MONITORING PROTOCOLS AND LIFE-CYCLE COSTS FOR GEOLOGIC STORAGE OF CARBON DIOXIDE

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ABSTRACT

In this study two scenarios are used to evaluate the applicability of the monitoring techniques and the costs of deploying them over the life-cycle of a storage project. Key assumptions underlying the cost estimates such as reservoir size and depth are provided and major cost dependencies are described. For each scenario a "package" of suitable monitoring techniques is proposed with a commentary on how the components were selected. For each monitoring scenario a basic and enhanced monitoring program is evaluated. Estimated costs for monitoring geologic storage over the full life-cycle of a project at a range from \$0.05 to \$0.10 per tonne of CO_2 (discounted at 10%/year, undiscounted cost range from \$0.16 to \$0.31 per tonne). This paper summarizes one part of a study performed for the International Energy Agency Greenhouse Gas R&D Programme (IEA GHG) to provide an overview of monitoring techniques for geologic storage of CO_2 [1].

INTRODUCTION

Every geologic storage project will go through a series of phases which constitute the life-cycle of the project. During each of these phases, monitoring will serve different purposes. For this study, we suggest that there are four distinct phases of life-cycle of a geologic storage project: a pre-operation phase, an operational phase, a closure phase and a post-closure phase. A similar, but not identical discussion of the life-cycle of a storage project can be found in Keith and Wilson [2]. The closure phase of the project begins when CO_2 injection has stopped. The purpose of this phase is two-fold. First, surface facilities will be removed and the injection wells plugged and abandoned if they are no longer required for monitoring. Second, it will be used as a confirmatory period to demonstrate that the storage project is performing as expected and that it is safe to decrease or discontinue further monitoring. The duration of the closure phase will vary, depending on a number of factors such as the type of storage project, the regulatory requirements, and the degree to which the project performed as expected. At the end of the closure phase, a complete set of records about the location and status of the CO_2 plume and abandoned wells would be turned over the regulatory authorities who would maintain a permanent archive of this information. It is proposed here that monitoring will no longer be required except in the event of monitoring ongoing leakage, legal disputes or other matters that may require new information about the status of the storage project. This proposal is predicated on gaining experience and using appropriate technology to ensure that abandoned wells do not present an unacceptable risk of creating a pathway for CO_2 leakage back to the surface. Nevertheless, where the cost of monitoring is discussed, we also examine a scenario where on-going monitoring is required over a 1000 year period.

MONITORING SCENARIOS

The estimated life-cycle costs of monitoring geologic storage projects are presented here for two scenarios: 1) a project modeled after the Schrader Bluff oil field and 2) CO_2 storage in a hypothetical saline formation. For both scenarios we consider storage of the CO_2 from a 1,000 MW coal-fired power plant with a 30-year lifetime. Such a plant, with current technology, would produce about 8.6 million tonnes of CO_2 per year. For each case, costs are estimated for the pre-injection, operational, closure and post-closure phases described above. Assumptions for the two scenarios are provided in Table 1.

For the saline formation scenario, two cases are considered: one for a low residual gas saturation (LRG) CO_2 plume that does not move after injection stops, and a high residual gas saturation (HRG) CO_2 plume which keeps moving after injection until after 80 years it stops moving and growing. The HRG plume is one in which the residual gas saturation is high (25%) and thus is easily trapped in the pore spaces of the storage formation. HRG plumes tend to be comparatively compact and retained in the vicinity of the injection wells. The LRG plume has a lower residual gas saturation (5%) and will migrate until it dissolves, becomes trapped in local features or the residual gas saturation is reached. This increases the footprint of the geophysical surveys, and hence increases the cost of monitoring. Using the parameters listed in Table 1, after 30 years the CO_2 plume will have an extent of 216 km^2 (note that we assume that LRG and the HRG plumes will be the same size during the operational phase of the project). During the closure phase we assume that the LRG plume will grow by 1% per year, thus, grow to have an eventual footprint of 348 km^2. For the oil-field, we assume that geophysical surveys are conducted over the entire reservoir area of 360 km^2 during the operational phase of the project. We have also assumed that the closure phase will last significantly longer (50 years) for the saline formation scenario than for the oil field scenario (20 years). This is based on the presumption that the oil field has a well-defined caprock and the caprock has not been compromised during the operational phase of the project, thus leakage through the caprock is highly unlikely. In this case, the 20 year closure period would however provide the opportunity to confirm that the injection wells or other abandoned wells are not leaking. The longer closure period for the saline formation storage may be needed to demonstrate that the caprock is providing an effective seal for retaining the CO_2 in the storage formation. Again, we reiterate that these are hypothetical scenarios, and are not intended to prescribe the appropriate duration of the closure phase for a project. Site specific risks and local regulations will dictate the appropriate length and frequency of monitoring during all phases of a storage project.

