APPENDIX II

ESTIMATION OF THE FREQUENCY OF LEAKS FROM CO_2 SEQUESTRATION IN GEOLOGICAL STRUCTURES

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Contents

II.1 INTRODUCTION

II.1.1 Purpose

This appendix documents the methods and results of a quantitative estimate of the frequency of leaks from CO_2 sequestration in geological structures.

The purpose is to quantify the likelihood and size of accidental releases from different types of geological reservoirs. It does not cover the CO_2 capture and transportation systems, or the impacts of releases on people or the environment.

II.1.2 General Approach

Estimating the geological risks is challenging since there is no directly relevant leak experience. The nearest available experience is in blowouts from oil and gas production reservoirs, which are well documented by the offshore industry. To apply these to CO_2 sequestration requires substantial modifications, necessarily based on judgement. To assist this process, DNV used a Delphi technique to seek judgements from a panel of experts. Despite our best efforts at preparation, most of the experts felt unable to supply quantitative risk estimates through this technique. Nevertheless, sufficient quantitative responses were obtained to provide some useful input to an estimate of risks, which remains primarily based on judgements by DNV.

II.2 BASELINE RISK DATA

II.2.1 Choice of Baseline

DNV's approach to the quantification exercise rests on relatively well-established baseline risks, which are modified to account for the known differences between the baseline activity and CO_2 sequestration. The chosen baseline is the production of oil and gas from offshore reservoirs. We recognise that this approach introduces a bias towards the baseline, but we consider that overall this is preferable to making absolute judgements about risks in CO_2 sequestration with which there is little practical experience.

In future work it would be desirable to collect experience from actual ongoing use of CO_2 in enhanced oil recovery (EOR) operations, and from gas storage in natural caverns. However, the necessary leak frequencies were not available for this study.

II.2.2 Baseline Accident Experience

The following case descriptions are examples of blowouts from offshore oil and gas wells that were under production or workover (drawn mainly from CMPT 1999 and other DNV internal sources). Many more blowouts have occurred during drilling, but these are considered less relevant to CO_2 sequestration. The case histories are in chronological order. It should be noted that safety equipment and safety management have improved since the earliest of the events, resulting in fewer relevant events from recent years.

II.2.2.1 South Timbalier 26

The US *South Timbalier 26* platform suffered a blowout from a production well on 1 December 1970. The platform had 22 wells, but one had become plugged by detached plastic coating from the tubing. During a wireline operation to clear it, the DHSV was removed and the surface control valves were left incompletely closed while the well was unattended, during which time the well began to flow. Despite DHSVs being fitted, 11 other wells also blew out. The release ignited and killed 4 of the 60 people on board. Five rigs were used to drill 10 relief wells, and the blowout lasted 137 days, spilling 8000 tonnes of oil. The platform was a total loss.

Ref: DNV BLOWOUT database
”*Risk of Blowout Accidents on the Norwegian Continental Shelf*”, DNV, July 1978.

II.2.2.2 Ekofisk B

The Norwegian platform *Ekofisk B* suffered a blowout from an oil production well on 22 April 1977. The platform had 15 wells, and the one that blew out had been producing at 16,700 bpd. During a workover after killing the well with mud, between removing the Xmas tree and installing the BOP, a DHSV which had been incorrectly installed blew out when the well kicked. Mud streamed uncontrollably out of the well into the derrick followed by oil and gas.

This was the first uncontrolled blowout in the Norwegian Sector and the largest oil spill from any North Sea platform. The flow was not ignited and the platform was not seriously damaged. The initial flow was about 28,000 bpd. The well was not capped for 8 days, due to part of a BOP having been fitted upside-down. During this time there had been an average flow of 21,000 bpd (2 kg/s) oil and 0.2 x 10^6 m^3/d (1 kg/s) gas. The total spill has been estimated by different sources as 12,700 or 22,800 tonnes. There was no discernible damage to fisheries, but about 500 birds were killed.

Ref: Norwegian Commission of Inquiry Report
Lloyd's Casualty Reports
"*Oil Pollution by the Offshore Industry*", BPM Sharples, IMechE 1990
"*Managing Technological Accidents: Two Blowouts in the North Sea*", D.W. Fisher, IIASA, Pergamon Press, 1982.

II.2.2.3 Ship Shoal 246

The US *Ship Shoal 246B* platform suffered a blowout from a gas production well on 9 March 1980. Gas began to leak from a needle valve on the wellhead. The DHSV and 2 master valves would not close, due to improper maintenance. The platform had to be abandoned, but the well was killed within 1 day by pumping mud through a wing valve.

Ref: SINTEF blowout database

II.2.2.4 Placid L10A

The Dutch complex L10A suffered a leak from a gas production well on 15 May 1983. The wellhead platform had 9 wells drilled during 1973-76. The gas had a high CO_2 content, and chrome tubing was installed, but a non-chrome connection had mistakenly been fitted below the sub-surface safety valve. This corroded and allowed gas to enter the annulus. The high annulus pressure was disregarded by the operators. Eventually the gas corroded the $9^5/_8$" and $13^3/_8$" casing and emerged through the annulus between the $13^3/_8$" and 20" casing, which was open at the sea-bed Xmas tree.

