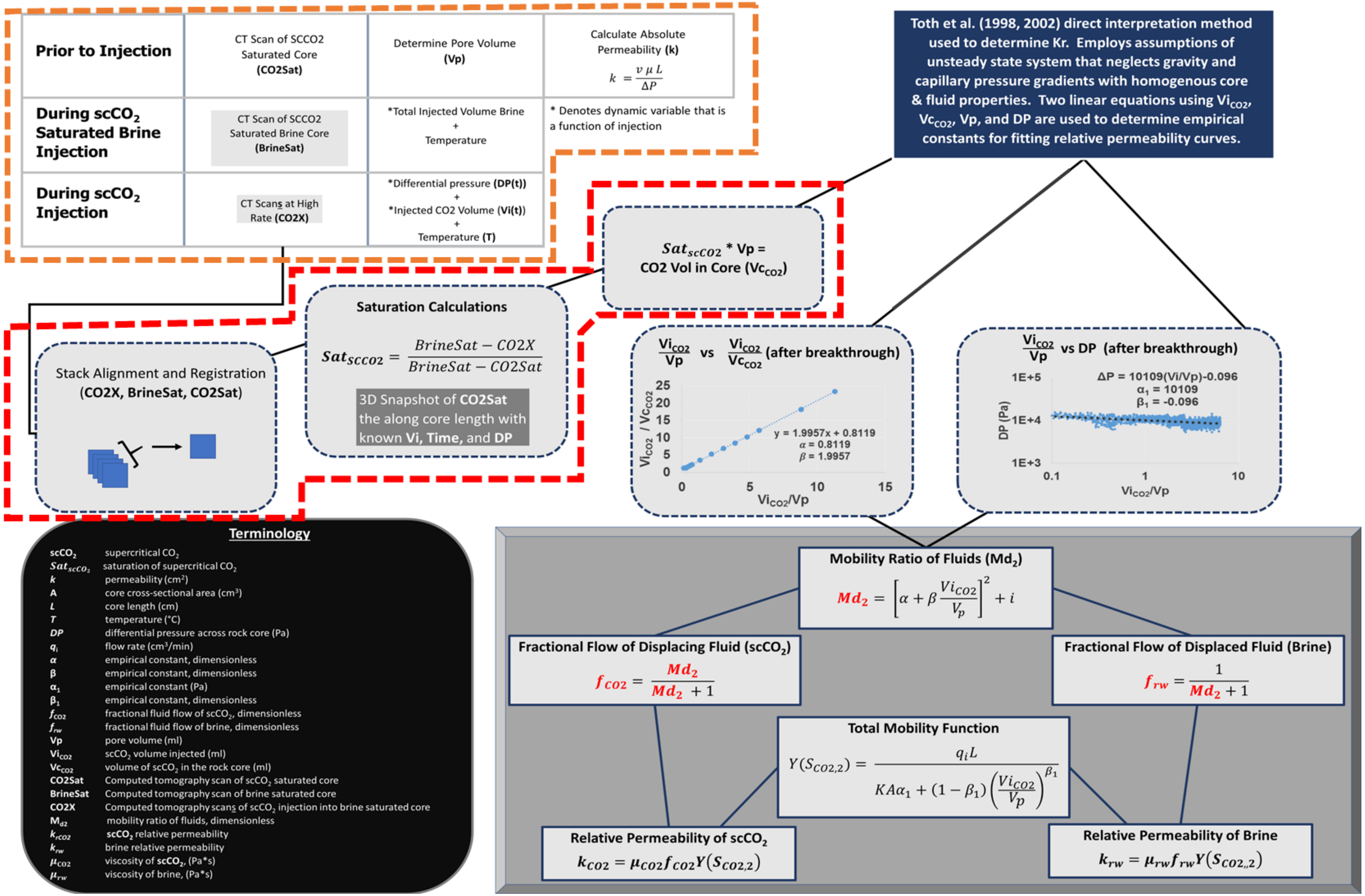
$$Z = \frac{V}{V-b} - \frac{a}{VRT-2RTb-(\frac{RTb^2}{V})}$$

The volumetric expansion results in a higher flow rate within the core than what is being initiated with the pump

