# Risk Evaluation for $CO_2$ Geosequestration in the Knox Supergroup, Illinois Basin Final Report

Topical Report

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An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins

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# Executive Summary

This report describes a process and provides seed information for identifying and evaluating risks pertinent to a hypothetical carbon dioxide ($CO_2$) capture and sequestration (CCS) project. In the envisioned project, the target sequestration reservoir rock is the Potosi Formation of the Knox Supergroup. The Potosi is identified as a potential target formation because (1) at least locally, it contains vuggy to cavernous layers that have very high porosity, and (2) it is present in areas where the deeper Mt. Simon Sandstone (a known potential reservoir unit) is absent or nonporous. The key report content is discussed in Section 3.3, which describes two lists of Features, Events, and Processes (FEPs) that should be considered during the design stage of such a project. These lists primarily highlight risk elements particular to the establishment of the Potosi as the target formation in general. The lists are consciously incomplete with respect to risk elements that would be relevant for essentially all CCS projects regardless of location or geology. In addition, other risk elements specific to a particular future project site would have to be identified.

Sources for the FEPs and scenarios listed here include the iconic Quintessa FEPs list developed for the International Energy Agency Greenhouse Gas (IEAGHG) Programme; previous risk evaluation projects executed by Schlumberger Carbon Services; and new input solicited from experts currently working on aspects of CCS in the Knox geology. The projects used as sources of risk information are primarily those that have targeted carbonate reservoir rocks similar in age, stratigraphy, and mineralogy to the Knox-Potosi.

Risks of using the Potosi Formation as the target sequestration reservoir for a CCS project include uncertainties about the levels of porosity and permeability of that rock unit; the lateral consistency and continuity of those properties; and the ability of the project team to identify suitable (i.e., persistently porous and permeable) injection depths within the overall formation. Less direct implications include the vertical position of the Potosi within the rock column and the absence of a laterally extensive shale caprock immediately overlying the Potosi. Based on modeling work done partly in association with this risk report, risks that should also be evaluated include the ability of available methods to predict and track the development of a $CO_2$ plume as it migrates away from the injection point(s). The geologic and hydrodynamic uncertainties present risks that are compounded at the stage of acquiring necessary drilling and injection permits.

It is anticipated that, in the future, a regional geologic study or $CO_2$-emitter request may identify a small specific area as a prospective CCS project site. At that point, the FEPs lists provided in this report should be evaluated by experts for their relative levels of risk. A procedure for this evaluation is provided. The higher-risk FEPs should then be used to write project-specific scenarios that may themselves be evaluated for risk. Then, actions to reduce and to manage risk can be described and undertaken.

The FEPs lists provided as Appendix 2 should not be considered complete, as potentially the most important risks are ones that have not yet been thought of. But these lists are intended to include the most important risk elements pertinent to a Potosi-target CCS project, and they provide a good starting point for diligent risk identification, evaluation, and management.

# 1. Purpose and Scope

## 1.1. Knox Project Task

The primary aims of Knox Project Task are to (1) identify key risk elements and (2) define a process by which these elements can be evaluated. The identified risk elements would be those that are especially relevant to limited components of a hypothetical CCS project whose target reservoir is the Potosi Formation of the Knox Group, at a location in the southern Illinois Basin. The complete statement of Task is provided in Appendix 1.

## 1.2. Definition: "Knox-FX Project"

Funding documents and current deliverables have already used the name "Knox Project" to formally identify a set of pre-front end engineering design (FEED) type studies related to $CO_2$ injection into the geologic Knox Group at a nonspecific location. Risks associated with executing that "Knox Project" are minor, similar to the risks associated with executing most office-based projects that lack a significant physical component. To avoid ambiguity, the name **"Knox-FX Project"** (FX for "Full Execution") is defined herein to refer to an actual (but hypothetical) future project in which dense-phase $CO_2$ would be injected into the Potosi Formation of the Knox Group at a specific to-be-defined site within the southern Illinois Basin. This defined Knox-FX Project is limited to the geosequestration (GS) component and does not encompass the full CCS chain, which also includes $CO_2$ capture, processing, and transport. Task focuses on the risks associated with a Knox-FX Project.

## 1.3. Scope

This report identifies risk elements relevant to a Knox-FX Project, and describes a process by which these elements could be evaluated for the purpose of minimizing (treating) and actively managing risk while executing an actual project. The report does not address applying the risk-evaluation results to the development of risk treatments and, as such, it constitutes only the first step in developing a risk management plan. This report will not provide insight into the risk level of any specific Knox-based project; rather, its intent is to provide a template for thoroughly and efficiently evaluating these risks.

Consideration of risk per Task focuses mainly on the physical implications and requirements of a Knox-FX Project, in accordance with preliminary designs developed in part through "Knox Project" pre-FEED studies. Additional risk areas considered include legal, procedural, and budgetary; however, emphasis is on aspects of a Knox-FX Project that *would differ in a systematic way* from parallel aspects of other possible GS projects in the US Midwest, *because of* the specific target reservoir (Potosi Formation of the Knox Group).

Because the Knox-FX Project has no specific site selected, the scope of Task *does not* include (a) risks related to the potential impact of project activities upon surface features or (b) risks related to the suitability of surface characteristics for project activities. In the event that a specific site or sites were evaluated at a later time for an actual Knox-FX Project, surface-related risks would have to be identified and evaluated.

The identification of relevant risk elements relies upon two main sources: (1) The experience and knowledge of Hannes Leetaru of the Illinois State Geologic Survey (ISGS) and that of employees of Schlumberger Carbon Services about Knox Group geology and sequestration technologies; and (2) The experience of the author in designing more than 10 similar risk evaluations for GS projects.[1, 2] The design of risk evaluation methods (workshops and other processes) draws primarily upon the experience of the author.

# 2. Risk Evaluation Framework

## 2.1. General Statement

The risk evaluation framework described here was developed without reference to a specific project site. All aspects – but especially the assumptions–should be reconsidered and adapted as necessary to a specific proposed site and project.

## 2.2. Assumptions and Information Base

The assumptions and general information basis for risk identification for a Knox-FX Project are shown in Table 1. A Knox-FX Project would be sited in the southern part of the Illinois Basin south of Decatur, IL (tinted area; Figure 1). In Figure 2, the southern Illinois Basin is represented in the three chronostratigraphic columns to the left.

**Table 1: Assumptions and information base.**

| | |
|---|---|
| **Assumption 1: Location** | A hypothetical Knox-FX Project would be located in the Illinois Basin south of Decatur, IL, in southern Illinois, southwestern Indiana, or northern Kentucky (Figure 1). Reasons for this geographic focus include (1) the possibility that the Mt. Simon Sandstone is not present or generally not suitable as a GS target in this area; and (2) the St. Peter Sandstone overlying the Knox (Figure 2) probably has salinity greater than 10,000 ppm in this entire area and would therefore not be identified as a underground source of drinking water (USDW). This subarea is varied in surface and cultural attributes (geographic features, distributions of residences, industry, farming and recreational activities, etc.). Task incorporates **no** assumptions about surface attributes. |
| **Assumption 2: Information** | Risk identification is based on information from two principal sources:<br>(1) Regional data and understanding of the Knox Group and its geologic setting, as specified and provided by Hannes Leetaru and as provided by other participants in the Knox Project; and<br>(2) Experience with execution of $CO_2$ GS projects: the Illinois Basin–Decatur Project (IBDP) in particular and projects in other regions. This aspect is important because many risks arise not simply from geologic conditions per se, but also from the ability of the project to respond to geologic and operational variations. |
| **Assumption 3: Geologic attributes** | The table of Knox Group and Potosi Formation attributes (Table 2) is taken as broadly representative of geologic conditions throughout the southern Illinois Basin. In this report, risks are identified primarily with reference to this set of assumed conditions. Risk evaluation for an actual Knox-FX Project should account for the risk effect of site-specific deviations from these generalizations and for generalizations deemed incorrect. |
| **Assumption 4: Injection target and schedule** | A Knox-FX Project is planned (hypothetically) to inject 3.2 million tonnes per annum (3.5 million tons per annum [MTPA]) of dense-phase $CO_2$ into the Potosi Formation of the Knox Group over a period of 30 years. The time period of interest relative to the effects of $CO_2$ injection extends for 100 years after injection ceases. Injection via a single well is assumed. |
| **Assumption 5: Geologic seal** | The geologic seal is assumed to be the upper Ordovician-age Maquoketa Shale (Figure 2). The Maquoketa Shale thickness in the subject region is 30.5–152 m (100–500 ft). The probability that the Maquoketa is absent or too thin for adequate seal at specific sites is unknown to poorly known. Sealing characteristics are poorly known but assumed to be good based on regional lithologic observations. |
| **Assumption 6: Regulatory setting** | The Knox-FX Project will be subject to Underground Injection Control (UIC) Class VI regulations and other pertinent regulations and permitting requirements as they exist in July 2013. |

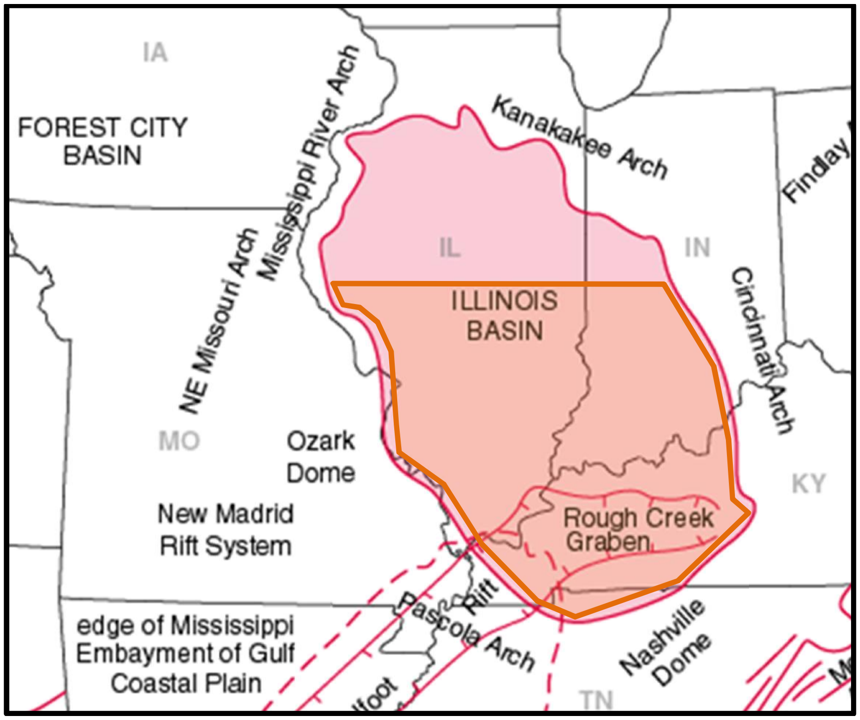


Figure 1: Illinois Basin; southern part highlighted (credit: ISGS).

