# Deep Geological Storage of $CO_2$ on the UK Continental Shelf: Containment Certainty

## Supplementary Note D: Well Leakage Risks

February 2023

Any enquiries regarding this publication should be sent to us at: alt.formats@beis.gov.uk

# Contents

# Quality Control

| | |
|---|---|
| **Issue/revision** | V1 |
| **Remarks** | First issue |
| **Date** | 23rd January 2023 |
| **Prepared by** | L Hardiman<br>D Hartgill<br>N Robertson |
| **Internally reviewed by** | D Cook, WSP<br>J Gluyas, GeoEnergy Durham |
| **Externally reviewed by** | C Vincent, British Geological Survey<br>E McKay, Heriot-Watt University<br>D Buchmiller, DNV |

# 1. Supplementary information: well data sources

## 1.1 Introduction

This document provides additional technical information that underpins our assessment of the containment certainty of deep geological storage of $CO_2$ in offshore sites on the UK continental shelf (UKCS). The aim of this document is to present a thorough explanation and justification of the key findings and conclusions of the main report [1], and is aimed at a technically experienced engineering audience.

Large scale geological storage of $CO_2$ is yet to be undertaken on the UK continental shelf (UKCS) and so estimating the risk of leakage from $CO_2$ wells relies on failure data from relevant analogous sites globally. The topic of potential leaks from CCS wells has been the subject of considerable study over several decades, and $CO_2$ injection has been undertaken worldwide for more than 40 years for Enhanced Oil Recovery (ref Duncan, 2009 [2]) and 25 years for $CO_2$ storage  (ref Furre, 2017 [3]). There is therefore a significant body of research that can be used to estimate the probability of different sizes of leak from a well penetrating the cap rock of a $CO_2$ geological store. However, relatively few studies have estimated leak rates linked to probabilities and durations as this study has attempted and often, they only contain part of the picture.

In estimating the probability of leakage from $CO_2$ wells, two approaches have been taken:

1. A review of literature. Relevant data for active and inactive wells on $CO_2$ stores on the UKCS has been extracted and normalised into common units to allow comparison and analysis between data sources. This is addressed by this Supplementary Note.
2. Access to the WellMaster database provided by Peloton has allowed a review of real well failure data and the creation of a representative well model with overall failure rates built up from individual component failure rates. This is addressed in Supplementary Note C.

## 1.2 Method

In preparing this literature review report, over 100 separate sources have been reviewed. Of those, 29 sources provided estimates of failure rates or leak volumes that were relevant to this analysis. There has been considerable variety of approach taken in addressing these risks within the reviewed source documents. For example, different studies have estimated leak rates in $CO_2$ store wells by considering:

- Failure databases from oil and gas well service records.
- Failure databases from gas storage well service records.
- Fugitive emissions measured from decommissioned onshore oil and gas wells in Canada and USA.
- Numerical modelling of typical decommissioned wells.
- Numerical modelling of cement barriers under $CO_2$ attack.
- Test results from laboratory tests of cement with $CO_2$.
- Actual service data from $CO_2$ injection wells used for Enhanced Oil Recovery (generally also onshore in the US).
- Production wells from naturally occurring $CO_2$ stores (exploited as source $CO_2$ for EOR operations).
- Blow out data for oil and gas wells.
- Blow out data from incidences of injected steam intersecting old injection wells.
- Blow out data from the $CO_2$ well blow out in Sheep Mountain, Colorado.

To provide an overall estimate of store leakage risk, it is necessary to address all types of wells that could exist in the store:

- $CO_2$ injection wells which could be new construction or re-purposed oil and gas wells.
- Decommissioned wells (includes previously drilled wells at the storage site, e.g., oil and gas wells (production, appraisal or exploration) and previously active $CO_2$ wells of all types after closure of the store. It also includes previously drilled wells outside the immediate area of the store which could provide a route to surface for geological leaks migrating laterally from the store.
- Monitoring wells.
- Brine producing wells (used to reduce pressure on saline aquifer stores).

In the literature, the majority of which relates to oil and gas wells, the main differentiator is between active (producing or injecting) and inactive (decommissioned) wells. This analysis has continued this categorisation. Active wells can leak internally past the mechanical barriers in place or externally through the cement between the casing and the geological formation. With inactive wells, the mechanical barriers have been removed and replaced with two or more cement plugs for permanent isolation from the reservoir and so leakage would result from seepage past or through the cement plugs and from there through the well bore casing or around the outside of the well (casing cement sheath).

Monitoring wells and brine producing wells are specific to $CO_2$ storage and so are not addressed in the literature, but as the risks associated with these wells is similar to those related to a $CO_2$ injector well their design and construction will be similar and will, therefore, have similar failure rates. However, it is likely that the overall probability of $CO_2$ leakage from monitoring and brine producing wells will be lower as they would not normally be expected to be in contact with the $CO_2$ stored. As it has not been possible to assign a quantum to this probability reduction due to a lack of available data, probabilities are assumed to be the same as for injection wells which will be conservative.

An excel workbook (supplementary note E) has been created to capture and analyse data extracted from the individual papers. A worksheet tab has been created for each paper to replicate the key data extracted from each paper.

Three key items of information were sought:

- Probability of a leak to the environment.
- Leak rate associated with the probability.
- Duration of the leak.

Although a loss of containment in the storage complex will trigger remedial action to recover the situation, the $CO_2$ involved would not necessarily reach the atmosphere due to the thickness of the storage site overburden. For loss of containment through a well the outcome is more likely to be a release into the environment (sea or atmosphere) as the well provides a conduit through the overburden to the seabed.

Probabilities are converted into probability of a leak per well per annum (or per well for continuous leaks). Where leaks were not directly addressed in the source document, but data was provided on the frequency of failure of single barriers this was also recorded. Leak rates have been converted into equivalent Tonnes/day (t/d) of $CO_2$[1] and durations recorded in days. A comparison table was created in a single worksheet with three columns for data from each paper. These columns were replicated on the individual paper worksheets to allow easy referencing and transfer of data into the comparison sheet.

With all the data collected in the comparison sheet, the range of leak rates and associated probabilities are comparable as they have been normalised on the basis of t/d of $CO_2$. In reviewing and comparing the data from these diverse sources, the leak rates have been fitted into four categories of leak:

[1] It is to be noted that this method of converting hydrocarbon release rates to $CO_2$ release rates is likely to be conservative due to the differences in thermodynamic properties and flow properties of $CO_2$. Lindeberg et al in "Aliso Canyon leakage as an analogue for worst case $CO_2$ leakage and quantification of acceptable storage loss" [22] calculated that if the same leak conditions had occurred for a $CO_2$ injection well as were observed in the Aliso Canyon gas storage well incident, then mass flow rates of $CO_2$ would be ~40% lower than the natural gas flow rates. This calculation excluded any effects due to hydrate deposition along the leak path to reduce flow rates.

- Less than 1 t/d
- Between 1 and 50 t/d
- Between 50 – 1000 t/d
- Greater than 1000 t/d

These have been termed as Seepage, Minor, Moderate and Major Leakage and defined as follows:

| Category | Leak Rate t/d) | Description |
|---|---|---|
| Seep | Less than 1 | Low level nuisance leaks through micro cracks in casing cement or tiny gaps valves or seals. Tolerated as not dangerous and easily dispersed or absorbed into seawater. Detected through testing or targeted monitoring. Expected to be continuous and unnecessary to remediate once established. |
| Minor | 1 - 50 | Failure of well barrier components or cement plugs in decommissioned wells resulting in a minor leak that can be addressed by minor well intervention and component /plug replacement. Detected through failed regular testing (allowable leak rate of 15 standard cubic feet per minute (scf/min) gas equivalent to approx. 1.1 t/d $CO_2$) or wellhead area monitoring. The leak is resolved within six-months of discovery (non-urgent) and can usually be shut in until fixed. |
| Moderate | 50 – 1000 | Similar to the Minor Leak scenario except that there is an escalation in the rate of the leak. As the concentrations of $CO_2$ would be at a level to make a well intervention unsafe for drill crews it is assumed that an emergency relief well is required to stop the flow. Typically, this takes four months to drill the relief well. However, temporary plugging techniques can usually be deployed to shut in the leak while mobilising for repair. |
| Major | Greater than 1000 | Represents an unconstrained flow rate. Occurs more frequently (although still very rare) during drilling & well intervention, when emergency blowout preventers may be effective. Could also be the result of structural failure and so may be difficult to shut in pending repair. Force of release and volumes involved may be a risk to life and assets. May require an emergency relief well to stop the flow. Typically, this takes four months to drill. |

**Table 1 - Leak categories**

Major leaks are often referred to as blowouts in the oil and gas industry. For the purposes of providing more specific terminology for this review we have avoided use of blowout due to its generic nature and its use to describe a wide variety of leak rates in the literature.

These categories should be thought of as average leak rates (in some cases they have been calculated from total volumes leaked and the duration of the leak). In reality, leaks are unlikely to be a constant leak rate. Leaks that are pressure driven may decline over time as the pressure declines through leakage. Leaks that are escaping through small openings in cement or mechanical components may increase over time as flow erodes the aperture of escape and opens up the leak path. It is possible a combination of those scenarios may apply where an initially small leak gets progressively worse, then stabilises and eventually slowly declines as the pressure being released is vented. Very small leak paths through cement have been observed to self-heal as the cement reacts with $CO_2$ and forms calcite, reducing porosity, in turn directly impacting $CO_2$ leakage rates by infilling pathways (Xiao, McPherson 2017 [4]).

Leaks may occur at any time during the life of a well. Although we categorise wells as Active or Inactive, all the $CO_2$ store active wells will become inactive when injection is complete and all injection, monitoring and brine extraction wells will be decommissioned. Active $CO_2$ wells are therefore inactive for the majority of their life post closure of the $CO_2$ store.

### 1.2.1 Data analysis – active wells

The data sources provided a variety of probability of occurrence estimates for different leak rates, but by arranging the data in broad alignment with the categories above it has been possible to ascertain a range of probabilities for each category that aligns with the vast majority of the diverse data sources. This was done initially by inspection of the data comparison table with subsequent more detailed analysis to confirm.

Probabilities of occurrence are generally provided in occurrences per well per year. The exception is the first category of continuous leak where the probability is given as a probability per well since the estimates are based on the proportion of wells historically that have developed continuous seepage of fluid.

Note: In the following tables, blue text is used to indicate data is relevant, red text highlights where there is some aspect of the data that means it isn't directly relevant e.g., it refers to single barrier failure rather than an actual leak to the atmosphere.

**Seeps (Less than 1 t/d)**

The following table shows the seep leakage data from the literature for active wells. Only one of the data sources specifically identified a leak rate associated with the probability. For the others, terms such as fugitive emissions, continuous seep, nuisance leaks identified them to be in the same category.

