



Two-phase or not two-phase: that is the question

Multidisciplinary approach to two-phase CCS injector well design

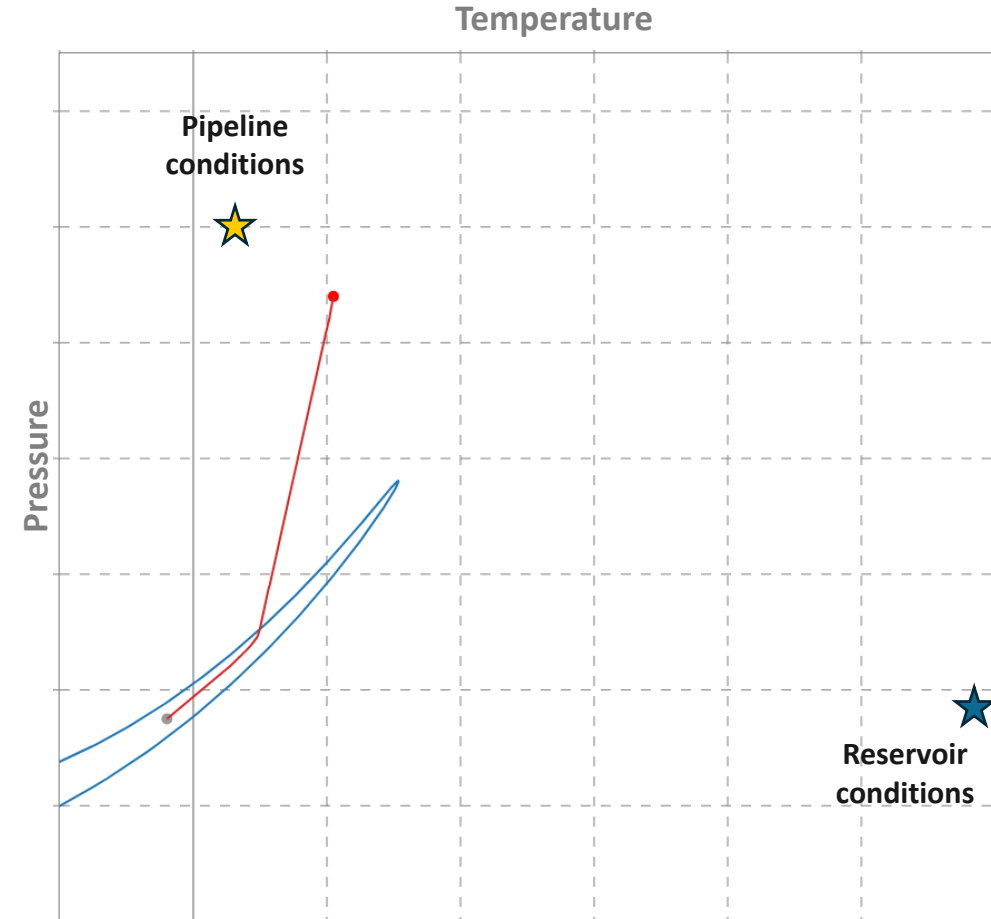
A. Belikov (Lead Well Engineer), R. Haddad (Lead Reservoir Engineer),
G. Sprega (Head of Storage Complex Management), *all Eni CCUS Netherlands*

CO₂ Storage Conference 2026
Aberdeen, United Kingdom
6–7 October 2026

Why two-phase happens — and why it matters



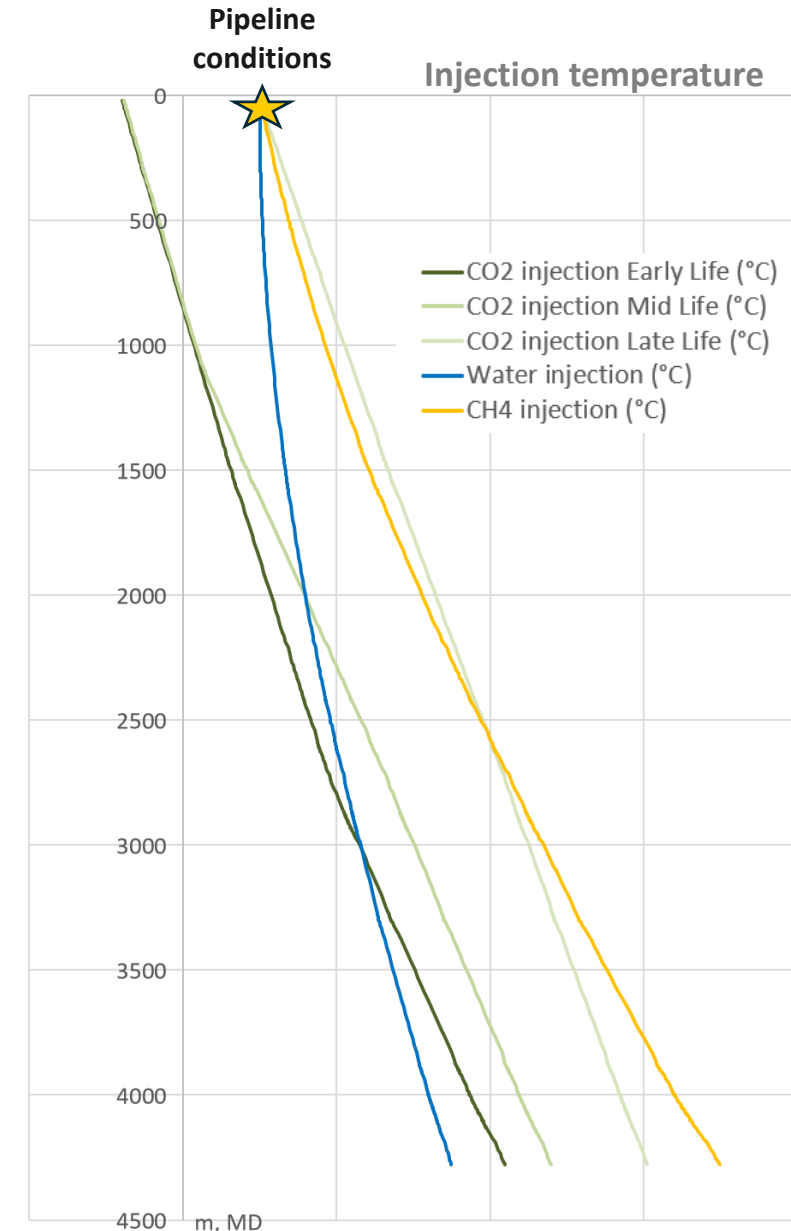
- **CCS economics are driven by injected mass rather than fluid volume.**
Maximizing tonnes stored while minimizing transport and compression costs is key
- **Depleted gas reservoirs provide attractive storage opportunities.**
However, their low Early-Life pressures often make two-phase conditions unavoidable
- **CO₂ phase continuously evolves** as pressure and temperature change from pipeline to reservoir.
- **The engineering challenge is not to avoid two-phase flow, but to define and validate the operating envelope around it**
- **Two phase flow inside the well is a feature, not a bug.**