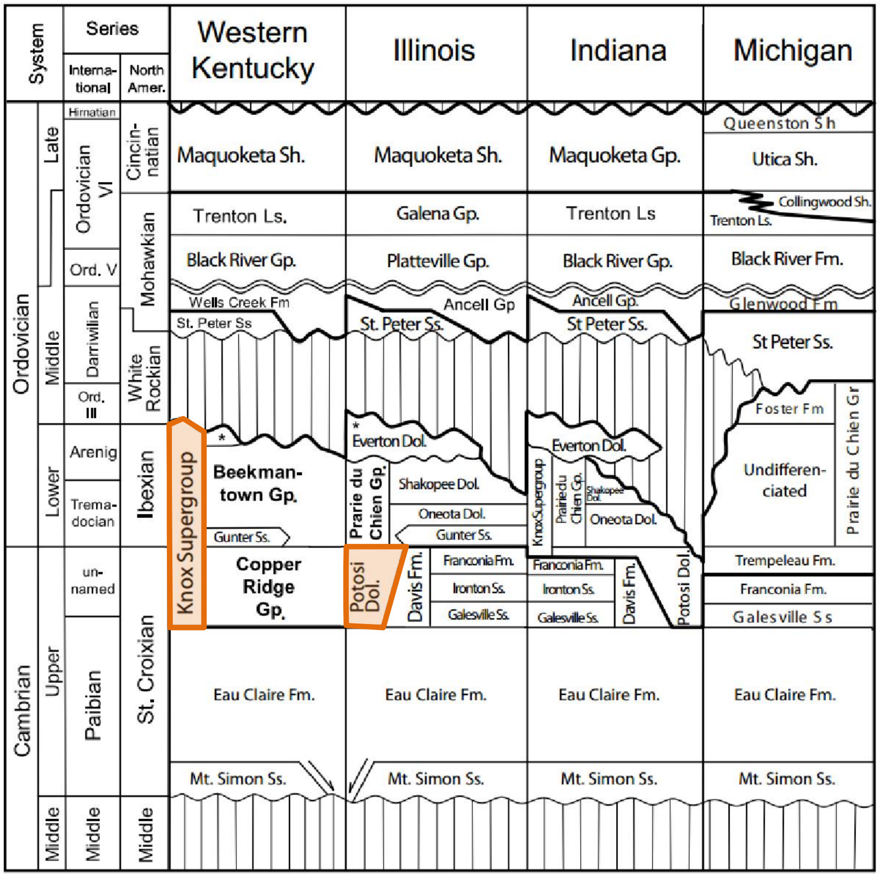


Figure 2: Chronostratigraphy of Knox-associated units (credit: ISGS).

**Table 2: Knox Group and Potosi Formation attributes.**

| | Aspect | Knox (Potosi) attributes in southern Illinois Basin |
|---|---|---|
| 1 | Lithology overall | Mixed carbonates, especially dolostones |
| 2 | Lithology variation | Thin sandstones especially in upper part of Knox and especially in northern basin.<br>Gunter Ss. formation (part of Knox) was tested in Blan well, KY. |
| 3 | Bedding | Thin |
| 4 | Mineralogy - grains | Dolomite, calcite, quartz |
| 5 | Mineralogy - cements | Presume carbonate, some anhydrite? |
| 6 | Porosity structure | Matrix, vuggy, cavernous, fracture |
| 7 | Porosity quantity | Extreme variation |
| 8 | Depth | Variable; "sequestration depth" greater than about 914 m (3,000 ft). |
| 9 | Formation pressure | Variable, depending on depth |
| 10 | Fracture pressure | Could be limited due to brittleness? |
| 11 | Formation temperature | Site-specific and depth-dependent |
| 12 | Subcrop unit identification | Thick section of other Knox Group geologic units underlies the Potosi Formation. |
| 13 | Subcrop lithology | Dolostone |
| 14 | Subcrop topography | Possible depositional topography, e.g., reefs? |
| 15 | Internal unconformities | Common, variable dip |
| 16 | Upper contact conformability | Erosional? Likely to be not very planar: collapses, etc. |
| 17 | Overlying unit identification | St. Peter Sandstone overlies the Knox Group in much of the region. |
| 18 | Overlying unit lithology | Sandstone |
| 19 | $CO_2$ sequestration caprock identification | Maquoketa Shale (above thick Ordovician limestones) |
| 20 | Thickness to caprock | 457 m (1,500 ft) (Decatur area) |
| 21 | Caprock thickness | 46–122 m (150–400 ft) (regional) |
| 22 | Overlying protected aquifer identification | Probably various aquifers in Mississippian or Pennsylvanian sections |
| 23 | Vertical thickness to USDW | Probably various; a few hundred feet of limestone above Maquoketa |
| 24 | Fault spatial density | Relatively high; potential caprock offset |
| 25 | Fault spatial density (seismic) | Could be high; “triggerable” fault could exist nearby depending on site |
| 26 | Well-penetration spatial density | Variable; because of shallower depth, likely to be greater than the “reference” CCS project in this region (IBDP) |
| 27 | Geologic data density | Higher due to more penetrations and nearer outcrop |
| 28 | Orphan well spatial density | Variable and highly site-specific |
| 29 | Reservoir seismic imageability | Probably regionally good; probably mainly depends on surface access and topography |
| 30 | $CO_2$ -saturation imageability | No reason to expect particular problems except related to plume thinness? |
| 31 | Injection well integrity | Problematic to case and perforate; might lean toward openhole |
| 32 | Injection well instrumentability | Less monitorable if completion is openhole |
| 33 | Monitoring well integrity | Not particularly problematic unless reliant on well seal within Potosi section. |
| 34 | Monitoring well instrumentability | May be difficult in Potosi section; may be excellent if St. Peter is monitored. |
| 35 | Natural seismicity? | Not negligible in Knox-FX area, including chance of New Madrid-type earthquake. |
| 36 | Seal subsurface conflicts | Is Maquoketa a target for shale gas drilling? |
| 37 | Surface characteristics | Much of the Knox-FX area is more hilly and treed than near Decatur |
| 38 | Reservoir subsurface conflicts | Notably site-specific. Knox-FX area more or less coincides with regional oil and gas production in the Illinois Basin. Questions would include: Is there Knox production near a project site? Abandoned wells? Will future drilling be impeded by injection-elevated pressure? Are there water or waste disposal wells into the Knox? |

## 2.3. *Project Values*

To identify and evaluate risk, a project operator must identify the persons, groups, budgets, and other valued entities and principles that may be *at risk*. It is also useful to describe, for each of these entities, a desired state of "no negative impact", so that degrees of possible negative impact can be clearly conceived and scaled with respect to this goal. A set of project values and project-value goals for a hypothetical Knox-FX Project is provided in Table 3, based largely on the IBDP. For an actual project located at a specific real site and having the involvement of specific operator, partners, regulators, insurers, and stakeholders, these values should be reconsidered and adjusted as needed. Given that a Knox-FX Project would be intended to be commercial, the principal objective of storing a given flow rate and total mass of $CO_2$ would also be defined as a project-specific project value.

**Table 3: Knox-FX project values.**

| **Knox-FX PROJECT VALUE** | **Knox-FX Project Value Description** | **Knox-FX Project Value Goal** |
|---|---|---|
| Health and Safety | Health and safety of project staff and project neighbors are paramount considerations. | No lost days due to health or safety incidents, no public health impacts. |
| Schedule and Budget | The goals of executing on time and within budget are assumed. Because schedule and budget are not fully defined, risk assessment will characterize issues of this nature that are likely to be encountered. | On time, within budget. |
| Environment | The Knox-FX Project will comply with requirements for well UIC permitting, the National Environmental Policy Act (NEPA), local ordinances, and all other applicable environmental regulations. | No adverse environmental impacts, no regulatory violations. |
| Reservoir Characterization | Understanding of the distribution of Knox (Potosi) porosity, permeability, and mineralogy (and their heterogeneity), at the scales significant to $CO_2$ flow. | Published peer-reviewed paper(s) describing Knox (Potosi) architecture at scales affecting reservoir flow. |
| Plume Tracking | The progressive development of a separate-phase $CO_2$ plume will be monitored through its geomechanical and geochemical effects, using combined measurement, physical sampling, and simulation methods. | Continuous ability to account for the physical location and phase of 99% of the injected $CO_2$, with reasonable precision and accuracy. Continuous ability to demonstrate beyond a reasonable doubt that no more than a negligible amount of $CO_2$ can have moved out of the defined sequestration complex (the injection reservoir plus lowest defined overlying seal; within the lateral limits of the defined Area of Review [AOR]). |
| Societal Support | Increased professional and public understanding and support for $CO_2$ injection as a viable greenhouse gas technology. | Public endorsement exceeds any public opposition. Professional papers published. |

## 2.4. Risk Scales

In industrial contexts, risk is typically quantified as the product of the likelihood (probability; Table 4) and severity of impact (Table 5). Both likelihood and severity are typically conceived as logarithmically rather than linearly scaled quantities. For a Knox-FX Project, likelihood (L) would be evaluated according to the scale shown in Table 4. The same scale would be used whether the evaluated risk elements were conceptual FEPs or concrete scenarios (see Section 3).

