

Abandoned well leak rate models from analytical to CFD

DEVEX2025



Presenter:

Mike Byrne (Axis)

On behalf of Phil McCurdy (Axis)

Slide contents

- Why am I here??
- Leak rate model basics and Introduction
- Analytical leak rate models
- Analytical model example
- Numerical models example
- Wrap Up

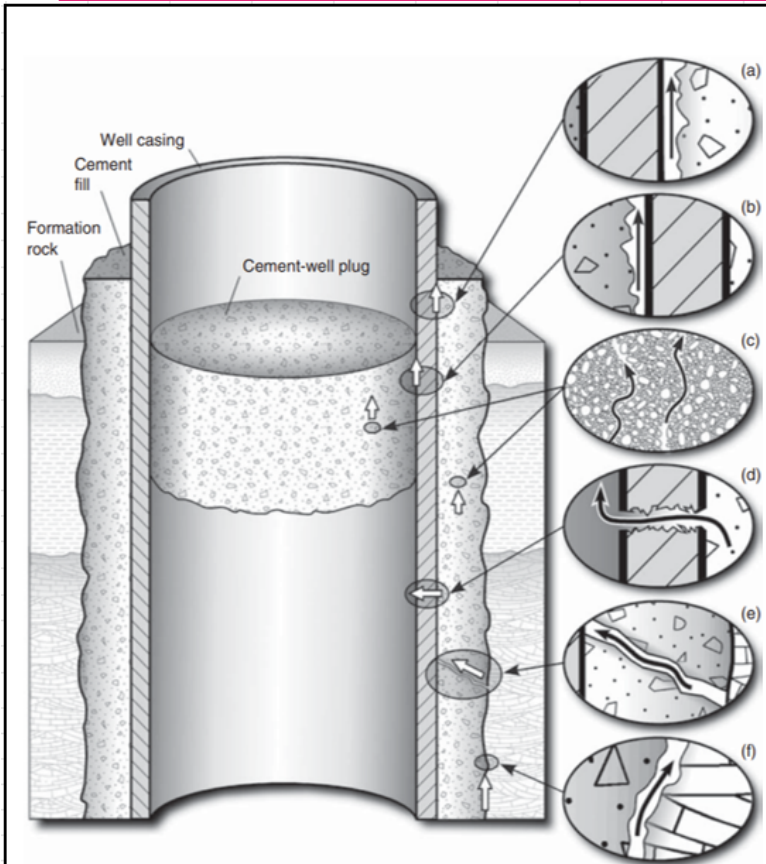
Why am I here??



Well leaks – what is the concern

- For well abandonment the general approach is to leave the abandoned field as it was found
- Leakage from wells is a concern from an abandonment perspective (long term shut in for hydrocarbon reservoirs)
- Increasingly a new challenge using shallower aquifer or re-using depleted reservoirs to store CO₂. This represents a massive opportunity for UKCS and beyond and several ongoing projects are (and more planned in future) reviewing this
- Field geological history often shows intact seals and low risk of fluid escape for pressure conditions back to original (or up to a certain limit in aquifers)
- Invariably it is the man made leak paths (e.g. local wellbores) that represent the most significant risk of containment loss
- This can be from legacy wells / sidetracks abandoned decades in the past which had not foreseen or planned for CO₂ scenarios
- Understanding possible leak paths and rates can be critical to CCS project viability

Analytical Well Leak Rates – Estimation/Methodology - Equations



Drawing: Different leakage pathways through an abandoned well (Gasda et al. 2004)

(c) Leakage Through Bulk Cement

$$Q = \left(\frac{kA}{\mu L} \right) \Delta P$$

A=	Cross section of the cement plug or the cemented annulus (m ²)
ΔP=	Pressure difference between bottom of cement and top of cement (Pa)
μ=	CO ₂ viscosity @ P & T (Pa.s)
L=	Length of the plug or annular cement (m)
k=	Permeability of the cement (m ²) - (Statistical)
Q=	CO ₂ volumetric flowrate (m ³ /s)

(e) Leakage Through Cracks

$$Q = \left(\frac{h^3 \cos \alpha}{12\mu} \right) \left(\frac{\Delta P}{L} \right) W$$

ΔP=	Pressure diff. between bottom of cement and top of cement (Pa)
μ=	CO ₂ viscosity @ P & T (Pa.s)
L=	Length of the plug or annular cement (m)
α=	Fracture orientation with respect to the overall pressure gradient axis that controls the flow (deg)
h=	Fracture aperture (m) - (Statistical)
W=	Fracture width (m) - (Statistical)
Q=	CO ₂ flowrate (m ³ /s)

(a,b & f) Leakage Through Microannuli

$$Q = \left(\frac{\pi R_c \Delta P}{6\mu L} \right) \delta R^3$$

R _c =	Casing radius (m)
ΔP=	Pressure difference between bottom of cement and top of cement (Pa)
μ=	CO ₂ viscosity @ P & T (Pa.s)
L=	Length of the plug or annular cement (m)
δR=	Microannuli gap (m) - (Statistical)
Q=	CO ₂ volumetric flowrate (m ³ /s)

