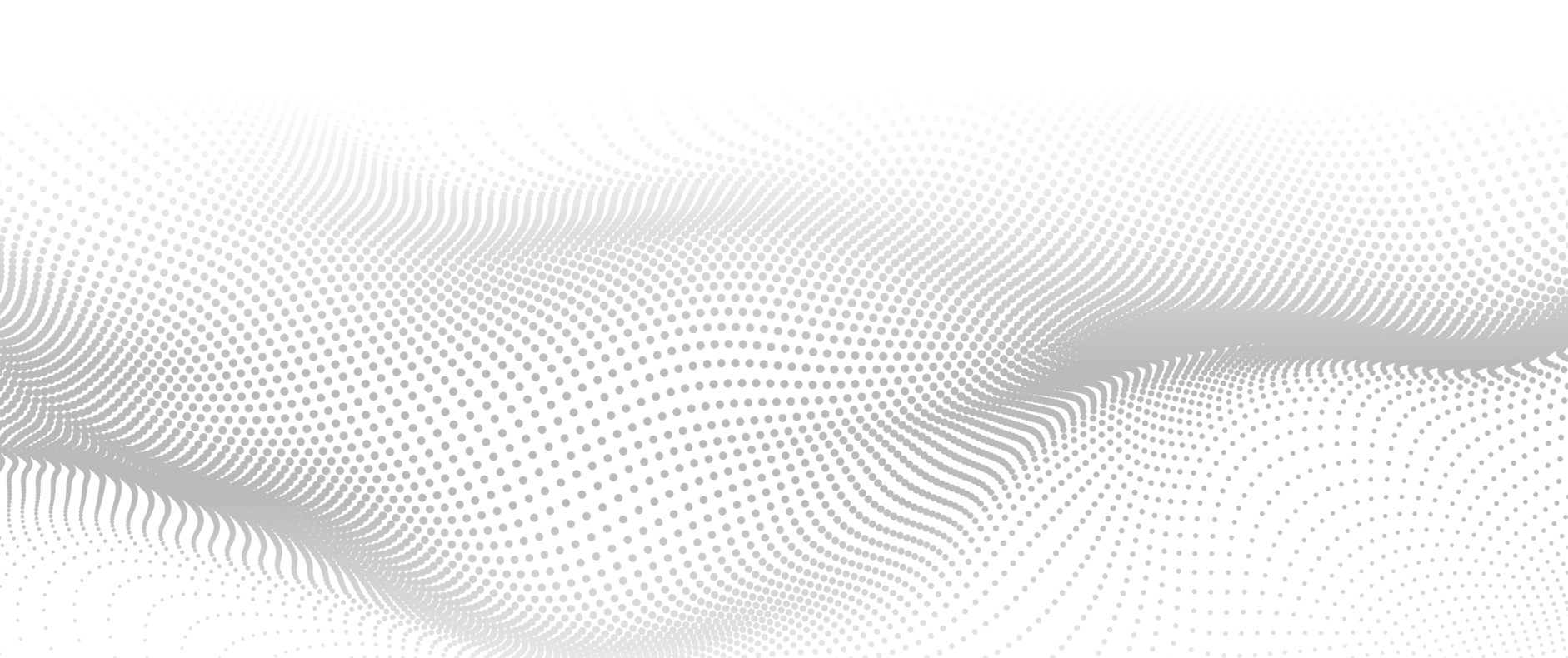
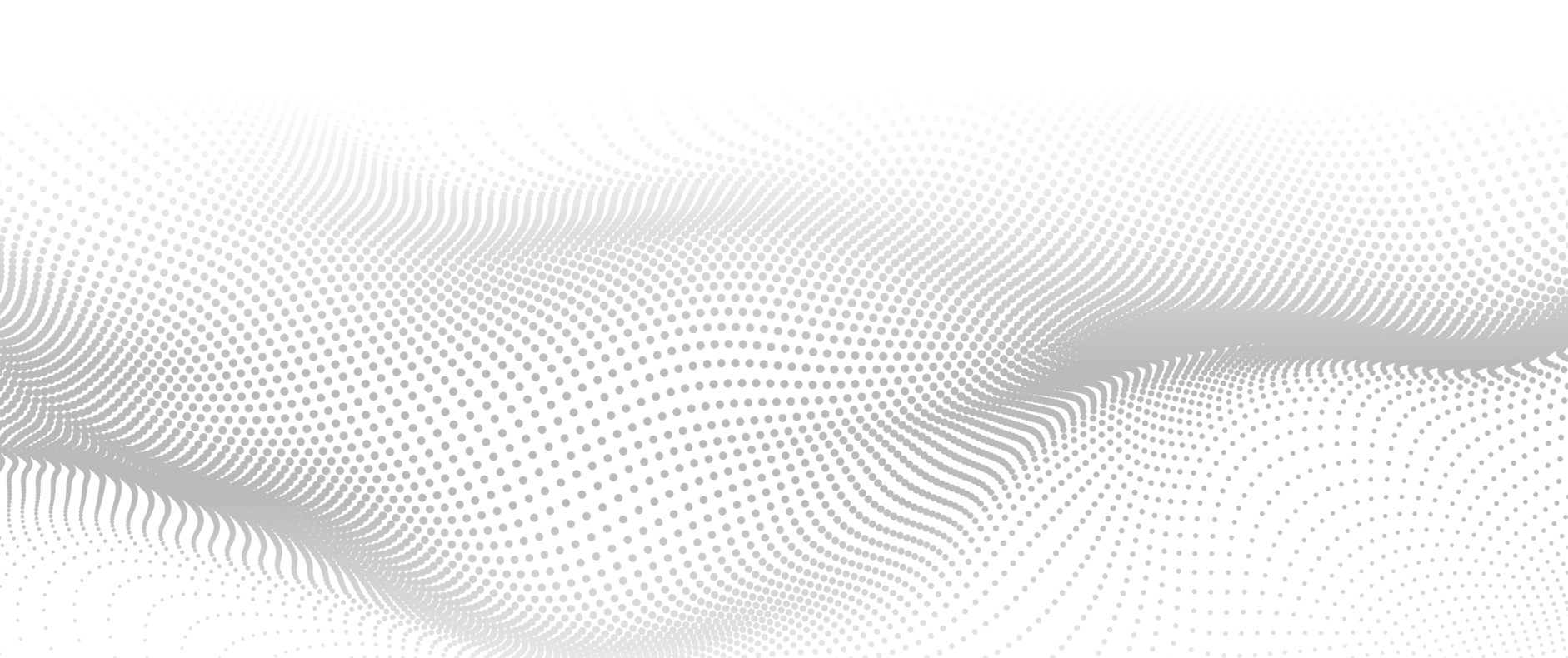
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| Prepared for: | Harbour Energy &  North Sea Transition Authority |  |
| Prepared by: | ERCE |
| Date released to client: | 10 June 2022 |

Independent Review of Harbour Energy’s Early Risk Assessment

Relating to the Victor CO2 Storage Complex





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Approved by: Paul Chernik

Date released to client: 10 June 2022

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10 June 2022

Harbour Energy

Rubislaw House

Anderson Drive

Aberdeen

AB15 6FZ

Attn: Andrew Hood

Dear Mr. Hood,

**Re: P5912: Independent Review of Harbour Energy’s Early Risk Assessment**

In accordance with your instructions, ERC Equipoise Limited has prepared an independent review of Harbour Energy’s Early Risk Assessment relating to the Victor CO2 Storage Complex.

Project execution has been led by the ERC Equipoise’s wholly owned energy transition focused subsidiary, ERC Evolution Limited. In this report both ERC Equipoise Ltd and ERC Evolution Ltd shall be referred to as ERCE.

In this report, ERCE has assessed:

* Harbour’s risk assessment process.
* The quality of Harbour’s documentation.
* The uncertainties and biases which Harbour has in its dataset.
* The subsurface risks Harbour has identified in its ERA, and the associated consequence and likelihood and appropriateness of mitigations.
* Any relevant risks we think Harbour has omitted.

ERCE has not been engaged to verify the technical work completed by Harbour and its suppliers. In the completion of this report, we have assumed that the technical studies supplied to ERCE have been conducted to acceptable industry standards. ERCE has also not been engaged to assess risks at the interface between the subsurface and surface operations and interfaces with emitters. We assume that this is being assessed as part of a separate risk study. Finally, in this engagement ERCE has not assessed how nearby reservoirs, such as those within the Viking field could be used as part of the area CCS development strategy or form part of the regional mitigation plans.

**Use of the Report**

ERCE understands that this report has been prepared for the purposes of being included, in its entirety, in a storage license application process with the UK North Sea Transition Authority and hereby consents to the disclosure of this report in that process. This report may not be used for any other purpose without the prior written approval of a Director of ERCE. Any other third party, besides the UK North Sea Transition Authority, to whom the client discloses or makes available this report shall not be entitled to rely on it or any part of it

Harbour Energy agrees to ensure that any publication or use of this report which makes reference to ERCE shall be published or quoted in its entirety and Harbour Energy shall not publish or use extracts of this report or any edited or amended version of this report, without the prior written consent of ERCE. In the case that any part of this report is delivered in digital format, ERCE does not accept any responsibility for edits carried out by the client or any third party or otherwise after such material has been sent by ERCE to the client.

**Disclaimer**

ERCE has made every effort to ensure that the interpretations, conclusions and recommendations presented in this report are accurate and reliable in accordance with good industry practice. ERCE does not, however, guarantee the correctness of any such interpretations and shall not be liable or responsible for any loss, costs, damages or expenses incurred or sustained by anyone resulting from any interpretation or recommendation made by any of its officers, agents or employees.

ERCE has used standard petroleum and carbon capture and storage evaluation techniques in the generation of this report. These techniques combine geophysical and geological knowledge with assessments of porosity and permeability distributions, fluid characteristics, production performance and reservoir pressure. There is uncertainty in the measurement and interpretation of basic data and ERCE has assessed this uncertainty as we have considered the risks presented by Harbour Energy. ERCE reserves the right to review all calculations referred to or included in this report and to revise the estimates in light of erroneous data supplied or information existing but not made available which becomes known subsequent to the preparation of this report.

No site visits were undertaken in the preparation of this report.

**Professional Qualifications**

ERCE is an independent consultancy specialising in geoscience evaluation, engineering and economic assessment. ERCE will receive a fee for the preparation of this report in accordance with normal professional consulting practices. This fee is not dependent on the findings of this report and ERCE will receive no other benefit for the preparation of this report.

Neither ERCE nor the signatory of this report who is responsible for authoring this report, nor any Directors of ERCE have at the date of this report any shareholding in Harbour Energy. Consequently, ERCE, the signatory and the Directors of ERCE consider themselves to be independent of the Company, its directors and senior management.

ERCE has the relevant and appropriate qualifications, experience and technical knowledge to appraise professionally and independently the assets.

The work has been supervised by Paul Chernik, Director of ERCE, who holds a B.Sc. in Chemical Engineering from the University of Calgary, M.Sc. in Chemical Engineering from the University of Alberta, and an MBA from the University of Cambridge. He is Professional Engineer, registered with APEGA, and a Member of the Society of Petroleum Evaluation Engineers (SPEE).

Yours faithfully,

Paul Chernik

Director, ERCE

# Executive Summary

ERCE has prepared this report for use by Harbour Energy (Harbour) and the North Sea Transition Authority (NSTA) as providing a third-party assessment of Harbour’s Early Risk Assessment (ERA) Report for the Victor CO2 storage site, document number HBR-SNS-P-XX-X-GG-02-00001 entitled “Early Risk Assessment Report – Victor” associated with CS005 licence commitment. This report addresses ERCE’s opinion on:

* Harbour’s risk assessment process.
* The quality of Harbour’s documentation.
* The uncertainties and biases which Harbour has in its dataset.
* The subsurface risks Harbour has identified in its ERA, and the associated consequence and likelihood and appropriateness of mitigations.
* Any relevant risks we think Harbour has omitted.

Overall, ERCE is of the opinion Harbour has undertaken extensive research to understand the potential threats to containment and the uncertainties in defining the storage site and the storage complex. Harbour has recognised legacy wells as the highest risk in the ERA report. However, in ERCE’s opinion, the risks posed by new wells need to be elevated and given equal attention. We note Harbour has no organisational experience in the design and operation of CO2 injection wells, so will rely on industry partners for guidance and knowledge sharing. In addition, industry standard software does not exist which can appropriately handle CO2 injection into a depleted reservoir and the impact this has on wellbore integrity. We note there have been a number of well design failures in the Oil and Gas industry when fields are developed in unusual conditions, such as HPHT[[1]](#footnote-2). As there are limited CO2 injection projects globally, we would consider well design a key risk.

ERCE has not found any significant omissions with respect to CO2 storage risks within Harbour’s ERA. We have identified some further risks we recommend Harbour evaluate but are of the opinion none of these risks would be considered significant. These risks include unmodelled high permeability pathways through the aquifer, bypass of Bunter closure 2 or Haisborough group cap rock, microbial impact, drilling into reservoir altered by faulting and the risk of changing regulation on legacy wells requirements. We note Harbour plan to account for some of these risks in their ongoing work program, nevertheless we advise on breaking out these points to ensure they are given due consideration.