**Table 4: Likelihood scale.**

| **Knox-FX Risk Element Likelihood** | | |
|---|---|---|
| Very Unlikely | **1** | <1% chance during the project |
| Unlikely | **2** | 3% chance |
| Possible | **3** | 10% chance |
| Likely | **4** | 30% chance |
| Very Likely | **5** | >= 90% chance during the project |

In practice, different risk evaluators (for example, different participants in a risk workshop) find it easier to begin using either textual values (“likely”–“unlikely”) or the probabilistic values (“10% chance”) of the severity scale, and then resolving the chosen value level into the categorical 1 through 5 scale. Either practice is acceptable and, after some experience, most participants gravitate quickly toward direct use of the 1 through 5 scale itself.

Table 5: Impact severity scales.

| | | **Impact Severity** | | | | |
|---|---|---|---|---|---|---|
| | | **Light** | **Serious** | **Major** | **Catastrophic** | **Multi-Catastrophic** |
| | | **-1** | **-2** | **-3** | **-4** | **-5** |
| **Knox-FX Project Values** | **Health and Safety** | Minor Injury or Illness, First Aid | Temp. Disability, Hospital to 1 day, Lost Days 1–100 | Perm. Disability, Lost Days >100, Intensive Care >1 day | Fatality | Multi-Fatality |
| | **Schedule and Budget** | <5% impact on project budget; few days unplanned downtime; a month overall delay | 10% impact on project budget; two weeks unplanned downtime; 2 months overall delay | 25% impact on project budget; two months unplanned downtime; 4 months overall delay | 50% impact on project budget; four months unplanned downtime; 8 months overall delay | >100% impact on project budget; a season unplanned downtime; >1 year overall delay |
| | **Environment** | Minor temporary impact to worksite | Significant temporary impact on or near worksite | Significant long-term impact on or near worksite | Significant long-term impact upon 0.65 km$^2$ (¼ square mile) | Significant long-term impact beyond 0.65 km$^2$ (¼ square mile) |
| | **Reservoir Characterization** | Impact levels to be specified by each project. | Impact levels to be specified by each project. | Impact levels to be specified by each project. | Impact levels to be specified by each project. | Project's characterization data have minimal wider application. |
| | **Plume Tracking** | Impact levels to be specified by each project. | Impact levels to be specified by each project. | Impact levels to be specified by each project. | Impact levels to be specified by each project. | Free-phase project $CO_2$ appears at aquifer, surface, or non-project well. |
| | **Societal Support** | Individuals opposed to project. | Group(s) opposed to project | Substantial local negative media coverage | Substantial regional or national negative media coverage | Widespread opposition to $CO_2$ injection |

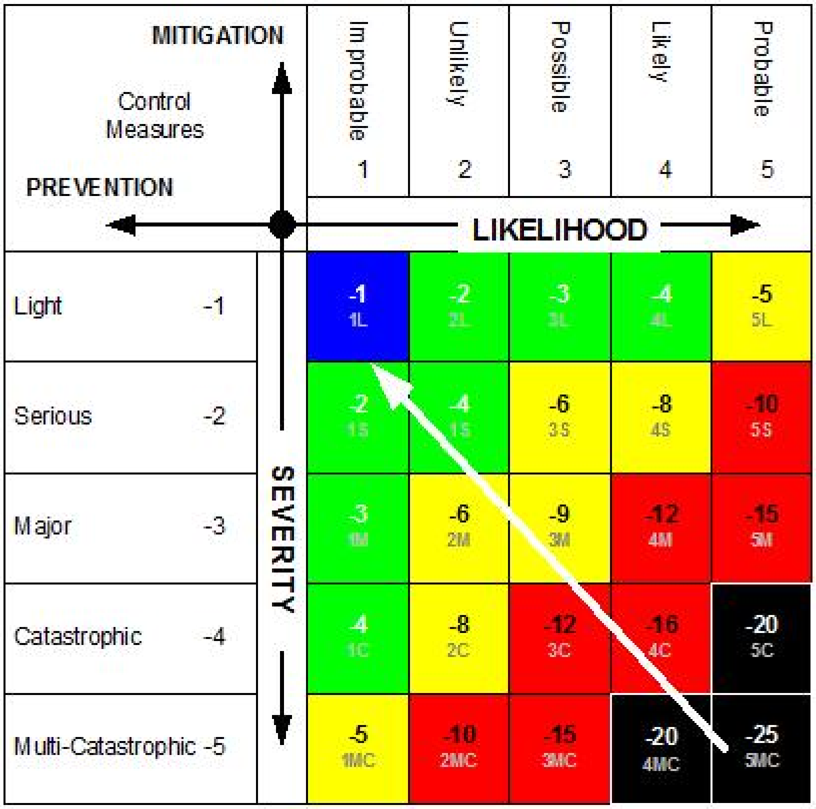
## 2.5. Risk Tolerance and Risk Matrix

Some words about policy of project operator and risk tolerance (Table 6; Figure 3).

**Table 6: Risk tolerance table.**

| **Values may be calculated averages (i.e., not integers). Boundaries are** | | |
|---|---|---|
| −25 to −18 | **BLACK** | Non-operable: Abandon project if this risk cannot be lowered |
| −18 to −9.5 | **RED** | Intolerable: Do not accept this risk |
| −9.5 to −4.5 | **YELLOW** | Undesirable: Demonstrate that risks are ALARP[1] before proceeding |
| −4.5 to −1.5 | **GREEN** | Acceptable: Proceed carefully, with continuous improvement |
| >−1.5 | **BLUE** | Negligible: Safe to proceed |

[1] ALARP: As Low As Reasonably Practical



| | Improbable 1 | Unlikely 2 | Possible 3 | Likely 4 | Probable 5 |
|---|---|---|---|---|---|
| Light -1 | -1<br>1L | -2<br>2L | -3<br>3L | -4<br>4L | -5<br>5L |
| Serious -2 | -2<br>1S | -4<br>1S | -6<br>3S | -8<br>4S | -10<br>5S |
| Major -3 | -3<br>1M | -6<br>2M | -9<br>3M | -12<br>4M | -15<br>5M |
| Catastrophic -4 | -4<br>1C | -8<br>2C | -12<br>3C | -16<br>4C | -20<br>5C |
| Multi-Catastrophic -5 | -5<br>1MC | -10<br>2MC | -15<br>3MC | -20<br>4MC | -25<br>5MC |

**Figure 3: Risk matrix.**

# 3. FEPs and Scenarios

## 3.1. Diligence in Risk Identification

Experience in GS project design and execution provides insight into the ways that project values are commonly at risk. While it is not possible to identify all potential chains of events that could cause negative impact, reference to established risk-element checklists and to previously experienced chains of events is helpful. In addition to these steps, thorough risk identification includes input from both (a) persons who are highly knowledgeable about project facts and plans, and (b) persons who are highly experienced with GS projects in general and reasonably familiar with the proposed project. These are often the same persons who are later asked to *evaluate* the identified risks for a specific project (Section 4). Diligent risk identification demands that multiple methods and avenues be applied so that the chance of overlooking an important risk is as small as possible.

## 3.2. Risk-Bearing Elements: FEPs vs. Scenarios

A key aspect of the "multiple avenues" criterion for thorough risk identification is consideration of risk at multiple levels of detail. This aspect is served by identifying risks at both the "broad concept" level and the "specific chain of events" level.

FEPs are the broad project-relevant concepts or elements that may combine through various chains of events to create various desirable and undesirable outcomes. A list of 178 FEPs relevant to $CO_2$ GS was developed in 2004 by Quintessa Ltd. for the IEAGHG Programme,[3] and this list forms the core of FEPs risk consideration for a Knox-FX Project. Through work on numerous GS projects, Schlumberger Carbon Services has identified more than 100 additional FEPs. FEPs indicated for risk evaluation for a Knox-FX Project (Section 3.3 and Appendix 2) are drawn from the combined Quintessa–Schlumberger Carbon Services FEPs list. When a project expert evaluates risk associated with a FEP, he or she implicitly considers all of the potential scenarios that involve that FEP. FEPs evaluated as having "higher risk" are typically used to develop project-specific scenarios.

Scenarios are well defined chains of events that result directly in discrete outcomes, possibly including negative impacts to project values. A project's "risk register" is essentially a set of scenarios that has been evaluated for risk. Risk management consists of developing and undertaking actions to "treat" each unacceptably high risk; that is, to reduce its impact severity or its likelihood of occurrence. For discrete risk-treatment actions to be developed and carried out, specific scenarios must be catalogued.

With increasing experience, consideration of scenarios tends to dominate risk consideration; however, awareness of broader FEP concepts must always be maintained because new, surprising, and impactful chains of events can always occur.

## 3.3. List of FEPs

An extended list of FEPs identified as specifically important for risk assessment in a Knox-FX Project is given in Appendix 2. These FEPs were selected considering the assumptions (Table 1), distinctive attributes (Table 2), and solicited expert feedback (Appendix 3). This list forms a useful core and starting point for risk assessment in an actual Knox-FX Project, but should always be considered open-ended rather than finite.

## 3.4. Scenarios

Scenarios identified as specifically important for risk assessment in a Knox-FX Project are provided for many of the "A-List" FEPs in Appendix 2. Although a single FEP may be involved in multiple scenarios, only a single scenario is shown for any given FEP, as an example. Some of these scenarios will likely need rewording for application to an actual site-specific Knox-FX Project. In addition, as for the FEPs, the list of scenarios should always be considered open-ended rather than finite.

# 4. Areas of Expertise

## 4.1. Identifying Areas of Expertise

The set of areas of expertise needed to evaluate risk associated with FEPs and scenarios follows from a topical grouping of the FEPs. While the topic groups shown (Table 7) are not unique and some FEPs could fall into more than one group, the listed topic areas can be readily mapped onto widely used professional disciplines and/or roles typically held by persons employed by organizations expected to take part in GS projects.

While Table 7 breaks down the 218 total FEPs by topic group, the numbers do not show relative value. For example, the small number of quality, health, safety, and environment (QHSE) FEPs should not be taken to indicate that health and safety concerns are of little importance. In contrast, it is recommended that individuals representing as many areas of expertise (Table 8) as practical be included in brainstorming-type sessions to identify risks.