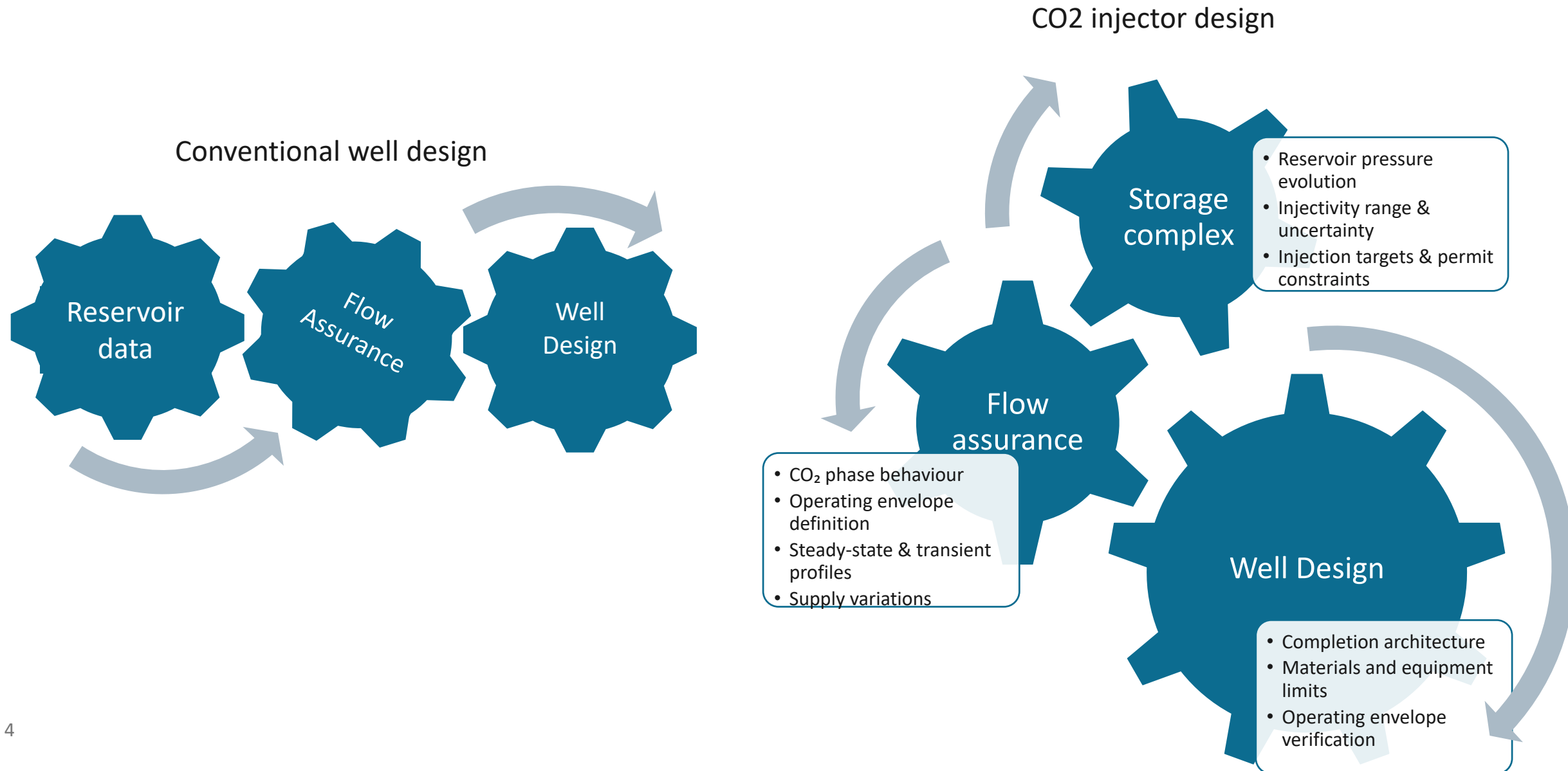
Same well architecture, different design drivers



	Conventional injector	CO ₂ injector in depleted reservoir
Fluid behaviour	Single phase assumption	Phase transition is part of normal operations
Thermal loads	Predictable profiles	Coupled with phase behaviour
Design envelope	Standard load cases based on standard set of inputs	Integrated multidiscipline workflow with iterations
	Steady State is usually most conservative case	Transients can be the governing cases
Lifecycle evolution	Well understood change in operating conditions over time	Strong dependency on reservoir pressure and injectivity evolution

