CARBON CAPTURE AND STORAGE IN BRITISH COLUMBIA

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ABSTRACT

The British Columbia government has implemented ambitious targets to reduce atmospheric discharge of greenhouse gases. One possible mitigation strategy is carbon capture and storage - the collection of carbon dioxide (CO_2) produced at large industrial facilities and its permanent sequestration deep underground in geological rock formations. Large sources of anthropogenic greenhouse gases in BC have been identified and matched where possible with potential storage sites.

Some industries, such as natural gas processing, are well suited for carbon capture because the technology is available with storage opportunities often located reasonably nearby. In northeastern BC, there are a number of large natural-gas processing plants and several commercial-scale sequestration projects and the Western Canada Sedimentary Basin (WCSB) provides suitable porous and permeable reservoirs for CO_2 storage in depleted natural gas pools and deep saline formations.

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INTRODUCTION

Anthropogenic greenhouse gases include CO_2, methane (CH_4), nitrous oxide (N_2O), and various fluorocarbon groups. In BC, CO_2 constitutes 80% of these anthropogenic emissions (Environment Canada 2007). Many scientists consider the significant increase in CO_2 concentration in the atmosphere to be responsible for enhancing the Earth's natural "greenhouse effect" and thus heightening global warming (IPCC 2007).

The Province of British Columbia has introduced legislation setting targets to reduce greenhouse gas emissions by 33% below 2007 levels by 2020, increasing to 80% by 2050. Figure 1 is a simplified illustration of this challenge. The "business as usual" trend could exceed 80 Mt CO_2 equivalent by 2020 if not constrained. The actual emissions level for 2007 is being stringently reviewed to provide a more accurate baseline. The 2007 value estimated in Figure 1 (69.5 Mt CO_2 equivalent) was projected using the most recent data available from Environment Canada (Environment Canada 2007). To achieve these aggressive targets, all available mitigation strategies must be utilized, including conservation, energy efficiency, use of alternative energy sources, and carbon capture and storage.

Carbon Capture and Storage

Carbon capture and storage is a process to reduce the amount of anthropogenic CO_2 emitted into the atmosphere. It entails collecting CO_2 from large industrial sources and permanently storing it deep underground in the pore space of geological rock formations. The first step is to identify major CO_2 sources that are located within approximately 300 km of potential geological storage sites. A concentrated

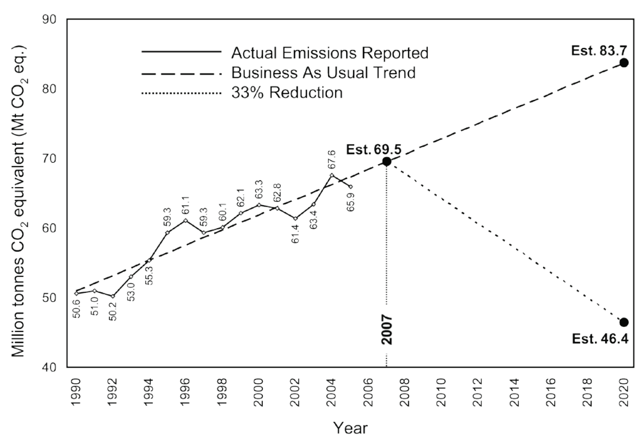


Figure 1: Greenhouse gas emissions in British Columbia (Environment Canada 2007), business as usual trend through 2020 based on historic data, and projection of a 33% reduction in emissions from an estimated 2007 value (69.5 Mt CO_2 equivalent) through 2020.