Table 7: FEP groups. See Appendix 2 for more description of the “A” and “B” lists.

| FEP Group | "A"-List FEPs | "B"-List FEPs | Total |
|---|---|---|---|
| 01-QHSE | 1 | 4 | 5 |
| 02-Legal & Regulatory | 6 | 17 | 23 |
| 03-Setting: people | 5 | 6 | 11 |
| 04-Setting: physical | 6 | 22 | 28 |
| 05-Geology: basic & regional | 17 | 21 | 38 |
| 06-Geology: site detail | 24 | 5 | 29 |
| 07-Drilling & Wells | 11 | 11 | 22 |
| 08-Injection Operations | 2 | 14 | 16 |
| 09-Injection Effects | 6 | 13 | 19 |
| 10-Measurement & Monitoring | 7 | 7 | 14 |
| 11-Simulation | 4 |  | 4 |
| 12-Management | 2 | 7 | 9 |
| **Total** | 91 | 127 | 218 |

## 4.2. List of Areas of Expertise

Table 8: Areas of expertise.

| FEP topic group | Expertise 1 | Expertise 2 | Expertise 3 | Expertise 4 |
|---|---|---|---|---|
| 01-QHSE | Health and Safety | Project Management | Regulatory Regime | |
| 02-Legal & Regulatory | Regulatory Regime | External Communications | Project Management | |
| 03-Setting: people | Local Knowledge | External Communications | Demographics | |
| 04-Setting: physical | Local Knowledge | Geography | Meteorology | |
| 05-Geology: basic & regional | Geology | Stratigraphy | Structural Geology | Hydrogeology |
| 06-Geology: site detail | Reservoir Geology | Carbonate Geology | Mineralogy | |
| 07-Drilling & Wells | Well Operations | Well Design | Fluid Mechanics | |
| 08-Injection Operations | Reservoir Engineering | Well Design | Hydraulic Engineering | |
| 09-Injection Effects | Reservoir Engineering | Plume Simulation | Geomechanics | Geochemistry |
| 10-Measurement & Monitoring | Geophysics (seismic and non-seismic) | Wireline Logging | Groundwater Sampling | Plume Simulation |
| 11-Simulation | Expertise Groups<br>Plume Simulation | Reservoir Geology<br>Reservoir Engineering | Geomechanics | |
| 12-Management | Project Management | Risk Management | Internal Communications | External Communications |

## 4.3. Identifying Individual Experts

Once a FEPs list has been finalized for a specific Knox-FX Project, the Areas of Expertise table (Table 8), after adjustment, should make apparent what areas are most needed to competently evaluate risk for the specific project. These areas can then be compared with professional expertise held by staff of the organizations participating in the project, gaps identified, and a decision made regarding the need for additional outside expertise. To the extent that outside experts are needed, it will be advisable to prepare and allow time for extensive information sharing as a preparatory step in the risk evaluation process (Section 5).

# 5. Risk Evaluation Process and Path Forward

## 5.1. Workshop Process

Risk evaluation for a proposed project—especially in a relatively new industrial field like CCS—relies on imagining events that may seldom have happened; on envisioning alternative pathways to similar outcomes; and on synthesizing and evaluating information in a rapid and qualitative way. A workshop setting involving participants who together possess a broad array of applicable skills is well suited to this challenge. The chief objective of a successful risk workshop is to bring together all participants' professional experience and judgment, layer on the new project-specific knowledge, and extract probabilistic judgments about possible events that may affect project success. Envisioning and understanding these possible events—thorough risk identification and evaluation—is the only gateway to effective risk management and control.

## 5.2. Pre-Workshop Activities

To best support and inform the risk workshop, two kinds of project information should be assembled and distributed to participants beforehand: project data and project plans. The project data consists of static information about the project's setting in all ways, including the project's geologic, physiographic, cultural, financial, and regulatory contexts. The project plans consist of the set of objectives that the project is designed to reach, and the general intended strategy for reaching them. The twin goals of (a) achieving desired project objectives and (b) avoiding undesired consequences are jointly codified as "Project Values." In order to consistently evaluate risks to the project values, participants must understand the project values and the scaled potential negative impacts to them.

Workshop participants more thoroughly assimilate pre-workshop information if they have an opportunity to apply it. It is recommended that pre-workshop screening or collection of "FEPs or scenarios of concern" be undertaken through email; this can provide important input as well as establish a shared information base.

An additional piece of information capture best done at the pre-workshop stage is the self-evaluation of expertise. Workshop participants are asked to rate (scale) their expertise level for each of the topic groups of draft risk elements (FEPs or scenarios). The need to rate expertise in this way provides additional incentive for participants to familiarize themselves with the risk elements before the workshop, and also provides assurance that specific expertise is accounted for and applied during the risk evaluation.

## 5.3. Workshop Techniques

Various techniques can be used for collecting participants' evaluation of risk elements according to their scaled severity and likelihood of occurrence (Tables 4 and 5). While it may appear convenient to merely collect individual numerical evaluations through isolated individual work on written or electronic spreadsheets—and this can even be done without a formal face-to-face workshop—it is strongly recommended that the workshop forum be used for both discussion and evaluation. Options exist: each participant's individual values can be captured using software, or on electronic or paper sheets that are tallied after the workshop; or discussions can be used to generate "group consensus" values for each risk element. In order to benefit most from varied perspectives, it is strongly recommended that all discussion and evaluation be held in plenary session,[4] rather than in breakout subgroups.

The three quantitative factors—Upper-Bound Severity, Best-Guess Severity, and Best-Guess Likelihood (abbreviated respectively $S_{ub}$, $S_{bg}$, and $L_{bg}$)—should be collected in this order for each evaluated risk element. Reasons for this design element include:

- Beginning a risk-element evaluation each time with $S_{ub}$ helps to apply the cognitive heuristic of "anchoring"[5] in a consistent and positive way, reducing random influences.
- Ending the risk-element evaluation each time with $L_{bg}$ helps to clarify the event (for a scenario) or set of events (for a FEP) whose likelihood is being evaluated. Note that $L_{bg}$ is defined as the likelihood of occurrence of an event having severity equal to $S_{bg}$.

Given the availability, convenience, and small expense of wireless keypads and web-based voting systems, it is strongly recommended that these methods be used to capture individuals' numerical evaluations. The use of wireless keypads and polling software facilitates electronically capturing individual values that are then immediately aggregated and displayed for instant feedback. Post-workshop data analysis in more nuanced or statistically rigorous ways is also facilitated. With pre-workshop grounding in project facts and plans, it is feasible for an expert group (lead by an experienced facilitator) to evaluate 60–80 risk elements during a 7-hour session. Regarding the order of risk elements addressed, it is recommended that risk elements from different topic groups be intermixed throughout the session, rather than addressing each entire topic group in turn. This tends to improve discussions among participants having different areas of expertise and maintain interest through the day.

## 5.4. Post-Workshop Activities

Post-workshop activities for workshop participants are of two types: (1) Completion of evaluations for any elements not finished at the end of the workshop; and (2) Extension of information generation into the next stage of risk management. Depending on the specific type of risk element evaluated (FEPs or scenarios), the second activity type may consist of generating *risk treatments* for the scenarios that are deemed higher risk, or it may be the generation of *scenarios* for FEPs that are rated as higher risk. Because demands from other commitments often limit the time that participants are able to spend on post-workshop activities, it is recommended that these activities be kept relatively simple and quick to complete.

## 5.5. Data Evaluation

If scaled risk-rating values (severity and likelihood) have been collected from individuals and not only from a workshop group as a whole (e.g., so-called "consensus" values), then post-workshop data evaluation can make use of individual factors (such as expertise) and demographic factors (such as employer or home city) in evaluation. While there is considerable variety in the filtering and aggregation algorithms that may be applied, the following two computed values are recommended as the primary risk-ranking factors:

- **Average Risk = Average (Individual $S_{bg} \times L_{bg}$).**
  Note that this value is not equal to (Average Individual $S_{bg}$) × (Average Individual $L_{bg}$).
- **Average $S_{ub}$.**

These values can also be computed within risk-element topical groups.

Collection of participants' self-rated expertise (Section 4) enables distinguishing, for any given risk element, the evaluations that are provided by "experts" as opposed to "informed non-experts." While sometimes there are marked differences in the range of opinion or degree of certainty between experts and non-experts, the rankings of scenarios or FEPs by risk are generally similar.[5]

Data analysis commonly reveals the influence of a positive linear correlation between $S_{bg}$ and $L_{bg}$. This trend is generally taken to be evidence of cognitive anchoring,[6] because (a) the $S_{bg}$ quantity is always elicited immediately before the $L_{bg}$ quantity, so that $S_{bg}$ inevitably establishes a cognitive anchor for $L_{bg}$; and (b) in reality, it is typical that *inverse* correlation actually exists between the intensity (severity) and probability (likelihood) of events. The $S_{bg}$-$L_{bg}$ correlation is *not* believed to impair the accuracy of risk ranking according to the quantity $S_{bg} \times L_{bg}$.

Although the fundamental value of "risk" is viewed as being the product of $S_{bg}$ and $L_{bg}$, it is strongly recommended that evaluation **according to $S_{ub}$ alone** also be conducted. This is because evaluating the probability of extremely impacting (high-$S_{ub}$) scenarios is inherently extremely uncertain, since few such events have occurred. Yet, for at least some of these cases, actions to reduce the severest impacts may be feasibly carried out—if the opportunities are recognized.[7]

## 5.6. Deliverables

The principal deliverable from a risk workshop is the ranking of evaluated elements (FEPs or scenarios) according to risk, computed as described in the preceding section. Depending on project needs, the risk ranking may be provided as a simple list, or as part of an extended formal report. In either case, it is recommended that the basic results of risk evaluation be made available as soon as possible to project managers and applied in project design.