ERCE is of the opinion that some uncertainties and biases relating to well control, well data and geomechanical data have been underestimated. Harbour has taken into consideration the uncertainty in the petrophysics at the wells but does not account for uncertainty in the reservoir away from well control which should be factored in.

The risk assessment methodology has been adopted from Harbour’s risk management process and hence expected to be embedded within the organisation. The ERA does not provide information on the organisational roles and responsibilities in relation to risk management. Harbour should designate a responsible person to ensure all Existing Controls and Additional Controls are in place and will have the desired outcome. The risk matrix used has been effective in risk identification. However, ERCE has differences in opinion on the treatment of Initial Risk ratings to arrive at Residual Risk ratings. In ERCE’s opinion, the Residual Risk remains unchanged if the Additional Control specified is a study. Only once these studies have been completed, and the results analysed, can Harbour consider altering the Residual Risk rating.

Based on the ERA associated documentation submitted to ERCE, we are of the opinion the Harbour has an effective quality management system in place. Harbour has engaged relevant personnel with varied experience to work collaboratively in delivering the ERA report.

# Introduction

This report summarises ERCE’s opinion, as a third-party assessor, on Harbour’s ERA. Note the final acceptance of findings, or statements to refute findings, will be documented in a findings register and will be agreed at a later date between Harbour and the NSTA.

Following initial submission of this report, ERCE presented and discussed our findings with the NSTA at a workshop on the 11th May 2022. This workshop was also attended by a second third-party assessor, Ross Offshore. The roles of those present at the workshop are as follows:

1. The North Sea Transition Authority (licensor)
2. Harbour Energy (prospective CCS storage licensee)
3. ERCE (independent risk assessor)
4. Ross Offshore (independent risk assessor)

Harbour provided ERCE with a set of documents they judged would assist ERCE in our assessment of their ERA. A full list of these documents can be found in Table 8.2. Harbour did not submit any technical data to ERCE.

Harbour provided ERCE with its ERA on 12th April 2022. This report provides background on Harbour’s risk assessment process and contains an appendix of 64 identified risks. Harbour has grouped these risks into the following categories:

* Storage Site Containment
* Storage Complex Containment
* Conformance
* Legacy Wells
* New Wells

This report is intended to be read in conjunction with Harbour’s ERA. We have therefore not repeated background information and definitions which Harbour already detail in the ERA.

ERCE had meetings with Harbour to gain clarifications with respect to its technical work as well as overall risk processes and methodology (Section 8.4). ERCE has based this report on the documents provided by Harbour and the conversations we have had during our clarification meetings. In providing opinions, ERCE has ensured all relevant supporting documents are referenced as footnotes and stated where verbal conversations with Harbour are relevant. Note for ease of reading, we do not reference the ERA as a footnote in our report. Where a statement is made without a reference it should be presumed that the source of the statement was the ERA.

The requirements of this report by the NSTA are as follows:

1. provide reasoned opinion that the risk assessment process is robust and aligned with industry best practice, or provide evidence where ERCE deems a potential gap may exist;
2. provide reasoned opinion on Harbour’s identified risks and associated risk consequence and likelihood assessment, or provide evidenced rational where ERCE deems an alternative assessment outcome may be considered or risks omitted;
3. provide reasoned opinion on Harbour’s uncertainties and help Harbour identify any potential sources of bias in the risk assessment, with reasoned argument as to how Harbour may identify means to reduce bias or incorporate appropriate uncertainties
4. provide reasoned opinion on whether Harbour results and risk assessment supporting evidence are documented in a clear and consistent manner
5. assess whether Harbour identified mitigations provide confidence, in ERCE’s reasoned opinion, that the risk will be reduced and maintained at an acceptable level

The licensor’s objectives for the 11th May 2022 workshop are to:

1. review Harbour’s work programme and other Harbour work in respect of the project
2. identify any risks to a future operational storage site including, but not limited to, any threats to containment of carbon dioxide in the storage site and storage complex and the uncertainties in defining the storage site and storage complex
3. be apprised of Harbour’s criteria for the assessment of the storage site and storage complex and Harbour’s acceptable level of certainty.
4. identify and agree with Harbour Energy any further risk reduction measure to be taken; and
5. inform Harbour of the requirements for a potential future carbon dioxide storage permit application including, but not limited to, the measurement, monitoring and verification and corrective measures plans

The remainder of this report is broken into five sections to address separately our opinions required as by the NSTA but with due reference to the licensor’s objectives in the workshop.

# Risk Assessment Process

ERCE deems the risk assessment process used by Harbour to be aligned with typical industry process safety risk assessments, conducted prior to detailed HAZOP studies. We understand the Semi-quantitative Risk Assessment used is based on Harbour’s standard risk management process embedded within the organisation. This, in conjunction with assessment of uncertainties as well the application of bow-tie method for selected risks, fulfils the scope of work for this stage of the work programme described in Appraisal and Storage licence CS005[[2]](#footnote-3).

ERCE has assessed whether Harbour has followed standard industry practice for CCS risk management. In light of limited industry practice within the field of offshore storage of CO2, ERCE relies on a number of guidelines and standards as background reference material, including:

* EU CCS Directive Guidance Document 1 - CO2 Storage Life Cycle Risk Management Framework
* EU CCS Directive Guidance Document 2 - Characterisation of the Storage Complex, CO2 Stream Composition, Monitoring and Corrective Measures
* ISO 27914:2017 Carbon dioxide capture, transportation and geological storage — Geological storage DNV Recommended Practice and Service Specifications for geological storage

Detailed references can be found in Appendix 3.

We note that all relevant professional disciplines were involved in signing off the report, which gives confidence that all areas falling under those disciplines were addressed.

The following recommendations in the subsections are provided to improve the process further in the future.

## Context Within Company Risk Management System

The ERA makes use of the risk matrix presented in Appendix 7, where it is stated that “this risk matrix applies globally to Chrysaor and its subsidiaries”. This indicates that the risk assessment process is well anchored within the organisation, but this is not described in the text of the report. The introduction to the report would benefit from a description of how this risk assessment process fits in to the company wide risk management system and whether this is certified against ISO or an alternative risk management standard.

## Context Within Project Risk Management Plan

It is not clear from the report how this risk assessment fits into the overall risk management plan for this CCS project and how often it will be reviewed and updated. The report would benefit from a description of how it relates to non-technical and non-subsurface risks. We are aware from discussions with Harbour that they are contained in a separate report.

The report would also benefit from a description of roles and responsibilities. Identifying who has overall responsibility for risk management within the project as well as individual risk owners.

We note the authors of the ERA cover the disciplines of geophysics, petrophysics, geology, reservoir engineering, drilling engineering and P&A engineering. We also note the report has been reviewed by Andrew Hood, Subsurface and Wells Development Manager, and signed off by the Project Director Graeme Davies. The participants of the risk workshop conducted by Harbour included personnel both internal and external to this project. From our experience with similar projects, ERCE is of the opinion that this array of disciplines will ensure the majority of the subsurface risks associated with CCS are covered. We would ask Harbour to detail their team’s experience in CO2 injection. The disciplines lacking are those of geomechanics and geochemistry, but Harbour has provided an externally produced report which covers the geomechanical risks[[3]](#footnote-4). We would advise Harbour to detail in the report how the interface with external consultants is conducted, and how they are integrated into the risk assessment process.

## Context Within UK CCS Development

The acceptance of sub-salt monitoring options and certain formations as plug and abandonment barriers may be common issues across multiple fields and may require input from a regulatory authority.

Future risk assessments may benefit from describing this background context since it may introduce a degree of permitting uncertainty.

## Suitability of Chrysaor Risk Matrix

ERCE note the risk matrix which Harbour has adopted is named ‘Chrysaor Risk Matrix’, as it was developed prior to Harbour’s establishment in its current status.

### Appropriateness of Consequence Categories

The majority of Harbour’s 67 identified risks fall under the reputational and financial categories, with 24 of those being assigned environmental and/or safety risks.

Environmental consequences are grouped with Socio-economic consequences and are limited in their scope to local environmental topics such as local habitats and ecosystems. Leakage of CO2 is not mentioned with respect to climate change impacts, and this should be addressed in future risk assessments. Incorporation of the potential magnitude of leakage events including flux rates is advised by the EU CCS Directive[[4]](#footnote-5). The severity levels for local impacts of CO2 leakage may benefit from reference to detectability of leakage against natural background levels and variability.

With respect to financial risk, we note that Harbour uses a financial consequence risk of 3 where there may be the requirement for drilling a new injection well as a mitigation. This level of risk relates to a cost impact of $1 - $25MM in Harbour’s risk matrix. Based on our experience, drilling may exceed this range. We would recommend Harbour reconsider their financial risk where this is the case. We have commented on individual risks where we think Harbour should include the drilling of a new injection well as a mitigation.

As a general comment, we note that environmental and safety consequences impact a wide variety of external stakeholders, whereas reputational and financial consequences have a greater impact on stakeholders internal to Harbour, its financiers and its shareholders. As a communication tool, the risk matrix may benefit from being organised by this difference in stakeholder interests.

ERCE notes that Harbour only includes a safety or environmental consequence when the CO2 escapes the storage complex, which we agree with. However, Harbour restricts these risk consequences to migration out of the Bunter to surface and does not consider lateral migration out of the Leman, and thus storage complex, to constitute a safety or environmental risk. ERCE is of the opinion that the risk of leakage to surface due to lateral migration out of the storage site is low but should be considered.

### Appropriateness of Likelihood Categories

ERCE notes that the descriptions associated with each of the Likelihood ranking from 1 – 5 are based on the oil and gas industry, and how often these events are likely to occur across all oil and gas assets, either globally or in the North Sea. As oil and gas projects are based on hydrocarbon production, rather than CO2 injection the use of these projects as analogues may be inappropriate.

We would recommend Harbour revisit the definitions associated with each of these likelihood categories and base them on likelihood of occurrence in analogue projects. Harbour may categorise analogue projects as all injection projects, including CO2, natural gas and water, or specifically just CO2 injection projects, depending on Harbour’s analogue experience. We would recommend Harbour then use a proportional description instead of generic. For example, rather than ‘occurs a few times in the industry’, have ‘occurs in x% of analogue projects worldwide’.

### Decision on Risk Category

ERCE note that the Harbour will extract value from this early risk assessment by using it as a tool to allocate resources to address the risks. To provide focus to future teams, we would recommend Harbour consider inclusion in their report a discussion on how they assigned each risk to the associated category. We note there is overlap of categories, for example a risk of leakage in a legacy well is assigned to the Legacy Well category, but it would also be suitable within the Storage Site Containment category.

Harbour may want to consider further grouping risks in a similar manner to the way we have grouped them in this report. This could aid with assigning risks to certain teams and allow better clarity on responsibilities and where there is overlap or gaps.

## Bow Tie Risk Analysis

ERCE note that Harbour has adopted bow-tie analysis risk evaluation techniques in its assessment of CO2 leakage up wells 49/17-8 and well 49/22-2. Having reviewed the analysis, ERCE finds it fair and reasonable and therefore we do comment further in this report.

## Appropriateness of Additional Controls

ERCE is of the opinion that the following are additional controls which Harbour has identified which are appropriate in reducing the initial risk at this stage:

* Well operating design and procedures will ensure injectivity rates are kept within allowable limits.
* Consider storage site recharge philosophy in the context of preventing CO2 reaching 49/17-8 if necessary.
  + ERCE would consider this an appropriate mitigation providing the philosophy includes repositioning of the injection well and/or limitation of CO2 flow if required. We would recommend Harbour are clearer in what this philosophy involves.
* Injection wells will be strategically placed in areas of high reservoir quality and also to ensure full reservoir coverage if compartmentalisation is present as in Victor.
* Choke philosophy may mitigate this risk if downhole choking is selected.
  + ERCE accept this as a valid mitigation, providing the choke philosophy is appropriate.
* Work with vendors to identify the most appropriate completion solution (probably sand screens) which will account for low-temperature CO2 injection and transient conditions.
* Corrective measures plan including the initial design for a generic relief well.
  + ERCE is of the opinion that the drilling of a relief well would be appropriate for all wells, except well 49/17-8. Should a leak occur in this well, then intersecting the original wellbore at the top of the cement plug will be challenging as magnetic and resistivity ranging both rely on the presence of steel to locate the well, which is absent in this well. Acoustic ranging will in this case only work if the flow is sufficient to generate noise levels that can be detected at distance[[5]](#footnote-6).
  + If we assume the relief well is successful, ERCE is of the opinion this would reduce the consequence of the risk rather than the likelihood. A leak would be just as likely to occur, but the magnitude of leakage would then be limited.
  + Harbour includes the design for a relief well in the existing controls of multiple risks, and then the implementation of a relief well in the additional controls within the same risks. Harbour has clarified that the mitigation of a relief well should be considered in the Additional Controls, and would involve “Engagement with well control specialists and identification of trigger points for a relief well execution within the corrective measures plan would be additional controls.”[[6]](#footnote-7). Where Harbour lists the relief well as an Additional Control, ERCE has treated it as such.

