ENHANCE ENERGY CLIVE MMV PLAN

APPENDICES H:

Monitoring Tool Cost Benefit Analysis & Selection

July, 2019

Monitoring technique screening

Technique	Tools	Pros	Cons	Cost	Benefit	Screening Selected Y/N	Notes
ATMOSPHERE					**Benefit**	**Select In?**	
CO_2 detection	Optical (natural or induced light), eddy covariance, tracers (perfluorocarbons)	Can cover large areas. Some techniques relatively inexpensive.	Difficult to distinguish natural from leaking CO2. Natural variability of CO2 concentration due to natural processes. Some techniques may require background levels to be established and/or require off-site analysis of samples due to specialized equipment required (time delay). Tracer may not be carried by CO2 along leakage pathway.	M	L	N	Difficult to attribute.
H2S detection	Sensors/SCADA, personal alarms, odour	H2S sensors will provide continuous electronic monitoring and alarms at injection pads. Operator personal alarms provide continuous, mobile electronic monitoring and alarm as operator performs daily field rounds. Odour can be detected by operators, contractors, public, etc. with no specialized equipment providing widest possible areal coverage. Able to detect small leaks quickly, isolate and repair quickly. Operators are trained and equipped to recognize and respond. Public have been informed and provided contact information to alert Enhance if they notice odour.	Areas outside detector range rely on human detection; potential short time lag.	L	H	Y	H2S detection done as safety measure. No appreciable additional cost involved.
BIOSPHERE							
Ecosystem stress monitoring	Satellite imagery, aerial photography, spectral imagery.	Can cover large areas. Relatively inexpensive. Interpretation can be automated.	Many other factors can cause ecosystem stress. Significant leakage over long time would need to occur to cause changes. Requires ground truthing to calibrate. Vegetation response to CO2 depends on species and CO2 concentration. May miss leak occuring in a small area.	L	L	N	
Soil gas monitoring	Sampling and chemical analysis to detect natural or introduced tracers	Can provide definitive distinction between leakage and natural CO2 if done correctly. Good public assurance tool.	Expensive. Cost limits areal and temporal coverage. Requires specialized expertise to sample, analyze, interpret and attribute.	H	H	Y	Assurance to landowners. Baseline will provide some indications of variability should concerns arise in future.
Surface displacement monitoring	Satellite based radar (SAR/InSAR), tiltmeters (surface or downhole), GPS instruments	Potential application where there are pressure changes in reservoir sufficient to cause detectable volume changes. Satellite systems can cover large areas with high degree of precision. Tiltmeters are high precision instruments that have shown utility in hydraulic fracturing and steam/water injection monitoring. GPS systems have been shown to be capable of detecting millimetre scale displacements.	Other factors (land use, drought/wet conditions, etc.) can complicate interpretation. Clive will operate below pool discovery pressure; little chance of appreciable volume increase in reservoir so therefore no chance of surface displacement due to CO2 plume.	L	L	N	Clive project will operate below original discovery pressure and with minimal pressure increase from current conditions. No significant surface heave would be expected.
HYDROSPHERE							
Dedicated observation well	Well can be equipped with pressure, temperature, TDS and sampling capability.	Pressure, temperature and TDS sensors can provide continuous data feed. Can be located based on geoscience input. Sensors can potentially monitor a number of horizons.	Requires additional land disturbance. Doesn't have continuous drawdown so will not tend to draw leakage towards it. Enhance analysis suggests pressure change due to CO2 leakage into an aquifer would be undetectable for an observation well 200 m away (Appendix I). Expense.	H	L	N	Logging tools could be used diagnostically on existing wells if an issue is suspected.
Landowner well monitoring	Sampling and geochemical and isotopic analysis.	Provide assurance to landowners that their wells are not contaminated due to leaking CO2.	Requires specialized expertise to sample, analyze, interpret and attribute. Subject to well condition and landowner permission.	H	H	Y	Sampling water wells provides assurance to landowners, provides baseline against potential future concerns.