The flow rate was estimated as 30mmscfd. It emerged under the wellhead platform in the form of a 40m diameter bubbling pool. The water depth was only 15m, but the large pool was due to the low pressure and low velocity of the release. Although weather conditions were calm, no significant gas concentrations were measured on the platform.

There was no derrick on the platform, and one could not be mounted since the blowout was underneath the crane. The well was snubbed after 10 days by lowering equipment from a helicopter. A relief well had been started from a jack-up rig nearby, and had set the 20" casing by the time the well was killed. A biological survey showed that no pollution had occurred.

Ref: Lloyd's Casualty Reports, 16 May 1983
BLOWOUT Database
North Sea Field Development Guide
"*Ecological Survey of a North Sea Gas Leak*", J.T. van Buuren, Marine Pollution Bulletin, vol 15, no 8, August 1984

II.2.2.5 Mississippi Canyon 311A

The US *Mississippi Canyon 311A* platform suffered an underground blowout in a gas production well on 4 November 1987. Sustained pressure in the production tubing caused a leak into the annulus, and one of the casings failed, resulting in a deep underground blowout with a gas plume around the platform. The well was killed and the flow decreased. The blowout caused loss of piling and tilted the platform, causing damage estimated at $220 million.

Ref: SINTEF blowout database

II.2.2.6 Enchova Central

The Brazilian *Enchova Central* platform suffered a blowout from a gas injection well on 24 April 1988. During a workover, a gas release was initiated as a drill pipe was being pushed up from the well. The BOP failed to activate for unknown reasons, and pumping of water, mud and chemicals did not stop the escaping gas. The drillpipe hit one of the steel legs of the platforms, causing sparks that ignited the escaping gas. The release and the fire were stopped one month later as mud and salt water were pumped into the well through two diversion wells. The platform was declared a total loss.

Ref: Noroil, June 1988

II.2.2.7 Qatar North Field

The Qatar North Field suffered a leak from a closed-in gas well in August 1990. Due to poor cement quality, gas was found seeping up the sides of at least 2 wells and bubbling to the surface. Due to war in the Gulf, the leak was allowed to continue for at least a year.

Ref: SINTEF blowout database

II.2.3 Baseline Risk Parameters

The following parameters are based on experience with offshore oil and gas production and on typical practice in offshore quantitative risk assessment (QRA). Except where public sources are acknowledged below, the source is internal DNV offshore QRA methodology (ARF Vol IV App VII).

The frequency of blowouts from offshore gas wells during production has been estimated as 9.8×10^{-5} per well year, based on the SINTEF database of blowouts in the Gulf of Mexico and North Sea during 1980-96 (CMPT 1999). Over this period, there is no apparent trend in blowout frequency for production wells. Most other estimates include both oil and gas wells, which give lower values. Holand (1996) recommends 5×10^{-5} per well year, although this excludes wirelining, workovers and external causes. If these are included, values as high as 2.5×10^{-4} per well year may be obtained. Overall, a frequency of 1×10^{-4} per well year is considered to be a best-estimate of the average blowout frequency from a gas production well, with 0.5 to 2.5 times this value representing the 90% confidence range.

The above values are for a single well. For a reservoir with 10 wells, the frequency would be 1×10^{-3} per reservoir year. This figure is used as the baseline for estimating frequencies in CO_2 sequestration below.

The initial release rate in a blowout from a production well depends on the flow path and the maximum flow potential from the well, which is of course very variable. There is very little information published on this, and the initial flow rate in a blowout is typically assumed to be 5x the production flow rate. Some events are smaller leaks rather than full blowouts. Available data shows relatively few of these, amounting to only about 10% of the blowout frequency. Their initial flow rate is typically taken as 10% of that for blowouts, i.e. 0.5x the production flow rate.

The duration of blowouts depends on the methods used to regain control, or on their flowing characteristics if they are allowed to cease naturally. Available information on the duration of 12 production blowouts in the Gulf of Mexico and North Sea during 1970-89 shows a range of 1 hour to 200 days, with a median of approximately 2 days and a mean of 35 days. More recent data for the period 1980-94 gave a range of 1 to 3 days based on 5 events, and a mean of only 1.7 days (Holand 1996). In part this reflects better monitoring and control techniques in the more recent period, but it also excluded blowouts due to external events (collisions, storms etc), which are relevant for the present study.

The reduction in release rate with time also depends on the methods used to regain control and the flowing characteristics. If a blowout is stopped mechanically at an early stage, the flow rate may remain roughly constant for its duration. If the well bridges naturally or the well pressure depletes, an exponential decay in flow rate may be expected. If the blowout escalates to affect other wells, the flow rate may increase before it begins to reduce. In offshore QRA, a typical assumption is a linear decay over the duration, giving a modification factor M = 0.5.

II.3 DELPHI PANEL INPUT

II.3.1 Methodology

In the absence of any risk estimates from directly relevant experience, quantifying risks of leaks from geological storage must rely on expert judgements. This study obtained expert input using a Delphi technique, in which a panel of experts share their judgements in a structured and documented way. Inputs from each panel member are collected using a questionnaire, and reported to the group as a whole. Each member is given an opportunity to revise or clarify their inputs. In order to allow reflection without pressure from other panel members, we circulate the questionnaire by e-mail and keep the individual contributions anonymous.