## 5.7. Path Forward for an Actual Sited Project

A common early application of a risk ranking (and less formally, of the discussions held during the risk workshop) is to inform the design bases for:

- Initial efforts of data acquisition toward geologic characterization;
- Baseline monitoring;
- Preliminary plume simulations;
- Injection-effects monitoring, especially those elements that are especially costly or have long preparation times; and
- Well drilling and completion.

Design progress in the above-listed areas will also provide an information basis to address fundamental project management concerns such as cost, schedule, staffing, and insurance.

To proceed with formal risk management after ranking FEPs by risk, procedures should be defined to address questions including those listed below. Should a risk-management task be initiated for a specific Knox-FX project, such procedures would be detailed, expanded, and adapted to project needs.

1. For which FEPs (e.g., for what minimum risk level) must risk-reduction actions be undertaken?
2. How can specific scenarios be written to represent the critical risk-bearing aspects of the important FEPs?
3. How can *scenarios* be evaluated for risk?
4. How can treatments be developed for each scenario, and how can treatment effectiveness be judged and documented?
5. How will risk and treatment information be managed? How will critical risk summary information be made available to project management in support of key project decisions?
6. How can changing risks be tracked?
7. How will new scenarios be incorporated into the risk management scheme?

# 6. Limitations

This report provides a list of FEPs that are considered to be pertinent to risk evaluation for a hypothetical $CO_2$ GS project for which the Potosi Dolomite (part of the Knox Supergroup) is the target sequestration reservoir. The hypothetical project would, in concept, be undertaken at a presently undefined location in the southern Illinois Basin. Beyond providing a starting list of FEPs, this report also describes a generic pattern for activities to formally identify, evaluate, and begin managing risks in such a project.

The hypothetical basis is an important attribute of this report. It is important to recognize that meaningful project risk evaluation can only be executed in respect to a reasonably well defined (a) project environment and (b) set of objectives. Accordingly, the FEPs list provided herein should be viewed only as a starting point for risk evaluation in an actual "Knox-FX" project to be pursued at a specific geographic site and within a specific timeframe. Given that the key project descriptor is "target reservoir is the Potosi/Knox," the FEPs listed here emphasize the implications of this specific geo-engineering element. The FEPs extend in part to other project aspects that could be substantially affected by this geo-engineering element.

Risk elements that should be considered in *any* potential GS project are partially covered in the "B-List" of FEPs in Appendix 2, but non-Knox-related aspects of project risk should be considered to be incomplete.

# 7. References

1. Hnottavange-Telleen, K., E. Chabora, R.J. Finley, S.E. Greenberg, S. Marsteller, Risk management in a large-scale $CO_2$ geosequestration pilot project, Illinois, USA 10th Intl Conference on Greenhouse Gas Control Technologies, Amsterdam (Elsevier) *Energy Procedia*, *Volume 4*, *2011*, *Pages 4,044–4,051.*
2. Hnottavange-Telleen, K., I. Krapac, C. Vivalda, 2008, "Illinois Basin – Decatur Project: initial risk-assessment results and framework for evaluating site performance." 9th Intl Conference on Greenhouse Gas Control Technologies, Nov. 16–21, 2008, Washington D.C., USA. *Energy Procedia*, *Volume 1, Issue 1*, *February 2009*, *Pages 2,431–2,438.*
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5. Hnottavange-Telleen K. Common Themes in Risk Evaluation Among Eight Geosequestration Projects, *Energy Procedia*, *Volume 37*, *2013*, *Pages 2,794–2,801*.
6. Kahneman, D., Slovic, P., Tversky, A., editors. Judgment under uncertainty: heuristics and biases. Cambridge, UK: Cambridge University Press; 1982.Taleb, N.N. The black swan: The impact of the highly improbable. New York: Random House; 2007.

# Appendix 1: Knox Project Task

The below text defining Task is modified after the document ***Definition of Deliverables - Illinois Basin Knox Study, Federal Sub-award Agreement , Amendment No. 04, Subaward No. 2011-01609-01*** by Nick Malkewicz, dated July 6, 2013.

## Task: Initial Risk Assessment.

1. Risk evaluation framework: Defined assumptions, project values, risk scales, and risk matrix (grid-format risk acceptability criterion).
2. List of FEPs and/or scenarios (risk elements) pertinent to a Knox CCS project at a yet-to-be-determined specific location in the Decatur area.
3. List of areas of professional experience needed to evaluate the above list of risk elements.
4. Develop a process for identifying individuals who have the requisite expertise for project risk evaluation, who would be nominated to take part in evaluating the risk elements.
5. General outline of a risk evaluation process (e.g., a workshop with pre-workshop and post-workshop information gathering activities), including the design elements already completed as [the above deliverables].
6. Delivery ~August 29, 2013

# Appendix 2: FEPs Lists

Two lists of FEPs are provided:

- **List "A"** includes FEPs that are recommended to be evaluated for any potential Knox-FX CCS project, once the specific project is generally conceived and a site is selected. The "A-List" FEPs emphasize the planned use of the Potosi Formation as the target reservoir, and include implications of the Potosi target for geologic characterization, permitting, drilling, monitoring, and other aspects. For many of these FEPs, example scenarios are provided. For others, scenarios specific to the proposed project site and workflow should be written.

- **List "B"** includes FEPs that are less specific to the Potosi target reservoir, are more generic or tangential, or may partly overlap in meaning with an "A-List" FEP. A project operator should consider evaluating pertinent ones of these FEPs once a project site and design are chosen.

In concept, there is always a "C-List" of FEPs: This list—not provided here—includes those FEPs that signal ***risks that are important to the project but have not yet been envisioned***. In some sense, this blank list can be the most important list of all. It is critical that complete consideration of a list of FEPs or scenarios ***not*** be mistaken as considering "all possible project risks." There are always more.

**FEPs List A**

| seq | FEP ID# | FEP NAME | Scenario Example | FEP Group |
|---|---|---|---|---|
| A001 | KD-JLI161 | **On-road driving** | Project workers driving to project site far from the office or base are in a collision and a fatality occurs. | 01-QHSE |
| A002 | KD-LC013 | **Area of review** | Modeled plume footprint causes definition of a large AOR that will be very expensive to monitor. | 02-Legal & Regulatory |
| A003 | KD-LC011 | **Permits: Drilling** | | 02-Legal & Regulatory |
| A004 | KD-LC011 | **Permits: Injection** | | 02-Legal & Regulatory |
| A005 | P# 49 | **Pore space ownership** | | 02-Legal & Regulatory |
| A006 | KD-x55 | **Property rights and trespass** | Owner refuses surface access to a key area for seismic acquisition. | 02-Legal & Regulatory |
| A007 | KD-LC019 | **Protected Waters definition** | Upon drilling at the selected project site, St. Peter Sandstone is sampled and has <10,000 ppm TDS; regulators require extensive additional work to define a caprock beneath this level. | 02-Legal & Regulatory |
| A008 | KD-LC242 | **$CO_2$ (non-project): Nearby EOR activity** | | 03-Setting: people |
| A009 | KD-LC062 | **Drilling activities (non-project)** | | 03-Setting: people |
| A010 | KD-LC250 | **Monitoring: Assurance and Protection** | Because the project cannot uniquely predefine the likely caprock horizon, regulators require much more extensive assurance monitoring of surface air and soil and of shallow groundwater. | 03-Setting: people |
| A011 | KD-LC232 | **Public perception of groundwater threat** | Public perceives important project threat to groundwater, and drilling and injection permits are strongly opposed. | 03-Setting: people |
| A012 | KD-LC236 | **Public perception of seismicity threat** | | 03-Setting: people |
| A013 | KD-LC177 | **Boreholes: Non-project, abandoned or orphaned** | "Abandoned" boreholes are sealed but "orphaned" boreholes have not. After time, components could degrade and allow leakage even if a well were properly abandoned per regulation. | 04-Setting: physical |
| A014 | KD-LC229 | **Boreholes: Non-project, operational** | | 04-Setting: physical |
| A015 | KD-LC026 | **Seismicity (Non-project-induced earthquakes)** | Natural earthquake not related to project operations damages project infrastructure. | 04-Setting: physical |
| A016 | KxAt-36 | **Subsurface conflicts, caprock** | Maquoketa becomes a target for shale gas production, and operators object to CCS injection permits that involve Maquoketa. | 04-Setting: physical |
| A017 | KxAt-38 | **Subsurface conflicts, reservoir** | Abandoned wells from former oil production in project area require effort to inspect, monitor, and potentially re-seal. | 04-Setting: physical |

| seq | FEP ID# | FEP NAME | Scenario Example | FEP Group |
|---|---|---|---|---|
| A018 | KxAt-37 | **Surface characteristics** | Hilly, treed setting complicates monitoring both technically and in terms of access, leading to increased cost and opposition to permit. | 04-Setting: physical |
| A019 | KD-JLI076 | **Caprock fracture pressure** |  | 05-Geology: basic & regional |
| A020 | KD-LC155 | **Caprock Identification: Primary** | $CO_2$ trapping may occur somewhere within the thick dolostone beneath the Maquoketa. Inability to positively identify a single discrete trapping horizon before injection causes expansion, extra cost, and uncertainty in monitoring design. | 05-Geology: basic & regional |
| A021 | KD-x80 | **Caprock permeability** |  | 05-Geology: basic & regional |
| A022 | KxAt-20 | **Caprock separation thickness above reservoir** | Position of Maquoketa caprock, large thickness above the injection horizon (Potosi), and uncertainty about trapping in the intervening dolomite causes long delay in injection permit. | 05-Geology: basic & regional |
| A023 | KxAt-21 | **Caprock thickness and continuity** |  | 05-Geology: basic & regional |
| A024 | KxAt-24 | **Faults: proximity and spatial density** | Seismic data show that a reservoir-crossing fault is likely located close to proposed injection location; increased expense, possible re-siting. | 05-Geology: basic & regional |
| A025 | KxAt-25 | **Faults: seismicity** | Modeled pressure effect from proposed project may reach an area of known active faults; increased expense in re-siting and/or other mitigations. | 05-Geology: basic & regional |
| A026 | KxAt-27 | **Geologic data density** | Large geologic uncertainties and sparse data require additional well and/or seismic data for characterization. | 05-Geology: basic & regional |
| A027 | KxAt-18 | **Overlying unit lithology** | The unit above the Potosi target reservoir is also dolostone that cannot be distinguished seismically, increasing uncertainty in static earth model. | 05-Geology: basic & regional |
| A028 | KD-LC162 | **Reservoir fluid properties** | Formation water (brine) in the target reservoir is found to contain $H_2S$ and/or $CH_4$, increasing uncertainty in plume prediction (and monitoring requirements) due to additional phases present. | 05-Geology: basic & regional |
| A029 | KxAt-10 | **Reservoir fracture pressure** |  | 05-Geology: basic & regional |
| A030 | KD-JLI079 | **Reservoir gross porosity** | Gross porosity at proposed project site is inadequate to enable placing the desired $CO_2$ mass within an acceptable reservoir volume. | 05-Geology: basic & regional |
| A031 | P# 28 | **Reservoir hydrogeology** | Target vuggy reservoir zone is extensive, and regional hydrogeologic flow affects plume development. | 05-Geology: basic & regional |
| A032 | NMb-01 | **Reservoir lithology** | Carbonate lithology has irregular layering with many discontinuities, preventing prediction of plume migration. | 05-Geology: basic & regional |