Deeper sampling/monitoring points in CBM horizons.	Sampling and geochemical and isotopic analysis.	CBM wells monitor hydrosphere ~100m below deepest domestic wells. Leaking CO2 would be drawn to wells by pressure draw-down. Wide areal coverage.	Requires cooperation from CBM operator to obtain samples.	M	H	Y	Although CBM production is generally above BGWP, it is well below the deepest domestic water wells so provides early warning of leakage prior to impacts on groundwater being used.
GEOSPHERE							
Dedicated observation well	Well can be equipped with pressure, temperature, TDS and sampling capability and periodically logged with tools that could detect saturation changes.	Pressure, temperature and TDS sensors can provide continuous data feed. Can be located based on geoscience input. Sensors can potentially monitor a number of horizons.	Requires additional land disturbance. Doesn't have continuous drawdown so will not tend to draw leakage towards it. Enhance analysis suggests pressure change due to CO2 leakage into an aquifer would be undetectable for an observation well 200 m away (Appendix I). Expense.	H	L	N	Logging tools could be used diagnostically on existing wells if an issue is suspected.
Injection well monitoring	Injection well monitoring as required by AER D-51 (Class II and III)	D-51 has proven largely effective in ensuring injection well integrity. In addition to cement bond and hydraulic isolation logs, D-51 requires a casing pressure test on initial well completion. Enhance will add continuous annulus and wellhead pressure monitoring on the injectors to provide further safeguards against wellbore failure. Annual packer isolation testing and hydraulic isolation logging every five years will provide ongoing assurance of well integrity.	Hydraulic isolation logging requires a workover on the well that adds cost and risks creating a leakage pathway.	L	H	Y	Regulatory requirement.
Monitor zonally abadoned legacy wells	Operator surveillance, surface casing vent flow (SCVF) testing, casing pressure monitoring.	Focuses monitoring effort at the only potential leak path. Daily operator surveillance can detect leaks through: -H2S odour or personal alarm -audible gas flow -visual shimmer from gas leak -ice fog from gas leak SCVF test can detect extremely small leaks. Casing pressure monitoring can detect leakage of abandonment plugs.	Risk of "false positive" due to CBM gas but lack of H2S and/or isotopic analysis should help distinguish source.	L	H	Y	
Monitor producing Nisku wells .	Production response and fluid analysis.	Nisku wells are directly above the target Leduc (separated by the Ireton shale), are creating pressure drawdown and are routinely monitored and production tested. Along with ongoing fluid sampling and analysis, production data offers an ongoing check on the integrity of the Ireton shale. They offer the deepest possible detection point for containment issues. Using existing wells minimizes further surface disturbance and does not create additional potential leak paths.		L	H	Y	Has a greater chance of detecting leakage pathway due to drawdown and availability of these wells offers the opportunity to add this monitoring at little additional cost or risk.
Monitor suspended Nisku wells.	Pressure surveys.	Nisku wells are directly above the target Leduc (separated by the Ireton shale), are creating pressure drawdown and are routinely monitored and production tested. They offer the deepest possible detection point for containment issues. Using existing wells minimizes further surface disturbance and does not create additional potential leak paths.	Enhance has investigated the potential pressure response of leakage occuring into an aquifer and concluded that it would be extremely difficult to detect such 200m offset to the leakage pathway.	L	L	Y	No response expected unless leakage pathway occurs very close to well but the availability of these wells offers the opportunity to add this monitoring at little additional cost or risk.
Monitor producing Leduc wells.	Production response and fluid analysis.	Using existing wells minimizes further surface disturbance and does not create additional potential leak paths. Production response on these wells will provide additional information regarding CO2 distribution in the Leduc.		L	H	Y	