To ensure that the experts making the judgements have a good common understanding of the risk issues, all but one of them previously attended a qualitative hazard identification exercise on this subject using the Structured What-If Technique (SWIFT), as described in Appendix I. In this, the experts discussed relevant hazards and safeguards, which are critical in forming the risks that are to be estimated.

To assist the experts in making judgements about the risks, we used a simple risk model, together with baseline parameters obtained from experience in offshore oil and gas production as in Section I.2. We suggested that the expert panel modify the parameters of this model using their best judgement, in order to reflect the differences between CO_2 sequestration and offshore oil and gas production.

For each parameter, we asked for a median (50%ile of the probability distribution) and 90% confidence range (between the 5%ile and 95%ile of the probability distribution). We asked panel members to use confidence ranges to represent their individual uncertainty in answering the questions, as well as about the variability in actual conditions in which CO_2 sequestration might actually take place. We also asked for a brief qualitative explanation of how the answer was obtained (e.g. subjective judgement, references to published models etc).

Round 1 of the Delphi exercise gave an opportunity for panel members to comment on the methodology, model and questions, with the aim of making them clearer and easier to answer. In Round 2, responses were requested. In Round 3, the responses from all panel members were reported, in order to allow them to be checked and modified if appropriate. In practice, very few inputs were received in Round 1 and none in Round 3.

In responding to the questions, the panel members were encouraged to consult with colleagues and make use of any available models or research. However, they were requested not to exchange views with other panel members other than through the Delphi exercise. Where two people from one organisation attended the SWIFT, it was assumed that they would combine to provide one reply, and are treated as a single panel member.

II.3.2 Panel Members

The panel members were:

Tony Espie	BP	Reservoir engineer

John Gale	IEA	Chemical engineer
Wolf Heidug	Shell	Physicist, geomechanics
Paul Johnston/Gabriele Goerne	Greenpeace	Ecologist/geologist
Anna Korre/Sevket Durucan	Imperial College	Coal bed methane
Nick Riley	BGS	Geologist
Dave Savage	Quintessa	Geochemist

II.3.3 Reservoir Types

Answers were requested for each of the following reservoir types:

- Offshore oil reservoir, filled with CO_2 as part of an enhanced oil recovery programme, but eventually sealed with the CO_2 left in situ.
- Offshore saline aquifer.
- Onshore coal field, with CO_2 used as part of a methane extraction programme.

For the purpose of risk comparison, it is assumed that each option involves a reservoir that accepts CO_2 at the rate of 1000 tonnes/well-day through each of 10 injection wells, giving a total sequestration rate of approximately 4 Mt/reservoir-year. It is assumed that the reservoir in each option has a total capacity of 40 Mt, and hence requires 10 years to fill. The design life for the storage is assumed to be 1000 years.

II.3.4 Model

A simple generic model is used, in order to minimise as far as possible any model uncertainty (which cannot be captured), while emphasising the parameter uncertainty (which should be represented in the responses).

The model represents the quantity of CO_2 leaking from the storage reservoir in its design lifetime as follows:

$$Q_L = P \times Q_R$$

$$P = 1 - \prod_{i=1}^{L} (1 - F_i)$$

$$Q_R = R_o \times D \times M$$

where:

Q_L = quantity of CO_2 leaked (tonnes) in lifetime
Q_R = quantity of CO_2 leaked (tonnes) in a release
P = cumulative probability of significant leak in lifetime
F_i = frequency of significant leaks (per reservoir year) (assumed small)
R_o = initial release rate in leaks (tonnes per day)
D = overall release duration (days)

M = modification reflecting the reduction in release rate over the duration
L = reservoir design lifetime (years)

These parameters are mutually dependent variables, but for simplicity in the model they are assumed to be independent probability distributions. Apart from the design lifetime L, which is an input assumption, probability distributions for the other parameters were requested through the Delphi technique.

II.3.5 Qualitative Responses

From the 7 panel members, we received 6 responses, of which 4 were qualitative. We record these responses first below.

