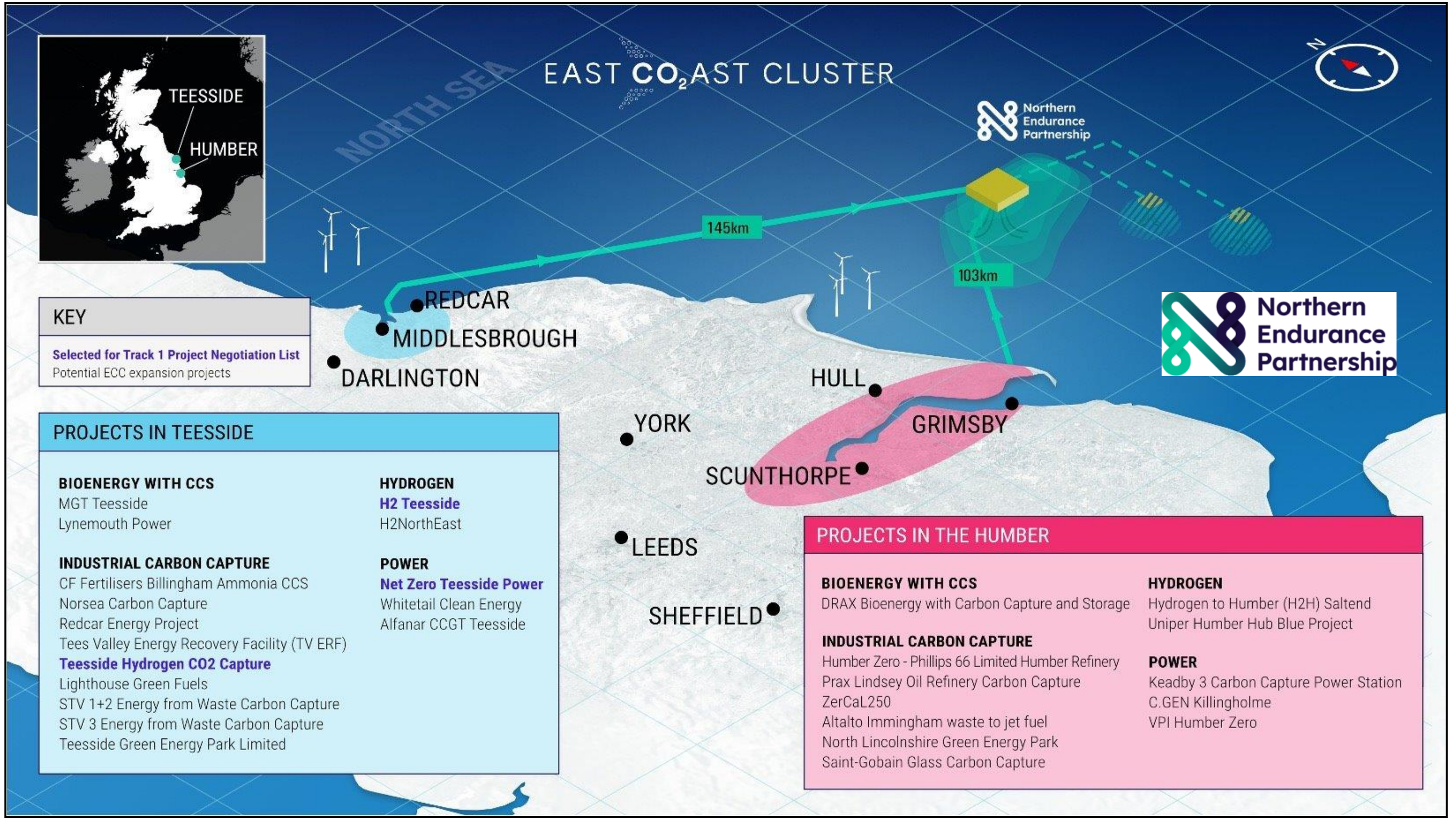
Repeated Cycling on a Carbon Capture Storage Well: How to Simulate Fatigue Stresses in Cement?

