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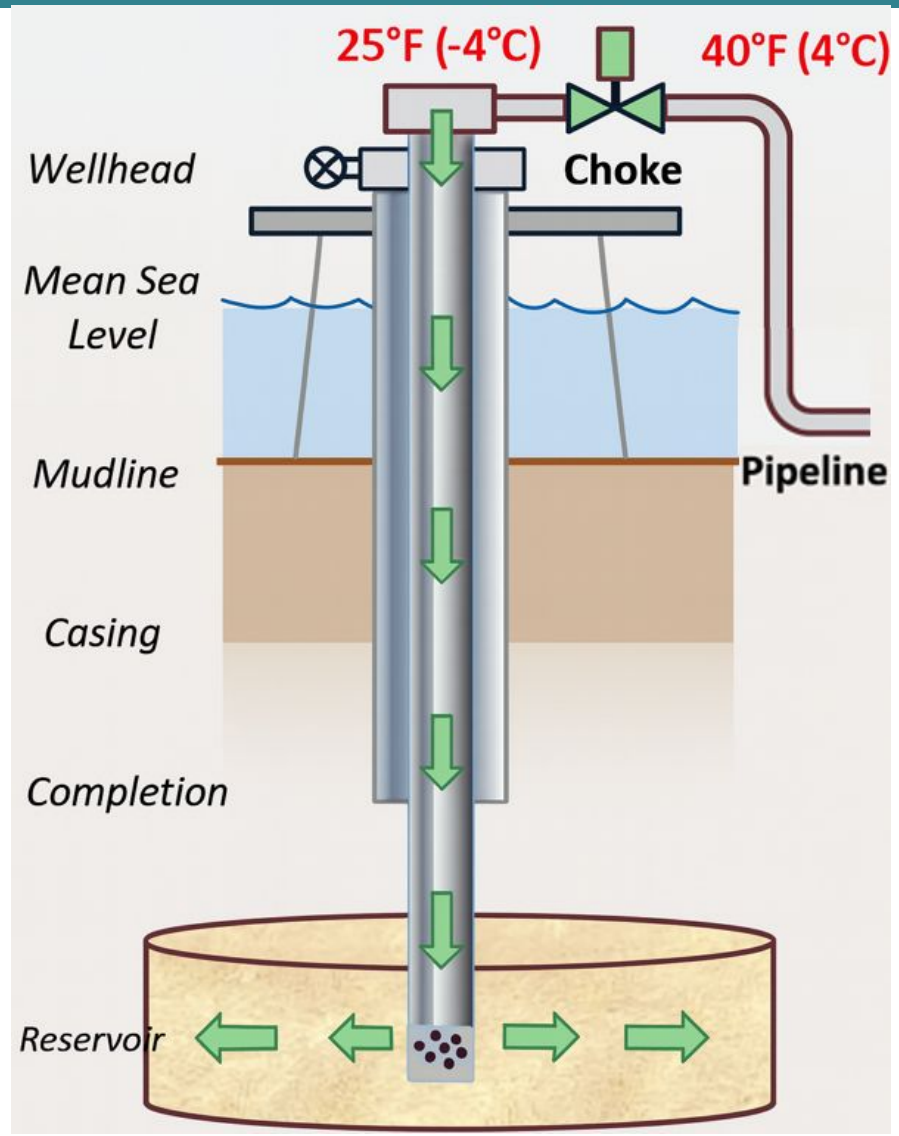
Restart of Injection Operations in CCUS Wells: Thermal Impacts and Well Design Considerations

Ruggero Trevisan

VP Europe - Altus Well Experts

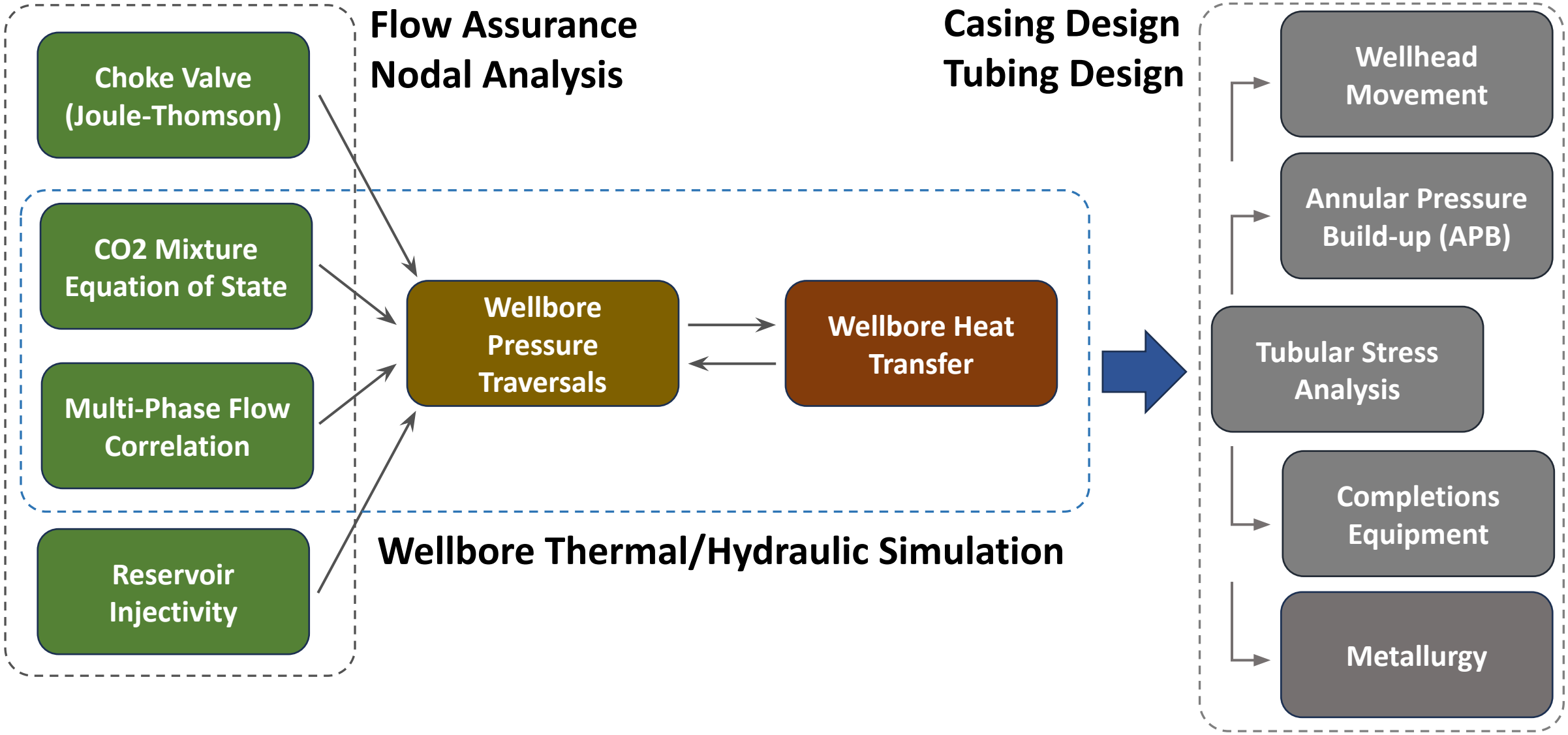
Agenda

- Overview of CCUS Operations
- Challenges and Simulation Requirements
- Example simulations of transient Restart (or Start-up) period
- Wellbore integrity – tubular and completion loads
- Conclusions and Objectives for Further Work