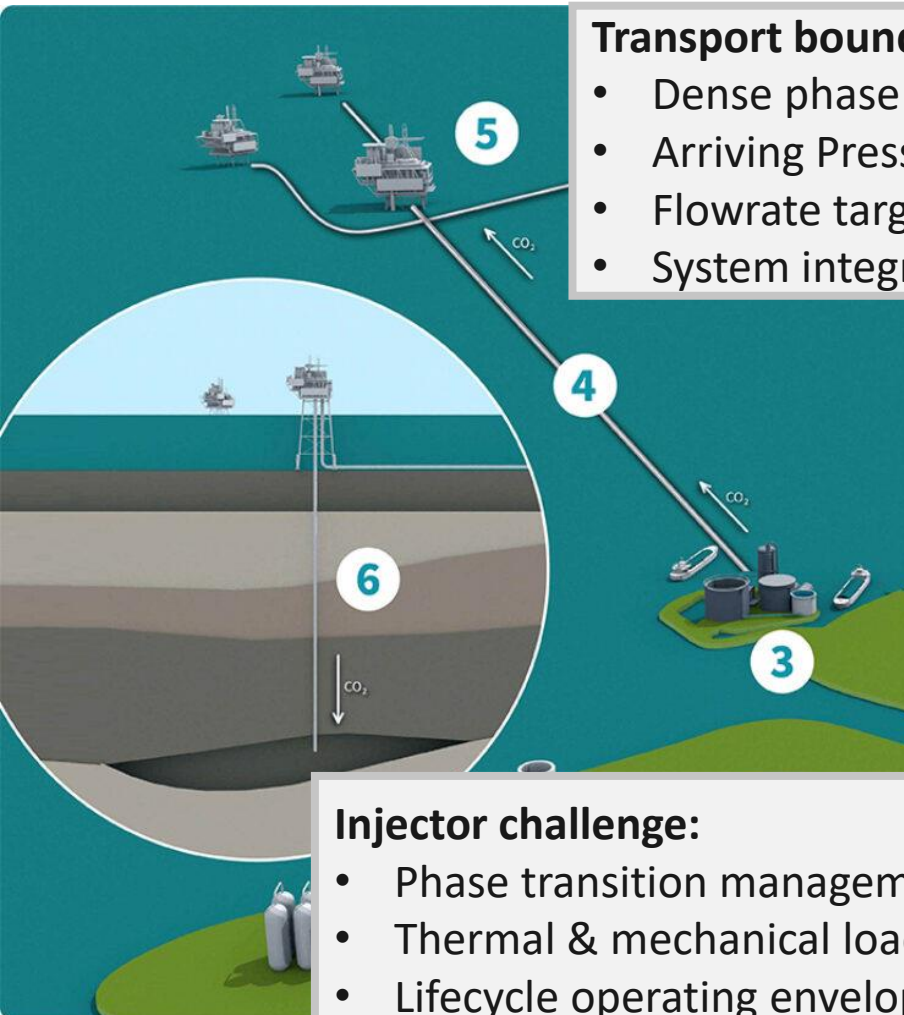


From fixed set of inputs to an integrated design loop





Case study: connecting dense-phase transport to depleted storage



Transport boundary:

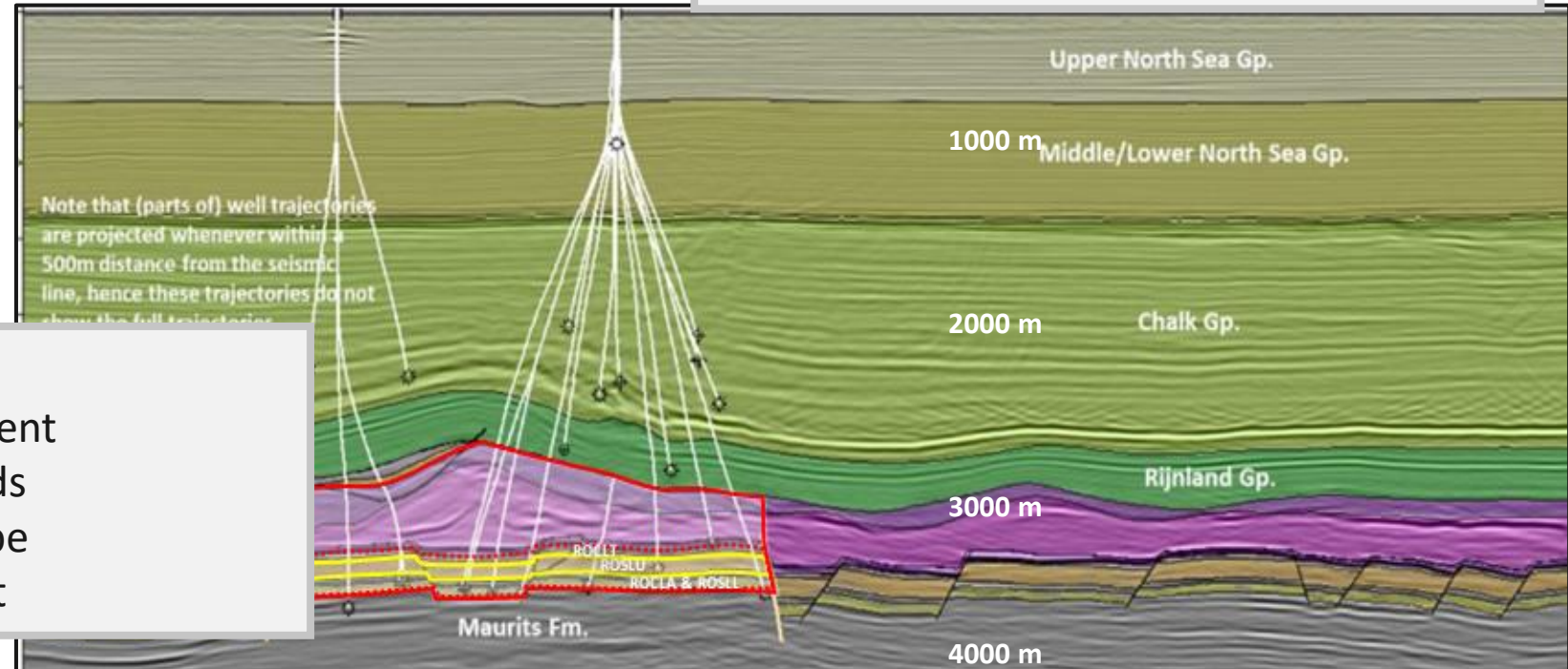
- Dense phase CO₂ supply
- Arriving Pressure and Temperature
- Flowrate targets and variations
- System integration

Storage boundary:

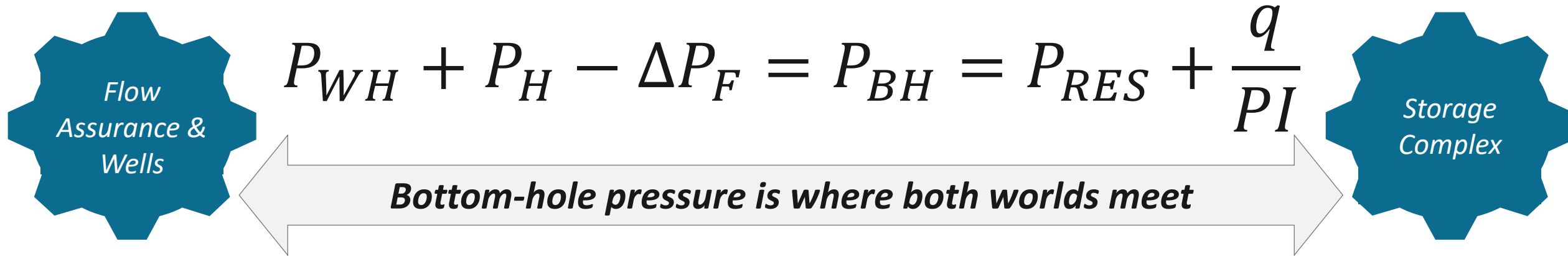
- Reservoir pressure evolution
- Injectivity uncertainty
- Capacity requirements
- Permit conditions compliance