Qualitative responses

PANEL MEMBER	RESPONSE
A	As I said at the SWIFT meeting, I don't feel that I'm capable of answering any of the questions in the DELPHI documentation without carrying out some further calculations. Unfortunately, the timescale for these calculations will be outside both the timescale you have for your own project and your budget. The approach you've defined might be suitable for estimating leakages from blowouts etc on fairly short timescales (up to a hundred years), but I think further information is needed on metal corrosion rates, cement degradation rates and fluid flow in geological media to be able to make estimates for other types of leakages in the long-term. This type of data acquisition and model calculations are ongoing in other CO2-related projects over 3-4 year timescales. I'm sorry if this response is somewhat negative, but I see little point in supplying answers from pure guesswork!
B	Personally, I am finding it extremely difficult to make a judgement on risk where there is no data or field experience. I am assuming that the findings of this work will be reported in the public domain. Trying to quantify the risk without any data, nor experience of CO2 storage and subsequent observation, and reference to the fundamentals of CO2 retention in different types of reservoirs may have serious consequences for the technology in the future. In your notes you say "We suggest that the expert panel modify the parameters of this model using their best judgement, in order to reflect the differences between CO2 sequestration and offshore oil and gas production. We recognise that this approach introduces a bias towards the baseline, but we consider that overall this is preferable to asking for absolute judgements about events that are beyond most people's experience…", which underlines the fact that the judgements made would be subjective. Without speaking for other colleagues and referring to other fields of expertise, anything I say for coalbed methane in my case would have almost no scientific basis to it. I personally am not prepared to do this, not before some fundamental research is done, published and discussed between my peers on the subject of "risk assessment and leakages of CO2 stored in coalbed methane reservoirs". One of my concerns relate to the choice of the case example. Applying equal storage volumes with uniform well numbers and well spacing and a sequestration capacity may standardise the process, however, it does not take into account one fundamental aspect which is the nature of the reservoir rocks and reservoir fluids in situ, their CO2 retention capacities and processes, and potential for geochemical - hydrochemical reactions. For example, coal would retain CO2 in an adsorbed state which is not the case for an oil reservoir or a saline aquifer. Therefore, the leakage control mechanism would be totally different.

	Furthermore, making an analogy between blow outs from oil and natural gas wells (I am assuming that these are production wells) and designed CO2 sequestration wells (even if this was for enhanced recovery with the dual objective of sequestration/storage) also makes me uncomfortable. With what we know and have researched so far, which is very little to say the least, I am unable to go along with this analogy for CBM wells. I appreciate it that you have a difficult task, and there is not much data available. However, I am concerned with the possible consequences of a "quantitative" risk assessment based on subjective judgement at this stage of development and knowledge in the field. I am sorry that I cannot help you any more than raising my concerns about this matter.
C	Following the useful workshop discussions which served to identify the very considerable uncertainties, we find it very difficult to see how reliable risk terms can be assigned to CO2 geological storage options. Apropos the various schemata proposed for geological storage, we are inclined to a similar view to that expressed by Panel Member B in relation to the coal bed methane option. Moreover, the point made that there is a danger that once risk terms have been defined, they will then be used in an unqualified manner in decision making processes, is an important one top consider in depth. Accordingly, we do not feel able to help in defining values or uncertainty factors for these options.
D	I have consulted with my colleagues and we think that the questions are impossible to answer as posed. We also question whether the relationship of potential well failure with CO2 injection into a storage site is operationally comparable to blow outs recorded in routine hydrocarbon E&P operations. In a nutshell you are asking for generic answers which require site specific information. Each site is unique and the risk of failure is directly related to the choice of site, design of the injection and the geological knowledge used in that choice. I would think a more informative assessment of risk (in terms of is a CO2 leak safe) would be look at the impact of natural seeps from natural CO2 systems. This is exactly what the Nascent project is doing. A lot could also be gleaned by looking at CO2 EOR operations in N. America and CO2 production operations from natural reservoirs.

II.3.6 Quantitative Responses

Among the 7 panel members, only 2 were willing to give quantitative answers to the questions. We record these below for each set of questions.

There were too few quantitative responses to support a statistical analysis of them. Therefore, in selecting parameters for the model, we have used the smallest 5%ile, the largest 95%ile and the geometric mean of the medians supplied by the panel members. The resulting distribution selected for the model is included in the tables below.

In view of the very small number of quantitative responses, it would not be appropriate to describe these as "the result from the Delphi panel". In fact, the result from the Delphi panel was that the majority of panel members were unwilling to supply quantitative responses for the reasons stated above. However, in order to complete the specified contract, DNV need to select parameters for the model. These parameters are therefore described as "DNV's suggestions, based on input from a Delphi panel". They are considered illustrative of the type of results that could be obtained from a larger panel, preferably where each panel member had previously been able to conduct their own quantitative research.

Question 1	What frequency of leaks would you expect from the sequestration reservoirs?		
Definitions	The frequency (the parameter F in the model above) is the annual number of leaks in a single reservoir. Leaks are defined as significant releases of CO_2 from the ground, seabed, wells or wellhead equipment into the atmosphere, the sea or surface water systems. This does not include CO_2 in solution or other fluids displaced by underground CO_2. Significant is defined as an initial rate of at least 10 tonnes/day (0.1 kg/s) of CO_2.		
Required response	Give your response as a median and 90% confidence range for the annual frequency of leaks for each type of reservoir, expressed as a fraction of the leak frequency estimated above for hydrocarbon gas production reservoirs.		
	OFFSHORE OIL RESERVOIR or OFFSHORE SALINE AQUIFER		
	PANEL MEMBER E	PANEL MEMBER F	SELECTED FOR MODEL
Annual leak frequency during sequestration / hydrocarbon gas production leak frequency			
5%ile	0.5	0.5	0.5
Median	1	1	1
95%ile	2.5	2.5	2.5
Justification	I see no reason why the frequency should be any different to that of current experience from the hydrocarbon industry	Use the baseline data for median and distribution	The two responses are the same.
Annual leak frequency 10 years after reservoir capped / hydrocarbon gas production leak frequency			
5%ile	0.5	0.01%	0.0001
Median	1	0.1%	0.03
95%ile	2.5	1%	2.5
Justification	In the short time frame I think corrosion/cement degradation should be minimal		Large difference between responses. Proposed to use the smallest 5%ile, largest 95%ile and geometric mean of the medians.
Annual leak frequency 100 years after reservoir capped / hydrocarbon gas production leak frequency			
5%ile	0.5	0.1%	0.001
Median	2	1%	0.14
95%ile	5	10%	5
Justification	I expect cement failure /degradation be more important and has the potential to increase leakage in this time frame, but have limited knowledge on cement degradation rates to work from.		As above.
Annual leak frequency 1000 years after reservoir capped / hydrocarbon gas production leak frequency			
5%ile	0.5	0.1%	0.001
Median	2	10%	0.45
95%ile	5	100%	5
Justification	I guess I feel that cement degradation will remain a constant over this period		As above.