(d) Leakage through the casing wall (not considered)

- Values in green are generally known / fixed input parameters
- values in yellow are harder to determine precisely – approach often applied is to use uniform-distributed random input parameters
- The outcome is the CO₂ volumetric leak rate in blue

Equations used for the estimation of the leak rates, for the bulk cement, cracks and microannuli (*)

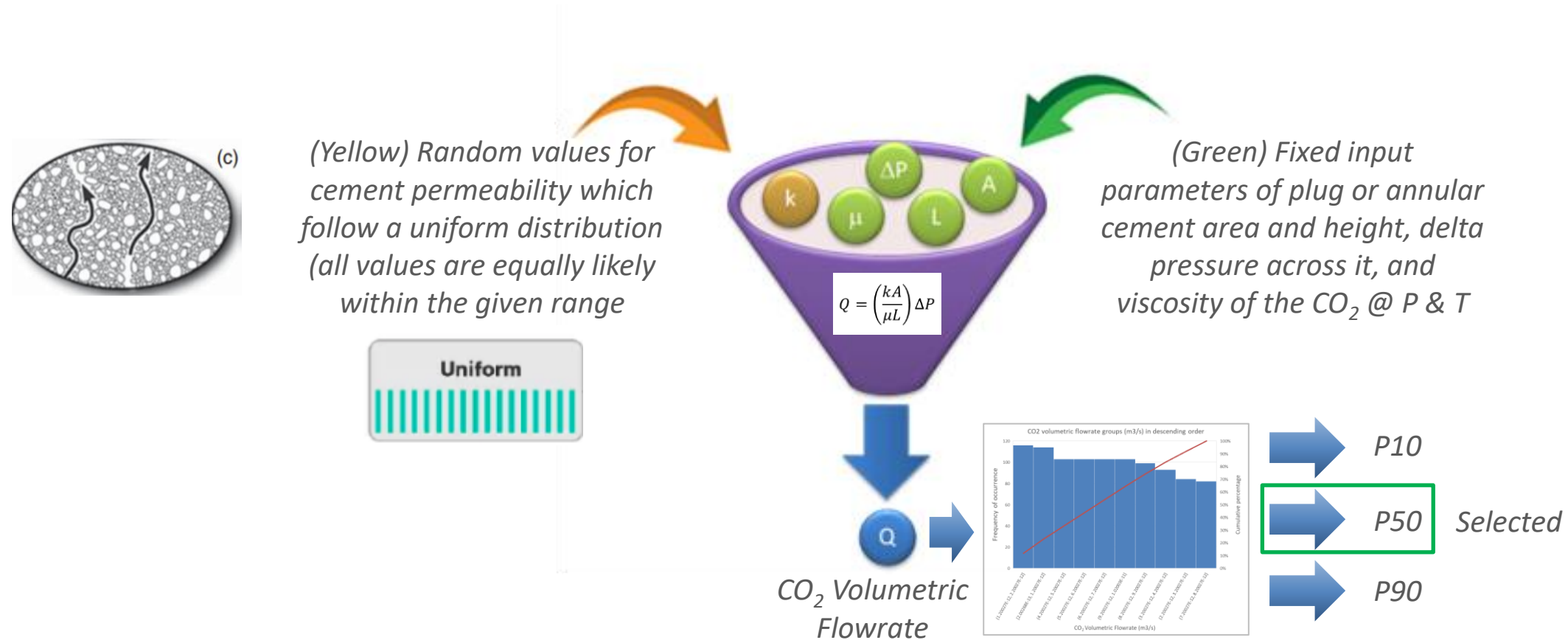
(*) SPE185890: "Leakage Calculator for Plugged-and-Abandoned Wells", Fatemeh Moeinikia et al., 2018.

Analytical model – tool development

- Given the wide possible range of certain parameters and difficulty in being precise on the specific value of a given well or field, the most reasonable approach is where a statistical range is considered for a defined leak pathway
- As outlined in slide 4 the main uncertain parameters are
 - Cement permeability
 - Fracture width and aperture of any cracks
 - The size of any micro annular gap
- A tool was developed to handle a range of input parameters and to allow some weighting on risks to get an overview of possible leak rate scenarios

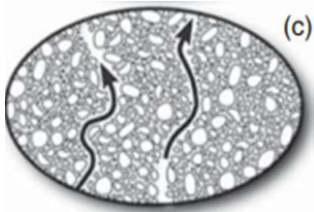
Analytical model – dealing with uncertain input parameters

- The outcome in this case is the CO₂ volumetric leak rate 50 percentile



Analytical model – dealing with uncertain input parameters

Permeability of Cement



Cement permeability (Uncertainty variable/Uniform distribution)	Min. Value	Max. Value
k	0.1 μ darcy	5 μ darcy

- A very large distribution of cement permeability is noted in various literature sources, however, much of the variation relates to imperfections in the cement (eg micro-annuli and cracks) these are accounted for separately.
- As a result, the variation in cement permeability we are interested in relates more to the variation in INTACT cement blends and associated cement strength. We assumed possible increase to $\sim 5 \mu$ darcy for a weaker blend and for stronger cement blends may decrease to 0.1 μ darcy
- Note : The good cement blend providing an intact cement value of 1 μ darcy is supported by SPE185890: “Leakage Calculator for Plugged-and-Abandoned Wells”, Fatemeh Moeinikia et al., 2018 and by SPE200608: “Development of a Probabilistic Framework for Risk-Based Well Decommissioning Design”, Caroline Johnson et al., 2021, HWU.