Injector challenge:

- Phase transition management
- Thermal & mechanical loads
- Lifecycle operating envelope
- Well integrity management



Designing for an envelope, not a single point



Why do we design an operating envelope:

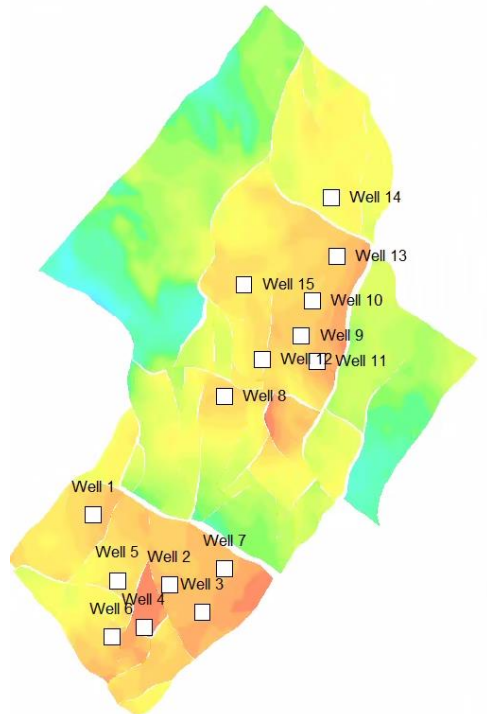
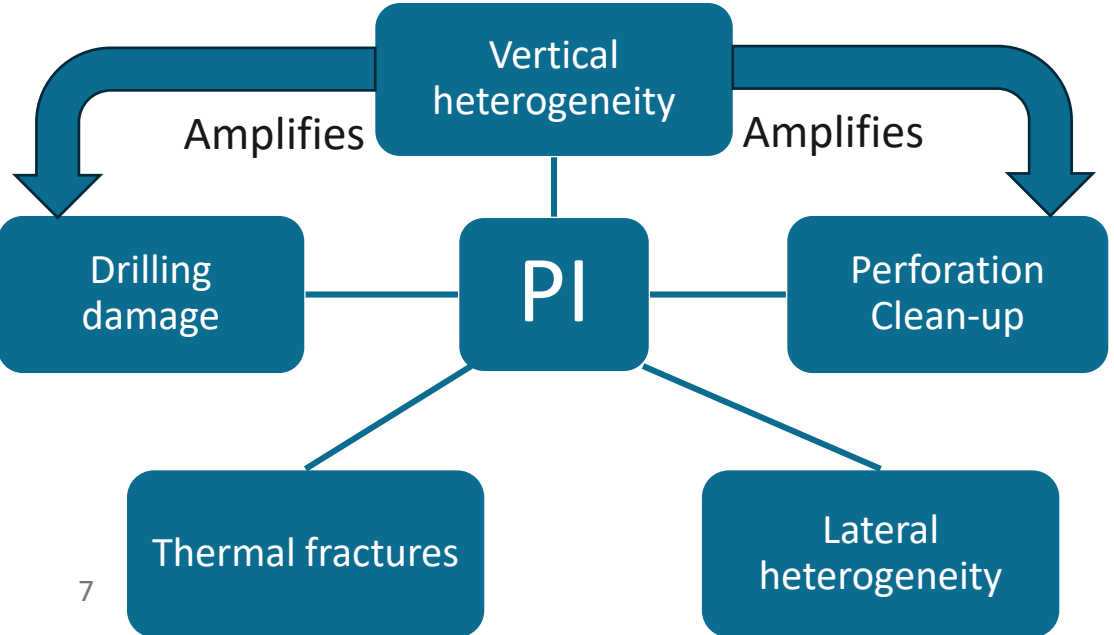
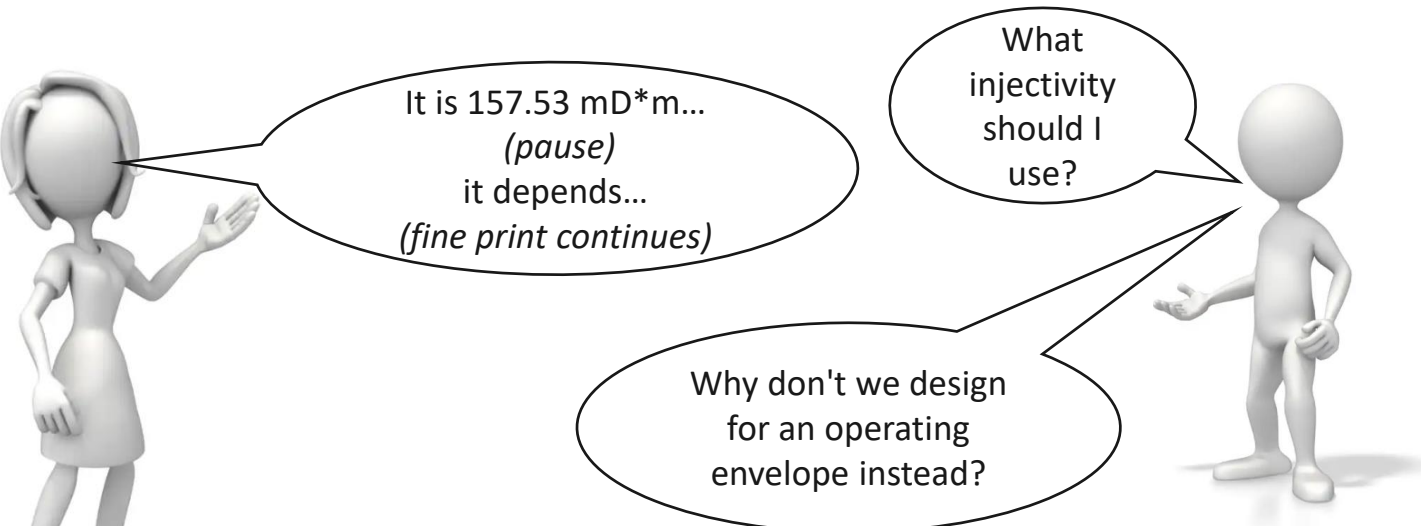
- Targeting a flexible Injection rate q to accommodate CO₂ supply variations and commercial agreements
- P_{WH} , P_H and ΔP_F vary with injection rate q and CO₂ phase behaviour
- P_{RES} evolves throughout the injection lifecycle (Early – Mid – Late Life)
- PI is uncertain and varies across the storage complex