ERCE is of the opinion that the following are additional controls over and above those which Harbour currently describe which they could employ to reduce the initial risk at this stage:

* Drilling of replacement injection well.
* Drilling of a backup injection well with spare flow capacity.
* Workover of existing injection well.
* Limitation or cessation of CO2 flow rate.
* Method of temporary storage or disposal of CO2.
  + This could be the generation of biochar, fertilizer or other product which would be run at a small scale if a flow rate issue arises

ERCE would recommend Harbour examine the financial risk related to restricted CO2 injection rate, and whether drilling of a backup injection well or construction of a temporary CO2 tank or disposal method would result in a greater cost to Harbour than the loss of revenue from vented CO2. ERCE note that small scale CO2 disposal methods would not be appropriate for the scale of CO2 disposal Harbour will need to accommodate but could complement the project to allow a buffer for the CO2 flow when constraining issues arise.

Harbour has identified a number of further studies to enhance its knowledge of the storage site and the storage complex. However, Harbour has categorised these studies as controls and reduced the associated risks already. By definition[[7]](#footnote-8), control is a measure that maintains and/or modifies risk. Controls include, but are not limited to, any process, policy, device, practice, or other conditions and/or actions which maintain and/or modify risk e.g. limiting CO2 injection rates and/or pressure, or drilling a new well. In accordance with risk management principles, a study is not a control. Undertaking a study may change uncertainty but it will not reduce the identified risk.

ERCE is therefore of the opinion that the “residual risk” for the majority of Harbour’s identified risks should remain the same as the initial, based on the additional controls Harbour describes. Only once these studies have been completed, and the results analysed, can Harbour then consider where it is appropriate to reduce the risk. The results of these studies may in fact serve to increase the risk, depending on the conclusions. Based on our experience with risk evaluation for other projects, we would view it as appropriate at this early stage that a high number of the residual risks remain the same as the initial risks.

## Overview Risk Matrix Graphic

The report would benefit from a risk matrix illustration showing the relative position of each risk with respect to likelihood and consequence. This graphic would allow the reader to quickly identify the key risks to the project.

## Scheduling

The report would benefit from a schedule which discusses the impact on the project if risk mitigation measures do not go as planned and result in a delay to project progression and execution.

## Interface Management

External interfaces to the project that can alter project risks are not included in the ERA. Interface management with emitters is key and needs to go beyond contractual agreements. One example would be the composition of the CO2 stream. Any process variations at the emitter’s end could lead to impurities in the supplied CO2. This could go unidentified in the absence of continuous CO2 composition monitoring. The presence of unexpected impurities could alter the subsurface risks.

# Quality of Documentation

ERCE regards the quality of documentation provided by Harbour to be fit for purpose. The risk assessment findings are well documented, and all supporting documents are shown to have gone through a quality assurance process before issue.

A suitable system for document management and control has been followed and all supporting reports show a table of version history and document number referencing. Harbour used transmittals to issue documentation.

External references and internal cross referencing between project documents appear to be consistent and valid.

There are instances where small improvements could be made. An appendix of abbreviation nomenclature used within the ERA would help the reader better understand some of the specific nomenclature. This would include Harbour’s internal FEL acronym which external readers may not be familiar with, and a brief schematic of the Harbour Phase Gate Project Management System with estimate timings would provide further clarity.

# Uncertainties and Biases

ERCE is to “provide reasoned opinion on Harbour’s uncertainties and help Harbour identify any potential sources of bias in the risk assessment, with reasoned argument as to how Harbour may identify means to reduce bias or incorporate appropriate uncertainties”.

## Petrophysical Data Uncertainty

ERCE is of the opinion that the quantification of uncertainty relating to the petrophysical data uncertainty at the wells is reasonable, providing it relates to the uncertainty at the wells and not away from wellbore. Harbour has clarified the uncertainty relating to the petrophysics relates only to the uncertainty at the wells, and not away from well control[[8]](#footnote-9).

The Harbour petrophysical modelling incorporates data from the Viking field as well as Victor to increase the data volume. ERCE recommends Harbour rely on the Victor data for modelling as we note there is sufficient porosity and permeability to model Victor without including the Viking data[[9]](#footnote-10). Alternatively, if Harbour can demonstrate that the Victor data is similar to the Victor and Viking data combined then we would see this as sufficient to demonstrate the validity of their methodology.

ERCE would recommend treating horizontal and vertical permeability as separate uncertainties, as they are key parameters in understanding the movement of CO2.

Harbour has used a 6.0 P.U. cut-off which appears to be equivalent to a permeability cut-off of 0.1 mD, which is a typical value for gas reservoirs under depletion. However, for the analogous situation of an oil well that has been turned around from primary production (depletion) to water injection, a higher permeability cut-off is often used[[10]](#footnote-11) to account for the viscosity increase. We would recommend Harbour consider if this would also apply to the CO2 dense phase injection case. A single well fine grid sector simulation model could be constructed to investigate if there is a difference in active net pay under gas production versus CO2 injection and this may aid with the appropriate cut-off to use.

## Seismic Data Uncertainty

ERCE is of the opinion that Harbour’s description of the uncertainty relating to the Seismic Data Uncertainty is reasonable given data currently available. We note Harbour intend to refine their seismic interpretation and depth conversion over the coming year. We understand Harbour will have a reprocessed seismic volume on which to undertake horizon and fault interpretation. We cannot comment to what degree the reprocessed seismic will reduce uncertainty in the interpretation without reviewing vintage and reprocessed seismic volumes ourselves.

We note Harbour has included Additional Permeable Zones where it discusses the possibility of migration through Rhaetic sands (Section 7.2.2), but does not mention the possibility of permeable zones within the Zechstein. We would recommend these zones are included in the uncertainty analysis.

As the P/z analysis does not match the total GIIP in the static model, uncertainty remains around depth conversion, as well as fault transmissibility and reservoir modelling. We note there is a high degree of uncertainty in the depth conversion of the SE segment 8[[11]](#footnote-12), which may explain the difference observed. We would recommend consideration is given to the velocity pull up effects of Plattendolomite rafts, as well as a subdivision of the chalk to capture the velocity differences between the uniform lower layer and variable upper layer. Analysis of the 22-04A well and 22-02 wells could determine if there is a velocity contrast between the BCU and top Triassic and that layer would benefit from further subdivision.

## Static Data Uncertainty

Based on our experience of static modelling, we are of the opinion that the uncertainty related to the NTG, porosity and permeability should be increased. Although we agree with the uncertainty in these parameters at the well locations, there is greater uncertainty away from the wells which has not been taken into consideration.

Based on our experience in the oil and gas industry, producing wells are often drilled in locations which are judged by the operator to be locations of high reservoir quality within the field. We understand the wells drilled on Victor are likely to have been targeting crestal locations in separate compartments, rather than the highest quality reservoir[[12]](#footnote-13). We would therefore be of the opinion that there is limited bias in the dataset.

## Dynamic Data Uncertainty

Harbour defined seven fault compartments and four separate hydraulic regions with three different free water levels. They relied on allocated daily gas production, static and dynamic pressure data for individual wells ands well as the static model for this definition. Harbour, in the ERA report, states that the main dynamic modelling uncertainties have been identified. ERCE notes that, to obtain a history match for the CMG dynamic model, Harbour used pressure-dependent barrier transmissibilities that remain open when a certain differential pressure is reached and the flow between regions is governed by a user assigned transmissibility[[13]](#footnote-14). ERCE believes that having the freedom to alter these two parameters independently might also allow different pathways to achieve an acceptable a history match. A higher pressure differential combined with a higher transmissibility could give the same result (an history match of acceptable quality) as low-pressure differential combined with a low transmissibility. The rationale for the selection of these parameters should be documented.

Currently, Harbour has only one static model (Reference Case Petrel Model) built with a corresponding GIIP and this was used in the dynamic model(s), and neither Low nor High Case GIIP models have been constructed at this stage. ERCE accepts that the GIIP range should be relatively narrow enough not to warrant full Low and High Case independent static models to be built. In the development phase Harbour intends to construct a range of static and dynamic models to assist with optimising well locations and ERCE supports this approach.

However, as there is still a wide range of uncertainty evident in basic reservoir properties as porosity-permeability from core data per zone, as well as uncertainty in CO2 displacement mechanism in a gas-water system. ERCE understands these will be investigated more thoroughly in the next phase of the work, including laboratory Special Core Analysis (SCAL) CO2 flood studies.

For the injectivity modelling, given the uncertainty of using an history matched realisation in predictive mode (with different fluid and flow mechanism than depletion) ERCE would also recommend considering an Experimental Design (ED) workflow, often used in the pre-development studies to capture the uncertainties. The workflow would allow, once the parameters with highest impact are identified, an efficient and robust approach to describe a set of models that would sample the whole uncertainty space. Following the ED work it should be possible to identify the most likely case for development planning purposes, and relative downside/upside.

## Additional Uncertainties

### Geomechanical Dataset

ERCE is of the opinion that Harbour should give additional consideration to the uncertainties and biases within the geomechanical dataset. The following discusses suggestions for consideration.

There is an uncertainty in defining the stress field, which is relevant for evaluating fault reactivation[[14]](#footnote-15). Axis discuss, but do not model this uncertainty, in their report.

Minimum Horizontal Stress (Shmin):

* Data from leak off tests in the overburden, but none at Leman reservoir in Victor which gives uncertainty around fracturing in the reservoir itself[[15]](#footnote-16).
* The Leman Shmin is estimated from leak of tests (LOT) from nearby fields and Victor mudweight, which shows that Shmin is lowest in the Leman and Bunter Fm.

Maximum Horizontal Stress (Shmax):

* Max horizontal compression directions estimated as NW-SE from regional data and nearby fields (borehole break out data)[[16]](#footnote-17).
* However, there is no data for stress magnitude[[17]](#footnote-18). Estimates were done assuming an anisotropy between 5 and 15% (SHmax =  Shmin + 5 to 15%), corresponding to a normal and strike-slip regime respectively. This is based on Axis’ experience. No assumption was made for a reverse stress regime.
* There can be a difference in the stress regime above and below the Zechstein salt. Published data, e.g. word stress map, does not define a stress regime for the SNS[[18]](#footnote-19). Published data from onshore UK show evidence for strike-slip and marginally a reverse stress regime[[19]](#footnote-20).

In the absence of knowledge on the stress regime, we may recommend simulating fault reactivation also for a reverse stress regime, where SHmax > Sv.  Although we acknowledge this may be difficult in the absence of any data for SHmax magnitudes. Injection within a reverse stress regime will have a higher risk for fault reactivation in comparison to normal or strike-slip regimes as it enlarges the Mohr circle and shifts it to the failure envelop quicker.

Drilling through the Leman seems to be associated with mud losses rather than induced fractures, so it may be a reasonable assumption not to consider a reverse regime but evidence should be presented why this is not the case.

### Well Data

The degree to which there is uncertainty in the data recorded on the historical wells cannot be determined but should be acknowledged. Harbour has inherited the document management (MaxWell) and well files from Chrysaor[[20]](#footnote-21), who inherited them from ConocoPhillips who operated the fields. In that respect the documents can be verified as accurate since the well files from the ConocoPhillips operatorship are still active in Harbour Energy today. Document management systems have not changed during parent company changes. However human error, including poor communication and/or documentation, may have resulted in some degree of inaccurate reporting within historical documents..

In addition, for wells plugged in the 1970s there will be a degree of uncertainty in the current state of these wells, especially considering the salt mobility. ERCE would recommend Harbour acknowledge this in their uncertainty evaluation.

# Identified Risks

ERCE is to “provide reasoned opinion on Harbour’s identified risks and associated risk consequence and likelihood assessment, or provide evidenced rational where ERCE deems an alternative assessment outcome may be considered or risks omitted”

ERCE is to “assess whether Harbour identified mitigations provide confidence, in ERCE’s reasoned opinion, that the risk will be reduced and maintained at an acceptable level”.

The following sections detail risks Harbour has identified where ERCE would take a different view on the risk, consequence, likelihood or mitigation strategy. In this report we do not address individual risks where we find Harbour’s complete risk assessment to be fair and reasonable.

ERCE has grouped risks based on our opinion of which risks are similar. These groups were determined in a way that would allow us to discuss risks where we judged there were overlapping elements, to avoid repetition in this report.

## Storage Site Containment – Lateral Spill or Migration through Reservoir

### Harbour’s Risk description

Harbour has identified risks associated with CO2 plume spill or migration out of the Leman reservoir in risk IDs 16, 30, 36 and 39. This section specifically deals with risks of spill or migration through the reservoir and will not discuss the risks associated with migration up faults or fractures. We note Risk 39 does not specifically relate to spill or migration risks, but it is the spill risk element of Risk 39 which we wish to discuss in this report.

* Risk 36: CO2 interaction with reservoir aquifer leading to overspill via the NE closing dip or through aquifer connectivity to other Leman units.
* Risk 39: CO2 plume / dispersion is significantly different than modelled expectations.
* Risk 30: Lateral interactions with other hydrocarbon resources, development activities or resource exploitation.
* Risk 16: Accidentally over-filling of the designated storage site leading to overspill.

