Health, Safety, and Environmental Screening and Ranking Framework for Geologic CO_2 Storage Site Selection

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Abstract

This report describes a screening and ranking framework (SRF) developed to evaluate potential geologic carbon dioxide (CO_2) storage sites on the basis of health, safety, and environmental (HSE) risk arising from possible CO_2 leakage. The approach is based on the assumption that HSE risk due to CO_2 leakage is dependent on three basic characteristics of a geologic CO_2 storage site: (1) the potential for primary containment by the target formation, (2) the potential for secondary containment if the primary formation leaks, and (3) the potential for attenuation and dispersion of leaking CO_2 if the primary formation leaks and secondary containment fails. The framework is implemented in a spreadsheet in which users enter numerical scores representing expert opinions or general information available from published materials along with estimates of uncertainty to evaluate the three basic characteristics in order to screen and rank candidate sites. Application of the framework to the Rio Vista Gas Field, Ventura Oil Field, and Mammoth Mountain demonstrates the approach. Refinements and extensions are possible through the use of more detailed data or model results in place of property proxies. Revisions and extensions to improve the approach are anticipated in the near future as it is used and tested by colleagues and collaborators.

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1 Introduction

In order to minimize the possibility that carbon dioxide (CO_2) storage projects will result in health, safety, and environmental (HSE) impacts due to CO_2 leakage and seepage, it is essential that sites be chosen to minimize HSE risk. This is particularly important for early pilot studies for which leakage and seepage for any reason could be perceived as a failure of the general approach of geologic CO_2 storage. Apart from site-specific operational choices once a given CO_2 pilot injection project is underway, the best way to avoid unintended leakage and seepage is to choose a good site at the outset.

This report describes a spreadsheet-based Screening and Ranking Framework (SRF) for evaluating multiple sites on the basis of their potential for HSE risk due to CO_2 leakage and seepage. The results of comparisons can be used to help select the best CO_2 injection sites from a number of candidate sites through screening and ranking. Although designed to be used in the early stages of site selection or for pilot CO_2 injection studies, the approach with extensions may find application in full geologic CO_2 storage site development. This report describes the philosophy behind the approach and its basic elements, and presents three case studies to demonstrate the use and applicability of the framework. Revisions and extensions are anticipated as feedback is received from colleagues and collaborators.

Before describing the framework, it is useful to clarify some terminology. The term *leakage* refers to migration of CO_2 away from the intended target formation. *Seepage* is slow or diffuse CO_2 migration across an interface in the near-surface environment such as the ground surface or the bottom of water body such as a lake. The *near-surface environment* is defined loosely as ±10 m from the ground surface. The term *flux* is used in its formal sense to refer to mass per unit area per unit time (e.g., kg m^{-2} s^{-1}), in contrast to *flow* which refers to mass per unit time (e.g., kg s^{-1}) with no area specified. A *plume* of CO_2 is a large relatively concentrated volume of CO_2 either in the subsurface or above ground. The word *impact* refers to consequences or effects of a given high CO_2 concentration on people and the biota for a given time. *Risk* is often defined as the product of probability of occurrence and consequence in order to reflect both the elements of likelihood and impact, and this same definition is used here. However, rather than treating likelihood in any kind of formal probabilistic sense, the SRF is qualitative with respect to risk and uses subsurface properties as general proxies for processes and features as described in the following section, "Executive Summary".

2 Executive Summary

In order to reduce the possibility that geologic carbon dioxide (CO_2) storage projects will result in health, safety, and environmental (HSE) impacts due to CO_2 leakage and seepage, it is essential that sites be chosen to minimize HSE risk. Here we present a spreadsheet-based Screening and Ranking Framework (SRF) for evaluating multiple sites on the basis of their potential for HSE risk due to CO_2 leakage and seepage. Application of the framework to three California sites (Rio Vista Gas Field, Ventura Oil Field, and the Mammoth Mountain natural analog site) demonstrates the approach. Although designed to be used in the early stages of site selection, the SRF approach, with extensions, may find application in full geologic CO_2 storage site risk assessment.

The HSE effects of concern are caused by persistent high concentrations of CO_2 in the near-surface environment where humans, plants, and other living things reside. To minimize HSE effects, it is necessary either to (1) prevent CO_2 from leaking away from the primary target formation, (2) prevent CO_2 leakage from reaching the near-surface environment, or (3) attenuate the leakage flux or disperse the CO_2 if it should reach the near-surface environment. With this understanding of the underlying origin of HSE impact, the SRF was formulated to evaluate three fundamental characteristics of a geologic CO_2 storage site:

1. Potential for long-term primary containment by the target formation,

2. Potential for secondary containment should the primary formation leak, and

3. Potential of the site to attenuate and/or disperse leaking CO_2 should the primary formation leak and secondary containment fail.

The SRF spreadsheet is designed to provide an independent assessment of each of these three characteristics through an evaluation of the properties of various attributes of the three characteristics. For example, the attributes of Primary Containment are given by the properties of the caprock and the reservoir, including reservoir depth. Similarly, Secondary Containment is determined by the properties of secondary and shallower seals, and Attenuation Potential is determined by surface characteristics, hydrology, and the presence and nature of existing wells and faults. These attributes are scored by the user based on suggested ranges of properties and values given in the spreadsheet. Arbitrary weights can be used to express the importance of some properties over others. Many of the properties and values of attributes are actually proxies for uncertain and undetermined quantities that could eventually be measured or modeled with additional site characterization effort.