Question 1	ONSHORE COAL FIELD		
	PANEL MEMBER E	PANEL MEMBER F	SELECTED FOR MODEL
Annual leak frequency during sequestration / hydrocarbon gas production leak frequency			
5%ile	0.5	0.05	0.05
Median	2	0.1	0.45
95%ile	5	0.25	5
Justification	I feel more uncertain in this regard, but feel this may even under estimate the uncertainty	Use 10% of baseline (to account for the fact that CO2 on coal is immobilised) and the same pdf-distribution as in the base case	
Annual leak frequency 10 years after reservoir capped / hydrocarbon gas production leak frequency			
5%ile	0.5	0.0001%	1×10^{-6}
Median	2	0.001%	0.0045
95%ile	5	0.01%	5
Justification	As above and again in shorter time frames there may be less of an impact		
Annual leak frequency 100 years after reservoir capped / hydrocarbon gas production leak frequency			
5%ile	0.5	0.001%	1×10^{-5}
Median	4	0.01%	0.02
95%ile	10	0.1%	10
Justification	Reflects my increased uncertainty		
Annual leak frequency 1000 years after reservoir capped / hydrocarbon gas production leak frequency			
5%ile	0.5	0.01%	1×10^{-4}
Median	4	0.1%	0.06
95%ile	10	1%	10
Justification	As before		

Question 2	What distribution of initial release rates would you expect in the above leaks?		
Definitions	The initial release rate (R_o in the model above) is defined as the rate of release of CO_2 when the leak is first established.		
Required response	Give your response as release rates (measured in tonnes of CO_2 released per day) that exceed 5%, 50% and 95% of leaks for each type of reservoir. For simplicity, the same distribution is assumed to apply at all stages of the reservoir life.		
	OFFSHORE OIL RESERVOIR or OFFSHORE SALINE AQUIFER or ONSHORE COAL FIELD		
	PANEL MEMBER E	PANEL MEMBER F	SELECTED FOR MODEL
Initial release rate (tonnes/day)			
5%ile	0.5 x flow		500
Median	4.55 x flow		4,500
95%ile	10 x flow		10,000
Justification	Unsure of this response, based on industry experience of small leaks for lowest value, median reflects range, 90/10 proportion for blow out/leak, upper value a guess	I have no quantitative feel for a general answer as this will be very site specific.	Baseline flow rate is 1000 tonnes/well-day

Question 3	What distribution of release duration would you expect in the above leaks?		
Definitions	The release duration (D in the model above) is defined as the time from the start of the release until it becomes negligible (assumed to be less than 1 tonne/day).		
Required response	Give your response as release durations (measured in days) that exceed 5%, 50% and 95% of leaks for each type of reservoir. For simplicity, the same distribution is assumed to apply at all stages of the reservoir life.		
	OFFSHORE OIL RESERVOIR or OFFSHORE SALINE AQUIFER		
	PANEL MEMBER E	PANEL MEMBER F	SELECTED FOR MODEL
Release duration (days)			
5%ile	1		1
Median	1.7		10
95%ile	3		1000
Justification	From a social acceptance perspective I think we will over engineer these reservoirs, therefore I have based the value on best practise. I think collisions will be minimal	This will depend on the nature of the leakage mechanism (wellbore, faults, etc). I would expect release durations to be in the order of months to years	In interpreting F, it is assumed that: Median="Months" = 60 days 95%ile="Years" = 1000 days

Question 3	ONSHORE COAL FIELD		
	PANEL MEMBER E	PANEL MEMBER F	SELECTED FOR MODEL
Release duration (days)			
5%ile	0.5		0.5
Median	3.4		15
95%ile	6		1000
Justification	I am less certain in this area therefore have doubled my release durations.	This will depend on the nature of the leakage mechanism (wellbore, faults, etc). I would expect release durations to be in the order of months to years	As above