### ERCE’s Opinion on Risk Description

ERCE notes that with respect to lateral spill or migration of CO2 through the reservoir:

* The volume of CO2 which can be stored in the reservoir is based on the volume of natural gas produced, so can be determined to a relatively high degree of accuracy[[21]](#footnote-22).
* The reservoir is fault sealed on all sides, except in the NE where there is dip closure[[22]](#footnote-23).
* The reservoir sealing faults served as an effective trap of natural gas over geological time periods.
* Harbour interpreted De Keyser faults to have broken down over production timescales[[23]](#footnote-24).
* The porosity/permeability plots for the Victor field show a range of permeability from 0.001 – 1200 mD. The majority of the points fall between 1 – 1000 mD[[24]](#footnote-25).
* The interaction with aquifer may be minimal as Harbour modelling suggests “a predominance of dissolution into the reservoir water compared with the underlying aquifer”[[25]](#footnote-26).
* Due to the averaging nature of geological modelling, the extremities of the reservoir architecture will not be present in the modelling.
* Preliminary p/z analyses suggest that the aquifer may not be extensive or not providing support[[26]](#footnote-27).
* P/z analysis does not match the current in place volumes in the static model, so uncertainty remains around depth conversion, segment communication and reservoir deposition[[27]](#footnote-28).

Based on the above points, ERCE is of the opinion that Risks 16, 30, 36 and 39 are accurate in their description of highlighting the potential risks with the CO2 migrating or spilling out of the storage complex through the reservoir, though we would suggest Risk 36 may be considered a storage site containment issue, rather than conformance, as lateral movement of CO2 outside the storage site could result in a leak to surface, for example via open faults or legacy wells.

ERCE would suggest an additional risk is included which covers the risk of CO2 plume migration through unmodelled high permeability pathways through the aquifer. This additional suggestion is expanded in 7.1.1.

### ERCE’s Opinion on Initial Consequence and Likelihood

We agree with Harbour’s initial risk consequence and likelihood for Risks 30 and 36. We are of the opinion the likelihood of Risk 16 should be increased from 1 (improbable) to 2 (remote). We are of this opinion because an injection plan has not been confirmed at this stage which ensures the CO2 has time to enter all the pore space vacated by the natural gas. The Victor field was on production for 31 years. If Harbour were to implement an injection plan which involved filling the structure in under this timeframe, the CO2 may enter the aquifer and spill prior to filling in the furthest reaches of the void space.

We are also of the opinion that were the CO2 to exit the storage complex, this could constitute a safety or environmental risk, as well as financial and reputational. Without demonstrating that there are no direct routes for the CO2 to travel to surface out with the storage complex, these risks should not be discounted.

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

We are of the opinion the residual risk should remain the same as the initial risk for all risks, based on the proposed additional controls from Harbour (see Section 3.5 for discussion on studies). Harbour has kept the residual risk for Risk 16 the same as the initial but has decreased the likelihood after the additional controls for Risk 30, 36 and 39.

ERCE is of the opinion that the mitigations are suitable next steps to aid in the uncertainty related to the lateral spill or migration through the reservoir, but as discussed would not result in reduction of the residual risk at this stage.

We would however suggest the following additional studies to understand uncertainty:

* Risk 16: Coherency or frequency blending to better identify faults which may inhibit flow of CO2 and result in it travelling beneath the original GWC.
* Risks 30 & 36: Improved aquifer characterisation by undertaking, for example, reservoir engineering techniques common in the industry such as Havlena Odeh analysis.
* Risks 16, 30, 36 & 39: Further sensitivities to achieve alternative history matches. For example, compartments communication through aquifer rather than faults could be investigated. Although the subsurface models have been history matched to the historical natural gas production and pressure data, these models remain a single realisation of the subsurface, and other permutations will exist. We understand Harbour will investigate further sensitivities which will help to investigate the extreme limits related to injectivity.
* Risks 16, 30, 36 & 39: Prior to injection and as monitoring tool, ERCE would also suggest considering recording baseline saturation cased hole logging to identify current GWC (if visible) for comparison against initial earlier logs to detect movement.

## Storage Site Containment – Migration through Zechstein Cap Rock

### Harbour’s Risk description

Harbour has identified risks associated with CO2 migration out of the Leman reservoir through the Zechstein caprock in risk IDs 1, 2 and 10. This section does not include the risks of thermal fracturing leading to loss of caprock integrity, which is dealt with in section 6.3.

* Risk 10: Migration of CO2 into permeable Z1 / Z2 formations.
* Risk 1: CO2 escape through Zechstein cap rock due to recent natural or human-induced seismic events (repressurisation).
* Risk 2: CO2 escape from Leman into Bunter Sand through Zechstein cap rock due to fracture/faults (new/existing) propagated by repressurisation.

### ERCE’s Opinion on Risk Description

ERCE note that with respect to the Zechstein caprock:

* The Zechstein cap rock is ~500 ft thick at its thinnest point over the Victor field[[28]](#footnote-29).
* The Zechstein is primarily composed of alternating dolomites, anhydrites, and halites and has a thin shale at the base[[29]](#footnote-30).
* The Zechsteinkalk, Hauptodolomit and Plattendolomit are all carbonates within the Zechstein which have poor, to good reservoir [[30]](#footnote-31).
* Gas has been found in the permeable formations within the Zechstein in some areas of the Southern North Sea[[31]](#footnote-32).
* All faults observed to intersect the Leman appear on seismic to die out within the Zechstein[[32]](#footnote-33).
* The effect of CO2 on carbonate depends on the type of carbonate, the details on the CO2 injection and any impurities in the CO2 stream[[33]](#footnote-34).
* Harbour has stated they do not intend to pressure the reservoir beyond hydrostatic.
* There have been seismic events in the Southern North Sea which may or may not be related to human activity in the area[[34]](#footnote-35).

Based on the above points, ERCE is of the opinion that Risks 1, 2 and 10 are accurate in their description of highlighting the potential pathways for CO2 to migrate into and through the Zechstein caprock. ERCE is of the opinion that these risks cover all the risks which could be associated with CO2 migrating through the Zechstein. However, we recommend Harbour draw attention to Risk 10 in the body of their report as intervals within the Zechstein could form part of the storage complex as reservoir into which leaked CO2 may migrate, in a similar way to the Bunter sandstone. This would serve to reduce the overall risk to the project.

We would recommend amalgamating the possibility of leakage relating to seismic events into Risk 2. The leakage pathways due to induced seismic would be up old or new faults, which is already captured and discussed in Risk 2. We note that Risk 13 groups leakage pathways through the Haisborough Group due to seismic events, fractures and faults so would see no reason to split out the risk of leakage for these pathways through the Zechstein Group. This would allow consolidation of these risks for the Zechstein, simplifying the risk register.

However rather than eliminating Risk 1, we would recommend focusing on the impacts other than leakage which could arise from induced seismic events, such as damage to topside infrastructure.

### ERCE’s Opinion on Initial Consequence and Likelihood

We agree with Harbour’s initial risk consequence and likelihood for Risks 1 and 2. We are of the opinion that the likelihood Harbour has assigned to Risk 10 should be increased from 2 (Remote) to 3 (Occasional). We are of this opinion based on our regional knowledge of the Zechstein and observation of faults which would offset the Leman against the basal facies of the Zechstein.

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

Harbour has not changed the residual risk for Risks 1 and 2 but has reduced the residual likelihood risk for Risk 10 based on the additional controls. We are of the opinion the residual risk should remain the same as the initial risk for each of the three risks, based on the proposed additional controls from Harbour (see Section 3.5 for discussion on studies).

ERCE is of the opinion that the mitigations are suitable next steps to aid in the uncertainty related to the migration of CO2 through Zechstein caprock.

We would however suggest the following additional studies to understand uncertainty:

* Risks 1 & 2: Use of passive seismic may be deployed to track seismic activity, and cease injection if this approaches threshold.
* Risk 10: Create Allan diagrams of the faults to assess where and which units the Leman contacts the Zechstein
* Risk 10: Investigate implications of the risk of CO2 entering carbonate formations, and the mineralogical changes and consequences from this.
* Risks 1, 2 & 10: Undertake coherency or frequency blending to better identify faults which will allow optimal well placement reducing the risk of reactivation of nearby faults.

## Storage Site Containment – Thermal Effects

### Harbour’s Risk description

Harbour has identified risks related to thermal effects in risk IDs 7, 12, 5, 6, 11 and 15.

This group encompasses risks originated by the alteration of mechanical properties of rock and cement caused by the CO2 exchanges of heat with the surrounding environment.

Harbour’s risk matrix broadly covers two types of risks related to the understanding and modelling of thermal fracturing and fluid expansion.

Thermally induced fractures may have a critical impact on certain potential routes for loss of containment: fracturing cap rock/seals (risks 7 and 15), migrations along fault/fractures (risks 5 and 6), migration along wells (again risk 7, with cement sheath). Harbour also reports a risk related to the overall accuracy (and hence control) of simulation of the thermal fractures (risk 12), relevant to the breach of any of the aforementioned migration paths.

Possible thermal effects originated by fluid expansion are covered in risk 11.

The following are risk IDs relevant to this section:

* Risk 7: Near wellbore thermal fracturing in new injection wells affecting containment at Zechstein or Bunter Shale horizon due to cold internal well temperatures generated by multi-phase CO2 (cap rock embrittlement or cement sheath)
* Risk 12: Inaccurate modelling of thermal fracture growth
* Risk 5: Leakage through side faults separating discrete hydraulic units in the Leman Sandstone due to repressurisation
* Risk 6: Thermal fracturing in reservoir due to sub-zero temperatures leading to breach of side faults.
* Risk 11: In-situ injected CO2 heats up over time and expands.
* Risk 15: Near wellbore thermal fracturing in new injection wells affecting containment at Haisborough Group horizon due to cold internal well temperatures generated by multi-phase CO2 (cap rock embrittlement or cement sheath).

### ERCE’s Opinion on Risk Description

We agree with Harbour’s description of risk event and impact for Risks 7, 5, 6 and 15. ERCE would add into Risk 12 the occurrence of out-of-zone fracturing when reservoir exhibits different stress contrast than modelled and geological properties not conforming to static model assumptions. ERCE would recommend improving the description of the Risk 11, to specify when this specific expansion might be expected. Harbour has provided clarifications about the risk being foreseeable in the post-injection phase when “the reservoir starts to heat up and cause expansion of the fluids that have been injected, the assumption is that it may be a reservoir issue related to late life”.[[35]](#footnote-36)

### ERCE’s Opinion on Initial Consequence and Likelihood

We agree with Harbour’s initial risk assessment of consequence and likelihood for Risks 7, 12, 5, 6, 11 and 15. With reference to literature[[36]](#footnote-37), ERCE has qualitatively checked Harbour’s evaluation workflow with respect to the main parameters controlling thermal fracturing. It is reported how “key parameters that affect the stress distribution and maximum aperture can be broadly divided into two categories: (i) downhole conditions and (ii) thermal and mechanical properties. The injection temperature, and the effective in-situ horizontal stress are the primary downhole conditions that influence the stress state near the wellbore. The thermo-mechanical properties include the thermal conductivity, thermal expansion coefficient and elastic modulus of cement". We understand Harbour has studied all these aspects, with the exception of the elastic modulus of the cement. This parameter is expected to be evaluated in the additional controls during the design of the cement.

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

We are of the opinion the residual risk should remain the same as the initial risk for all of the risks, based on the proposed additional controls from Harbour (see Section 3.5 for discussion on studies).

ERCE is of the opinion that the mitigations are suitable next steps to aid in the uncertainty, but as discussed would not result in reduction of the residual risk at this stage.

For Risk 12 ERCE would suggest investigating the risk in the scenario of thermal fractures propagating and putting injection wells in direct communication. This event may be unlikely but should not be ruled out, particularly with higher well count reducing spacing between boreholes.

For Risk 5, given that the interaction of juxtaposed units across the fault surface section can be complex, ERCE would suggest the use of Allan diagrams.

For Risk 6, ERCE would suggest a study on well placement locations in the worst-case scenario of poor reservoir injectivity and highest well count. Ideal stand-off from fault and well spacing may become more challenging when the number of injection wells increases. Likely this would be carried out during the optimisation work.

For Risk 15, sensitivities on casing and cement thermal conductivities would be suggested in future assessments. This should also include initiating early dialogue with the cementing service companies and casing and tubing providers, essentially Schlumberger, Halliburton and Baker Hughes and request sharing of experiences and recommendations. ERCE also believes it would be beneficial to engage further with operators in the Norwegian Sector, most notably Equinor, with experience in designing “cold” CO2 injection wells in the next phase of work.

For all the risks related to thermal effects identified Harbour, ERCE does not agree with Harbour’s expectation that additional control will reduce risks likelihood. By mean of example, for Risk 12, ERCE is of the opinion that only a change of operating conditions may reduce the risk likelihood. Additional modelling and improved understanding will provide greater confidence in the uncertainty scenarios and will support operational decisions but not reduce the risk itself. Similarly in Risk 6 additional modelling and understanding will provide greater confidence in the uncertainty modelling and operational decisions, but only measures such as stand-off distances from faults will help with the risk mitigation.

## Conformance – CO2 Plume Monitoring Methodology

### Harbour’s Risk description

The following are risk IDs in which Harbour has identified CO2 plume monitoring risks:

* Risk 23: Difficulty or inability to directly monitor primary storage site and CO2 plume below Zechstein salt.
* Risk 28: Inability to display conformance stabilisation at end of storage life leading to delayed decommissioning and site transfer.
* Risk 34: Ineffective MMV strategy or poor efficacy of MMV technologies.