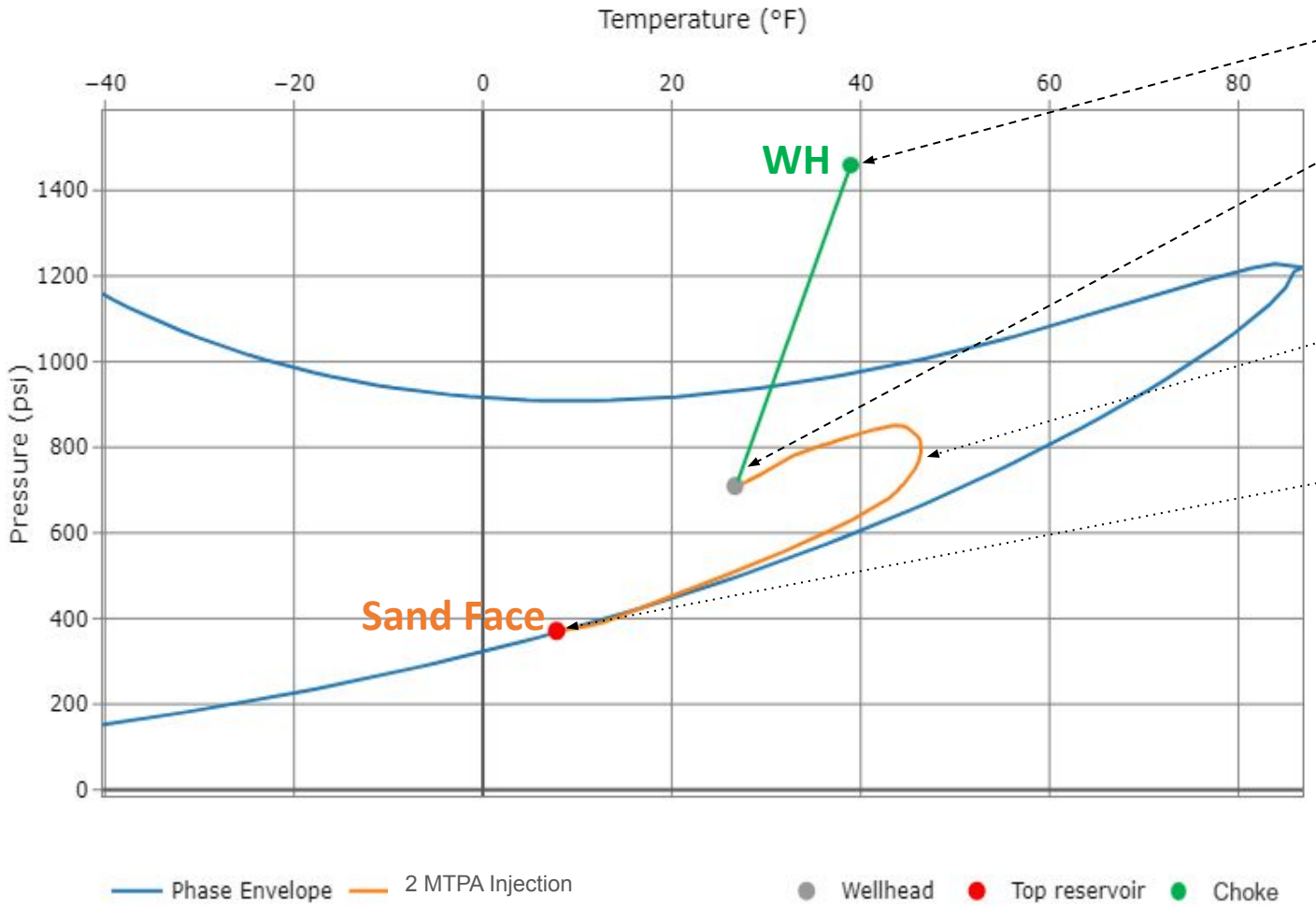


CCUS Well Design Challenges

- Pipeline flow condition as input
- Choke: Temperature boundary condition
- Phase behavior of fluid during flow
- Frictional pressure losses
- Heat transfer with formation
- Wellbore integrity:
  - Tubulars & Connections
  - Completion / Packers
  - Cement
- Transients versus steady-sate conditions
- Perforation: Pressure boundary condition
- Reservoir Injectivity


Flow Assurance
Nodal Analysis
Casing Design
Tubing Design
Choke Valve (Joule-Thomson)
CO2 Mixture Equation of State
Multi-Phase Flow Correlation
Reservoir Injectivity
Wellbore Pressure Traversals
Wellbore Heat Transfer
Wellbore Thermal/Hydraulic Simulation
Wellhead Movement
Annular Pressure Build-up (APB)
Tubular Stress Analysis
Completions Equipment
Metallurgy

EOS Phase Envelope: CCUS Mixtures w/Impurities



Pipeline supply

CO_2 mixture flashing across choke - J-T temperature drop

Multiphase behavior throughout wellbore

Early life injection to depleted gas reservoir:

- low BHP
- gass acceleration near perf → downhole friction losses
- J-T temperature drop

Case Study: Transient Simulation of Well Restart

1. Shut-in well following a period of steady-state injection
2. Restart of 2 MTPA CCUS operation into Depleted Gas Reservoir
   - Reservoir Conditions: 340 psi (23 bar) , 200°F (93°C)
   - Pipeline Conditions: 1450 psi (100 bar) , 40°F (4°C)
   - Gradually open choke to terminal position: 30 minutes
   - Rapid vs Slow Choke Opening:

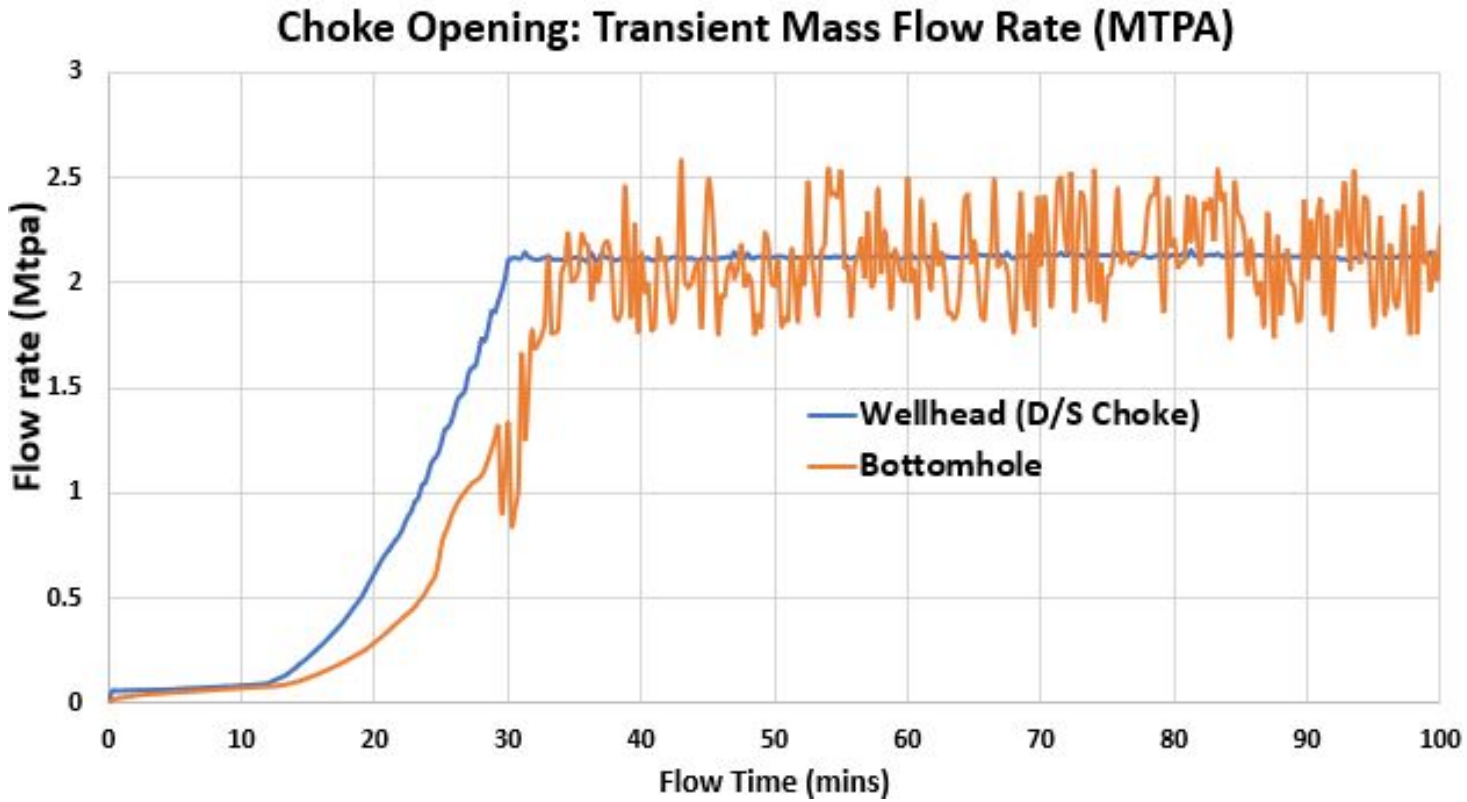
Choke Cavitation

vs

Thermal Shock

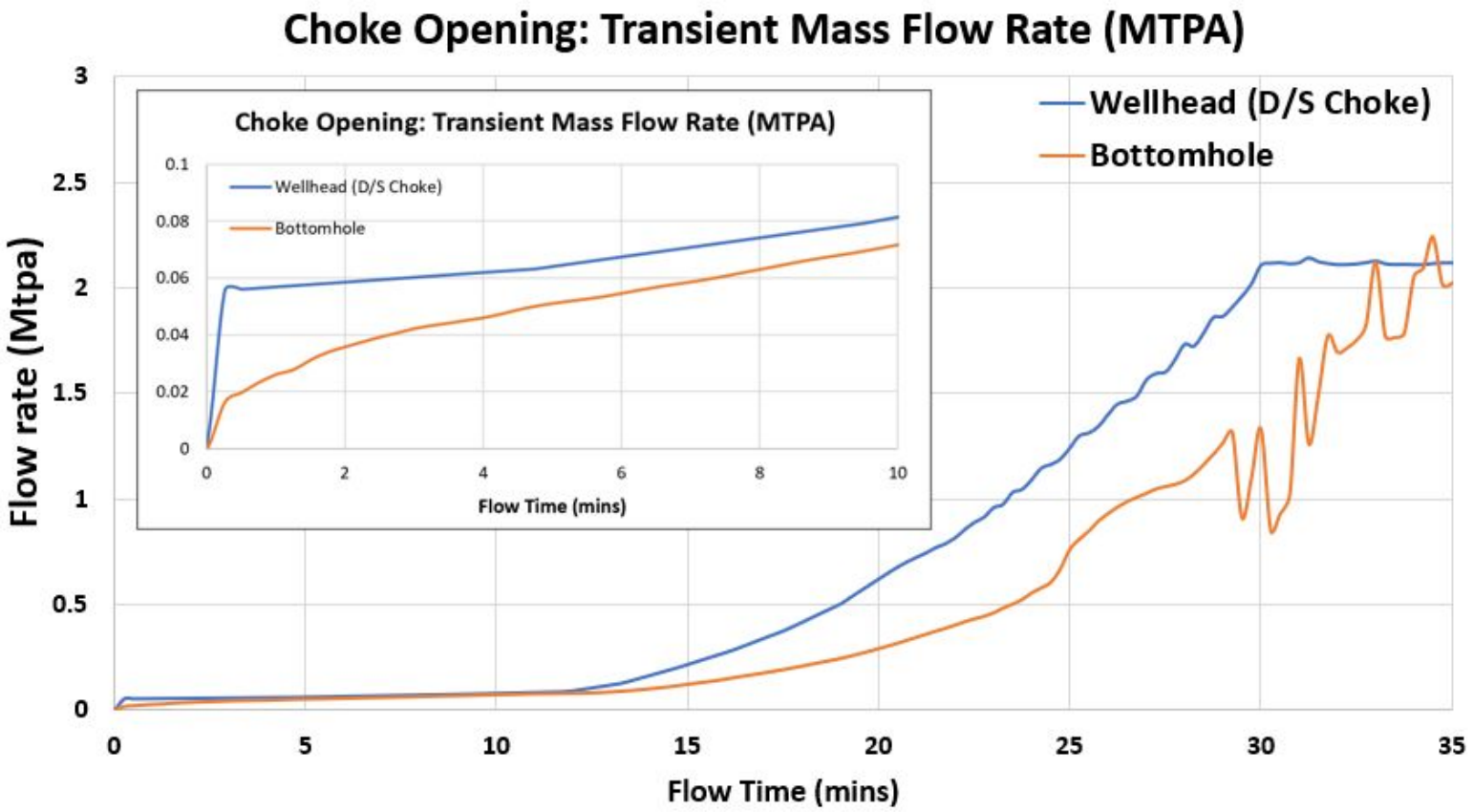
Simulation of Well Restart: Mass Flow Rate

- Gradually open choke–30 mins
- Reservoir mass flow lags @ WH
- Mass accumulation or “line packing” in the well
- Fully established flow for final choke %
- Flow instability due to multiphase flow & reservoir simulation model feedback

