Managing Environmental and Human Safety Risks Associated with Geologic Storage of CO_2

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ABSTRACT

With less attention than other mitigation strategies, geologic storage of CO_2 has become an important approach to managing the problems associated with climate change. By analyzing analogs in the oil and gas industry, this thesis demonstrates that CO_2 transportation, injection and storage has been operational and scaling up in size and geographical distribution for over 30 years. As a result, a great deal of expertise has been acquired and lessons learned for managing the risks associated with geologic storage of CO_2.

Risks are categorized in two subsystems -- operational and *in situ*. The operational subsystem is composed of the more familiar components of CO_2 capture, transportation and injection, which have been successfully deployed in existing applications. Once CO_2 is injected in the reservoir it enters an *in situ* subsystem in which the control of CO_2 is transferred to the forces of nature. Years of technological innovation and experience have given us the tools and expertise to handle and control CO_2 in the operational subsystem with adequate certainty and safety; however, that same level of understanding is largely absent once the CO_2 enters the storage reservoir. As geologic storage moves forward, it will be important for proponents to manage and communicate the risks particularly associated with the *in situ* subsystem. Finally, this thesis attempts to highlight potential obstacles and needed approaches that could affect the willingness, opportunity and capacity for the key stakeholders to change in ways that will stimulate the wider adoption of geologic storage of CO_2.

Thesis Supervisor: Howard Herzog
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Table of Contents

List of Figures

1.0 Introduction

Initiatives to reduce and prevent carbon dioxide (CO_2) from reaching the atmosphere have led to new technological approaches aimed at mitigating climate change. Essentially, there are three primary CO_2 mitigation strategies: reducing CO_2 at the source by substituting lower carbon energy sources, using less energy for a given application by increasing energy efficiencies, and storing CO_2 in secure reservoirs such as underground cavities. Figure 1.1 summarizes these strategies. The third strategy, CO_2 storage, is a promising technique which involves actively capturing CO_2 emissions and storing them in underground geologic reservoirs such as depleted oil and gas fields, aquifers and deep coal beds. Though still a relatively new idea in the context of climate change mitigation, the practice of injecting CO_2 into underground reservoirs has been occurring for many years.

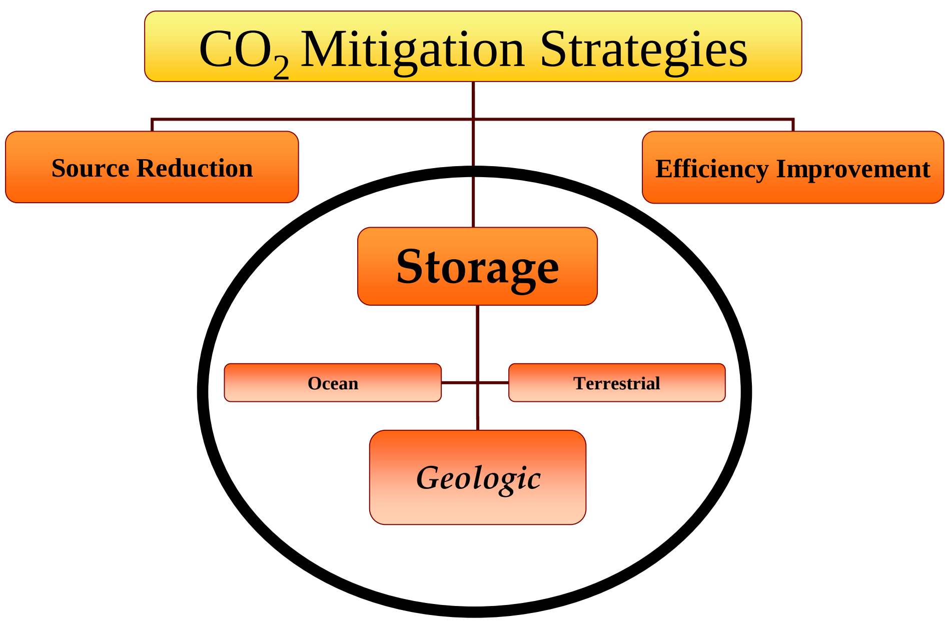

Figure 1.1: CO_2 Mitigation Strategies

Since the 1970's the US has been the leader in CO_2 injection for Enhanced Oil Recovery (EOR). By 2000, there were a total of 84 operations worldwide (72 in US) involving enhanced oil and gas recovery using CO_2 floods.[1] Not only has CO_2 been injected to enhance hydrocarbon production, it has been injected and stored in underground formations for the purpose of storage as well. In 1998, 12 acid gas re-injection and storage projects were active in Alberta, Canada. Although the original intention of acid gas injection was to dispose of H_2S (hydrogen sulfide), a peripheral benefit only recently recognized has been the storage of CO_2.

Smaller scale transportation, injection and storage (at least in the short-term) of CO_2 have been commonplace in the oil and gas production industry for decades. In addition, lessons for CO_2 storage can be learned from other functionally similar activities such as underground natural gas storage. As a result of this knowledge and experience, innovative energy companies including Statoil, a Norwegian oil and gas producer, have taken steps to enhance the scale of CO_2 transport, injection and storage. Moreover, EnCana's Weyburn Field is the first explicit EOR/storage project designed especially to study the long-term potential of geologic CO_2 storage as a strategy for climate change mitigation.

As the evidence indicates, there is a great deal of expertise and knowledge about the handling, injecting and even storage, albeit to a lesser degree, of CO_2. This thesis is intended to identify the important environmental and public safety issues associated with geologic storage and provide insight into these issues by drawing out lessons from analogs in the oil and gas industry. Specifically, it will focus on examining the aforementioned activities in greater detail and will attempt to draw out some key practices and techniques used to mitigate potential risks and engage the public to ensure the safety and success of these operations. After addressing some of the more salient environmental and safety risks specific to CO_2 storage that have emerged from the literature, it will assess the current research underway regarding CO_2 storage and provide recommendations for moving forward.

[1] Kinder Morgan CO_2 Company, "Rules of Thumb," [online document], 2001, [cited September 4, 2002], http://www.kindermorgan.com/co2/flood.cfm

2.0 Existing Operations and Technologies

Although geologic CO_2 storage is still at an early stage, there has been more extensive experience with several important analogs from the oil and gas industry. Four analogs -- acid gas injection, enhanced oil recovery, natural gas storage and CO_2 transport -- have been selected. All are functionally similar and in some respects identical to various aspects of CO_2 storage operations. Besides the distinction in offshore versus onshore injection, the major functional differences between acid gas injection schemes and Statoil's Sleipner project are the composition and volume of CO_2 being injected into the geologic formation.

World's First Major CO_2 Storage Project

Since 1996, Statoil, a Norwegian state-owned oil company, has been injecting carbon dioxide, a byproduct of natural gas recovery, into a 32,000 km^2 aquifer 800m below the floor of the North Sea. This innovative approach to greenhouse gas reduction was spurred in 1991 by a government imposed carbon tax on all carbon emissions from extraction activities on Norway's continental shelf. In order to avoid a NOK 1 million/day penalty due, Statoil developed a carbon injection mechanism that stores the carbon dioxide in the underground aquifer once it has been removed from the natural gas.

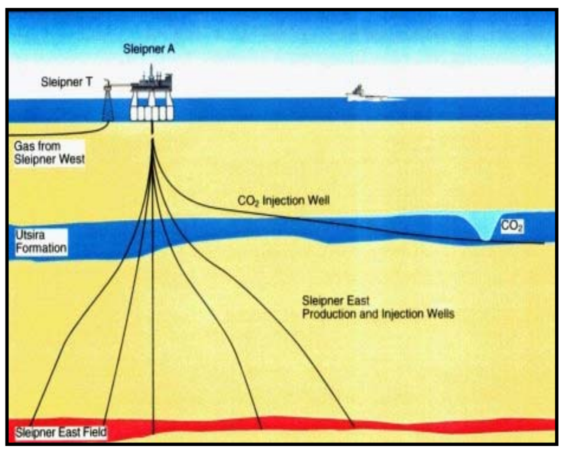

Figure from International Energy Agency, "Saline Aquifer CO2 Storage," http:// www.ieagreen.org.uk/sacshome.htm, May 2002

These analogs offer lessons about the safety, feasibility, environmental impacts, technologies, operations, engineering and economics of future storage activities. In addition, they are useful for informing us on many of the political and regulatory drivers as well.

In the next four sections, this thesis will present a general overview of these four activities and attempt to draw out some key themes concerning the development, operation as well as the environmental and social impacts from these technologies as currently practiced in the oil and gas industry.

3.0 Acid Gas Injection

Before oil can be sent to the marketplace from the production fields, oil producers must remove impurities from the produced oil stream. These impurities often include various concentrations of CO_2, methane, butane and H_2S to name a few. During the processing stages, these impurities are removed and can be flared, used as fuel, sold in the marketplace or stored in the underground. Acid gas injection is one method now commonly used to remove some of these impurities. Essentially, acid gas injection schemes remove carbon dioxide and hydrogen sulfide from the produced oil or gas stream, compress and transport the gases via pipeline to an injection well and re-inject the gases into a different formation for storage. Driven by stricter H_2S regulations adopted in 1989, acid gas injection has become a popular alternative to sulfur recovery and acid gas flaring particularly in Western Canada. In 2001, nearly 6.5 billion cubic feet of acid gas was injected into formations across Alberta and British Columbia at more than 30 different locations.[2] Proponents of acid gas injection, which has become a predominant storage method for H_2S, claim that these schemes result in less environmental impact than other alternatives for processing and disposing unwanted gases.

In most of these schemes, CO_2 represents the largest component of the acid gas, in some cases CO_2 composes over 90% of the total volume injected for storage. Thus, by volume, many of the acid gas schemes are essentially small-scale CO_2 storage projects. By comparison, Statoil's Sleipner CO_2 storage project in the North Sea injects about 50 million standard cubic feet (MMscf) of CO_2 per day into a sub seabed aquifer, whereas most acid gas injection operations range between 50 thousand and 5 million scf per day.

[2] Roche, Pat, "Deep Disposal," *New Technology Magazine*, March 2002, pp. 36-39.

One of the newest acid gas injection schemes is quite large, approaching the size of Sleipner. This acid gas injection scheme built earlier this year by Westcoast Energy injects 28 million scf per day of acid gas into a nearby depleted gas reservoir. Figure 3.1 shows most of the existing acid gas injection sites in Alberta and identifies them by the type of reservoir into which injection occurs. A slight majority of acid gas injection sites utilize saline aquifers, but a significant number of sites inject into depleted reservoirs. Proximity to the source of extraction and processing is one of the most important factors in selecting a storage site due to the cost of transportation.