MONITORING PACKAGES

The monitoring packages recommended for a particular storage project will depend on site specific objectives. For each of the three scenarios presented here, two different monitoring packages are considered. The first package is called the "basic monitoring package" and is designed primarily to provide assurance that the CO_2 staying within intended the storage formation. The second monitoring package, called the "enhanced monitoring package" which includes groundwater sampling, surface CO_2 flux monitoring and a geophysical monitoring program that includes gravity and electromagnetic measurements. Table 2 lists the components of both monitoring packages.

Both monitoring packages include seismic imaging on a regular basis. Two or three-dimensional seismic imaging of the geologic structure of the proposed storage site will be needed during the pre-operational phase of the project. In the case of the EOR scenario, we assume that this survey has already been done and therefore, need not be done as part of the monitoring program. During operations, it will be used repeatedly to track migration of the plume and detect leakage from the storage formation. The frequency of the surveys should depend on a risk assessment, and for the cases illustrated here, the EOR scenario has surveys at 5, 10, 15 20 and 30 years during the operational phase of the project. In contrast, the saline formation scenarios have more frequent surveys because the storage integrity of the site may not be as well known. In this scenario, repeat seismic surveys are conducted at 1, 2, 5, 10, 15, 20, 25 and 30 years during the operations phase of the project. Obviously, over the course of the project it may be determined that this many surveys are not needed and therefore the program could be curtailed. In the closure phase, seismic surveys will be used to confirm that the CO_2 remains trapped within the storage formation. Both monitoring packages will also include injection rate measurements and wellhead pressure measurements. These are used to verify the quantity of CO_2 that is injected into the storage formation and to ensure that the injection pressure does not exceed a safe threshold. In addition, depending on the well construction, pressure measurements will also be made in the annulus between the injection tubing and the well casing in order to monitor the condition of the injection well. For the enhanced monitoring package, it may be desirable to maintain continuous wellhead pressure monitoring in some fraction of the wells that are not abandoned during the closure phase. Watching the rate at which the pressure changes will provide additional insight into a number of processes, namely, dissipation of the pressure increase by equilibration with the surrounding formations, continued dissolution of CO_2 into the saline water or oil, and potentially, leakage out of the storage reservoir through wells or the caprock. In addition, both packages contain microseismicity monitoring to provide assurance that unsafe microseismic activity is not occurring. A similar philosophy underlies the recommendation that atmospheric CO_2 sensors are located at each injection well to ensure that it is not leaking. Obviously, sub-sea floor storage projects will not include atmospheric monitoring sensors.

