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Report on range of long-term scenarios to be simulated

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Abstract
In order to proceed with speculative modelling of the impacts of potential leakage of geologically stored carbon, it is necessary to develop plausible scenarios. Here a range of such scenarios are developed based on a consensus of the possible geological mechanisms of leakage, namely abandoned wells, geological faults and operational blowouts. Whilst the resulting scenarios remain highly speculative, they do enable short term progress in modelling and provide a basis for further debate and refinement.

1. Introduction

Whilst the regulatory presumption is that geological carbon storage reservoirs should not leak, experience in internationally widespread hydrocarbon extraction industries and marine academia suggests that it is prudent to evaluate the potential for detrimental impacts both economically and environmentally, should a leak event occur.

Within ECO2 the ambition is to develop a chain of models that are capable of simulating the processes that govern CO_2 flow from a leaking storage complex through the overburden, shallow marine sediments and water column and eventually to the atmosphere. Further the model systems aim to evaluate the potential impact of leaked CO_2 in both environmental and economic terms.

A coherent evaluation of the overall impacts, risks, and costs of leakage requires common scenarios that are simulated or addressed by all participating model systems. There are virtually no observed or operational information available that identify an unambiguous range of scenarios. Hence the purpose of this document is to define a range of potential generic leakage scenarios that set the boundaries of plausibility and will enable initial model development. Reservoir modelling within the project will determine a range of site specific scenarios in due course.

The ultimate motivation for this work is to quantify firstly, whether there could be sufficient input of CO_2 to natural systems to cause measurable and/or significant environmental impact, secondly the potential economic impact of leakage and thirdly to what extent leakage could impair the climate change mitigation that provides the ultimate aim for CCS.

The impact models require information describing:

- the amount of CO_2 potentially leaked, both as mass and fraction of stored CO_2,
- the flux, either out of the reservoir complex, into the ecosystem or into the atmosphere,
- the form of leakage, in terms of the area impacted and the phase chemistry (whether as bubbles, droplets or dissolved),
- Changes in flux with time.

2. The geological basis

Any plausible leakage scenario needs to be geologically realistic and restricted to the known pathways that allow flow through rock. Three categories of leakage are identified:

I. ***Leakage via abandoned wells.*** In this scenario the expanding reservoir of sequestered CO_2 could migrate through an abandoned oil/gas exploration well (many of them are not tightly sealed) which would provide a conduit to the surface. The resulting flux would be related to the reservoir pressure and the speed of horizontal migration within the storage reservoir. In a reservoir that was not over-pressured the resulting flux would be low, in terms of percentage of reservoir contents, but if undetected and unchecked could persist for a relatively long time. Such a leak could be mitigated by plugging the well, however as a point source, detection could be challenging.

II. ***Leakage via fracture.*** In this scenario the sequestered CO_2 reservoir could expand across a pre-existing geological fracture and subsequently migrate to the surface. As with the well scenario the resulting flux would be related to the reservoir pressure and reservoir expansion rate. Given that a fracture would likely provide a larger cross-sectional area to permit flow than an abandoned well the flux could be larger than in the well scenario, but likely to remain a relatively small fraction of reservoir contents. Mitigating such a fault would be at best challenging and potentially only achievable by ceasing sequestration activity.

III. ***Catastrophic blowout.*** The scenario is an analogue to the Tordis event (*http://www.statoil.com/en/ouroperations/explorationprod/ncs/tordis/pages/tordisincident2008.aspx*) and would arise if a reservoir was over-pressured resulting in a fracturing of the overburden. In a well-regulated operation, such an eventuality should not occur. If CCS were to become widespread then the possibility of such an event would increase, analogous to accidents in the oil and gas industry. The resulting flux could potentially be a large fraction of sequestered CO_2 and mitigation again challenging and probably only achievable by ceasing sequestration. Detection of such an event would not be a challenge.

A final non-geological category of leakage exists, not explicitly covered by the ECO2 project, namely a pre-sequestration transportation or pipeline failure. The flux would be determined by the pipeline flow, the duration from hours to days. Detection and mitigation would be relatively simple.

Scenario	Flux	Duration	Detectability	Mitigation
Abandoned Well	Low	Medium to Long term	Low	Capping/plugging
Geological Fracture	Low-Medium	Medium to long term	Medium	Ceasing injection
Catastrophic Blowout	High	Short term	High	Ceasing injection

Table 1.A qualitative summary of leakage scenario characteristics.