By inspection, it appeared that a probability range of 0.001 to 0.1 (1E-3 to 1E-1) broadly covered the majority of estimates. How the data source compares with the selected probability range is identified in the third column.

| SEEP Leakage | Probability (per well) | Probability between 1E-3 to 1E-1? | Leak rate specifically linked to probability (t/d) |
|---|---|---|---|
| Peloton Data Analysis | 5.00E-02 | YES | |
| Jewell et al 2012 [5] | 5.00E-05 | NO: LOWER | |
| Alcalde, Flude et al. (2018) [6] | 1.14E-01 | NO: HIGHER | 0.434 |
| Davies et. al. 2014 [7] | 0.1-0.3 | NO: HIGHER | |
| Sandl et. al. 2021 [8] | 7.92E-03 | YES | |
| Marlow 1989 [9] | 6.00E-02 | YES | |
| King & King [10] | 0.18 – 0.34 | HIGHER | |

**Table 2 – Active well seep leak rates in the literature**

On closer investigation, it became apparent there were reasons why some of the outlying data was likely to be unrepresentative. The following table explains these findings.

| Data Source | Comment on applicability |
|---|---|
| Jewell et al 2012 [5] | Active well probability is lower than other data but is a per well/per annum based on anecdotal estimates of poor cement. Assumes a period of 20 years but should perhaps be a per well value as cement is either good or bad and less likely to develop a failure over time. If this were the case, result would be 1.00E-3 per well, which is then consistent with other sources. |
| Alcalde, Flude et al. (2018) [6] | Contains mainly Gulf of Mexico data from a survey and may include single barrier failures and sustained casing pressure incidents, so thought to be an overestimate of leak probability. |
| Davies et.al. 2014 [7] | Offshore wells in North Sea 10-30% have 1 barrier failure. Active well probability is higher than other sources but relates to single barrier failure rather than a leak. Probability of both barriers failing would be expected to be an order lower, and which would then be consistent. |
| King & King [10] | (1) 18% wells with single barrier issues in Norway<br>(2) 34% wells have single barrier issues UK<br>Active well probability is higher than other sources but relates to single barrier failure rather than a leak. Probability of both barriers failing would be expected to be an order lower, and which would then be consistent. |

**Table 3 – Comments on outlying seep data**

The Sandl et.al. data [8] is particularly useful as it physically measured gas migration from 25,000 wells in British Columbia, Canada, so it is a large well population covering wells constructed over many years. It also established that much of the gas migration came not from leaking reservoir gas, but from shallow gas pockets. It was concluded that sealing cement is usually of better quality through the cap rock. These leak rates are therefore likely to be conservative for estimating $CO_2$ well leaks from a store.

Taking this information into consideration the selected range for probability of a 1 t/d or less leak from an active well of between 0.001 and 0.1 appears to be appropriate.

SEEP - ACTIVE

| Data Source | Probability (per well) | Probability (per well) | Modified data | Comment |
|---|---|---|---|---|
| David Hartgill, Peloton Data Analysis | 5.00E-02 | 0.05 | | Failure rate per well. Leak rates <1.1 t/d |
| Jewell et al 2012 | 5.00E-05 | 0.00005 | 0.001 | Adjusted to per well probability |
| Alcalde, Flude et al. (2018) | 1.14E-1 | 0.14 | | Mainly GoM from survey used for report, may include single barrier failures and sustained casing pressure incidents. |
| Davies et. al. 2014 | 0.1-0.3 | 0.1 | | Relates to single barrier failure rather than a leak |
| Sandl et. al. 2021 | 7.92E-03 | 0.00792 | | Data for gas migration from 25,000 wells in BC, Canada. GM studied from shallow gas pockets; unlikely to come from reservoir as sealing cement usually of better quality. So, leak rates from reservoir would be lower still. |
| Marlow 1989 JPT 1146-1153 | 6.00E-02 | 0.06 | | Well pre-1965, modern cement well construction techniques should improve. |
| King & King | 0.18 – 0.34 | 0.34 | | Relates to single barrier failure rather than a leak |

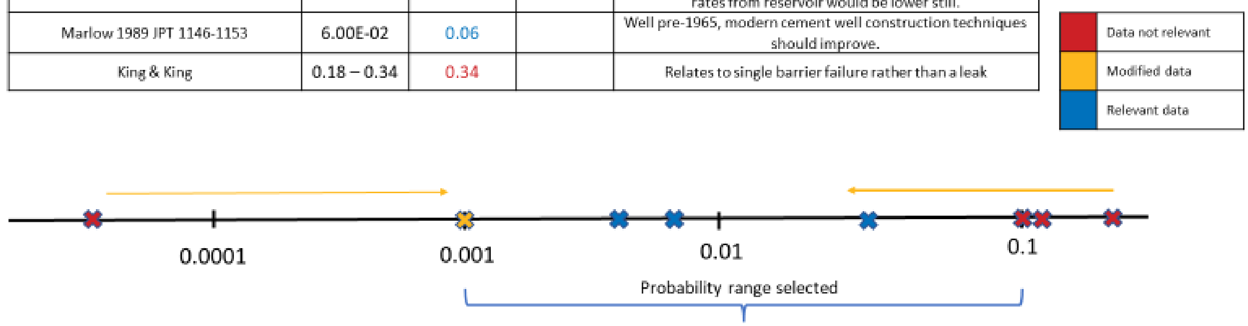



**Figure 1 – Spread of active well seep leak data with selected range**

**Minor leaks (1 – 50 t/d)**

The following table shows the minor leakage data from the literature for active wells. Only three of the data sources specifically identified a leak rate associated with the probability. For the others, terms such as minor leaks, minor blowouts, double barrier failure, or other description of the event identified them to be in the same category.

By inspection, it appeared that a probability range of 0.00001 to 0.001 (1E-5 to 1E-3) broadly covered the majority of estimates.

| Minor Leakage | Probability per well per annum | Probability between 1E-5 to 1E-3? | Leak rate specifically linked to probability (t/d) |
|---|---|---|---|
| HSE HC Release Info 1992-2015 [11] | 1.80E-03 | NO: HIGHER | 1 to 50 |
| Jewell et al 2012 [5] | 4.70E-05 | YES | 4-8 |
| IOGP Blowout Freq. [12] | 8.80E-05 | YES | |
| Richard A. Schultz, et. Al. [13] | 5.90E-04 | YES | |
| PSA [14] | 2.20E-03 | NO: HIGHER | 8.64 – 86 |
| Jordan & Carey 2016 [15] | 1.00E-05 | YES | |
| IEA Greenhouse Gas R&D [16] | 5.1E10-5 | YES | |

**Table 4 – Active well minor leak rates in the literature**

On closer investigation, it became apparent there were reasons why the PSA data was likely to be unrepresentative. The following table explains this finding.

| Data Source | Comment on applicability |
|---|---|
| PSA [14] | PSA data is well integrity data which includes wells with 1 barrier failed and degraded second barrier and split by leak rates (where a leak occurs). Probability is higher than the other data sources, which may reflect that data includes wells not actually leaking. It is thought this will be an overestimate of the probability of a (minor) leak. |

**Table 5 – Comments on outlying minor leak data**

The other data point outside the selected range is the analysis performed for this report of HSE gas release data 1992 - 2015 [11]. This data base lists all leaks reported to the HSE including amounts leaked and duration of leaks. Data was extracted for all well loss of containment with leak rate of 1 – 50 t/d. Many of the leaks were very small and all were contained within 1 day, so may not be consistent with the minor leak category addressed by other sources.

Taking this information into consideration the selected range for the probability of a 1 - 50 tonne/day leak from an active well of between 0.00001 and 0.001 appears to be appropriate.

MINOR LEAK - ACTIVE

| Data Source | Probability (per well) | Probability (per well) | Modified data | Comment |
|---|---|---|---|---|
| HSE HC Release Information 1992-2015 | 3.3E-03 | 0.0033 | | Analysis of HSE gas release data 1992 - 2015. All leaks under 1 day duration. |
| Jewell et al 2012 | 4.70E-05 | 0.000047 | | |
| IOGP Blowout Frequencies | 8.80E-05 | 0.000088 | | (Yes, if rounded up) Probability refers to active producer failure one barrier - no leak rate provided |
| Richard A.Schultz, et. al. | 5.90E-04 | 0.00059 | | Data refers to saline Aquifer well; for Depleted oil and gas field probability is 1.3E-4 |
| PSA | 2.20E-03 | 0.0022 | | Active well higher probability, but data includes wells with 1 barrier failed and degraded second barrier (not actually leaking), so a conservative number for leaks |
| Jordan & Carey 2016 pre-print | 1.00E-05 | 0.00001 | | |
| IEA Greenhouse Gas R&D Programme | 5.1E10-5 | 0.000051 | | Categorised for an average loss (could be 50 - 1000 t/d) which would then be consistent with our probability bands. |

| Legend |
|---|
| Data not relevant |
| Modified data |
| Relevant data |

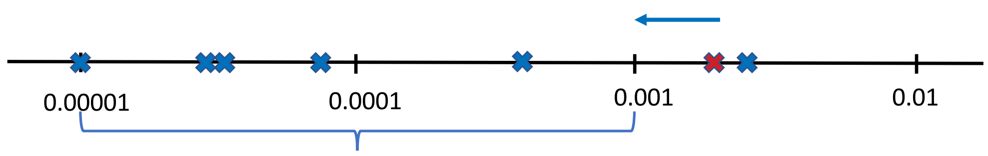



**Figure 2 – Spread of active well minor leak data with selected range**

## Moderate leaks (50 – 1000 t/d)

The following table shows the moderate leakage data from the literature for active wells. Only three of the data sources specifically identified a leak rate associated with the probability. For the others, terms such as significant well release, serious blow outs, mid-size event or other description of the event identified them to be in the same category.

By inspection, it appeared that a probability range of 0.00001 to 0.0001 (1E-5 to 1E-4) broadly covered the majority of estimates.

| Moderate Leakage | Probability per well per annum | Probability between 1E-5 to 1E-4? | Leak rate specifically linked to probability (t/d) |
|---|---|---|---|
| HSE HC Release Info 1992-2015 [11] | 5.43E-04 | NO: HIGHER | 50 - 1000 |
| ZEP-Report [17] | 1.00E-05 | YES | 50 |
| IOGP Blowout Frequencies [12] | 7.20E-05 | YES | |
| Richard A. Schultz, et. al. [13] | 1.60E-05 | YES | |
| PSA [14] | 7.40E-04 | NO: HIGHER | 86.4 - 864 |
| Jordan & Carey 2016 [15] | 1.00E-05 | YES | |
| Sandl et.al. 2021 [8] | 6.87E-05 | YES | |

**Table 6 – Active well moderate leak rates in the literature**

Only one of the data points is thought to be unrepresentative, and this can be to some extent explained by looking closer at the data sources as detailed in the following table.

| Data Source | Comment on Applicability |
|---|---|
| PSA [14] | This source includes data for primary barrier failed and secondary barrier compromised (i.e., not a leak, necessarily) so may be an overestimate for leakage to surface. |

**Table 7 – Comments on outlying moderate leakage data**

The other data point outside the selected range is the analysis performed for this report of HSE gas release data 1992 - 2015. This data base lists all leaks reported to the HSE including amounts leaked and duration of leaks. Data was extracted for all well loss of containment with leak rate of 50 – 1000 t/d. With the exception of one incident all leaks were less than one hour duration, so although the leak rates are moderate the incidents may be minor in comparison to those described by other data sources. This may explain why the probability calculated is outside of the range of the others.