TABLE 1: PARAMETERS USED FOR ESTIMATING THE COSTS OF STORAGE FOR EACH OF THE SCENARIOS

Scenario Parameters	**Oil-Field**	**Saline Formation**
Storage Scenario	CO_2 storage combined with enhanced oil recovery	CO_2 storage in a saline formation
Number of Injection Wells	20 injection, 12 production wells distributed evenly over the foot print of the reservoir, based on the Schader Bluff scenario	10 injection wells located within a 10 sq. km area, based on the injectivity of vertical wells in a Frio-like formation with a permeability of 0.5 Darcy
Reservoir Properties	25 m thick, areal extent of 360 km$_2$	100 m thick, 20% porosity, capacity factor of 10%, density of CO_2 at reservoir conditions 800 kg/m$_3$
Operational Period	30 years	30 years
Closure Period	20 years	50 years
Post-Closure	0 years (assume no leakage from the storage formation)	0 years (assume no leakage from the storage formation)
Mass of CO_2 Injected	258 million tonnes CO_2	258 million tonnes CO_2
Frequency of Geophysical Monitoring	5, 10, 20, 30, 40 and 50 years	1, 2, 5, 10, 15, 20, 25, 30, 40, 50, 60, 70 and 80 years
Project foot Print	360 km$_2$ (area of the oil reservoir)	HRG Plume: 19 km$_2$ after the first year, growing to 216 km$_2$ after 80 years LRG Plume: 18 km$_2$ after the first year, growing to 348 km$_2$ after 80 years

For the enhanced monitoring package two additional geophysical monitoring techniques are recommended: gravity and electromagnetic measurements. In addition, periodic well logs are recommended to check the integrity of the injection wells and surface flux monitoring is recommended to provide an extra degree of assurance that the CO_2 is not leaking back into the atmosphere. Spatial and temporal changes in the gravity response can be used to obtain low resolution maps of lateral movement of CO_2 within a formation. Forward and inverse modeling of the gravity data can be constrained by the structural information provided by the seismic data. Gravity data, while having the ability to detect lateral changes associated with plume migration, have very limited ability to map vertical changes. Therefore, while adding to the information provided by seismic imaging, they can not be used to replace it. The second combination, seismic-electromagnetic, has two potential advantages; first the electromagnetic response is directly sensitive to changes in water saturation, and second the spatial resolution of electromagnetic data is superior to gravity data. The direct sensitivity to water saturation is potentially important if geophysics is to be used to quantitatively predict saturation levels in an oil/hydrocarbon gas/CO_2 system where the number of fluid components precludes doing so using seismic alone. In addition, collection of electromagnetic data using grounded electric dipole sources and measuring electric fields can be performed relatively inexpensively provided that a permanent installation of electrodes is done at the start of the project.

The enhanced monitoring package also includes monitoring pressure changes and water quality in a shallower permeable formation above the storage formation. Changes in pressure above the storage formation can be a sensitive indicator of leakage, although other factors such as groundwater pumping and seasonal changes in groundwater elevation may obscure storage-related pressure changes. Periodic water quality sampling can also be used to detect the presence of CO_2. However, siting the observation well at the optimal location for leak detection, based on changes in water quality, is problematic – and for this reason, observation wells are rarely required for liquid waste disposal projects in the U.S. [3].

TABLE 2: COMPONENTS OF THE BASIC AND ENHANCED MONITORING PACKAGES

Basic Monitoring Package	**Enhanced Monitoring Package**
Pre-Operational Monitoring Well Logs Wellhead Pressure Formation Pressure Injection and Production Rate Testing Seismic Survey Atmospheric CO_2 Monitoring	**Pre-Operational Monitoring** Well Logs Wellhead Pressure Formation Pressure Injection and Production Rate Testing Seismic Survey Gravity Survey Electromagnetic Survey Atmospheric CO_2 Monitoring CO_2 Flux Monitoring Pressure and water quality above the storage formation
Operational Monitoring Wellhead Pressure Injection and Production Rates Wellhead Atmospheric CO_2 Monitoring Microseismicity Seismic Surveys	**Operational Monitoring** Well Logs Wellhead Pressure Injection and Production Rates Wellhead Atmospheric CO_2 Monitoring Microseismicity Seismic Survey Gravity Survey Electromagnetic Survey Continuous CO_2 Flux Monitoring at 10 stations Pressure and water quality above the storage formation
Closure Monitoring Seismic Survey	**Closure Monitoring** Seismic Survey Gravity Survey Electromagnetic Survey Continuous CO_2 Flux monitoring at 10 stations Pressure and water quality above the storage formation Wellhead pressure monitoring for 5 years, after which time the wells will be abandoned