3. Form of leakage

Observed emissions of gas at the seafloor from natural analogues of CO_2 or methane seeps are predominantly in the form of discrete single or multiple bubble plumes (Inagaki, 2006; Hall-Spencer, 2008; Leifer, 2006; McGinnis, 2011; Clarke, 2010; Haeckel, 2004p; Naudts, 2010). The areal extent is generally restricted, of the order of a hectare. However, the alternative scenario, one of diffuse flow of CO_2 dissolved in pore water would be hard to detect, hence lack of observation rather than lack of the phenomenon could be a factor. There is some evidence that a few metres of unconsolidated sediment layer over-lying a geological conduit could act to spread flow from a point source into a number of distinct bubble plumes over an area of a few hundred square metres (refs: Klaucke, 2006; Naudts, 2010).

4. Temporal evolution of leakage.

As CO_2 flow engineers a pathway to the surface during the initial phases of leakage it is possible to conceive that the flux would increase over a time period related to the flow through the overburden. Once a leakage pathway is established and the flux acts to depressurise the reservoir, the flux would be expected to decrease over time. In general a trade-off between high flux and longevity is expected.

5. Estimating fluxes.

There is a lack of direct evidence that informs fluxes, Klausman (2003 a & b) reports rates of between 170-3800 Tonnes per annum (about 0.01% of input per decade) at Rangely Field, Colorado where CO_2 is injected for enhanced oil recovery, rather than sequestration. The other information sources available are system end-members, namely the injection rate to reservoirs, the capacity of individual reservoirs and the storage potential of pre-defined regions. Examples of these, largely drawn from NW European systems, are summarised in table 2.

Injection rate at Sleipner and In-Salah	1MT/A
Injection rate at Weyburn	2.8MT/A
Likely injection rate of new generation systems	2-4MT/A
Maximum likely injection rate	10MT/A
Current storage at Sleipner	15MT
Predicted storage at Sleipner	20MT
Predicted North Sea storage capacity (depleted hydrocarbon reservoirs)	18000MT
Predicted North Sea storage capacity (saline aquifers)	200000MT

Table 2.End-members for injectivity and capacity.

The following leakage scenarios are acknowledged to be speculative and approximate, the aim is to set out a logical process of derivation that can be quantitatively modified and debated as evidence allows. By making some very generic assumptions about leakage it is possible to derive a series of scenarios, here illustrated in table 3 and figure 1. For this purpose we assume a reservoir holding 50 million tonnes of CO_2, with 1, 10 and 50% of reservoir contents vulnerable to leakage in the well, fracture and blowout scenarios respectively, assuming that the remainder would be retained via capillary action created by the pore spaces. We assume that leakage occurs as a fixed proportion of available reservoir contents, hence over time the flux will follow a standard exponential decay curve. Initial development of a leakage is ignored for simplicity.

5.1 Well bore mediated leakage.

With a single conduit to the surface, it is hypothesised that only a small fraction of the reservoir contents would by proximate enough to be at risk of leakage, here we adopt a figure of 1%. The suggested flux range is of the order of 1 to 10 tonnes per day. This compares with the lower end of the Rangely Field observations and is similar to some of the natural analogue CO_2 seeps seen in volcanic regions. Such a leak could however be hard to detect and would make an insignificant impact on reservoir pressure, hence a continuous or long term event is plausible (figure 1, scenarios a&b). The semi analytical solution developed by Nordbotten et al. (2005), predicts leakage through an abandoned well to be at maximum 0.25% (well permeability <1 D) or 2.5% (well permeability 10 D) of the injection rate. This gives some limited support to the estimation proposed here.

5.2 Geological fracture mediated leakage

The cross sectional area of a fracture would exceed that of a well bore, with correspondingly faster fluxes and proportion of reservoir contents at risk of leakage. Estimates are speculative but fluxes may be in the order of 10-100 tonnes per day. Presuming mitigation is not possible the duration would be long term, at least until reservoir pressure was diminished. Such a process could be of the decadal scale (figure 1, scenarios c&d). Cappa & Rutqvist (2011) simulate reactivation of a fault (width 10 m), including permeability changes, and resulting CO_2 escape, for a 15 year period. In this scenario, after 15 years, 1% of the injected volume has leaked out. The injection rate is 0.02 kg/m/s, (630 T/m/a). When the CO_2 reaches the fracture, pressure starts to slowly decline with time, but only a little as there is still CO2 injected and the leak is considerably smaller than the injection. Again this gives some qualitative support to the scenarios developed here.

5.3 Catastrophic blowout

In this scenario we anticipate an open, non-limiting conduit to the surface, with reservoir pressure enabling a high proportion of contents to leak, here we assume 50%. The flux would be high, perhaps constrained by injection rates. We suggest leakage fluxes of 1000 – 10000 tonnes per day, comparing with the current 3000 tonnes per day injection at Sleipner. Depressurisation would limit the duration of leakage, but under some assumptions significant leakage could last for several decades (figure 1, scenarios e&f).