Taking this information into consideration the selected range for the probability of a 50 – 1000 t/d leak from an active well of between 0.00001 and 0.0001 appears to be appropriate.

MODERATE LEAK - ACTIVE

| Data Source | Probability (per well) | Probability (per well) | Modified data | Comment |
|---|---|---|---|---|
| HSE HC Release Information 1992-2015 | 5.43E-04 | 0.00054 | | Analysis of HSE gas release data 1992 - 2015. All leaks under 1 hour duration except G4 incident. |
| ZEP-Report | 1.00E-05 | 0.00001 | | |
| IOGP Blowout Frequencies | 7.20E-05 | 0.000075 | | |
| Richard A.Schultz, et. al. | 1.60E-05 | 0.000016 | | Depleted oil and gas field |
| PSA | 7.40E-04 | 0.00074 | | Includes primary barrier failed and secondary barrier compromised so may be an over estimate for leakage to surface. |
| Jordan & Carey 2016 pre-print | 1.00E-05 | 0.00001 | | |
| Sandl etal 2021 | 6.87E-05 | 0.000069 | | |

| | |
|---|---|
| (red) | Data not relevant |
| (yellow) | Modified data |
| (blue) | Relevant data |

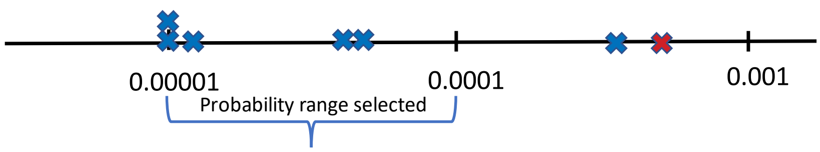



**Figure 3 – Spread of active well moderate leak data with selected range**

## Major Leaks (Greater than 1000 t/d)

The following table shows the major leakage data from the literature for active wells.  The majority of data sources specifically identified a leak rate associated with the probability. For the others, terms such as significant major blowout, full flow blowouts, catastrophic event or other description of the event identified them to be in this category.

By inspection, it appeared that a probability range of 0.000001 to 0.00001 (1E-6 to 1E-5) was broadly appropriate for the leak range, when less relevant data was discounted (discussed later in this section).

| Major Leakage | Probability per well per annum | Probability between 1E-6 to 1E-5? | Leak rate specifically linked to probability (t/d) |
|---|---|---|---|
| HSE HC Release Information 1992-2015 [11] | 2.09E-04 | NO: HIGHER | >1000 |
| ZEP-Report [17] | 3.00E-06 | YES | 5000 |
| Scandpower A/S [18] | (1) 1.1E10-4<br>(2) 4.5E10-5 | NO: HIGHER | (1) 2160<br>(2) 8640 |
| Alcalde [6] | 1.48E-04 | NO: HIGHER | 19440 |
| HSE Health and Safety Laboratory [19] | (1) 6.5E10-6 (Low)<br>(2) 1.2E10-5 (High) | YES | |
| PSA [14] | 1.40E-04 | NO: HIGHER | > 864 |
| Jordan & Carey 2016 [15] | 5.71E-06 | YES | |
| IEA [16] | 2.02E-05 | NO: HIGHER | |

**Table 8 – Active well major leak rates in the literature**

However, over half of the data sources predicted higher probabilities. A closer look at the source documents suggested reasons for this as detailed in the table below.

| Data Source | Comment on applicability |
| --- | --- |
| HSE HC Release Information 1992-2015 [11] | This data base lists all leaks reported to the HSE including amounts leaked and duration of leaks. Data was extracted for all well loss of containment with leak rate of > 1000 t/d. These were serious losses of containment, but all were contained within 1 minute. So, although they have been categorised as major leaks in terms of leak rate, had the category been on the basis of total amount leaked they would not have been comparable with major well blowouts. This category has been associated with 4 months duration to remediate the major leak. The probability of such events will be at least an order of magnitude less that calculated from the HSE events. |
| Scandpower A/S [18] | Norwegian sector well blowout data but includes exploration/appraisal wells which have a higher probability of blowout as the pressure regime is less defined. May be an over-estimate for only production/injection wells. Higher probability is related to 2000 t/d, lower probability for higher release (8000 t/d). It is known from other sources (IOGP [12]) that frequencies of blowout during exploration drilling are an order higher than in production/injection wells. If that was also true for this data, it would then be consistent with the probability ranges selected. |
| Alcalde [6] | Probability calculated from an average of GOM data and 2010 IOGP. Using the same methodology but substituting UK data and latest IOGP figures, gives a revised probability of 7.82E-05. Quotes a leak range of between 25 t/d and 19,440 t/d. Alcalde has tenuous links between probabilities and leak rates. It is suspected that the majority of the sample is leak rates < 1000 t/d i.e., in moderate range. 19,440 t/d is a Macondo equivalent flow rate, which may be unrepresentative of the probability. |
| PSA [14] | Norwegian well integrity data which includes primary barrier failed and secondary barrier compromised wells as well as loss of containment. This is likely to be at least an order of magnitude over estimation of probability of a major loss of containment (full flow) leak. |
| IEA Greenhouse Gas R&D Programme [16] | This probability is based on 16 events, but 9 of these are not well-related, therefore considering only significant well leakage events for the 791,547 well years in the IGU Underground Gas Storage database the probability is 8.8E-6. This is based on incidents from the 1950s to the mid-2000s, so it is expected than the probability for newly drilled wells would be lower. |

**Table 9 – Comments on outlying major leakage data**

It is notable that for these higher consequence/ lower probability events there is a wider spread of data. One of the data sources (Alcalde et. al. [6]) observed that because these are such rare events, the size of the data sample had an impact on the probability calculated. It possibly requires a global data set to provide a true reflection of event frequency as a proportion of well years. This, however, is not available and would include a large number of wells which are poor analogues for those drilled on the UKCS. Although there is an argument for extending the probability range to capture the higher probability estimates, it was concluded that there are sufficient grounds for believing they are over estimated and that consequently the probability range selected is appropriate.

MAJOR LEAK - ACTIVE

| Data Source | Probability (per well) | Probability (per well) | Modified data | Comment |
|---|---|---|---|---|
| HSE HC Release Information 1992-2015 | 2.09E-04 | 0.00021 | | Analysis of HSE gas release data 1992 - 2015. Includes very small short duration leaks, all under 1 min. So not really major leaks in terms of overall leakage. |
| ZEP-Report | 3.00E-06 | 0.000003 | | |
| Alcalde, Flude et al. (2018) | 1.48E-04 | 0.00015 | 0.000078 | Link between leak rates and probabilities tenuous, may be moderate. Using the same methodology but substituting UK data and latest IOGP figures, gives a revised probability of 7.82E-05. |
| Scandpower A/S | (1) 1.1E10-4<br>(2) 4.5E10-5 | 0.00011<br>0.000045 | | Norwegian sector data and includes drilling, so will be an over-estimate for production/injection wells. Higher probability is related to 2000t/d, lower probability for higher release (8000t/d) is consistent with the selected probability band. |
| HSE Health and Safety Laboratory | (1) 6.5E10-6 (Low)<br>(2) 1.2E10-5 (High) | 0.0000065<br>0.000012 | | |
| PSA | 1.40E-04 | 0.00014 | | Norwegian data. Includes primary barrier failed and secondary barrie compromised so likely to be an over estimate of probability of a majo leak. |
| Jordan & Carey 2016 pre-print | 5.71E-06 | 0.0000057 | | |
| IEA | 2.02E10-5 | 0.000022 | 0.0000088 | The figure of 2.02e-5 is based on incidents including non-well related ones, if well related only are included there are 7 incidents in 791,547 well years, a probability of 8.8E-06. |

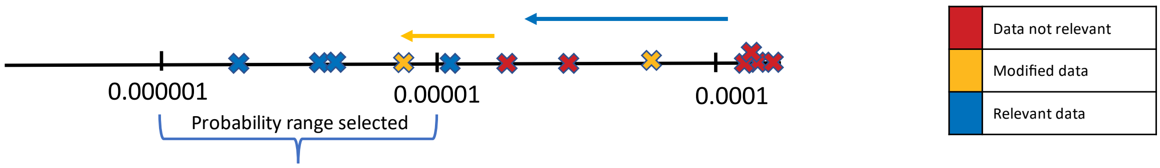



**Figure 4 – Spread of active well major leak data with selected range**

### Active Well Data – Discussion

The overall spread of data is shown on Figure 5.