Emmanuel Therond, Curt Jones, Russell Haley, BP

Northern Endurance Partnership

Introduction to the Northern Endurance Partnership (NEP)



NEP is an incorporated joint venture formed by **bp, Equinor and Total**.

It provides the infrastructure needed to transport CO_2 from emitters on **Teesside** and in future, **Humberside**, to facilitate offshore storage in the North Sea.

Offers access to the **Endurance field** in the southern North Sea – the UK's largest appraised saline aquifer for carbon storage.

Further expansion is planned for nearby storage structures - to provide a total storage capacity **for 1 billion tons of CO_2.**

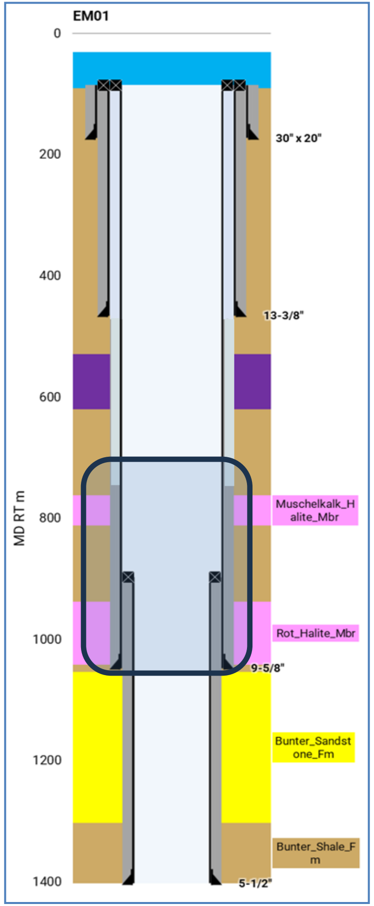
NEP Phase 1 is planned to inject **~4Mtpa CO_2** in 2028.

6 new wells spudding in H1 2026 – 5 CO_2 injectors and one monitoring well.

** 1 Mtpa ~52mmscf/d or ~25mbd water for supercritical CO_2*

NEP Well Design

Casing	Cement Design
30" Conductor	• Structural support • Cemented to the mudline
13-3/8" Casing	• Top of cement back to mudline.
9-5/8" Casing	• Shoe set in Rot clay. • TOC below the 13 3/8" casing shoe and at least to top of the Mushelkalk formation.
7" x 5 ½" Liner	• TOL placement back to above Rot Halite top: dual concentric cemented casing strings across the Rot Halite. • Cement to TOL • Consideration of Thermal & Mechanical cycling fatigue failure – In service of **dispatchable** power



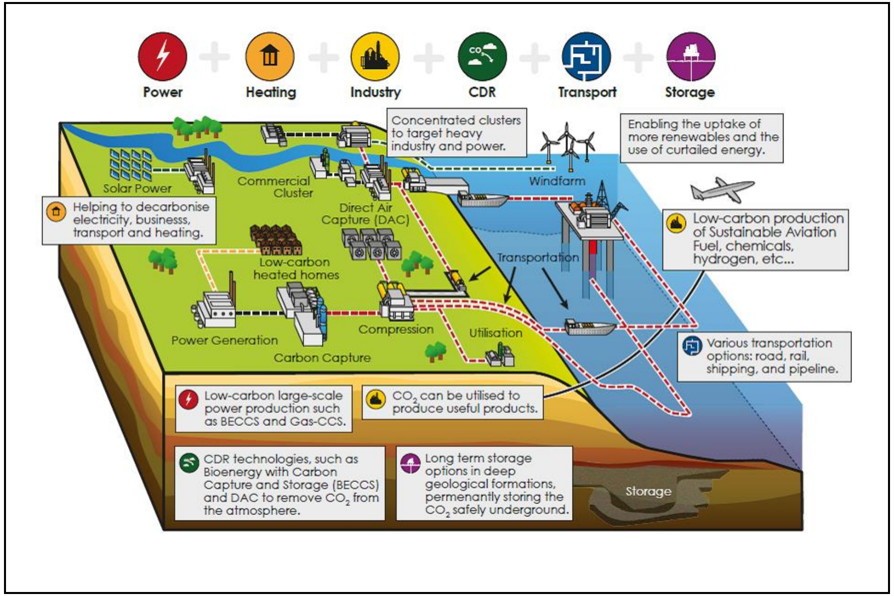
Dispatchability

Term for Bringing on Generators to Meet Grid Demand

- Integrated with UK power market - hierarchy of generators – greenest first
- NZT-NEP CCGT power station effectively fills the gap between supply and demand with renewables on a cloudy, still day
- Process plant design for dispatchability a first

