

**SOLUTION MINING
RESEARCH INSTITUTE**

3336 Lone Hill Lane
Encinitas, California 92024, USA

Telephone: 858-759-7532 ♦ Fax: 858-759-7542
www.solutionmining.org ♦ smri@solutionmining.org

**Technical
Paper**



**Carbon Dioxide Sequestration Potential in
Salt Solution Caverns in Alberta, Canada**

Maurice B. Dusseault

PRISM Production Technologies & University of Waterloo
Waterloo, Ontario, Canada

Stefan Bachu

Alberta Geological Survey, Div. of the Energy Conservation Board
Edmonton, Alberta, Canada

Brett C. Davidson

PRISM Production Technologies
Edmonton, Alberta, Canada

**Fall 2001 Meeting
7 – 10 October 2001
Albuquerque, New Mexico, USA**

Solution Mining Research Institute, Fall 2001 Technical Meeting
Albuquerque, New Mexico, USA, October 8-9-10

Carbon Dioxide Sequestration Potential in Salt Solution Caverns in Alberta, Canada

Maurice B. Dusseault, PRISM Production Technologies Inc. and Department of
Earth Sciences, University of Waterloo, Waterloo, ON, N2L 3G1, CANADA

Stefan Bachu, Alberta Geological Survey, Division of the Energy Conservation Board
4th Floor - Twin Atria, 4999 -98 Ave, Edmonton, AB, T6B 2X3, CANADA

Brett C. Davidson, PRISM Production Technologies Inc.
#207 – 11434 - 168 St, Edmonton, AB, T5M 3T9, CANADA

Abstract

Anthropogenic effects on climate can be mitigated through various measures, among them being CO₂ sequestration in geological media. Geological sinks for CO₂ do not need any major new technological development; the technology exists and has been applied for other uses. The challenge is rather to identify the most appropriate methods and sites for long-term sequestration. There are several potential methods for CO₂ sequestration using geological media: utilization in enhanced oil and gas recovery, injection in depleted oil and gas reservoirs, displacement of methane in coal beds, injection in deep saline aquifers, and storage in salt caverns.

Although perhaps of low priority among carbon sequestration schemes, salt caverns may be suitable permanent (>1000 yr) or temporary (decades) repositories for CO₂ separated from flue gases or from other major point sources. Despite the cost and other potential environmental issues associated with cavern mining, the advantages of salt caverns are high capacity, high filling rate, the potential economic value of leached brine, and the local potential for CO₂ sequestration sites in areas where other sequestration options are problematic. Intact halite is impermeable to supercritical CO₂ and, as slow closure takes place because of the time-dependent behavior of halite, the pressure in the cavern will likely asymptotically approach the isotropic stress state in the salt. If a cavern leaks, possibly around the injection well, there are mitigating factors that will most likely preempt massive CO₂ release into the atmosphere. Overlying salts and horizontal shale aquitards should stop upward migration of CO₂, while overlying saline aquifers should trap the CO₂. A layer-cake type of stratigraphy and the absence of tectonic activity in bedded salt deposits greatly enhance the retardation ability of these strata against any potential leak.

Alberta, the province with the largest CO₂ emissions in Canada, has massive bedded salt resources in an area where there are significant current emissions from heavy oil operations, where additional development is proceeding rapidly, and where other geological means for geological CO₂ sequestration are absent or of low quality. These salt beds are currently used for LPG and refined product storage in central Alberta, as well as brine recovery and non-hazardous oilfield waste placement elsewhere in eastern Alberta, and they have the potential to be used for other storage purposes (natural gas, heavy oil, excess process coke or biosolids waste). The characteristics of the Lotsberg Salt and Prairie Evaporite in Alberta are presented in the context of possible use for CO₂ sequestration.

1 Introduction

1.1 Anthropogenic Atmospheric Effects and Mitigation Options

Human activity since the industrial revolution has had the effect of increasing atmospheric concentrations of gases with a greenhouse effect, leading to climate warming and weather changes (Bryant, 1997). Of greenhouse gases, CO₂ is by far the most important, being responsible for about 64% of the enhanced “greenhouse effect” (Bryant, 1997). Given their inherent advantages, such as availability, competitive cost, ease of transport and storage, and large resources, fossil fuels which today provide about 75% of the world’s energy are likely to continue to remain the major component of world’s energy supply for at least this century (Bajura, 2001). Thus, the world, including Canada and the US, has an interest in reducing CO₂ emissions into the atmosphere while at the same time ensuring sustainable economic development.

Mitigation of human-induced climate change involves basically three approaches: conservation, substitution and sequestration. The first approach is to increase primary energy conversion and end use efficiency so that fewer energy units are required to provide the same or a suitable alternate service. The second approach is to substitute lower carbon content (e.g. CH₄ for coal) or carbon-free (wind, solar...) energy sources. The third approach is carbon sequestration; keeping anthropogenic carbon from reaching the atmosphere by capture, isolation and storage, or by direct removal of CO₂ from the atmosphere. Any such sequestration system must of course be safe, environmentally benign, effective, economical and socially acceptable.

Large CO₂ sinks are terrestrial ecosystems (soils and vegetation), oceans and geological media, with retention times of the order of 10-10⁵ years, respectively (Gunter *et al.*, 1998). Terrestrial ecosystems represent a diffuse natural carbon sink that captures CO₂ from the atmosphere after release from various sources. The oceans represent possibly the largest potential global sink, but ocean disposal involves issues of poorly understood physical and chemical processes, sequestration efficiency, cost, technical feasibility and environmental impact (Herzog *et al.*, 1997). For landlocked regions, such as the North American mid-continent, ocean disposal is not an option. Biomass fixation of CO₂ is an option for the mid-term reduction of CO₂ emissions, but issues of practicality, uncertainty and cost make this an improbable solution as yet (Herzog *et al.*, 1997). On the other hand, as a result of technology and practices developed in other industrial sectors, carbon or CO₂ sequestration in geological media is an immediately available option.