- Since injection rate is constant, conversion of CO_2(l) to $scCO_2$ should be constant
- The 26 flow tests available were evaluated based on backpressure pump receiving rate
    1. Data was evaluated from core contact to breakthrough
    2. During this timeframe the only fluids that are present in the core are Brine and $scCO_2$
    3. Incompressible brine is displaced by $scCO_2$ which in turn gives us the rate of $scCO_2$ injection rate



1. Clear agreement regardless of lithology, absolute permeability, or flow rate
2. Illustrates a consistent state conversion within the system that results in a higher flow rate through the core



Terminology

$scCO_2$	supercritical CO_2
Sat_{scCO_2}	saturation of supercritical CO_2
k	permeability (cm^2)
A	core cross-sectional area (cm^3)
L	core length (cm)
T	temperature (°C)
DP	differential pressure across rock core (Pa)
q_i	flow rate (cm^3/min)
α	empirical constant, dimensionless
β	empirical constant, dimensionless
α_1	empirical constant (Pa)
β_1	empirical constant, dimensionless
f_{CO2}	fractional fluid flow of $scCO_2$, dimensionless
f_{rw}	fractional fluid flow of brine, dimensionless
Vp	pore volume (ml)
Vi_{CO2}	$scCO_2$ volume injected (ml)
Vc_{CO2}	volume of $scCO_2$ in the rock core (ml)
CO2Sat	Computed tomography scan of $scCO_2$ saturated core
BrineSat	Computed tomography scan of brine saturated core
CO2X	Computed tomography scans of $scCO_2$ injection into brine saturated core
M_{d2}	mobility ratio of fluids, dimensionless
k_{rCO2}	$scCO_2$ relative permeability
k_{rw}	brine relative permeability
μ_{CO2}	viscosity of $scCO_2$, (Pa*s)
μ_{rw}	viscosity of brine, (Pa*s)