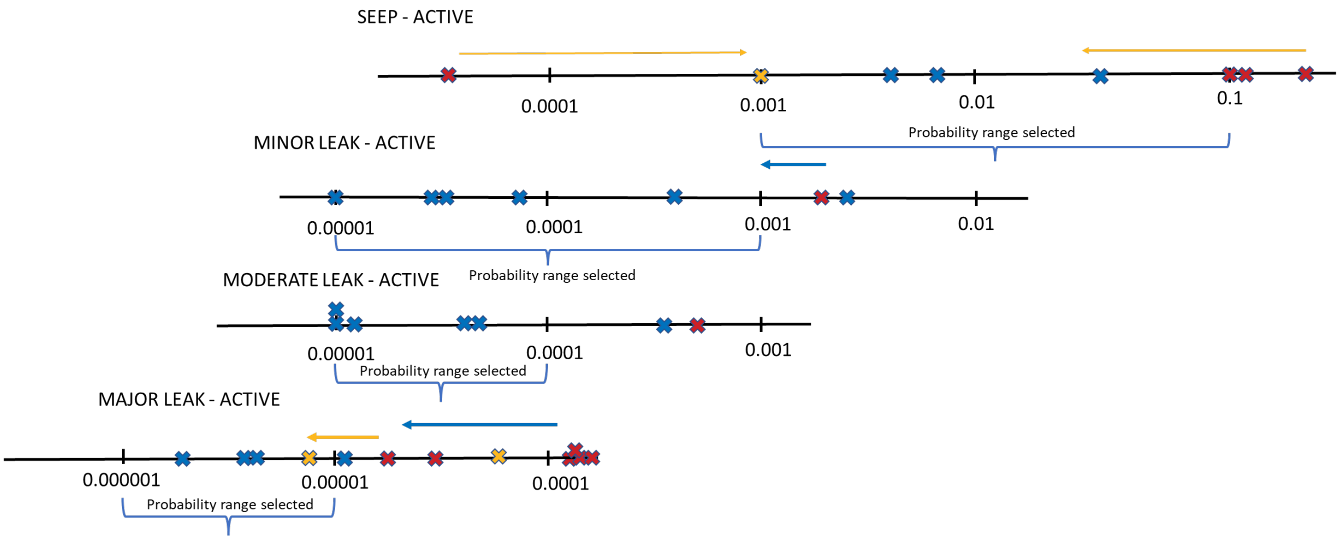



**Figure 5 – Overall spread of active well leak probabilities**

The following points can be noted:

- The probabilities of higher volume leaks reduce with the size of the leak as would be expected.
- The probability distribution of minor and moderate leaks is quite similar, suggesting a single category of leak from 1 to 1000 t/d could have been proposed. No clear explanation of this has emerged, and the data is not detailed enough to investigate further. It can be speculated that above the level of a seep which relates to small gaps in sealing elements (cement or mechanical closure devices) the larger leaks relate to combinations of well barrier failures. Although barriers can fail in many ways and create a variety of different sized leaks, the mechanical failure mechanisms are common (overloading, corrosion, fatigue etc.) which may explain why the probability of this wide range of leak rates is relatively consistent. These failure mechanisms also share the ability to be restored relatively quickly by installing replacement parts.
- There are fewer outlying data sets in the minor and moderate leak categories suggesting less uncertainty surrounding the probability assessments. The only outlying data in both these categories relates to failure of single barriers and not leaks; it could be argued the probability of a leak representing failure of the second barrier in combination with the first would be an order of magnitude lower and thus bring those point into closer alignment.
- Conversely, the uncertainties appear greater for the very small (seep) leaks and the major catastrophic leak events. The reasons for this are suspected to be different.

- Seep leakage is primarily, but not exclusively related to quality of cement bonds between the casing and the surrounding formation. In many cases the gas migrating is not from the reservoir, but higher gas-bearing zones, so probability of $CO_2$ leakage via cement failure may be over-stated when using this as an analogue. The quality of cement varies with application and through time, so for example very old (pre-1965) wells are likely to have more seepage than more recent (post 1997) wells. A broad range of probabilities has been selected for seep leaks, but the expectation is that new $CO_2$ injections wells (and not all planned $CO_2$ injection well will necessarily be newly constructed) are likely to be in the lower part of the probability range selected as a result of more careful cementing techniques. Many authors have made this point, for example Bachu & Watson [20] showed well failure rates had declined after 1994 when tighter regulations were introduced.
- Very large major leakage events are very rare, so probability estimates are influenced by the size of the data sample. Again, there are arguments to suggest that major loss of containment events with active wells in a $CO_2$ store (injection, monitoring and brine producers) is likely to be less frequent than for oil and gas wells (from where the estimates are derived). This is because drilling with $CO_2$ in the reservoir will be less frequent (only when infill wells are drilled). Interventions on wells after injection has started will be another source of major events. Currently, it has been assumed intervention frequency will be comparable with oil and gas wells, but this is still an area of uncertainty and will depend on injection performance of the actual wells during operation.
- As far as the authors are aware there have only been two major leakage (>1000 t/d) events of $CO_2$ through a well (Sheep Mountain event [2], a $CO_2$ production well from a natural $CO_2$ store released approx. 10,526 tonnes of $CO_2$ per day for 1 week and Torre Alfina event [21] in Italy where a Geothermal well released 7200 tonnes of $CO_2$ per day for 3-1/2 days). Both events occurred while drilling into natural $CO_2$ deposits, which is analogous to $CO_2$ storage infill drilling but not $CO_2$ injection wells. However, the number of $CO_2$ wells of any type is a fraction of the number of oil and gas wells, so the data sample is not comparable. For now, major events happening at the same frequency as observed on oil and gas wells should be a reasonable and conservative assumption.
- One data source (Lindeberg [22]) modelled a $CO_2$ well major release based on a historical gas well blowout at Aliso Canyon. This study concluded that due to the different fluid properties of $CO_2$, the event would release only around 60% of the fluid mass released in the gas well. The leak rates associated with the probabilities of occurrence in the table above may therefore be higher than what would actually happen.

### 1.2.2 Data analysis – inactive wells

As with the data for active wells, the data sources provided a variety of probability of occurrence estimates for different leak rates, but by arranging the data in broad alignment with the categories above it has been possible to ascertain a range of probabilities for each category that aligns with the vast majority of the diverse data sources. This was done initially by inspection of the data comparison table with subsequent more detailed analysis to confirm.

Probabilities of occurrence are generally provided in occurrences per well per year. The exception is the first category of continuous leak where the probability is given as a probability per well since the estimates are based on the proportion of wells historically that have developed continuous seepage of fluid.

**Seeps (Less than 1 t/d)**

The following table shows the seep leakage data from the literature for inactive wells. Only two of the data sources specifically identified a leak rate associated with the probability. For the others, terms such as fugitive emissions, continuous seep, nuisance leaks identified them to be in the same category.

By inspection, it appeared that a probability range of 0.001 to 0.1 (1E-3 to 1E-1) covered all the estimates. A study by Harp et.al. [23] which provided no specific data but highlighted that cement quality (measured in permeability) has a huge impact on whether leaks will be present and the size of the leak.

| SEEP Leakage | Probability (per well) | Probability between 1E-3 to 1E-1? | Leak rate specifically linked to probability (t/d) |
|---|---|---|---|
| Peloton Data Analysis | 5.50E-02 | YES | |
| Alcalde, Flude et al. (2018) [23] | 5.40E-02 | YES | 0.630 |
| Y. Le Guen, et. al. [24] | 4.51E-01 | NO: HIGHER | 0.21 - 0.41 |
| Sandl et. al. 2021 [8] | 1.27E-03 | YES | |

**Table 10 – Inactive well seep leak rates in the literature**

The uncertainty effect of cement quality to some extent explains the range of inactive well seep probabilities in the literature, as different service wells (oil/gas/$CO_2$), different age wells, different date of decommissioning and even wells in different geographic areas will have different cement quality inherent in their construction and decommissioning (installation of cement plugs).

Further analysis of the data shows that one of the data sources is significantly higher probability than the others. The following table provides some commentary.

| Data Source | Comment on applicability |
|---|---|
| Y. Le Guen, et. al. [24] | Data derives from modelling of leak paths in an abandoned well over 1000 years. The probability shown has been calculated using the same methodology applied by Jewell in "$CO_2$ Liabilities in the North Sea: An Assessment of Risks and Financial Consequences, a Summary Report for DECC" [5] (which used the same data source) but using all seep leak rates. However, this method derives a probability per well per annum and an annual leak rate from the probability and amount of leakage over 1000 years which assumes linear behaviour over time. Without access to the raw data this introduces uncertainty. When compared to actual observed leakage from other papers, this result appears over conservative. The data is therefore not considered directly applicable when compared against other sources. |

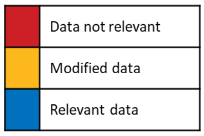
**Table 11 – Comments on outlying seep leakage data**

The Sandl et.al. [8] data is particularly useful as it physically measured gas migration from 25,000 wells in British Columbia, Canada, so it is a large well population covering wells constructed over many years. It also established that much of the gas migration came not from leaking reservoir gas, but from shallow gas pockets. It was concluded that sealing cement is usually of better quality through the cap rock. These leak rates are therefore likely to be conservative for estimating $CO_2$ well leaks from a store.

While it is likely that all inactive wells in the vicinity of the store will be reviewed for leakage risk prior to the permitting process, and therefore permitted stores would be unlikely to have inactive wells with the highest risk present, at this stage it was felt prudent to keep the selected range wide to reflect the potential risk. For a specific store, after all the inactive wells in the vicinity have been identified, it will be possible to be more specific around the probabilities of leakage from individual wells. The probability range selected is therefore possibly conservative but reflects the broadest view of leak probabilities possible until age and condition of inactive wells at the specific sites become available.

SEEP - INACTIVE

| Data Source | Probability (per well) | Probability (per well) | Modified | Comment |
|---|---|---|---|---|
| Peloton Data Analysis | 5.50E-02 | 0.055 | | Failure rate per well. Leak rates <1.1 t/d |
| Alcalde, Flude et al. (2018) | 5.40E-02 | 0.054 | | Based on Marlow (which is active wells) but assumes seepage through cement would be a common mechanism. All wells in this data set were drilled pre 1965 and best cementing techniques not present. Newer well in North sea are likely to have significantly lower leakage. |
| Y. Le Guen et. al. | 4.51E-01 | 0.45 | 0.056 | This is % well leaking after 1000 years, so conservative as assumes all seeps start early. Could multiply by 125/1000 (5.6E-02) for a different approximation if assume leak paths start leaking at a constant rate over time. |
| Sandl et.al 2021 | 1.27E-03 | 0.0013 | | Data for gas migration from 25,000 wells in British Columbia, Canada. GM studied from shallow gas pockets; unlikely to come from reservoir as sealing cement usually of better quality. So, leak rates from reservoir would be lower still. |



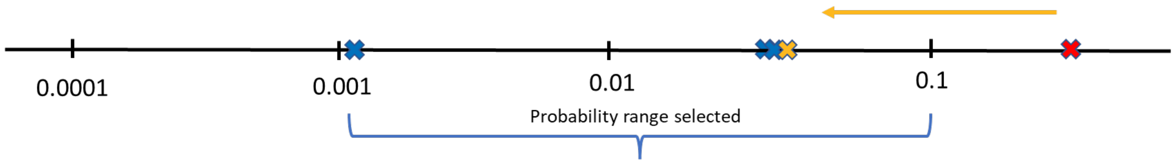




**Figure 6 – Spread of inactive well seep leak data with selected range**

### Minor leaks (1 – 50 t/d)

The following table shows the minor leakage data from the literature for inactive wells. The majority of data sources provided leak rates associated with the probabilities.

