Assessment of water leakage/crossflow rates from legacy wells in CCS projects

Introduction

Legacy wells—defined as all existing wells within or near a CO_2 storage licence area that may experience pressure increases or lie within the predicted CO_2 plume. In general, wells represent a potential—though typically unlikely—pathway for the migration and leakage of reservoir fluids to the surface or seabed. Considering that more than 20 thousand wells are drilled in the North Sea (Böttner et al., 2020), avoiding them in CCS projects is generally impractical. Often, these wells are inherited from previous oil and gas operators and could lack documentation on the quality and location of the cement barriers. The primary focus of historical plug-and-abandonment (P&A) operations was on isolating hydrocarbon bearing formations under depleted reservoir conditions, that introduces additional uncertainty about the integrity of those placed barriers and their ability to withstand increased pressures associated with CO2 storage. Furthermore, the absence of verified barriers in shallower aquifers can make well intervention operation costly and risky or, in certain cases, nearly impractical, because the exact location of the well may be unknown and the well head missing. Based on our experience in evaluation of legacy wells, the highest risk is represented by dry exploration. Both, the national and EU (Guidance, 2023; Regulations, 2024; EU Directive, 2009) authorities require estimation of leakage rates over time.

In CCS projects the primary leakage concern is related to the potential but unlikely leakage of CO_2. With current state of subsurface characterization and engineering technologies, placement of wells can be optimized in a way minimizing the risk of legacy wells exposure to CO_2 plume (Alkan et al., 2023). Because formation water is almost non-compressible, the pressure front generated by injection activities can propagate tens of kilometers beyond the CO_2 plume itself, extending the zone of potential influence far from the injection well. Since multiple projects are targeting CO_2 storage in cross-shared regional-scale saline aquifers like Horda platform, different storage operators are competing not just for the pore volume within the license area but, more critically for the pore pressure capacity and the overall compressibility of the shared storage system. If the legacy well is located close to cross-shared license boundary, its integrity maybe influenced by injection operations in the neighboring license. This requires additional assessment of barrier integrity and potential fluid crossflows. The focus of this paper is to evaluate potential leakage, crossflow, and migration rates of reservoir brine through compromised cement plugs.

Leakage rate assessment methodology

There are multiple approaches for estimation of potential leakage rates, some are based on experimental work (Bachu et al. 2009), while others rely on analytical or numerical solutions (Johnson et al., 2021). Equinor developed in-house solution (Torsæter et al., 2024; Bello-Palacios et al., 2024) with explicit fine-resolution discretization of the wellbore and Darcy-based flow simulations with open-source Cirrus reservoir simulator developed by OpenGoSim (Cirrus) primary focusing on CO_2 leakages. The concept is based on simulating the flow through the damaged plug with assigned effective permeability representing individual or multiple combined defects (Johnson et al., 2021).

Loss of integrity in the plug can be represented by three idealized types of defects that can create a flow pathway from the reservoir into inner section of the production casing: a) tensile or shear fracture, b) microannuli due to mechanical or chemical debonding between cement and casing wall, c) bubbling channel (Fig. 1). Fluid flow through these defects can be solved analytically (Table 1).

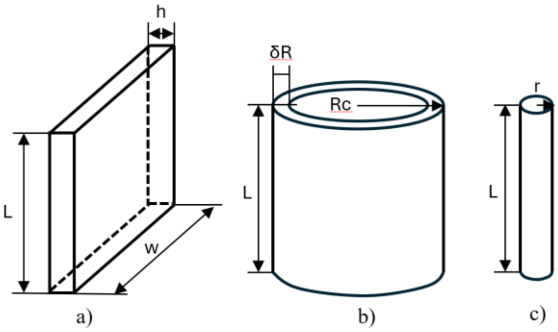

Figure 1 *Schematic representation of cement plug defect types (modified after Johnson et al., 2021).*

Table 1 *Analytical models for fluid flow through different type of defects*

Defect type	Formula
Cracks/fractures (Cubic law)	$Q = \frac{wh^3}{12\mu}\frac{\Delta P}{L}$
Microannuli (Cubic law)	$Q = \frac{\pi R_c}{6\mu}\frac{\Delta P}{L}\delta R^3$
Channel (Poiseuille equation)	$Q = \frac{\pi r^4}{8\mu}\frac{\Delta P}{L}$

μ – fluid viscosity, ΔP – pressure gradient between inlet and outlet.