For example, deep well drilling and hydraulic fracturing technology from the petroleum industry make direct biosolids slurry injection feasible. An aqueous biosolids slurry (municipal biosolids waste, animal feedlot biosolids, waste sawdust and other organic materials) is placed into suitable geological strata through high-pressure continuous hydraulic fracturing, with good environmental security and potential cost benefits. Acid gas (a mixture of CO₂ and H₂S) is currently injected into deep geological formations at more than 50 sites in western Canada and US. Similarly, all geological C or CO₂ sequestration methods rely on various petroleum industry developments, and issues of fate can be addressed with the geological and hydrogeological scientific and technical advances that the petroleum industry has generated.

If the sequestration process involves molecular CO₂, various physical properties and other criteria play a role in the selection of the appropriate means and sites for geological media storage (Bachu, 2000; 2001a,b). Depending on *in situ* temperature and pressure and other characteristics, CO₂ can be stored through several mechanisms in geological media as a gas, a liquid, or in a supercritical state (Bachu 2001a, Figure 1) by:

- a) Trapping in depleted hydrocarbon reservoirs and other stratigraphic and structural traps;
- b) Solubility trapping in oil reservoirs (enhanced oil recovery) and in deep aquifer brines;
- c) Hydrodynamic trapping in regional-scale aquifers;
- d) Mineral trapping through carbonate precipitation;

- e) Adsorption trapping onto the coal matrix in uneconomic coal beds and in enhanced coalbed methane recovery; and
- f) Cavern trapping in dissolved salt caverns.

The method of geological storage, available volumes and retention time depend on media characteristics and *in situ* conditions (Bachu, 2000). These factors have a direct role in the identification of potential sites for CO₂ sequestration.

Fossil fuels are fortuitously linked with sedimentary basins in which CO₂ can be sequestered (Hitchon *et al.*, 1999). The Alberta basin is no exception, being rich in conventional oil and gas, heavy oil and oil sands, coal and coalbed methane, and salts (Bachu and Gunter, 1999). Most anthropogenic CO₂ emissions in the Alberta basin come from large point sources associated with power generation from fossil fuels and large industrial processes such as refineries and heavy oil upgraders, steel and cement furnaces, and petrochemical manufacture. CO₂ separated from flue gases, effluents, and during fuel-decarbonization processes could be captured and concentrated into a liquid or gas stream, pipelined, and injected into deep geological formations. Generally, the Alberta basin is suitable for CO₂ sequestration by all methods because it is tectonically stable, it has regional-scale aquifers confined by aquitards or aquicludes, it has oil and gas reservoirs in various stages of depletion, it has uneconomic or CH₄-bearing coal seams, and it has extensive salt beds (Bachu and Gunter, 1999). Various basin regions have different degrees of suitability for CO₂ sequestration that range from extremely suitable in southwestern and central Alberta to not suitable along the shallow eastern edge of the basin (Bachu and Stewart, 2002). The Athabasca and Cold Lake areas in northeastern and eastern Alberta, where current and planned oil sands and heavy oil plants will soon produce > 21 Mt CO₂/yr, are situated in a region not suitable for CO₂ sequestration, except, possibly, for storage in deep caverns mined in the thick and extensive salt beds that underlie the region (Bachu and Stewart, 2002).

1.2 Why Salt Caverns?

Whereas it is unlikely that salt cavern placement could acquire a priority sequestration position such as CO₂ injection for oil and gas recovery, cavern placement may be attractive for several reasons:

- The cavern can be dissolved for sales brine production. Sequestration is thus free of a large capital expenditure, as the facilities can handle CO₂ placement once brining ceases.
- Pure salt is essentially impermeable (<10⁻¹⁹ m²). Also, bounding strata usually have pores plugged by crystalline salt for some distance beyond the massive salt bed. This reduces risk of CO₂ escape through porous media, leaving only the wellbore and the possibility of roof rock fracturing as possible leakage paths from the cavern.
- Salt is naturally self-sealing by virtue of creep behavior. Fissures or fractures created by drilling and dissolution processes will heal and a sound permeability seal will be re-established in a relatively short time frame.
- In some environments (e.g. east-central Alberta), salt strata can provide storage sites where other suitable unfractured geological sites are not easily found.
- CO₂ can be stored in relatively shallow, cool salt caverns in supercritical form, allowing a far more concentrated storage capacity than storing CO₂ in solution, as a free gas, or through adsorption onto a substrate with micro-porosity, such as coal or oil shale.
- The rate of filling or emptying of salt caverns is not limited by porous media flow capabilities, only by the flow capacity of the tubular delivery system.
- The CO₂ can be quickly accessed and is available in pure form at any future time.
- Even if slow leakage occurs, there are several security mechanisms through which the CO₂ will be retained at depth in the geological media and not enter the atmosphere suddenly.

Clearly, CO₂ storage in salt caverns could also be used for temporary large volume storage (scale of months to decades) with rapid storativity to serve as a useful buffer for other, slower

geological sequestration technologies, helping to dampen out variations in annual supply (e.g.: from thermal energy power plants that may operate at different rates throughout the year).

Thus, salt caverns may have a useful role to play, and this merits further study of the option. In this context, this article focuses on broad qualitative issues of CO₂ sequestration in salt caverns, and also on the salt deposits of east-central Alberta as potential repository strata. We also note that the geological and geomechanical observations that are made may have some value in assessment of caverns for other uses.

1.3 Salt Caverns for Carbon Sequestration in Alberta

Caverns dissolved in salt have been used for decades to store hydrocarbons (oil, natural gas, ethane, propane...) and non-aqueous fluid products (e.g. ethylene glycol); a number of caverns in the Lotsberg Salt in central Alberta provide storage capacity to the local high concentration of chemical plants. Several old dissolved cavern sites have in the last few years have been converted to disposal of non-hazardous oilfield wastes (Hughenden and Lindbergh in Alberta; Unity in Saskatchewan). Also, new caverns have been created specifically for waste disposal (Husky Oil at Lloydminster on the Alberta-Saskatchewan boundary).