Analytical model – dealing with uncertain input parameters

Microannuli Gap

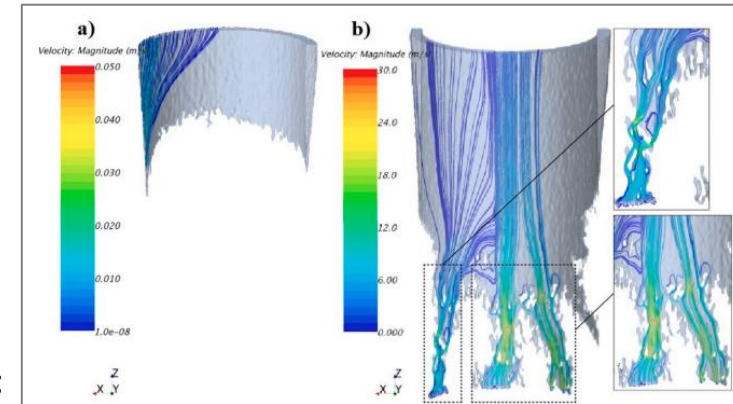


Microannulus Gap (Uncertainty variable/Uniform distribution)	Min. Value	Max. Value
k	3 μ m	70 μ m

The equation for this leak rate mechanism considers a gap around the 360 degrees of the cement plug or annulus (microannulus circumference). In this respect this equation represents a worst-case scenario. The Journal of Petroleum Science and Engineering 196 (2021) 107669 “Simulation of fluid flow through real microannuli geometries” Anisa Noor Corina et al., indicates:

Real microannuli have fracture-like and complex geometries with non-uniform apertures, and do not always form around the entire circumference of the cement.

Note : The above variation in microannulus parameters is supported by SPE185890: “Leakage Calculator for Plugged-and-Abandoned Wells”, Fatemeh Moeinikia et al., 2018 and by SPE200608: “Development of a Probabilistic Framework for Risk-Based Well Decommissioning Design”, Caroline Johnson et al., 2021, HWU.



Casing, cement and formation configuration

BHT = -15degC

F: Case 4 Sv+SH+Sh_HDT_Static Structural_QG

Equivalent Total Strain

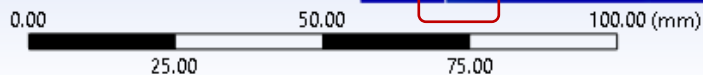
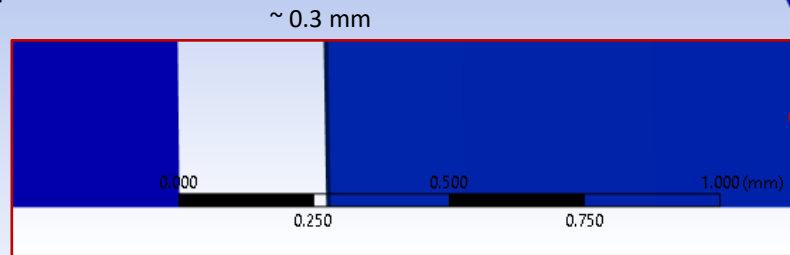
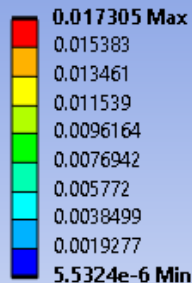
Type: Equivalent Total Strain

Unit: mm/mm

Time: 1 s

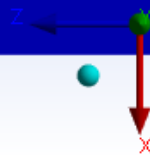
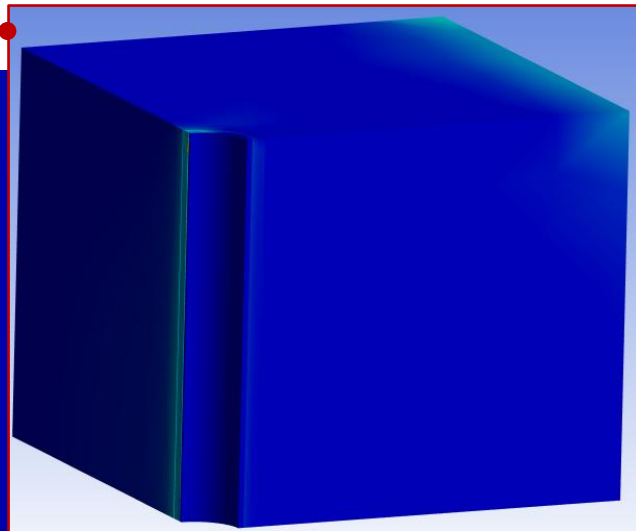
Deformation Scale Factor: 1.0 (True Scale)