By inspection, it appeared that a probability range of 0.0001 to 0.001 (1E-4 to 1E-3) broadly covered the majority of estimates.

| Minor Leakage | Probability per well per annum | Probability between 1E-4 to 1E-3? | Leak rate specifically linked to probability (t/d) |
|---|---|---|---|
| Jewell et al 2012 [5] | 2.20E-04 | YES | 13.7 |
| Alcalde, Flude et al. (2018) [6] | 1.00E-04 | YES | 34 |
| ZEP-Report [17] | 5.00E-05 | NO: LOWER | 7 |
| Y. Le Guen, et. al. [24] | 7.18E-04 | YES | 1.03-12.33 |
| Jordan & Carey 2016 [15] | 2.00E-04 | YES | |

**Table 12– Inactive well minor leak rates in the literature**

Only one data source did not agree and although it is a lower estimate, the following table provides some commentary on it.

| Data Source | Comment on applicability |
|---|---|
| ZEP-Report [17] | Data refers to saline Aquifer well; for Depleted oil and gas field probability is 4E-06. Data interpretation of a number of studies but it is not clear on the methodology. Also refers to 7 t/d as a seep, but this would be a very low probability for a seep when compared with observed frequencies from oil and gas wells reported in other studies. Confidence in the accuracy of this estimate is therefore low. |

**Table 13 – Comments on outlying inactive minor leak data**

Taking this information into consideration the selected range for the probability of a 1 – 50 tonne/day leak from an inactive well of between 0.0001 and 0.001 appears to be appropriate.

MINOR LEAK - INACTIVE

| Data Source | Probability (per well) | Probability (per well) | Modified data | Comment |
|---|---|---|---|---|
| Jewell et al 2012 | 2.20E-04 | 0.00022 | | |
| ZEP-Report | 5.00E-05 | 0.00005 | | Data refers to saline Aquifer well; for Depleted oil and gas field probability is 4E-06 |
| Alcalde, Flude et al. (2018) | 1.00E-04 | 0.0001 | | |
| Y. Le Guen et. al. | 7.18E-04 | 0.00072 | | |
| Jordan & Carey 2016 pre-print | 2.00E-04 | 0.0002 | | |

Data not relevant
Modified data
Relevant data


**Figure 7 – Spread of inactive wells minor leak data with selected range**

**Moderate leaks (50 – 1000 t/d)**

The following table shows the moderate leakage data from the literature for inactive wells. Only one source of data was found and did not specifically identify a leak rate associated with the probability.

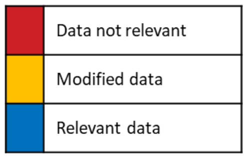
| Moderate Leakage | Probability per well per annum | Probability between 1E-5 to 1E-4? | Leak rate specifically linked to probability (t/d) |
|---|---|---|---|
| IOGP Blowout Frequencies [12] | 2.30E-05 | YES | |

**Table 14 – Inactive well moderate leak rates in the literature**

The selected probability range of 0.00001 to 0.0001 covers the single data source and provides some margin for error for the possibility of higher probabilities given the uncertainty engendered by the lack of data.

MODERATE LEAK - INACTIVE

| Data Source | Probability (per well) | Probability (per well) | Modified data | Comment |
|---|---|---|---|---|
| IOGP Blowout Frequencies | 2.30E-05 | YES | | |



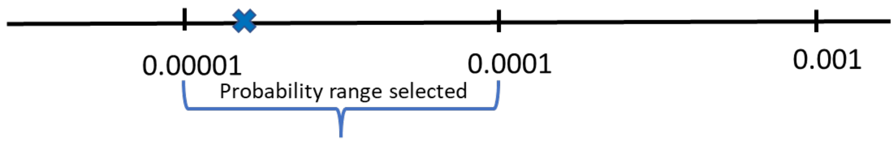




**Figure 8 – Spread of inactive well moderate leak data with selected range**

### Major leaks (Greater than 1000 t/d)

The following table shows the major leakage data from the literature for inactive wells. Three sources on inactive well blowout probability have been found. A probability range of 0.000001 to 0.00001 (1E-6 to 1E-5) fits these data points and is also consistent with the major leak probabilities for active wells.

| Major Leakage | Probability per well per annum | Probability between 1E-6 to 1E-5? | Leak rate specifically linked to probability (t/d) |
|---|---|---|---|
| ZEP-Report [17] | 2.00E-06 | YES | 3000 |
| Alcalde, Flude et al. (2018) [6] | 1.00E-05 | YES | 19440 |
| IEA [16] | 1.30E-06 | YES | |

**Table 15 – Inactive well major leak rates in the literature**

However, inactive well leaks of this magnitude do not appear to have occurred in the industry, or if they have, they are very rare. Because of the simple construction with two or more cement plugs requiring to fail in a manner to create full bore flow, major leak events seem practically unfeasible. Intrinsically, in comparison with active wells, it could be expected inactive major leaks would be an order lower in probability from the same magnitude leaks in active wells. Although the basis of the ZEP report [17] assessment is not clear, it is lower than any of the published estimates of active well major leaks.

Further research on the data on active wells in the IEA Greenhouse Gas R&D Programme report [16] revealed that one of the significant leaks was from an inactive well allowing an inactive probability to be estimated based on 1 event in 791547 well-years as 1.3E-06. However, this was not associated with a specific leak rate. The Alcalde [6] probability is based on Jordan & Carey [15] work on steam injection well blowouts but has been associated with an extreme example of uncontrolled leak rate from the Macondo blowout. The steam injection blowouts are thought to be of lower leak rates and the frequency of Macondo style releases is expected to be lower.

However, in the absence of other data sources, it has been decided to keep the probability range consistent with active wells.

MAJOR LEAK - INACTIVE

| Data Source | Probability (per well) | Probability (per well) | Modified data | Comment |
|---|---|---|---|---|
| ZEP-Report | 2.00E-06 | 0.000002 | | |
| Alcalde, Flude et al. (2018) | 1.00E-05 | 0.00001 | | |
| IEA | | | 0.0000013 | Analysis of inactive significant leak showed 1 event in 791547 well years. |

| | |
|---|---|
| (red) | Data not relevant |
| (amber) | Modified data |
| (blue) | Relevant data |

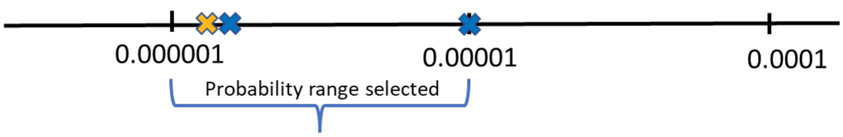



**Figure 9 – Spread of inactive well major leak data with selected range**

### Inactive well data – discussion

The overall spread of data is shown on Figure 10.

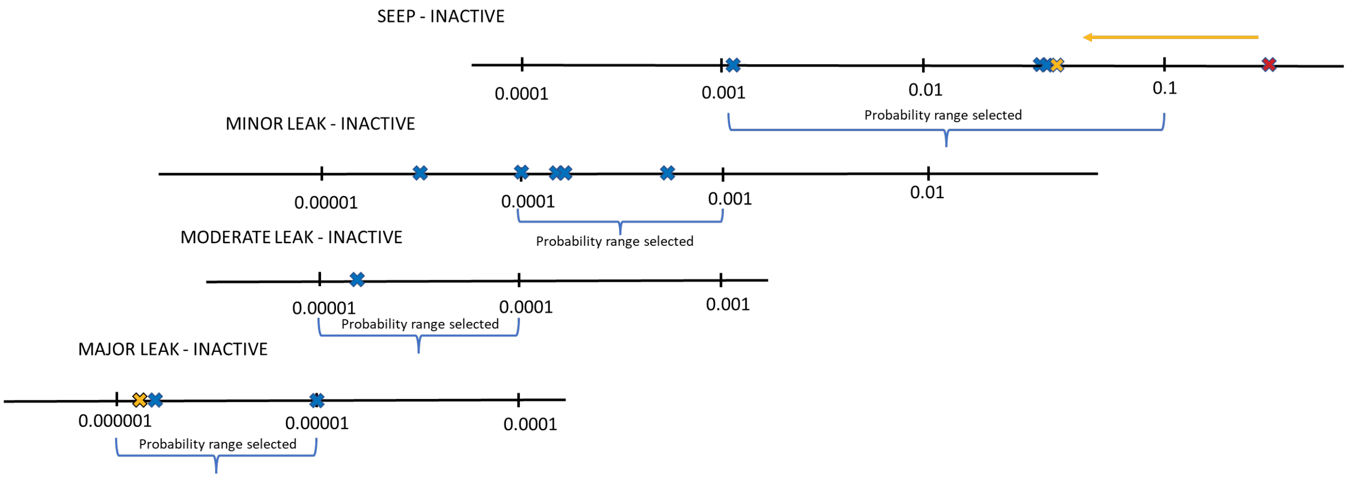



**Figure 10 – Overall spread of inactive well leak probabilities**

The following points can be noted:

- The probabilities of higher volume leaks reduce with the size of the leak as would be expected.
- The quantity of data for inactive wells is lower than for active wells, and in particular for the larger leak rates (only 3 data sources for leaks over 50 t/d).
- Inactive well leakage is primarily, but not exclusively related to quality of cement bonds between the casing and the surrounding formation. This varies with application and through time, so for example very old (pre-1965) wells are likely to have more seepage than more recent (post 1997) wells. A broad range of probabilities has been selected for seep leaks, because, currently, legacy wells in the vicinity of a storage site may be of a variety of well ages and construction quality. However, the expectation is that the majority of UK inactive wells are likely to be in the lower part of the probability range selected due to being of relatively recent construction and also the presence of legacy wells of poor construction will likely mean the store will be deemed unsuitable.
- Although the probability range selected for moderate and major leaks is the same as for active wells, such data as there is suggests the probability of large flows from decommissioned wells is less likely. This is plausible because it is difficult to imagine a failure mode that results in multiple full bore cement plugs being removed almost entirely in order to create full bore flow. For all of the data in this range there is considerable ambiguity around the term blowout. Although, sources have estimated flow rates from an inactive well release the link between probability and flow rate is not strong. The IOGP [12] data covers any unintended release and the Alcalde [6] data references assumes the same leak rates as for active wells but a delay in remediation due to an assumed longer lead time to a leak being discovered. Large flow rate releases from decommissioned wells are virtually unknown. However, due to the lack of data it is prudent to assume the same range to active wells (for which there is more data), noting that this is likely to be conservative.

- The key risk from inactive wells is continuous seep, which could develop into minor leakage and require intervention to remediate. As the majority of abandoned wells are cut several meters below the seabed, any intervention other than drilling of a relief well will be challenging. The permitting process will therefore focus on identifying any inactive wells in the vicinity of the store and require a well specific risk assessment for each, with attention given to what is known about the quality of casing and plug cement.

## 1.3 Remediation

Once a leak or degradation in well integrity has been identified it will be necessary to develop a detailed programme based on the corrective measures plan to:

- Understand the root cause.
- Determine the risk to people, environment, and assets, including the potential for the failure mode to be latent on other wells (increased risk of leakage from all active and inactive wells across the store).
- Monitor the issue until it requires to be or can be remediated.
- Develop options for remediation.
- Perform a risk assessment of each remediation option.
- Execute the preferred remediation and/or monitoring programme.