### ERCE’s Opinion on Risk Description

ERCE note that with respect to CO2 plume monitoring:

* Regulation requirements in the UK for monitoring are not yet defined.
* CCS regulatory requirements in other global jurisdictions do not set out a clear minimum set of universal criteria, and there is precedent for CCS regulator requirements to be site specific [[37]](#footnote-38) [[38]](#footnote-39).
* Based on ERCE’s analogue studies, 4D is accepted as a satisfactory monitoring technique. However, the Leman sandstone is a depleted gas field below salt at depths > 8300 ft TVDSS, making 4D a challenging option[[39]](#footnote-40). 4D will be more useful at the Bunter level.
* In the absence of reliable 4D monitoring then monitoring wells could be required and/or a combination of multi-physics measurements with 3D seismic.
* There is a small risk that CO2 could leak from the easternmost part of the Victor structure, in which case there is a chance that migration could lead to partial filling of the Bunter Closure 1. This would not be an issue if Viking was also being developed for storage because the Viking 4D would “catch” that plume. However, developing Victor in isolation leaves open that risk. Dynamic modelling will aid to reduce the risk.

Based on the above points, ERCE is of the opinion that Risks 23, 28 and 34 are accurate in their description of highlighting the potential issues arising from monitoring the CO2 plume. ERCE is of the opinion that these risks cover all the risks which could be associated with difficulty in monitoring the plume development except for the risk of CO2 migrating into Bunter Closure 1.

### ERCE’s Opinion on Initial Consequence and Likelihood

We agree with Harbour’s initial risk consequence and likelihood for Risks 28 and 34. We are of the opinion that the likelihood Harbour has assigned to Risk 23 should be increased from 3 (occasional) to 4 (probable). We are of this opinion as we think it probable that Harbour will not be able to directly monitor the CO2 plume in the Leman, based on the discussion in 6.4.2.

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

We are of the opinion the residual risk should remain the same as the initial risk for all of the risks, based on the proposed additional controls from Harbour (see Section 3.5 for discussion on studies). ERCE is of the opinion that the mitigations are suitable next steps to aid in the uncertainty, but as discussed would not result in reduction of the residual risk at this stage.

From our experience in sub salt reservoirs at this depth, we would think it unlikely the rock physics results will show that the CO2 plume can be tracked using 4D seismic in the Leman. Monitoring techniques including passive seismic have been shown as potentially alternatives[[40]](#footnote-41), but we cannot opine on the suitability of these alternative options with respect to this study.

We would suggest the following additional studies to understand uncertainty:

* Risk 23: Fluid replacement modelling carried out on the Bunter Sandstone. If the Leman is unsuitable for 4D monitoring, then it may be possible to determine whether any CO2 has leaked into the Bunter Sandstone instead. Whether monitoring of the overburden for CO2 migration rather than the primary reservoir is acceptable would be a regulatory decision from the NSTA. This should be discussed at the earliest possible convenience.
* Risk 28: Agree with NSTA on a minimum value of CO2 leakage allowed per year, in line with natural CO2 leakages and on an order which would still mean the overall project is far more beneficial to reducing CO2 than not. As it is critical to reduce CO2 emissions over the coming decades, then if CO2 leaks out once levels have stabilized, and the risk to local environment and safety is not impacted, then this would still be a successful project.
* Risk 34: Consider monitoring wells at spill points of Leman structure. We understand Harbour eliminated this possibility, but it would warrant further consideration of cost savings on monitoring wells. This could include monitoring the Bunter Sandstone with the injection well.
* Risk 34: Consider seabed CO2 baseline and continuous monitoring. If this is installed after CO2 bubbles are observed, then there is a risk the project has to terminate when this CO2 may in fact be natural.
* Risk 34: Do not dispel CSEM and Gravity at this stage. If seismic 4D monitoring is not possible or prohibitively expensive, then techniques are developing to integrate CSEM and Gravity with 3D seismic. CSEM[[41]](#footnote-42) and Gravity[[42]](#footnote-43) lack vertical resolution but may help map laterally the plume migration mapping.

## Conformance – Poor Injectivity due to formation characteristics

### Harbour’s Risk description

Harbour has identified risks related to certain injectivity issues in risk IDs 25 and 22.

* Risk 25: Reservoir injectivity lower than predicted
* Risk 22: Reservoir properties impeding injection rates through:
  + compartmentalisation
  + local wellbore issues
  + crossflow between different reservoir units.

ERCE understands that these risks are related to fieldwide or areal reservoir characteristics (lateral variations of reservoir properties or near wellbore uncertainty in reservoir quality) and/or to certain characteristics such as compartments, communication (near or far from wellbore).

### ERCE’s Opinion on Risk Description

ERCE agrees on the risk identification but notes that both risks appear to cover a broad range of causes. For Risk 25 ERCE would recommend clarification (or to be more specific) on the cause (mechanism) of permeability reduction. The risk might become more severe when an injection well would be drilled into poor reservoir, as found in Well J004. We would recommend breaking out the risk of drilling a well into similar reservoir as J004 as an individual risk, to ensure the associated risk is given due consideration. We discuss this in more detail in Section 7.3.2.

For Risk 22 multiple mechanisms appear to be included. ERCE would recommend more specific description, for example of local wellbore issues. More detailed reservoir description of permeability contrasts between zones might be required as it is not necessarily the case that active producing pay during a gas depletion phase will be active during a CO2 injection scheme as viscosities are different at the sand-face. This is a common practice when an oil producer is turned around to water injection and could be analogous here. In that case different petrophysical cut-offs might be appropriate and is therefore a potential uncertainty for consideration in Section 5.1

### ERCE’s Opinion on Initial Consequence and Likelihood

We agree with Harbour’s initial risk consequence and likelihood for Risks 22, and with the likelihood for Risk 25. For this Risk, ERCE is of the opinion that the financial risk may be underestimated. A fieldwide lack of injectivity could lead to financial consequences potentially more severe than anticipated (from 3 to 4, proposed by ERCE), because of higher well count requirement and possible breach of contract due to not achieving the injected contractual volumes. ERCE is of the opinion that the reputational consequences for Harbour could be higher as contractual non-delivery on Harbour’s flagship CCS project in the UK might jeopardise this business line in the future.

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

We are of the opinion the residual risk should remain the same as the initial risk for all of the risks, based on the proposed additional controls from Harbour (see Section 3.5 for discussion on studies).

ERCE is of the opinion that the mitigations are suitable next steps to aid in the uncertainty, but as discussed would not result in reduction of the residual risk at this stage.

ERCE is of the opinion that significant early data acquisition and reservoir surveillance activities are likely required to allow the dynamic model to be used to understand the mechanism for poor injectivity and update forecasts. The timescale to achieve this is usually longer than operational and contractual needs would dictate. Therefore, one mitigation strategy might be to have an “N+1 sparing philosophy” for development wells, whereby an extra well would always be available for injection as a mitigation measure. This would also build in some flexibility if initial injectivity is poorer than expected or increased in injectivity potential, if injectivity is as planned, and this extra well could then be used for monitoring purposes. As this is a Project Team decision not an uncertainty, ERCE recommends that Harbour conduct an Expected Monetary Value (EMV) analysis assessment of the economics of pre-investing in drilling N+1 development wells (with drilling campaign efficiencies and synergies included) versus a notional injectivity loss in N development wells and delay in drilling the required N+1th well due to the time it would take to history match the dynamic model and mobilisation of a jack-up rig and equipment in distressed circumstances (worst case being in the middle of winter). The value of an economic trade-off against the expected reputational, environmental and legal consequences will then become apparent to the Harbour Project and Management Team.

## Conformance – Poor Injectivity due to rock-fluid and fluid-fluid interaction

### Harbour’s Risk description

Harbour has identified risks related to certain injectivity issues in risk IDs 27, 41, 20, 21, 26, 31, 29, and 33. These risks are related to possible interaction between the injected fluids and the rocks and between fluids (CO2 and water, CO2 and gas) as follows:

* Risk 27: Final storage pressure or injectivity is impacted by CO2 impurities
* Risk 41: Lack of understanding of impurity behaviour, chemical reactions and solubility during injection results in unforeseen impacts on pressure, temperature and transient changes in system
* Risk 20: Hydrate formation or freezing in wellbore causing blockages and low injectivity
* Risk 21: Freezing water (from drop-out or connate water) or vapour gases impairing injectivity performance due to ice formation impeding matrix injection
* Risk 26: Salt crystallisation forming around wellbore
* Risk 31: CO2 liquid phase permeability
* Risk 29: CO2 injection alters reservoir mineralogy, deposits mineral cements or reacts with formation water
* Risk 33: Residual gas saturation creating miscible flood

### ERCE’s Opinion on Risk Description

ERCE has generally found the description of the individual risk events and impacts clear. ERCE agrees with Harbour’s risk identification on the basis of the evidence provided for all risks, except Risk 29 and 31.

ERCE would recommend Risk 29 is reworded to include the possibility of impurities in the CO2 stream altering reservoir mineralogy or reacting with formation water. Limiting the consideration of the risk to CO2 only would omit interaction with the rock of any other non-inert well stream impurities, such as acid gases like SO2 leading to the creation of sulphuric acid[[43]](#footnote-44). ERCE is of the opinion that in the next phase screening level Reactive Transport Modelling (RTM) should be performed to better understand the interaction of injected fluids on connate water and rock mineral dissolution kinetics.

We would recommend Risk 31 is reworded to include supercritical and gas phase permeability, as well as liquid.

We would also recommend further explanations for Risk 33. Harbour has later clarified how this risk is related to a lack of understanding on “how these two fluids will interact, whether they will remain separate or saturate each other and whether or not this will have an impact on our CO2 mobility and pressure build-up vs time assumptions."[[44]](#footnote-45)

### ERCE’s Opinion on Initial Consequence and Likelihood

We agree with Harbour’s initial risk consequence and likelihood for Risks 41, 20, 21, 26 and 33. As discussed in Section 3.4.1, we would anticipate a higher financial consequence than Harbour’s assessment in case certain injectivity issues were encountered. For the risks identified in this section certain mitigation actions might be effective at a well level, but for more general low injections issues, such as Risks 27 and 31, we would anticipate financial consequences potentially more severe than anticipated (quantification from 3 to 4, proposed by ERCE).

ERCE agrees with the likelihood of all the risks above with the exception of the one identified for Risk 31 and Risk 29. Harbour has assigned Risk 31 a likelihood of 2, meaning a remote occurs (i.e. occurs few times in the industry). ERCE would agree with such an estimate in the oil and gas upstream industry, but we understand that CO2 relative permeabilities are poorly known in the CO2 storage industry[[45]](#footnote-46). ERCE would assign a higher likelihood of 3.

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

We are of the opinion the residual risk should remain the same as the initial risk for all of the risks, based on the proposed additional controls from Harbour (see Section 3.5 for discussion on studies).

ERCE is of the opinion that the mitigations are suitable next steps to aid in the uncertainty, but as discussed would not result in reduction of the residual risk at this stage.

We would also suggest the following additional studies to understand uncertainty:

* Risk 29: ERCE would recommend further studies to determine impact of higher concentrations of CO2 on the reservoir rock, as well as the interaction of the CO2 with the cap rock. Although CO2 has been present in the reservoir over geological timescales, this will have been at lower concentrations than that which will result from the project. Without further studies, it will be unclear what the impact of this higher concentration would be on the rock.
* Risk 29: Review of impact of impurities in the CO2 stream.
* Risk 31: Review literature to determine the potential for assessing relative permeability of CO2 using analogous cores, for example over Viking[[46]](#footnote-47) [[47]](#footnote-48).

## Conformance – Poor Injectivity associated to wellbore issues

### Harbour’s Risk description

Harbour has identified risks related to certain injectivity issues in risk IDs 37, 38 and 42. These risks are specific to near wellbore effects related to changes of the sand face induced by drilling or injection operations. These risks are:

* Risk 37: Sand failure induced through pressure cycling impeding injectivity rates
* Risk 38: Rock failure due to cooling causing high skin
* Risk 42: Inability to clean up or ineffective well clean up ahead of injection

### ERCE’s Opinion on Risk Description

Based on the above points, ERCE is of the opinion that Risks 37, 38 and 42 are accurate in their description. ERCE believes that Harbour captures well in Risks 37 and 38 the possibility of in-situ stress environment changes around wellbore/perforations due to pressure and temperature effects potentially causing sanding. ERCE agrees with Harbour on this assessment based on the evidence provided.

### ERCE’s Opinion on Initial Consequence and Likelihood

We agree with Harbour’s initial risk consequence and likelihood for Risks 37 and 38. The sanding risk is studied and discussed extensively in the Geomechanical report prepared for Harbour.[[48]](#footnote-49) The report highlights how “*…near vertical wells horizontal perforations are at risk of sand failure for the highly depleted scenario currently in place in Victor”*. ERCE agrees with the likelihood estimated by Harbour for Risk 42. During the drilling of first or early wells there may a risk of mud losses with likelihood higher than “occasional”, however we would expect a rapid learning curve in the mud programme so we agree with the likelihood of 3. ERCE disagree however on the consequence of this risk. The inability to properly clean a well and to achieve planned injectivity may necessitate additional drilling. ERCE would raise the financial consequence from 2 to 3.