Well Design for Dispatchability

- Well cycling common: Water injection wells (P&T cycling), Gas storage wells (P&T cycling)
- Failures in cement occur in first few cycles if they do at. e.g. JPT paper* of 6,062 wells, 7% leaked. For the wells that leaked, 90% occurred within the first 4 cycles
- Stress simulations and Water Injection project modelling** (134 cycles of 6000psi – no failure)

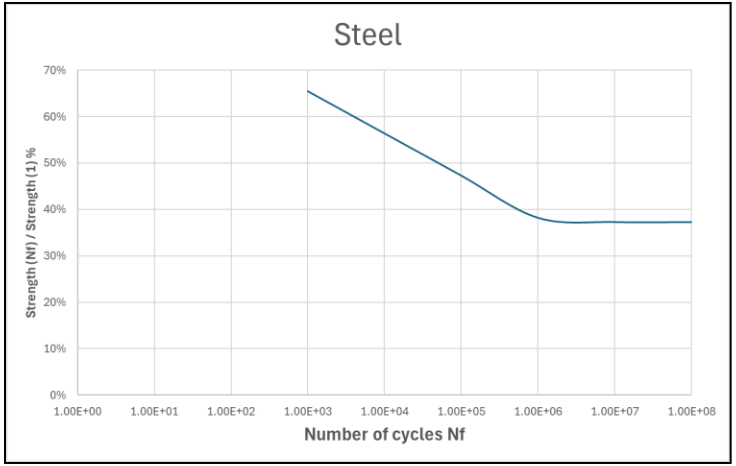


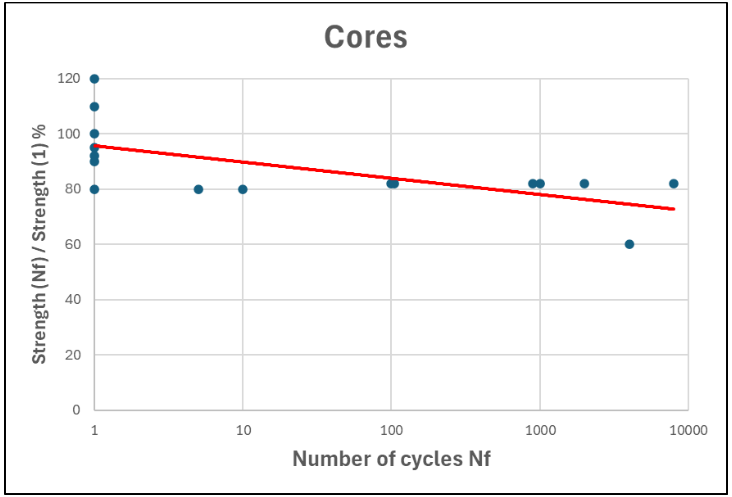
Source: UK Policy paper - Carbon Capture, Usage and Storage: a vision to establish a competitive market (2023)

** Journal of Petroleum Technology, Volume 41, Number 11, 1989, Cement Bonding Characteristics in Gas Wells, Roy S. Marlow*

*** SPE-181428: Large-scale testing and modelling for cement zonal isolation in water-injection wells*

Cycling Fatigue : S-N curves for Metal & Cement





S-N Curve for metal

Most failure of metals occur due to fatigue.

100 million cycles

Linear behaviour, then flat.

S-N Curve for cement

Study: Nordic Rock Mechanics Symposium: Fatigue of Rocks-2017-020 ISRM - Conference Paper – 2017.

10,000 cycles.