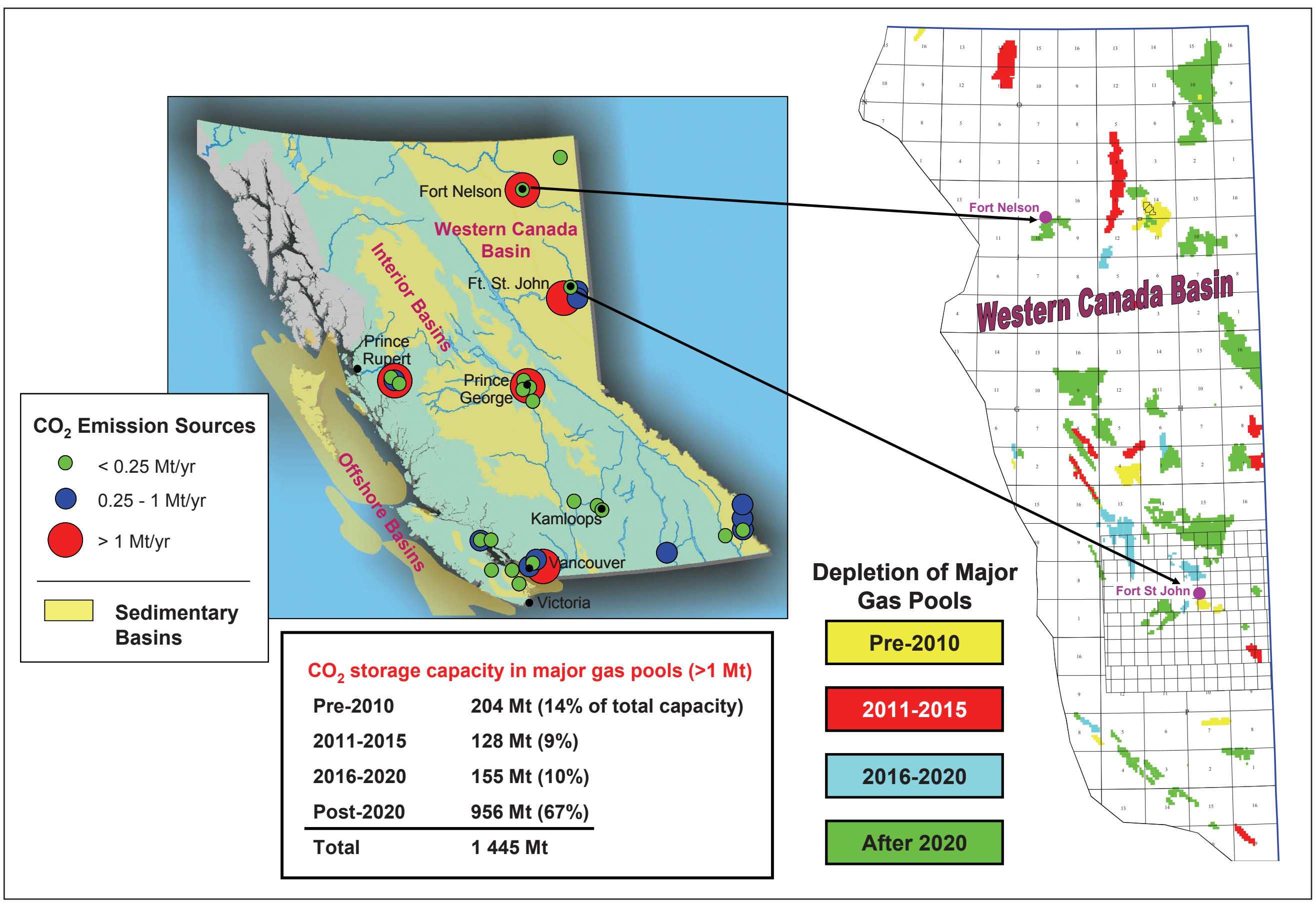
stream of CO_2 is captured at the source and compressed in preparation for transport (generally via pipeline) to a storage facility, where it is injected through a well bore into the pore space of a suitable geological reservoir. The storage reservoir must a) have enough capacity to contain the CO_2 delivered throughout the project life; b) have sufficient permeability to allow injection of CO_2 more-or-less as it arrives on-site; and c) be able to permanently confine the injected gas. The area surrounding the site should be monitored to track CO_2 movement within the geological formation and verify there is no leakage.