The expected users of the SRF are geoscientists or hydrologists with some general knowledge of the site and/or access to published information in reference books or maps. It is expected that one user or group of users will evaluate all of the sites in a given screening or ranking process, thereby ensuring a measure of consistency in each assessment. The system is sufficiently simple and transparent that anyone can review the assessments done by other users and re-do the assessment if there is disagreement. Simplicity and transparency are key design features of the SRF spreadsheet Uncertainty in the SRF is defined broadly and includes parameter uncertainty and variability. Uncertainty is kept separate from the scores for the characteristics and is a primary graphical output along with the attribute assessment for each of the three characteristics. The primary output graphic of the SRF spreadsheet is a plot of attribute assessment for each of the three characteristics on the *y*-axis, and certainty on the *x*-axis. A demonstration of the SRF approach through comparison of two potential CO_2 storage sites (Rio Vista and the Ventura Oil Field) along with a leaking natural analogue site

(Mammoth Mountain, California) is presented. Primary Containment at Rio Vista is expected to be very good, while secondary containment is not as favorable. Dispersion of leaking CO_2 is expected to be effective because of low topographic relief and fairly consistent winds. The Ventura Oil Field site ranks lower than Rio Vista, while the natural analogue site Mammoth Mountain ranks by far the lowest the three sites as we would expect.

A framework for screening and ranking candidate sites for geologic CO_2 storage on the basis of HSE risk has been developed based on three fundamental characteristics of a geologic CO_2 storage site. We emphasize that this is a screening and ranking tool intended to guide the selection of the most promising sites for which more detailed risk assessment would be carried out. Example applications of the framework show that plausible comparative evaluations of prospective sites with limited characterization data can be accomplished based on the potential for CO_2 leakage and seepage and related HSE risk.

3 Experimental

3.1 Philosophy Behind the Approach

Although leakage and seepage are unlikely in the case of pilot studies involving small amounts of CO_2 injection, there is always the possibility that injected CO_2 will migrate away from the intended target formation. The wide variety of recognized potential pathways for leakage and seepage to the near-surface environment is shown schematically in Figure 1. Note that all of the leakage pathways involve the potential for secondary entrapment at higher levels in the system, that is, leakage pathways may not result directly in seepage. Furthermore, all of the pathways involve the potential for attenuation or dispersion. In particular in the near-surface environment, for example where the CO_2 plume is shown mixing with air in a ground plume, the potential for CO_2 to disperse and mix with water, air, or other fluids and gases is always present.

The HSE effects of CO_2 that are of concern are caused by persistent high concentrations of CO_2 in the near-surface environment where humans, plants, and other living things reside. For example, high concentrations in soil gas can lead to root respiration limitations and corresponding plant stress or death (e.g., Farrar *et al.*, 1995; Qi *et al.*, 1994). In potable groundwater aquifers, high concentrations can lead to leaching of heavy metals that could adversely affect water quality (Wang and Jaffe, 2005). In the above-ground environment or in basements and houses, high CO_2 concentrations can lead to health effects ranging from dizziness to death in humans and other animals (Benson *et al.*, 2002). To minimize HSE effects, it is necessary either to (1) prevent CO_2 leakage, (2) prevent CO_2 leakage from reaching the near-surface environment, or (3) attenuate the leakage flux or disperse the CO_2 if it should reach the near-surface environment so that CO_2 never builds up to persistent high concentrations at which it is an HSE risk.

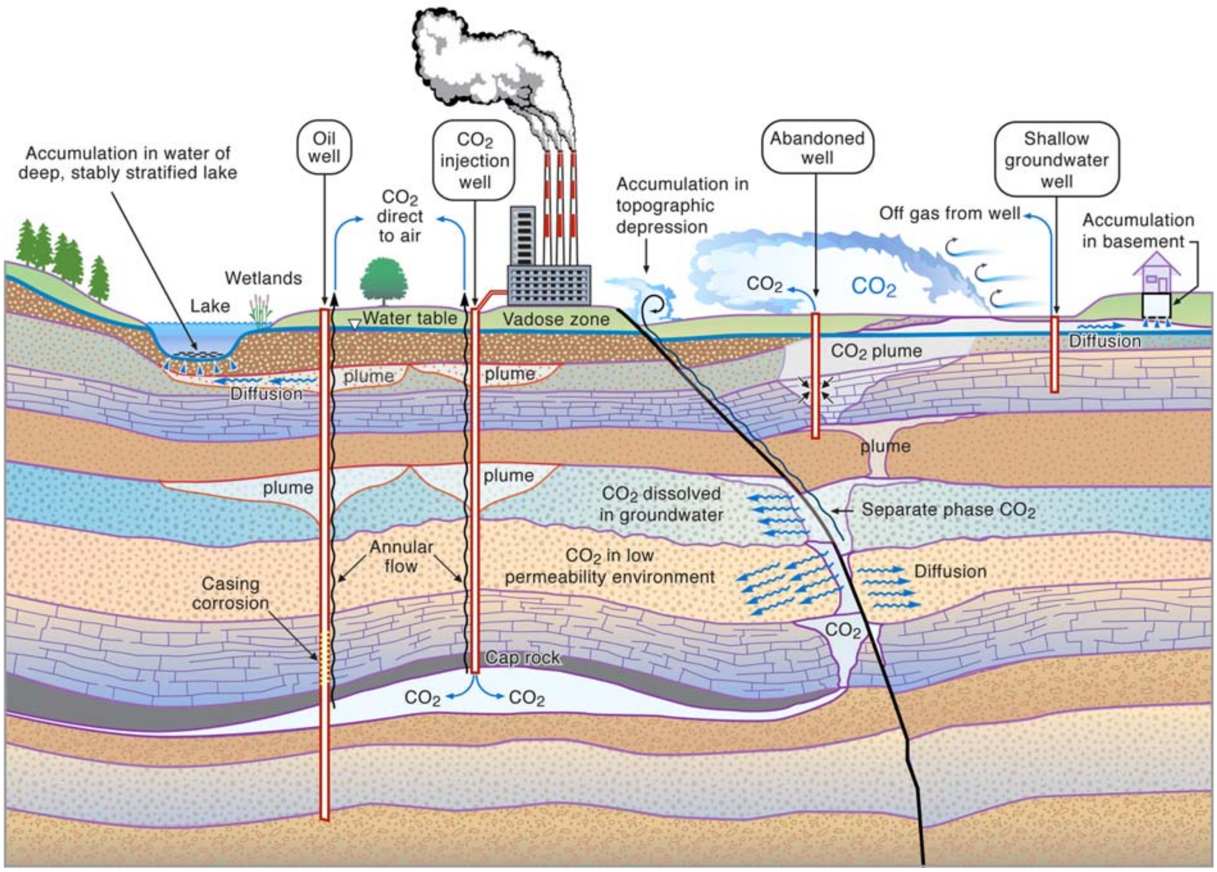

Figure 1. Schematic of various leakage and seepage pathways and processes for CO_2 from a geologic storage site

It is with this understanding of the underlying origin of HSE impact that the SRF for evaluating the potential for HSE impact was formulated. Specifically, the approach stems from the realization that potential HSE impact is related to three fundamental characteristics of a geologic CO_2 storage site:

1. Potential of the target formation for long-term containment of CO_2,

2. Potential for secondary containment should the primary target site leak, and

3. Potential of the site to attenuate and/or disperse leaking CO_2 should the primary formation leak and secondary containment fail.