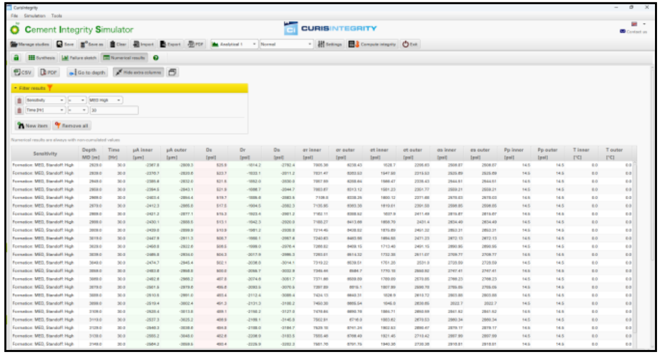
Is it a linear behaviour?

20% strength reduction after 2,00 cycles?

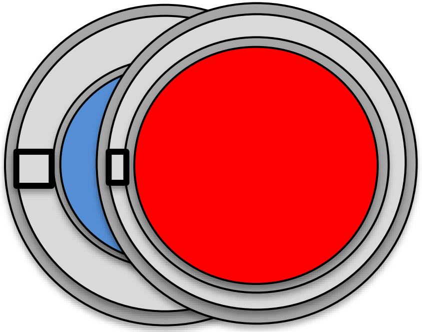
Step 1: Modeling Cement stresses in CCUS

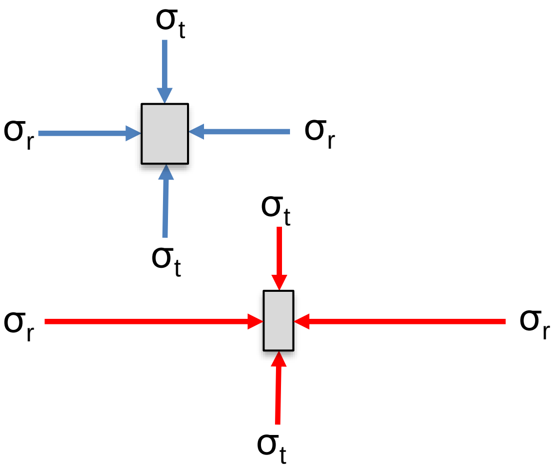
Cement Integrity Simulation: 5 1/2in x 9 5/8 in Annulus

- **Injection:** Cooling + Pressure increase
- **Stop Injection:** Heat up + Pressure decrease
- σ_r Radial Stress
- σ_t Tangential Stress
- Stresses are compressive (expanding agent in the cement)
- Modelling performed with BP Cement Integrity Simulator (CurisIntegrity)



Stress	Injection	Stop Injection	Δσ
$\sigma_{r\ (psi)}$	+1,056	+1,645	+589
$\sigma_{t\ (psi)}$	+2,662	+2,763	+101

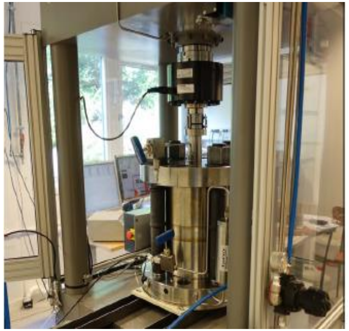




Step 2: Testing Cement fatigue in CCUS

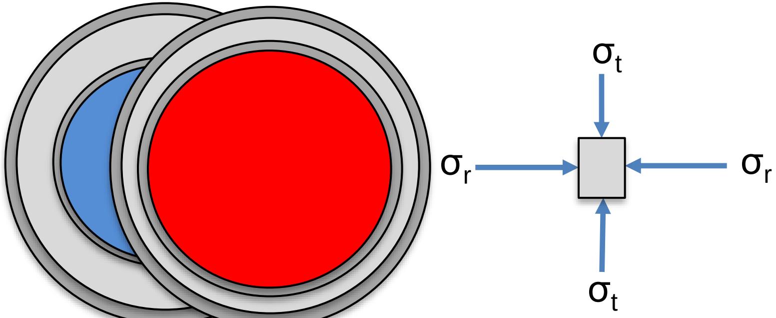
Modeling

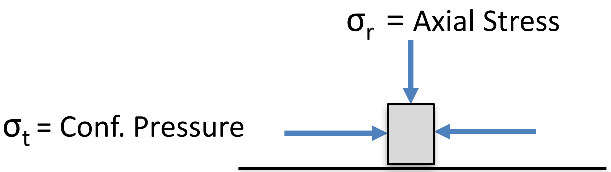
Stress	Injection	Stop Injection	Δσ
$\sigma_{r\ (psi)}$	+1,056	+1,645	+589
$\sigma_{t\ (psi)}$	+2,662	+2,763	+101