Carbon Dioxide

CO_2 under normal surface conditions is a colourless, odourless, non-flammable gas that is denser than air. At elevated pressure and temperature the density increases, reaching a critical point at 7.38 MPa and 31.1 °C, where CO_2 behaves as a dense, supercritical fluid. These conditions are met across much of BC at burial depths below approximately 800 m. The solubility of CO_2 in water increases with pressure (i.e., depth) while decreasing with rising temperature and/or salinity (i.e., depth). These characteristics are important parameters when selecting a storage reservoir. Storage efficiency is significantly improved if this dense, supercritical phase is maintained because more CO_2 can be injected into the rock's pore space. Supercritical CO_2 is less buoyant in formation fluid, thereby migrating more slowly in the subsurface.

SOURCES

All Canadian companies that emit greenhouse gases in excess of 0.1 Mt CO_2 equivalent are required to report the volumes to Environment Canada under the *Canadian Environmental Protection Act, 1999*. In BC, 38 companies filed emission reports for 2006; their emissions totalled 12.3 Mt CO_2 equivalent (Environment Canada 2007) and represented 18.5% of the provincial emissions estimate of 69.5 Mt. Figure 2 shows the locations of these facilities, the relative amounts of CO_2 emitted, and the sedimentary basins found within BC.



CO_2 storage capacity in major gas pools (>1 Mt)

Pre-2010	204 Mt (14% of total capacity)
2011-2015	128 Mt (9%)
2016-2020	155 Mt (10%)
Post-2020	956 Mt (67%)
Total	1 445 Mt

Figure 2: Sedimentary basins, large CO_2 emission sources, and the storage capacity and geographic distribution of depleting gas pools in British Columbia. (Data sources: Environment Canada 2007; Bachu 2006a, 2006b).

Major causes of anthropogenic CO_2 emissions include the combustion of fossil fuels (oil, gas, and coal), industrial processes, such as the "sweetening" of raw natural gas (removal of CO_2 and hydrogen sulphide, H_2S), and deforestation.

CAPTURE

Carbon capture is the collection of a concentrated stream of CO_2 using chemical reactions and/or physical means. CO_2 can be captured in a variety of ways from industrial processes or from combustion of fossil fuels.

Sour gas (greater than 0.5% H_2S) produced from deeper pools in northeastern BC contains varying amounts of naturally occurring CO_2 and H_2S. These impurities must be removed to improve the heating quality of the product and to meet pipeline specifications. Legislation prohibits the release of sulphur into the atmosphere; as a result, either sulphur is stripped out and retained at surface or the H_2S is re-injected underground. Twelve sites have been approved (9 currently active) for acid gas disposal in northeastern BC. Approximately 40 sites are operational in similar settings in Alberta, all of which act as commercial-scale demonstration projects illustrating the feasibility of carbon capture and storage technology.

Flue gas emitted from industrial complexes because of the burning of fossil fuels generally has a low concentration of CO_2, ranging from 5 to 15%. Other constituents, primarily nitrogen, oxygen, and water vapour, are not considered harmful to the environment and do not require abatement measures. It is impractical to capture, compress, transport, and store the entire flue gas stream, so CO_2 must be removed from the flue gas on-site.

There are 3 possible means of capturing CO_2 from flue gas:

- Post-combustion: CO_2 is removed using an amine solvent;
- Pre-combustion: fossil fuel is pre-mixed with steam and oxygen to produce carbon monoxide (CO) and hydrogen (H). The CO is combined with steam resulting in CO_2 (seperated) and H (used as fuel); and
- Oxyfuel combustion: oxygen is used during initial combustion, creating water vapour and CO_2. The water vapour is cooled and condensed, leaving relatively pure CO_2.