It is also possible to sequester and store carbon permanently in caverns in the form of materials such as process coke. Massive amounts of coke are produced by heavy oil and bitumen upgrading facilities, and upgrading processes could be modified to produce even more coke and use less CH₄ for hydrogenation. It is technologically simple to grind coke and pipeline it to salt caverns and place it as thick aqueous slurry. The coke will settle out, the cavern could be filled with coke, and the aqueous phase could even be largely displaced by CO₂ injection (coke should be an excellent adsorber of CO₂), thereby increasing the unit volume carbon storativity of the facility. This option could be interesting in the context of the rapid heavy oil and tar sand development taking place in Alberta at the present time.

In the case of CO₂ sequestration, eventual fate is important. Technical issues that arise if gas is stored in salt caverns are related to both short-term and long-term fate as the salt cavern slowly experiences closure. The fluid pressure will eventually rise well above the pore pressure in surrounding rocks, and if there is a leakage path, CO₂ will seep into surrounding rocks. However, even this does not “invalidate” CO₂ sequestration in salt caverns because any escaping CO₂ will likely be trapped or absorbed into the formation waters in the strata above the cavern.

Figure 2 shows a possible cavern cross-section. The design rationale must of course correspond to “best-possible-practice”, given the cavern purpose, and optimum cavern parameters and location in the stratigraphic sequence would be site-specific.

2 Alberta Salt Deposits

Salt strata in Alberta are particularly suitable for CO₂ sequestration for a number of reasons:

- There are two major salt deposits (Lotsberg Salt and Prairie Evaporite sequences) that contain beds of sufficient thickness (up to 200 m) and purity to permit the construction of suitable caverns at optimum geometries.
- Suitable salt strata in Alberta underlie or are close to major point sources of CO₂ (oil sand plants, coal thermal power plants, heavy oil upgrading plants). The number of CO₂ and coke point sources in the region is certain to increase.
- The strata are at relatively low temperatures (30-45°C) for the depth of burial (hence better storage capacity), there are no overpressured regions, no areas of strong formation water flow, and very few negative structural features (faults or folds) of any magnitude.

The only significant structural feature that must be kept in mind in any salt cavern utilization scheme in Alberta is the presence of the solution front in the Prairie Evaporites toward the eastern edge of the sedimentary basin.

2.1 Geology and Geography of Alberta Halite Deposits

The Alberta basin, located in western Canada on a stable Precambrian platform, is bounded by the Foothills thrust and fold belt and Rocky Mountains to the west and southwest, the Tathlina high to the north, the Canadian Precambrian Shield to the northeast, and the Williston basin to the east and southeast (Figure 3a). The basin consists of a layer-cake wedge of sedimentary rocks that increases in thickness from zero at the Canadian Shield in the northeast to close to 6000 m in the southwest at the thrust and fold belt (Figure 3b). The Cambrian to Lower Jurassic succession was deposited during the passive-margin stage of basin evolution and comprises Cambrian age siliciclastics, evaporites of the Middle Devonian Elk Point Group, and Middle-Upper Devonian shallow-water carbonates with a few intervening shales (Porter *et al.* 1982). The Upper Jurassic to Tertiary strata consist of a succession of regional-scale thin sandstones and thick shales deposited during the foreland stage of basin evolution. Because of basement tilting and significant pre-Cretaceous erosion, successively older strata subcrop from west to east below the Cretaceous Mannville Group. All Cretaceous strata crop out beneath a veneer of unconsolidated Quaternary sediments resulting from Tertiary to Recent erosion and deposition since the peak of the Laramide orogeny that led to the beginning of the Rocky Mountain uplift and permanent retreat of the epicontinental seas ~65 Ma ago. A veneer of glacial sediments of Pleistocene age overlies all areas, averaging in thickness perhaps 100 m, but locally varying from a few to more than 300 m.

Four major, extensive salt-bearing units, deposited in a restricted marine environment during the Middle Devonian, are present in the Alberta basin at depths varying from ~200 m at the shallow NE basin edge to >2100 m downdip in the SW (Figure 3). These units are, in ascending order the Lower and Upper Lotsberg salts, the Cold Lake Formation, and the Prairie Formation, all in the Elk Point Group. Their areal distributions and position in the stratigraphic succession are shown in Figure 3, and a “typical” log signature from the Cold Lake area is shown in Figure 4. The Lotsberg and Cold Lake salts are separated by red beds and argillaceous carbonate rocks (Figure 4). The Prairie salt is underlain by the Keg River carbonate rocks, and overlain by the shale beds of the Watt Mountain Formation (Figure 4). The salt beds are overlain by an Upper Devonian carbonate-dominated succession, eroded at the sub-Cretaceous unconformity, and by a Cretaceous siliciclastic shale-dominated succession.

Salt is solution-mined from the halite beds at various locations in the Alberta basin for domestic and petrochemical use, and salt caverns are presently used for the storage of liquid petroleum products (Figure 3a) and for waste placement.

The salt in the Lower and Upper Lotsberg salts is of very high purity (greater than 90%). The Lower Lotsberg salt is found at depths ranging from 2100 m in the west to 1100 m in the east, and reaches 60 m thickness at the evaporitic basin depocentre. Intervening red beds thickness between the Lower and Upper Lotsberg salts varies between approximately 30 and 65 m. The Upper Lotsberg salt is found at depths ranging from 2100 m in the west to 500 m in the northeast and reaches more than 150 m in thickness. The salts of the Cold Lake Formation are located in two areas in east-central and in northern Alberta (Figure 3a). The southern salt bed is found at depths ranging from 1600 m in the southwest to less than 600 m in the northeast, and reaches 60 m in thickness.