Testing

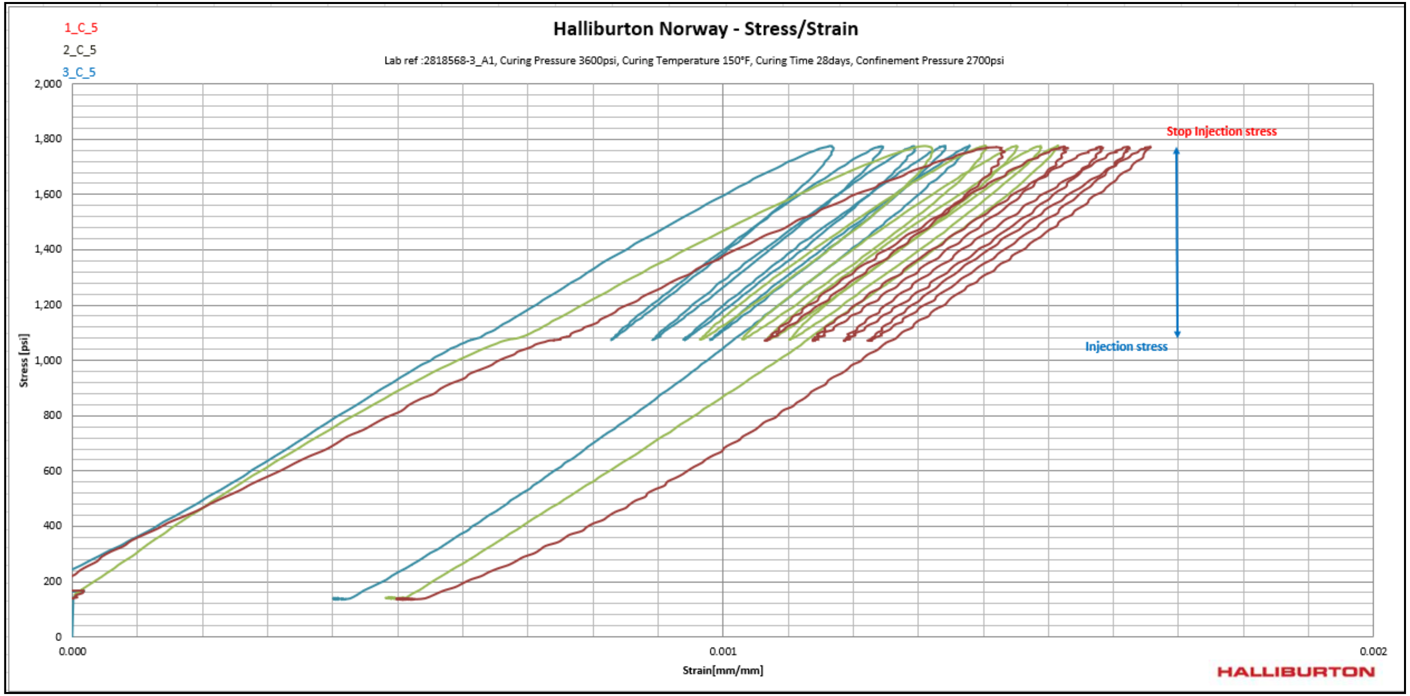
Cycling Test (2,000 times)	Injection	Stop Injection
Axial Stress (psi)	+1,000	+1,700
Confinement Pressure (psi)	+2,700	+2,700





Radial stress is treated as axial stress
Tangential stress is treated as confinement pressure

Compressive Cycling Results: Stress versus Axial Strain (5 cycles)



Cement sample is cycled 5 times from injection to no injection stress state under constant confinement pressure.