The SRF spreadsheet was designed to provide a qualitative and independent assessment of each of the three characteristics through an evaluation of the properties of various attributes of these three characteristics. The SRF is designed so that it can be applied to sites with limited data. This is considered appropriate for early site selection or for pilot study sites when multiple sites are under consideration and where detailed site-characterization data will be lacking. Many of the properties and values of attributes that the user will input into the SRF spreadsheet are actually proxies for uncertain and undetermined quantities that could eventually be measured or modeled with additional site characterization effort. However, because of the lack of data that will be the norm for most site-selection processes (especially in the early phases), uncertainty has been made a fundamental input and output of the SRF that is kept separate from the scores for the characteristics. Uncertainty in the SRF is defined broadly and includes parameter uncertainty (e.g., how well known a given property is) and variability (e.g., how variable a given property is). Uncertainty is handled by the SRF as a primary graphical output along with the qualitative risk score for each of the three characteristics. The overall uncertainty reflects the user's confidence in how well the characteristics are known. Users can utilize this graph to compare sites, taking into account both the expectation of HSE risk and some estimate of how well-known is that risk. The comparison of sites in this context can be used for screening or ranking of sites based on the HSE risk criterion.

The SRF relies on input by a user who either already knows something about the site, has opinions about the site based on general information, or who has gained knowledge from published information about the site. As discussed above, the reason for the choice to use relatively qualitative and/or opinion-based information rather than hard data and/or modeling results is that detailed site-characterization information—especially for pilot CO_2 injections—will rarely be available. The expected users of the SRF are geoscientists or hydrologists with some general knowledge of a site and/or access to limited published information about the site in reference books or maps. It is expected that one user or group of users will evaluate all of the sites in a given screening or ranking exercise, thereby ensuring a measure of consistency in each assessment. The system is sufficiently simple and transparent that anyone can review the assessments done by other users and even redo the assessment if there is disagreement. Simplicity and transparency are key design features of the SRF spreadsheet.

The methods behind the SRF differ from other approaches such as the Features, Events, and Processes (FEP) approach (e.g., Wildenborg *et al*., 2005), and the probabilistic approach (e.g., Rish, 2003). In the FEP approach, a comprehensive list of FEPs is developed and codified in a database that is then used to define scenarios for leakage and seepage, or any other performance-affecting event. Modeling is then used to evaluate the consequences of that scenario in terms of CO_2 impact due to high concentrations and long residence times, for example. The FEPs have subjective probabilities associated with them, and risk can be calculated from the product of consequence as simulated in the scenario and probability as assigned to the FEPs. The FEP scenario approach is laborious and requires significant site-specific information to be carried out effectively. In the probabilistic approach of Rish (2003), probabilities of events are input and the likelihood of various detrimental events is calculated. The probabilistic approach relies upon accurate probability distributions—something that will be difficult at best to estimate for multiple sites especially during the early phases of site selection.

In the SRF approach, there is no modeling and simulation nor are probabilities assigned. The reason for this approach is that detailed site-characterization information, especially for pilot CO_2 injections, is not expected to be sufficient to undertake a FEP-scenario analysis, nor to assign probabilities for a probabilistic analysis. Instead the SRF uses qualitative pieces of information, for example as gleaned from general reports or an expert's knowledge of an area, as proxies for potential FEPs and consequences combined. By this approach, the analysis is greatly simplified and includes explicitly the level of confidence that the user assigns to the assessments as a primary output. In short, the SRF is designed to answer the question "From a choice of several potential sites, and based on existing information, which site has the lowest HSE risk?" In "Screening and Ranking Framework" (below), the SRF approach and its input and output are described in detail.

3.2 Screening and Ranking Framework

The SRF approach is based on an independent evaluation of the three fundamental characteristics of a site that control the HSE risk of CO_2 leakage and seepage. Although developed based on past experience with CO_2 storage rather than with the formality of decision analysis, the approach falls loosely under the category of multi-attribute utility theory (e.g., Keeney and Raiffa, 1976; Keeney, 1980). The three scores that are evaluated for each site are proxies for combinations of impact and likelihood (i.e., risk) of leakage, secondary entrapment, and attenuation. The utility function in this case would be a measure of tendency for minimal HSE impact while injecting a maximum amount of CO_2. The SRF approach was not developed using any formal guidelines, and some unconventional aspects are included for the case of subsurface environments about which very few hard facts will be known. The input required by the SRF is quite general and may rely primarily on expert opinion depending on the degree of characterization and/or published information available for the sites.

The assessment made in the framework is based on four classes of information: (1) site characteristics which are defined by (2) attributes, which are defined by (3) properties which are defined by (4) values input by the user. Table 1 shows the relationship between characteristics, attributes, and properties, and what properties these proxies represent. For example, Table 1 shows that the three attributes of the potential for the target formation to contain CO_2 for long periods are (1) the nature of the primary caprock seal, (2) reservoir depth, and (3) reservoir properties. The properties of the primary caprock seal attribute are thickness, lithology, demonstrated sealing capacity, and lateral continuity. The far right-hand column shows that these four properties are proxies for (1) likely effectiveness of the seal, (2) permeability and porosity of the seal, (3) the probability of leakage through the seal, and (4) the integrity of the seal against CO_2 spreading that could exceed the spillpoint. Properties and proxies for all of the attributes are shown in Table 1.