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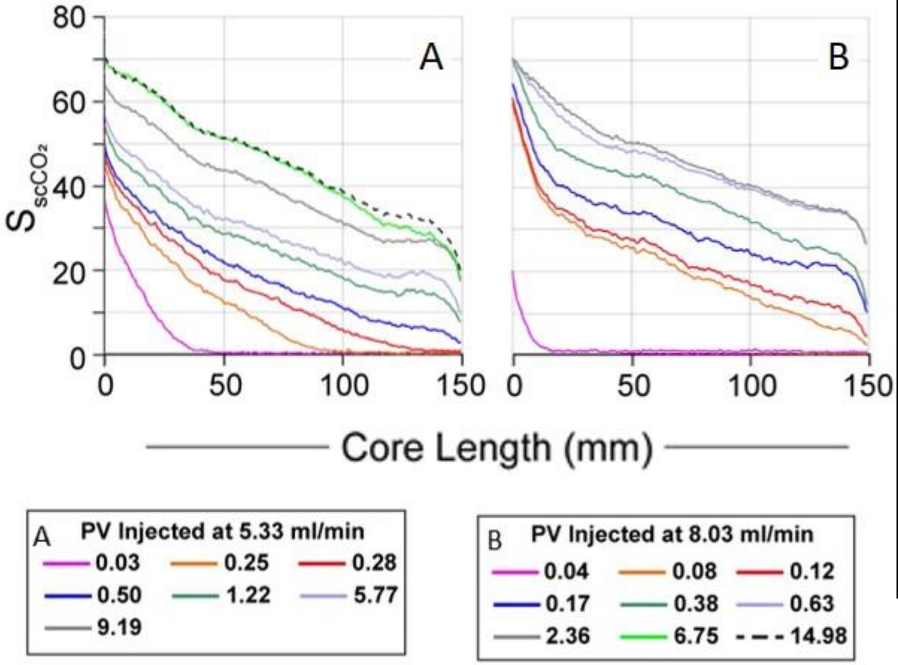
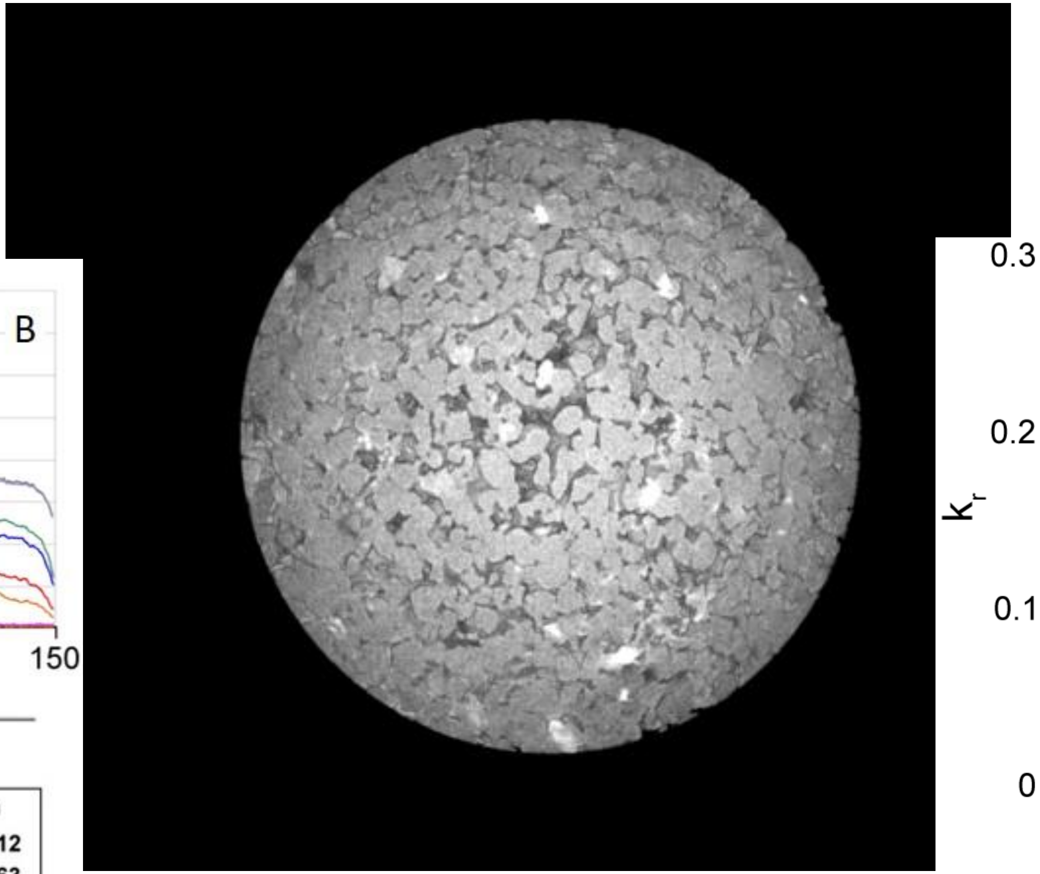
Non-Reactive kr

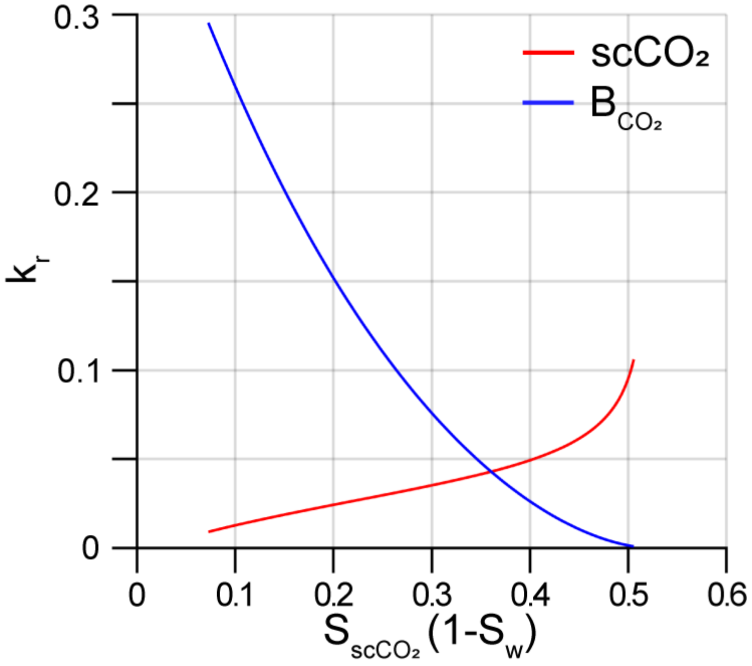
Berea Sandstone
- PV 57.1 ml
- k 424 mD
- Ø 18.8%