1/8/2024 1:12 AM



Point of gap closure

Note:
With cross section area it is possible to assess leak rate(s)



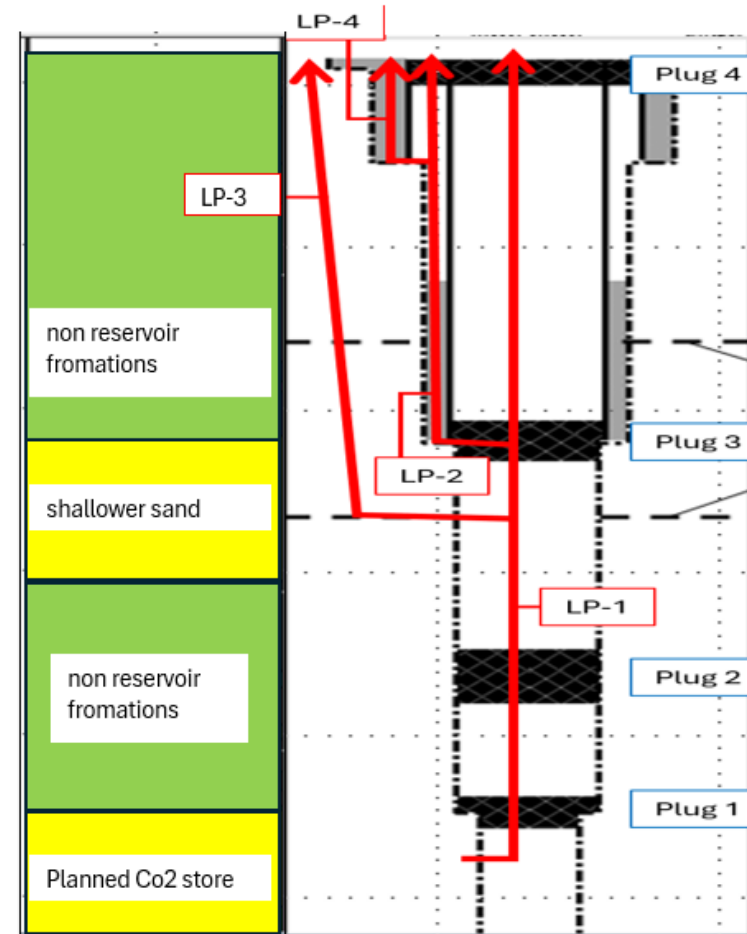
Example application

LP1: Linear leak through plug 1, plug 2, plug 3 and plug 4.

LP2: Linear leak through plug 1 and plug 2, then linear leak on 13 3/8 " casing side of annular cement, and linear leak through plug 4.

LP3: Linear leak through plug 1 and plug 2, then from store MSAD formation fracture.

LP4: Linear leak through plug 1 and plug 2, linear leak on 13 3/8" casing side of annular cement, and linear leak on 20" casing side of annular cement.



Calculation assumptions

- For all calculations, the steady state equations use steady state leaking conditions which assume a CO₂ Leak has already occurred and as such CO₂ properties should be used and not the brine/mud that may have been in the wellbore prior to the leak occurring.
- For all leak rate calculations, the leak rates are assumed to be sufficiently low that no friction loss is accounted for and no JT cooling either.
- In the full project, crossflow from the planned to shallower sand was also reviewed but for simplicity is not shown here.
- Weighting factors for each leak mechanism (planned Co₂ store):

Matrix:	0.1	Low probability of a leak due to this mechanism
Micro-Annulus:	0.6	Higher probability of a leak due to this mechanism
Cracks:	0.3	Higher value used in planned reservoir due to the higher pressure

Analytical model – output

- P50 case shows a leak of max 37.9 Tonnes /year , with weighting this is max 22.7 T/yr
- For context this weighted leak of 22.7 T is equivalent to 1.62 “cows” of CO₂ (cow = 38 kg/day adjusted for methane to CO₂ conversion)
- In this example it would be 62% of the individual “low level seep” well leak rate from (1) or 6.2 % of the store low level leak, following the same recommendations (1)