The Prairie Formation is found throughout the eastern part of the Alberta Basin (Figure 3a) and extends into the Williston basin to the southeast into Saskatchewan and the US. To the north, the halite (salt) of the Prairie Formation changes into anhydrite of the Muskeg Formation. During basin history, fresh meteoric water dissolved and carried away the salt along the eastern boundary of Prairie evaporite, forming a southeast-trending salt-dissolution edge and a salt escarpment along the eastern boundary. Unlike the Lotsberg and Cold Lake Formations, the salt content and purity in this formation are highly variable, decreasing from greater than 90% along the northeastern dissolution edge to less than 20 per cent along the western depositional edge. Depth to the top of the Prairie Formation in the area where the salt content is between 40 and 90 per cent

ranges from 2200 m in the southwest to 200 m in the northeast. Thickness of the formation in the same area varies from less than 25 m in the south-southwest, where the salt content is low, to greater than 275 m in the north near the salt-dissolution edge. The thickness of the Prairie Formation decreases rapidly to zero along the salt escarpment. In addition, the strata above the region from which the salt was dissolved are highly permeable because of collapse and distortion, causing extensive regions of open joints hydraulically connected at distance with low-elevation valleys.

2.2 *In Situ* Conditions

The stress regime in the salt beds was evaluated using well density logs. Vertical stress gradients at the top and bottom of the salt beds are in the 21 to 24 kPa/m range, and differ by only 0.1-0.3 kPa/m between the two, indicating that, basically, they are constant across the entire rock package containing the salts. The vertical stress induced by the weight of the overburden varies between <8 MPa at the top of the Prairie salt at its shallowest in the northeast, and >50 MPa at the top of the Prairie salt at its deepest in the southwest, where the other salt beds are absent. For the more areally-restricted but purer Lotsberg salts, vertical stresses vary between >10 MPa at the extreme northeast corner of the Upper Lotsberg salt, and >45 MPa at the deep top of the Lower Lotsberg salt in the southwest. The average minimum horizontal stress orientation determined from borehole breakouts in the overlying carbonate and shale strata is $283^{\circ} \pm 13^{\circ}$. (A reasonable approximation of the principal stress directions is that they are parallel and perpendicular to the deformation front east of the Rocky Mountains.) As usual, it is assumed that within the salt strata the stresses are isotropic and equal to the overburden (lithostatic) because slow creep tends to dissipate shear stresses over times of several hundred years (rate depending on depth and temperature).

Geothermal gradients in the area vary within a 20-30°C/km range (Bachu and Burwash, 1991). Accordingly, temperature in the salt beds varies from ~10°C at the top of Prairie Formation in the NE, to ~50°C at the top of Lower Lotsberg and Prairie salts in the SW.

3 Hypothesized Long-Term Cavern Behavior

A “type” case chosen for study would likely be a cavern 1250 m deep at a temperature of 35°C, in the (Lower) Lotsberg salt (Figure 4), approximately in the depocentre area where the salt is thick and of high purity with few interbeds. The Lotsberg salt in some areas is particularly interesting because it has a reasonably competent roof beam of shale, carbonate and anhydrite about 30 m thick, which is in turn overlain by another salt stratum of regional extent. This undeformed sequence will lead to excellent roof conditions because strain in the roof can be accommodated by viscous deformation of the overlying “barrier salt” without risk of fracture and gas escape. Furthermore, this means that local (wellbore scale) and regional (formational scale) permeability seals should remain intact and even be enhanced through the slow creep distortion of the overburden salt.

3.1 Cavern Design Concept

A 75 m vertical extent for an axisymmetric cavern with a width to height ratio of ~1.33:1 will have a working volume of about 150,000 to 200,000 m³, depending on the geometric details and the insolubles ratio (Figure 2). Some of the design principles are outlined here; in general, these principles are well understood in salt cavern design.

The optimum shape of the cavern is approximately that of an ellipsoid of revolution with a vertical axis. This geometrical shape allows *in situ* stresses to redistribute “smoothly” around the cavern. Because the salt material that lies within the ellipsoidal boundary does not contribute to the structural integrity of the cavern, there is an incentive to maximize the working volume during cavern construction by approaching the “ideal” smooth shape. This concept conforms to the

“equivalent opening” idea that was alluded to by Barr (1977), formalized by Mraz (e.g. Mraz *et al.* 1991; Dusseault and Fordham, 1994), and confirmed by more recent measurements and modeling (e.g. Munson *et al.*, 1997).

Given that the Lotsberg salt is relatively pure and thick, allowance for intact salt security zones above and below the cavern (~20 m) to provide security against leakage is feasible while retaining sufficient volume capacity to make cavern storage viable.

3.2 Roof Beam Integrity in the Short Term and Long Term

There are two factors related to the integrity of the roof slab: its stability against collapse, and its permeability integrity. Both have short and long term behavioral aspects, but short-term collapse and long-term flow integrity are the major issues.

The shape of the upper part of the cavern (Figure 2) is designed to generate better roof beam support so that collapse of the beam is not a concern (Bauer *et al.*, 1998, Rothenberg *et al.*, 1999a). Roof beam stability is not considered to be in any way an impediment to design of sequestration caverns, given what has been learned over the last 20-30 years of salt cavern use. Because a sequestration cavern will not be pressure cycled, because the internal pressure will slowly approach lithostatic, and because the pressure gradient is strongly outward, roof fall should not be an issue if the overall closure strains are modest.

If long-term closure of a cavern is appreciable, it may be impossible to retain the permeability integrity of a roof beam that is undergoing flexure if this material is a non-viscous geomaterial (shale, anhydrite, limestone). Even if all the salt is deforming viscously, the non-creeping interbeds and roof rocks cannot conform to the flow of the salt, and must bend and fracture where extensional strains develop, even if they remain structurally stable. Extensional strains arise during slow roof beam bending and the joints and fissures that are opened lead to a massive gain in permeability, even if the pore space was initially occluded by salt (as is often the case in bounding strata in bedded salts). This makes a lithostratigraphic sequence such as Figure 4 of particular interest, as creep in the barrier salt will always be fast enough to eliminate fracture and fissure development in the salt. This is also the reason to leave roof and floor salt security zones: as long as these can remain under compressive stress indefinitely, they will behave in a viscous manner to retain flow seal characteristics.