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

We are of the opinion the residual risk should remain the same as the initial risk for all of the risks, based on the proposed additional controls from Harbour (see Section 3.5 for discussion on studies). In the case of breaker treatment testing on core samples for Risk 42, this could be classified as a mitigation action and hence reduce initial risks but only if testing proves successful.

ERCE is of the opinion that the mitigations are suitable next steps to aid in the uncertainty, but as discussed would not result in reduction of the residual risk at this stage.

## Conformance - Fault response to Repressurisation

### Harbour’s Risk description

Harbour has identified a risk related injectivity issues in risk ID 40. This risk is described by Harbour as follows:

* Risk 40: Pressure transmissibility over identified faults is different during repressurisation phase compared to depletion phase

### ERCE’s Opinion on Risk Description

ERCE is of the opinion that Risk 40 is accurate in the description of the event and its impact. Preliminary dynamic modelling relies on fault transmissibility as a primary history match parameter. The impacts of this risk may be a limited CO2 dispersion in the reservoir and the inability to reach predicted storage capacity. ERCE is in agreement with Harbour and observes that the modelled fault threshold pressures may not be the same during depletion and pressurisation process i.e., fluid flow across fault may not be fully reversible.

### ERCE’s Opinion on Initial Consequence and Likelihood

ERCE agrees with the consequence and likelihood identified by Harbour. De Keyser faults would not be expected to provide any vertical flow, due to the cataclastic nature of the filling[[49]](#footnote-50). However horizontal transmissibility may not be the same during depletion and repressurisation, and a likelihood of 2 (occurs a few times in the industry) is judged appropriate.

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

We are of the opinion the residual risk should remain the same as the initial risk for all of the risks, based on the proposed additional controls from Harbour (see Section 3.5 for discussion on studies).

ERCE is of the opinion that the mitigations are suitable next steps to aid in the uncertainty, but as discussed would not result in reduction of the residual risk at this stage.

Sensitivity analyses and additional modelling will be key to increase the confidence in the simulator and address the uncertainty (Section 5.1) but are not believed to be mitigation actions at this stage.

## Conformance and Storage Site Containment - Hydraulic fracturing/high injectivity

Harbour has identified risks related to high pressure or high injectivity issues in risk IDs 8, 9 and 32.

* Risk 8: Hydraulic fracturing due to high injectivity rates per well
* Risk 9: Higher than expected injection rates lead to unexpected transient effects
* Risk 32: Hydraulic fracturing due to supply pressure exceeding reservoir rock strength

### ERCE’s Opinion on Risk Description

Based on the above points, ERCE is of the opinion that Risks 8, 9 and 32 are described accurately by Harbour. ERCE concurs with Harbour in the identification of the possibility that high pressure or high injectivity could results in unwanted fracturing or transient effects in the reservoir.

### ERCE’s Opinion on Initial Consequence and Likelihood

ERCE agree with Harbour on the consequence and the likelihood assessed by Harbour for Risks 8, 9 and 32. Geomechanical modelling provided no evidence of (non-thermally induced) fracturing or fault reactivation that penetrated either the caprock or the side-bounding faults.[[50]](#footnote-51) Injection pressures are expected to be known during injection and that should allow to consider a safe margin from rock fracturing pressure.

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

We are of the opinion the residual risk should remain the same as the initial risk for Risk 32, based on the proposed additional controls from Harbour (see Section 3.5 for discussion on studies).

ERCE agrees with the following additional control to reduce initial risk proposed for Risks 8 and 9: “Well operating design and procedures will ensure injectivity rates are kept within allowable limits.”. We believe this is a valid mitigation measure to ensure injectivity rates are kept within allowable limits.

As overall comment, ERCE notes that if excess CO2 supply, relative to safe injection capacity, becomes a problem, mitigation methods may include restricting flow through existing injection wells or the drilling of more wells. A general mitigation action should include contractual arrangements with the supplier of the CO2 to address operational challenges such as Harbour not able to meet its contractual injection obligations.

## Legacy Wells – Failure of Reservoir P&A Barrier

### Harbour’s Risk description

Harbour has listed the following six risks related to the failure of the reservoir P&A barrier of the legacy wells, either directly or as a derived risk:

* Risk 44: Existing cement degradation due to carbonic acid / other contaminants in any legacy well at Victor.
* Risk 45: Existing casing degradation due to carbonic acid / other contaminants in any legacy well at Victor.
* Risk 43: Failure of reservoir P&A barrier for wells rated 4 or higher (meets or exceeds current OGUK Guidelines) at Victor.
* Risk 46: Failure of reservoir P&A barrier for well 49/17-8.
* Risk 47: Failure of reservoir P&A barrier for well 49/22-2.
* Risk 52: Unforeseen issues arise during the P&A of Victor JM threatening ability to decommission it to current guidelines.

### ERCE’s Opinion on Risk Description

ERCE agrees with Harbour’s opinion that the Victor legacy wells introduce a relatively high level of risk to the project. Six of the total eight wells penetrating the Victor reservoir have been abandoned according to the OGUK Well Decommissioning Guidelines at the time of abandonment. ERCE would advise Harbour to clarify the version of this document which was used. Harbour assess the risk of failure relating to these six wells in Risk 43. Risk 46 evaluates the risk associated with Well 49/17-8, which was abandoned in 1972 and does not meet current requirements for permanent abandonment. Well 49/17-11 is still to be abandoned and the potential issues which may arise from this are discussed in Risk 52. Finally, Risk 47 discusses well 49/22-2, which does not meet the requirements for permanent abandonment due to insufficient length of the annular barrier.

Common to all legacy wells is the risk of cement degradation and/or casing degradation due to the effect, primarily, of carbonic acid which is discussed in Risks 44 and 45.

ERCE is of the opinion that the risks are well described and the existing controls are well accounted and well detailed.

### ERCE’s Opinion on Initial Consequence and Likelihood

Harbour has rated Risk 46 as the highest risk in their assessment, where they have assigned a Significant risk to the initial financial risk, prior to implementation of additional controls. This risk relates to leakage up well 49/17-8, which was abandoned in the 1972. The well was drilled open hole from the 13-3/8” casing shoe at 2,577 ft to 9,520 ft and was abandoned with an open hole cement plug from 9,027 ft to 8,808 ft[[51]](#footnote-52). Note these depths are estimated depths due to the assumption that the cement plug has slumped.

Harbour describes how the risk is driven by a reservoir abandonment plug set without a mechanical base which is likely to have slumped close to the free water level, thus increasing the likelihood of the creation of carbonic acid and subsequent degradation of the cement and casing. In addition, Harbour notes the length and quality of the cement plug is questionable. The high initial risk is due to both high likelihood and high consequence. Harbour assigned a likelihood of 3 (Occasional) for Environmental, Reputation and Financial risk. It then set a 3, 3 and 4 for the consequence for each of these categories respectively.

Due to the time period which has elapsed since abandonment and the mobile formations between the top of the cement plug and the casing shoe, ERCE is of the opinion it is unlikely that there would be a clear flow path to surface. It is therefore ERCE’s opinion that the likelihood Harbour assigned to the risk may be too high given the history of the well. It could be argued that the likelihood of failure of the barrier is 2 (Remote) rather than 3 (Occasional).

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

We are of the opinion the residual risk should remain the same as the initial risk for Risk 52 based on the proposed additional controls from Harbour (see Section 3.5 for discussion on studies). ERCE is of the opinion that the mitigations are suitable next steps to aid in the uncertainty, but as discussed would not result in reduction of the residual risk at this stage. We are of the opinion that the likelihood for Risk 43, 44, 45 and 47 should remain the same as the initial risk, but the residual consequence for these risks should reduce based on the proposal Additional Control of a relief well.

The additional controls which Harbour proposes to mitigate Risk 46 include a number of studies, as well as the consideration of preventing the CO2 plume from reaching well 49/17-8 and the implementation of a relief well. ERCE is of the opinion that if Harbour places its injection wells and plan injection rates such that the modelled CO2 plume does not reach the well bore, then this mitigation is a valid method to reduce the residual risk. However ERCE is of the opinion that the drilling of a relief well may be unrealistic for this well. Should a leak occur, then intersecting the original wellbore at the top of the cement plug will be very challenging as magnetic and resistivity ranging both rely on the presence of steel to locate the well, which is absent in well 49/17-8. Acoustic ranging will in this case only work if the flow is sufficient to generate noise levels that can be detected at distance[[52]](#footnote-53). ERCE therefore agrees with Harbour that the residual consequence should remain the same as the initial. We would suggest Harbour clarify how they plan to drill this relief well, and if they think it may be challenging to locate well 49/17-8 then remove it as an Additional Control from Risk 46.

## Legacy Wells - CO2 Migration

### Harbour’s Risk description

Harbour describes the risks related to the movement of CO2 into the Bunter Sand via legacy wells in risk IDs 3 and 17:

* Risk 3: CO2 escape from the Leman into the Bunter Sand via a poorly isolated legacy well.
* Risk 17: Migrated CO2 into Bunter Sand reaching legacy wellbores.

Harbour classify Risk 3 as storage site containment and Risk 17 as storage complex containment.

### ERCE’s Opinion on Risk Description

Harbour describe the risk of CO2 leakage from the Leman to the Bunter and the mechanisms allowing the leakage in a general sense in Risk 3 and Risk 17. This leakage up legacy wells is also discussed in several other risks, but in a more specific scenario and so we address those risks in separate sections in this report. The wells Harbour identify have the highest potential for leakage are wells 49/17-8 and 49/22-2, which were not decommissioned according to the OGUK guidelines. ERCE agrees with this assessment. Harbour used well 49/22-2 for a worst-case study on CO2 leakage conducted at Heriot Watt University[[53]](#footnote-54). Harbour use the conclusions of this report, along with demonstrated mobile formations in both the Zechstein and Rot Halite[[54]](#footnote-55), to rate the likelihood of leakage to be 3 (occasional).

Risk 17 discusses the risk of CO2 accumulating at the legacy wells. Harbour consider this improbable as the legacy wells penetrate the Bunter sandstone at a structural low and there is evidence to suggest the onwards path from the Bunter sandstone is limited due to competent cap rock in place as well as the mobile Rot Halite formation.

### ERCE’s Opinion on Initial Consequence and Likelihood

ERCE agrees with the initial risk Harbour has assigned to both Risk 3 and Risk 17. It is suggested that leakage into the Bunter can be both the Bunter 1 and Bunter 2 structure and both structures should be evaluated versus the legacy wells location (Risk 17).

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

We are of the opinion the residual risk should remain the same as the initial risk for Risk 3 based on the proposed additional controls from Harbour (see Section 3.5 for discussion on studies). ERCE is of the opinion that the mitigations are suitable next steps to aid in the uncertainty, but as discussed would not result in reduction of the residual risk at this stage.

Harbour retains the same residual risk as initial risk for Risk 17 but reduces the likelihood. ERCE are of the opinion the consequence could be reduced due to the additional control of a relief well, but the likelihood should remain the same.

ERCE would suggest Harbour include in these studies an assessment of the legacy wells in Bunter 1, if there is a risk of leakage into this structure. We discuss this risk in Section 7.2.1.

## Legacy Wells - Operationally Introduced Risks

### Harbour’s Risk description

The following risks which ERCE has classed as Operationally Introduced are risks that arise as a consequence of the changes that will take place in the reservoir as the structure is repurposed as a CO2 storage facility.

* Risk 48: Thermal cooling of reservoir or localised pressure build up at legacy well locations.
* Risk 51: Design recharge pressure is exceeded leading to self-degradation of existing cement barriers or complete failure of barrier.

### ERCE’s Opinion on Risk Description

Both risks 48 and 51 are threats to the containment and the failure mechanism is common to the two risks; that changing reservoir conditions will lead to degradation and failure of the cement barriers in the legacy wells. ERCE is of the opinion that these risks are well described and relevant.

### ERCE’s Opinion on Initial Consequence and Likelihood

ERCE is of the opinion that Harbour’s initial risk for both risk 48 and 51 is reasonable. We agree with Harbour that the likelihood of occurrence in both instances is relatively low as several conditions must be met before an occurrence can take place.

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

We are of the opinion the consequence can be reduced for both Risk 48 and 51, based on the Additional Control of a relief well (see Section 3.5 for discussion on studies). In addition, we are of the opinion the Additional Control assigned to Risk 51, placement of wells, would result in a likelihood reduction for this risk. We are of the opinion the remaining Additional Controls are studies which would not decrease the residual risk at this time.

## New Wells – Well Design and Construction

### Harbour’s Risk description

Harbour’s risks related to the design and construction of the new CO2 injection wells can be sorted into two categories: inadequacies of design and design tools, and inadequacies of the materials specified and the execution of the well construction. We will discuss both of those categories in this section.

* Risk 55: Lack of availability of appropriate software for modelling CO2 injection impact on casing loads.
* Risk 61: Casing design loads and design cases for CO2 injection wells may differ from conventional O&G production.
* Risk 66: Uncertainty around appropriate minimum design temperature.
* Risk 54: Qualification and long-term reliability of equipment for cold temperatures (Xmas Tree, wellhead, casing hangers, pack-offs, SSSV).
* Risk 67: Tubing connection leakage of CO2 into annulus threatening well integrity.
* Risk 4: CO2 escape from the Leman into the Bunter Sand via a poorly isolated new injection well.