P_{WH}	– Wellhead pressure
P_H	– Hydrostatic pressure
ΔP_F	– Friction pressure loss
P_{BH}	– Bottom-hole pressure
P_{RES}	– Reservoir pressure
PI	– Productivity (Injectivity) Index
q	– Injection rate

How do we design an operating envelope:

$$(P_{RES} \text{ EL, ML, LL}) \times (PI_{Low}, PI_{High}) \times (q_{min}, q_{max}) = 12 \text{ design cases}$$

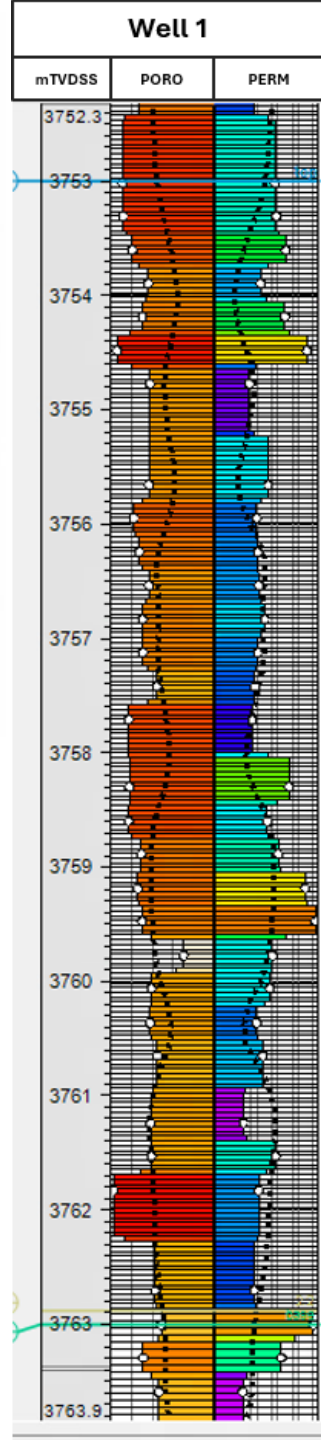
Injectivity: one number or uncertain reality?



Same storage reservoir:

Well #	KH effective	Well #	KH effective
01	233	08	110
02	157	09	180
03	138	10	91
04	147	11	123
05	198	12	315
06	142	13	275
07	49	14	240

~ 6x KH variation laterally,
and order of magnitude vertically

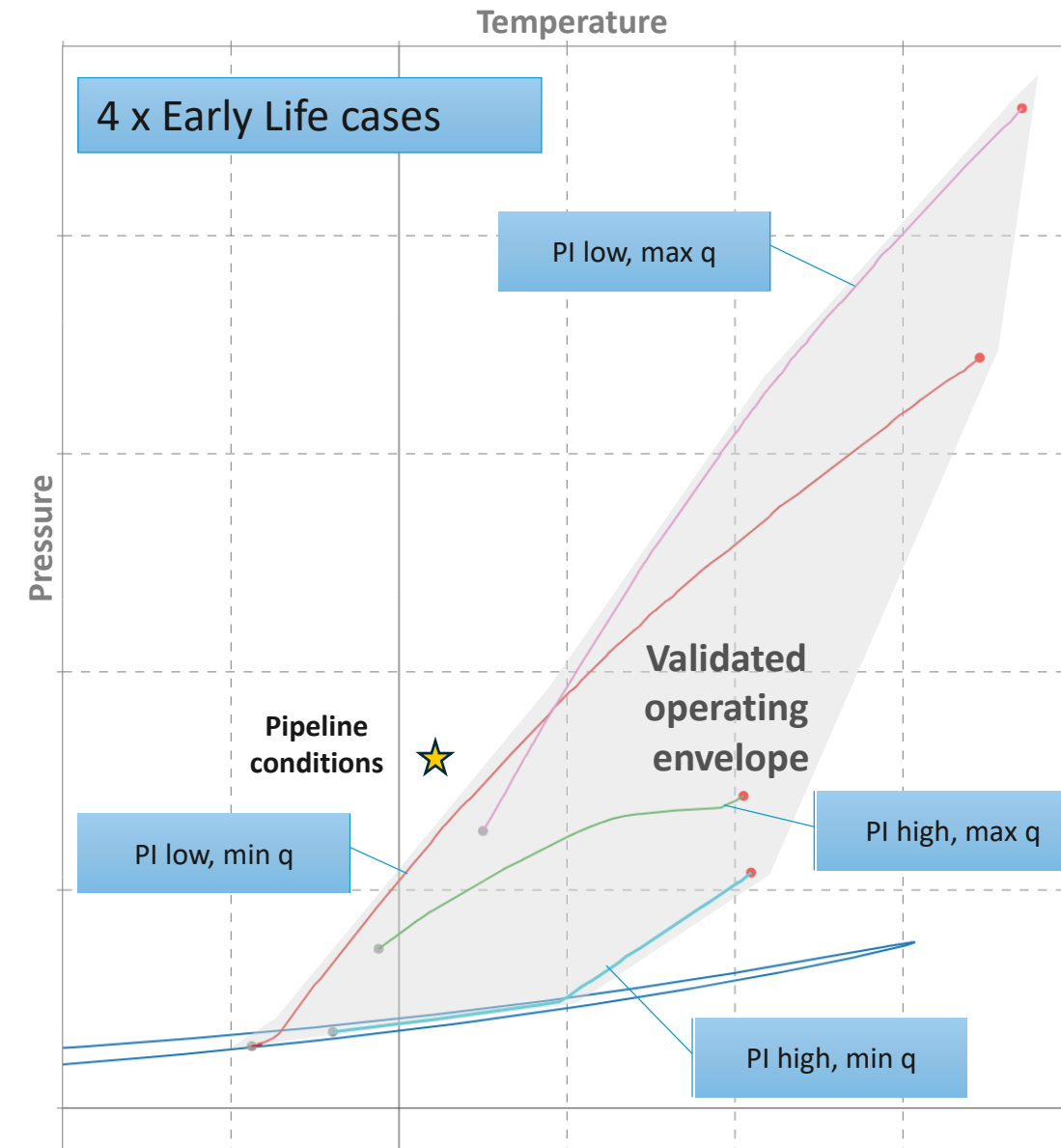


The answer: friction controlled two-phase injection



Key design principles

- **Two-phase flow is managed** – not eliminated
- **Tubing friction becomes a design instrument** rather than a hydraulic penalty
- **The four corner cases define the validated operating envelope** for each stage of injection lifecycle (Early, Mid, Late life).
- **Any operating condition within this validated envelope is acceptable.**
- **No universal design-driving case exists.** Different combinations of PI and injection rate govern different well sections and completion components.

