

Risk Evaluation for CO₂ 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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Table of Contents

EXECUTIVE SUMMARY	5
1. PURPOSE AND SCOPE	6
1.1. Knox Project Task	6
1.2. Definition: “Knox-FX Project”	6
1.3. Scope	6
2. RISK EVALUATION FRAMEWORK	7
2.1. General statement	7
2.2. Assumptions and information base	7
2.3. Project values	10
2.4. Risk scales	11
2.5. Risk tolerance and risk matrix	13
3. FEPS AND SCENARIOS	14
3.1. Diligence in risk identification	14
3.2. Risk-bearing elements: FEPS vs. scenarios	14
3.3. List of FEPS	14
3.4. Scenarios	14
4. AREAS OF EXPERTISE	15
4.1. Identifying areas of expertise	15
4.2. List of areas of expertise	16
4.3. Identifying individual experts	17
5. RISK EVALUATION PROCESS AND PATH FORWARD	18
5.1. Workshop process	18

5.2. Preworkshop activities	18
5.3. Workshop techniques	18
5.4. Postworkshop activities	19
5.5. Data evaluation	19
5.6. Deliverables	20
5.7. Path forward for an actual sited project	20
6. LIMITATIONS	21
7. REFERENCES	22
APPENDIX 1: KNOX PROJECT TASK	23
APPENDIX 2: FEPS LISTS	24
APPENDIX 3: “TOP RISKS” POLLING FEEDBACK	37

Tables and Figures

Table 1: Assumptions and information base.	7
Table 2: Knox Group and Potosi Formation attributes.	9
Table 3: Knox-FX project values.	10
Table 4: Likelihood scale.	11
Table 5: Impact severity scales.	12
Table 6: Risk tolerance table.	13
Table 7: FEP groups. See Appendix 2 for more description of the “A” and “B” lists.	15
Table 8: Areas of expertise.	16
Figure 1: Illinois Basin; southern part highlighted (credit: ISGS).	8
Figure 2: Chronostratigraphy of Knox-associated units (credit: ISGS).	8
Figure 3: Risk matrix.	13

Executive Summary

This report describes a process and provides seed information for identifying and evaluating risks pertinent to a hypothetical carbon dioxide (CO₂) 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 CO₂ 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 CO₂-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 CO₂ 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 CO₂ 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 CO₂ 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: (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 (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.

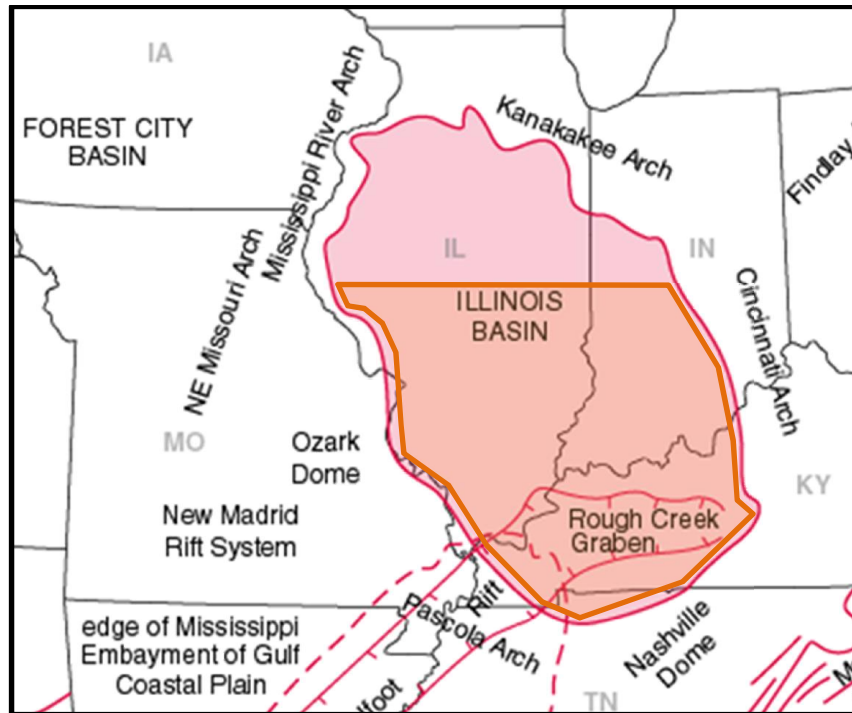


Figure 1: Illinois Basin; southern part highlighted (credit: ISGS).