Minimum

Leak Path		Leak Type	P50	P50	Weighting	Weighted	Weighted	Weighted	Weighted
No.	Description		Leak Rate m3/s	Leak Rate (T/y)		Leak Rate (T/y)	Leak Rate (Cow Equivalent)	Leak Rate (% of well target)	Leak Rate (% of store target)
LP1	Plugs 1 to 4	Matrix Micro-Annulus Cracks	1.998E-11	4.97E-04	0.1	4.97E-05			
			3.882E-07	9.66E+00	0.6	5.80E+00			
			1.132E-07	2.82E+00	0.3	8.45E-01			
			9.7	TOTAL	5.8	0.41	16%	1.6%	
LP2	Plug 1 + Plug 2 + 13 3/8in Annular Cmt + Plug 4	Matrix Micro-Annulus Cracks	1.283E-11	3.19E-04	0.1	3.19E-05			
			3.891E-07	9.69E+00	0.6	5.81E+00			
			1.096E-07	2.73E+00	0.3	8.18E-01			
			9.7	TOTAL	5.8	0.42	16%	1.6%	
LP3	Plug 1 + Plug 2 + Frac to Surf	Matrix Micro-Annulus Cracks	1.921E-11	4.78E-04	0.1	4.78E-05			
			3.576E-07	8.90E+00	0.6	5.34E+00			
			8.53E-08	2.12E+00	0.3	6.37E-01			
			8.9	TOTAL	5.3	0.38	15%	1.5%	
LP4	Plug 1 + Plug 2 + 13 3/8" Annular Cmt + 20" Annular Cm	Matrix Micro-Annulus Cracks	1.283E-11	3.19E-04	0.1	3.19E-05			
			3.866E-07	9.62E+00	0.6	5.77E+00			
			8.755E-08	2.18E+00	0.3	6.54E-01			
			9.6	TOTAL	5.8	0.41	16%	1.6%	
Sum'AL LEAK RATE				37.9		22.7	1.62	62%	6.2%

Notes:

(1) The report “Deep Geological Storage of CO₂ On The Continental Shelf (Containment Certainty)” provides 1 T/day (365 T/yr) as easily dispersed or absorbed into seawater with limited impact on their surroundings (a “seep”), which could be considered “acceptable;”. This is an independent report, commissioned by BEIS, with involvement of the NSTA.

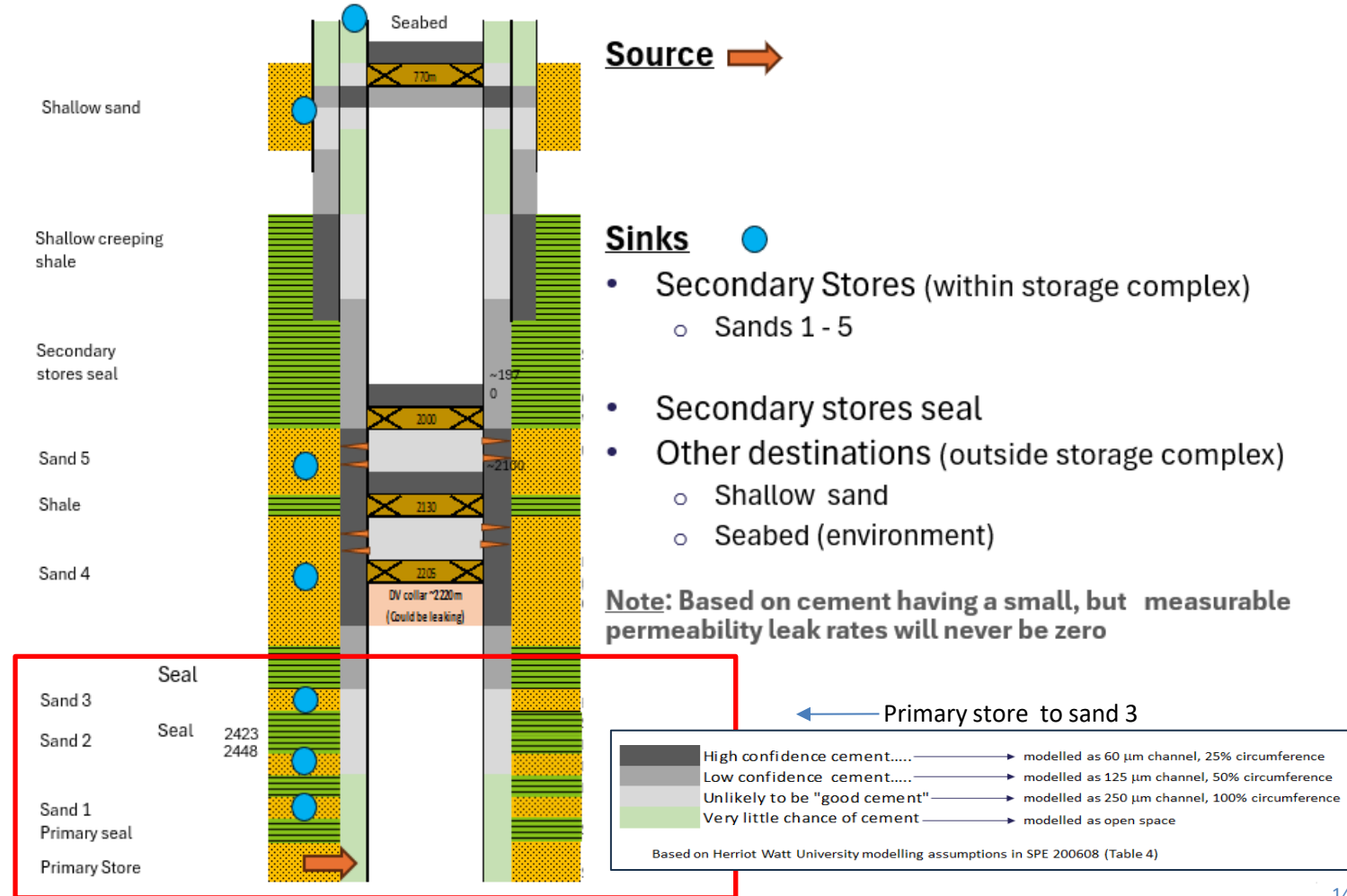
(2) **STORE:** Target acceptable store CO₂ leak rate assumed as <1 T/day (<365 T/yr)