These steps are common for both active and inactive wells, however the likely remediation options will differ between them.

### 1.3.1 Active well remediation

In a large majority of cases well integrity degradation will be identified prior to a leak outside of the well envelope (casings, cement, tubing hanger, wellhead and Xmas Tree). Where a leak does occur, in most cases it will be possible to isolate it immediately (within 1 day) to stop the leak. Full remediation may take several months at which time injection can be restarted, but if shut in, no leakage will occur in that time period. Well isolation can be accomplished by a variety of actions, for example:

- A shallow tubing/tubing hanger leak could be shut-off by closing the sub-surface safety valve and injecting fluid into the A-Annulus.
- A Xmas Tree wing valve leak coupled with a sub-surface safety valve leak could be controlled, by closing other valves on the tree.
- A deep tubing leak could be controlled by the injection of heavy fluid into the well to push the $CO_2$ out of the area, followed by installing a temporary plug (by wireline) to block the well until a permanent repair can be undertaken.

The UK HSE Hydrocarbon release [11] data allows inspection of gas well leaks to determine frequency, leak rate and duration. As can be seen from Figure 11 below, during the period 1992 to 2015 there were only two well leaks reported to the HSE that took more than a day to be shut-off, although the duration before the well was returned to service was often likely to be significantly longer.

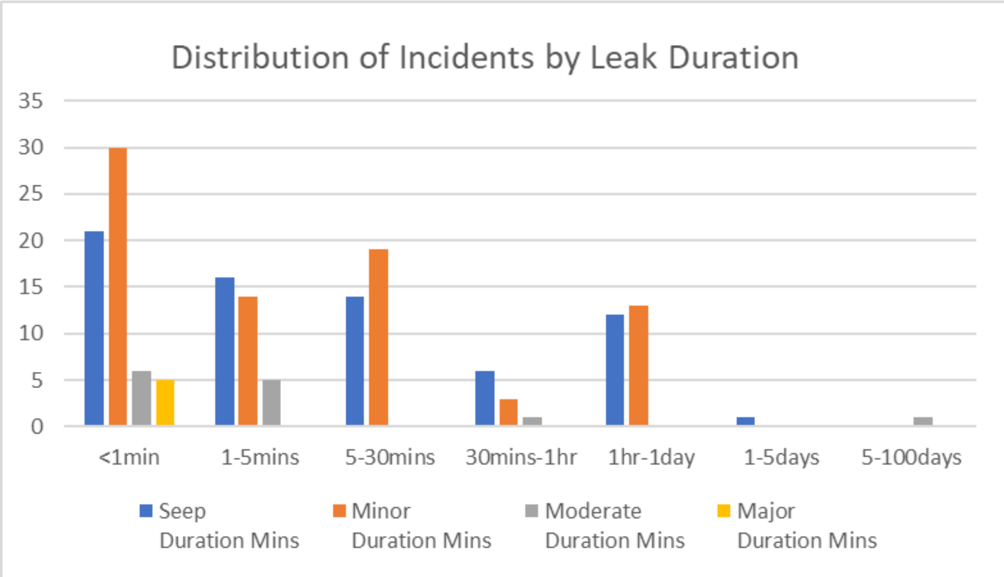



**Figure 11 – Distribution of gas well leak durations by leak rate from UK HSE data 1992 to 2015**

The trigger for well remediation may be an observed leak or a failed single barrier/degraded well integrity. The diagram below (Figure 12) shows an example process to follow when either of these events occur. The thinking behind this process is that repairs would be performed at the earliest opportunity, i.e., before there is a leak beyond the well envelope. Therefore, a remediation would be performed unless either (a) the risk of escalation to a major leak is lower than the risk of the intervention to remediate, or (b) the cost of remediation versus the impact of the leak is deemed unacceptably high. If immediate remediation is not deemed necessary, then the risks of continued injection would be assessed and the well monitored for any worsening of the well integrity.

Once a leak of greater than 1 t/d is observed it is assumed that continued injection and monitoring is not a realistic proposition, although in reality the threshold required will be determined by detailed risk and cost analysis. As demonstrated by the UK HSE data [11] in Figure 11, the vast majority of leaks are shut-in within a day of observation which will reduce volumes leaked from the store.

If it has not been possible to isolate the leak, then it is assumed that above 50 t/d it will not be possible to intervene on the well due to the volume of $CO_2$ emitted in the vicinity causing:

- Concentrations which would result in harm to well intervention crews due to $CO_2$'s toxic effect.
- Lack of buoyancy for floating intervention vessels.

The actual threshold for interventions will be site specific and depend on the location/distribution of the leak.

In the event a serious leak cannot be shut in or a well intervention be performed to rectify the leak, then a relief well would be required. It is assumed that in this scenario a rig would be made available within weeks to drill the relief well to intersect and isolate the original well within 90-days of operations. The well will then be decommissioned, and decision made as to whether a replacement well is necessary.

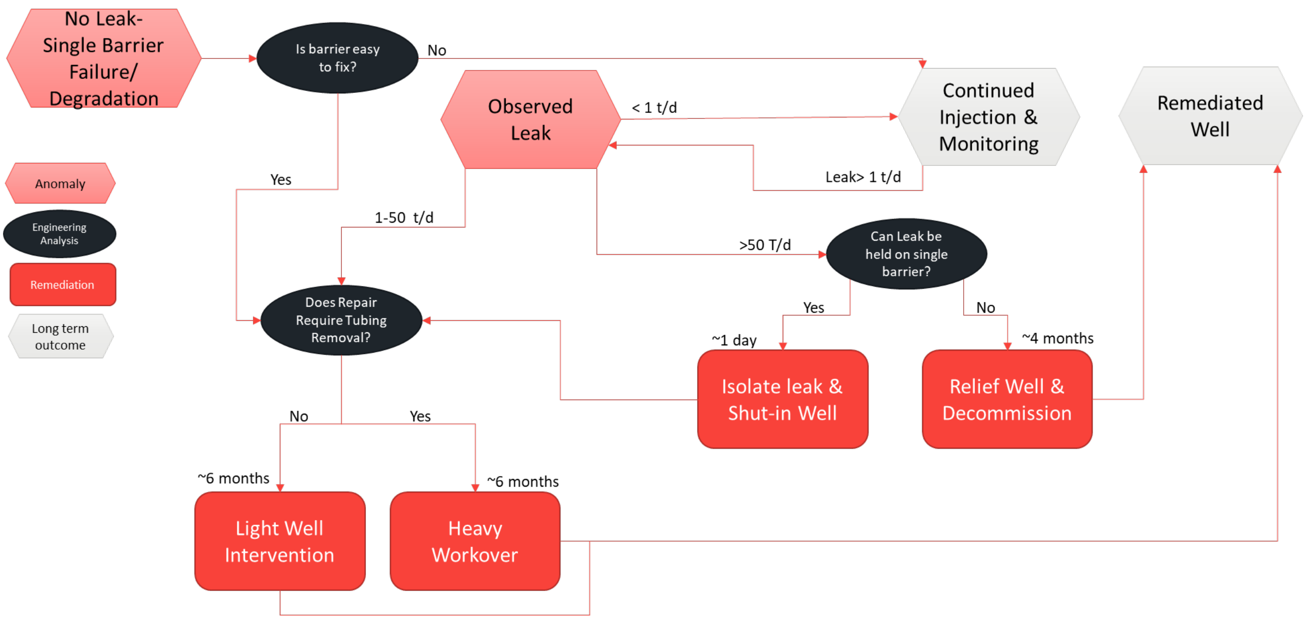



**Figure 12 – Well remediation example decision process**

In the case of a well intervention, i.e., if the leak is controlled or at low enough rates to not endanger the crew, then it is assumed that the remediation may be designed and performed within 6 months. For a light well intervention on a platform where a rig or vessel is not required the duration may be significantly shorter. For a light well intervention on a subsea well a light well intervention vessel (LWIV) or rig would be required; it is usually possible to source one of these within 6 months for a short campaign. For an intervention requiring tubing to be pulled (Heavy Workover) a rig would be required, usually a jack-up for a platform or a semi-submersible for subsea. These durations will be shorter for larger leaks as mobilisation is expedited to prevent harm to people and the environment.

The following assumptions have therefore been made in relation to leak durations to calculate the overall leakage from the store during injection and the post closure period.:

| Leak Category | Leak rate (t/d) | Duration (Days) | Assumption |
|---|---|---|---|
| Seep | < 1 | Continuous | No safety or environmental impact and not cost effective to remediate. |
| Minor | 1 – 50 | 180 | Routine light or heavy well intervention depending on the remediation needed (tubing removed or not). |
| Moderate | 50 – 1000 | 120 | Assumed too high a leak rate for an intervention unless it can be shut in. Expedited relief well to minimise loss of fluid to the environment. |
| Major | >1000 | 120 | Expedited relief well to minimise loss of fluid to the environment. |

**Table 16 – Active well leak durations assumed**

Note: in calculating the overall mass of $CO_2$ released in each of these leak events it has been assumed that the leak continues until the remediation is completed. In all but the most serious well failures this will not be the case and the well will be shut in on a single barrier whilst remediation is organised.

### 1.3.2 Inactive well remediation

In inactive wells (see Figure 13) the tubing, wellhead and Xmas Tree have been removed and plugs (usually cement and mechanical) set at various depths in the wellbore to prevent flow from the reservoir. Often the casings have been cut to inhibit the annulus formed by the casing to the surrounding formation acting as a conduit to flow; a cement plug is then set across this gap in the casing to act as a barrier to flow. At surface the seabed is restored to original with no well equipment visible.