Question 4	What reduction in release rates would you expect during the above duration?		
Definitions	The release rate modification factor (M in the model above) is defined as $Q_R/(R_oD)$, where Q_R = the total quantity released; and the other parameters are as defined above.		
Required response	Give your response as modification factors (non-dimensional) that exceed 5%, 50% and 95% of leaks for each type of reservoir. For simplicity, the same distribution is assumed to apply at all stages of the reservoir life.		
	OFFSHORE OIL RESERVOIR or OFFSHORE SALINE AQUIFER or ONSHORE COAL FIELD		
	PANEL MEMBER E	PANEL MEMBER F	SELECTED FOR MODEL
Release rate modification factor			
5%ile	0.1		0.1
Median	0.5	0.5	0.5
95%ile	2		2
Justification	See no reason to modify industry experience, felt difficulty in answering this	A linear decay profile would be a good first assumption	

II.4 RESULTS

II.4.1 Annual Leak Frequencies

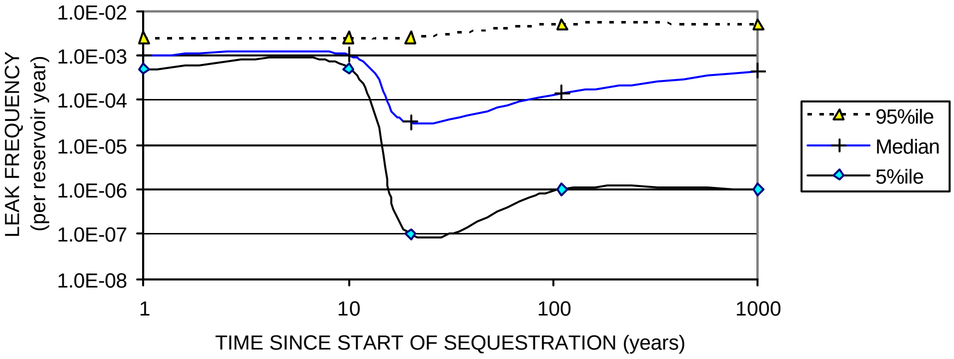
The following calculations refer to the offshore oil reservoir. Given the uncertainties in estimating risks for even this scenario, it is not considered feasible to estimate differences in risk for other reservoir types.

There was general agreement during the SWIFT that the likelihood of leaks from a CO_2 reservoir during the sequestration process would be expected to be similar to that from hydrocarbon reservoirs during production. Based on the data in Section II.2.3, this would be expected to be approximately 10^{-3} per reservoir year.

After the reservoir is sealed, the uncertainty about leak frequency is greater. Unlike abandoned hydrocarbon reservoirs, the CO_2 reservoir will be under pressure. The degradation processes for the sealed well and the reservoir behaviour over long timescales are very difficult to predict. It might be expected that the annual leak frequency would be lower immediately after sealing the reservoir, and would subsequently rise over time. However, it was not possible to conclude with any confidence even whether the average leak frequency would be higher or lower than for hydrocarbon production.

The same conclusion is shown in numerical form by the values selected from the Delphi panel inputs. Figure II.4.1 shows the leak frequency as a median and 90% confidence range at different times after the start of sequestration. The reservoir is assumed to be full and sealed after 10 years.

Figure II.4.1 Annual Leak Frequencies through Reservoir Life

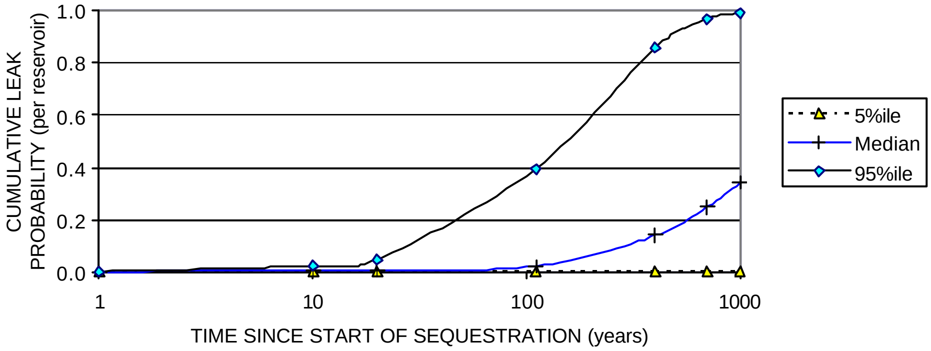


The uncertainty (defined by the 90% confidence range) is less than an order of magnitude while sequestration is taking place, but rises to 4 orders of magnitude soon after sequestration is complete, and does not change greatly during the next 1000 years. The trend shown by the median values is not significant when set against these very large confidence ranges. Although this is only based on the responses of 2 panel members, it reflects the great uncertainty felt by the other panel members who did not give quantitative responses. This type of uncertainty can only be resolved by further research and field experience.

II.4.2 Cumulative Leak Probability

The annual frequencies above can be integrated to give the cumulative probability of a leak during the 1000 year assumed reservoir design life. In doing so, the uncertainties are assumed to be correlated (i.e. likely to act in the same direction in each year) rather than independent (which would tend to cancel out in the long term). Figure II.4.2 shows how the resulting leak probabilities grow during the reservoir life.