(3) **WELL:** Target acceptable well CO₂ leak rate assumed as 1/10th of store <0.1 T/day (<36.5 T/yr)

(4) **COW:** Cow equivalent CO₂ leak rate <38 kg/day (<14 T/yr)

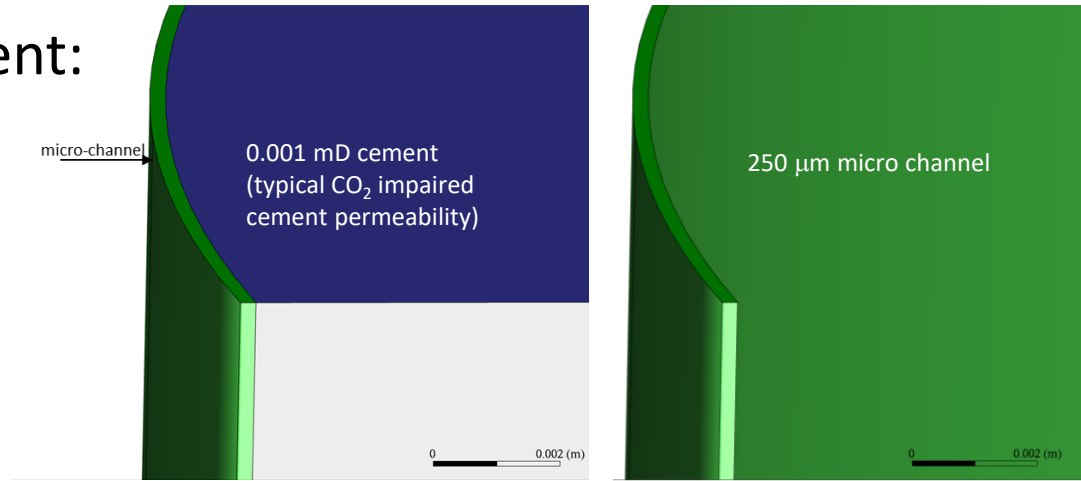
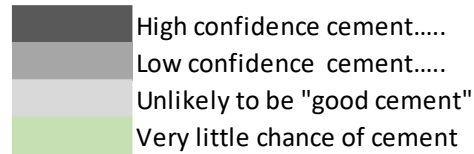
CFD model example

- Poor to no cement suspected at primary store near reservoir in legacy well from sand 3 downwards
- Build a detailed well model incorporating precise geometry and flow properties of each relevant unit
- This example focuses on stacked sands in possible Co₂ store (Norway)