Table 1. Characteristics, attributes, properties, and proxies

Characteristics	Attributes	Properties	Proxy for…
Potential for primary containment	Primary seal	Thickness Lithology Demonstrated sealing Lateral continuity	Likely sealing effectiveness Permeability, porosity Leakage potential Integrity and spillpoint
	Depth	Distance below surface	Density of CO_2 in reservoir
	Reservoir	Lithology Permeability and porosity Thickness Fracture or primary porosity Pore fluid Pressure Tectonics Hydrology Deep wells Fault permeability	Likely storage effectiveness Injectivity, capacity Areal extent of injected plume Migration potential Injectivity, displacement Capacity, tendency to fracture Induced fracturing, seismicity Transport by groundwater Likelihood of well pathways Likelihood of fault pathways
Potential for secondary containment	Secondary seal	Thickness Lithology Demonstrated sealing Lateral continuity Depth	Likely sealing effectiveness Permeability, porosity Leakage potential Integrity and spillpoint Density of CO_2
	Shallower seals	Thickness Lithology Lateral continuity Evidence of seepage	Likely sealing effectiveness Permeability, porosity Integrity and spillpoint Effectiveness of all seals
Attenuation Potential	Surface characteristics	Topography Wind Climate Land use Population Surface water	CO_2 plume spreading Plume dispersion Plume dispersion Tendency for exposure Tendency for exposure Form of seepage
	Groundwater hydrology	Regional flow Pressure Geochemistry Salinity	Dispersion/dissolution Solubility Solubility Solubility
	Existing wells	Deep wells Shallow wells Abandoned wells Disposal wells	Direct pathway from depth Direct pathway Direct pathway, poorly known New fluids, disturbance
	Faults	Tectonic faults Normal faults Strike-slip faults Fault permeability	Large permeable fault zones Seal short-circuiting Permeable fault zones Travel time

The first thing the SRF spreadsheet user must do in evaluating the attributes of one of the three characteristics is decide the importance of a given property through the specification of weighting factors for each of the *j* properties of each attribute. The weighting factors (w_j) are normalized by the spreadsheet as

$$\sum_j w_j = 1 \qquad (1)$$

so any arbitrary scale can be used. The weighting option allows the user great latitude in applying his/her judgment to the evaluation. For example, if the user feels strongly that caprock seal thickness is the overriding property controlling leakage and seepage, then a large number can be assigned for the weight of that property and the caprock thickness value will dominate the assessment of the attribute Primary Seal. Figure 2 shows an example of the Primary Containment worksheet from the SRF spreadsheet. The light blue cells indicate those that require user input. As shown, the weight of the seal thickness property is assigned a value of 10 out of a total of 21 making approximately one-half of the weight of the primary seal attribute and its uncertainty rest on the seal thickness value. For comparing sites in the process of screening or ranking, the use of different weighting factors for the properties of different sites should be carefully considered. In the test cases presented below, constant weighting factors are used for consistency.

8/18/2004	Rio Vista Gas Field	Revision:	2.0					
				Overall score for this sheet		Average of the weighted assessments of attributes		Average certainty
	Primary Containment			2.49		1.30		1.87
	Attribute	Weight 10 = most import 1 = least	Normalized Weight	Property/Value		Assessment of Attribute Property Relative to HSE Risk 2 = excellent (positive attribute) 0 = neutral (fair attribute) -2 = poor (negative attribute)	Weighted Assessment of Attribute	Certainty Factor 2.0 = Very well known 1.0 = Generally accepted 0.1 = Poorly known
	Primary Seal			**Description**				
	Thickness	10	0.48	100 m		0	0.00	2
	Lithology	5	0.24	Shale		2	0.48	2
	Demonstrated sealing	5	0.24	Good seal		2	0.48	2
	Lateral continuity	1	0.05	Large areal extent of gas		2	0.10	2
		21	1.00		Average:	1.50	1.05	2.00
	Depth			**Description**				
	Distance below ground	10	1.00	some v. shallow, but most 1000 m -		2	2.00	2
		10	1.00		Average:	2.00	2.00	2.00
	Reservoir			**Description**				
	Lithology	1	0.07	Sandstone		2	0.13	2
	Perm., poros.	2	0.13	5-1800 mD, 20-34%		2	0.27	2
	Thickness	1	0.07	150 m		2	0.13	2
	Fracture or primary poros.	1	0.07	Primary		2	0.13	2
	Pores filled with...	1	0.07	ural gas and low-TDS water		2	0.13	1
	Pressure	1	0.07	Hydrostatic to depleted		1	0.07	1
	Tectonics	2	0.13	wth faults, but not v. active		0	0.00	2
	Hydrology	2	0.13	Water drive		0	0.00	1
	Deep wells	2	0.13	Many deep wells		-2	-0.27	2
	Fault permeability	2	0.13	Trapping faults (low k)		2	0.27	1
		15	1.00		Average:	1.10	0.87	1.60

Figure 2. Example worksheet from the SRF spreadsheet for the characteristic Primary Containment

The second thing the user of the SRF spreadsheet does is assign a numerical value (a_j) to the properties based on suggestions in pop-up comments in the spreadsheet. Examples of property values can be seen in Figures 2–4, which show the worksheets for Primary Containment, Secondary Containment, and Attenuation Potential. The numerical values are chosen as integers ranging from –2 (poor) to +2 (excellent) with 0 considered neutral (neither good nor bad). Broad ranges of values are offered for various conditions in the pop-up comments to guide the user in selecting an integer between –2 and +2. Real numbers can also be used in cases when the user feels it is warranted.