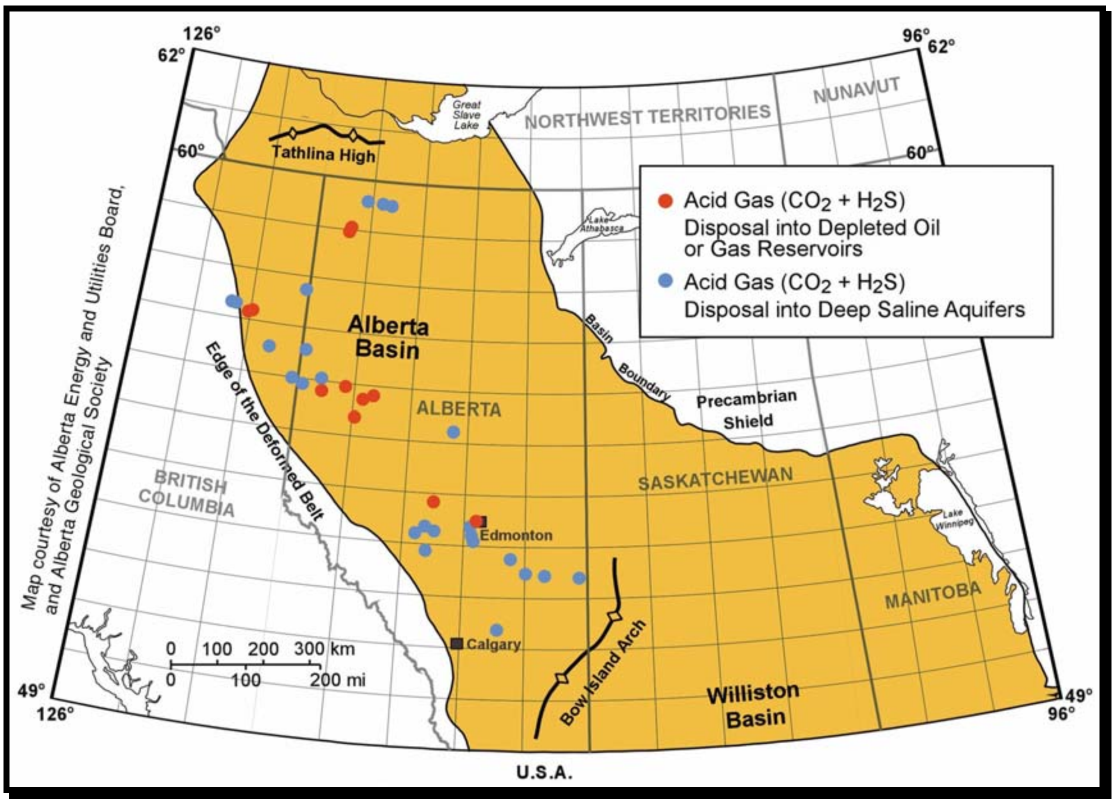

Figure 3.1: Acid Gas Storage sites in Alberta, Canada. Map provided by Nickle's *New Technology Magazine*, September 13, 2002.

The advantages of acid gas injection include: elimination of sulfur transportation costs (transport costs have exceeded the value of the sulfur product in the past decade); reduced capital costs and operating costs (injection eliminates the need sulfur recovery facilities); zero continuous sulfur emissions sites; CO_2 storage (CO_2 is usually emitted into the atmosphere during sulfur recovery); and the ability to handle a wide range of H_2S/CO_2

composition ratios.[3] While acid gas injection can provide significant benefits in terms of cost savings and reduced air emissions, it is not suitable for every sour or waste gas storage situation. Successful acid gas injection requires a nearby reservoir with sufficient porosity amply isolated from producing reservoirs and water zones. These conditions are not always present. In fact, Chevron Canada Resources, a pioneer in developing this technology, attempted injection into multiple reservoirs in the Acheson Field before one with adequate porosity was found in the Ostracod formation, a depleted gas field approximately 950 feet above the producing oil reservoir.

3.1 Operation

The design of an acid gas injection scheme requires in depth knowledge of the behavior and physical properties of the acid gas mixtures. Near the critical point, the physical properties of CO_2 change dramatically with small changes in temperature and pressure. In some cases, this may make CO_2 handling more difficult, thereby increasing the need to plan for and reduce the probability of any environmental or safety consequences. Because each situation (i.e. gas composition, water content and volume) is different, the technology used for acid gas injection is largely customized to fit the needs of the specific injection site, which can increase cost.[4]

Westcoast Energy Inc., which has almost 50 years of gas processing experience, opened it first acid gas injection plant in northeastern British Columbia in 1996 and a second one in the same location in 1997. This year, Westcoast's new Kwoen plant became Canada largest acid gas storage operation. It will process 300 MMcfd of natural gas and inject 28 MMcfd of acid gas into a nearby depleted gas reservoir. To do this, the plant operates three 3,750-horsepower acid gas compressors and transports the gas through a 6-inch diameter pipeline to the storage well.[5] Figure 3.2 shows a typical acid gas injection well

[3] Bosch, Neil, EnerPro Midstream Inc., "Acid Gas Injection: A Decade of Operating History in Canada," presented at the Canadian Gas Processors Conference, Calgary, Alberta, April 5, 2002.
[4] Interview with Jim Maddocks, P. Eng., Gas Liquids Engineering, Calgary, Alberta, August 27, 2002.
[5] Roche, 2002, pp. 36-39.

house. At an injection site, the wells are normally covered with a shed like this to contain any H_2S release in the event of a leak or accident. This is one visible example of how operators have taken special measures to reduce the safety risks associated with acid gas injection.

Figure 3.2: Acid Gas Injection Well House, Acheson Field (Photo taken by the author August 29, 2002, courtesy of EnerPro Midstream Inc.)

Acid gases dissolved in water create weak acids and commonly cause corrosion problems. To mitigate this effect, operators have installed stainless steel on pipes, valves and casings and have employed other more expensive techniques to reduce corrosion. However, these problems are well understood and have been managed since well drilling and pipeline transport began. Some operators believe that the CO_2 reduces the durability and effectiveness of the cement and therefore weakens the seal along the well bore.[6] Although other operators are not as worried about the CO_2 in this respect, over time, this phenomenon could potentially create a conduit for gas to escape and migrate along the well bore. For example, at a CO_2 injection site in Utah, the cement seal was eroded and isolation was lost within weeks. This has lead to new sealant technologies that are now employed in many CO_2 injection and flooding schemes including the Weyburn Field in Saskatchewan.[7]

Although geologists and hydrocarbon producers have made tremendous advances in understanding subsurface conditions as well as the behavior of fluids in geologic formations, this component still represents an area characterized by the greatest amount of uncertainty. Despite the confidence most operators in the business espouse about the ability of depleted oil or gas field to contain disposal gases over time -- based on the fact

[6] Interview with Scott Wehner, Kinder Morgan CO_2 Company, Midland, TX, August 22, 2002.
[7] Roche, 2002, pp. 36-39.

that hydrocarbons had been trapped there for millioins of years -- the only way to verify their ostensibly logical conclusion is with pressure testing. Before large capital investments are made, operators can test a formation's suitability and porosity by injecting nitrogen or CO_2 from portable tankers and then monitoring the pressure. This is common practice in the industry. Voidage calculations based on how much oil or gas has been depleted are often used to determine a reservoir's capacity for storing disposal gases. However, these calculations can vary depending on the compressibility of the gas and other fluid flow within the formation. Nevertheless, operators have developed down hole pressure tests and other measurement techniques characterized by high degrees of accuracy and reliability.

Monitoring is also critical especially when acid gases are re-injected into the producing formation. Historically though, depleted and producing reservoirs have proven to be extremely reliable containers of both hydrocarbons and acid gases over time. Boundaries, pressure limits and volume capacity of these reservoirs are usually well known.[8] In Alberta, the Energy and Utilities Board (EUB) requires operators to monitor and file reports on a regular basis according to Informational Letter (IL) 94-2. These regulations call for continuous monitoring of the fluid pressure and packer as well as monthly monitoring of wellhead pressure, temperature, volume and fluid at the injection well. Moreover, twice per year operators are required to report the results of monitoring, storage well workovers and overall performance.[9]

Over the life of the project, yearly subsurface pressure tests of the formation take place at the injection wellhead. This involves stopping the flow to the well in order to conduct more extensive reservoir pressure and integrity tests.[10] When problems arise, they are often traced to issues around the well bore or the tubing. Well problems are easily repairable while issues with the formation's integrity, should they occur, are relatively

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[8] Chakma, Amit, "Acid Gas Re-Injection – A Practical Way to Eliminate CO_2 Emissions from Gas Processing Plants," *Energy Conversion Management,* Vol. 38, Suppl. pp. S205-S209, 1997.
[9] Longworth, H.L., G.C. Dunn and M. Semchuck, "Underground Disposal of Acid Gas in Alberta, Canada: Regulatory Concerns and Case Histories," Society of Petroleum Engineers 35584, 1995.
[10] Interview with Brad Lock, Vice President of Operations, EnerPro Midstream Inc, Calgary, Alberta, August 27, 2002.

unfixable. There are essentially no engineering practices available at this time to recondition a formation or improve its integrity beyond the well bore zone. Should operators discover that a formation is unsuitable after injection has occurred, the remediation alternatives would be limited to shutting in the well or possibly extracting the injected gas. Although no acid gas injection scheme has been abandoned, there are no post-abandonment reservoir monitoring requirements in place at this time.

3.2 Political and Regulatory Considerations

In Alberta, oil and gas producers are regulated by two main provincial bodies and the appropriate municipalities. Oil and gas operators are primarily concerned with compliance standards established by the Alberta Energy and Utilities Board (EUB), which is charged with reviewing permit applications and regulating acid gas storage activities under the authority of the Oil and Gas Conservation Act. The Alberta Environment Ministry, which carries out its work under the authority of the Environmental Protection and Enhancement Act and the Water Act, is also an active regulator, although it has less impact on the oil and gas industry. Regulations are well developed in the permitting, operating and monitoring phases of a project, with the permitting phase being the most extensive.