| seq | FEP ID# | FEP NAME | Scenario Example | FEP Group |
|---|---|---|---|---|
| A033 | KxAt-04 | **Reservoir mineralogy** | Target reservoir is carbonate rock, but non-carbonate grains (e.g., quartz) become liberated and mobile and injectivity is impaired. | 05-Geology: basic & regional |
| A034 | P# 23 | **Sequestration concept** | $CO_2$ generator (source company) is not satisfied that vertically migrating $CO_2$ will likely be trapped at an unknown depth within thick dolostones, and project financing cannot be achieved. | 05-Geology: basic & regional |
| A035 | KxAt-13 | **Underlying unit lithology** | | 05-Geology: basic & regional |
| A036 | KD-LC258 | **Ability to characterize confining formation** | Because of likelihood that trapping will occur at an unanticipated level within dolostones, extensive coring and analysis program is required before injection is permitted. | 06-Geology: site detail |
| A037 | KD-LC248 | **Ability to characterize reservoir** | | 06-Geology: site detail |
| A038 | KD-JLI072 | **Caprock geochemical properties** | | 06-Geology: site detail |
| A039 | KD-LC139 | **Fluids besides $CO_2$ and water** | Formation water (brine) in the target reservoir is found to contain $H_2S$, increasing requirements for well engineering, safety, and monitoring. | 06-Geology: site detail |
| A040 | KD-x42 | **Fracture and fault pathways** | A fracture pathway allows pressurized brine to move from the target reservoir into a freshwater aquifer. | 06-Geology: site detail |
| A041 | KD-LC143 | **Heterogeneity of reservoir formation** | Plume movement is unpredictable due to reservoir heterogeneity and additional wells are required for physical sampling. | 06-Geology: site detail |
| A042 | KD-LC164 | **Hydrocarbons** | Multiple scenarios related to previous oil and gas activity, future resource availability and/or sterilization (including possibility of shale gas in Maquoketa), abandoned or orphaned wells. | 06-Geology: site detail |
| A043 | KD-LC113 | **Mineral dissolution (reservoir)** | Carbonate dissolution creates fast migration pathways that prevent plume prediction and increase monitoring cost. | 06-Geology: site detail |
| A044 | KD-LC108 | **Mineral precipitation** | Dissolved carbonate re-precipitates, reducing injectivity. | 06-Geology: site detail |
| A045 | NMb-07 | **Physical samples** | Representative core and fluid samples from Potosi cannot be collected nor successful tests be run because of its vuggy to cavernous porosity. | 06-Geology: site detail |
| A046 | KD-JLI081 | **Reservoir injectivity** | | 06-Geology: site detail |
| A047 | KxAt-06 | **Reservoir porosity architecture** | Multiple scenarios re: low injectivity, plume unpredictability, difficulty in permitting. | 06-Geology: site detail |
| A048 | D1b-02 | **Reservoir porosity connectivity** | Injection well is completed in porous zone, but initial good injectivity declines quickly because of poor connectivity. | 06-Geology: site detail |
| A049 | NMb-03 | **Reservoir relative permeability** | | 06-Geology: site detail |

| seq | FEP ID# | FEP NAME | Scenario Example | FEP Group |
|---|---|---|---|---|
| A050 | NMb-08 | **Reservoir testing** | Because of heterogeneous porosity structure, testing results from the Potosi are difficult to interpret and yield little guidance for injection operations or plume development. | 06-Geology: site detail |
| A051 | KD-JLI061 | **Reservoir thickness** |  | 06-Geology: site detail |
| A052 | MCb-01 | **Secondary porosity architecture** | Challenge in characterizing secondary porosity requires an additional well mainly for reservoir information. | 06-Geology: site detail |
| A053 | KD-LC281 | **Stacked reservoirs** | Injected $CO_2$ migrates within multiple discrete high-porosity zones that cannot be seismically distinguished, and knowledge of plume development is poor. | 06-Geology: site detail |
| A054 | MCb-02 | **Static earth model** | Porosity characterization has broad uncertainties, so that static earth model is poorly defined, and plume predictions are of little use for monitoring design. | 06-Geology: site detail |
| A055 | D1b-01 | **Sequestration efficiency** | Uncertainty in degree of porosity connectivity (therefore sequestration efficiency) forces an over-estimate of number of required injection wells, increasing project financing and monitoring costs. | 06-Geology: site detail |
| A056 | D1a-03 | **Stratigraphic heterogeneity - vugular layers** | Multiple scenarios re: well completion difficulty, well integrity, plume unpredictability, permitting difficulty, reservoir seismic-imaging challenges, plume seismic-imaging challenges. | 06-Geology: site detail |
| A057 | KD-LC148 | **Stress and mechanical properties** |  | 06-Geology: site detail |
| A058 | KD-LC160 | **Unconformities** | Topographic relief on the top of Knox "sub-Tippecanoe" regional unconformity causes variable permeability at top of Knox and variable thickness of overlying St. Peter Sandstone, impairing the use of the St. Peter as a monitoring horizon. | 06-Geology: site detail |
| A059 | KD-LC145 | **Undetected features** | Multiple scenarios re: caverns, faults, fracture corridors, "tight streaks", etc. | 06-Geology: site detail |
| A060 | KD-LC286 | **Borehole stability** | Cavernous porosity in the target injection zone causes an unstable borehole where completion with desired instrumentation cannot be executed. | 07-Drilling & Wells |
| A061 | KD-LC275 | **Drilling and well completion (general)** | Multiple scenarios re: costs, well integrity, HSE, ability to identify completion zone, ability to complete the desired zone. | 07-Drilling & Wells |
| A062 | KD-LC176 | **Drilling and well completion:<br>Lost Circulation** | Lost circulation in the upper Knox increases drilling expense. | 07-Drilling & Wells |
| A063 | KxAt-32 | **Injection well: Instrumentability** | Difficult hole conditions prevent executing a stable completion while installing desired instrumentation,<br>so plume monitoring ability is lost in the injection well. | 07-Drilling & Wells |

| seq | FEP ID# | FEP NAME | Scenario Example | FEP Group |
|---|---|---|---|---|
| A064 | KxAt-31 | **Injection well: Integrity** | | 07-Drilling & Wells |
| A065 | KD-LC015 | **Mechanical Integrity Testing** | MIT results are inadequate to document the mechanical integrity of casing and cement. | 07-Drilling & Wells |
| A066 | KxAt-34 | **Monitoring well: Instrumentability** | Difficult hole conditions prevent executing a stable completion while installing desired instrumentation,<br>so plume monitoring ability is lost in a monitoring well. | 07-Drilling & Wells |
| A067 | KxAt-33 | **Monitoring well: Integrity** | Monitoring well integrity is compromised by poor seal in the upper Knox/basal St. Peter. | 07-Drilling & Wells |
| A068 | KD-x09 | **Seal integrity of project abandoned wells** | A project abandoned well (e.g., an injector that is sealed because of inadequate injectivity) allows along-wellbore communication; regulators require an additional monitoring well completed in the St. Peter Formation. | 07-Drilling & Wells |
| A069 | NMb-04 | **Wellbore quality** | Poor quality wellbore impairs log quality, causing poorly constrained modeling and simulation parameters. | 07-Drilling & Wells |
| A070 | KD-LC169 | **Workover operations and success rate** | Workover to improve injectivity results in a borehole leakage path. | 07-Drilling & Wells |
| A071 | P# 54 | **$CO_2$ Delivery System operation: Effects on downhole components** | Injection-well completion in vuggy Potosi is less than ideally robust, and over time injection cycling (temperature and pressure changes) damage well integrity. | 08-Injection Operations |
| A072 | KD-KDadd01 | **$CO_2$ Injectate: Fluids besides $CO_2$ and $H_2O$** | Constituents in injectate cause reactions in reservoir that impair injectivity. | 08-Injection Operations |
| A073 | P# 52x | **Groundwater contamination** | Drinking-water well in the project area shows increasing salinity and the owner claims the CCS project has caused the change. | 09-Injection Effects |
| A074 | P# 53 | **Impacts on exploitation of other earth resources** | Injection permit is delayed by claims of impact upon potential hydrocarbon production near proposed project site. | 09-Injection Effects |
| A075 | KD-LC111 | **Mineral dissolution (borehole)** | Target reservoir is carbonate rock. Lack of precedent<br>in CCS into carbonates causes additional measures to<br>be required to ensure wellbore integrity. | 09-Injection Effects |
| A076 | KD-LC112 | **Mineral dissolution (caprock)** | Plume becomes trapped at progressively shallower levels as pathways are dissolved through dolomitic caprock, preventing plume imaging and prediction of migration. | 09-Injection Effects |
| A077 | KD-LC125 | **Seismicity (project-induced earthquakes)** | | 09-Injection Effects |
| A078 | YAb-02 | **Vertical migration** | | 09-Injection Effects |
| A079 | KD-LC253 | **Interpretation** | Acoustic impedance measurements cannot | 10- |