Most CO_2 capture technology is available, though presently being applied to other industrial processes or for much smaller-scaled purposes. These CO_2 capture techniques can be more effective when applied to large, fossil fuel-fired industrial facilities, such as power generation plants. If CO_2 can be sequestered, emission levels from such facilities can be drastically reduced. These capture systems and compression necessary for transportation require an estimated 10 to 40% additional fuel consumption but can provide net emission reductions up to 80 to 90%. There are currently no large (500 MW) power plants employing CO_2 capture in the world, though a number are in the planning stage (outside BC).

TRANSPORTATION

Relatively pure CO_2 is compressed into a supercritical state at source in preparation for transportation, usually via pipeline, to a storage site. To minimize metal corrosion, the gas is dehydrated before entering the pipeline. Transportation efficiency is improved by maintaining pipeline pressure above 8 MPa, keeping the CO_2 in its supercritical phase. Upstream compressors provide the drive mechanism, with booster stations installed as needed along the line.

There are several short acid gas (CO_2 + H_2S) pipelines presently active in northeastern BC. There are more than 2 500 km of pipeline in the southern Unites States transporting greater than 45 Mt CO_2/year for enhanced oil recovery (EOR) projects, mainly in Texas. Of note, a 320 km pipeline currently supplies roughly 6 500 tonnes/day CO_2 to an EOR project at Weyburn in southeastern Saskatchewan.

GEOLOGICAL STORAGE

Geological storage requires a porous and permeable reservoir to contain the injected CO_2. The sedimentary rocks most likely to have suitable reservoir characteristics are unique to sedimentary basins, of which there are a number throughout BC (Figure 2). The geological setting of a potential sequestration site must be well understood before its suitability can be determined; the Western Canada Sedimentary Basin in northeastern BC is promising because of the abundant geological data generated by the oil and gas industry.

Potential CO_2 storage reservoirs include depleted oil and gas pools, deep saline formations, unmineable coal beds, salt caverns, and abandoned gas storage facilities. In BC, the most feasible options are depleted gas pools and deep saline formations; these provide a good combination of storage capacity, cost effectiveness, minimal leakage risk, and public acceptance. There are also many existing oil pools at of near depletion that could potentially utilize CO_2 for enhanced oil recovery (EOR), extending their economic life by producing as much as 15% incremental reserves. The reservoirs can be filled with CO_2 prior to decommissioning the EOR project.

Optimal conditions for CO_2 sequestration include:

- Proximity to large CO_2 source
- Existing wells in good condition
- Favourable reservoir characteristics to maximize storage efficiency (capacity and injectivity commensurate with project volumes, reservoir pressure and temperature above CO_2 critical point)
- Very low risk of leakage (stratigraphic isolation/competent seals)
- Minimal risk of contaminating nearby hydrocarbon pools
- Existing regulatory regime
- Expertise, knowledge, and workforce readily available
- Infrastructure available
- Potential for EOR or desulphurization projects to create economic value
- Tectonically stable area

Given these criteria, the best opportunities for early implementation of CO_2 storage exist in the northeast of the province - there are large CO_2 point sources (gas processing plants), and the Western Canada Sedimentary Basin provides ample storage space in gas pools that will be depleting over the next few decades as well as in deep saline formations. Also, there is infrastructure, expertise, a knowledgeable workforce, and existing regulations because of the active oil and gas industry and on-going acid gas re-injection operations.

Bachu (2006a) estimated a CO_2 storage capacity in northeastern BC of 1 935 Mt in 353 existing hydrocarbon pools. Of this volume, 1 440 Mt (approximately 75%) is found in the largest 80 pools, ranging in size from 1 Mt (minimum size considered) to 118 Mt. Virtually all of the capacity will be in depleted gas pools, with a very small contribution from depleted oil pools (5 Mt). The timing of availability for the 80 largest pools is not uniformly distributed, with 67% not accessible until after 2020 (Figure 2). Consequently, deep saline formations will have to be utilized to meet storage requirements in the short to intermediate term.