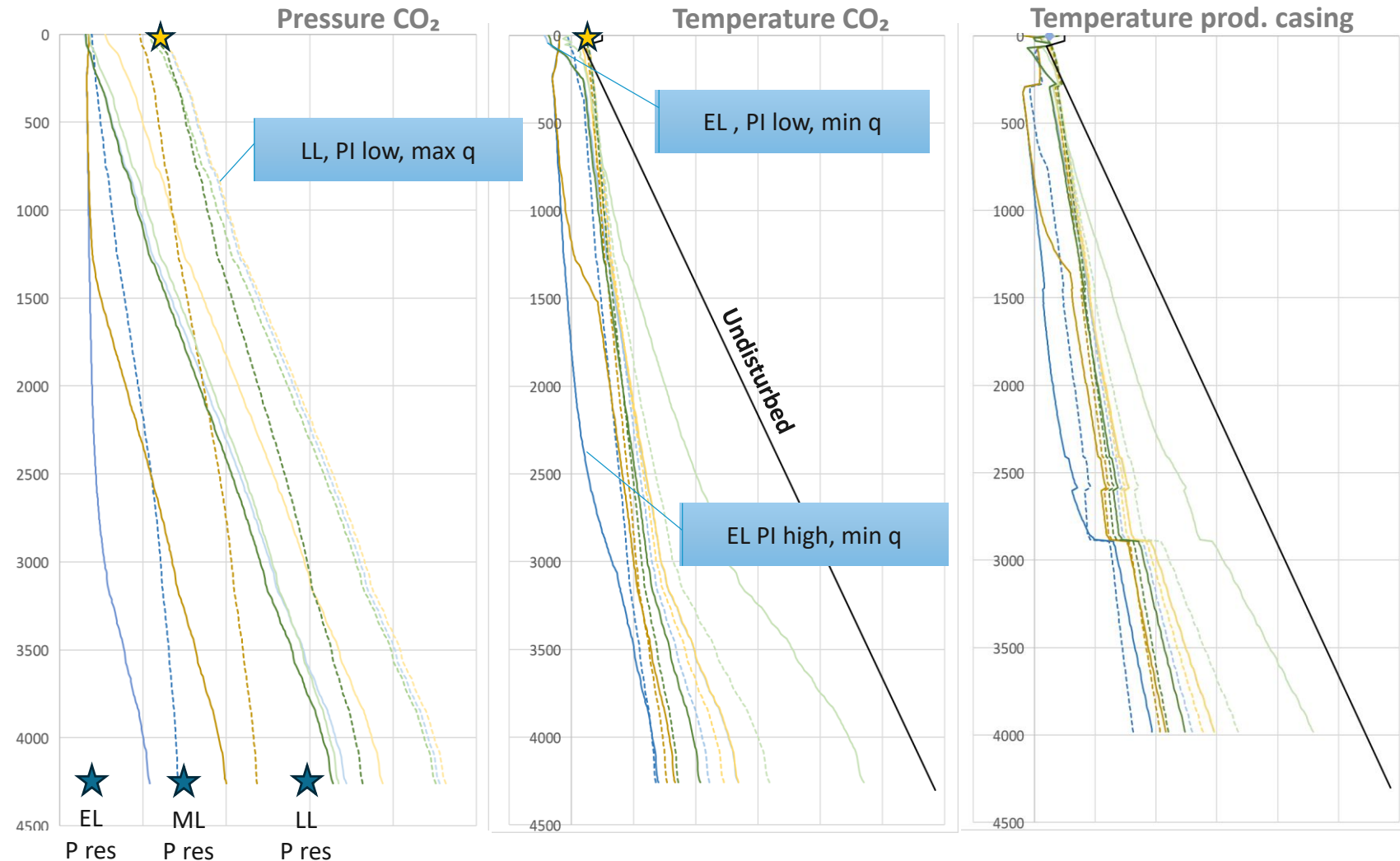


Steady State conditions – all 12 cases validated



Key validation findings

- In our project, Early Life defines the governing steady-state cases. As reservoir pressure builds up, temperature generally becomes less critical, while pressure constraints may become increasingly important.
- Validation requires project-specific acceptance criteria. For this case study, the external well temperature remained above 0°C under all representative steady-state cases.
- The selected completion provides sufficient hydraulic and thermal margin. All operating conditions remain within the validated operating envelope.