8/18/2004	**Rio Vista Gas Field**	**Revision:**	**2.0**					
				Overall score for this sheet		Average of weighted assessments of attributes		Average certainty
	Secondary Containment			**0.51**		**0.22**		**1.63**
	Attribute	Weight 10 = most import. 1 = least	Normalized Weight	Property/Value		Assessment of Attribute Property Relative to HSE Risk **2 = excellent (positive attribute)** **0 = neutral (fair attribute)** **-2 = poor (negative attribute)**	Weighted Assessment of Attribute	Certainty Factor **2.0 = Very well known** **1.0 = Generally accepte** **0.1 = Poorly known**
	Secondary Seal			**Description**				
	Thickness	10	0.38	150 m (Sidney Flat shale)		0	0.00	2
	Lithology	5	0.19	Shale		2	0.38	2
	Demonstrated sealing	1	0.04	as prod. from multiple horiz.		1	0.04	2
	Lateral continuity	5	0.19	Laterally continuous		1	0.19	2
	Depth	5	0.19	Sidney Flat shale ~800 m		0	0.00	2
		26	1.00		Average:	0.80	0.62	2
	Shallower Seals			**Description**				
	Thickness	10	0.33	Thin mudstone		-1	-0.33	1
	Lithology	5	0.17	Mudstone		0	0.00	1
	Lateral continuity	5	0.17	Extensive		1	0.17	1
	Evidence of seepage	10	0.33	Historic gas seeps		0	0.00	2
		30	1.00		Average:	0.00	-0.17	1.25

Figure 3. Example worksheet from the SRF spreadsheet for the characteristic Secondary Containment

8/18/2004	**Rio Vista Gas Field**	**Revision:**	**2.0**					
				Overall score for this sheet		Average of weighted assessments attributes		Average certainty
	Attenuation Potential			**0.92**		**0.52**		**1.94**
						Assessment of Attribute	Weighted	
	Attribute	Weight	Normalized	Property/Value		Property Relative to HSE Risk	Assessment of	Certainty Factor
		10 = most import	Weight			**2 = excellent (positive attribute)**	Attribute	**2.0 = Very well known**
		1 = least				**0 = neutral (fair attribute)**		**1.0 = Generally accepted**
	Surface Characteristics			**Description**		**-2 = poor (negative attribute)**		**0.1 = Poorly known**
	Topography	5	0.15	Flat		2	0.30	2
	Wind	10	0.30	Windy		2	0.61	2
	Climate	2	0.06	Sub-humid		-1	-0.06	2
	Land use	4	0.12	Farmland/wetlands		1	0.12	2
	Population	10	0.30	Rural		1	0.30	2
	Surface water	2	0.06	Perennial wetlands exist		-2	-0.12	2
		33	1.00		Average:	0.50	1.15	2.00
	Groundwater Hydrology			**Description**				
	Regional flow	6	0.32	riable, away from Mont. Hills		1	0.32	2
	Pressure	7	0.37	Hydrostatic		0	0.00	2
	Geochemistry	2	0.11	Fresh, slightly alk.		2	0.21	2
	Salinity	4	0.21	Very low TDS		2	0.42	2
		19	1.00		Average:	1.25	0.95	2.00
	Existing Wells			**Description**				
	Deep wells	5	0.25	Many deep wells		-2	-0.50	2
	Shallow wells	4	0.20	Numerous shallow gw wells		-2	-0.40	2
	Abandoned wells	10	0.50	Many abandoned wells.		-2	-1.00	2
	Disposal wells	1	0.05	Water is re-injected.		-2	-0.10	2
		20	1.00		Average:	-2.00	-2.00	2.00
	Faults			**Description**				
	Tectonic faults	10	0.59	o permeable tectonic faults		2	1.18	2
	Normal faults	1	0.06	Normal faults form traps		2	0.12	2
	Strike-slip faults	1	0.06	Few strike-slip faults		2	0.12	1
	Fault permeability	5	0.29	6 of gas plays are fault traps		2	0.59	2
		17	1.00		Average:	2.00	2.00	1.75

Figure 4. Example worksheet from the SRF spreadsheet for the characteristic Attenuation Potential

The third thing the user must do is enter a value for the confidence with which each property is known (2 is very certain; 0.1 is highly uncertain). This confidence information will be carried along and plotted with attribute assessments for each of the three characteristics. The worksheets depicted in Figures 2–4 show that there are three attributes ($i = 3$) for the Primary Containment characteristic, two attributes ($i = 2$) for the Secondary Containment characteristic, and four attributes ($i = 4$) for the Attenuation Potential characteristic. These reflect the current version of the SRF and are subject to change in future revisions.

From this user input, a variety of averaged quantities is generated by the spreadsheet. The fundamental calculation the spreadsheet does is to add up the weighted property assessments and average them across the attributes to arrive at a score for each of the three fundamental characteristics. This is done for each of the j properties shown in Table 1, and then averaged over i attributes ($i = 3$ for Primary Containment and $i = 2$ for Secondary Containment, and $i = 4$ for Attenuation Potential (see Table 1)). The score (S) for site n is a function of the j properties and values (a)

$$S_n = \frac{1}{i}\sum_{1}^{i}\left[\sum_{j} w_j a_j\right]_i \quad . \tag{2}$$

For site *n*, the overall confidence (*C*) for the *j* properties and values is averaged over *i* attributes as follows:

$$C_n = \frac{1}{i}\sum_{1}^{i}\left[\frac{1}{j}\sum_{j} c_j\right]_i . \qquad (3)$$

The results are summarized and displayed graphically in the plot on the Summary worksheet, an example of which is shown in Figure 5 for the Rio Vista Gas Field.