The EUB evaluates permit applications based on the need and location for the proposed facility, alternative pipeline and processing options, potential impacts associated with project development and consultations with industry and the public. To be approved, applications must demonstrate measures have been taken to encourage conservation of hydrocarbon resources, minimize environmental impacts, promote public safety and protect the owners of the mineral rights.[11] In the past, regulators and applicants have worked together closely to ensure compliance with these conditions. Prior to 1988 [after the EUB issued IL 88-13, the allowable volume of acid gas flaring was reduced to 1 tonne/day of sulfur dioxide] sulfur recovery and incineration were the two most

[11] Longworth, et al., 1995.

economical methods of sulfur disposal. Since then, acid gas injection technology has evolved primarily as a result of declining sulfur prices, more stringent sulfur recovery requirements and increasing concerns about global warming.[12,13]

Communication, Education and Responsiveness is Key

In Aberta, oil and gas production accounts for over 40% of the province's revenues, 60% of its total exports and provides employment for over 183,000 residents. Thus, oil and gas operators have faced relatively little public opposition even when they dispose of waste gases underground near populated areas. At the Acheson facility, three miles outside Edmonton, EnerPro participates in and hosts various joint committees involving the public and nearby residents. They have been very successful at communicating with the public through regular meetings, hosting open house barbeques, handing out holiday turkeys, promptly responding to complaints, and holding informational/educational sessions. These activities have facilitated more open communication and credibility with the public and allowed them to be more attuned to public concerns. Thus, oil and gas operators have faced relatively little public opposition even when they have disposed of waste gases underground so close to a major population center.

3.3 Safety and Environmental Concerns

Safety and environmental concerns, at least at the operational level, focus on the management, monitoring and containment of H_2S. In fact, relatively little attention is paid to the CO_2 component of the acid gas stream, primarily due to low volumes and the non-

[12] Bosch, 2002.
[13] Carroll, John, and James Maddocks, "Design Considerations for Acid Gas Injection," Presented at the Laurance Reid Gas Conditioning Conference, Norman, Oklahoma, February 1999. p. 1.

toxic (perceived benign) nature of CO_2. The storage of CO_2 in these acid gas schemes is a fortuitous benefit of H_2S storage. One of the most important issues in developing acid gas storage wells is the potential size of the Emergency Planning Zone, which is based on the volume and potential for harm of the H_2S in the event of a release.

Although there are many significant health and safety risks associated with acid gas injection, they have thus far been effectively managed by existing industry practices. Risk reduction strategies, which again are primarily focused on H_2S containment, include operator training and routine maintenance procedures, automated pressure monitoring and gas detection systems, automated emergency shutdown valves and response systems, effective regulatory enforcement and reporting, years of operating experience, and a good understanding of subsurface conditions and fluid behavior as a result of many years of resource exploration and production.

One of the most important metrics one can use to evaluate the system's performance and better gauge some of the risks involved is the overall system reliability. On-line time for Chevron's four injection systems has averaged 99.2% since it began in 1989.[14] These high reliability levels are critical as backup emergency flaring systems are only permitted to operate for certain periods of time before production must be reduced.[15] On-line reliability has been achieved through preventative maintenance programs, operator training, using high reliability motors, stocking spare parts, and 24 hour access to maintenance personal.[16,17]

Ensuring well bore integrity is also a chief concern**.** Even though, well technology, drilling operations, pressure monitoring and maintenance procedures are mature and routine, well drilling is often the most risky process in oil and gas production as unexpected blowouts can occur. Drilling down thousands of feet into new formations can still be a fairly uncertain process. Once the well has been completed and equipped with

[14] Bosch, 2002.
[15] See EUB Guide 60: Upstream Petroleum Industry Flaring Requirements
[16] Bosch, 2002.
[17] Interview with Jim Maddocks, P. Eng., Gas Liquids Engineering, Calgary, Alberta, August 27, 2002.

safety valves and monitoring equipment, operation can begin. Routine pressure tests and well bore logs to ensure casing integrity are completed on a regular basis. These records are the most important issues for regulators. Injection wells, which are normally enclosed, are continuously monitored with H_2S and pressure detection equipment, and like other production technologies are equipped with Emergency Shutdown devices that are automatically triggered in case of emergency.

Similar to well bore integrity, the verification of the formation's integrity is also critical. According to engineers in the industry, the ability of a depleted oil or gas field to store waste gases for extended periods of time is not a concern. The logical argument is based on the fact that oil and gas would not stay in a formation over thousands of years if there was an issue with containment. Plus, operators evaluate a formation's suitability by injecting CO_2 or nitrogen from portable tankers and conducting pressure tests. Unfortunately, there is no way to recondition a well that is found to be unsuitable. The only remediation options available once gas has been injected are to stop injection and/or extract the gas if a formation is determined unsuitable after the fact.

Although the transportation network can and does fail on occasion, pipeline technology, maintenance programs and monitoring procedures are well established in industry. Operators continuously monitor high and low pipeline pressures throughout the entire process. Once in a while pipeline damage or leaky valves or joints cause inadvertent release of gases; however, these instances are infrequent, normally the result of operator error and are usually corrected within minutes of discovery. In addition, emergency shutdown systems are located at various points throughout the pipeline network. Automated systems can shutdown all or part of the operation if pressure readings move out of the high and low ranges or if gas detection monitors sense excessive levels of gas (i.e. H_2S). Near populated areas, additional shutoff valves can be installed to minimize the amount of release. Sensitive leak detection systems, training and awareness programs, automated shut-in equipment, and pipeline patrols (aerial and ground) being used by industry have increased pipeline safety from previous years.

In every gas processing facility, whether it is an acid gas scheme or an EOR project, compression is a critical component of the gas processing and injection operation. Fully functioning compressors are important for extracting other gases such as methane, propane and NGLs as well as adding sufficient pressure necessary for injection into a reservoir. When a compressor fails, often as a result of a power outage, the inlet gas stream is diverted to flare, which if necessary over longer periods of time (i.e. over a few hours) can create issues with regulatory compliance in addition to public discomfort. Normally when compressor equipment fails, it can be operational again in a matter of minutes.[18]

Storing CO_2 and other waste gases in the ground has raised some concern over chemical incompatibility in the subsurface. For the most part, there is no evidence in the literature or from discussions with operators that would suggest compatibility problems between the reservoir and the acid gas. However, it is important to ensure adequate injectivity levels to dispose of the volume required and that injectivity is not compromised by incompatibility issues. This may cause injection pressure to increase which increases costs, safety concerns and can lead to increased fracture levels.[19] In most cases, well bores taken from the injection zone have been tested for compatibility with the acid gas in a laboratory. So far, no significant problems within the reservoir have been reported.[20]

The advancement of well and pipeline technology, geological mapping, core drilling and testing, automated monitoring systems, training exercises and risk management plans have all contributed to making acid gas injection a safer process. For example, all sour gas plants in Alberta, are required to develop extensive Emergency Response Plans (ERPs), which guide operators in the event of an incident. ERPs contain various scenarios concerning the release of sour gas, maps of the area, contact information and evacuation procedures. ERPs include Emergency Planning Zones (ERZs), which maps an

[18] Interview with Colin Wilson, EnerPro Midstream Inc, Acheson Field, Alberta, August 28, 2002.
[19] Bennion, D. B., Brent Thomas, Douglas Bennion, Ronald Bietz, “Formation Screening to Minimize Permeability Impairment Associated with Acid Gas or Sour Gas Injection/Disposal,” Paper No. CIM 96-93, Presented at the 47th Annual Technical Meeting of the Petroleum Society of CIM, Calgary, Alberta, June 1999. pp. 1-6.
[20] Interview with Brad Lock, Vice President of Operations, EnerPro Midstream Inc, Calgary, Alberta, August 27, 2002.

area of influence around the operation and documents all residents, their special health needs and even their pets and animals. Should an incident occur, computer systems automatically phone residents with pre-recorded information and evacuation instructions. Residents verify receipt of the message through their phone systems, which reduces response time.

Sufficient preparation and well developed contingency plans for all types of emergencies are essential. Systems normally are tested and checked multiple times to ensure compliance and proper functionality. In addition, a keen understanding of instrumentation, fluid behavior, and process maintenance are all necessary for an effective and safe acid gas injection system. At the minimum, the installation should consist of blowdowns, blowbacks, and purges for additional safety measures.[21]

Fortunately, there have been no known incidences where significant harm has occurred as a result of an acid gas injection operation. When a problem has occurred, it has usually been the result of an operator error rather than mechanical failure. H_2S odor, aesthetic annoyance, emissions, flaring and machinery noise seem to be the most frequent sources of public complaint especially when operations are near residential units. Noise has been reduced with various technologies and enclosing equipment while a significant number of the odor problems have been attributed to human error (i.e. valves that have not been completely closed).[22]

3.4 Drivers of Operational Success and Risk Reduction

Acid gas injection schemes have increased in size and number over the last decade for a variety of reasons including growing environmental concerns, a depressed sulfur market and stricter regulations. The following list highlights some of the key factors of success for this quickly advancing technology.[23]

[21] Carroll and Maddocks, 1999. p. 14.
[22] Interview with Maurice Bezinett, EnerPro Midstream Inc, Acheson Field, Alberta, August 28, 2002.
[23] For more information on best engineering practices associated with acid gas injection see: Bosch, 2002.

- **Just the right volume**: The disposal of small quantities of H_2S is a problem. In most cases where acid gas injection is an attractive options, H_2S volumes are too large to flare but too small to justify investment in a sulfur recovery plant. More stringent regulations have disallowed flaring as a disposal method.

- **Near-zero emissions**: In theory, acid gas injection is a zero emissions operation; however, in practice, small amounts of emissions can occur during emergency flaring or from compressor or pipeline leakage. Nevertheless, nearby residents have viewed underground storage as an attractive alternative to H_2S flaring and CO_2 venting.

- **Public Management, Education and Communication**: Acid gas injection operators, especially near urbanized areas have served themselves well by maintaining constant communication with the public. This communication has occurred in the form of joint citizen-industry committees, public informational meetings, open house at the plant site, providing contact information to nearby residents, practicing emergency response plans with all parties, and quickly responding to resident complaints.

- **Experience with the Geology**: In parts of the world where oil and gas exploration and production have occurred extensively, operators and geologist have developed a keen understanding of the subsurface, fluid compositions and fluid behavior within it. This lends confidence to operators and the public that acid gas injection will be a safe alternative to sulfur recovery and or flaring. Further, testing the suitability of a formation using mobile CO_2 or nitrogen injection tanks has been an essential activity for operators.

- **Up-to-date Technologies**: Automated safety systems and monitoring techniques have greatly improved the confidence, safety record and ability for operators to handle and respond to issues associated with highly energized gases such as H_2S

and CO_2. Emergency Shutdown Devices and extremely sensitive gas detection and pressure monitoring equipment have largely removed opportunities for human error and large catastrophes as a result of accidental releases.