3.3 Carbon Dioxide as a Supercritical Fluid

Under normal atmospheric conditions, CO₂ is a thermodynamically stable gas that is heavier than air. At temperatures greater than 31.1°C and pressures greater than 7.38 MPa (critical point), CO₂ is in a supercritical state (Figure 5a); it still behaves like a gas by filling all the available volume, but has a “liquid” density that increases, depending on pressure and temperature, from 200 to 900 kg/m³ (Figure 5b) (Holloway and Savage, 1993; Hendriks and Blok, 1993). Note that if one assumes isothermal conditions over the long-term, the slope of the pressure-density relationship defines the compressibility of the supercritical fluid, and the volumetric closure potential of a non-leaking cavern at a particular depth can thus be calculated.

For conditions below the critical point, CO₂ is either a gas or a liquid, depending on temperature and pressure (Figure 5a). Thus, depending on the *in situ* temperature and pressure, CO₂ can be stored in salt caverns as a **compressed gas**, as a **liquid**, or in **supercritical state**. Storing CO₂ as a gas is inefficient because the mass of stored CO₂ would be small, but storing CO₂ as a liquid or in supercritical state may help realize sequestration opportunities.

3.4 Asymptotic Pressurization of the Cavern (Figure 6)

Long-term pressurization of a CO₂ sequestration cavern is perhaps the major issue to be addressed, and is undoubtedly one of the most challenging because of the need to make predictions for a distant future. In any diffusion process (flow, salt creep...), the precision of

long-term predictions becomes problematic as small discrepancies in parameter choices can lead to large differences after long times. This is an issue to be addressed in great detail in the future.

There are apparently five possible reasons for long-term pressure changes in a cavern (Bérest *et al.*, 2000):

- a) Salt creep;
- b) Thermal expansion of the cavern fluid;
- c) Transport of the fluid out of the cavern into surrounding porous strata;
- d) Leakage along the well path; and,
- e) Additional dissolution and precipitation of the salt in the cavern (e.g., driven by temperature differences and convection currents in a cavern).

Salt creep is clearly the dominant process and will be the focus of further study. Because of its intermediate compressibility, the gradual pressurization of CO₂ in a supercritical state will be much slower than for a liquid (e.g. Ehrgartner and Linn, 1994), but faster than for a gas such as methane. Because large cavern closure strains lead to substantial flexure of the overburden strata, which in turn could substantially increase their permeability, it seems that cavern filling to a pressure just below lithostatic before cavern sealing is a means of restricting excessive strains, perhaps indefinitely if the cavern does not leak. This is a key aspect for sequestration design.

Bérest *et al.* (2000) show that thermoelastic expansion from slow heating of brine in a salt cavern has a much more important effect on cavern pressure increase than creep itself. Bérest's analysis of creep effects alone shows that cavern pressure approaches lithostatic only asymptotically if creep is the only process (i.e. no leakage). Because supercritical CO₂ is highly compressible compared to brine, thermal expansion is not relevant except if the fluid is placed in a cold (liquid) state and then is heated *in situ* during cavern filling, and if the placement pressure is already close to the lithostatic value. In general, cold placement (Schalge and Swartz, 1998) is not advocated.

Porous media flow of supercritical CO₂ and leakage along the well path are possible mechanisms for pressure change, and are revisited in Section 4. It should be mentioned that, as pressures asymptotically approach lithostatic, local pressure gradients become quite large.

Can salt surrounding a supercritical CO₂ storage cavern undergo mass transfer through the effects of solution/precipitation combined with slow convective fluid flow under a thermal gradient? In a brine-filled cavern of great vertical extent, e.g. up to 600 m high in the American Strategic Petroleum Reserve in domal salts, slow downward growth can take place because salt solubility is fractionally higher at the base; the thermal gradients generate slow convection currents causing salt deposition at the top of the cavern. Although this is irrelevant in the time frame of a conventional cavern, at the +1000 year time frame, it could be of interest. However, such a mechanism cannot be important because of the insolubility of salt in the CO₂ fluid phase, and because in a bedded salt deposit the vertical cavern extent is only 50-100 m, giving a very small temperature difference across the cavern height. Furthermore, rapid convection in the fluid will even out the thermal gradient rapidly in the cavern through convection, and salt itself has a thermal conductivity approximately three times that of the surrounding non-salt rocks, therefore the intrinsic gradient is less than in other rocks. In the case of Alberta salts, low geothermal gradients (Bachu and Burwash, 1991) will create a temperature difference of only <2-3°C across the cavern height, which may be insufficient to induce convective flow in the supercritical CO₂.

3.5 Maintenance of Compressive Stresses

In order for salt to retain its integrity against fracture and flow, it is important for the compressive stress in the salt and surrounding rocks to remain extant. In other words, the minimum stress in the salt must remain less than the pressure in the cavern fluid. Numerical modeling suggests that compressive stresses are maintained during closure of a smooth shape because of the slow inward movement of the salt in all directions (remember that the roof and floor have salt barriers). If the pressure in the cavern is even slightly lower than lithostatic in the far-field of the surrounding

salt, the tangential stress (σ_θ) in the cavern walls should be higher than the radial stress, and therefore higher than the internal cavern pressure (p_i). This difference, which also dictates the shear stress level that causes salt creep (creep rate is highly and non-linearly dependent on the major stress difference), diminishes as p_i asymptotically approaches lithostatic over time.

The key design element in maintaining $\sigma_\theta > p_i$ arises in the design of the roof. The curvature and span of the roof must be chosen to reduce or eliminate chances of tensile stress generation, and therefore a limit on total ultimate closure volume must be set. Otherwise, if there is too much strain, there can be no guarantee against roof geometry altering in such a way as to violate this criterion. This suggests that the placement of CO_2 should be done in such a manner as to increase p_i toward perhaps 90% of lithostatic, yet not too fast, so that salt creep can always keep the tangential stresses compressive.