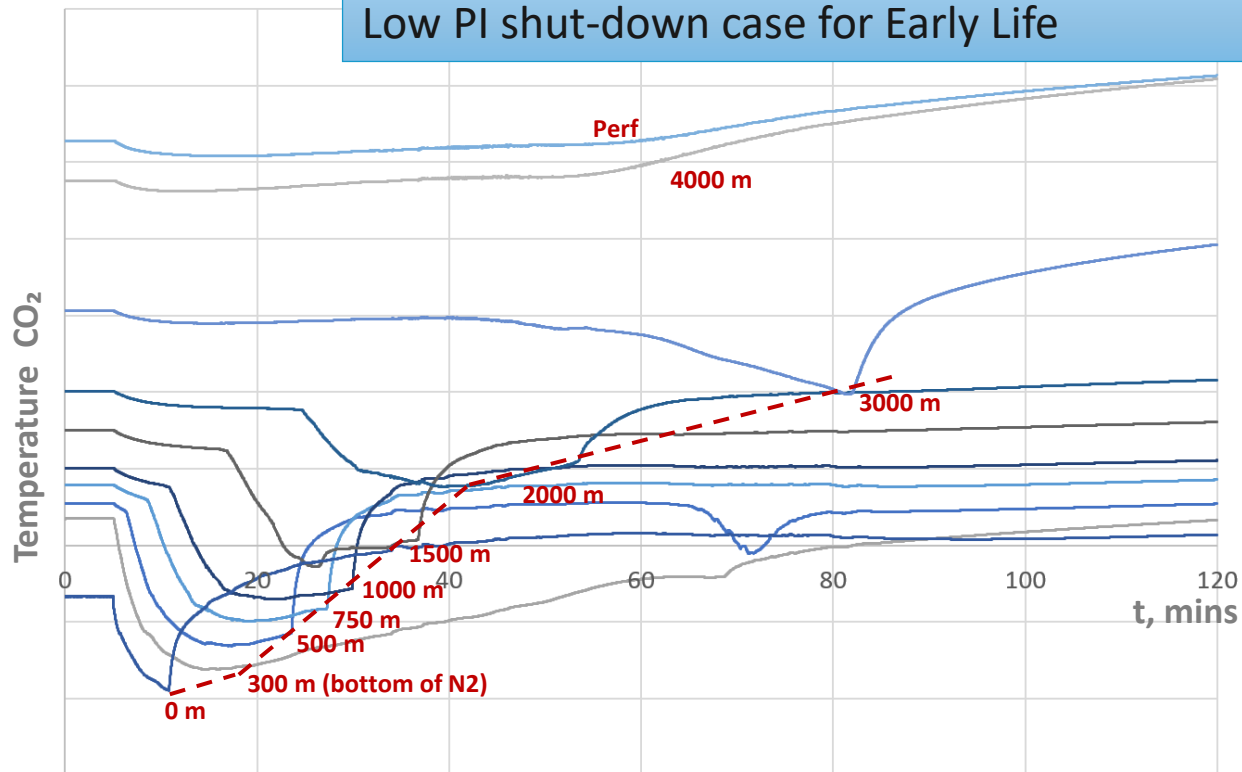
Shut-down: friction disappears, the reservoir doesn't



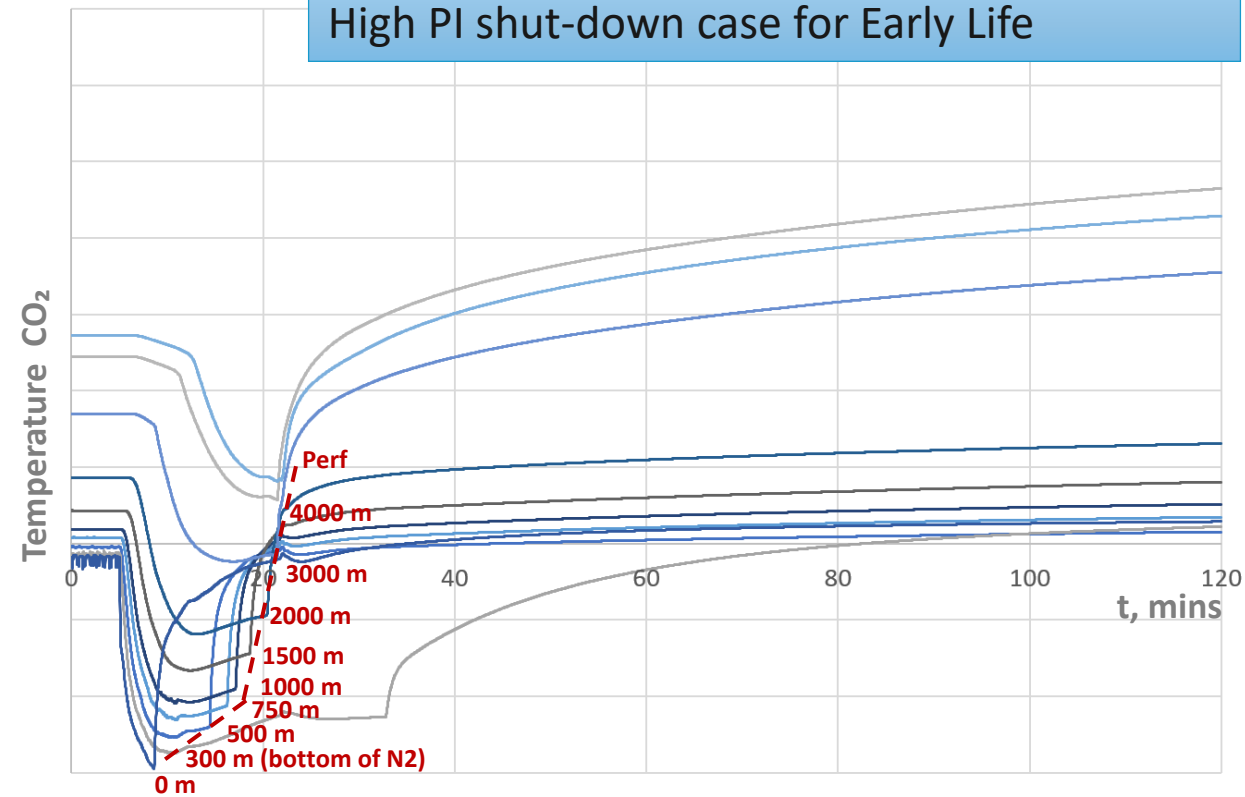
Key transient observations:

- **Tubing friction disappears immediately after shut-down.** Reservoir leak-off continues and is still controlled by injectivity
- **The flashing CO₂ front propagates differently for high and low injectivity.** The most severe transient case is therefore not obvious
- **Transient thermal response remains coupled to the reservoir.** The governing shut-down case must therefore be identified through integrated well–reservoir modelling