Saturation vs PV Injected



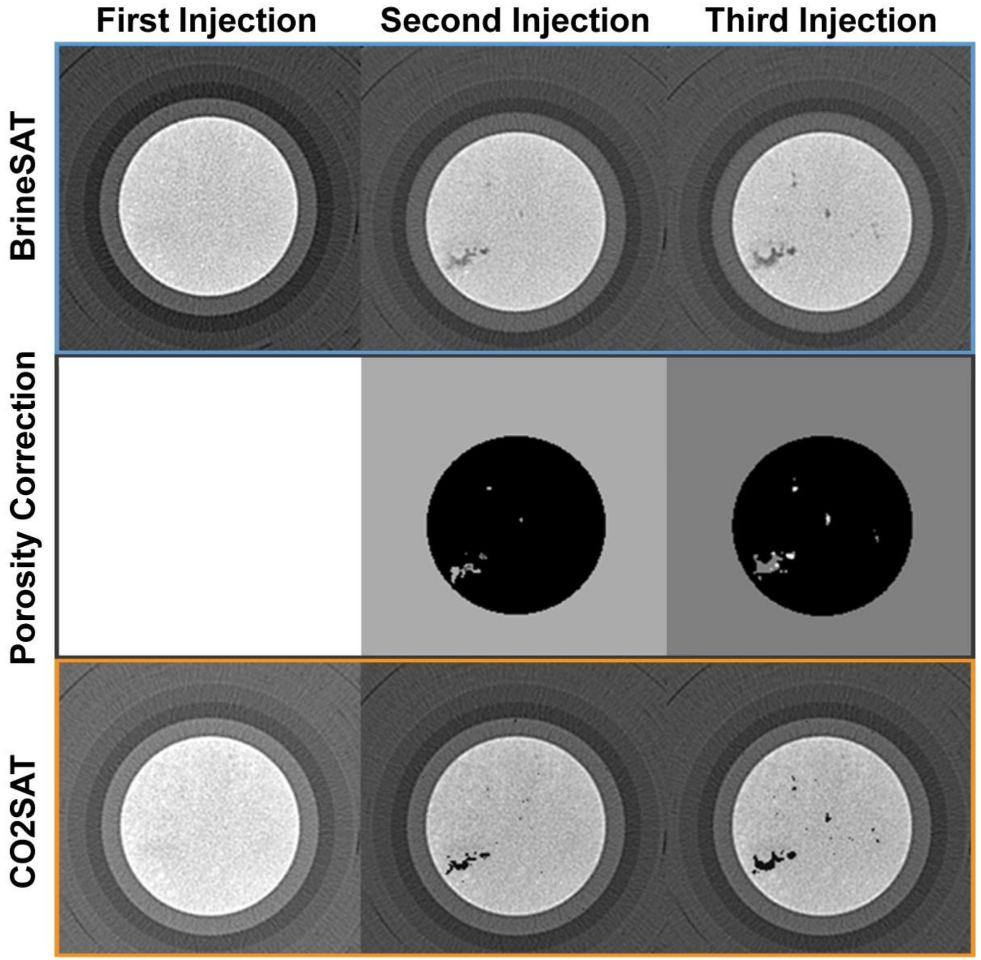


Example k_r curve

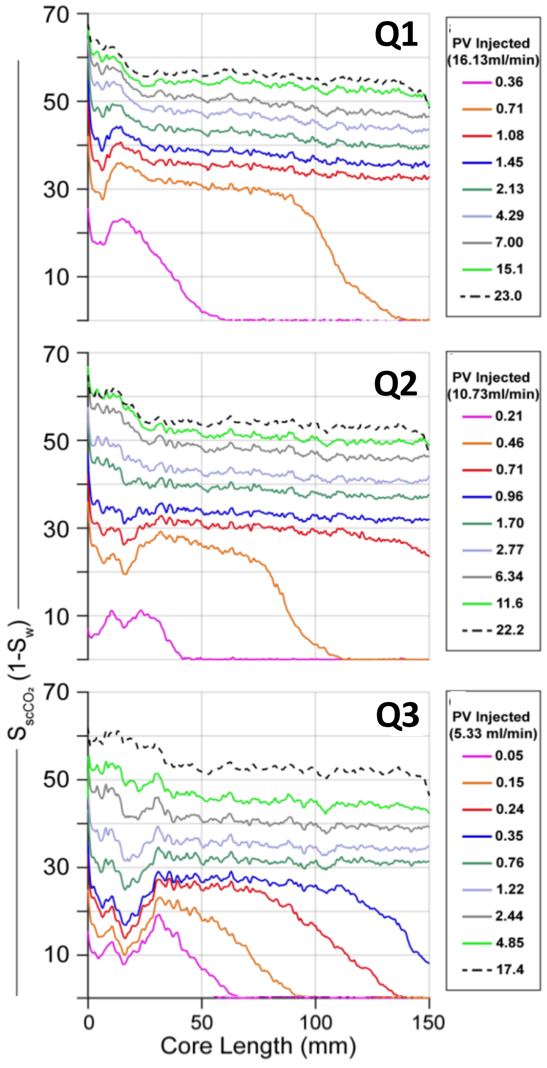


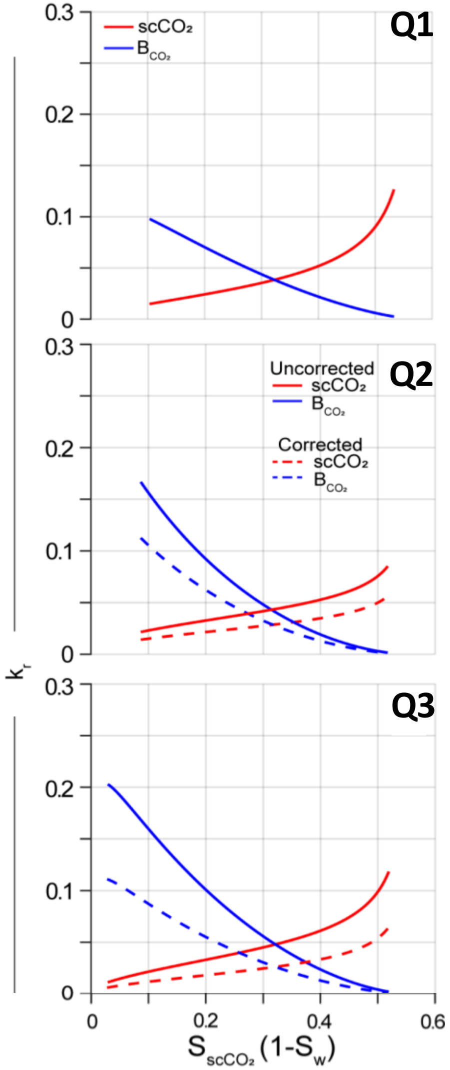
Reactive kr – Methodology Modification

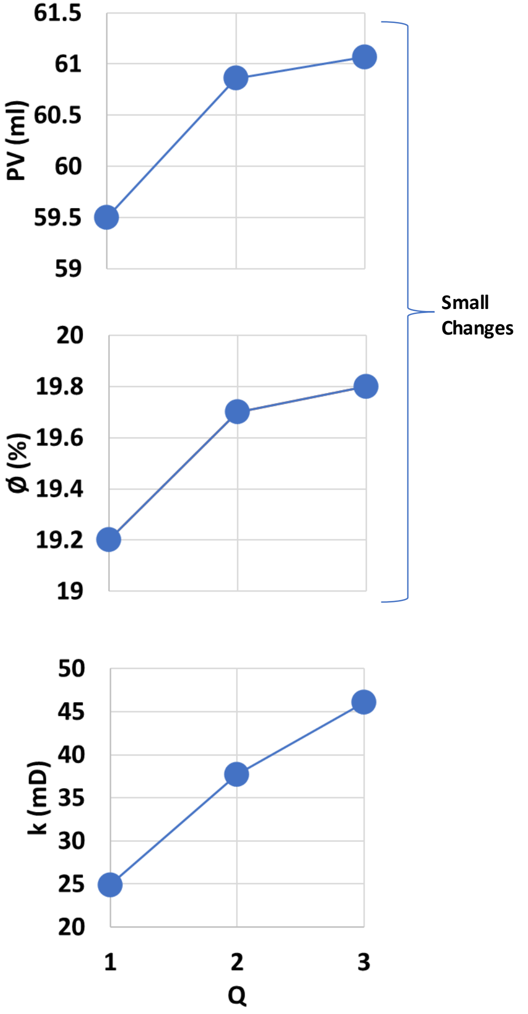
- As dissolution occurs, two physical changes happen:
  - **Ø/PV** both increase
  - **k** increases, dependent upon connectivity of new dissolution features
- In general, small pores are difficult to isolate in systems that obtain 3D tomographies quickly (order of seconds)
  - Luckily, wormholes are quite large comparably to the resolution of the scanner and easy to isolate.
  - Ilastik used to isolate pores and imagej® for image modification
- The resaturation of the pore space with **brine** after each **$scCO_2$** flood allows for the determination of **k** between each test
- Increase in fluid flow pathways, 'super-highways', resulted in a drastic changes in **k**, but only moderate changes in **Ø/PV**