### ERCE’s Opinion on Risk Description

Risks 55, 61 and 66 are related to the design and software required to perform the evaluation of the well design. Some of the design load cases and special requirements for CO2 injection may not be directly available in existing software suites and modelling may have to be done in custom load cases. ERCE is of the opinion these are relevant considerations and the complications introduced by “workarounds” can produce additional risks, such as underestimating the temperature variations and subsequent impact on the materials selected.

Risk 54 and 67 are related to materials selection and the qualification of equipment. ERCE is of the opinion that these are key topics and agree with Harbour’s description. ERCE recommend Harbour divide of Risk 54, as this includes a wide range of infrastructure from SSSVs to Xmas Trees in single risk. The impact of failure of these different pieces of equipment may be quite different. Procurement and installation times and costs may vary widely which will impact injection down-time assumptions. In turn this will impact assessments of financial and reputational consequences. Whilst the various equipment listed in Risk 54 will be designed to last the whole field life, the risk analysis will benefit from equipment having , different likelihoods and consequences assigned to them.

### ERCE’s Opinion on Initial Consequence and Likelihood

Harbour has given all these risks a Medium rating driven by significant consequences, however the likelihood, in ERCE’s opinion, has been underestimated. A rating of 2, as applies to all risks in the group, implies current controls will be adequate. Based on experience from the Oil and Gas well construction industry, we are of the opinion there is a significant risk that the likelihood of introduction of design shortcomings will carry over into the construction phase leading to failures during operations. To ensure the appropriate focus is assigned to ensuring the appropriate tools are available and used correctly, it is ERCE’s recommendation that the likelihood of occurrence, prior to implementation of Additional Controls, is increased to a 3 (Occasional) for Risks 55, 61, 66 and 67. This would result in these risks becoming Significant financial risks to Harbour.

We cannot opine on likelihood and consequence of Risk 54 as Harbour group multiple aspects into this one risk.

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

We are of the opinion the residual risk should remain the same as the initial risk for Risk 4, based on the proposed additional controls from Harbour (see Section 3.5 for discussion on studies). ERCE is of the opinion that the mitigations are suitable next steps to aid in the uncertainty, but as discussed would not result in reduction of the residual risk at this stage.

We are of the opinion that the likelihood for Risk 54, 55, 61, 66 and 67 should remain the same as the initial risk, but the residual consequence for these risks should reduce based on the proposal Additional Control of a relief well.

For Risks 61 and 67, Harbour describe an Additional Control as ensuring compliance with its own well design standards. ERCE would expect this to be an existing control.

## New Wells – Well Operation

### Harbour’s Risk description

The risks ERCE has grouped into Well Operation consider changes in the reservoir and wellbore that may lead to damage to either. Harbour’s consequences range from inefficient utilisation of the reservoir to wellbore damage and loss of containment.

* Risk 53: Failure of new well leading to leakage from storage site (assume rig not on location):
  + Inadequate design (including P&A)
  + Poor operating procedures
* Risk 65: Incorrect wellbore operating conditions leading to damage of wellbore:
  + trapped pressure due to incorrect operation leading to thermal expansion loads
  + valve failure leading to trapped pressure and thermal expansion loads
  + CO2 liquid hammer effects in wellbore during shut down causing wellbore damage.
* Risk 57: Cryogenic well operation leading to freezing of annular fluids
* Risk 58: Connate water mobilised due to hydraulic or thermal fracture
* Risk 59: Erosion of wellbore equipment due to high rate gas flow or solidified impurities.
* Risk 37: Sand failure induced through pressure cycling impeding injectivity rates.
* Risk 60: Cooling of the conductor and ice formation in seawater column or above splash zone
* Risk 64: Shallow cooling affecting the drilling of new injection wells once initial injection has started

### ERCE’s Opinion on Risk Description

ERCE is of the opinion the risk descriptions are general but relevant and at this point in the project, adequately described. We would expect Harbour to describe and map the mechanism of failure and the failure modes as work progresses on the project.

We are of the opinion Risk 65 is a catch all risk, and would recommend Harbour split out the risks contained within here as they each have different likelihoods and consequences.

### ERCE’s Opinion on Initial Consequence and Likelihood

ERCE’s overall conclusion is that Harbour has appropriately rated the consequences and likelihoods for each of these risks. We are of the opinion some of the risks could be rated higher to ensure adequate attention, specifically Risks 37 and 65. At present, no risk falls into the Significant category demanding further control measures to bring the risk into the broadly acceptable level. We are of the opinion that Risk 37 if not dealt with effectively, could result in several redrilling operations to rerun reservoir completions that could push the cost impact to level 4 for financial consequence, and the overall initial risk to ‘Significant’.

We cannot opine on 65 as there are too many elements to consider.

### ERCE’s Opinion on Mitigations, and Residual Consequence and Likelihood

We are of the opinion the consequence can be reduced for Risks 53, 57, 58, 59, 60 and 64, based on the Additional Control of a relief well (see Section 3.5 for discussion on studies).

We are of the opinion that the following additional control Harbour assign to Risk 64 is appropriate to reduce the likelihood of the residual risk: “Choke philosophy may mitigate this risk if downhole choking is selected, depending on the philosophy.”

We are of the opinion that the following additional control Harbour assign to Risk 37 is appropriate to reduce the likelihood of the residual risk: “Work with vendors to identify the most appropriate completion solution (probably sand screens) which will account for low-temperature CO2 injection and transient conditions.”

# Unidentified Risks

This section details risks which ERCE would suggest Harbour add into their risk assessment or, if possible, incorporate more explicitly into existing risks.

## Storage Site Containment

### Unmodelled high permeability pathways through the aquifer

ERCE would recommend Harbour include a risk which details the possibility of high permeability intervals being present in the geology which are not included in the geological and simulation modelling. The current methodology of using average permeability from logs to model permeability in the dynamic simulator means that the extreme high and low intervals will not be captured. The CO2 will preferentially travel along the highest permeability pathways, and so modelling of such potential phenomena will help capture uncertainty in potential CO2 plume behaviour. If there is a particular high permeability pathway which is present from the injection well into the aquifer, below the original GWC, then it is possible the CO2 will migrate out with the storage site prior to it being filled.

Harbour have clarified that the reservoir over Victor is observed to be homogenous and there are no observable high permeability streaks within the reservoir[[55]](#footnote-56) so we are of the opinion that this risk would be low likelihood of occurrence. We would still recommend the inclusion of them in sensitivities, but not the base case model. This would account for intervals which may occur away from well control but have not been penetrated, as well as those which are below the resolution of the sonic log (~2 ft).

## Storage Complex Containment

### Bypass of Bunter Closure 2

As the Bunter Closure 2 is offset to the SW of the Victor field[[56]](#footnote-57), Harbour should consider the risk that the CO2 which migrates out of the storage site does not enter Bunter Closure 2. This migration could be a migration route into Bunter Closure 1. As a worst-case scenario this risk should include a direct migration of CO2 to surface via open faults or outcrop to seabed. Based on our regional experience in the area, ERCE is of the opinion this risk is low as there would still remain a tortuous CO2 migratory route to surface.

Harbour discuss further work they plan to carry out to better characterise the storage complex, so this risk may be addressed as part of this ongoing study.

### Bypass of Haisborough Group Cap Rock

There exists the possibility of sandstone juxtaposition of the Bunter with the permeable Rhaetic Sandstone (Winterton formation) above the Haisborough Group cap rock. Based on ERCE’s experience in the area, we are of the opinion the likelihood of this is low, but should be examined via Allan diagrams. We note Harbour discuss the possibility of the Rhaetic Sandstone acting as a permeable layer with the possible impact of providing an additional pathway for CO2 to migrate out of the storage complex within the body of their ERA[[57]](#footnote-58), but do not discuss it with their risk register. Harbour discuss the possibility of CO2 leakage through the Haisborough cap risk in Risk 13, but this discussion focuses on leakage through faults or fractures rather than thief zones. From discussions with Harbour[[58]](#footnote-59), we understand they are currently reviewing the seismic with respect to these overburden intervals and plan to give this due consideration in their work process.

## Conformance

### Microbial impact storage site

ERCE would recommend Harbour include and evaluate the risk of microbial activity on CO2 containment and conformance. One such example includes the alteration of CO2 to methane within the reservoir[[59]](#footnote-60). Another risk may arise from impurities introduced within the CO2 stream impacting the microbial communities[[60]](#footnote-61). We would recommend a literature review, with consideration given to the conditions of the Leman reservoir. We are of the opinion the risk of microbial activity leading to containment or conformance issues with CO2 is low as the reservoir is located at depths greater than 2 km where microbial activity declines, but should still be considered at this stage.

### Drilling an injection well into reservoir similar to J004

Harbour discuss the possibility of reduced injectivity in a number of risks, specifically Risks 22 and 25 which we discuss in Section 6.4. On inspection of the production data for J004, it is apparent that were a well drilled into similar reservoir, Harbour would likely need to drill a new injection well which would have financial costs larger than those Harbour anticipate in their currently discussed risks.

ERCE would recommend detailed analysis of the J004 well to identify why it did not produce as intended. This could include a review of any image logs or core to determine if this was due to intersection of granulation seams or deformation bands. However ERCE understands from discussions with Harbour that no core or image logs are available for the J004 well[[61]](#footnote-62). We understand they are currently undertaking a literature review of the wells in the surrounding areas and based on this review are confident the J004 performed poorly due to proximity to faulting. Based on ERCE’s regional knowledge, wells which are drilled in close proximity to faults have a higher chance of intersecting reservoir artefacts which can lower permeability. We understand Harbour plan to drill their injection wells away from nearby faults, which would help to reduce this risk. We would also recommend detailed assessment of the reprocessed seismic to determine if any sub seismic faults have been missed in the current interpretation, to aim to further reduce the possibility of drilling into reservoir altered by faulting.

## Legacy Wells

### Changing regulation leading to additional requirements

At the time of the Harbour assessment of the legacy wells, there were no UK industry guidance with specific focus on the decommissioning of wells to retain CO2 store integrity. Guidelines are being developed through OGUK but these guidelines are not expected to be published prior to Q2/Q3 2022[[62]](#footnote-63). Harbour has evaluated the legacy well abandonment barriers against the current OGUK Well Decommissioning Guidelines introducing the risk that the new guidelines will introduce more stringent requirements that could potentially lead to requirements to improve the existing well abandonments.

Harbour have clarified that a member of their team sits on the panel for drafting the new OEUK Well Decommissioning Guidelines for CO2 Storage[[63]](#footnote-64). They confirmed that the planned additions for these new guidelines have been considered as part of their current assessment.

# Appendices

## Appendix 1: Nomenclature

|  |  |
| --- | --- |
| **Bscf** | thousands of millions of standard cubic feet |
| **CCS** | Carbon capture and storage |
| CO2 | carbon dioxide |
| **CMG** | Computer Modelling Group Ltd. |
| **ED** | experimental design |
| **EMV** | expected monetary value |
| **ERA** | Harbour’s Early Risk Assessment Report |
| **ft** | feet |
| **GIIP** | gas initially in place |
| **HAZOP** | Hazard and Operability Study |
| **km** | kilometres |
| **LOT** | Leak off test |
| **m** | metre |
| **M MM** | thousands and millions respectively |
| **NSTA** | North Sea Transition Authority |
| **OGUK** | Oil and Gas United Kingdom (Now Offshore Energies United Kingdom) |
| **P&A** | Plug and abandonment |
| **PPFG** | Pore pressure and fracture gradient predictions |
| **rb** | reservoir barrels |
| **SCAL** | special core analysis |
| **scf** | standard cubic feet measured at 14.7 pounds per square inch and 60 degrees Fahrenheit |
| **Shmax** | maximum horizontal stress |
| **Shmin** | minimum horizontal stress |
| **SSSV** | subsurface safety valve |
| **stb** | stock tank barrel (42 US gallons measured at 14.7 pounds per square inch and 60 degrees Fahrenheit) |

## Appendix 2: Documents Provided

Table 8.1 gives details on the ERA documents provided by Harbour.

Table 8.1: Documents suppled to ERCE pertaining to Harbour's Early Risk Assessment

|  |  |
| --- | --- |
| Name | Title |
|
| HBR-SNS-P-XX-X-GG-02-00001 | Early Risk Assessment Report – Victor |

Table 8.2 provides a list of documents supplied by Harbour for ERCE’s independent assessment.

Note when we refer to these documents in footnotes within this report, we refer to them by their document title, rather than document name.