As can be seen, all these analytical formulations are based on a cubic law written in one or another way. Fluid leakage is by nature a temporal problem. Since water can be considered incompressible in comparison to CO_2 and will not exhibit a phase change and rapid acceleration during upwards flow, the short-term transient effects can be neglected with steady-state flow conditions being applicable for evaluation of long-term leakage calculations and environmental impact assessment. In addition to using general purpose reservoir simulators, as mentioned before, a steady-state pipe flow simulator could be utilized as well.

Independently of the methodology, the key uncertainty is within the input data to be used, particularly on the cement side. In a P&A-ed well with a current state of technology it is impossible to define what kind of defects are present in a cement plug and what are their combined effects on permeability. The channel formation caused by gas bubbling is the least probable one reaching the surface.

Review of the effective cement permeability data showed a huge spread in reported values with 10^{12} orders of magnitude difference (Figure 2).

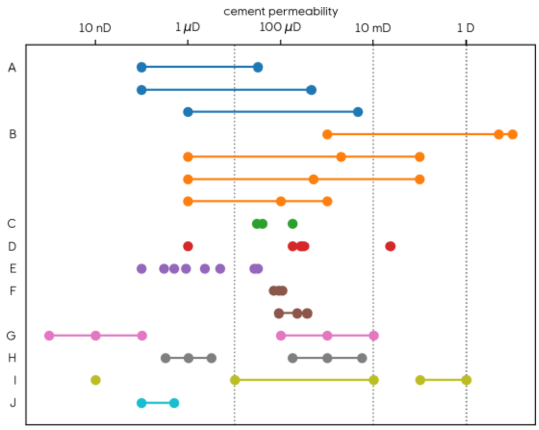

Figure 2 *Reported values of effective cement permeability (Bello Palacios et al., 2024).*

Considering this uncertainty, a pragmatic approach with Low, Mid and High case definitions should be applied for practical estimation of the potential leakage rates. Since all analytical models are based on geometrical properties of possible defects, after additional review of the literature the following average dimensions of the defects were selected Table 2. We couldn't find any reliable reference for channel diameter, but based on sensitivity runs, above 10 mm the rate quickly increases towards open flow conditons where remediation measure need to be evaluated.

Table 2 *Representative defect sizes in mm for Low, Mid and High cases*

Defect type	Low	Mid	High
Crack/fracture hydraulic aperture	0.01	0.10	5.00
Microannuli opening	0.01	0.10	1.00
Channel diameter	0.10	1.00	10.00

Estimation of potential brine leakage rates was done for a typical North Sea vertical exploration well with casing placed at 1200 m TVDSS and one barrier cement plug of 20 m at 500 m TVDSS. The wellbore is assumed to be filled with sea water above and below the plug. Two key scenarios considered – over pressure of 5 and 50 bars below the bottom of the plug due to reservoir pressurization from CO2 injection. Several assumptions and simplifications were applied. In case of analytical solution only the pressure drop component considered, surface roughness is taken as 10% of the geometrical dimensions. The real flow path will be highly tortuous with non-uniformed roughness, therefore idealization with simple shapes and length equal to the hight of the plug can be rather considered as an upper boundary. Independently of potential type of defect, the flow restriction conduit can be generalized as channel that can be explicitly modelled by Darcy-based finite volume reservoir or steady-state pipe flow simulators using standard, for example Darcy-Weisbach, or proprietary correlations. In addition, the flow through choke-type restriction was calculated to estimate the rate at which flow will become critical.

Conclusion and results

Some difference in calculated leakage rates was observed between analytical, finite-volume and commercial pipe flow simulations, with explicit finite volume method being two orders of magnitude smaller than the rest. This difference can be explained by a different way of defining boundary conditions particularly at the well head with sea column sink and the way Darcy flow through the conduit (represented by cells with very high permeability) is modelled.

Table 3 presents the average reference values of leakage rates at steady-state conditions. For long-term environmental risk analysis (ERA) it should be multiplied with a respective time-period. The critical flow rate for 10 mm channel conduit is 200 m^3/d for 5 bars (worst-case) while the 50 bar case (600 m^3/d) is an unrealistically high bounding scenario included for comparative purposes only.

Table 3 *Reference values of reservoir brine leakage rates (m^3/d) for Low (0.1 mm), Mid (1 mm) and High (10 mm) conduit size scenarios*

Overpressure / Leakage scenario	Low	Mid	High
5 bars	8E-5	0.04	12
50 bars	2E-4	0.15	50

Even so the estimated leakage seems to be high with up to 50 m^3/d they are two orders of magnitude smaller than the single point water disposal rates, which at 3000 m^3/d, 50 PSU (practical salinity unit) and brine contamination with generic metal concentrations show negligible local environmental risk (Heitnes Hofstad and Frost, 2025).

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