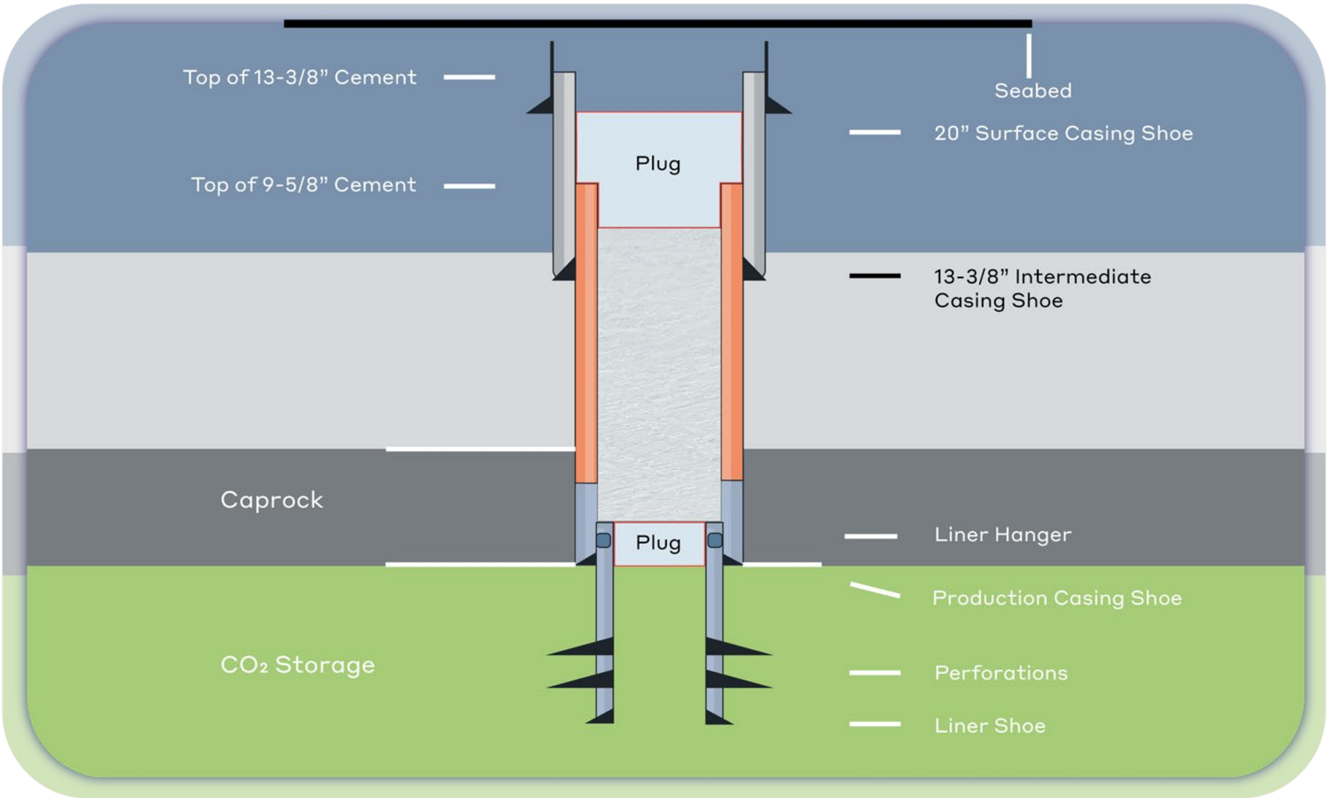



**Figure 13- Inactive well schematic**

The monitoring programme for inactive wells will be simpler, perhaps only consisting of seabed surveys and sampling on a periodic basis to identify leaks from the well at seabed or permanent seabed acoustic monitoring for leaks. Deeper leaks outside the storage complex, where the $CO_2$ has not yet or will never reach the surface are likely only to be detected on seismic, and then only if the leak is of a sufficient volume.

High leak rates from inactive wells are very unlikely, as discussed above, so any leak observed is likely to be in the seep-minor range and development of the leak is likely to progress very slowly. Therefore, it may be judged appropriate to only monitor the leak. This decision will include an assessment of the risk of increased emissions during or following a remediation attempt balanced against the current and anticipated future leak rates, the impact of the leak on humans in close proximity, marine organisms and flora.

There are essentially two remediation methods that may be performed on identification of a leak from an inactive well:

- To locate the well and rig-up to it (connect to the remaining casing and install pressure control equipment) to enable entry into the wellbore to perform an intervention such as casing removal and/or plug installation.
- To drill a relief well to intersect the inactive well from the side and enable similar interventions.

Whilst it is theoretically possible to locate the well and rig-up to it, it is likely that the durations required will exceed those for a relief well and there will be a non-negligible risk that the intervention will not be possible, ultimately resulting in the requirement for a relief well. Given the cost of both remediation methods is dominated by rig day rate contract price, then reducing the duration of the remediation is the preferred option. As a relief well that intersects the inactive well to allow intervention to stop the leak permanently provides more certainty of duration then this is the most likely remediation method followed.

As discussed above a relief well may be planned and executed within 4 months. However, whilst the remediation method is likely to be a relief well regardless of whether the category is minor, moderate or major, we have extended the lead time to remediation for a minor leak to 6 months, reflecting the reduced urgency for resolution in this scenario.

| Leak Category | Leak rate (t/d) | Duration (Days) | Assumption |
|---|---|---|---|
| Seep | < 1 | Continuous | No safety or environmental impact and not cost effective to remediate. |
| Minor | 1 – 50 | 180 | Relief well, not-expedited, to remediate the leak. |
| Moderate | 50 – 1000 | 120 | Expedited relief well to minimise loss of fluid to the environment. |
| Major | >1000 | 120 | Expedited relief well to minimise loss of fluid to the environment. |

**Table 17- Inactive well leak durations assumed**

## 1.4 Results

The results are presented for active $CO_2$ injection wells and decommissioned wells.

| | Leak category | Leak rate (t/d) | Probability of occurrence /well | | Duration (days) |
|---|---|---|---|---|---|
| | | | max | min | |
| Active Wells | Seep | <1 | 1.00E-01 | 1.00E-03 | continuous |
| | Leak category | Leak rate (t/d) | Probability of occurrence /well/annum | | Duration (days) |
| | | | max | min | |
| | Minor | 1 - 50 | 1.00E-03 | 1.00E-05 | 180 |
| | Moderate | 50 - 1000 | 1.00E-04 | 1.00E-05 | 120 |
| | Major | 1000-5000 | 1.00E-05 | 1.00E-06 | 120 |

**Table 18 - Active well results**

| | Leak category | Leak rate (t/d) | Probability of occurrence /well | | Duration (days) |
|---|---|---|---|---|---|
| | | | max | min | |
| Inactive Wells | Seep | <1 | 1.00E-01 | 1.00E-03 | continuous |
| | Leak category | Leak rate (t/d) | Probability of occurrence /well/annum | | Duration (days) |
| | | | max | min | |
| | Minor | 1 - 50 | 1.00E-03 | 1.00E-04 | 180 |
| | Moderate | 50 - 1000 | 1.00E-04 | 1.00E-05 | 120 |
| | Major | 1000-5000 | 1.00E-05 | 1.00E-06 | 120 |

**Table 19 – Decommissioned (inactive) well results**

Very few data sources quoted different probabilities for leaks from wells in saline aquifers and depleted oil and gas fields. However, when they did it was not clear how these different values had been derived. It was felt that the leakage risks between wells in saline aquifers and depleted oil and gas field are likely to be very similar and so no distinction has been made and the results presented above are applicable to wells in both store types.

## 1.5 Discussion

The literature review and analysis has identified some important points:

1. There is considerable alignment in the various sources despite the variation in approach. The majority of the literature addresses very low seepage (sometimes referred to as fugitive emissions in gas wells) or large uncontrolled releases. The variation in assumed flow rates for uncontrolled releases is quite wide.

2. Studies from the oil and gas industry are generally focussed on loss of integrity (e.g., sustained casing pressure or known loss of a barrier) rather than leaks. As explained in the Peloton supplementary note, the loss of a barrier is not necessarily the prelude to a leak and most loss of barrier integrity is restored without any leakage. Barrier loss data is relevant as part of a wider understanding of what can lead to a leakage failure and emphasises the importance of integrity monitoring to provide ‘early warning’ / ‘leading indicators’ to prevent leakage events in wells.

3. Less attention has been given to intermediate leak rates in the literature, which often focusses on loss of integrity, i.e., single barriers rather than leakage. This reflects the fact that the data (almost exclusively) comes from the oil and gas industry where the focus is on reliability rather than loss of containment, given that the loss of a barrier requires remediation activity sooner or later and can lead to well downtime. Probability of leakage is not often presented and is inferred from the likelihood of the second barrier failing whilst the first is compromised and before it is repaired.

4. Studies are often very broad or very focussed. So, for example they may look at integrity of all wells in Western Canada, but this will include many very old wells, some abandoned but not plugged, so large amounts of the population sample are not relevant to $CO_2$ wells in the offshore UK context. Alternatively, many studies are very focussed, looking at just one actual blowout or only looking at gas storage wells or steam injection wells. In this case, it is unclear if the results are only applicable to that application. Despite these limitations no data has been disregarded and it has been noted above where data is outside of the numbers selected and why it is believed to be unrepresentative.

5. Relatively few studies have estimated leak rates, probabilities and durations as has been done here, often they only contain part of the picture. Often leak rates are descriptive only and assumptions have been made on how those descriptions relate to the leak rate categories used in this report. As the data analysis section above has shown, when comparing data, it was suspected leak rates were less than assumed as if this were the case a better match on probabilities would be achieved. However, to be conservative, assumed leak rates have been kept in the category first identified and commentary provided where it is believed there is scope for re-interpretation.

6. Many of the data sets were not collected for the purpose to which they have been put in this report and were not in the form required. Some extrapolation of data has been undertaken to process probabilities into consistent units (per well per annum) and similarly where leak rates were quoted for gas leaks these have been converted to the same mass in t/d of $CO_2$ at standard conditions. Leak rates are expected to be lower for $CO_2$ due to its different fluid properties.

7. A number of studies use numerical modelling to estimate leak rates and/or probabilities rather than real-world observed data. It is often unclear how the models have been calibrated, although, in general we have found that the results correspond well with the real-world observation studies.

## Conservative assumptions made in well risk probabilities and leak rates

The probabilities and leak durations for each of the leak categories have been selected from an analysis of the data. The selection also includes some assumptions. These have been made with a deliberate conservative bias so there will be confidence in the overall well risk results. The following conservative aspects to the selected probabilities are noted:

8. A large amount of the data comes from Onshore Canadian or USA wells. The oil and gas industry onshore North America has a longer history and provides a large data set in comparison to the UK industry. However, there is doubt over how analogous well performance will be compared to $CO_2$ offshore wells in the UK. It could be argued UK wells, whether new or legacy are likely to be newer and constructed under tighter regulations than those in the data and therefore could be expected to have lower failure rates.
9. The source data for the probabilities and leak rates covers a broad range of well types and service. Data consulted comes from oil and gas wells, gas storage wells (with high cyclic loading), $CO_2$ injection wells used for Enhanced Oil Recovery (generally also onshore in the US), production wells from naturally occurring $CO_2$ stores (exploited as source $CO_2$ for EOR operations), and from steam injection wells in Colorado. Although as has been shown, there is broad agreement across the data, it is believed wells newly constructed specifically for $CO_2$ storage or re-examined existing wells permitted for re-use as $CO_2$ storage wells are likely to have a lower probability of failure than the broad data sample considered. UK $CO_2$ wells will have considerable focus on leak prevention.
10. The same is true for decommissioned wells, where the data used covers a wide range of global decommissioned wells abandoned over a long period of time. $CO_2$ stores will be required to go through a detailed permitting process with considerable focus on the leakage risks from any decommissioned wells present in the area. It is plausible that selected stores will have a lower leakage risk from decommissioned wells than the global population of decommissioned wells due to this scrutiny.
11. Monitoring wells and brine producing wells are specific to $CO_2$ storage and so are not addressed in the literature, but as the risks associated with these wells is similar to those related to a $CO_2$ injector well their design and construction will be similar and will, therefore, have similar failure rates. However, it is likely that the overall probability of $CO_2$ leakage from monitoring and brine producing wells will be lower as they would not normally be expected to be in contact with the $CO_2$ stored.