3.6 Cavern Field Design

Ultimately, implementation of the salt cavern option for CO_2 sequestration in Alberta bedded salts implies that a number of caverns will be located in a relatively compact area. This is partly to ensure long-term security against breaching caused by future human activity. Figure 2 shows a spacing chosen to be stable and yet to give a reasonably high storage volume, given a uniform bed of salt. In terms of extraction ratio at the cavern midpoint, the area is diminished by 33%, but because caverns are shaped as ellipsoids, only 14-17% of the volume of salt in the cavern height is dissolved, and, if the roof and floor barrier salts are included, less than 10% of the salt is actually removed from a typical target stratum. Of course, spacing of caverns, as well as their optimum shape, must be chosen based on careful simulation using long-term creep models (e.g. Rothenberg *et al.*, 1999b)

If a large cavern field is developed, once the width becomes larger than the overburden thickness, large-scale stress arching effects in the overburden cease to be important, and all “pillars” carry the full weight of the overburden (Mraz *et al.*, 1991). This will accelerate closure, in comparison to an isolated cavern, where some of the stress concentration (i.e. shear stress) is transferred farther from the cavern through the rigidity of the non-salt roof rocks above the cavern. This means that an isolated cavern will close more slowly than a cavern group, all other factors being equal.

In a cavern field, the closure mechanics actually becomes more uniform, as all creep strains in the salt horizon can be accommodated by direct downward movement of the overburden, making cross-strains and beam bending less important. Less bending means smaller differential strain in the beams, thereby reducing the rate of development of local extensional strains.

4 Leakage and Fate of CO_2

Storage of gases such as CH_4 or C_2H_6 for heating or chemical industry purposes involves short-term leakage issues and regular pressure cycling; similar issues would arise for cavern use in temporary CO_2 storage, except that leakage is not as great a concern because there is no fire or potable-groundwater contamination hazard. There appear to be three mechanisms leading to leakage of CO_2 from a salt cavern (Figure 7):

- Flow paths of sufficient permeability in the salt or associated interbeds;
- Flow via a hydraulic fracture generated from the crest of the cavern; or,
- Leakage along the salt-cement interface in the cased wellbore.

4.1 Leakage Through Porous Media Near the Cavern

Salt is essentially impermeable: the 1% porosity typical of recrystallized salt (Lotsberg) is in the form of occluded porosity at grain contacts, and an interconnected network of porosity may not exist. Note also that the low “permeability” of halite ($\sim 10^{-20} - 10^{-21} \text{ m}^2$) may reflect slow solution/precipitation processes rate controlled by salt/brine diffusion processes (Spiers *et al.*, 1988) rather than true advective (Darcian) mass transport. In the presence of a non-dissolving

supercritical CO₂ phase, we presume salt will behave impermeably, but this remains an issue to be addressed.

Will CO₂ escape through non-salt interbeds or through intersection with the non-salt caprock? In general, interbeds within otherwise continuous salt sequences have all macropores (pore diameter > 2-5 μm) and joints filled with crystalline salt. It is not expected that the minor non-salt interbeds in the Lotsberg salt could be a significant leakage source, and the overlying rocks are also likely blocked with salt for some distance. We believe that leakage to strata that could allow porous media flow of CO₂ could occur only through either hydraulic fracturing of the rocks or through leakage along the borehole (casing).

4.2 Hydraulic Fracture Mechanisms

If the condition $\sigma_0 > p_i$ is maintained in the walls of the salt cavern, hydraulic fracture cannot take place. If the condition $\sigma_0 \sim p_i$ is approached, fracturing may develop; it is not clear whether, under such circumstances, any safety factor associated with the tensile strength of salt (~2 MPa, Hansen *et al.*, 1984) can be relied on in the long term. (We favor ignoring any such effect in the spirit of conservatism.)

Because salt creeps, there is reason to believe that hydraulic fracture will not occur except in the roof beam if it undergoes sufficient downward deflection at the midpoint. In the stratigraphy shown in Figure 4, this could result in a breach of the overlying 30 m non-salt roof beam, but the fracturing would likely terminate in the superincumbent salt zone, forming a barrier to continued upward migration of a fracture. Of course, the propagation of a fracture through a material that is behaving in a viscous manner is also a time-dependent process, and any sudden local breach could result in fracture propagation before the stresses have a chance to redistribute viscously to everywhere re-establish the condition $\sigma_0 > p_i$. This is a difficult issue worthy of careful analysis.

Nevertheless, we believe that a simple cavern design and a filling strategy can be easily devised to reduce or eliminate the risk of hydraulic fracture propagation through the salt barriers. We also note that, if a fracture condition is reached, the release of a small amount of pressure will result in the closure of the fracture, eliminating the existence of the path.

4.3 Casing and Borehole Integrity

The major leakage mechanism of genuine concern may well be the borehole and casing. The steel casing is cemented in place, and, although it is surrounded by salt, there is a strain incompatibility interface between the non-salt material (cement) and the viscous salt. In any CO₂ sequestration scheme, it is most likely that the access boreholes will be sealed in some fashion, and, to reduce the chances of leakage along this path, a viscous substance, perhaps recompacked granular salt (Fordham *et al.*, 1988), will have to be placed along the path of the borehole. This issue is precisely the same as the sealing issues for a nuclear repository (Hansen *et al.*, 1993, 1997), except that there will be a much higher pressure in the cavern in the case of supercritical sequestered CO₂.

If a path exists or is created in the borehole vicinity, does it stay open indefinitely, or does the salt creep re-establish a high enough compressive stress to eliminate leakage? This is an important issue as well, and we believe that the borehole itself is the likely the weakest link in the use of salt caverns for CO₂ sequestration.

4.4 Fate After Cavern Leakage

Assuming that a breach occurs by one of the mechanisms mentioned above and that cavern leakage takes place, is this leakage catastrophic (i.e. full escape to the atmosphere) or not? We conclude that flow will be blocked or that the leaked CO₂ will be largely taken up by the overlying strata for a number of reasons.