		Reservoir capacity (MT)	**% of reservoir capacity leaking**	**Initial rate (T/d)**	**Scenario**
Well bore leakage	Lower flux estimate	50	1	1	a
	Higher flux estimate	50	1	10	b
Geological fracture	Lower flux estimate	50	10	10	c
	Higher flux estimate	50	10	100	d
Blowout	Lower flux estimate	50	50	1000	e
	Higher flux estimate	50	50	10000	f

Table 3. Summary of proposed scenarios

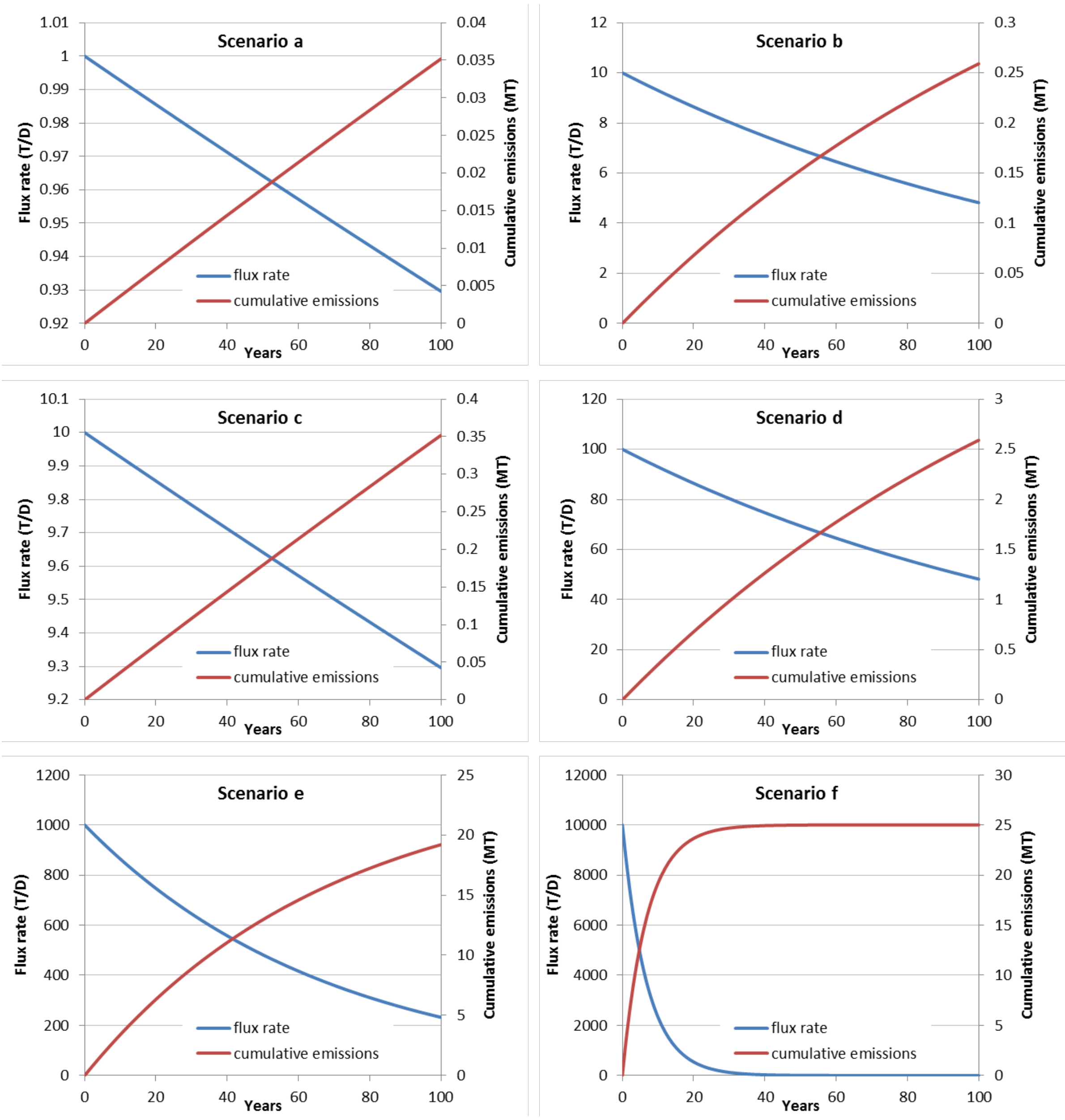

Figure 1. Illustrative evolution of leakage fluxes and total emissions for the scenarios a-f as identified in table 3. No mitigation is considered.

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