12. Seep leakage is primarily, but not exclusively related to quality of cement bonds between the casing and the surrounding formation. In the data used, in many cases the gas migrating is not from the reservoir, but higher gas-bearing zones, so the probability of $CO_2$ leakage via cement failure may be over-stated when using this as an analogue. The quality of cement varies with application and through time, so for example very old (pre-1965) wells are likely to have more seepage than more recent (post 1997) wells. A broad range of probabilities has been selected for seep leaks, but the expectation is that new $CO_2$ injections wells (and not all planned $CO_2$ injection well will necessarily be newly constructed) are likely to be in the lower part of the probability range selected as a result of more careful cementing techniques. Many authors have made this point, for example Bachu & Watson [20] showed well failure rates had declined after 1994 when tighter regulations were introduced.

13. Very large major leakage events are very rare, so probability estimates are influenced by the size of the data sample. Again, there are arguments to suggest that major loss of containment events with active wells in a $CO_2$ store (injection, monitoring and brine producers) is likely to be less frequent than for oil and gas wells (from where the estimates are derived). This is because drilling with $CO_2$ in the reservoir will be less frequent (only when infill wells are drilled. The number of $CO_2$ wells of any type is a fraction of the number of oil and gas wells, so the data sample is not comparable. For now, major events happening at the same frequency as observed on oil and gas wells should be a reasonable and conservative assumption.

14. One data source [22] states that $CO_2$ flow will be more susceptible to hydrate formation when leaking which would tend to restrict flow. No account of these effects has been taken in the estimates of potential leakage. $CO_2$ flow will be more susceptible when leaking to hydrate formation which would tend to restrict flow. No account of these effects has been taken in the estimates of potential leakage.

15. Major leaks in inactive wells leaks do not appear to have occurred in the oil and gas industry, or if they have, they are very rare. Because of the simple construction after decommissioning with two or more cement plugs requiring to fail in a manner to create full bore flow, major leak events seem practically unfeasible. Intrinsically, in comparison with active wells, it could be expected inactive major leaks would be an order lower in probability from the same magnitude leaks in active wells. However, there is no data to confirm this hypothesis and so conservatively it has been assumed that the probability of these major event is similar to active wells.

16. The category of minor and moderate leaks covers a very wide range of leak rates. There was limited data in the literature that directly linked probabilities with specific leak rates. It is suspected that the vast majority of leaks in those categories are at the smaller end of the range and that larger leaks at the other end of the range are much less likely.

17. Studies from the oil and gas industry are generally focussed on loss of integrity (e.g., sustained casing pressure or known loss of a barrier) rather than leaks. The loss of a barrier is not necessarily the prelude to a leak and most loss of barrier integrity is restored without any leakage. Barrier loss data is relevant as part of a wider understanding of what can lead to a leakage failure and emphasises the importance of integrity to monitoring to provide 'early warning' / 'leading indicators' to prevent leakage events in wells. It is likely $CO_2$ wells in the UK will have a focus on well integrity monitoring and so it could be expected the probability of minor leaks, currently assumed to cover a wide range, will be in the lower part of the range assumed.

## 1.6 Conclusion

Despite the variation in approach from the different source literature authors it is reassuring that this analysis has shown broad alignment on probabilities. There is perhaps less alignment on leak rates, which is why the mid-leak categories are quite wide.

In conclusion, the majority of the literature we have reviewed supports the probabilities and leak rates selected as being those likely to be representative of future $CO_2$ storage well performance. The selected probabilities are then used along with the leak durations (time to restore the system; identify leak and mobilise repair) to calculate (combined with geological leak probabilities and rates) probable leakage for an example store over its injection life and post closure period. The maximum probability of occurrence and maximum leak rate have been used (in addition to other conservative assumptions noted in the body of this note) to provide a very conservative calculation of overall well leakage.

# 2. References


| | |
|---|---|
| [1] | S. Daniels, L. Hardiman, D. Hartgill, V. Hunn, R. Jones and N. Robertson, Deep Geological Storage of $CO_2$ on the UK Continental Shelf: Containment Certainty, 2023. |
| [2] | I. J. Duncan, J.-P. Nicot and J.-W. Choi, “Risk Assessment for future $CO_2$ Sequestration Projects Based $CO_2$ Enhanced Oil Recovery in the U.S.,” in *Energy Procedia, 9th International Conference on Greenhouse Gas Control Technologies (GHGT-9), 16–20 November 2008*, Washington DC, February 2009. |
| [3] | A.-K. Furre, O. Eiken, H. Alnes, J. N. Vevatne and A. F. Kiær, “20 years of monitoring $CO_2$-injection at Sleipner,” in *13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland*, Lausanne, July 2017. |
| [4] | T. Xiao, B. McPherson, A. Bordelon, H. Viswanathan, . Z. Dai, H. Tian, R. Esser, W. Jia and W. Carey, “Quantification of $CO_2$-cement-rock Interactions at the Well-Caprock-Reservoir Interface and Implications for Geological $CO_2$ Storage,” *International Journal of Greenhouse Gas Control,* vol. 63, August 2017. |
| [5] | S. Jewell and W. Senior, “$CO_2$ Storage Liabilities in the North Sea: An Assessment of Risks and Financial Consequences, Summary Report for DECC,” May 2012. |
| [6] | J. Alcalde, S. Flude, M. Wilkinson, G. Johnson, K. Edlmann, C. E. Bond, V. Scott, S. M. Gilfillan, X. Ogaya and R. S. Haszeldine, “Estimating geological $CO_2$ storage security to deliver on climate mitigation,” *Nature Communications,* no. 9, p. Article 2201, 12 June 2018. |
| [7] | R. J. Davies, S. Almond, R. S. Ward, R. B. Jackson, C. Adams, F. Worrall, L. G. Herringshaw, J. G. Gluyas and M. A. Whitehead, “Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation,” *Marine and Petroleum Geology,* vol. 56, pp. 239-254, 2014. |
| [8] | E. Sandl, A. G. Cahill, L. Welch and R. Beckie, “Characterizing oil and gas wells with fugitive gas migration through Bayesian multilevel logistic regression,” *Science of The Total Environment,* vol. 769, 2021. |
| [9] | R. S. Marlow, “Cement Bonding Characteristics in Gas Wells,” *Jounral of Petroleum Technology,* vol. 41, no. 11, pp. 1146-1153, November 1989. |
| [10] | G. E. King and D. E. King, “Environmental Risk Arising From Well Construction Failure: Difference,” *SPE Production & Operations,* vol. 28, no. 04, pp. 323-344, November 2013. |
| [11] | Health and Safety Executive, “Statistics/Offshore Hydrocarbon Releases 1992 - 2016 (.xls),” [Online]. Available: https://www.hse.gov.uk/offshore/statistics/index.htm. [Accessed 13 June 2022]. |

| | |
|---|---|
| [12] | International Association of Oil and Gas Producers, “IOGP Risk Assessment Data Directory Blowout Frequencies Report,” International Association of Oil and Gas Producers, September 2019. |
| [13] | R. Schulz, D. Hubbard, D. Evans and S. Savage, “Characterization of Historical Methane Occurrence Frequencies from U.S. Underground Natural Gas Storage Facilities with Implications for Risk Management, Operations, and Regulatory Policy,” *Risk Analysis,* vol. 40, no. 3, November 2019. |
| [14] | Petroleum Safety Authority Norway, “Summary Report 2020 The Norwegian Continental Shelf Trends in Risk Level in the Petroleum Activity,” Petroleum Safety Authority Norway, Stavanger, 2021. |
| [15] | P. Jordan and W. Carey, “Steam blowouts in California Oil and Gas District 4: Comparison of the roles of initial defects versus well aging and implications for well blowouts in geologic carbon storage projects,” *International Journal of Greenhouse Gas Control,* vol. 51, pp. 36-47, August 2016. |
| [16] | International Energy Authority Greenhouse Gas R&D Programme, “Safe Storage of $CO_2$ from the Natural Gas Storage Industry,” January 2006. |
| [17] | Zero Emissions Platform (ZEP), “$CO_2$ Storage Safety in the North Sea: Implications of the $CO_2$ Storage Directive,” November 2019. |
| [18] | Scandpower AS for Gassnova, “Hazard identification and risk analysis of $CO_2$ storage at Lower Jurassic Johansen Formation,” Gassnova, February 2012. |
| [19] | Keeley, Deborah; Health and Safety Laboratory, “Failure rates for underground gas storage: Significance for land use planning assessments,” Health and Safety Executive, 2008. |
| [20] | S. Bachu and T. L. Watson, “Review of failures for wells used for $CO_2$ and acid gas injection in Alberta, Canada,” in *Proceedings of the 9th International Conference on Greenhouse Gas Control Technologies (GHGT-9), 16–20 November 2008, Washington DC, USA*, Washington DC, February 2009. |
| [21] | J. Lewicki, J. Birkholzer and C.-F. Tsang, “Natural and IndustrialAnalogues for Release of $CO_2$ from Storage Reservoirs: Identification of Features, Events, and Processes and Lessons Learned,” *Environmental Earth Sciences,* vol. 52, no. 3, pp. 457-467, April 2007. |
| [22] | E. Lindeberg, P. Bergmo, M. Torsæter and A.-A. Grimstad, “Aliso Canyon leakage as an analogue for worst case $CO_2$ leakage and quantification of acceptable storage loss,” in *13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland*, 2017. |
| [23] | D. R. Harp, R. Pawar and C. W. Gable, “Numerical modeling of cemented wellbore leakage from storage reservoirs with secondary capture due to thief zones,” in *12th International Conference on Greenhouse Gas Control Technologies, GHGT-12, Energy Procedia*, 2014. |

| | |
|---|---|
| [24] | Y. Le Guen, V. Meyer, O. Poupard, E. Houdu and R. Chammas, "A Risk-Based Approach for Well Integrity Management Over Long Term in a $CO_2$ Geological Storage Project," in *Asia Pacific Oil and Gas Conference & Exhibition*, Jakarta, Indonesia, August 2009. |

This publication is available from: www.gov.uk/government/publications/deep-geological-storage-of-carbon-dioxide-co2-offshore-uk-containment-certainty

If you need a version of this document in a more accessible format, please email alt.formats@beis.gov.uk. Please tell us what format you need. It will help us if you say what assistive technology you use.