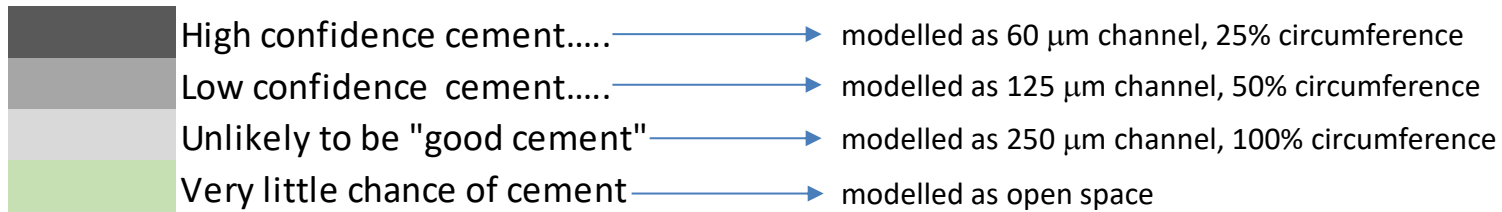


CFD model example

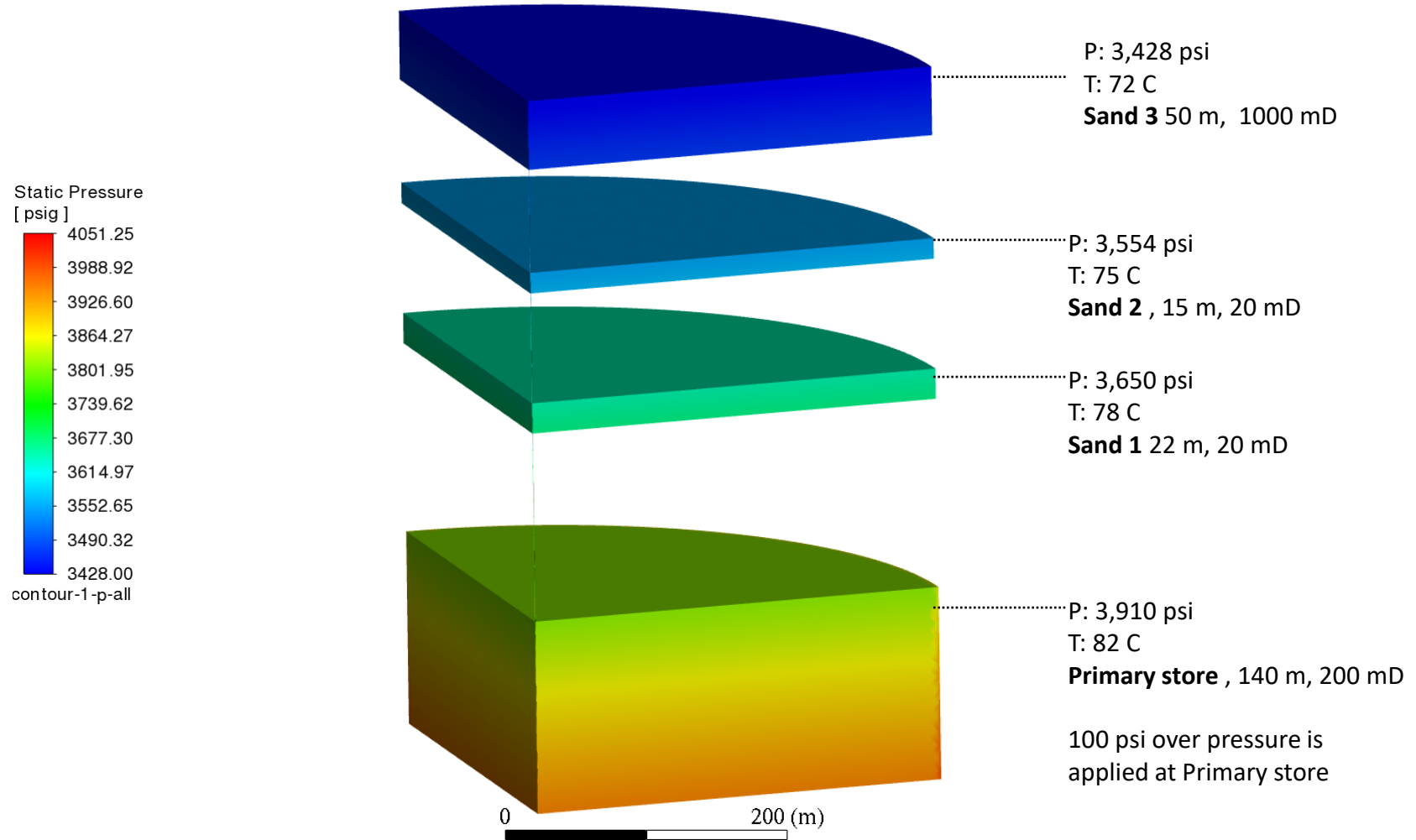
- Micro channel and Cement:



- The micro channel, at the sandface side, will dominate the flow compared to the low permeable cement
 - → model the different cement quality as different micro channel size and coverage