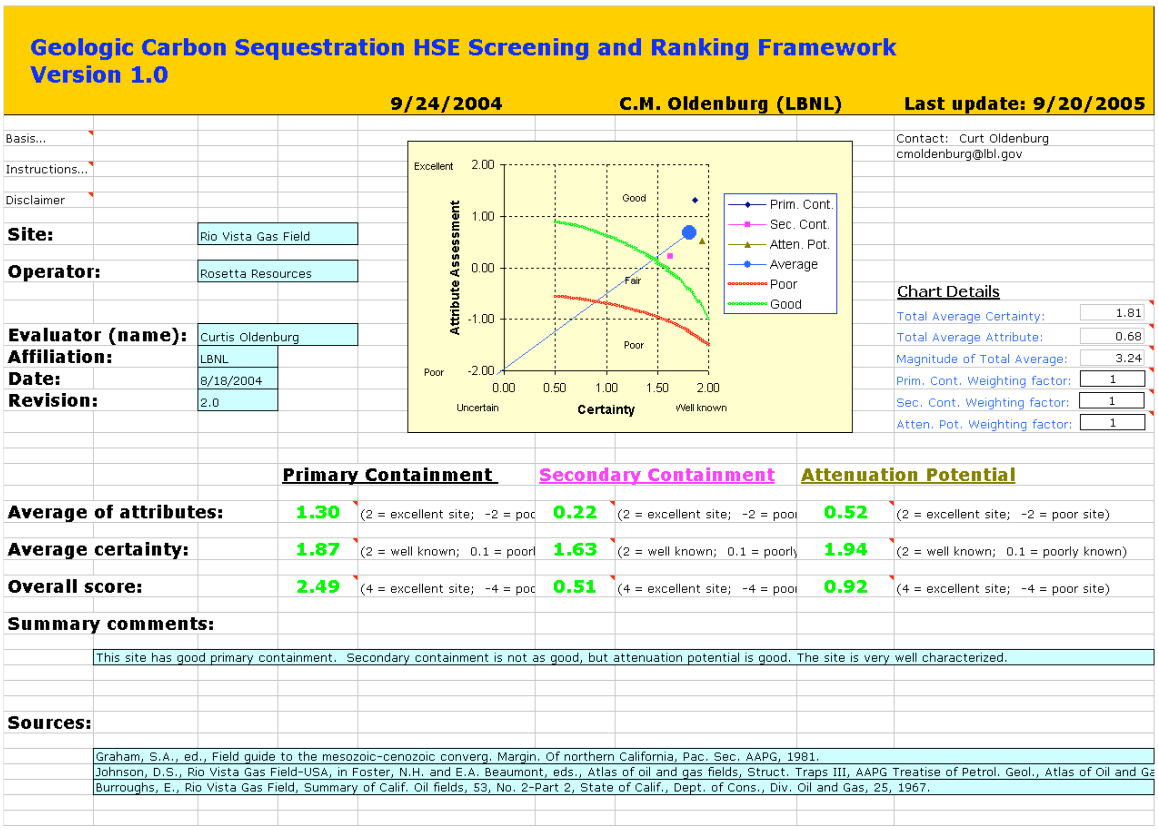

Figure 5. Summary graphic showing the attribute assessment (*y*-axis) and uncertainty (*x*-axis) of the three fundamental characteristics along with qualitative regions of poor, fair, and good HSE risk for the Rio Vista Gas Field

There are additional display elements of the Summary worksheet worthy of note. To the right of the plot in Figure 5 is a table ("Chart Details") containing numerical values of the averages of the three characteristics and certainties as shown by the large circle symbol in the plot. The third number—"Magnitude of Total Average"—in the "Chart Details" table is the distance from the lower-left-hand corner of the plot (lowest assessment, least certainty) to the average point. This distance is a measure of the overall quality of a site, taking into account both the average scores and average uncertainty. The three numbers below the table are additional weighting factors that users can assign for the purpose of weighting the importance of the three characteristics, heretofore assumed to be of equal importance, and which are assigned default values of one. Additional scores of the three characteristics are displayed along the bottom of the plot and defined in comments. These scores are automatically colored based on the scores (red implies poor, green implies good). The overall score ranges from –4 to +4 and is a product of the assessments and uncertainties. The low end –4 would be a site that the user is very certain is very poor, while a +4 would be a site that the user is very certain is very good. Because the overall score collapses expected behavior and certainty together into one number, it is neither emphasized nor plotted, but rather included simply as additional information. The summary worksheet graphic displays tentative screening curves delineating Good, Fair, and Poor regions on the summary graphic. These screening curves are entirely provisional and arbitrary and may be modified in future versions.

It is important to emphasize that the relative assessments of different sites are not necessarily linearly related to their relative physical behaviors. For example, a site that scores a 1.0 for the primary containment characteristic does not necessarily leak 50% more than a site that scores 1.5 for primary containment. In fact, such sites could be orders of magnitude different in their ability to contain CO_2. The assessment scores simply represent relative rankings of the sites without indicating absolute performance.

4 Results and Discussion

4.1 Rio Vista Gas Field

The Rio Vista Gas Field is located in the delta region of the Sacramento-San Joaquin Rivers in the Sacramento Basin of California, approximately 75 km (47 mi) northeast of San Francisco. The Rio Vista Gas Field is the largest on-shore gas field in California, and has been producing gas since 1936 from reservoirs in an elongated dome-shaped structure extending over a 12 km by 15 km (7.5 mi by 9.3 mi) area. The largest production has been from the Domengine sands in fault traps at a depth of approximately 4,500 ft (1,400 m) with sealing by the Nortonville shale. Details of the field can be found in Burroughs (1967) and Johnson (1990).

We have used published materials and our knowledge of the geology of the area to fill in values in the SRF spreadsheet and arrive at overall attribute assessments and certainties for the Rio Vista Gas Field under the assumption that it would be used as a geologic CO_2 storage site. As shown in the Summary worksheet in Figure 5, the high attribute score displayed by the SRF spreadsheet reflects the very effective primary containment expected at Rio Vista. Secondary containment is not expected, as sealing formations above the Nortonville shale are largely absent; however, the attenuation potential is excellent at Rio Vista due largely to steady winds and flat topography. As shown in Figure 5, confidence in the attribute assessments is quite high for subsurface and surface characteristics at Rio Vista because of the long history of gas production at the site. The high score and certainty at this site suggest that Rio Vista Gas Field is a good candidate for geologic CO_2 storage.

4.2 Ventura Oil Field

The Ventura Oil Field taps reservoirs in young folds and fault traps of marine sediments in the tectonically active coastal area northwest of Ventura, California. The primary structure is the Ventura Anticline, a dramatic fold that is visible in outcrop in the deeply incised canyons of the area. Natural oil seeps and tar are widely found in the area. Using geological information from published references (Sylvester and Brown, 1988; Harden, 1997) and our own knowledge of the site, we assigned values appropriate for the Ventura Oil Field to assess attributes and uncertainty for HSE risk if the site were to be used for geological CO_2 storage.