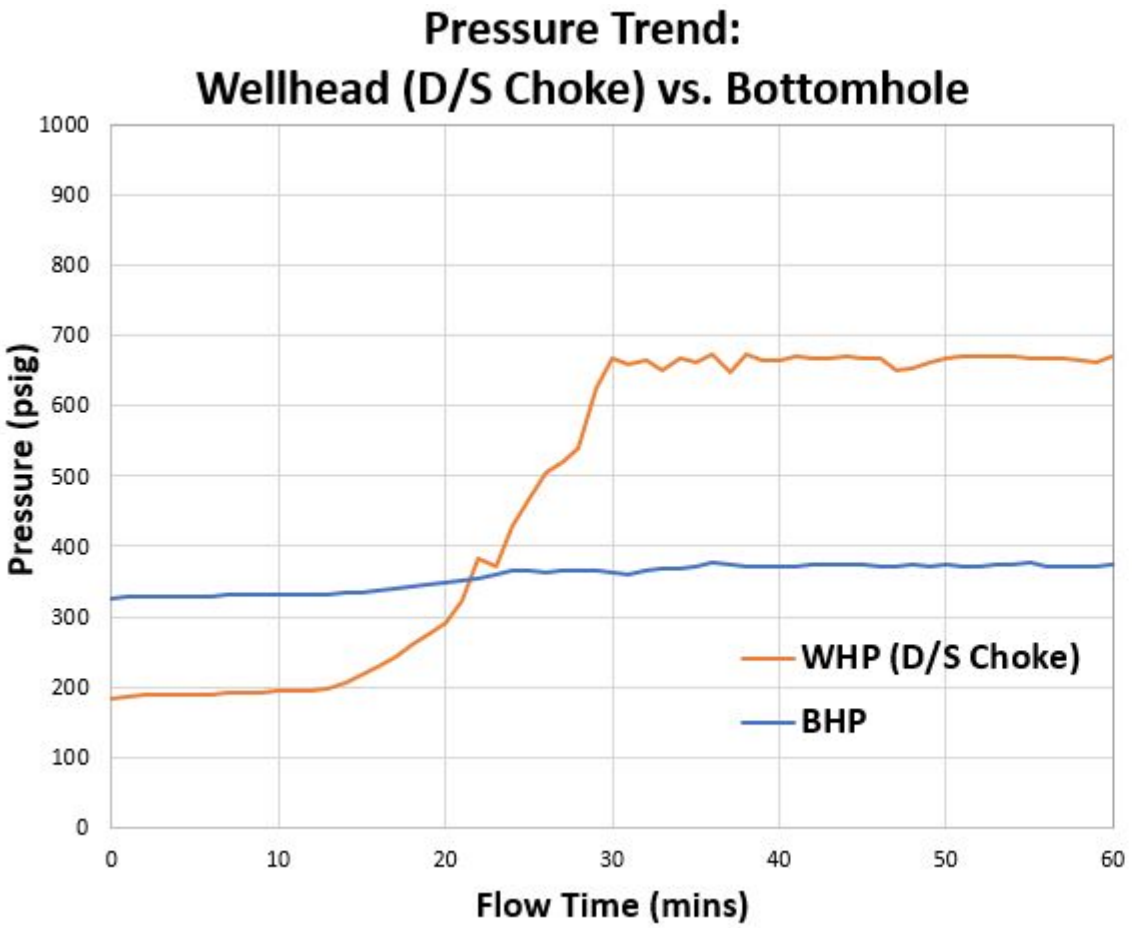


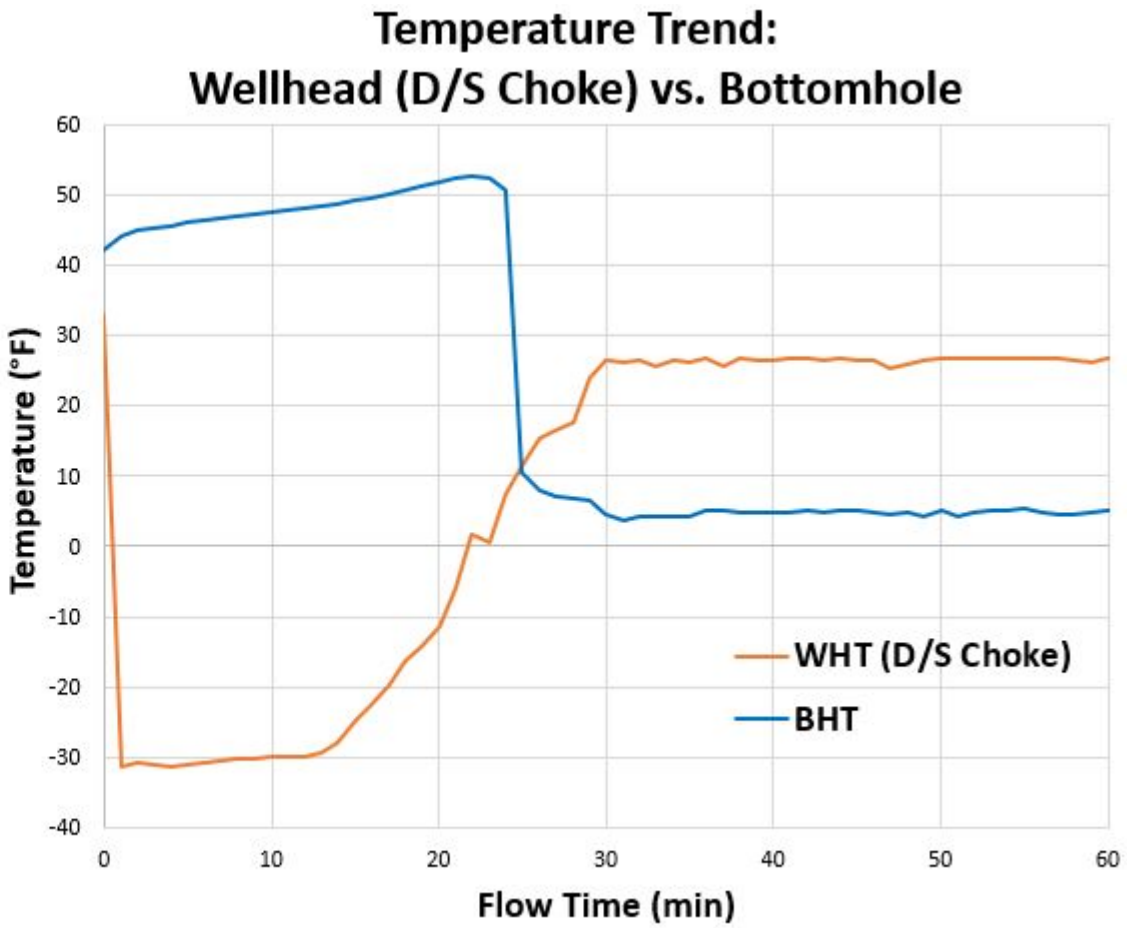
Simulation of Well Restart: Mass Flow

- Choke opening assumption:
  - Initial opening to ~5% open
  - 5-10 mins of minimal choke opening
  - 15-20 mins period for a linear opening schedule
- At early time periods and minimal mass flow rates, mass accumulation and line packing is evident
- Differential Mass Flow Rate of 1 MTPA still evident after 30 mins of flow