It is difficult to estimate the potential storage volume of deep saline formations as there is a significant shortage of data necessary for accurate calculation. There are a number of deep saline formations that could bridge the timing and areal distribution gap until more storage is available in depleted gas pools. These saline formations are sufficiently well understood to allow for safe usage. Key parameters such as porosity, permeability, reservoir pressure and temperature, and depth of burial can be obtained from existing well data (petrophysical well logs, core analyses) or estimated using information obtained from nearby hydrocarbon pools or similar formations analysed elsewhere. When assessing the risk of CO_2 leakage, proxy data can be used to better understand cap rock competency and the effect of reservoir heterogeneity on fluid migration.

Bachu (1995, 1997) demonstrated very slow (cm/year) regional-scale hydrodynamic flow up-dip to the northeast (Figure 3) in the BC portion of the Western Canada Sedimentary Basin. The flow is topographically driven from a

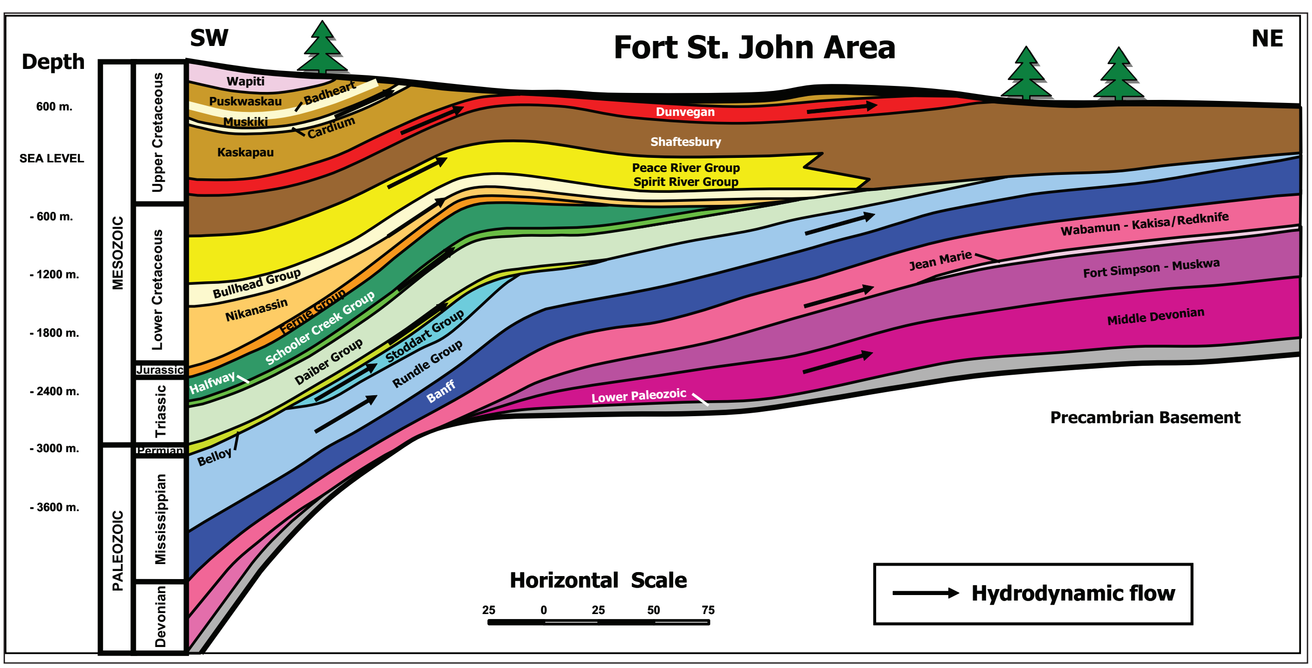


Figure 3: Diagrammatic structural cross-section of geological formations, northeastern British Columbia (modified from BC Ministry of Energy, Mines and Petroleum Resources, Oil and Gas Division 2008).

recharge area in the elevated southwest thrust belt to discharge in the low-lying Great Slave Lake region, Northwest Territories. Supercritical CO_2 injected into a deep saline formation is slightly less dense than formation brine and will gradually migrate up-dip, driven by its buoyant force and the regional hydrodynamic movement.