As shown in Figure 6, the Ventura Oil Field comes out worse on average than the Rio Vista Gas Field (Figure 5). The very significant oil accumulations at Ventura indicate that good traps exist, but the evidence of widespread oil and tar seepage along with the lack of significant natural gas accumulation suggest that pathways to the surface also exist. As for secondary containment, some of the oil reservoirs in the area are quite shallow, suggesting that secondary containment may occur but there is a high degree of uncertainty, especially in light of the abundant seepage. As for attenuation potential, the Ventura area is highly dissected with steep canyons that do not promote dispersion of seeping CO_2. There is also considerable population and agriculture to the southeast which could be exposed to seeping CO_2. Therefore, attenuation potential is also judged worse at Ventura than at Rio Vista.

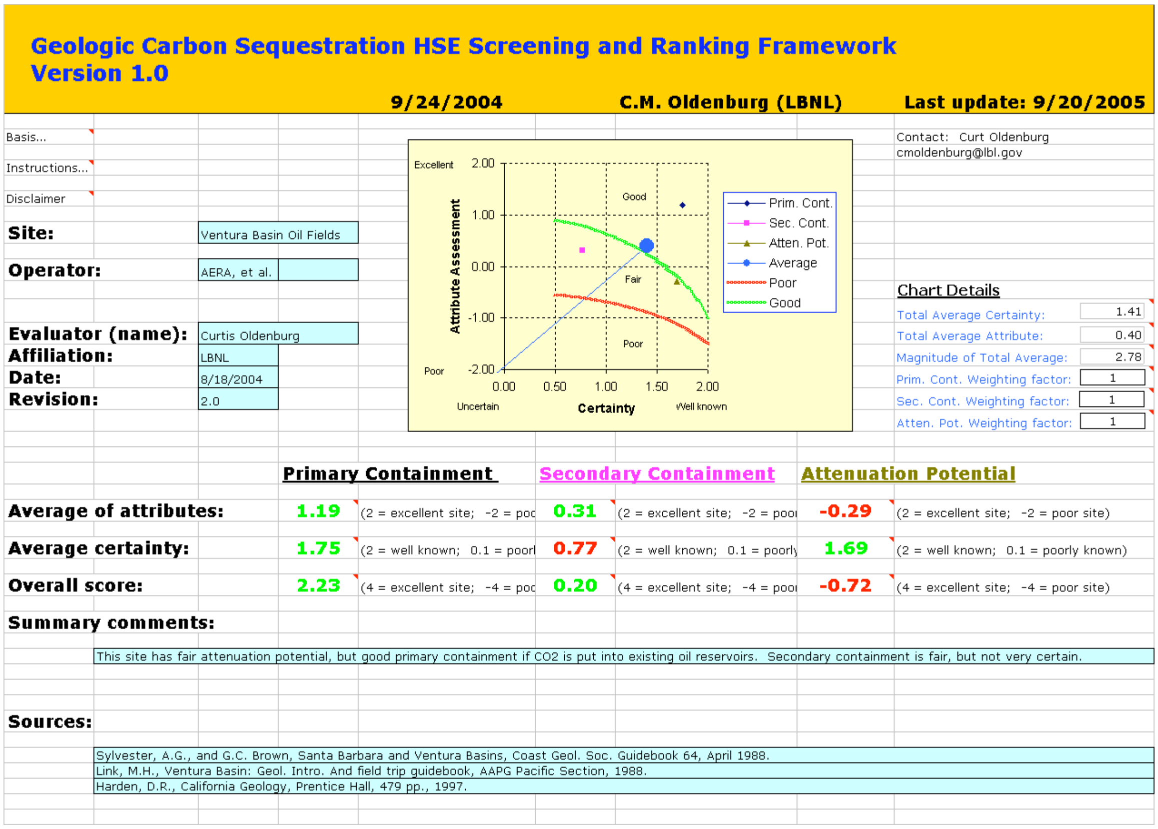

Figure 6. Summary worksheet showing the attribute assessment (*y*-axis) and uncertainty (*x*-axis) of the three fundamental characteristics for the Ventura Oil Field

4.3 Mammoth Mountain

Finally, this study ran an example of a naturally leaking site to see how it compares using the SRF. Mammoth Mountain, California, is a 200,000 year-old dormant volcano with active springs and geothermal anomalies. Carbon dioxide seeps out of the ground and has built up high enough concentrations in some areas in soil to kill native trees. For this purely academic analysis of the potential HSE effects of deliberate CO_2 injection, we assumed that the area under consideration was comparable to Rio Vista and Ventura in terms of size by considering the entire Mammoth Mountain area, not simply the Horseshoe Lake tree-kill area where natural CO_2 seeps from the ground.

Using published information from Farrar *et al.* (1995) and Sorey *et al.* (1999), we filled in values and properties of the SRF spreadsheet. Many of the properties are given the lowest values because they simply do not apply at Mammoth Mountain. For example, as evidenced by the extensive seepage, we concluded that there is no effective seal present, and therefore scored those properties with the lowest values. Other properties are not very well known and we scored them accordingly. As shown in Figure 7, the Mammoth Mountain site scored badly as expected in primary and secondary containment. The site does better on attenuation potential because it is fairly windy there and the population is relatively sparse. Nevertheless, the SRF spreadsheet demonstrates what we knew *a priori*, namely, that Mammoth Mountain has natural CO_2 HSE risk and would not be a good place to store CO_2 in the subsurface.