Figure II.4.2 Cumulative Leak Probabilities through Reservoir Life



The median leak probability in 1000 years is 0.34, but the confidence range is from 0.006 to 0.99. In other words, while an optimistic view suggests a good probability of containment throughout the reservoir life, a pessimistic view suggests that a leak is virtually inevitable over a 1000-year timescale. It seems unlikely that this uncertainty could be reduced on the basis of current knowledge, even with a much larger Delphi panel.

II.4.3 Release Rate

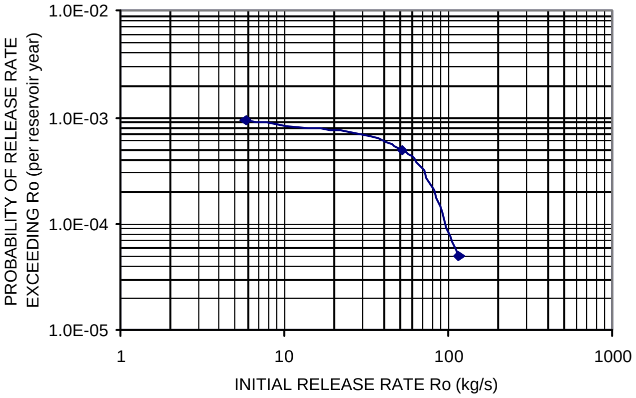
The initial release rate in a leak from a CO_2 sequestration reservoir is very difficult to represent quantitatively, as it might vary from very small to very large, and there is little information on which to base a probability distribution characterising either the natural variability (between one leak and another, or between one reservoir and another) or the uncertainty concerning what this distribution might actually be.

In offshore risk analyses, the initial release rate is normally taken as 5x the production rate. If this assumption were applied in this case, the release rate could be taken as 5x the initial sequestration rate for one well. Based on the assumptions above, this would be 4000 tonnes/day (46 kg/s) of CO_2.

In practice, the release rates from sequestration reservoirs once sealed could be much higher or lower, depending on the flow path. Although very minor seepages might be considered most likely, these are difficult to model using the present approach, which assumes discrete events, and have in effect been eliminated by defining the leak frequency as "significant" leaks of at least 10 tonnes/day (0.1 kg/s) of CO_2.

The only input from the Delphi panel on the release rate was a median of 4500 tonnes/day (90% range 500 to 10,000 tonnes/day). In the present analysis, DNV have adopted this directly. It is plotted in Figure II.4.3 as an exceedence distribution, showing the frequency (per reservoir year) of leaks exceeding any given release rate. This is based on a leak frequency of 10^{-3} per reservoir year.

Figure II.4.3 Probability Distribution for Initial Release Rate



Given the difficulty in obtaining any values for this parameter, it was not feasible to quantify the associated uncertainty. However, the uncertainty in the frequency of any given release rate will be no less than shown in Figure II.4.1 for the basic release frequency. Additional uncertainty in the release rates could amount to a factor of 5. For example, it would be credible, given the state of current knowledge to assume that the releases occurred at the sequestration rate, rather than 5x this value.

II.4.4 Release Quantity

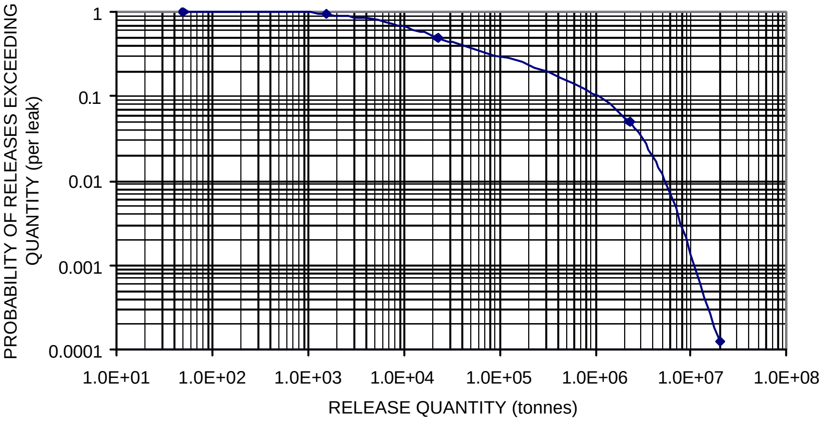
The quantity released in any leak is represented by the product of the parameters R_o D M in the model (Section II.3.4), and by the responses to Questions 2 3 and 4 of the Delphi exercise. These are each probability distributions with ranges that reflect both uncertainty in the parameter values and variability between leak events. The selected values (medians and 90% ranges) are:

- Initial release rate, R_o = 4500 tonnes/day (range 500 to 10,000)
- Release duration D = 10 days (range: 1 to 1000)
- Release rate reduction parameter M = 0.5 (range: 0.1 to 2)

In this case, the uncertainties in each parameter are likely to be independent. Hence, the probability of simultaneously having less than the 5%ile values of R_o D and M is expected to be 0.05^3, i.e. approximately 0.01%. The distributions could be combined using a Monte Carlo sampling technique, but this is not considered justified at present, given the uncertainty in the parameters and distribution shapes. Instead, each half of each distribution is assumed to be log-normal between the specified median and 5%ile or 95%ile. The uncertainties can then be combined using analytical methods (IPCC 2000). In future work, more rigorous modelling of the distributions would be desirable, distinguishing between parameter uncertainty and natural variability.