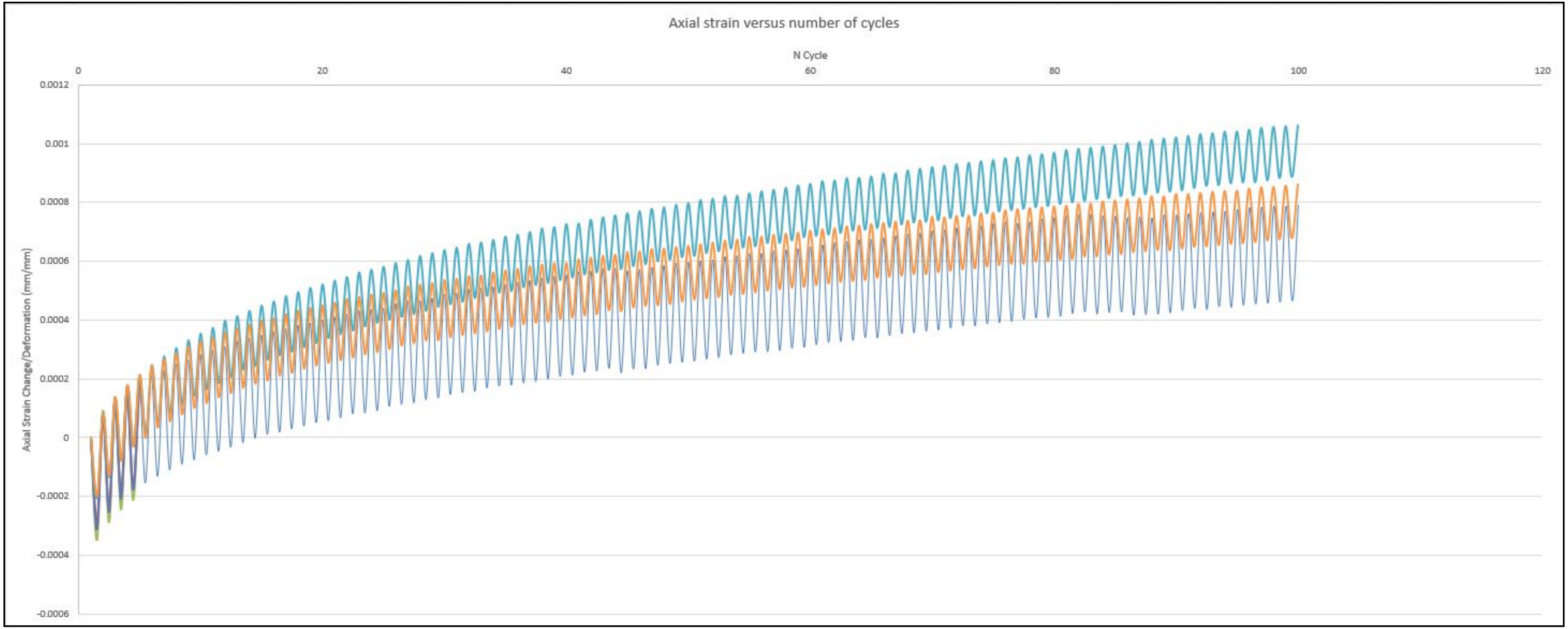
Hysteresis can be observed.

No yield or failure of the sample.