- **Process Management**: High on-line reliability is crucial for success. This has been achieved through extensive preventative maintenance programs, regular operator training, using high reliability motors, stocking spare parts, and 24 hour access to maintenance personal.

- **Communication with Regulators**: Maintaining a working relationship with regulators long after the permitting stage is also important. If a facility is facing problems, licensing may become an issue. Furthermore, keeping up with regulator relations can give them assurance that problems are being addresses in a timely manner.

4.0 Enhanced Oil Recovery (EOR)

EOR is a process by which CO_2 is injected into a producing reservoir to extract oil otherwise not attainable by primary production techniques. Although there are some important differences, the processes and technologies used in EOR operations are virtually the same as those employed in acid gas injection schemes. A few of these differences are found in the phase characteristics and final destination of the CO_2. In acid gas storage, CO_2 and H_2S are injected into a different geologic reservoir in a gaseous form. In EOR, the H_2S is separated and recovered while the liquid CO_2 is sent back into the producing formation to enhance oil production.

Primary recovery operations, which are generally able to recover around 37% of the available oil in a given reservoir, rely on the energy obtained from pressure differences between the surface and the underground formation to drive oil up the production well. When this pressure difference is no longer adequate to generate the energy necessary to move oil up the well, secondary recovery or water flooding is normally used to displace oil and drive it to the surface. As Figure 4.1 indicates however, a significant amount of oil can still be recovered using tertiary recovery techniques. [24] CO_2 flooding, one such technique, is the focus of this section.

Since the 1960s, enhanced oil recovery methods have been proven in the laboratory and later in the field. However, due to excessive capital and operational costs, these technologies have been slow to evolve in the industry. In recent years though, advances in analytical and assessment technologies facilitating a greater understanding of the geology in addition to physical and chemical processes governing multi-phase flow in porous media have lead to greater investment in enhanced oil recovery techniques.[25]

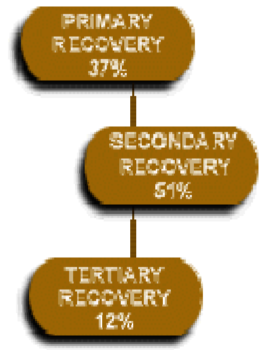

Figure 4.1: Percent of oil recovered during various stages of production.

The first CO_2 flood took place in 1972 in Scurry County, Texas. Since then, CO_2 floods have been used successfully throughout the Permian Basin, as well as in at least 10 other states. Outside the United States, CO_2 floods have been implemented in Canada, Hungary, Turkey and Trinidad.[26] In 2000, 84 commercial or research-level CO_2-EOR projects were operational worldwide. Combined, these projects produced 200,772 barrels (bbl) of oil per day, a small but significant fraction (0.3%) of the 67.2 million bbl per day total of worldwide oil production that year. The United States, the technology leader, accounts for 72 of the 84 projects, most of which are located in the Permian Basin. Currently, Turkey is the only other country with a commercial-scale application of CO_2-EOR, with Canada and Trinidad operating pilot-scale projects. [27,28] The six largest (Table

[24] Department of Energy, "Oil and Gas Reservoir Life Extension," [online document], http://www.fe.doe.gov/oil_gas/life_extension/, [cited September 4, 2002]
[25] ibid.
[26] Kinder Morgan CO_2 Company, "Rules of Thumb," [online document], 2001, [cited September 4, 2002], http://www.kindermorgan.com/co2/flood.cfm
[27] "OGJ Special – Worldwide EOR survey 2000," *Oil & Gas Journal*, pp. 44-61, Mar. 20, 2000.
[28] "OGJ Special – Worldwide production," *Oil & Gas Journal*, pp. 126-157, Dec. 24, 2001.

4-1) CO_2-EOR operations, most of which are located in the Permian Basin, combined for over 50 percent of enhanced oil production from CO_2 flooding in 2000.[29]

Table 4-1 : Six largest CO_2-EOR Projects (modified from Oil and Gas Journal)[30]

Operator	**Field**	**Region**	**Area (acres)**	**Production Wells**	**Injection Wells**	**EOR Production (bbl/day)**
Altura	Wasson (Denver)	Permian	27,848	735	385	29,000
Amerada Hess	Seminole (Main)	Permian	15,699	408	126	25,900
Kinder Morgan	SACROC	Permian	49,900	185	175	13,900
Chevron	Rangely Weber Sand	Rocky Mountain	15,000	341	209	11,208
ExxonMobil	Salt Creek	Permian	12,000	137	100	9,300
Altura	Wasson (ODC)	Permian	7,800	293	290	9,000

Why are such a large proportion of EOR operations in the US and in particular in the Permian Basin? First, the Permian Basin is a relatively cool reservoir relative to the critical temperature of CO_2. This condition improves the efficacy of a CO_2 flood. Hotter reservoirs (deeper) cannot reach Minimum Miscibility Pressure as easily. However, this is relatively a minor factor as to why CO_2 flooding is seemingly restricted to the US and the Permian Basin. A major reason has to do with the maturity of fields in the US and Permian Basin relative to other fields around the world, but equally important has been the availability of a nearby source of CO_2. Since the 1920s, more than 4,500 oil reserves and about 1,000 gas reserves have been discovered in the Basin with cumulative production of approximately 39 billion BOE (barrels of oil equivalent), making the Permian Basin the largest oil and gas producing region in the lower 48 states.

[29] ibid.
[30] "OGJ Special – Worldwide EOR survey 2000," *Oil & Gas Journal*, pp. 44-61, Mar. 20, 2000.

Between 1920 and today, the US depleted many of these reserves and is now a major importer. The only viable option for light oil EOR is tertiary recovery using CO_2. Fortunately, large natural CO_2 deposits existing within reasonable distance have been developed and transported to the Basin. Once the initial infrastructure was put into place, multiple projects were able to tap into the CO_2 supply. Natural occurring CO_2 deposits can be found in other parts of the world as well, but in many cases the capital to initiate and developed the infrastructure to support EOR operations is not available. In Brazil, operators are planning to sequester CO_2 from industrial sites because they cannot locate a natural source. Also, in Croatia and Hungary, where natural CO_2 sources exist, operators are looking to develop EOR operations.[31]

4.1 Operation

Most CO_2 floods achieve enhanced oil production through miscible, as opposed to immiscible, displacement. Oil and gas operators usually handle CO_2 in its supercritical phase. This means the CO_2 behaves like a gas with respect to viscosity and as a liquid with respect to density.[32] The six largest CO_2-EOR projects described above, for example, are all miscible CO_2 floods. In miscible flooding, CO_2 mixes with the oil in the reservoir whereas, in immiscible displacement, the CO_2 remains physically distinct from the oil. The type of displacement that occurs is dependent upon reservoir pressure, crude oil composition, reservoir depth, and oil density. Miscible displacement can leads to an enhanced recovery of about 7 to 15 percent of the original oil in place. Immiscible displacement yields relatively lower recovery rates, but can still achieve high recovery levels due to oil swelling and viscosity reduction. Currently, only one large CO_2-EOR project, located in Turkey, utilizes immiscible processes. However, it is expected that the number of immiscible CO_2 floods will increase as the use of CO_2-EOR becomes increasingly widespread.[33,34,35,36,37]

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[31] Interview with Scott Wehner, Kinder Morgan CO_2 Company, Midland, TX, August 22, 2002.
[32] Stevens, S.H., Kuuskraa, V.A. and J.J. Taber, "Barriers to overcome in implementation of CO_2 capture and storage (1): Storage in disused oil and gas fields," IEA Greenhouse R&D Programme, Cheltenham. Tech. Rep. PH3/22, Feb. 2000. p. 14.
[33] "OGJ Special – Worldwide EOR survey 2000," *Oil & Gas Journal*, March 20, 2000, pp. 44-61.

Because of the high costs associated with producing, transporting, processing and injecting CO_2, EOR operators try to maximize oil production while minimizing the CO_2 necessary to achieve the desired results. CO_2-EOR projects are optimized by manually alternating between CO_2 and water injection in a water-alternating-gas (WAG) process (Figure 4.2) [38]. This WAG process is carried out to help overcome the problem of high CO_2 mobility within the formation, which greatly reduces the effectiveness of CO_2 flooding. CO_2 mobility, caused by the CO_2 having a lower density and viscosity than the reservoir oil, is responsible for undesirable phenomena known as gravity tonguing and viscous fingering. Tonguing and fingering reduces the efficacy of flooding by permitting the CO_2 to flow through areas that have already been swept. Because water is less mobile than CO_2, the WAG process is able to improve the sweep efficiency by reducing CO_2 mobility. This, in turn, results in improved oil recovery while also preventing early CO_2 breakthrough in producing wells. [39,40,41]

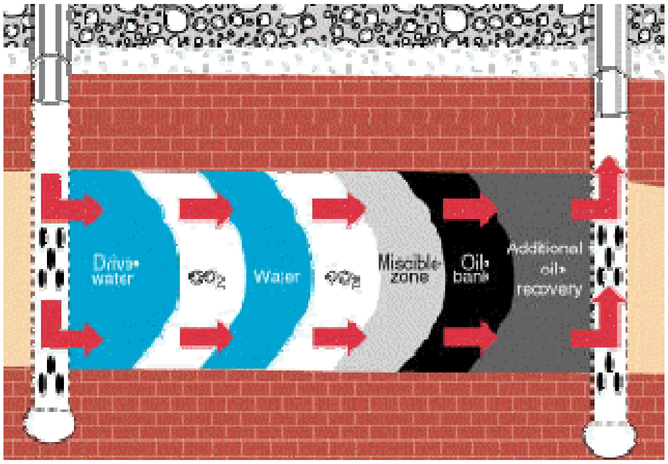

Figure 4.2: EOR Schematic - WAG Process, Kinder Morgan CO2 Company, 2001.