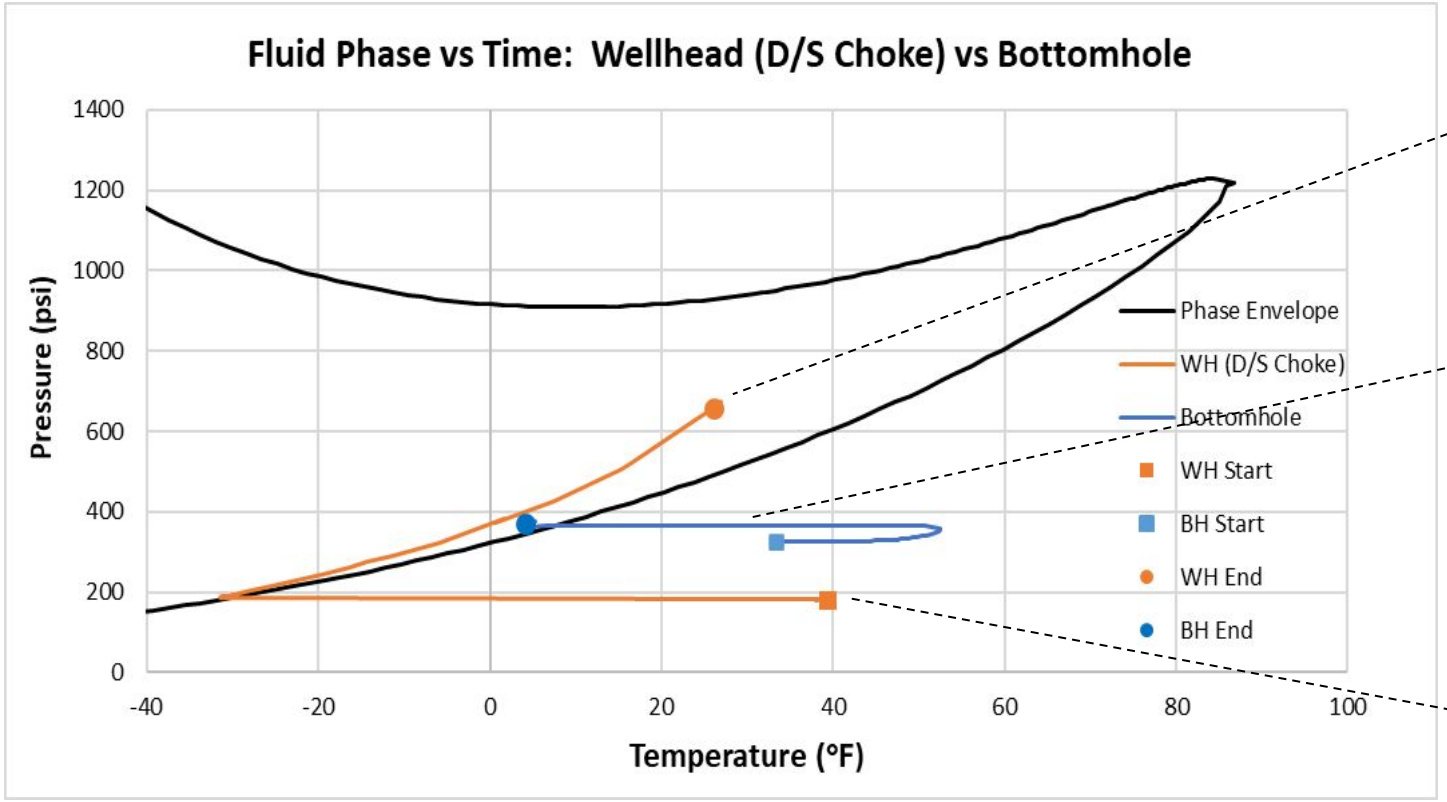


Simulation of Well Restart: WH vs BH Trend





Simulation of Well Restart: Fluid Phase



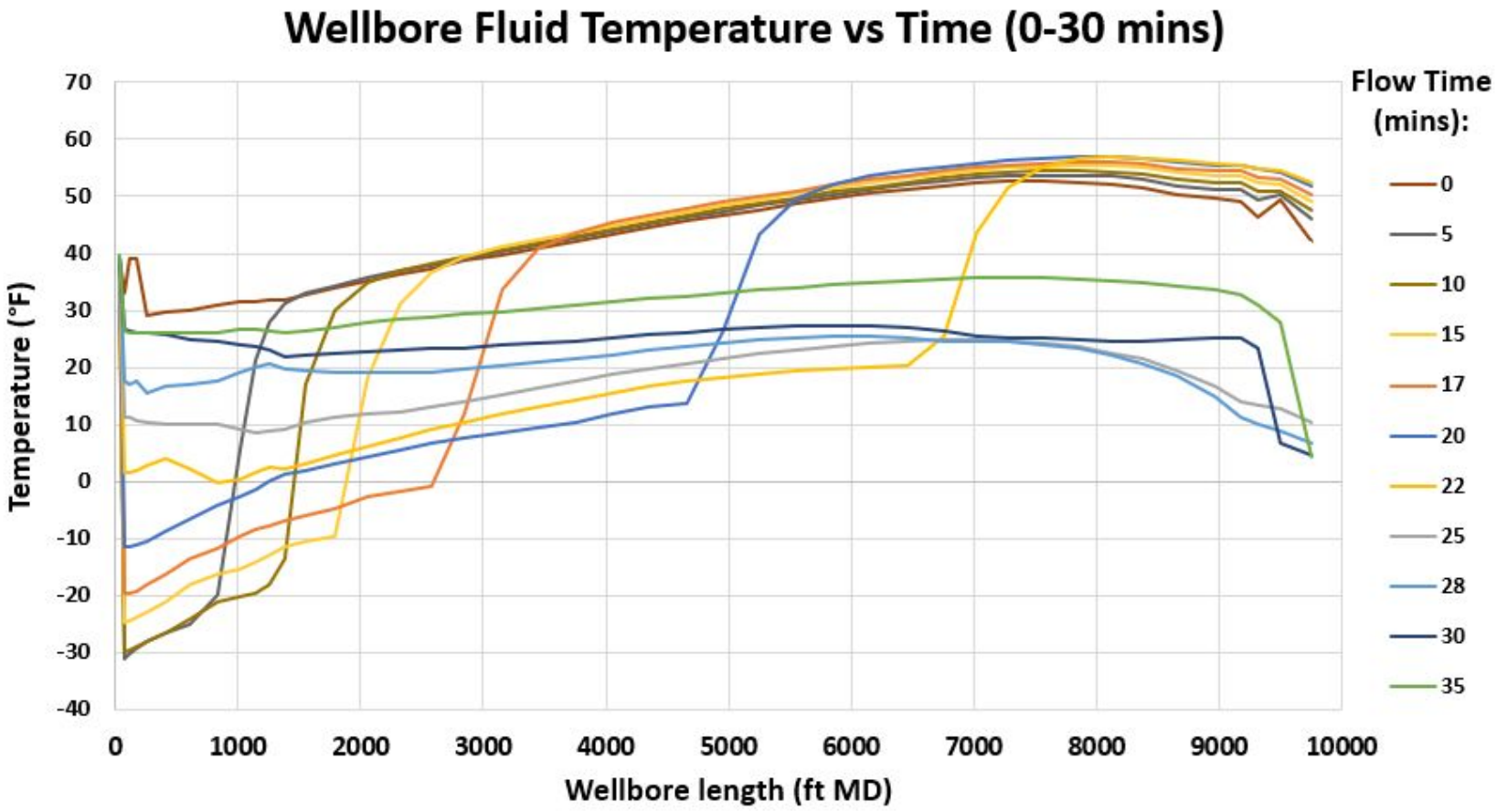
Flow across the surface choke flashes to multi-phase

Bottomhole fluid largely remains in vapor phase due to highly depleted reservoir conditions