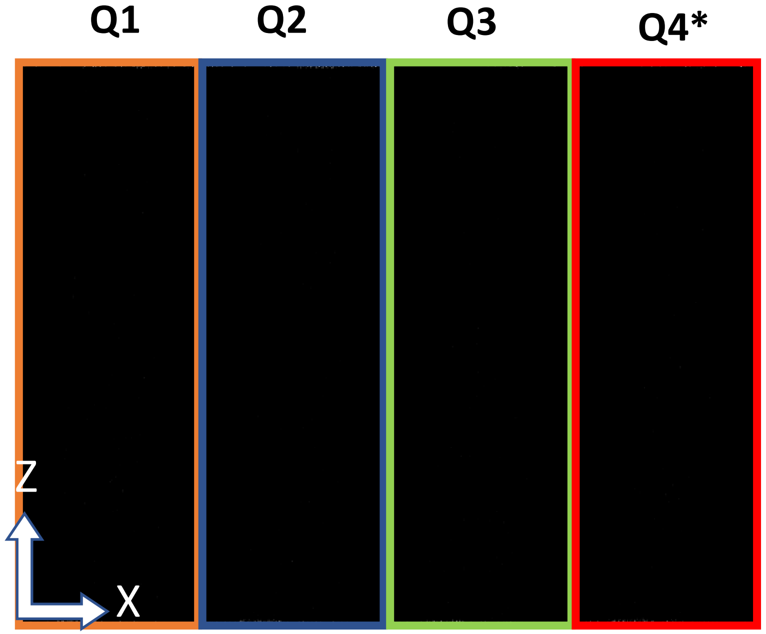


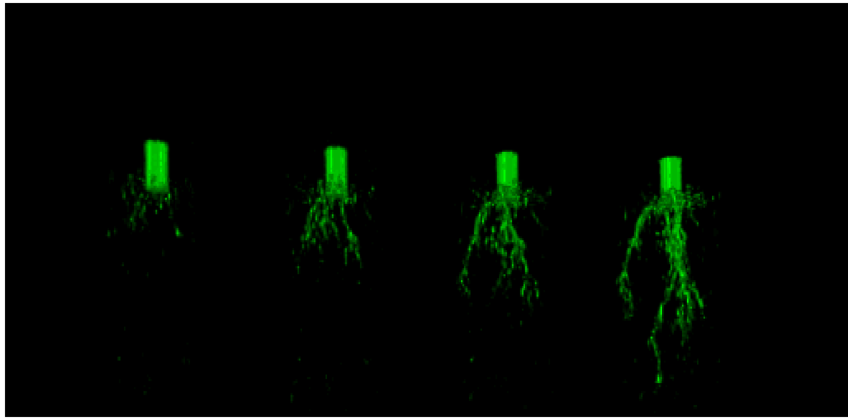
Reactive kr – Reactive Cores, Edwards Yellow