To further improve the effectiveness of CO_2 flooding, operators monitor CO_2 flow within the reservoir. Highly advanced geophysical surveys, which employ 4-dimensional, 3-

[34] "Enhanced Oil Recovery Scoping Study," EPRI, Palo Alto, CA. Tech. Rep. 113836, 1999.
[35] Moritis, G., "Future of EOR & IOR: New companies, infrastructure, projects reshape landscape for CO_2 EOR in U.S.," *Oil & Gas Journal*, May 14, 2001.
[36] Marle, C.M., "Oil entrapment and mobilization," in *Basic Concepts in Enhanced Oil Recovery Processes*, M. Baviere, Eds. Elsevier Applied Science, 1991, pp. 3-39.
[37] Klins, M.A. and C.P. Bardon, "Carbon dioxide flooding," in *Basic Concepts in Enhanced Oil Recovery Processes*, M. Baviere, Eds. Elsevier Applied Science, 1991, pp. 215-240.
[38] Kinder Morgan CO_2 Company, "Rules of Thumb," [online document], 2001, [cited September 4, 2002], http://www.kindermorgan.com/co2/flood.cfm
[39] "Enhanced Oil Recovery Scoping Study," EPRI, Palo Alto, CA. Tech. Rep. 113836, 1999.
[40] Klins, M.A. and C.P. Bardon, 1991, pp. 215-240.
[41] Morel, D., "Miscible Gas Flooding," In *Basic Concepts in Enhanced Oil Recovery Processes*, M. Baviere, Eds. Elsevier Applied Science, 1991, pp. 185-214.

component seismic reflection data, are employed to directly detect the movement of CO_2 within the systems over time. This information can improve oil recovery by enabling EOR operators to better direct CO_2 flow and reduce poor conformance.[42,43] Further, some operators are now using new and improved cross-well seismic time-lapse technologies to monitor CO_2 movement in the reservoir.[44]

In addition to oil production and CO_2 injection processes, EOR project operators must also be skilled at reservoir management as well as oil, gas and water processing. Reservoir management integrates reservoir modeling, simulation, fluid and rock properties and recovery technologies along with the underlying geoscience technologies to ensure maximum profitable recovery of the company's oil and gas assets. Moreover, the separation and re-utilization of gases is a critical value-added process.

Gas processing at Amerada Hess' Seminole Unit began in 1983 when their Ryan-Holmes unit became operational (Figure 4.3). Currently, inlet flow volume from the production field into the processing facility averages around 175 MMscf per day. This stream from the production field to the facility is composed of 85% CO_2, 15% hydrocarbons, and 0.6% H_2S. While the hydrocarbons are either reused or sold, the majority of CO_2 (145.9 MMscf) is sent to a distribution center where it is combined with additional CO_2 purchased from a third party and re-injected into the field. In all, this EOR operation injects approximately 260 MMscf of CO_2 per day into various parts of the Seminole Unit. No one knows for certain how

Figure 4.6: Amerada Hess Ryan Holmes Gas Processing Unit, Seminole, TX.

[42] Conformance refers to the gas injection processes which often suffer from poor sweep due to the high mobility of injected gas. This reduces oil recovery and contributes to higher operating costs when injected gases breakthrough to production wells.
[43] Stevens, S.H., et al., 2000. p. 98.
[44] Interview with Scott Wehner, Kinder Morgan CO_2 Company, Midland, TX, August 22, 2002.

much CO_2 has actually been permanently sequestered, operators now estimate that around 1.5 trillion cubic feet (Tcf) of CO_2 is stored in the geologic formation at any one time.

4.2 Political and Regulatory Considerations

~~N~~IMBY: In My Back Yard…Literally

This production well, in the center of the only public park in town, is located less than one hundred yards from the most affluent residential housing unit in the city.

These two production wells, located next to this house, are typical in Seminole, TX. Other wells are located across the street form the high school and in the front yard of the city's hospital.

In the Permian Basin, public opposition to proposed EOR developments has been limited to a few farmers and well-intentioned commissioners. For example, Amerada Hess appeased county commissioners by guaranteeing double safety standards on their gas processing facility when it was built just outside of Seminole, TX (pop. 5,000). In addition, each year the company invests a great deal of resources in coordinating and practicing emergency response plans with local public services. Outreach is necessary as Hess maintains over 70 wells within Seminole's city limits. Each well is checked twice per day. In Seminole, almost everyone works or knows someone who works in the oil industry. In fact, well problems are often reported by people known to the operators. Moreover, oil operations account for 85% of the local tax base. In recent years, corporate taxes and donations have been used to build new schools, football stadiums and to purchase buses for school children and sports teams.

In Texas, where the majority of EOR operations occur, the state gives tax breaks to companies who invest in CO_2 flooding regimes. Many other states including Mississippi, Louisiana and Oklahoma have incentives to stimulate exploration and production as well. However, in spite of the state programs, it seems the most important program for stimulating drilling and production activity is the federal scheme outlined in the Internal Revenue Code Section 29, a generous tax credit provisions that makes many formations economical to develop.[45] Moreover, Texas state law gives primary regulatory authority to the Texas Railroad Commission (responsible for oil and gas processing and gathering plants, wells, producing sites and pipelines) and the Texas Commission on Environmental Quality (TCEQ – responsible for air quality). The University Land System, which exists in Texas, is not a regulator but is in charge of leases and royalties on state lands. The Mineral Management Service on the other hand, deals with Federal leases and has significantly stricter regulations. The implications of operating on state or federal lands often mean a lengthier permit process compared to operations conducted on private grounds.

4.3 Safety and Environmental Concerns

As with acid gas injection, EOR operations in Texas are primarily concerned with managing the release of H_2S since there have been a few deaths caused by the gas over the years. Basically, the same techniques and technologies used for acid gas injection are also used in EOR for gas detection, pressure monitoring, safety training and public awareness. Environmental issues arising from CO_2 flooding seem to be minimal, though no environmental impact statements are required to confirm this hypothesis. Operators do admit that some CO_2 is lost (i.e. not recycled) in the formation most probably as a result of fingering or through the oil-water contact zone. EOR operators have estimated this to be anywhere from almost negligible levels to around 5%.[46] Leakage around the injection well bore would be the most likely source of a CO_2 release. Figure 4.4 shows estimated leakage rates from the Rangely, Colorado field, which has been undergoing

[45] Troy, Alan, Technology "A Comparision of Drilling Incentives in Louisiana, Mississippi, Oklahoma and Texas," Assessment Division Louisiana Department of Natural Resources, excerpt from the January 14, 1991 report available at http://www.dnr.state.la.us/SEC/EXECDIV/TECHASMT/lep/drilling/compare.htm, cited September 29, 2002.
[46] Wehner, 2002.

large-scale CO_2 injection since 1986. Again, pressure tests are used to detect leaks, and should one be found, zone isolation packers and cement are used to seal the leak zones.

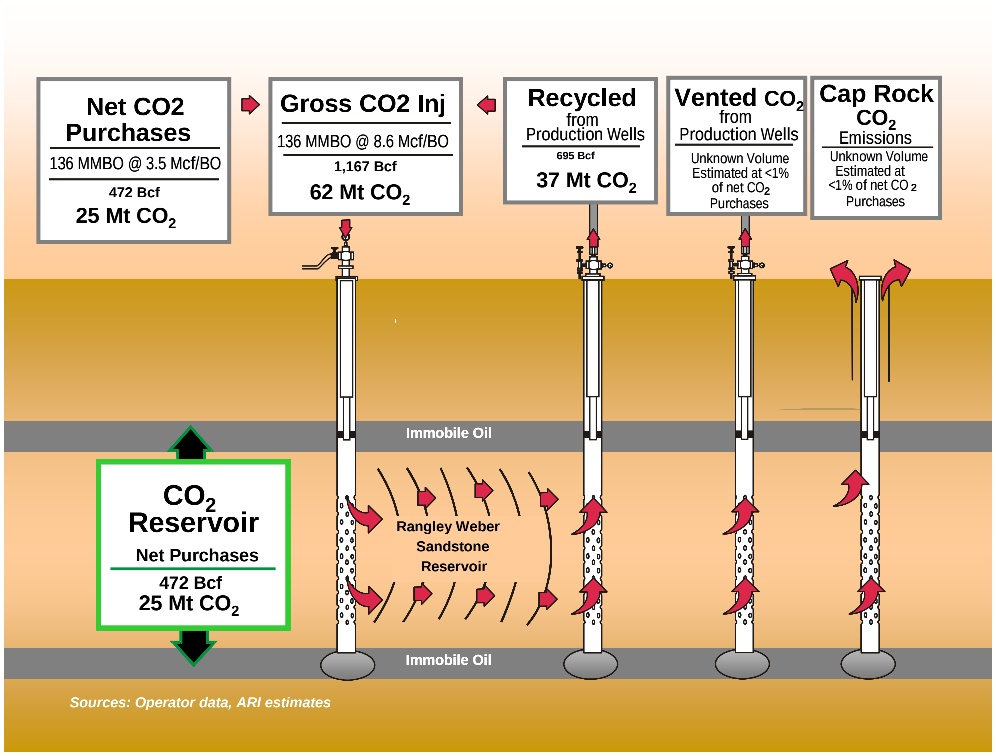

Figure 4.4: Rangely EOR Schematic, taken from a presentation by Dave Thomas, "Climate Change: A Challenging Opportunity for Industry and Government," IOGCC and the U.S. Department of Energy (DOE) meeting, Alta, Utah July 17-19, 2002, http://www.iogcc.state.ok.us/ISSUES/CO2%20Sequestration/co2sequestration.htm (note MMBO is million barrels of oil)

In the Permian Basin, better coordination and teamwork between operators and emergency response crews have reduced response times and improved their ability to react to threatening situations. For instance, nearby operators conduct joint training exercises with each other and with emergency service personnel on a regular basis. Furthermore, EOR operators have been important contributors to local emergency teams by supplying them with additional equipment and resources for reducing response times and reacting to various situations. Teaming up to share costs, equipment and expertise is a valuable lesson for future storage operations.

4.4 Drivers of Operational Success and Risk Reduction

Indeed, the opportunity to profit from extracting a significant portion of the remaining oil deposits from a depleting reservoir is the major driver of an EOR operation. But what are the factors that make an EOR operation safe and profitable? For starters, a nearby, reliable and inexpensive source CO_2 is critical. Below is a general list of a few of the most important elements of existing CO_2 flooding operations.

- **Proximity to a stable CO_2 source:** Because a plentiful and reliable source of CO_2 is needed for CO_2 flooding, the location of a depleting reservoir can often preclude it from being a candidate for EOR. In Brazil, operators are planning to sequester CO_2 from Steel Ingot manufacturing sites because they cannot locate a natural source. However, in Croatia and Hungary, where natural CO_2 sources exist, operators are looking to develop EOR operations.[47]

- **Management Skills and Experience:** As with many large capital projects, project management skills are essential. This implies that credentials and experience are crucial for any development team interested in developing a CO_2 flood.

- **State and Federal Tax Credits:** Oil producers are awarded a tax credit of 15 percent against their costs for producing domestic oil by a qualified "enhanced oil recovery" (EOR) method. Such methods allow for oil recovery otherwise not economical using conventional methods. Although the credit phases out at $28 per barrel, it covers costs of labor, materials, equipment, repairs, intangible drilling, and development.[48] According to Alan's (1991) review of incentive programs in four producing states, the only program that noticeably resulted in increased drilling activity was the federal Internal Revenue Code Section 29.