The above method gives an overall median release quantity of 22,500 tonnes and a 90% range from 1500 to 2.3 million tonnes. Figure II.4.4 shows the exceedence distribution. The mean release quantity is strongly influenced by the tail of this distribution. Numerical integration of Figure II.4.4 gives a value of 270,000 tonnes. Based on judgement, uncertainty in this value is considered to be at least a factor of 10, i.e. a confidence interval from 27,000 to 2.7 million tonnes.

Figure II.4.4 Probability Distribution for Release Quantities



II.4.5 Probability-Weighted Release Quantity

The release quantities estimated above can be multiplied by the leak probabilities to give the probability-weighted quantities of CO_2 released in leaks during the reservoir lifetime. This is represented by $Q_L = P \times Q_R$ in the model in Section II.3.4. Multiplying the mean release quantity of 270,000 tonnes by the cumulative leak probability in 1000 years of 0.34, the expected quantity released during the reservoir lifetime is 92,000 tonnes (CI: 1600 to 960,000). The confidence range has been obtained by assuming that the uncertainties in probability and quantity are independent, and combining as above.

II.4.6 Release Fraction

The above risks may be set in context by expressing the amount released as a fraction of the amount sequestered, as follows:

- The mean release quantity of 270,000 tonnes given a release represents 0.7% of the amount sequestered (CI: 0.07 to 7%).

- The probability-weighted release quantity of 92,000 tonnes represents 0.2% of the amount sequestered (CI: 0.004 to 2.4%).

II.5 CONCLUSIONS

The main conclusion from this analysis is that it is currently impossible to quantify with any confidence the likelihood of accidental releases from CO_2 sequestration reservoirs. The majority of the experts that we consulted, even after being involved in a detailed preparation exercise, retained the view that it was impossible to make reliable quantitative risk estimates in this field. Compared with other fields where this type of judgement-based risk quantification has been made (e.g. Vaughan & Spouge 2002), the main differences for CO_2 sequestration are the lack of detailed research and field trials, and the difficulty of assigning generic risks to what in reality would be extremely site-specific. On the positive side, this suggests that further research, combined with consideration of specific reservoirs, could eventually permit quantitative estimates of the risks. However, the negative consequence of this view is that it would be impossible to obtain quantitative input to current decision-making about CO_2 sequestration.

DNV continues to believe that quantitative risk estimates can be useful inputs to decisions about CO_2 sequestration, provided that their uncertainties are fully appreciated. These uncertainties are probably more important than the estimated likelihood of accidental releases, since they indicate the need for research, and serve as a benchmark against which developments in knowledge can be evaluated. In some cases, they can also indicate whether extremely confident or pessimistic predictions about the security of CO_2 sequestration lie outside the range of scientific uncertainty.

The following risk estimates are therefore made by combining DNV's judgement and experience in risk analysis, available data on blowouts in offshore hydrocarbon production (Section II.2), the qualitative insights gained in the SWIFT exercise (Appendix I), and the quantitative inputs from the two experts who were content to support this approach (Section II.3.5). For each result, confidence intervals are given representing the range in which we judge there is a 90% probability that future, more accurate risk studies would lie.

Key quantitative risk results are:

- The frequency of significant leaks (defined as greater than 10 tonnes/day) during the sequestration process is estimated as 10^{-3} per reservoir year (CI: 5×10^{-4} to 2.5×10^{-3}), based on experience in offshore hydrocarbon production. Once the reservoir is sealed, the uncertainty range rises to 4 orders of magnitude, and does not change greatly during the next 1000 years.
- The cumulative probability of significant leaks during the 1000 year design life for the reservoir is estimated as 0.34 (CI: 0.006 to 0.99). In other words, while an optimistic view suggests a good probability of containment throughout the reservoir life, a pessimistic view suggests that a leak is virtually inevitable over a 1000-year timescale.
- The probability distribution of initial release rates is estimated to have a median of 4500 tonnes/day (90% range 500 to 10,000 tonnes/day).
- The mean release quantity is estimated as 270,000 tonnes (CI: 27,000 to 2.7 million) given a release. This represents 0.7% of the amount sequestered (CI: 0.07 to 7%).

- The probability-weighted release quantity is estimated as 92,000 tonnes (CI: 1600 to 960,000) during the reservoir lifetime. This represents 0.2% of the amount sequestered (CI: 0.004 to 2.4%).

The above estimates refer to offshore oil reservoirs. It did not prove possible to estimate significantly different values for other reservoir types. The values are judged averages across many possible reservoirs. The variability between individual reservoirs could be greater than the ranges shown.

The estimates indicate that, even though a release from a CO_2 sequestration reservoir is quite likely during its life and would probably be large if it did occur, there is a high probability (95%) that the average quantity released during a reservoir life would be a small fraction (less than 2.4%) of the amount sequestered. This takes account of the very large uncertainties in the risk estimates. However, DNV recognise that the estimates are all very speculative, and that the methodology attracted the support of only a minority of the experts that we consulted.

II.6 REFERENCES

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