Monitor suspended Leduc wells.	Pressure surveys.	Using existing wells minimizes further surface disturbance and does not create additional potential leak paths. Pressure data from these wells will help to improve reservoir understanding.		L	H	Y	
Wellbore based fluid monitoring on new production wells.	Production response and fluid analysis.	As practised in CO2 EOR, measurement and analysis of produced fluids provides indications of reservoir response and allows ongoing updates of simulation models.	Geochemistry results may be difficult to interpret due to inherent sampling limitations and complexity of the system.	L	H	Y	Enhance will employ one meter for every two production wells allowing continuous measurement of produced fluid volumes on a well 50% of the time. This is well in excess of regulatory requirements of one 24 hr test/month. **Production wells in the EOR area will have a fluid analysis every 3 months until CO2 breakthrough is seen, then minimum monthly thereafter. Injection and recycle streams will be analyzed monthly at minimum.**
Emerging wellbore tools	Harmonic pulse testing	Harmonic pulse testing uses analysis of pulsed CO2 injection and could provide insights on storage reservoir performance.	Unproven. Analysis difficulties would be compounded by EOR operations.	L	L	N	This is a pressure transient technique, notionally similar to reservoir simulation and best suited to pure storage projects. The tools and data available at Clive offer a much better chance of understanding reservoir performance through simulation.
Emerging wellbore tools	Modular borehole tools	A multi-function tool that combines capabilities of fluid sampling, pressure measurement, temperature and heat pulse decay measurement and geophones for seismic surveys.	Unproven and complex tool requiring a dedicated well. Expense. Fluid sampling requires perforating the casing which increases risk of leakage. Requires additional land disturbance. Doesn't have continuous drawdown so will not tend to draw leakage towards it.	H	L	N	
Emerging wellbore tools	Novel tracers	Perflourocarbon tracers can be used to "dope" injected CO2, are generally not naturally occuring and can be detected at very low concentrations.	Expensive and in and of themselves can be a potent GHG agent (1000's to 10's of thousands higher than CO2).	H	L	N	The presence of H2S in the Clive reservoir provides a natural "doping" agent for injected CO2 that is easily detected.
Reservoir simulation	Geological model of reservoir coupled to history matched reservoir model.	Simulation is done as a means of optimising CO2 EOR response. A collateral benefit is that unexpected and unexplainable deviations from expected response could indicate containment or conformance issues triggering further investigation. The production metering used at Clive will provide timely, high quality data to complement the strength of simulation as a monitoring tool.	Indirect measurement. Small losses may not be immediately detectable.	L	H	Y	
Seismic geophysical methods	Employment of 3D Survey as a Baseline Seismic for contingent Cretaceous reservoir leakage mapping	Thid tool would extend the value of recently purchased 2004 3D survey beyond geological characterisation to serve as a baseline. In the event of a suspected leak into shallow (Cretceous) reservoirs, the baseline will serve to highlight fluid changes in the rocks due to possible CO2 movement. A study conducted by Enhance showed that changes in post Devonian aquifers caused by the emplacement of CO2 (at which depth would be gaseous) would be detectable by comparison of the existing 3D and a new seismic survey, if the need arose.	The process of repeat shoots of seismic to reveal changes in reservoir conditions work best when shot over the same conditions with respect to equipment, spacing etc. As repeat acquisition will be markedly different from baseline, the noise generated by these changes would mask more subtle fluid changes, particularly that of deeper reservoirs in which CO2 is in dense phase and porosity if low. A study conducted by Enhance (Appendix J) showed that changes fluid in the Leduc and Nisku may not be resolvable, although, this is not the case for shallower zones.	H	H	Y	
Seismic geophysical methods	Time Lapse (4D) Seismic Monitoring of Devonian Reservoirs	Time lapse 3D has shown utility in tracking CO2 movement and/or loss of containment when surface and subsurface conditions are suitable.	The depth, low porosity and existing gas saturation at Clive make it a poor candidate for seismic tools as they rely on large changes in seismic velocity due to substitution of less dense CO2 for more dense brine and oil. Time lag; typically best done in winter for access and limit to crop damage meaning best case would be 1X/yr. Expensive and potential for surface disturbance.	H	L	N	Enhance staff have experience from the IEA Weyburn project which suggests that seismic alone could not provide definitive CO2 plume tracking and was best combined with reservoir simulation to constrain the interpretation provided by both methods. The other techniques available at Clive negate the need for this method which is unlikely to provide definitive results. Should loss of containment to a saline aquifer be suspected, 2D or 3D seismic could be shot; the density difference of CO2 vs. salt water in an aquifer should be easily detectable just as seismic is used in exploration to identify gas accumulations.