Overlying strata are horizontally bedded, and there are two large salt deposits between the Lotsberg salt and the more porous overburden strata in the Cretaceous. Furthermore, shales and other low permeability strata such as anhydrite, limestone and dolostone are essentially horizontal in attitude, and of great lateral extent. Any CO₂ that escapes thus has a great horizontal distance to travel before encountering unimpeded permeable paths to the surface. Such a long path increases the chances of being locally trapped, of being dissolved into formation waters, and of being adsorbed in thin coaly and organic seams that exist in the overlying Cretaceous strata. Because the Cretaceous strata are of quite high porosity and may well be undersaturated with respect to CO₂, and because they are flat-lying with continuous low-permeability shale bodies and also contain a number of sandstone bodies that can serve as “aquifer storage sites”, these sequences could represent substantial security against direct movement to surface.

Locally, in the Cretaceous rocks about 500-600 m above the Lotsberg salt, there are a number of shallow natural gas pools that have recently been exploited. There is ample reason to believe that these would serve as traps for any escaping CO₂.

5 Closing comments

It appears at this stage that there are no obvious geological or technological reasons that would make CO₂ sequestration in salt caverns unworkable. The Lotsberg salt in east-central Alberta is located in an area close to present and future large point sources of CO₂. It is also a region where high-porosity strata that might be used for aquifer CO₂ sequestration are not deep enough to give adequate pressure and temperature conditions to allow supercritical or liquid storage. However, in this region, the Lotsberg salt is sufficiently deep for supercritical storage, and it appears that, by virtue of its thickness, purity, geological history, and stratigraphic position, is a superior candidate for creation of stable salt caverns of sufficient volume to be used for sequestration.

It is important to restate that, in a supercritical condition, CO₂ remains highly compressible, and if a cavern is filled to an intermediate pressure only (e.g. 20 MPa at a depth of 1250 m where σ_v is ~30 MPa), a great deal of closure must take place over long times as the internal cavern pressure asymptotically increases toward the lithostatic. The more closure that takes place, the greater the flexure and differential straining that must occur in the non-salt overlying rocks, and this can lead to increased permeability as joints open under local extensional strains. Thus, an optimum sequestration strategy will be to design caverns not only with the optimum geometrical shape, but to plan a filling (pressurization) strategy that achieves the goals of little distortion of the overlying strata, maximum storage, and yet maintains the condition of compressive tangential stresses ($\sigma_\theta > p_i$) everywhere in the cavern walls to predicate against any local breaching through hydraulic fracture.

In our opinion, the borehole and cement-sheathed casing are the weakest points in the cavern integrity spectrum. Other processes are sufficiently understood that they can be simulated faithfully using numerical models and the design modified appropriately. The long-term behavior of the salt around the cement and casing and the integrity of the cement seal at higher elevations in the non-salt rocks are issues, and if the experience of the oil and gas industry is an appropriate template (Dusseault *et al.*, 2000), this will have to be addressed carefully through better cements, better means of abandonment, and borehole backfilling with materials that will form excellent seals. Fortunately, the performance of access wellbores can be monitored during the filling life of the cavern, and only the lower part of the borehole sealed so that the upper cased hole can be monitored for much longer times. In any case, even if CO₂ escape by leakage along the cement-rock interface occurs, the rate of efflux will be small, and mitigation measures can be implemented.

Despite the potential existence of several leakage mechanisms for both short-term and long-term storage, any CO₂ leakage from salt caverns in this region is not likely to be massive and catastrophic. There is a great storage capacity in the porous, permeable and brine-saturated overburden (achieving CO₂ geological sequestration by other means), stratigraphic gas traps are

common, the vertical permeability is extremely low so that any escaping fluids will have long horizontal flow paths, and so on. We believe that these factors are important security aspects that will guarantee successful long-term sequestration of CO₂.

Thus, for the reasons outlined in the introduction and throughout the article, the sequestration of CO₂ in liquid or supercritical form in dissolved salt caverns in ideal deposits such as the Lotsberg salt represents an option that may be locally important, or that may have particular value in cases where quick retrievability is considered desirable. This may be an important asset if salt cavern storage is used as an intermediate stage for geological storage, as a means to smooth out annual fluctuations in CO₂ emissions.

6 References

- Baar, C.A., 1977. *Applied Salt Rock Mechanics, I*. Elsevier Sci. Pub. Co., NY, NY.
- Bachu S, and Stewart, S, 2002, "Geological sequestration of anthropogenic carbon dioxide in the Western Canada sedimentary basin: suitability analysis", *Canadian Journal of Petroleum Technology*, In press.
- Bachu S., 2000, "Sequestration of CO₂ in geological media: criteria and approach for site selection in response to climate change", *Energy Conversion and Management*, v. 41, p. 953-970.
- Bachu, S., 2001a, "Geological sequestration of anthropogenic carbon dioxide: applicability and current issues", In *Geological Perspectives of Global Climate Change* (Gerhard, L., W. E. Harrison and B.M. Hanson, eds), American Association of Petroleum Geologists Studies in Geology # 47, AAPG, Tulsa, OK, p. 285-304.
- Bachu, S., 2001b, "Sequestration of CO₂ in geological media in response to climate change: roadmap for site selection using the transform of the geological space into the CO₂-phase space", *Energy Conversion and Management*, In press.
- Bachu, S., and Burwash, R.A., 1991, "Regional-scale analysis of the geothermal regime in the Western Canada Sedimentary Basin", *Geothermics*, v. 20, p. 387-407.
- Bachu, S., and Gunter, W.D., 1999, "Storage capacity of CO₂ in geological media in sedimentary basins, with application to the Alberta basin", In *Greenhouse Gas Control Technologies*, (Eliasson, B., P.W.F. Riemer and A. Wokaun, eds), Pergamon, Elsevier Science Ltd., Amsterdam, p. 195-200.
- Bajura, R.A., 2001, "The role of carbon dioxide sequestration in the long term energy future", In *Greenhouse Gas Control Technologies – GHGT 5*, (Williams, D.J., R.A. Durie, P. McMullan, C.A.J. Paulson and A.Y. Smith, eds), CSIRO Publishing, Collingwood, VIC, AU, p. 52-58.
- Bauer, S.J., Ehrgartner B.L., Levin B.L. and Linn J.K., 1998. "Waste disposal in horizontal solution mined caverns, considerations of site location, cavern stability, and development considerations" (Sandia National Laboratories), *Proceedings 1998 SMRI Fall Meeting*.
- Berest, P., Brouard B. and Durup J.G, 2000. "Shut-in pressure tests: Case studies." *Proceedings 2000 SMRI Fall Meeting*
- Bryant, E., 1997, *Climate Process and Change*. 209 p. (Cambridge University Press, Cambridge, U.K.).
- Dusseault, M.B., Gray, M.N., and Nawrocki, P.A., 2000. "Why oilwells leak: cement behavior and long-term consequences." *Proceedings SPE Int. Oil and Gas Exhibition, Beijing, SPE 64733*.