System	Series		Western Kentucky	Illinois	Indiana	Michigan
	International	North Amer.				
Ordovician	Late	Hirnantian				Queenston Sh.
		Cincinnatian	Maquoketa Sh.	Maquoketa Sh.	Maquoketa Gp.	Utica Sh.
		Ordo. VI	Trenton Ls.	Galena Gp.	Trenton Ls.	Collingwood Sh. Trenton Ls.
	Middle	Ordo. V	Black River Gp.	Platteville Gp.	Black River Gp.	Black River Fm.
		Damwillian	Wells Creek Fm. St. Peter Ss.	Ancell Gp. St. Peter Ss.	Ancell Gp. St. Peter Ss.	Glenwood Fm. St. Peter Ss.
		Ordo. III				
	Lower	Arenig				Foster Fm.
		Tremadocian				Undifferentiated
						Prairie du Chien Gr.
	Cambrian	un-named				Trempealeau Fm.
Cambrian	Upper	Paibian				Franconia Fm.
						Galesville Ss.
	Middle					

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. Gunter Ss. formation (part of Knox) was tested in Blawie, 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 CO₂ 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

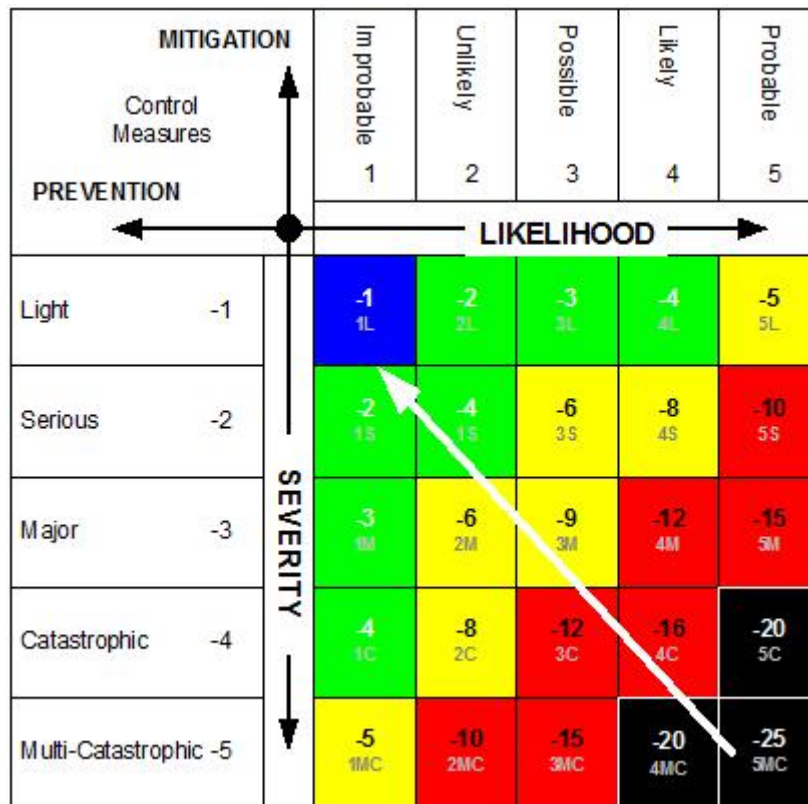


Figure 3: Risk matrix.

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 CO₂ 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 Plume Simulation	Reservoir Geology 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}) $\times$ (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 CO₂ 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

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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	CO₂ (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 ₂ S 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 CO₂ and water	Formation water (brine) in the target reservoir is found to contain H ₂ S, 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: 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, 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, 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	CO₂ 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	CO₂ Injectate: Fluids besides CO₂ and H₂O	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 in CCS into carbonates causes additional measures to 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 CO₂ 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 CO₂ 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, 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: 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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.
- CO₂ 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.