Reactive kr – Reactive Cores, Austin Chalk

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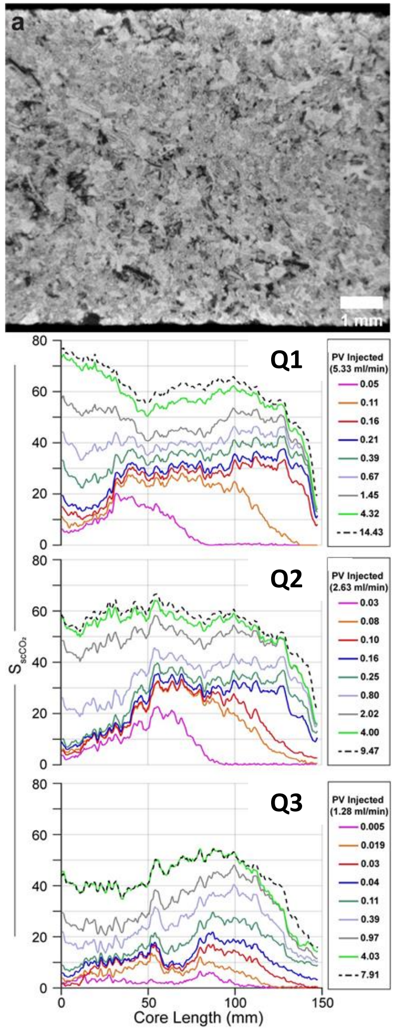
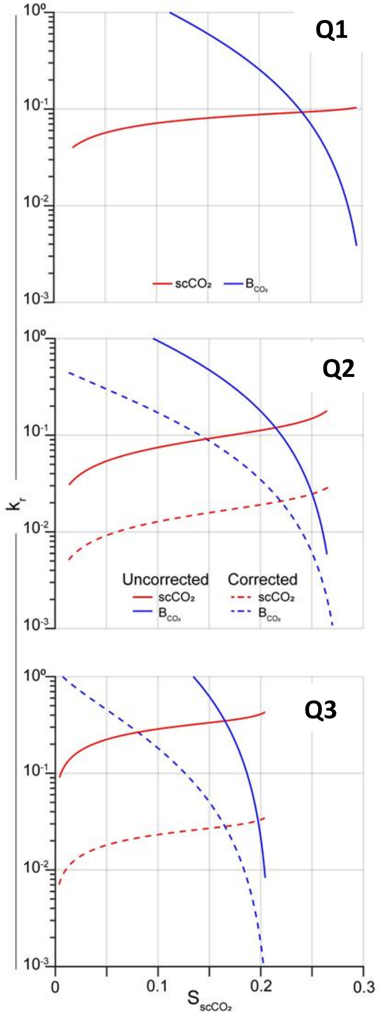
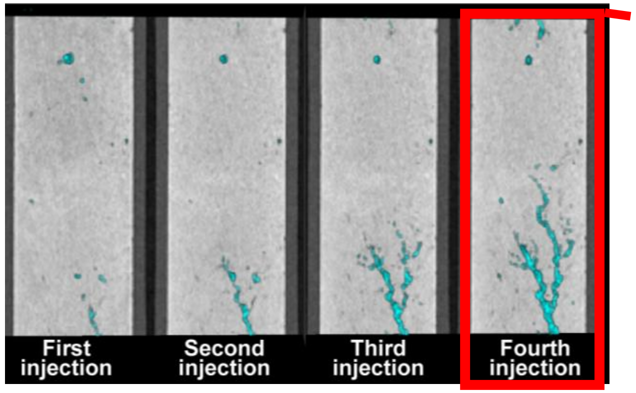
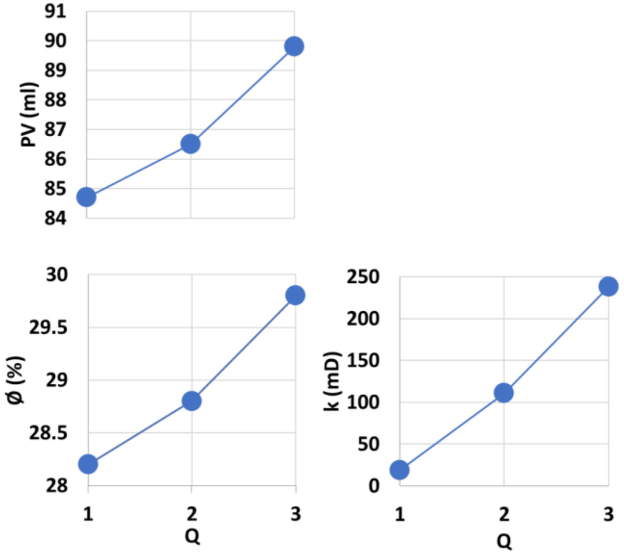