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[47] Wehner, 2002.
[48] Congressional Budget Office, REV-37, "Repeal the Tax Credit for Enhanced Oil Recovery Costs and Expensing of Tertiary Injectants," [online document], February 2001, [cited October 4, 2002] available at http://www.cbo.gov/bo2001/bo2001_showhit1.cfm?index=REV-37

- **Price of Oil:** There is an important relationship between the price of CO_2 and the price of oil. In order for a CO_2 flood to be operational, oil prices have to remain above a certain threshold. In the Permian Basin, oil prices need to be above approximately $20 per barrel in order for operators to break even. Operators in the Basin now pay around 70-80 cents per thousand cubic foot of CO_2.

- **Coordination with Response Teams:** Risk management is a primary concern among operators in the EOR business, not to mention an expensive one. Thus, operations that are close geographically can and have benefited from working together to enhance the capabilities of local emergency response teams by donating equipment and money. Also, joint training exercises have allowed operators to incorporate best practices, reduce costs and increase efficiencies above individual levels.

- **Generation of Tangible Public Benefits:** Oil production is a way of life in the Permian Basin and the primary source of jobs, tax revenues and economic vitality. Many towns in this part of the country have dwindled in parallel with depleting oil fields. EOR is a powerful tool employed to slow the decline in population of many of the smaller oil towns in the Midwestern part of the United States. These EOR projects have generated tax revenues that support education, athletics, community development and local pride. These elements have helped to greatly lower the barriers to implementation and public acceptance.

5.0 Natural Gas Storage

Natural gas storage activities can provide insight into the operations, risks and management strategies relevant to geologic CO_2 storage. Characteristically, natural gas, similar to CO_2, will tend to rise within a storage structure. In this sense, the storage of

CO_2, acid gas and natural gas are quite analogous. Although a number of differences exist, many lessons can be learned.

5.1 Operation

Since 1915, when natural gas was first injected and stored in a partially depleted gas field, underground natural gas storage has become a relatively safe and increasingly practiced process to help meet seasonal as well as short-term peaks in demand. [49] Because depleted oil and gas reserves were largely unavailable in the Midwest, saline aquifers were tested and developed for storage in the 1950's. Between 1955 and 1985 underground storage capacity proliferated from about 2.1 Tcf to 8 Tcf in order to respond to consumption increases.[50] However, since the 1980's, total storage capacity has stabilized at around 8 Tcf while the capability to deliver the natural gas to market has increased.[51] To put these numbers in perspective, total consumption in the US exceeded 22 Tcf in 2000 and is expected to increase rapidly over the next 20 years, which will mean new pipelines and

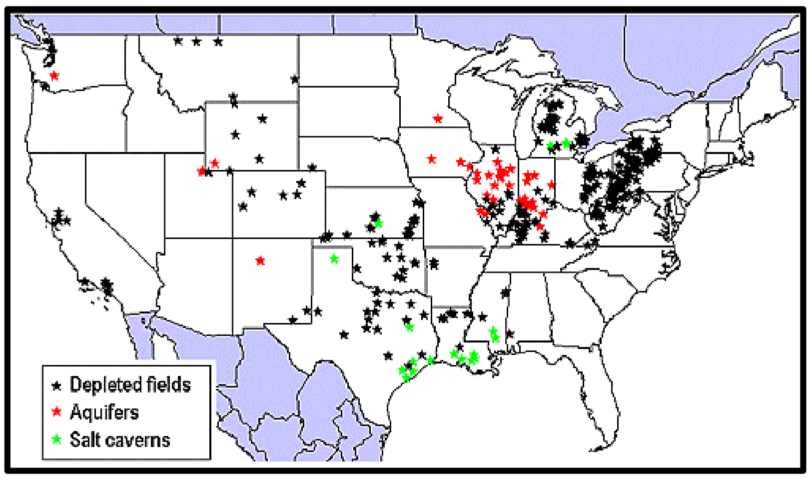

Figure 5.1: Natural Gas Storage by Type , National Energy Technology Laboratory, "Transmission, Distribution and Storage Natural Gas Infrastructure – Storage ," [online document] , 2002, [cited September 26, 2002] http://www.fetc.doe.gov/scng/trans-dist/ngs/ storage-ov.html

[49] Energy Information Administration, "The Value of Underground Storage in Today's Natural Gas Industry," March 1999, DOE/EIA-0591(95), Appendix A, pp. 43-53.
[50] EIA, 1999. p. 44.
[51] EIA, 1999. pp. 43-53.

storage expansions.[52] Figure 5.1 shows natural gas storage operations by type in the United States.

While depleted oil and gas reservoirs are the most widely available and most frequently used natural gas storage facilities, salt caverns and natural aquifers are suitable as well. Not only are oil and gas fields abundant, but they are often more convenient and less costly storage sites as developers are able to utilize existing wells, gathering systems and pipeline networks for storage and delivery operations.[53] For storage activity, depleted hydrocarbon reservoirs and natural aquifers offer the most potential for CO_2 storage. Salt caverns or salt domes on the other hand, lack sufficient capacity and would require excessive costs in order to make them suitable for CO_2 storage.

5.2 Political and Regulatory Considerations

Several federal and state regulating agencies have regulatory authority over natural gas underground storage and transportation in the US. Typically, the operations of storage facilities and intrastate pipelines are regulated by individual state programs; however, facilities serving interstate markets are regulated by the Federal Energy Regulatory Commission (FERC).[54] EPA is charged with enforcing the requirements of the Safe Drinking Water Act and therefore has established the state-run Underground Injection Control (UIC) program which provides safeguards for underground drinking water supplies.[55] The UIC program defines five classes of injection wells including Class II wells, which are wells related to oil and gas storage and recovery.[56] The US Department

[52] Tobin, James, "Natural Gas Transportation – Infrastructure Issues and Operational Trends," Energy Information Administration, October 2001available at http://www.eia.doe.gov/oil_gas/natural_gas/info_glance/pipelines.html. p. 1.
[53] Tobin, J., and James Thompson, "Natural Gas Storage in the United States in 2001: A Current Assessment and Near-Term Outlook," Energy Information Administration, 2001 available at http://www.eia.doe.gov/oil_gas/natural_gas/info_glance/storage.html, p. 7.
[54] ibid.
[55] EPA, Underground Injection Control Program, [online document] available at http://www.epa.gov/safewater/uic/whatis.html, [cited July 2002].
[56] 40 CFR 144.6

of Transportation's Office of Pipeline Safety (OPS), on the other hand, is concerned with safety, operational procedures and new developments of the pipeline system.[57]

Most natural gas storage operations face relatively little large-scale public opposition even though most operations are near urbanized areas. The most frequent problems arise from general quality of life issues, namely odor complaints originating from the additives in the natural gas. Hazards arise because of poor oversight or a lack of the appropriate technology. For the most part, occupational training programs and an occasional public meeting are standard practice, but extensive public outreach programs do not seem to be common in the industry. A significant number of people are not aware that they live on or near underground storage sites.[58]

5.3 Safety and Environmental Concerns

Although natural gas is the lowest carbon emitting fossil fuel, environmental footprints still arise from exploration, production and delivery. Land access, pipeline construction and air emissions are issues being addressed by the Department of Energy and other agencies to reduce these environmental impacts. Also, industry is contributing technical innovations to protect the environment. For example, "smart" pipes, remote sensing equipment and new materials have improved the capacity and reliability of pipelines while reducing the environmental footprint.[59] Pipeline construction times are being reduced and with less environmental damage by using new technologies that do not require trenching in sensitive areas. Leak detection by remote sensing devices notify operators in real time so that repairs can be made before extensive volumes of gas escape. These new methods and technologies, which are also applicable to the transportation of

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[57] Tobin, 2001, p. 3.
[58] Interview with Carl Johnson, Williams Energy Services, Conway, Kansas, August 23, 2002.
[59] National Energy Technology Laboratory, U.S. Department of Energy, "Transmission, Distribution and Storage Natural Gas Infrastructure – Pipeline Reliability," [online document] 2002 [cited October 17, 2002] available at http://www.netl.doe.gov/scng/trans-dist/ngi/pipeline.html

CO_2, have greatly reduced the environmental and safety hazards bought about by delivering natural gas to market.

There is not a comprehensive source of information in the literature regarding the safety issues associated with underground natural gas storage, but a recent incident in Hutchinson, KS, where two people were killed and several downtown businesses suffered millions of dollars in damage is one example of how gas leakage and migration in the subsurface can create substantial problems. The source of the gas geysers and explosions in downtown Hutchinson was determined to be a damaged well pipe from a 1992 reopening, which converted the salt cavern from propane to natural gas storage. A recent report concluded that the gas leak since 1993 coupled with pressurization levels exceeding recommended limits, caused the natural gas to escape and migrate more than 9 miles where it re-concentrated under the city and vented through old abandoned wells. [60] Well leaks resulting from mechanical failure are the most common in the natural gas storage business. Fortunately, most of these problems can be repaired, reconditioned, or plugged.[61] A more detailed analysis of the Hutchinson, KS events and after effects can be found in Section 7.

5.4 Drivers of Operational Success and Risk Reduction

In general, natural gas storage and transportation activity is driven by an increasing demand for energy. Roughly 1.3 million miles of pipelines transport natural gas to over 175 million customers. The yearly demand for natural gas is projected to grow at a rate of over 2% per year to over 34 trillion cubic feet by 2020.[62] In all likelihood, this will increase the amount of infrastructure around the country. As a result of reductions in private sector research and development, the Department of Energy has developed an

[60] "Report Links Gas Leak to Explosion," *Topeka Capital Journal*, July 30, 2002.
[61] Benson, Sally, John Apps, Robert Hepple, Marcelo Lippman and Chin Fu Tsang, "Health, Safety and Environmental Risk Assessment for Geologic Storage of Carbon Dioxide: Lessons Learned from Industrial and Natural Analogues," Lawrence Berkeley National Labs, 2002 available at http://www.co2captureproject.org/reports/reports.htm. p. 111.
[62] National Energy Technology Laboratory, 2002.

Infrastructure Reliability Program to help ensure the operational reliability, safety and security of natural gas infrastructure. This program has and will continue to help reduce the number of incidents associated with gas production and storage and will continue to be an important mechanism ensuring safety and therefore the public acceptance of natural gas distribution systems. In addition to those factors mentioned in the two previous sections, other important factors driving natural gas storage include the following:

- **Fewer Environmental Consequences**: The substantial growth of natural gas in the last few years is partially attributed to its lesser environmental impact than coal or other fossil fuels available in the US. Thus, the use of natural gas versus oil or coal to satisfy energy needs represents a partial solution to the risks associated with more intensive CO_2 emitting fuels.