LIFE CYCLE MONITORING COSTS

For the oil-field storage scenario, we assume that these monitoring costs are only those over and above what would be done for the enhanced oil recovery operations. Therefore, we assume that it is not necessary to get baseline seismic data, well logs, wellhead pressure, reservoir pressure or well test data. It is also important to recognize that costs of geophysical surveys can vary widely depending on surface terrain and the complexity of the survey. For the electromagnetic and gravity surveys, we have two sets of costs, one based on Texas and one based on costs in Alaska [see reference 1 for detailed cost data]. These may or may not span the range of costs and have been selected based on the availability of information. For this analysis we used the higher estimated costs typical of Alaska. Tables 3 and 4 provide cost estimates for both the basic and enhanced monitoring packages for the scenarios described above based on the cost data for individual techniques provided in Benson et al [1]. For the basic monitoring package, at a discount rate of 10%, costs for each of the scenarios is approximately \$0.05/tonne of CO_2, depending on the scenario. The discounted costs for the enhanced monitoring package range from \$0.075 to \$0.09/tonne. While the overall costs are similar for each of the scenarios, there are some significant differences. First, for the EOR scenario there are more injection wells (22 versus 10 for the saline formation), so measurements that are needed for each well cost more overall. Second, for the EOR scenario, the seismic survey costs more because we assume that the entire oil-field, which occupies a large area, is surveyed on a periodic basis. In contrast, for the saline formation, we assume that early in the life of the project, the much smaller area that underlies the footprint of the plume is surveyed, thus lowering costs significantly. Finally, the cost for monitoring injection and production rates is much higher for the oil-field case because it is necessary to monitor how much CO_2 is coming back to the surface with the produced oil using a gas/oil separator. These higher costs during the operational phase for the EOR scenario are off-set by lower pre-operational phase costs, and because we assume that the post closure period will need to continue for 20 years, in comparison to 50 years for the saline formation scenario. A comparison between the cost of the enhanced and basic monitoring packages shows that the additional information can be obtained at a premium of about \$0.027 to \$0.037 per tonne of CO_2. This may be a small incremental price to pay for the information afforded by these additional measurements. The benefits may very well outweigh the costs when looked at in this light. However, site specific considerations and risks would need to be considered before drawing such a conclusion.

If a storage project is known to leak, post-closure monitoring may be required. Moreover, since monitoring protocols have not been established, some form of post-closure monitoring may required even if leakage has not occurred. To assess the costs of long term monitoring, calculations were made over a 1000 year period for the basic monitoring package (e.g. periodic seismic surveys conducted every ten years). Not unexpectedly, with a discount rate of 10%, there is virtually no change in the cost of the monitoring because the present value of expenditures so far in the future is negligible. However, if an intergenerational discount rate of 1% is used after 30 years, then the discounted cost of the basic monitoring package increases from $0.053 to $0.059 for the saline aquifer scenario. Similar increases (e.g. 10%) are found for the other scenarios. This suggests that increased cost alone is not a major concern with regard to long term monitoring. Perhaps what is of greater significance is the question about who will be responsible for long term monitoring, should it be needed. Is it the government as suggested by Keith and Wilson [2]? Is the company who stored the CO_2? Or is it the field operator? Which institutions will be present and have the authority oversee the results of the monitoring programs? How will financial resources the set aside, reserved and made available for this purpose? Answering these questions and addressing these considerations will require thoughtful analysis and meaningful discussions among government policy makers, the private sector and other interested parties to come to agreement on the best approach.

CONCLUSIONS

For the scenarios examined here, estimated costs for monitoring geologic storage over the full life-cycle of a project at a range from $0.05 to $0.10 per tonne of CO_2 (discounted at 10%/year, undiscounted cost range from $0.16 to $0.31 per tonne). While this is small in comparison to the cost of separation and small even in comparison to long term goals for separation costs, it nevertheless may represent up to $50 to $80 over the life cycle of a typical project. For the basic monitoring package described here, repeated seismic surveys account for more than 50% of the total costs for a typical monitoring program. Therefore, finding ways to reduce the cost of seismic surveys or repeat them less often could considerably lower the overall cost of monitoring. For example, it may be possible to use time-lapse 3-D surveys during the early – confirmatory – stages of a project, but as time goes on, single lines over key features may be sufficient to demonstrate that the project is performing as expected. A comparison between the cost of the enhanced and basic monitoring packages shows that the additional information can be obtained at a premium of about $0.027 to $0.037 per tonne of CO_2. This may be a small incremental price to pay for the information afforded by these additional measurements. The benefits may very well outweigh the costs when looked at in this light. However, site specific considerations and risks would need to be considered before drawing such a conclusion.