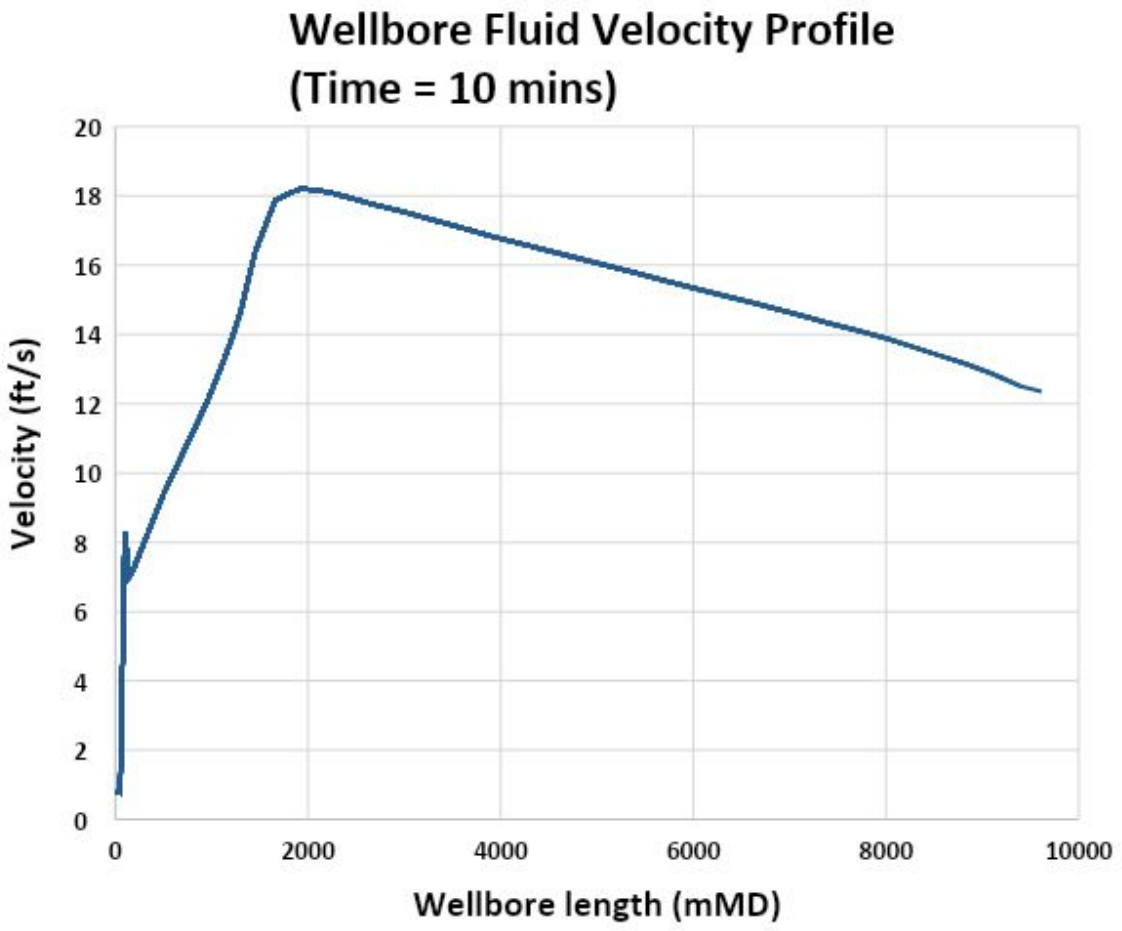
Initial shut-in wellhead state is vapor

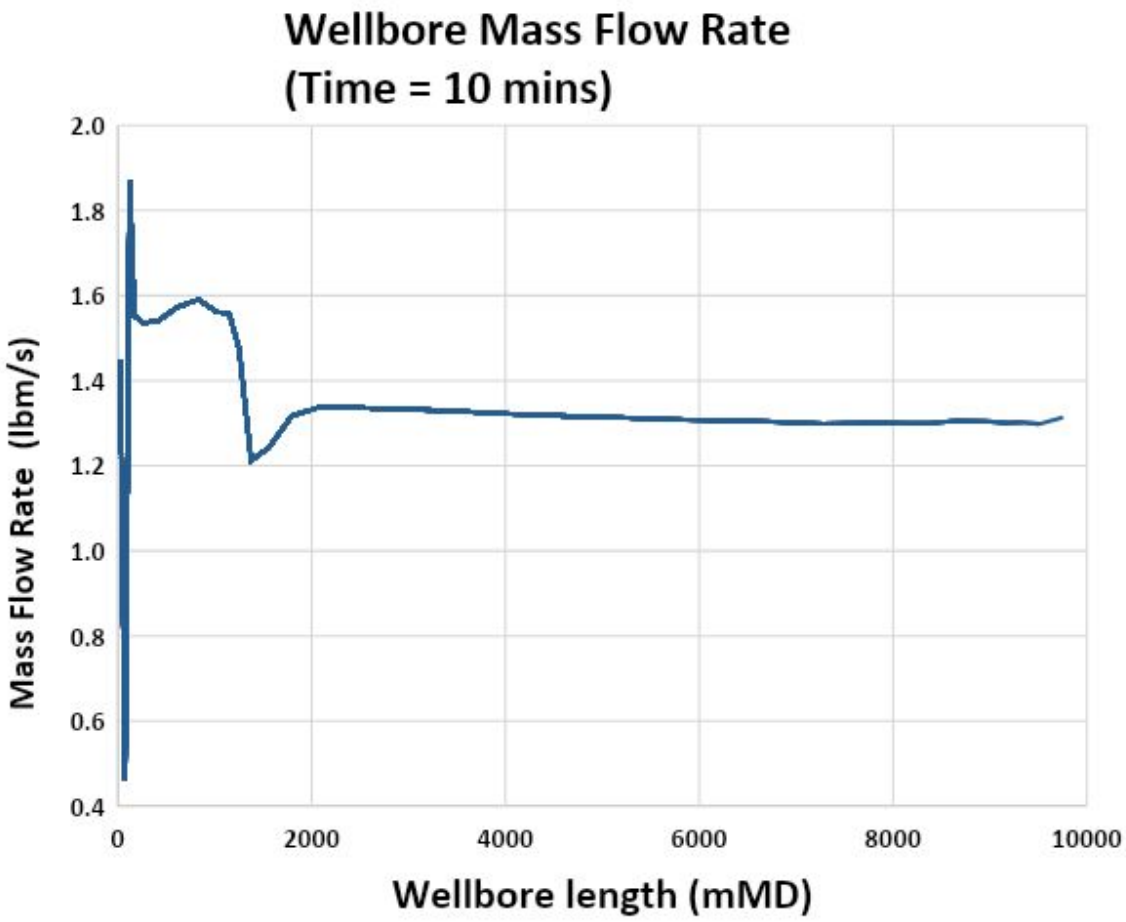
Simulation of Well Restart: Temperature Profile

- Start from shut-in well
- Distinct slug of COLD dense fluid in the upper wellbore
- Mass accumulation means upper zone is being charged with cold mass
- Original of static fluid is travels faster than newly injected volume
- Early transient phase does not allow time for heat gain
- Distinct fluid boundary is maintained for most of the Restart period

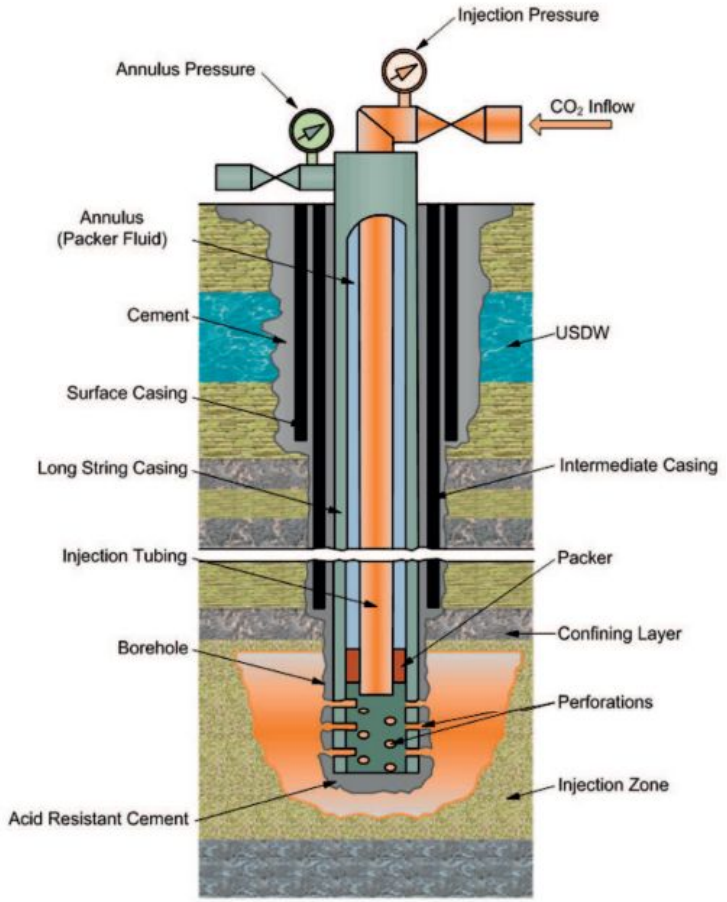


Simulation of Well Restart (or Start-up)