- **Security:** Underground storage, in particular is less vulnerable to natural disasters or malevolent actions. This element may not have been as important a factor in the past, but with new concerns about terrorism and energy security, natural gas underground storage provides a solution that is less vulnerable to insidious acts.

- **Improved Safety Practices:** One way natural gas companies have improved safety practices, is by applying a protective coating and cathodic protection to gas pipelines to prevent corrosion that could cause leaks and possible explosions. As a result, natural gas accidents related to pipeline corrosion have decreased steadily since cathodic protection was introduced. The National Transportation and Safety Board reports that on average, 50,000 people die in the United States each year from car related accidents, while 22 die from natural gas transmission and distribution. Regulations governing pipelines are tougher than ever and the materials and technologies used to build the infrastructure are better than they have ever been.

6.0 CO_2 Pipeline Transportation

6.1 Operation

Numerous large natural deposits of CO_2 have existed underground for millions of years and thus suggest that stable long-term storage of CO_2 can be achieved.[63] In the last 20 years, many of these CO_2 accumulations have been exploited and transported hundreds of miles for EOR operations. Concurrently, an extensive network of CO_2 pipeline was built up and now stretches nearly 2000 miles, mostly in the United States.[64] As a result, the technology, operations and risks associated with CO_2 transport are well understood and have not faced significant opposition.

Pipelines designed to transmit gases, liquids and supercritical fluids are used in a wide variety of applications and are generally viewed as safe vehicles to transport commodities in both urban and rural settings. For most pipelines, including those designed for transport of supercritical $CO_{2,}$ the ability to maintain adequate or "critical" pressure is important. This can be achieved by recompressing the CO_2 at certain points along the pipeline. Recompression is often needed for pipelines over 90 miles in length. In some cases, recompression can be avoided if a proper pipe diameter is used. For example, the Weyburn pipeline, which transports CO_2 over 200 miles from an industrial facility in North Dakota to an EOR site in Saskatchewan, Canada, operates without a recompression system.[65]

Also, the Canyon Reef Carriers pipeline, one of the first CO_2 pipelines constructed specifically for EOR operations, and similar systems, provide experience and the confidence that the barriers to future CO_2 handling and injection systems may be low. Initiated in 1972, the Canyon Reef Carriers pipeline has experienced only five failures

[63] Holloway, S., et al., "The Underground Disposal of Carbon Dioxide: Summary Report," JOULE II Project No. CT92-0031, British Geological Survey, 1996, pp. 1-24.
[64] Gale, John, "Geological Storage of CO_2 – Safety Aspects Related to Transmission of CO_2," IEA Greenhouse Gas R&D Programme, January 11, 2001.
[65] Hattenbach, R.P., Wilson, M. and K. Brown, "Capture of carbon dioxide from coal combustion and its utilization for enhanced oil recovery," in *Greenhouse Gas Control Technologies*, Elsevier Science, New York, 1999, pp. 217-221.

(with no injuries) during its first twelve years of operation. This pipeline, which extends 140 miles from McCamey, Texas, to Kinder Morgan's SACROC field is 16 inches in

Figure 6.1: Val Verde Pipeline, Petro Source Carbon Company, cited October 11, 2002 at http://www.petrosourcecorp.com/HP_co2.htm

diameter and has the capacity to deliver up to 240 MMcf of CO_2 per day.[66] The Val Verde Pipeline, pictured in Figure 6.1, is an 82-mile, 10-inch diameter pipeline which has the capacity to transport 70 million cubic feet of anthropogenic CO_2 from four gas treating plants to the Canyon Reef Carriers pipeline, which is then used for EOR operations.

6.2 Political and Regulatory Considerations

The regulatory authority, the US Office of Pipeline Safety reports that most natural gas pipeline accidents were caused from damage inflicted from an outside source (e.g. excavation equipment).[67] If an operator does not report the damage immediately, leaks may occur over long periods of time or more serious failure may result years later. Figure 6.2 illustrates the causes of incidents associated with hazardous liquids pipelines

[66] Kinder Morgan CO_2 Company, "Transportation," [Online Document], 2001, [cited September 18, 2002], http://www.kindermorgan.com/co2/transport_canyon_reef.cfm
[67] Office of Pipeline Safety, Research and Special Programs Administration, [online document], 2001, [cited August 2002] http://ops.dot.gov/stats.htm

in 2001. Although there is little or no comprehensive source on the causes of CO_2 pipeline failures, it is reasonably safe to assume that the causes of failure would be similar for all pipelines.

Title 49 of the Code of Federal Regulations, Parts 190-199 embodies the regulatory framework for ensuring the safety and environmental compliance of pipeline transportation. This regulatory framework is well developed and reflects a great deal about what is known in transporting materials via pipeline. Specifically, 49CFR195 addresses transport of hazardous liquids and CO_2. Under Federal Regulations, CO_2 pipelines are classified as "High Volatile/Low Hazard" and "Low Risk."[68]

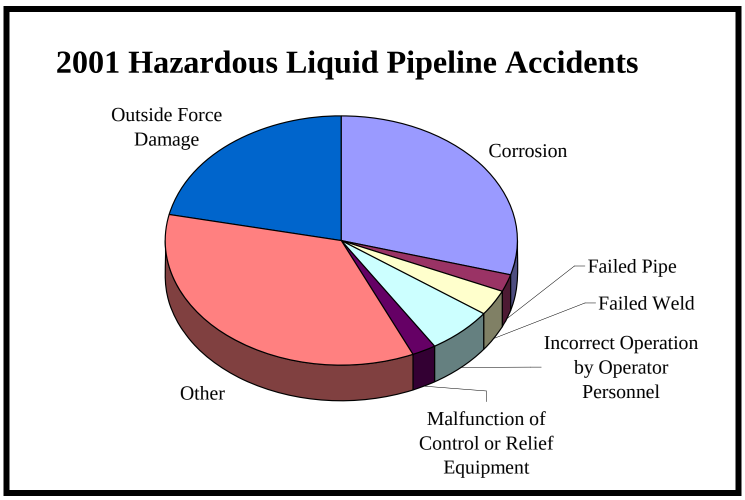

Figure 6.2: Data from Office of Pipeline Safety[69]

6.3 Safety and Environmental Concerns

Although the direct risk to humans is relatively low when proper safety measures are taken, pipeline development and construction is often disruptive to the local environment. Many examples of environmental and social degradation can be found especially in developing countries where construction of pipelines required the clearing of forests and

[68] Gale, John and John Davison, "Transmission of CO_2 – Safety and Economic Considerations," IEA Greenhouse Gas R&D Programme, presented at the GHGT-6 Conference, October 2002.
[69] Corrosion includes both internal and external corrosion while "other" refers to sabotage, natural disasters, mechanical failure, etc.

vegetation for the pipeline right of way. Most projects have environmental management plans established to mitigate damage, restore native vegetation and prevent vehicular access to the right of way.

Once built, safety concerns associated with CO_2, natural gas and hazardous waste transportation via pipeline are generally well understood. In fact, in terms of incidents per 1000km of pipeline, CO_2 pipelines are as safe as natural gas pipelines.[70] Risk management strategies are incorporated into the design, construction and operation of current and future pipelines. With regards to CO_2, best practices include but are not limited to selecting sites and methods that reduce the probability of accumulation resulting from leakage or injection well failure. Best siting practices would involve avoiding low-lying areas, or selecting a site with sufficient circulation (e.g. higher altitudes, open areas) to prevent accumulation. An additional measure to reduce risk could include adding odorous chemicals, like those added to natural gas, which help in detecting leaks especially around more populous areas. This technique has had a positive impact on leak detection at the Weyburn facility and its supplying pipeline.[71]

CO_2 transport is a widely practiced and accepted technological application presently employed in a variety of industries. Moreover, procedures to determine the risk of pipeline failure are well established.[72] Extraction, transportation, processing and injection of CO_2 are common exercises today and appear to be adaptable to handle larger-scale geologic storage operations.

6.4 Drivers of Operational Success and Risk Reduction

Most of the existing network of CO_2 pipelines has been developed in order to supply EOR operations in the southwestern United States. At present, the need for these systems depends on the potential for profitable enhanced oil recovery. CO_2 pipeline technology

[70] Gale, John, "Geological Storage of CO_2 – Safety Aspects Related to Transmission of CO_2," IEA Greenhouse Gas R&D Programme, January 11, 2001.
[71] Gale and Davison, 2002.
[72] Gale, 2001.

and engineering is similar to that used in other more abundant pipeline networks such as those for oil and natural gas. Therefore, most of the safety, monitoring and emergency response practices are similar and easily replicated. Because pipelines networks are often located in remote areas of the country coupled with the fact existing oil and gas operations often provide substantial economic benefits to the local public, most CO_2 pipelines have not encountered significant public opposition. In the near future, CO_2 pipeline development will continue to be driven by the need to transport a stable supply of CO_2 for enhanced oil and gas recovery, but the longer-term outlook is not as clear. Future CO_2 and greenhouse gas regulations may dramatically change current profit structures and reshape the future and geographical distribution of CO_2 pipeline development. Restricting CO_2 emissions may have the effect of increasing the profitability of EOR operations and therefore encouraging the development of new CO_2 pipeline networks in areas where natural CO_2 sources do not exist.

7.0 Yaggy Natural Gas Storage Field: A Case Study

The Yaggy Natural Gas Storage Facility, located 7 miles northwest of Hutchinson, Kansas, contains 98 caverns at depths greater than 500 feet with a total capacity to store 3.2 billion cubic feet (Bcf) of natural gas.[73] Total underground storage capacity in the state is approximately 30.15 Bcf.[74] Compared with many other underground sites around the country, the Yaggy field is quite shallow. For example, the average well depth at the Yaggy site is around 650 ft. compared to about 2,000 ft. on average in other states. The Yaggy facility, owned and operated by the Kansas Gas Service, is the only facility in Kansas in which natural gas is stored in salt caverns. Most salt caverns in the state store gas liquids. Formerly a propane storage facility, Yaggy field was closed in 1989 and then reopened in 1992 to help meet rising demands for natural gas.