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TABLE 3: COSTS FOR THE BASIC MONITORING PACKAGE FOR THE MONITORING
SCENARIOS. NOTE THAT COSTS ARE PRESENTED IN MILLIONS OF U. S.
NOTE THAT THE SUB-TOTAL COSTS,WISE, ALL COSTS ARE IN $MILLION.OF
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	Pre-Operational	Operational	Closure	Total

Monitoring Technique	Well logs	Wellhead Pressure	Formation Pressure	Injection and Production Rate Testing	Seismic Survey	MicroSeismicity Baseline	Baseline Atmospheric CO_2 Monitoring	Management (15%)	Sub-Total, including management@15%	Seismic Survey	Wellhead Pressure	Injection and Production Rates	Wellhead Atmospheric CO_2 Concentration	Micro Seismicity	Management (15%)	Sub-Total, including management@15%	Seismic Survey	Management (15%)	Sub-Total, including management@15%	Total Cost ($ million)	Total Cost at a Discount Rate of 10 %	Million metric tonnes of CO_2	Total cost / CO_2 Tonne ($/Tonne)	Total discounted cost / CO_2 Tonne ($/tonne)
Saline (LRG)	1.1	0.1	0.3	0.6	3.8	0.5	0.1	1.0	7.4	9.5	1.7	3.4	1.8	3.7	3.0	23	16	2.4	18	49	14	258	0.19	0.05
Saline (HRG)	1.1	0.1	0.3	0.6	2.4	0.5	0.1	0.7	5.7	9.5	1.7	3.4	1.8	3.7	3.0	23	12	1.8	14	42	12	258	0.16	0.05
EOR	0.0	0.0	0.0	0.0	0.0	0.5	0.3	0.1	0.9	16	1.5	6.5	2.5	3.7	4.5	34	7.9	1.2	9.1	44	13	258	0.17	0.05

TABLE 4: COSTS FOR THE ENHANCED MONITORING PROGRAM. NOTE THAT THE SUB-TOTAL COSTS INCLUDE THE COST OF THE BASIC MONITORING PROGRAM FROM TABLE 3 UNLESS INDICATED OTHERWISE, ALL COSTS ARE IN MILLIONS OF U.S

	Pre-Operational					Operational						Closure					Total				
Monitoring Technique	Baseline EM Survey	Baeline Gravity Survey	Baseline Atmospheric CO_2 Concentrations	Pressure and water quality above the storage formation	Sub-Total including basic monitoring progam (Table 3)	Casing Integrity Logs	EM Surveys	Gravity Surveys	CO_2 Flux Monitoring	Pressure and water quality above the storage formation	Sub-Total including basic monitoring progam (Table 3)	EM Surveys	Gravity Surveys	CO_2 Flux Monitoring	Pressure and water quality above the storage formation	Sub-Total including basic monitoring progam (Table 3)	Total Cost ($ million)	Total Cost at a Discount Rate of 10 %	Million metric tons of CO_2	Total cost / CO_2 Tonne ($/Tonne)	Total discounted cost / CO_2 Tonne ($/tonne)
Saline (LRG)	0.2	0.2	0.1	1.0	9.8	6.0	0.9	0.9	4.8	0.6	38	1.5	1.5	8.0	1.0	32	81	21	286	0.31	0.08
Saline (HRG)	0.2	0.4	0.1	1.0	8.3	6.0	0.9	0.9	4.8	0.6	38	1.1	1.1	8.0	1.0	27	73	19	286	0.28	0.08
EOR	0.4	0.4	0.3	1.0	3.7	13.2	1.4	1.4	4.8	0.6	59	0.7	0.7	3.2	0.4	15	78	23	286	0.30	0.09