Test to be repeated for 100 and 2,000 cycles

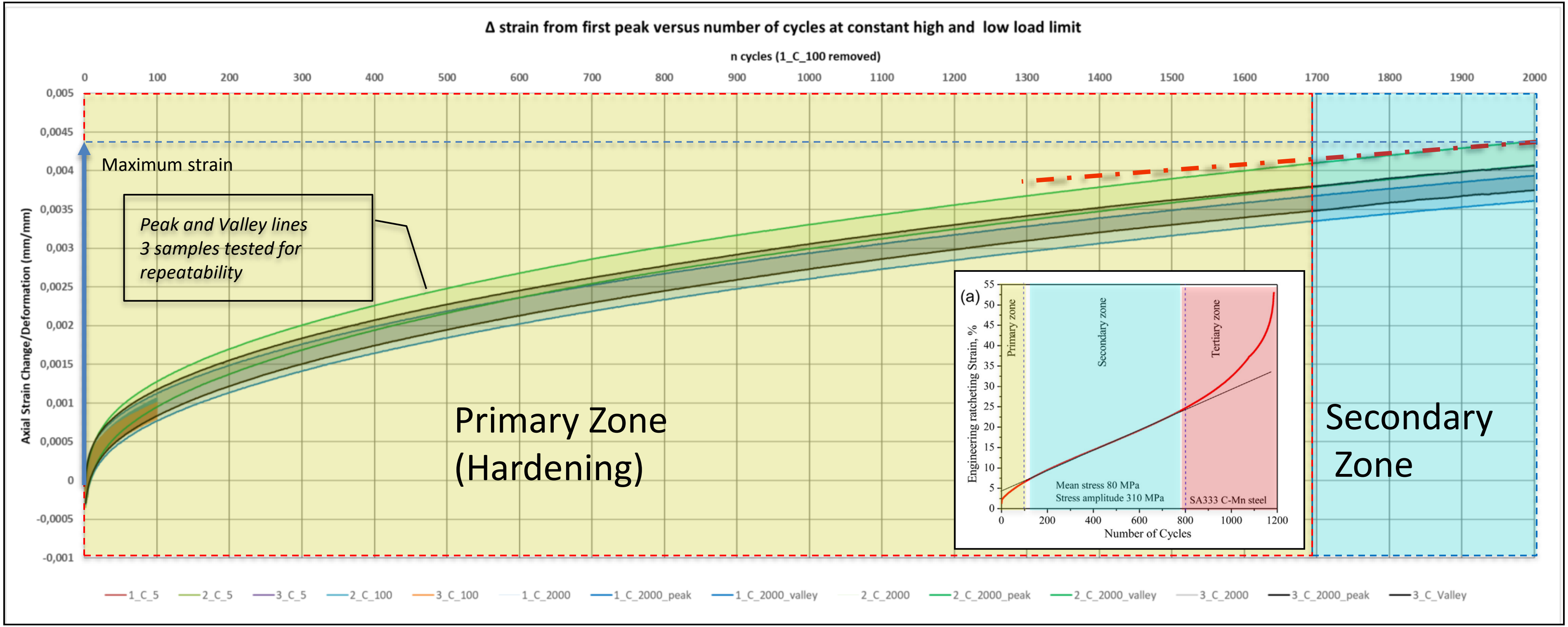
3 Samples per test

Compressive Cycling Results – Strain up to 100 cycles



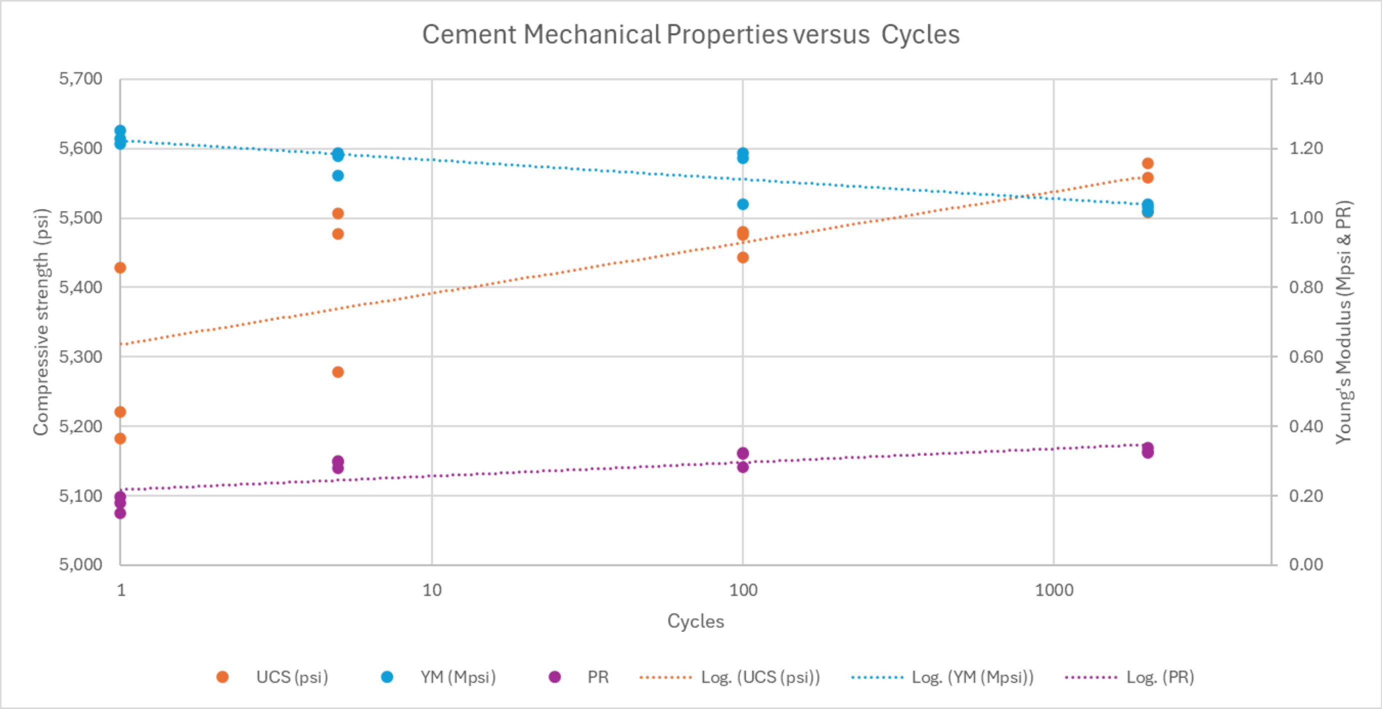
Peak and Valley
3 Samples per test

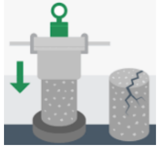
Compressive Cycling Results – Axial Strain up to 2,000 cycles

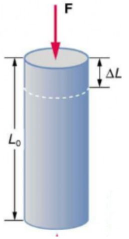


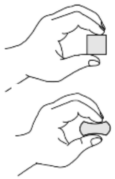
Cement sample is cycled 2,000 times from injection to no injection stress state under constant confinement pressure
Sample goes through the hardening zone and through the secondary zone after 1,700 cycles but never gets close to the softening (fatigue zone)
Maximum sample deformation after 2,000 cycles is 0.45%, equivalent to 171 µm for a 5.5 x 8.5 in cement width.

Mechanical Properties of cement after cycling









After 2,000 cycles

Compressive Strength
slightly increasing

Young's Modulus (E)
slightly decreasing

$$E = \frac{\sigma}{\varepsilon}$$

E = Young's modulus, pressure units
σ = uniaxial stress, or uniaxial force per unit surface, pressure units
ε = strain, or proportional deformation (change in length divided by original length), dimensionless

Poisson's Ratio (ν)
increasing, then stabilizing after 5 cycles.

$$v = -\frac{d\varepsilon_{trans}}{d\varepsilon_{axial}}$$

v = resulting Poisson's ratio
ε_{trans} = transverse strain
ε_{axial} = axial strain

No reduction of cement properties, no "fatigue" after 2,000 cycles.

Conclusions

- Very little research has been done on "cement fatigue" as most of the model available in the industry are "elastic".
- A new 2-step method has been developed to simulate and test stress cycling on a cemented annulus.
  - Calculation of stress in the cement annulus due to the pressure and the temperature changes when injecting CO2.
  - Testing stress cycling using a tri-axial compressional load machine to reproduce the on and off life of the well cycles up to 2,000 times.
- The results, using the conditions from the NEP CO2 injection schedule, show that the cement does not fail in fatigue, nor reaches the "softening zone", even after 2,000 cycles
- High confinement pressure and cycling causes creep axially and radially. The deformation of is small and will be compensated by formation overburden as well as cement expansion.

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Thank You / Questions

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