Optimal conditions must prevail for saline formations to be considered for CO_2 sequestration. There are a number of deep saline formations in northeastern BC with appropriate reservoir characteristics and competent stratigraphic barriers that make them excellent candidates (Table 1).

Any of these deep saline formations could be used for CO_2 sequestration on a site-specific basis, with the likely exception of the Upper Cretaceous. Overall, in the southern half of northeastern BC the Carboniferous-Triassic aquifer has the most beneficial CO_2 storage characteristics, while in the northern area the Lower Devonian aquifer offers the best potential.

Advantages of the Carboniferous-Triassic aquifer in the south:

- porosity developed over large geographic regions (significant capacity available);
- depth of burial often greater than 1 000 m and favourable to maintaining CO_2 as supercritical fluid;
- shallow enough to provide lower drilling, completion and CO_2 compression costs;
- stratigraphically isolated by regionally extensive, thick shales of the Fernie and Banff-Exshaw aquitards.

Advantages of the Devonian aquifer in the north:

- porosity well developed in some areas (need geological/geophysical mapping to establish porosity fairways and estimate capacity);
- depth of burial conducive to maintaining CO_2 as supercritical fluid (often more than 2000 m);
- stratigraphically isolated by areally extensive thick shales of the Banff-Eshaw, Fort Simpson-Waterways, and Chinchaga aquitards;

Physical and geochemical trapping will retain the CO_2 within these geological formations more-or-less permanently. Physical trapping mechanisms include:

- Structural/stratigraphic: containment within naturally formed fluid traps along migration pathway; reservoir heterogeneities form vertical and lateral boundaries that restrict migration rate.
- Hydrodynamic: residual traps form as some of the CO_2 is retained in the pore space by capillary forces; slow migration rate of injected CO_2 (because of buoyancy and hydrodynamic flow) provides more time for geochemical trapping to occur.

Geochemical traps include:

- Solubility trapping: CO_2 dissolves in formation fluid, loses buoyancy, and is carried by the prevailing hydrodynamic flow; CO_2-rich brine may be denser than formation fluid and sink to the base of the storage reservoir.

TABLE 1: CO_2 SEQUESTRATION OPPORTUNITIES IN SALINE FORMATIONS, NORTHEASTERN BRITISH COLUMBIA.

Age	Group/Formation	CO_2 Sequestration Opportunity
Upper Cretaceous	Dunvegan Fm. Cardium Fm.	Generally inadequate depth to maintain optimal reservoir pressure and temperature. Outcropping nearby (increased risk of leakage to surface).
Lower Cretaceous	Paddy/Cadotte Fm. Notikewin/Falher Fm. Bullhead Gp.	Hydrocarbon-rich, especially Deep Basin area (risk of pool contamination). Shale prone and shallow to the north and northeast (poor reservoir development).
Carboniferous-Triassic	Pardonet-Baldonnel, Halfway, Montney, Belloy Fm. Rundle & Stoddart Gp.	Burial depths more-or-less optimal throughout southern area. Strata eroded to the north. Hydrocarbon-rich (risk of pool contamination).
Upper Devonian	Wabamun Gp.	Good reservoir development in southern-most area; very argillaceous in northern portion.
	Jean Marie Fm.	Often shallow in the north (CO_2 in gas phase); large capacity reservoirs.
Lower Devonian	Keg River, Sulphur Point, Slave Point Fm. Pine Point and Elk Point Gp.	Porosity not uniformly developed (site specific—best developed near shelf/reef edges as a result of dolomitization). Optimal reservoir conditions in north; too deeply buried with poor reservoir characteristics in the south. Hydrocarbon-rich in north (risk of pool contamination).