CFD model set up



CFD model output

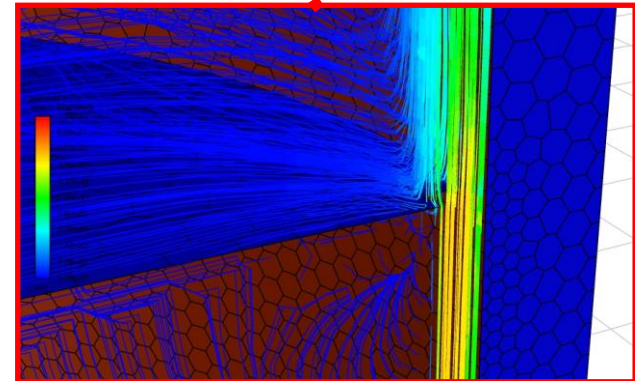
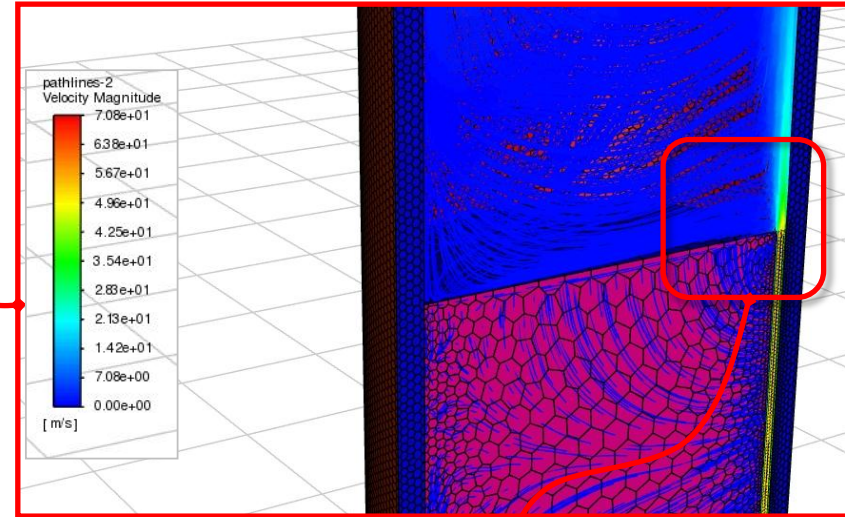
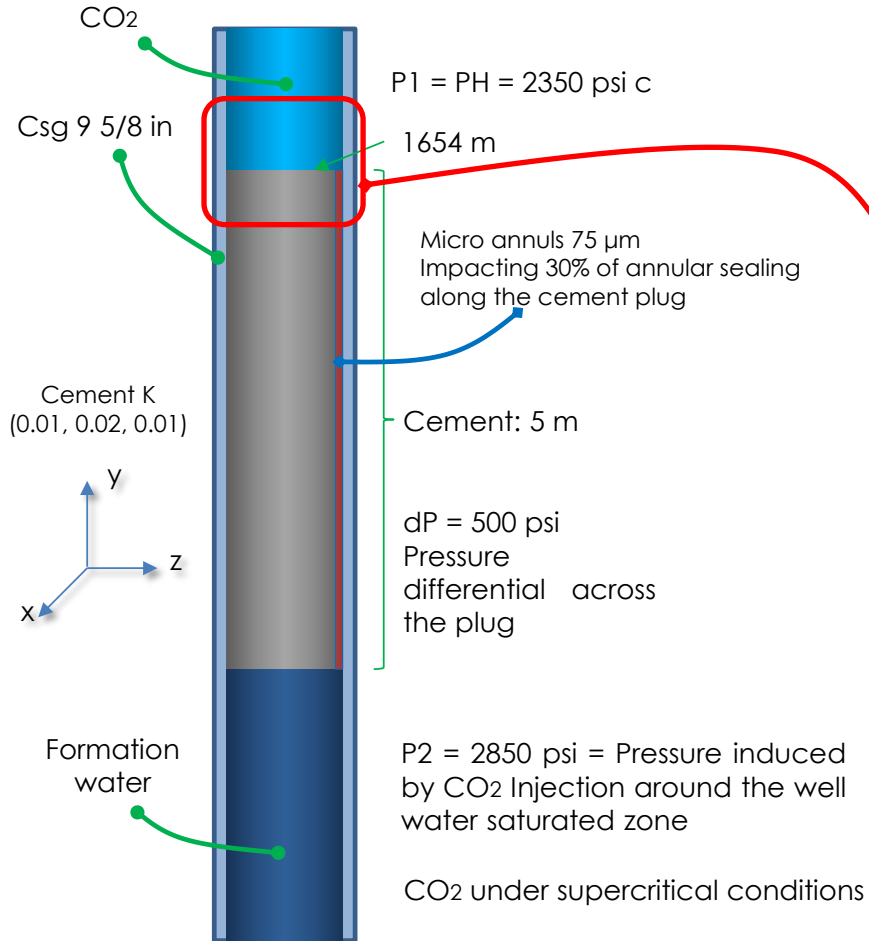
- Leak modelled from Primary store to sand 3 using green (no cement) & light grey (250 micron channel around 100% of well plugs circumference) cement model
- 100 psi over pressure in Primary store → ~ 0.1 Million ton/yr leak rate
- ~ 80% leak to sand 1 , ~19% leak to sand 2 , only ~ 1% leak to sand 3

Horizon	Top Sand	Perm - k	P @ Top	CO ₂ Q	CO ₂ Q	Distance from Primary store
	(m)	(md)	[psi]	[ton/yr]	[% Split]	(m)
Sand 3	2323	1000	3,428	-1,352	1.24%	379
Sand 2	2448	20	3,554	-20,995	19.24%	254
Sand 1	2543	20	3,650	-86,754	79.51%	159
Primary Store (100 psi over pressure)	2702	200	3,910	109,106	-	0

- Sand 3 has the lowest leak rate, despite having 1000 mD permeability
 - → the sand 1 & sand 2 pressure sinks + vertical distance from Primary store influences the sand 3 leak rate
 - This type of specific data cannot be obtained from analytical models

CFD modelling - example

Flow along Cement Plug & Micro Annulus



Wrap Up

Leak rate modelling

- Choose appropriate tool
 - If uncertainty is large and leak path is simple then analytical models suffice
 - If uncertainty is smaller and potential leak path is complex then numerical models may be more appropriate
 - A combination of analytical and numerical tools may be the optimum
- Reduce uncertainty
 - Logging
 - Laboratory testing
 - Simulations
 - Of path evolution using FEA
 - Of cement placement/quality using CFD
 - Of potential to fracture to surface/seabed through formation

Axis Ltd. has made every effort to ensure that the interpretations, conclusions and recommendations presented herein are accurate and reliable in accordance with good industry practice and our quality management procedures. Axis Ltd. does not however guarantee the correctness of any such interpretation and shall not be held liable or responsible for any loss, costs, damages or expenses incurred or sustained by anyone resulting from any interpretation or recommendation made by any of our officers, agents or representatives.