Low PI shut-down case for Early Life



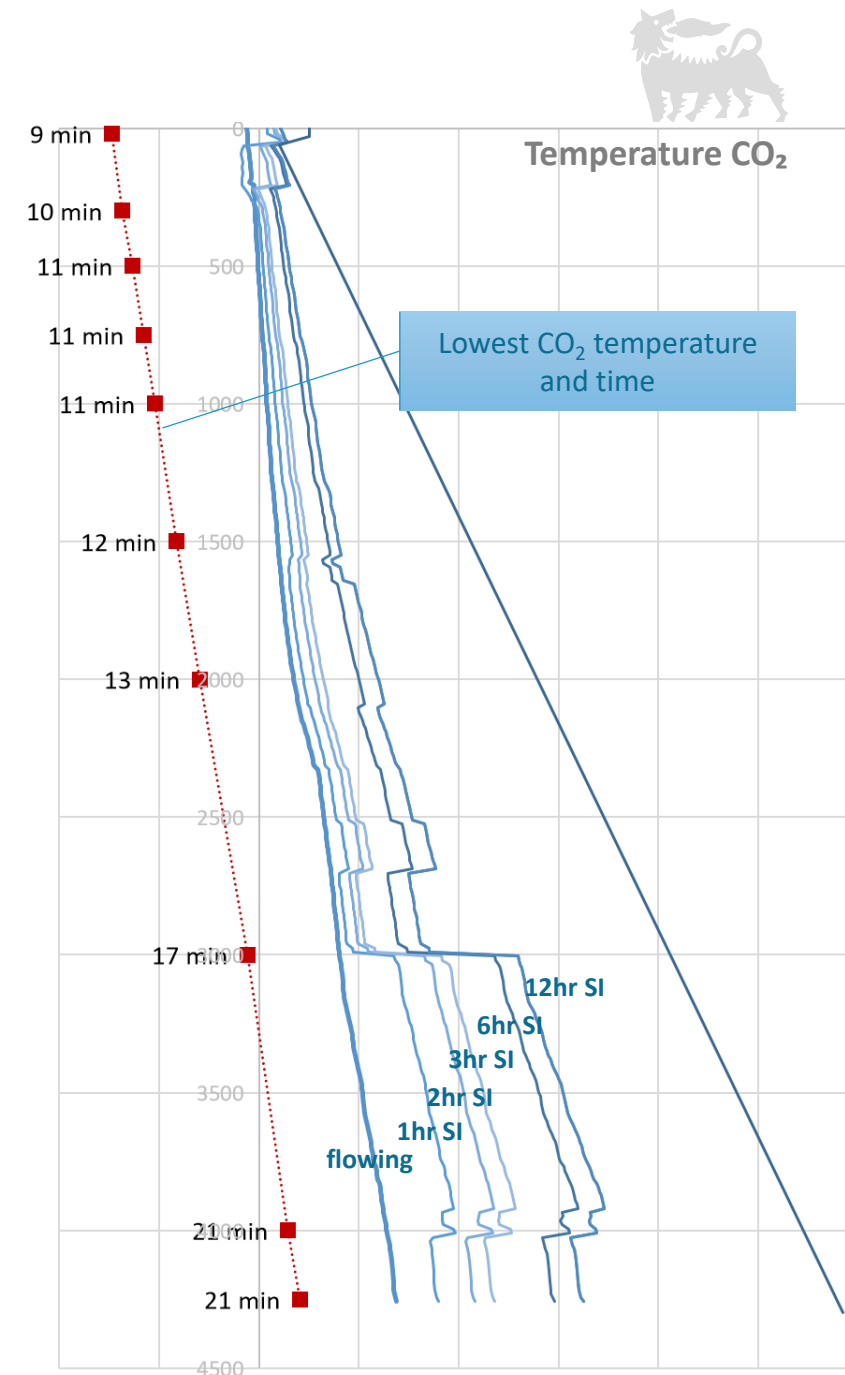
High PI shut-down case for Early Life



Warm-back: beyond heat transfer

Key engineering insights

- **Conventional shut-down models often assume mass preservation after shut-down.** For CO₂ injectors, reservoir leak-off continues and dictates the transient thermal response
- **Steady-state no longer guarantees the worst thermal loading.** Transient conditions may govern the stress analysis
- **For this case study, the governing transient case was the Early-Life shut-down at high injectivity.** Other CCS projects may instead be governed by restart, lower injectivity, or different operating conditions
- **The governing thermal load is distributed in both space and time.** Different completion components reach their minimum temperatures at different stages of the transient
- **Thermal design becomes a search problem.** The governing transient case cannot be assumed – it must be identified through project-specific coupled well–reservoir modelling

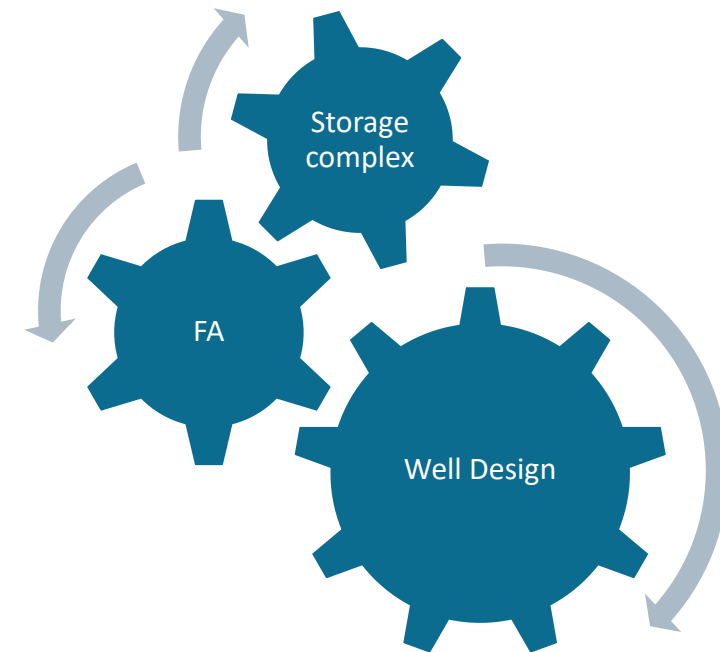




Beyond the case study: transferable engineering principles

The developed multidisciplinary workflow is transferable:

- **Every CCS project has its own dominant uncertainties.** The objective is to identify the variables that define the operating envelope – not to assume them
- **For this case study, injectivity range was the primary design driver.** In other projects, the governing uncertainty may be reservoir pressure evolution, CO₂ supply flexibility, EoS due to level of impurities, transport conditions, or facility limitations
- **The workflow remains the same, even when the governing variables change.** The operating envelope should always be built around project-specific uncertainties
- **The governing design cases are not an input to workflow, but the outcome of it**
- **Robust well design starts with multidisciplinary collaboration.** Reservoir, flow assurance and well engineering must converge on a common operating envelope before finalizing the well design





Two-phase or not two-phase, that is the question

Our answer – yes, two-phase, if uncertainty is engineered into the design!

Thank you!