Table 8.2: List of supporting documents provided by Harbour

|  |  |
| --- | --- |
| Name | Title |
|
| ATKL-SNS-P-XX-X-EN-02-00001\_C3\_AFC\_2021\_12\_09.pdf | Confidential Harbour Energy System Engineering Appraisal Pre-FEED Study |
| AXIS-GEN-P-XX-X-GG-02-00001\_A2\_IDC\_2022-01-14 | Victor CO2 Storage Geomechanical Modelling |
| Chrysaor\_Victor\_BondReview\_RevD | Formations as a Barrier & Historical Bond Log Review |
| CHRY-SNS-P-XX-X-GG-01-00001\_C1\_IFU\_02-07-2021 | V Net Zero - Preliminary Monitoring, Measurement and Verification (MMV) Philosophy |
| CHRY-SNS-P-XX-X-GG-02-00001\_C2\_IFU\_20211005 | V Net Zero - Preliminary Subsurface Characterisation |
| CHRY-SNS-P-XX-X-WO-02-00001\_IFU\_C1-01-07-2021 | V Net Zero Legacy Wells Assessment |
| Final Report\_HWU Risk-based Well P&A Modelling for VNZ CCS Project | Risk-based Modelling of Harbour Energy's P&A'd Well 49/22-2 |
| Pre-FEED Subsurface Workflow | Pre-FEED Subsurface Workflow |
| VICTOR\_FIELD\_CCS\_CMG\_STUDY | CO2 Sequestration modelling in Victor Field |

## Appendix 3: References

### Academic Papers

Anston-Race, S.E. and Ganesh, D., 2020. The Viking Fields, Blocks 49/11d, 49/12a, 49/16a, 49/16c, 49/17a, UK North Sea. Geological Society, London, Memoirs, 52(1), pp.273-287.

Bachu, S. and Bennion, B., 2008. Effects of in-situ conditions on relative permeability characteristics of CO2-brine systems. Environmental Geology, 54(8), pp.1707-1722.

Cobb, W.M. and Marek, F.J., 1998, September. Net pay determination for primary and waterflood depletion mechanisms. In SPE Annual Technical Conference and Exhibition. OnePetro.

Foulger, G.R., Wilson, M.P., Gluyas, J.G., Julian, B.R. and Davies, R.J., 2018. Global review of human-induced earthquakes. Earth-Science Reviews, 178, pp.438-514.

Hannah, I.M. and Seymour, D., 2006, March. Shearwater super duplex tubing failure investigation. In CORROSION 2006. OnePetro.

M.W. Fellgett, A. Kingdon, J.D.O. Williams, State of stress across UK Regions, , C.M.A. Gent, British Geological Survey, GeoAnalytics and Modelling Directorate, Open Report OR/17/048. 2017. <http://nora.nerc.ac.uk/id/eprint/517414/1/OR17048.pdf>

Morgan et al, Potential impacts of oxygen impurities in carbon capture and storage on microbial community composition and activity. Volume 111, October 2021, 103479 (2021).

Mathias, S.A., Gluyas, J.G., de Miguel, G.J.G.M., Bryant, S.L. and Wilson, D., 2013. On relative permeability data uncertainty and CO2 injectivity estimation for brine aquifers. International Journal of Greenhouse Gas Control, 12, pp.200-212.

Nogues, J.P., Fitts, J.P., Celia, M.A. and Peters, C.A., 2013. Permeability evolution due to dissolution and precipitation of carbonates using reactive transport modeling in pore networks. Water Resources Research, 49(9), pp.6006-6021.

Pearce et al, SO2 impurity impacts on experimental and simulated CO2–water–reservoir rock reactions at carbon storage conditions. Chemical Geology, Volume 399, 2 April 2015, Pages 65-86 (2015).

Roger Goobie and Benny Poedjono, 2019. ISCWSA: Well Intercept Sub-Committee EBook. Wellbore Ranging Technologies, Intercept Applications and Best Practices

Subagjo, I., Dupuy, B., Park, J., Romdhane, A., Querendez, E. and Stovas, A., 2018, September. Joint rock physics inversion of seismic and electromagnetic data for CO2 monitoring at Sleipner. In 24th European Meeting of Environmental and Engineering Geophysics (Vol. 2018, No. 1, pp. 1-5). European Association of Geoscientists & Engineers.

Tyne, R.L., Barry, P.H., Lawson, M. *et al.* Rapid microbial methanogenesis during CO2 storage in hydrocarbon reservoirs. *Nature* **600,**670–674 (2021). <https://doi.org/10.1038/s41586-021-04153-3>

Verdon, J.P., Kendall, J.M., White, D.J., Angus, D.A., Fisher, Q.J. and Urbancic, T., 2010. Passive seismic monitoring of carbon dioxide storage at Weyburn. The Leading Edge, 29(2), pp.200-206.

Wan, L., Han, M., AlJanobi, H.A. and Zhdanov, M.S., 2020. Feasibility study of gravity gradiometry monitoring of CO2 sequestration in deep reservoirs using surface and borehole data. In Active Geophysical Monitoring (pp. 123-140). Elsevier.

### Standards and Guidelines

Carbon dioxide appraisal and storage licence CS005, The Oil & Gas Authority and Chrysaor, 2021, <https://www.nstauthority.co.uk/media/8097/cs005-signed-copy-_redacted.pdf>

Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide

* Guidance Document 1 - CO2 Storage Life Cycle Risk Management Framework
* Guidance Document 2 - Characterisation of the Storage Complex, CO2 Stream Composition, Monitoring and Corrective Measures

ISO 27914 - Carbon dioxide capture, transportation and geological storage — Geological storage, International Organization for Standardization, 2017

OGUK Well Decommissioning Guidelines – Issue 6, June 2018

Recommended Practice DNV-RP-J203 – Geological Storage of Carbon Dioxide, DNV, 2017

Service Specification DNV-SE-0473 - Certification of sites and projects for geological storage of carbon dioxide, DNV, 2017

Service Specification DNV-SE-0617 - Qualification management for geological storage of CO2, DNV, 2022

## Appendix 4: Meetings with Harbour

As part of the consultation process, ERCE and Harbour held a series of meetings over the duration of the project. All meetings were held virtually over Microsoft Teams. The timings and purpose of these meeting are detailed in Table 8.3.

Note these exclude the Workshop held with Harbour and the NSTA on the 11th May 2022.

Table 8.3: Meetings Held Between Harbour and ERCE

|  |  |
| --- | --- |
| Date | Purpose |
|  |
| 11th April | Kick off meeting after ERCE received the ERA |  |
| 22nd April | Clarifications on the technical subsurface risks |  |
| 25th April | Clarifications on Harbour’s risk process |  |
| 9th May | ERCE present preliminary findings to Harbour |  |

1. Hannah and Seymour, 2006. Shearwater super duplex tubing failure investigation. [↑](#footnote-ref-2)
2. Schedule 4, Section 1.2, “Risk Assessment Report”, Carbon dioxide appraisal and storage licence CS005, The Oil & Gas Authority and Chrysaor, 2021 [↑](#footnote-ref-3)
3. Victor CO2 Storage Geomechanical Modelling [↑](#footnote-ref-4)
4. EU CCS Directive, 2009. Section 3.3.1 [↑](#footnote-ref-5)
5. Wellbore Ranging Technologies, Intercept, Applications and Best Practices, ISCWSA: Well Intercept Sub-Committee eBook [↑](#footnote-ref-6)
6. Email communication with Harbour, 06/05/2022 [↑](#footnote-ref-7)
7. ISO 31000:2018 Guidelines for risk management [↑](#footnote-ref-8)
8. Meeting with Harbour 09/05/2022 [↑](#footnote-ref-9)
9. Email communication, dated 21/04/2022 [↑](#footnote-ref-10)
10. Cobb and Marek, 1998. Net Pay Determination for Primary and Waterflood Depletion Mechanisms. [↑](#footnote-ref-11)
11. V Net Zero - Preliminary Subsurface Characterisation, Section 7.2.3 [↑](#footnote-ref-12)
12. Meeting with Harbour, 09/05/2022 [↑](#footnote-ref-13)
13. CO2 Sequestration modelling in Victor Field, page 27 [↑](#footnote-ref-14)
14. Victor CO2 Storage Geomechanical Modelling, Section 2.2 [↑](#footnote-ref-15)
15. Victor CO2 Storage Geomechanical Modelling, Section 6.3 [↑](#footnote-ref-16)
16. Victor CO2 Storage Geomechanical Modelling, Section 6.4 [↑](#footnote-ref-17)
17. Victor CO2 Storage Geomechanical Modelling, Section 6.1 [↑](#footnote-ref-18)
18. Victor CO2 Storage Geomechanical Modelling, Section 6.4, Figure 6-7 [↑](#footnote-ref-19)
19. State of stress across UK Regions, British Geological Survey [↑](#footnote-ref-20)
20. V Net Zero - Preliminary Subsurface Characterisation, Section 3.5 [↑](#footnote-ref-21)
21. V Net Zero - Preliminary Subsurface Characterisation, Section 10.3 [↑](#footnote-ref-22)
22. V Net Zero - Preliminary Subsurface Characterisation, Section 3.1 [↑](#footnote-ref-23)
23. V Net Zero - Preliminary Subsurface Characterisation, Section 9.2 [↑](#footnote-ref-24)
24. Email communication with Harbour, dated 21/04/2022 [↑](#footnote-ref-25)
25. CO2 Sequestration modelling in Victor Field, page 95 [↑](#footnote-ref-26)
26. V Net Zero - Preliminary Subsurface Characterisation, Section 9.2 [↑](#footnote-ref-27)
27. V Net Zero - Preliminary Subsurface Characterisation, Section 7.2.12 [↑](#footnote-ref-28)
28. V Net Zero - Preliminary Subsurface Characterisation, Executive Summary [↑](#footnote-ref-29)
29. Geomechanics Section 8.2 [↑](#footnote-ref-30)
30. V Net Zero - Preliminary Subsurface Characterisation, Section 2.4.1 [↑](#footnote-ref-31)
31. Meeting with Harbour, 22/04/2022 [↑](#footnote-ref-32)
32. V Net Zero - Preliminary Subsurface Characterisation, Section 3.4 [↑](#footnote-ref-33)
33. Nogues et al, 2013. Permeability evolution due to dissolution and precipitation of carbonates using reactive transport modeling in pore networks. [↑](#footnote-ref-34)
34. Foulger et al, 2018. Global review of human-induced earthquakes. [↑](#footnote-ref-35)
35. Email communication 21/04/2022 [↑](#footnote-ref-36)
36. Effect of thermal stress on wellbore integrity during CO2 injection, Pratanu Roy, Joseph P. Morris, Stuart D.C. Walsh, Jaisree Iyer, Susan Carroll [↑](#footnote-ref-37)
37. OGA Carbon Dioxide Storage Permit Application Guidance, Appendix 2 [↑](#footnote-ref-38)
38. EU CCS Directive 2009, (28) [↑](#footnote-ref-39)
39. Though we note 4D feasibility studies are planned for 2022 [↑](#footnote-ref-40)
40. Passive seismic monitoring of carbon dioxide storage at Weyburn, Verdon, Kendall et al, 2010 [↑](#footnote-ref-41)
41. For example: Subagjo et al, 2018. Joint Rock Physics Inversion of Seismic and Electromagnetic Data for CO2 Monitoring at Sleipner [↑](#footnote-ref-42)
42. Wan et al, 2020. Feasibility study of gravity gradiometry monitoring of CO2 sequestration in deep reservoirs using surface and borehole data. [↑](#footnote-ref-43)
43. Julie et al, 2015 [↑](#footnote-ref-44)
44. Email communication, 21/04/2022 [↑](#footnote-ref-45)
45. Relative permeability for multi-phase flow in CO2 storage reservoirs – Global CCS Institute and Stanford University - June 2015 [↑](#footnote-ref-46)
46. Mathias et al, 2013 [↑](#footnote-ref-47)
47. Bachu and Bennion, 2008 [↑](#footnote-ref-48)
48. Victor CO2 Storage Geomechanical Modelling – Axis, January 2022 [↑](#footnote-ref-49)
49. Anston-Race and Ganesh, 2020. The Viking Fields, Blocks 49/11d, 49/12a, 49/16a, 49/16c, 49/17a, UK North Sea. [↑](#footnote-ref-50)
50. Victor CO2 Storage Geomechanical Modelling, Section 2.4 [↑](#footnote-ref-51)
51. V Net Zero Legacy Wells Assessment, Section 6.6.1 [↑](#footnote-ref-52)
52. Wellbore Ranging Technologies, Intercept, Applications and Best Practices, ISCWSA: Well Intercept Sub-Committee eBook [↑](#footnote-ref-53)
53. Risk-based Modelling of Harbour Energy's P&A'd Well 49/22-2 [↑](#footnote-ref-54)
54. V Net Zero Legacy Wells Assessment, Section 1.4.1 [↑](#footnote-ref-55)
55. Meeting with Harbour, 09/05/2022 [↑](#footnote-ref-56)
56. V Net Zero - Preliminary Subsurface Characterisation, Section 1.1 [↑](#footnote-ref-57)
57. Early Risk Assessment Report – Victor, Section 3.3.2 [↑](#footnote-ref-58)
58. Meeting with Harbour, 09/05/2022 [↑](#footnote-ref-59)
59. Rapid microbial methanogenesis during CO2 storage in hydrocarbon reservoirs (Tyne et al, 2021) [↑](#footnote-ref-60)
60. Morgan et al, 2021 [↑](#footnote-ref-61)
61. Meeting with Harbour, 09/05/2022 [↑](#footnote-ref-62)
62. V Net Zero Legacy Wells Assessment – Section 1.2 [↑](#footnote-ref-63)
63. Meeting with Harbour, 09/05/2022 [↑](#footnote-ref-64)