| seq | FEP ID# | FEP NAME | Scenario Example | FEP Group |
|---|---|---|---|---|
| | | **and inversion of monitoring data** | demonstrate porosity estimates greater than 12%, leading to large estimates of plume footprint and AOR, causing permitting delay and monitoring cost. | Measurement & Monitoring |
| A080 | KD-LC251 | **Monitoring $CO_2$ plume via physical samples** | Inhomogeneous reservoir formation causes large uncertainty in predicting lateral plume migration, permit requires multiple monitoring wells and numerous sampling horizons within the Knox. | 10-Measurement & Monitoring |
| A081 | KxAt-30 | **Monitoring $CO_2$ plume via surface seismic** | Plume travels mainly in thin vuggy layer, seismic imaging is indefinite. | 10-Measurement & Monitoring |
| A082 | NMb-02 | **Monitoring strategy** | Because there is little experience with $CO_2$ sequestration in carbonates, regulators require multiple monitoring technologies before granting injection permit. | 10-Measurement & Monitoring |
| A083 | VSb-02 | **Plume vertical footprint** | | 10-Measurement & Monitoring |
| A084 | KxAt-29 | **Reservoir characterization via seismic methods** | Seismic method cannot distinguish porous zones within the Knox or Potosi, and injection-well site is poorly chosen. | 10-Measurement & Monitoring |
| A085 | KD-JLI267 | **Seismic survey operations** | Topography and trees make seismic acquisition very expensive, coverage is limited, and repeat surveys are infeasible. | 10-Measurement & Monitoring |
| A086 | D1a-02 | **Dynamic model: Boundaries** | Vertical permeability in Knox dolostones is undocumented, so simulation uses "Default" choice of no-flow boundaries at top and base of target reservoir. Model shows excessive pressure buildup and extensive AOR, and project is stopped. | 11-Simulation |
| A087 | D1a-01 | **Dynamic model: Footprint size** | Project extensive plume footprint significantly increases the probability that the plume will encounter a fault, and extensive seismic data is required. | 11-Simulation |
| A088 | D1b-03 | **Dynamic model: Irregular footprint** | Plume shape is expected to be irregular but in an unpredictable way, and additional monitoring wells are required. | 11-Simulation |
| A089 | KD-LC020 | **Simulation: Method and workflow validity** | Uncertainty about valid plume-simulation workflow causes wide variety in plume projections, delaying injection permit. | 11-Simulation |
| A090 | KD-JLI003 | **Risk characterization thoroughness** | Project fails to foresee an important risk, and an unexpected event (preventable or less damaging if it had been foreseen) causes significant impact. | 12-Management |
| A091 | KD-LC081 | **Schedule and planning** | | 12-Management |

**FEPs List B**

| seq | FEP ID# | FEP NAME | FEP Group |
|---|---|---|---|
| B001 | KD-LC219 | **Asphyxiation** | 01-QHSE |
| B002 | KD-JLI162 | **Off-road driving** | 01-QHSE |
| B003 | KD-JLI155 | **Release of compressed gases or liquids** | 01-QHSE |
| B004 | KD-JLI144 | **Working in confined areas** | 01-QHSE |
| B005 | KD-LC202 | **Construction and operations activities (project) other than drilling** | 02-Legal & Regulatory |
| B006 | KD-LC265 | **Contracting** | 02-Legal & Regulatory |
| B007 | KD-LC046 | **Data acquisition (Off site)** | 02-Legal & Regulatory |
| B008 | KD-LC045 | **Data acquisition (On site)** | 02-Legal & Regulatory |
| B009 | KD-LC008 | **Legal/regulatory framework** | 02-Legal & Regulatory |
| B010 | KD-LC261 | **Legal/regulatory: $CO_2$ ownership** | 02-Legal & Regulatory |
| B011 | P# 15 | **Legal/regulatory: Emergency Planning Zone** | 02-Legal & Regulatory |
| B012 | KD-x57 | **Legal/regulatory: lawsuits** | 02-Legal & Regulatory |
| B013 | KD-LC249 | **Legal/regulatory: Permits: Agency relationships** | 02-Legal & Regulatory |
| B014 | KD-LC288 | **Legal/regulatory: Permits: Seismic operations** | 02-Legal & Regulatory |
| B015 | KD-LC012 | **Legal/regulatory: Sequestration depth vs. Freshwater** | 02-Legal & Regulatory |
| B016 | KD-LC241 | **Operating standards, protocols, and procedures** | 02-Legal & Regulatory |
| B017 | KD-JLI112 | **Road access** | 02-Legal & Regulatory |
| B018 | KD-LC044 | **Security of principal and remote project sites** | 02-Legal & Regulatory |
| B019 | KD-LC293 | **Staffing and staff competency** | 02-Legal & Regulatory |
| B020 | KD-x88 | **Support from Government - political basis** | 02-Legal & Regulatory |
| B021 | KD-x89 | **Support from Government - technical basis** | 02-Legal & Regulatory |
| B022 | KD-LC048 | **Actions and reactions (local community)** | 03-Setting: people |
| B023 | KD-LC200 | **Community characteristics** | 03-Setting: people |

| seq | FEP ID# | **FEP NAME** | **FEP Group** |
|---|---|---|---|
| B024 | P# 12 | **Future human actions and behaviors,<br>human land use changes** | 03-Setting: people |
| B025 | P# 06 | **Human activities on surface (non-project)** | 03-Setting: people |
| B026 | P# 07 | **Infrastructure (surface and shallow)** | 03-Setting: people |
| B027 | KD-LC299 | **Near-surface aquifers and surface water bodies:<br>public perception** | 03-Setting: people |
| B028 | KD-JLI122 | **Baseline studies** | 04-Setting: physical |
| B029 | KD-LC201 | **Buildings** | 04-Setting: physical |
| B030 | KD-LC279 | **Climate and weather at project site** | 04-Setting: physical |
| B031 | NMb-09 | **Competing injection operations** | 04-Setting: physical |
| B032 | KD-LC070 | **Effects of $CO_2$ and pressure on future operations** | 04-Setting: physical |
| B033 | KD-LC302 | **Encroachment** | 04-Setting: physical |
| B034 | KD-LC183 | **Erosion and deposition** | 04-Setting: physical |
| B035 | KD-LC142 | **Geographic location** | 04-Setting: physical |
| B036 | KD-LC199 | **Land and water use** | 04-Setting: physical |
| B037 | KD-LC063 | **Mining and other nonproject underground activities** | 04-Setting: physical |
| B038 | KD-LC186 | **Near-surface aquifers and surface water bodies** | 04-Setting: physical |
| B039 | KxAt-28 | **Orphan well spatial density** | 04-Setting: physical |
| B040 | P# 04 | **Physical environment: Nonproject-induced changes** | 04-Setting: physical |
| B041 | KD-LC292 | **Project surface footprint: Environmental legacy issues** | 04-Setting: physical |
| B042 | KD-JLI241 | **Protection for above ground components** | 04-Setting: physical |
| B043 | KD-LC285 | **Reservoir spill point** | 04-Setting: physical |
| B044 | KD-LC278 | **Soils and sediments: Effects on project** | 04-Setting: physical |
| B045 | KD-x90 | **Surface infrastructure** | 04-Setting: physical |
| B046 | KD-LC181 | **Topography and morphology** | 04-Setting: physical |

| seq | FEP ID# | FEP NAME | FEP Group |
|---|---|---|---|
| B047 | KD-LC075 | **Transportation and logistics** | 04-Setting: physical |
| B048 | KD-JLI109 | **Water supply** | 04-Setting: physical |
| B049 | KxAt-26 | **Well-penetration spatial density** | 04-Setting: physical |
| B050 | KD-LC273 | **Caprock Identification: Secondary** | 05-Geology: basic & regional |
| B051 | KxAt-08 | **Depth** | 05-Geology: basic & regional |
| B052 | KxAt-11 | **Formation temperature** | 05-Geology: basic & regional |
| B053 | KxAt-02 | **Lithology variation** | 05-Geology: basic & regional |
| B054 | KxAt-22 | **Overlying protected aquifer identification** | 05-Geology: basic & regional |
| B055 | KxAt-17 | **Overlying unit identification** | 05-Geology: basic & regional |
| B056 | KD-LC283 | **Pressure effects from depleted field** | 05-Geology: basic & regional |
| B057 | KD-JLI060 | **Reservoir depth (Reservoir hydrostatic pressure)** | 05-Geology: basic & regional |
| B058 | KD-LC153 | **Reservoir geometry** | 05-Geology: basic & regional |
| B059 | KxAt-05 | **Reservoir mineralogy—cements** | 05-Geology: basic & regional |
| B060 | KxAt-07 | **Reservoir porosity gross quantity** | 05-Geology: basic & regional |
| B061 | KD-LC147 | **Reservoir pressure** | 05-Geology: basic & regional |
| B062 | KxAt-03 | **Reservoir: Bedding** | 05-Geology: basic & regional |

| seq | FEP ID# | FEP NAME | FEP Group |
|---|---|---|---|
| B063 | KxAt-15 | **Reservoir: Internal unconformities** | 05-Geology: basic & regional |
| B064 | KD-JLI058 | **Salt precipitation** | 05-Geology: basic & regional |
| B065 | KxAt-14 | **Subcrop topography** | 05-Geology: basic & regional |
| B066 | KxAt-12 | **Underlying unit identification** | 05-Geology: basic & regional |
| B067 | NMb-06 | **Underpressure** | 05-Geology: basic & regional |
| B068 | KxAt-16 | **Upper contact conformability** | 05-Geology: basic & regional |
| B069 | KD-LC146 | **Vertical geothermal gradient** | 05-Geology: basic & regional |
| B070 | KxAt-23 | **Vertical thickness to USDW** | 05-Geology: basic & regional |
| B071 | YAb-01 | **Injectivity** | 06-Geology: site detail |
| B072 | KD-LC154 | **Reservoir exploitation** | 06-Geology: site detail |
| B073 | KD-JLI063 | **Reservoir top topography** | 06-Geology: site detail |
| B074 | KD-LC226 | **Toxic geologic components (gases)** | 06-Geology: site detail |
| B075 | KD-LC280 | **Toxic geologic components (metals)** | 06-Geology: site detail |
| B076 | P# 42 | **Drilling and well completion (project): In-Zone** | 07-Drilling & Wells |
| B077 | KD-LC234 | **Drilling and well completion (project): Shallow monitoring wells** | 07-Drilling & Wells |
| B078 | KD-LC167 | **Formation damage** | 07-Drilling & Wells |
| B079 | KD-LC170 | **Monitoring and Verification Wells** | 07-Drilling & Wells |
| B080 | KD-x84 | **Shallow gas drift gas** | 07-Drilling & Wells |
| B081 | KD-LC182 | **Soils and sediments: Impact by project** | 07-Drilling & Wells |
| B082 | P# 43 | **Well lining and completion: Integrity** | 07-Drilling & Wells |
| B083 | KD-LC277 | **Well plugging/closure operations** | 07-Drilling & Wells |