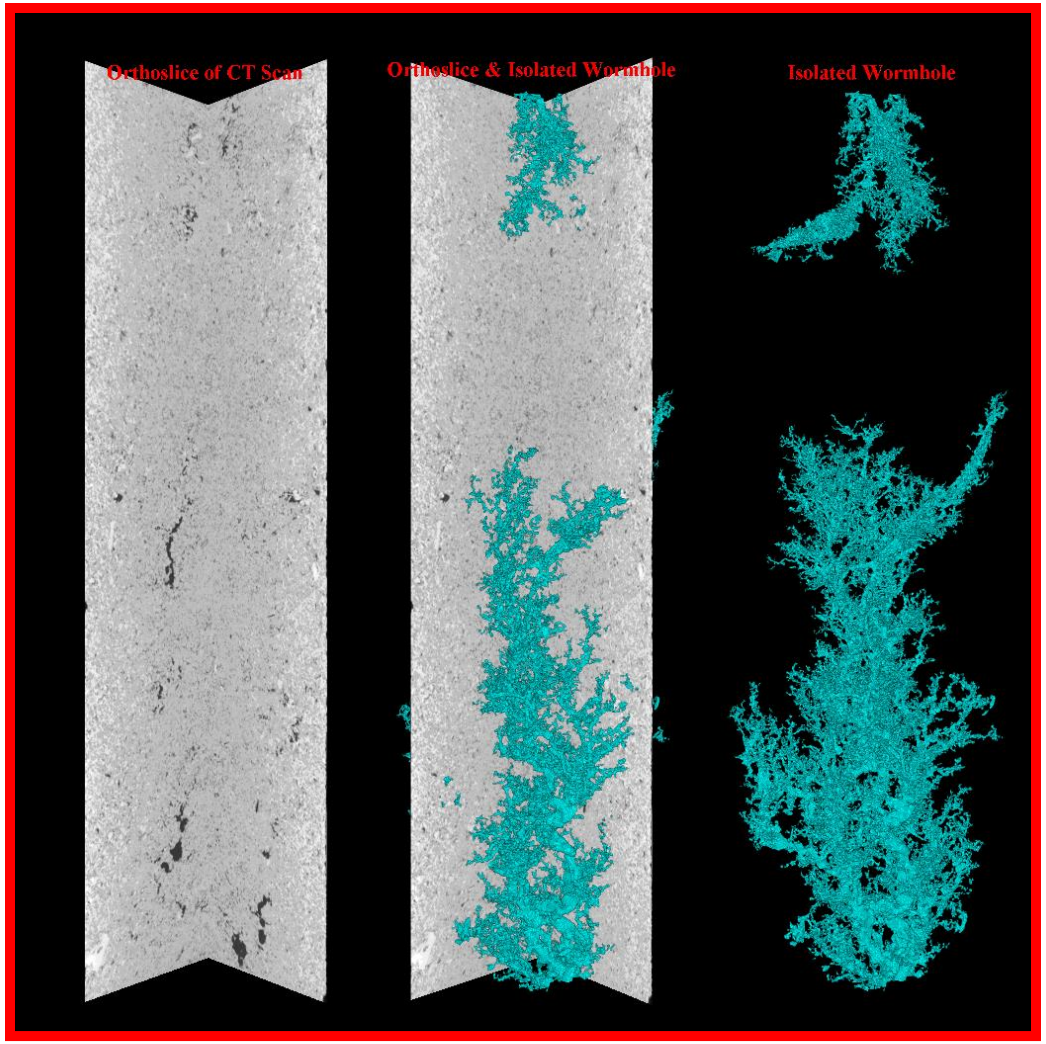


Medical CT Scans





Micro-Tomography



Conclusions

1. **It is possible to capture dynamic kr as a function of dissolution**
   - Time steps, not continuous
2. **Absolute k is the dominant dynamic variable**
   - System transitions from diffuse dominated flow to concentrated flow along primary flow path
3. **Kr shifts and recedes as a function of increased channelization of flow**
   - Cross-over occurs faster and at low $scCO_2$ saturation
   - Potentially less initial occupation of $scCO_2$ if preferential paths are formed

Future Work

1. **Image system at higher resolution during dissolution to capture micro-channels**
2. **Incorporate CFD to determine how channelization proceeds temporally**
3. **Incorporate geochemical modeling to estimate mass transport and determine equilibrium conditions/reactivty**

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