- Mineral trapping (carbonation): stable minerals precipitate as acidic, CO_2-rich water interacts with formation fluids and rock.
- Adsorption trapping: CO_2 is preferentially adsorbed by organic matter present in the formation (may include coal and organic-rich shales).

MONITORING AND VERIFICATION

Monitoring provides a means for tracking movement of CO_2 in the subsurface. The goals of a monitoring program include a) early detection of CO_2 escaping from the storage reservoir (identifies a possible need for remedial work); b) ensuring public safety and environmental protection at or near surface; and c) verifying that CO_2 is being retained. Monitoring is required to comply with government regulations in BC. It may also play a vital role in establishing liability for damages incurred as a result of leakage or for verification of permanent storage associated with the trading of carbon credits.

A monitoring program begins with a reservoir simulation model run before start-up. This establishes an area of interest surrounding the storage site by identifying most likely CO_2 migration pathways. Various methods and tools can be utilized to track subsurface movement, including:

- Seismic surveys: imaging the subsurface movement of CO_2 using standard 2D, 3D, or 4D seismic techniques; cross-well bore vertical profiling to track CO_2 movement between injection and observation wells.
- Atmospheric, soil, and groundwater sampling: direct measurement using existing sampling methods and tools to identify escaping CO_2 at or near surface (tracer minerals mixed with the CO_2 can improve resolution).
- Reservoir pressure and temperature measurements: indirect means of tracking CO_2 between injection and observation wells within the storage reservoir or into overlying formations.
- Well bore fluid sampling: direct measurement of CO_2 content in fluid samples collected from observation wells, including samples from overlying formations.
- Passive geophysical: standard electromagnetic and gravity surveys to image CO_2 movement.

RISK

The primary risk associated with CO_2 sequestration is leakage from the storage reservoir. Also, CO_2 escaping to surface may adversely affect human health or the environment, and encroachment of CO_2 into adjacent stratigraphic zones can result in contamination of commercial assets such as hydrocarbon pools or gas storage facilities.

The risk of CO_2 leaking from an appropriately selected storage site is minimal. Secure confinement is ensured by the interplay between physical and geochemical trapping mechanisms, the stratigraphic isolation of storage reservoirs by thick aquitards and by a rigorous inspection of the integrity of nearby well bores that may become exposed to migrating CO_2. The most likely leakage pathways are identified in the initial design, and monitoring of the site provides for early detection of escaping CO_2. Remedial work can rectify breaches.

Many geotechnical factors provide a high level of confidence in the safety of CO_2 storage in northeastern BC:

- Potential storage reservoirs are isolated from surface and other stratigraphic zones by competent seals provided by thick aquitards (shale and evaporate deposits).
- The slow-moving regional hydrodynamic system allows time for CO_2 to dissolve in formation water or precipitate as stable minerals.
- The tortuous path created by the regional geology and hydrology significantly impairs upward movement.
- Dense, supercritical CO_2 has relatively little buoyancy in formation water.

The most significant risk of leakage is from existing well bores, which may provide conduits to surface. The integrity of the cement and metal casings in existing wells must be ensured prior to injection and monitored for degradation as the casings are exposed to newly formed acidic CO_2-rich formation fluid.

CONCLUSION

Northeastern BC has significant geological CO_2 sequestration potential in depleted gas pools and deep saline formations. The storage space in depleted gas pools cannot be realized until production operations more-or-less cease (estimated to be decades away). Deep saline formations can be utilized to bridge the timing gap for short- to intermediate-term requirements. The technology, expertise, regulatory regime, and infrastructure are in place. The risk to human health, safety, and the environment is low.

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