- Dusseault, M.B. and Fordham, C.J. 1994. "Time dependent behaviour of rocks." Chapter in *Comprehensive Rock Engineering*, edited by J.A. Hudson, Pergamon Press, vol 4.
- Dusseault, M.B., Mraz, D.Z., and Rothenburg, L. 1987. "The design of openings in saltrocks using a multiple mechanism viscoplastic law." *Proceedings 28th US Symp. on Rock Mech.*, Balkema, Rotterdam, pp. 633-642.
- Ehgartner, B.L., 1994. *Long-Term Sealing Analyses for US Strategic Petroleum Reserve (SPR) Caverns*. SAND92-2891, Sandia National Laboratories, Albuquerque, NM
- Fordham, C.J., Dusseault, M.B. and Mraz, D., 1988. "Strength development in halite backfill", *Proc. 41st Canadian Geotechnical Conference*, Waterloo, ON, pp. 192-198.
- Gunter, W.D., Wong, S., Cheel D.B., and Sjostrom, G., 1998, "Large CO₂ sinks: Their role in the mitigation of greenhouse gases from an international, national (Canadian) and provincial (Alberta) perspective", *Applied Energy*, v. 61, p. 209-227.
- Hansen, F.D., Ahrens, E.H., Dennis, A.W., Hurtado, L.D., Knowles, M.K., Tillerson, J.R., Thompson, T.W., and Galbraith, D., 1997. "A shaft seal system for the waste isolation pilot plant," Fall 1997 SMRI Meeting Paper, El Paso, Texas, USA, October 5-8, 6 p.
- Hansen, F.D., Callahan, G.D., and Van Sambeek, L.L., 1993. "Reconsolidation of salt as applied to permanent seals for the waste isolation pilot plant," *Proc. Third Conference on the Mechanical Behaviour of Salt*, Trans Tech Publications, Germany, pp. 323-335.
- Hansen, F.D., Mellegard, K.D., and Senseny, P.E., 1984. "Elasticity and strength of ten natural rock salts", *Proc First Conf. on the Mechanical Behavior of Salt*, University Park, PA, 1981, pp. 71-83.
- Hendriks, C.A. and Blok, K., 1993, "Underground storage of carbon dioxide", *Energy Conversion and Management*, v. 34, p. 949-957.
- Herzog, H.J., Drake, E.M., and Adams, E.E., 1997, *CO₂ capture, reuse, and storage technologies for mitigating global climate change*. Final Report, United States Department of Environment Contract No. DE-AF22-96PC01257 (Cambridge, Massachusetts: Massachusetts Institute of Technology).
- Hitchon, B., Gunter, W.D., Gentzis, T., and Bailey, R.T., 1999, "Sedimentary basins and greenhouse gases: a serendipitous association", *Energy Conversion and Management*, v. 40, p. 825-843.
- Holloway, S. and Savage, D., 1993, "The potential for aquifer disposal of carbon dioxide in the UK", *Energy Conversion and Management*, v. 34, p. 925-932.
- Mraz, D.Z. and Dusseault, M.B. 1983. "Method of correlation of laboratory tests with in situ conditions." *Proc., VI Int. Symp. on Salt*, Toronto, Ontario, V.II, pp. 259-268.
- Mraz, D.Z., Rothenburg, L., and Dusseault, M.B. 1991. "Mine design in salt rocks." Invited State-of-the-Art Paper, *Proc. 7th Int. Rock Mechanics Congress*, Aachen, Germany.
- Munson, D., M. Molecke, and R. Meyers, 1998. "Interior cavern conditions and salt fall potential", *Proc. SMRI Spring Meeting*, p. 226.
- Porter, J.W., Price, R.A, and McCrossan, R.G., 1982, "The Western Canada sedimentary basin", *Philosophical Transactions of the Royal Society of London*, v. A305, no 1489, p. 42-48.
- Rothenburg, L., Dusseault, M.B. and Mraz, D.Z. 1999a. "Rock mechanics aspects of solution mining based on case histories of sinkhole formation in Windsor-Detroit area." *Proc Mecasalt 99*, Bucharest, Romania.
- Rothenburg, L., M.B. Dusseault, D.Z. Mraz, 1999b. "Steady-state creep of salt in mines follows a power-law exponent of 3.0, based on a reanalysis of published data and mine simulation." *Proc Mecasalt 99*, Bucharest, Romania.

Schalge, R., W. Swartz, 1998. "Chilling natural gas to increase salt cavern storage capacity." *Proceedings SMRI Fall Meeting*. 417.

Spiers, C.J., Janos, Urai, J.L., and Lister, G.S., 1988. "The effect of brine (inherent or added) on rheology and deformation mechanisms in salt rock." *Proceedings Second Conf. on the Mechanical Behavior of Salt*, Hannover, Germany, Transtech Publications, pp. 89-102.