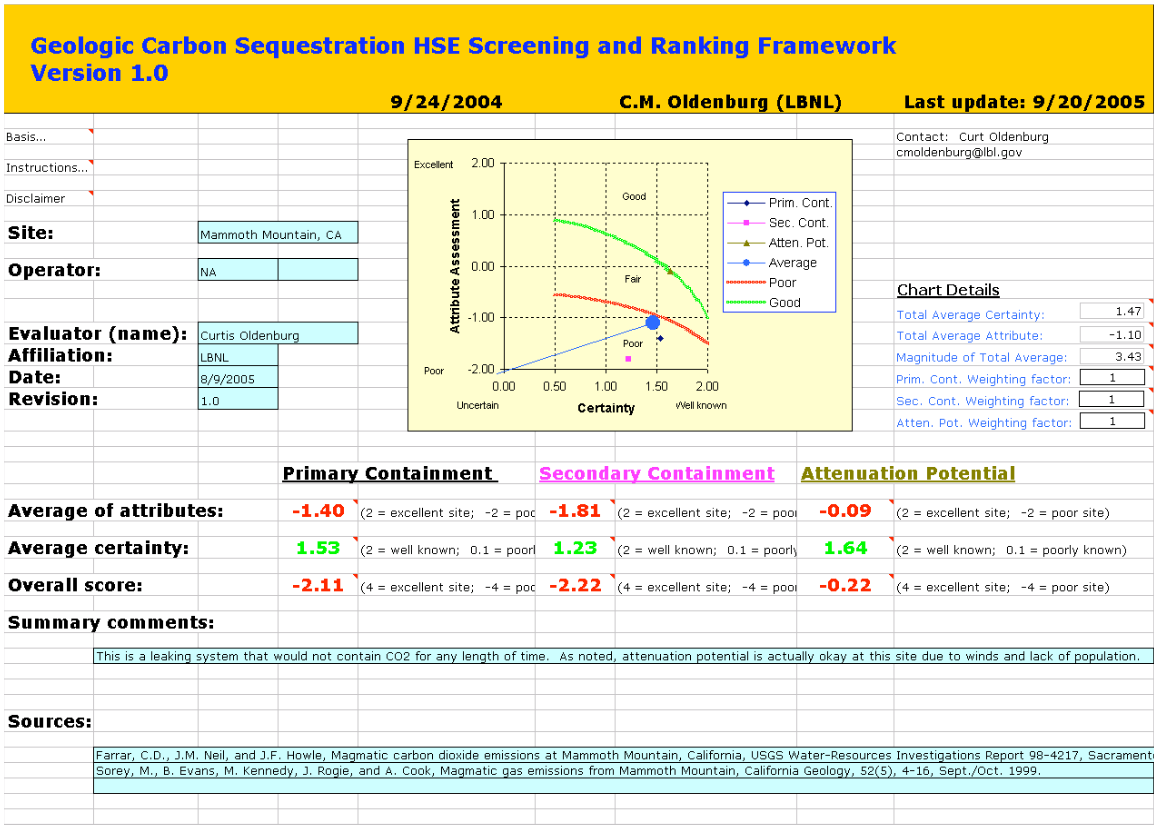

Figure 7. Summary graphic showing the attribute assessment (*y*-axis) and uncertainty (*x*-axis) of the three fundamental characteristics for the natural analog site Mammoth Mountain, California

5 Results and Discussion

The preceding demonstration of the SRF cannot formally be called a validation because no one has injected CO_2 into any of these sites and evaluated the three characteristics directly. Nevertheless, the results are consistent with our general knowledge and expectation of these three sites. The benefit of the SRF is that this knowledge and expectation is now formally expressed in a way that others can review, criticize, revise, or affirm. There is a large degree of arbitrariness allowed in the system by allowing the user to weight the importance of various properties. In the above examples, the weighting factors were the same for all three analyses. In the case that weighting functions are changed for various sites under comparison, it will be more difficult to defend direct comparisons. Nevertheless, the transparency of the system and simplicity will allow a critic or reviewer to alter the weighting functions and do the analysis again to compare the effect. Group efforts with multiple people evaluating the same sites may prove especially useful because this strategy would tend to capture a large range of opinions while simultaneously bringing uniformity to comparisons. As with any tool, misuse is possible and the SRF assumes an underlying integrity of the users. Because of the transparency and simplicity of the system, there is little possibility to hide abuses.

Several extensions of the system are possible. First, as more data become available, distributions—rather than single values—could be input by the user where such distributions are known. This approach would add a component of variability to the outcome, and potentially better represent the range of performance of a site rather than a worst-case, best-case, or average performance.

As shown in Table 1, the values and properties entered by the user combine to represent proxies for site characterization data that may not be known precisely. For example, for the Primary Containment attribute “Primary Seal”, lithology is a proxy for permeability and porosity. The idea here is that permeability and porosity may not have been measured but that the known lithology of the seal provides a fair representation of these properties. This proxy representation also occurs at the scale of the attribute. For example, the primary seal attribute is evaluated by assigning values and properties (e.g., thickness, lithology) to describe it. The combination of these values and properties is a proxy for the expected effectiveness of the seal. This proxy could be replaced by data or model results that represent seal effectiveness in more detail, e.g., by quantitative prediction of CO_2 flux. In this way, the SRF can be extended if more site characterization data are available to include more quantitative measures of performance. On the value and property scale, quantitative data or distributions could be input and evaluated if these data were available. On the attribute scale, model simulations or experimental data could be input and evaluated for sites undergoing more detailed levels of site characterization.

6 Conclusions

A framework for screening and ranking candidate sites for geologic CO_2 storage on the basis of HSE risk has been developed based on three fundamental characteristics of a CO_2 sequestration site. The framework allows users to arbitrarily weight and assign uncertainty to the properties of the attributes of the fundamental characteristics to evaluate and rank two or more sites relative to each other. We emphasize that this is a screening and ranking risk assessment tool intended to guide the selection of the most promising sites for which more detailed risk assessment would be carried out. Example applications of the framework show that comparative evaluations of prospective sites with limited characterization data can be accomplished based on potential for CO_2 leakage and seepage and related HSE risk. Testing and further development of the SRF are underway.

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8 Acknowledgments

I thank Tom McKone and Christine Doughty (LBNL) for reviews, and Larry Myer and Sally Benson (LBNL) for support and encouragement. Comments from Sean McCoy (Carnegie Mellon University) helped place this approach in the context of existing decision support theory. This work was supported in part by WESTCARB through the Assistant Secretary for Fossil Energy, Office of Coal and Power Systems, through the National Energy Technologies Laboratory (NETL), and by Lawrence Berkeley National Laboratory under Department of Energy Contract No. DE-AC03-76SF00098.