Seismic geophysical methods	Vertical seismic profile (VSP)	Similar to 3D surface seismic but places geophones in a well with sources on surface. Can provide better vertical resolution of saturation changes between wells in the vicinity of the geophone equipped well.	The depth, low porosity and existing gas saturation at Clive make it a poor candidate for seismic tools as they rely on large changes in seismic velocity due to substitution of less dense CO2 for more dense brine and oil. Time lag; typically best done in winter for access and limit to crop damage meaning best case would be 1X/yr. Expensive and potential for surface disturbance. Interpretation techniques not as well established as for conventional 3D.	H	L	N	Enhance staff have experience from the IEA Weyburn project which suggests that seismic alone could not provide definitive CO2 plume tracking and was best combined with reservoir simulation to constrain the interpretation provided by both methods. The other techniques available at Clive negate the need for this method which is unlikely to provide definitive results. Should loss of containment to a saline aquifer be suspected, 2D or 3D seismic could be shot; the density difference of CO2 vs. salt water in an aquifer should be easily detectable just as seismic is used in exploration to identify gas accumulations.
Seismic geophysical methods	Cross well seismic	Similar to VSP, but places both geophones and sources in wellbores therefore avoiding surface access/disturbance issues. Can provide better vertical resolution of saturation changes between wells in the vicinity of the geophone equipped well.	The depth, low porosity and existing gas saturation at Clive make it a poor candidate for seismic tools as they rely on large changes in seismic velocity due to substitution of less dense CO2 for more dense brine and oil. Expensive to deploy in existing wells or dedicated wells. Placing source in wells limits signal strength to avoid well damage. Interpretation techniques not as well established as for conventional 3D.	H	L	N	Enhance staff have experience from the IEA Weyburn project which suggests that seismic alone could not provide definitive CO2 plume tracking and was best combined with reservoir simulation to constrain the interpretation provided by both methods. The other techniques available at Clive negate the need for this method which is unlikely to provide definitive results. Should loss of containment to a saline aquifer be suspected, 2D or 3D seismic could be shot; the density difference of CO2 vs. salt water in an aquifer should be easily detectable just as seismic is used in exploration to identify gas accumulations.
Seismic geophysical methods	Passive seismic	Uses surface or wellbore deployed geophones to "listen" for micro-seismic activity induced by effective stress changes caused by pressure changes due to CO2 injection. Potential low impact, continuous monitoring technique.	Requires coupled geomechanical-reservoir models for interpretation which are not proven or widely available. Typically requires signficant pressure increase due to injection to trigger micro-seismic events. As Clive will operate below discovery pressure this scenario is unlikely.	M	L	N	Enhance staff have experience from the IEA Weyburn project which suggests that seismic alone could not provide definitive CO2 plume tracking and was best combined with reservoir simulation to constrain the interpretation provided by both methods. The other techniques available at Clive negate the need for this method which is unlikely to provide definitive results. Should loss of containment to a saline aquifer be suspected, 2D or 3D seismic could be shot; the density difference of CO2 vs. salt water in an aquifer should be easily detectable just as seismic is used in exploration to identify gas accumulations.
Gravity methods -direct field measurement -gradient measurement	Gravity field or gradient measurement tools.	Could provide direct CO2 mass measurement where there is a density contrast between the CO2 and the fluid that it is displacing.	Not yet proven. Typically requires detectors to be very close to storage zone which would require deployment in deep wells over a large area.	H	L	N	

Electrical methods -resistance tomography -electromagnetic tomography -controlled source EM		Contrast between brine and CO2 conductivity could be used to map distribution in saline aquifer storage projects.	Oil and gas are also non-conductive. N/A for CO2 EOR projects.	H	L	N	