| seq | FEP ID# | FEP NAME | FEP Group |
|---|---|---|---|
| B084 | KD-LC174 | **Well plugging/sealing/closure: Integrity** | 07-Drilling & Wells |
| B085 | KD-LC175 | **Well seal failure** | 07-Drilling & Wells |
| B086 | VSb-01 | **Wellbore integrity** | 07-Drilling & Wells |
| B087 | KD-KDadd02 | **$CO_2$ Delivery System: Integration** | 08-Injection Operations |
| B088 | KD-KDadd03 | **$CO_2$ Delivery System: Operational Monitoring** | 08-Injection Operations |
| B089 | KD-LC121 | **$CO_2$ injectate fate and effects: Interaction with hydrocarbons** | 08-Injection Operations |
| B090 | KD-LC268 | **$CO_2$ injectate: Gases besides $CO_2$ and water** | 08-Injection Operations |
| B091 | KD-LC270 | **$CO_2$ injectate: Particulates** | 08-Injection Operations |
| B092 | KD-LC269 | **$CO_2$ injectate: Water content** | 08-Injection Operations |
| B093 | KD-x20 | **$CO_2$ release from surface facilities** | 08-Injection Operations |
| B094 | KD-LC016 | **Injection well operations** | 08-Injection Operations |
| B095 | KD-LC254 | **Monitoring: Operational** | 08-Injection Operations |
| B096 | KD-JLI224 | **Natural force damage** | 08-Injection Operations |
| B097 | KD-JLI244 | **Operator error** | 08-Injection Operations |
| B098 | KD-x76 | **Procurement delays aboveground infrastructure** | 08-Injection Operations |
| B099 | KD-LC287 | **Startup/shutdown operations** | 08-Injection Operations |
| B100 | KD-LC266 | **Undefined specifications** | 08-Injection Operations |
| B101 | KD-LC100 | **$CO_2$ injectate: Phase behavior** | 09-Injection Effects |
| B102 | KD-LC078 | **$CO_2$ injectate: Quantity and rate** | 09-Injection Effects |
| B103 | KD-x30 | **Contamination of groundwater** | 09-Injection Effects |
| B104 | KD-LC110 | **Desiccation of clay** | 09-Injection Effects |
| B105 | KD-LC115 | **Gas stripping** | 09-Injection Effects |
| B106 | NMb-05 | **Hydrate** | 09-Injection Effects |

| seq | FEP ID# | FEP NAME | FEP Group |
|---|---|---|---|
| B107 | P# 48 | **Microbiological contamination** | 09-Injection Effects |
| B108 | KD-x74 | **Pressure effects on caprock** | 09-Injection Effects |
| B109 | KD-LC120 | **Pressure effects on reservoir fluids** | 09-Injection Effects |
| B110 | KD-x75 | **Pressure effects on reservoir fluids other than brine** | 09-Injection Effects |
| B111 | KD-LC074 | **Pressure: Reservoir overpressuring** | 09-Injection Effects |
| B112 | P# 55 | **Reversibility** | 09-Injection Effects |
| B113 | KD-LC127 | **Thermal effects on the injection point** | 09-Injection Effects |
| B114 | KD-LC259 | **Ability to characterize structure** | 10-Measurement & Monitoring |
| B115 | KD-LC233 | **Data acquisition: Competing demands** | 10-Measurement & Monitoring |
| B116 | KD-LC171 | **Data management** | 10-Measurement & Monitoring |
| B117 | KD-JLI268 | **Gravity surveys** | 10-Measurement & Monitoring |
| B118 | KD-JLI269 | **Interferometric synthetic aperture radar (InSAR) surveys** | 10-Measurement & Monitoring |
| B119 | MCb-03 | **Measurement inversion to physical properties** | 10-Measurement & Monitoring |
| B120 | KD-LC252 | **Monitoring $CO_2$ plume using subsurface geophysics** | 10-Measurement & Monitoring |
| B121 | KD-LC076 | **Accidents and unplanned events (nonproject)** | 12-Management |
| B122 | KD-LC267 | **Accidents and unplanned events (project)** | 12-Management |
| B123 | P# 17 | **Economics: Specific to project** | 12-Management |
| B124 | KD-LC297 | **Long-term project management and execution** | 12-Management |
| B125 | KD-LC276 | **Procurement: Downhole hardware, monitoring instruments, spares** | 12-Management |
| B126 | P# 52 | **Project funding** | 12-Management |
| B127 | KD-LC089 | **Quality control** | 12-Management |

# Appendix 3: "Top Risks" polling feedback

Knox experts were asked to identify, based on their own expertise, the main risks pertinent to executing a Knox-FX $CO_2$ GS project at a to-be-determined location in the southern Illinois Basin. While responses are concentrated in the area of Knox (Potosi) reservoir characteristics, their attribute ranges, and the level of knowledge and uncertainty about them, permitting and project management considerations are also cited. Responses have been edited for clarity.

1. **Respondent: Yasmin Adushita, Senior Reservoir Engineer, Schlumberger**

   **Risks corresponding to Knox reservoir characteristics**

   - Risk: Insufficient injectivity or inadequate injectivity estimation.
     Causes: Limited data on matrix-vug distribution, extent, and interconnectivity; on secondary porosity and vug permeability; on fracture pressure gradient.
   - Risk: Plume extent larger than expected.
     Causes: Limited data on matrix-vug distribution, extent, and interconnectivity; on secondary porosity and vug permeability.
   - Risk: Inadequate estimation of the vertical $CO_2$ plume migration (plume goes further vertically than expected).
     Causes: Limited data on matrix-vug distribution, extent, and interconnectivity; on secondary porosity and vug permeability.
   - Risk: Reservoir fracture due to injection.
     Causes: Limited data on fracture pressure gradient.
   - Risk: Seal fracture due to injection.
     Causes: Limited data on fracture pressure gradient.

2. **Respondent: Nick Malkewicz, Project Manager, Schlumberger Carbon Services**

   **Risks in executing a Knox-FX Project**

   - Special permitting requirements may be imposed because the target reservoir is a carbonate.
   - Given there is little experience with $CO_2$ sequestration in carbonates, monitoring technologies may be poorly chosen.
   - Relative permeability curves are very uncertain given the vugular porosity, increasing uncertainty in plume modeling.
   - Potential for connectivity of sequestration reservoir to fresh water zones.
   - Potential for the reservoir to be a fresh water zone near the injection site.
   - Poor quality wellbore may impair log quality, causing poorly constrained modeling and simulation parameters.
   - Dominance of vug porosity may have unexpected pressure-related effects such as hydrate formation.
   - Reservoir may be underpressured, causing unexpected stress effects when injection raises pressure (induced seismicity, matrix integrity).
   - Potosi is often a lost circulation zone; we may be unable to collect representative samples or run successful tests.
   - Chemical reactions could clog connectivity of vugs and fractures, reducing injectivity.
   - Heterogeneous vug distribution may cause inaccurate plume model predictions.
   - Large fracture corridors could transport $CO_2$ far away, expanding the AOR beyond the project's ability to monitor.
   - Small-scale injectivity tests may over predict reservoir permeability; long-term injectivity may be much lower.
   - Wastewater injection could be done near a chosen project site, causing pressure interference and complicating monitoring.

3. **Respondent: Valerie Smith, Reservoir Geophysicist, Schlumberger Carbon Services**

**Risks in executing a Knox CCS Project**

- Reservoir injectivity: The key uncertainty is assessing the reservoir's heterogeneity permeability. To complete a well with good integrity, the vugs must be cemented, which increases uncertainty in well log measurements. Means to further understand the dual porosity / dual permeability nature of the Potosi are strongly advised.
- $CO_2$ plume monitoring: Current modeling shows far-traveled migration and plume route may be tortuous. Monitoring may become very expensive.
- Wellbore integrity: Lost circulation events suggest possibility of a leakage pathway, though thick (900 feet) of overlying dolomite reduce the risk of contamination of shallower aquifers.
- Caprock: The seal may effectively be the 900 feet of overlying dolomite, which will complicate the monitoring scheme.

4. **Respondent: Marcia Coueslan, Senior Geoscience Consultant, Schlumberger Carbon Services**

**Risks in executing a Knox CCS Project**

- The single biggest challenge is characterizing the vugular or secondary porosity because this is what will probably control plume development in the Knox. Secondary porosity development may be especially laterally variable, so characterization may be especially dependent upon site-specific data. Site-specific data for most potential Knox CCS sites is likely to be sparse.
- A related challenge is to ***upscale*** and ***spatially distribute*** the data-driven, site-specific porosity characterization, to map porosity effectively so that simulations can be based on a realistic earth model.
- Current acoustic impedance measurements and computations yield only approximate estimates of porosity greater than 12% (essentially the secondary porosity), and porosity estimates higher than this tend to be low to an uncertain degree. Because of this, reservoir simulations may predict lower injectivity, lower capacity, and perhaps a smaller and thicker plume than will occur in reality.
- Ramifications of unrealistic or non-representative plume simulation include impaired guidance for monitoring strategy, increased monitoring cost, risk of permit violation, and difficulty in establishing the plume-fate and plume-stability knowledge that will eventually be needed to enable closure.