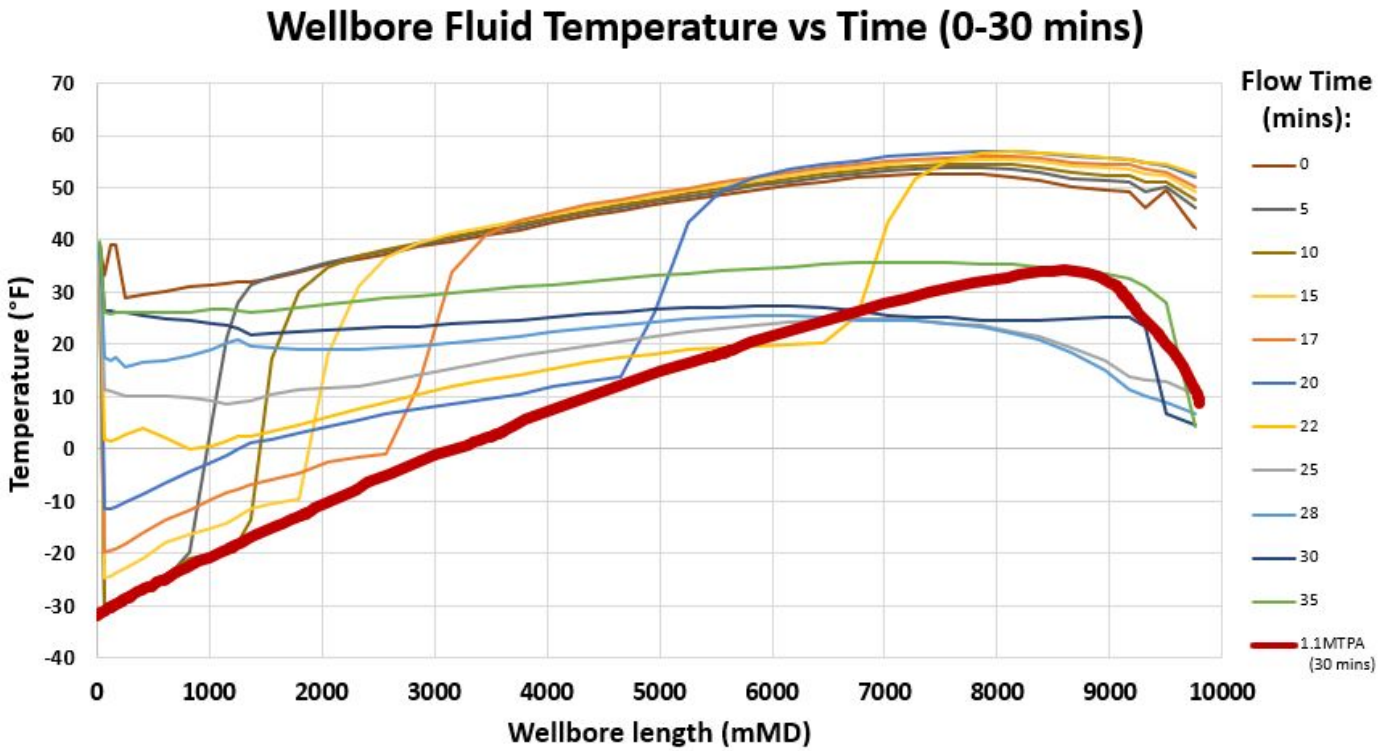
Tubular Design Considerations for CCS wells



- Cold loads → tension increase in tubing & casing strings
- Collapse loads dominate tubing/completion at early injection stage (e.g., depleted reservoir) → Tensile + Collapse
- Rapid change in temperature over short length of time can cause thermal shock – CO_2 injection restart after shut-in
- Fatigue issues due to cyclic loads
- Frictional contact in the wellbore may localize load effects
- Long term integrity → highest pressure load occurs at end of sequestration phase (reservoir re-charge) when tubing and casings strings might have suffered from wall reduction

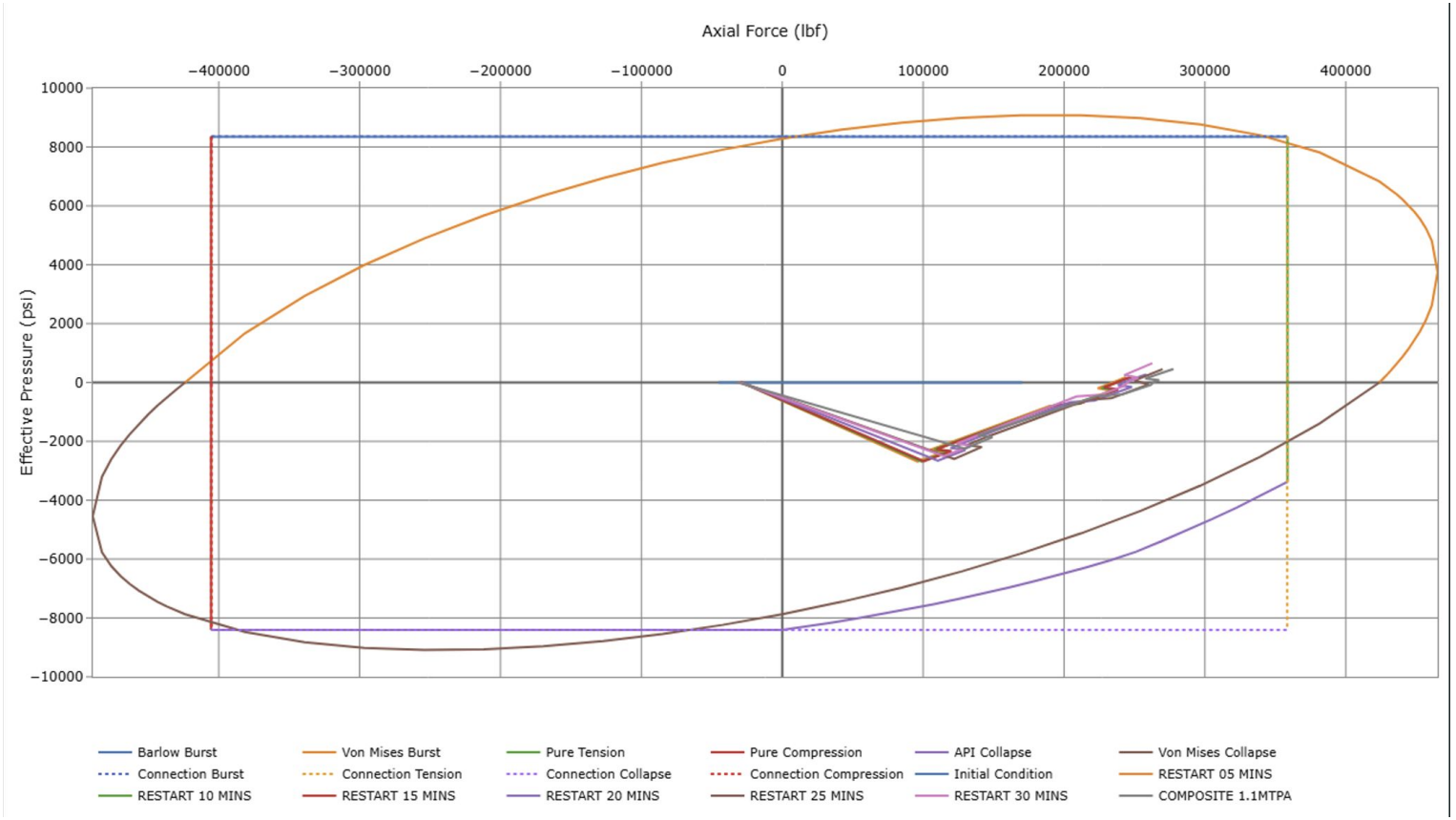
Simulation of Well Restart: Proxy Profile

- Detailed Restart simulations imported to tubing loads
- These simulations entail some computational burden
- Alternative analysis may use proxy operation w flow rate
- Assume worst WHT & BHP
- <u>Key design issues:</u>
  - Extreme temperatures (-40°F)
  - Localized to upper wellbore
  - Transient nature (30 minutes)



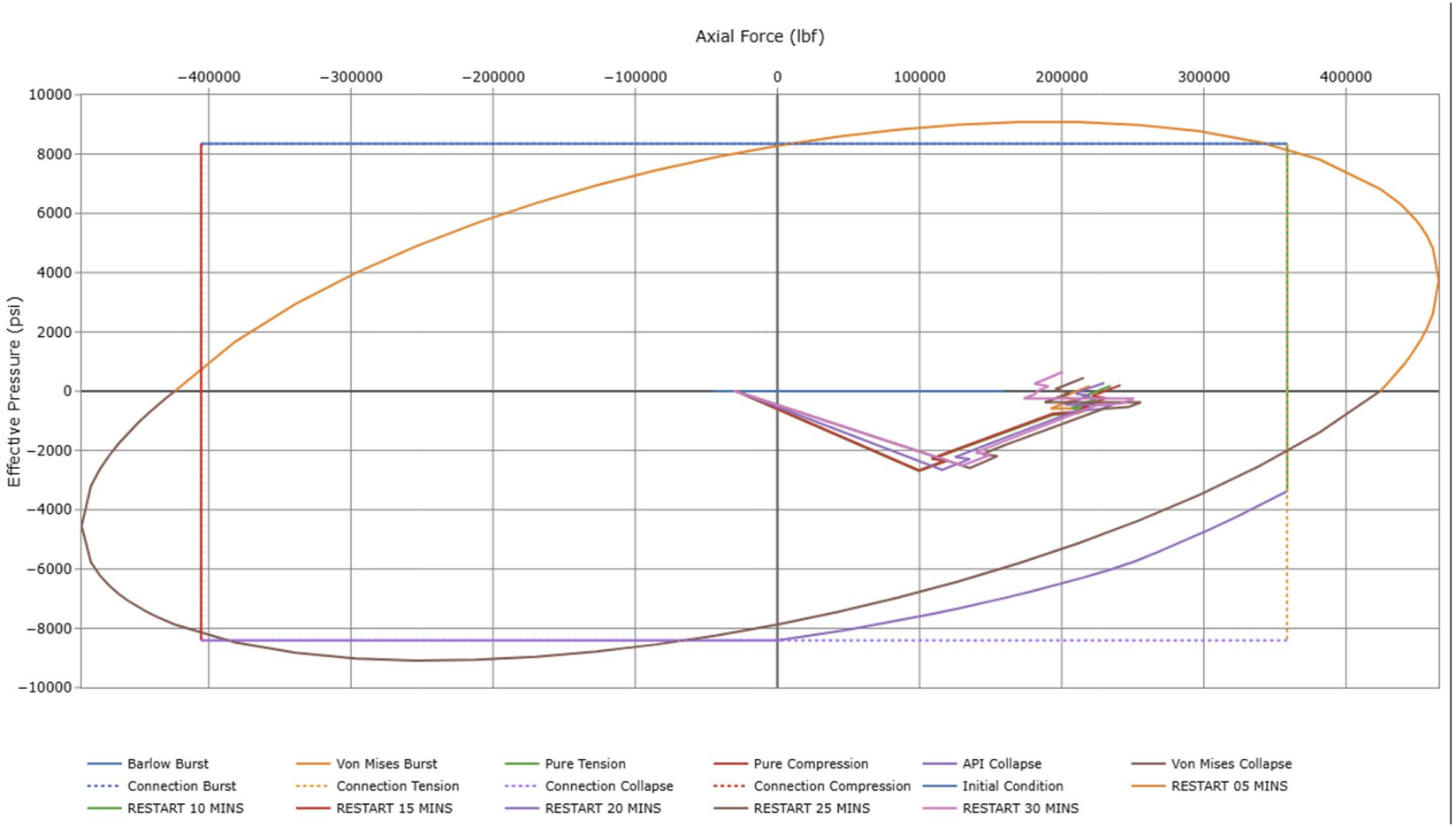
Tubing Completion Analysis: Well Restart Loads

- Tensile loads from cold temps
- Collapse loads due to the low internal pressures
- Overall loading conditions are within Design Envelope
- Worst-case COMPOSITE Restart load also included
- Example is based on 80 ksi yield strength tubular grade
- **Perhaps design concerns for operation conditions related to Restart are <u>exaggerated</u>?**



Tubing Completion Analysis: Restart Load w/ Friction

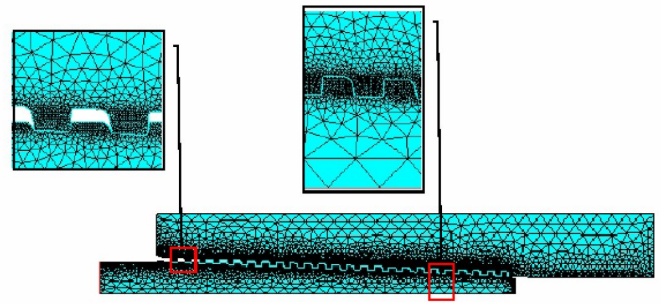
- Standard tubular analysis generally ignores friction
- Without friction axial loads are free to “redistribute”
- Localized Friction rom running, temperature effects…
- References: SPE-178905-MS - SPE-191640-PA
- Temporary Hydrate Plug??
- Friction assumptions here only make loads <u>marginally</u> worse



Potential Off-Design Modes of Failure?

- Cyclic Fatigue due to repeated Restart operations?
- Connections may be subject to cyclic fatigue?
  - Stress Concentration Factor (SCF) – e.g. BTC, SCF = 5

Fatigue Life Prediction of a BTC Exposed to Large Temperature Variations
Teodoriu & Falcone (2008)



- Thermal Shock – rapid temperature changes Cracking?
- Metallurgy - change in material behavior from Ductile to Brittle?
- Fluid Induced Vibration (FIV) – flashing at choke during opening or operation? Unstable multiphase flow in wellbore?

Conclusions and Observations

- Transient simulations of Restart require full nodal analysis
- Early transient stages involve mass accumulation
- Typically considered in Pipeline/Flow Assurance models but not in Wellbore Thermal and Stress Models
- Restart load conditions are characterized by:
  - Localized extreme cold zones near surface Tensile loads
  - Low internal pressure for depleted gas reservoirs Collapse Loads
- Loads may appear marginal vis-à-vis Design Envelope
- However … non-standard load and design issues may be critical

Areas of Further Investigation

- Focus to address “off-design” or non-standard load conditions
- Localization of stress due to friction / blockages / etc.
- Impact of cyclic loads from repeated Start-up / Restart operations
- Cyclic loads and Stress Concentrations leading to Connection Failure
- High cycle fatigue due Fluid Induced Vibrations (multiphase flow)
- Thermal Shock affects vs Tradeoff with Choke Reliability
- Altered metallurgy related to Brittle versus Ductile failure mode
- Impact on completion: SSSV / Control Lines / Fluid rheology

Thanks to the Altus Well Experts CCUS Team and to Dr. Afif Halal for their contribution

and

Thank you all for your attention!

Questions?