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[73] Kansas Geological Survey, "Hutchinson Response Project"[online document] cited June 2002 available at www.kgs.ukans.edu

[74] Energy Information Administration, "Table 14: Activities of Underground Natural Gas Storage Operators, by State, August 2002," [online document] cited August 2002 available at http://www.eia.doe.gov/pub/oil_gas/natural_gas/data_publications/natural_gas_monthly/current/pdf/table_14.pdf

On January 17, 2001, a transient underground plume of natural gas exploded in downtown Hutchinson, Kansas, causing millions of dollars in property damage and costing two residents their lives. According to the Kansas Geological Survey, gas had escaped from a ruptured pipe in the Yaggy natural gas storage facility nine miles northwest of Hutchinson, migrated and accumulated beneath the city, then vented to the surface through abandoned wells. Geologists believe a hole in a damaged well pipe resulting from a 1992 reopening eventually allowed the gas to escape. The plume then traveled uphill through a thin corridor of dolomite rock fractured by geologic forces.

In support of this theory, state investigators uncovered records on file with the Kansas Department of Health and Environment that indicated drilling crews struck a metal object inside the pipe casing of the salt cavern while trying to reopen it in 1992. Experts suspect that subsequent attempts to drill out the object might have damaged the casing, possibly creating a pathway for a gas leak from the cavern that is believed to be the cause of Hutchinson's natural gas accident. Surprisingly, the gas managed to travel through a fairly impermeable dolomite layer of rock via a small fracture zone in the formation. This pathway allowed the gas to make its way towards the populated areas in and around Hutchinson. "Officials said the leak from the underground storage cavern created nine plumes of gas -- eight clustered in the residential area and one downtown."[75] Once the gas re-accumulated underneath the city, it was able to reach the surface through old abandoned brine wells. Experts estimated that a total of 143-200 million cubic feet of gas was lost from the field.[76]

7.1 Regulatory Reform and Key Drivers

Although solution-mined caverns have been used to store hydrocarbons for nearly 50 years, the first regulations dealing with this activity are less than 25 years old. According to testimony before the Kansas Senate Utilities Committee, current regulations in most

[75] "Officials Working to Plug Natural Gas Leak," *Jefferson City News Tribune Online Edition*, January 20, 2001, available at http://newstribune.com/stories/012001/wor%5F0120010007.asp
[76] "Report Links ONEOK Gas Leaks to Hutchinson Blast," *Lawrence Journal World Online*, July 30, 2002, available at http://www.ljworld.com/section/hutchinsonfires/story/101041

other states are less than 10 years old.[77] In the natural gas industry, accidents affecting the public are a key regulatory driver, so it was not surprising that Kansas state legislators immediately called for a tightening and updating of underground storage regulations. This type of regulatory development has also been observed in Louisiana in which a fire erupted during the initial oil filling of an underground strategic oil reserve cavern.[78] Similarly, Texas regulations followed a LPG accident resulting from a leak in an underground salt dome. However, other states have developed regulations in the absence of accidents. Mississippi, Alabama and New York have regulations governing underground storage of hydrocarbons even though no accident had occurred within their state boundaries.[79]

Oklahoma, which borders both Texas and Kansas, does not have a regulatory regime concerned with the underground hydrocarbon storage even though this activity occurs in the state. In general, the call for more detailed regulations in Kansas specifically included the "mandated use of control-sensing devices, more frequent inspections and reports, and prompt public notification of problems[80]." The Kansas Department of Health and Environment (KDHE), which regulates underground natural gas storage, was criticized for its lack of effectiveness and dearth of capacity to adequately perform its duties. Compared to other states, KDHE has a staff about one-fifth the size per well for the same inspection and regulation. This amounts to about 1 part-time person to oversee 632 CNG storage wells. As a result, the agency has only conducted one on-site inspection since the Yaggy facility reopened in 1993. Kansas regulations, unlike those in Texas and Louisiana, do not require frequent monitoring and inspection.

Although some prominent environmental groups, such as the Sierra Club, joined the call for new regulations, it was the politicians who were the major drivers of regulatory reform following the accident. The media also played an important role informing the public on a local and regional level and for the natural gas storage industry on a national

[77] Ratigan, J., Sofregaz USA, Inc., Testimony to the Kansas Senate Utilities Committee, February 27, 2001.
[78] ibid
[79] ibid
[80] "Burning: Lost storage gas flares on in Kansas," *Gas Utility Manager*, April 2001, [online document] cited May 2002 available at www.gasindustries.com/articles/giapr01b.htm.

and international level. For example, most of the public news coverage occurred within a relatively small geographical area. Local papers in surrounding states such as Oklahoma, Missouri and Nebraska reported the incident although there was no real impact on existing regulations or agency practices. However, for interested members of the industry, the Kansas incident spread around the world in days via the internet, professional groups and word of mouth. The Europeans were especially interested in the what, why and how to prevent a similar incident. Proposed underground storage projects in England were temporarily halted until the mystery was solved.[81] Other LPG accidents have occurred within the industry where little damage occurred, yet each was still widely known throughout the industry. Unlike other mishaps (which seem to be somewhat common) the Hutchinson case had a significant impact because of the property that was damaged and especially the people who were killed. A one industry analyst observed, the subsequent regulatory changes can be directly attributed to the loss of life within the community. Industrial accidents involving workers are insignificant compared to industrial accidents killing others."[82]

7.2 Impact on Other Geographical/Jurisdictional Areas

One variable that may help inform an understanding of regulatory development in the natural gas industry and in a possible carbon storage scenario is the ripple effects or the pressure for regulatory change across jurisdictional or geographical boundaries. For instance, in this case, news of the explosion spread within days or even hours particularly among industry analysts, but had relatively little influence as a regulatory catalyst in other geographical and or jurisdictional areas. Again, news of the accident made its way into Oklahoma, Nebraska and Missouri, but with little effect. The Solution Mining Research Institute, a major professional society, was very active in disseminating information to both its industry members and other regulatory agencies across the country and the world. Although the specific type of storage in Kansas is fairly rare, many industry and regulator groups watched the developments closely. The incident prompted

[81] Phone interview with Michael Schumacher, Cargill Salt Division, March 13, 2002.
[82] ibid

operators and regulators to further scrutinize projects and assess problems around the county as well as in Europe where they watched intensely.

The information ripple definitely spread quickly throughout the industry, but most states and operators found that the Kansas regulations, safeguards and procedures were inadequate relative to those currently employed by others. As more information came to light about the Yaggy situation, the concern from industry and the ripple effects began to evaporate. As the investigation continued, the evidence that was uncovered seemed to suggest that the incident was largely the result of lax regulations, substandard monitoring and poor engineering practices specific to the situation. For example, Kansas had not incorporated safety standards recommended by the Interstate Oil and Gas Compact Commission (IOGCC) developed after a 1992 hydrocarbon storage accident in Texas that killed three people. The IOGCC represents the governors of 36 states that produce virtually all the domestic oil and natural gas in the United States. The IOGCC Guide, “Caverns--A Guide for State Regulators,” provides safety standards for the design, construction, and operation of gas storage caverns. Since the accident, Kansas regulators have worked to incorporate the IOGCC standards into the revised regulations.

> “If we were to conclude that this whole event was triggered by gas that escaped from Yaggy Field, traveled 8 miles through an underground geological formation — if we conclude it has the capacity to do that — I would have serious reservations, absent some significant changes in the way we monitor and the way Kansas Gas Service does business out there.”
>
> - Kansas Governor, Bill Graves

The ripple effects seemed to be small once it was determined that lax regulations and out-dated engineering practices were being employed in this case, however, news of the accident caused a great deal of concern for both regulators and operators around the world until there was greater understanding of the situation. It can be reasonably concluded then that had a new phenomenon been discovered, it could have had a large impact on new storage developments, operations and regulations around the world.

In the natural gas industry, regulations tend to be written after an incident occurs, thus the more caverns states have the higher the probability that an incident will occur, thus the higher the probability for more stringent regulations. In the Yaggy Field accident, a small staff was trying to regulate natural gas storage as well as a number of other things. Most likely the staff did not fully understand the case well enough to regulate with a great amount of diligence. A lax regulatory environment allowed operators to slack on engineering practices and probably didn't violate the rules even though the best engineering practices were not being used, but lax rules allowed them to be lax. After the incident, Kansas standards are converging with the stricter rules of other states.[83]

After the 1992 pipeline accident in Texas involving liquefied natural gas, the Research and Special Programs Administration (RSPA), within the Department of Transportation, decided that generally applicable federal safety standards may not be appropriate for underground storage facilities.[84] At the time, RSPA advised that underground hydrocarbon storage requirements should be tailored to a state's particular circumstances. Further, they encouraged state action and voluntary industry action as a way to assure underground storage safety instead of proposing additional federal regulations.

The professional society, Solution Mining Research Institute (SMRI), was an important source of information for both regulators and operators. They consistently published and mailed reports/updates to all its members and many regulatory agencies who were nonmembers to keep them informed on the Kansas situation. In addition to up-to-date news on the website, this method proved to be a valuable source of information to all parties. Furthermore, SMRI holds two forums per year where professionals and experts discuss current issues and present papers on related topics. This was another important conduit for disseminating information regarding the Kansas happenings.

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[83] Phone interview with Charles Chabennes, Duke Energy, March 14, 2002

[84] Federal Register: July 10, 1997 (Volume 62, Number 132) http://www.epa.gov/fedrgstr/EPA-GENERAL/1997/July/Day-10/g17722.htm

7.3 Main Points from Case Study

1. Gases stored in geologic formations have the ability to relocate and re-accumulate near populated areas thereby creating a potential hazard.

Many of the experts involved in the investigation were very surprised an accident of this nature could happen. This fact speaks to the potential for uncertainty and unpredictability of a gas's behavior in sub-surface geologic formations. It is essential to think and plan for all possible adverse scenarios; unfortunately, it's always the one not thought of that seems to happen.

2. New regulations are often an adoption/adaptation of regulations in other jurisdictions.

The Canadian province of Nova Scotia is in the process of updating their regulations by reviewing what other states and regulators are doing. This is a standard practice for regulators (i.e. to review other states regulations and adopt some form of others). In fact, the newly proposed Kansas regulations are essentially the same regulations already established in Texas.

Regulatory innovation usually only occurs when highly knowledgeable and proactive regulators are involved with the luxury of large budgets. This seems to be correlated with the size of underground hydrocarbon storage operations in the state. For example, Texas and Louisiana, two states with extensive storage operations and well-staffed agencies seem to have the most innovative regulations in the industry; therefore, they often act as leaders which others often emulate.

3. Calls for new regulation in this industry most frequently follow incidents affecting the public.

Although many accidents have occurred with liquid hydrocarbon storage, this was the first incident of underground natural gas storage in salt caverns. Other LPG accidents have occurred where little damage has occurred, yet it was still widely know throughout the industry. The Hutchinson incident had a substantial impact within the industry because of the property that was damaged and people that were killed.

4. Ripple effects (in terms of changing existing practices) were not especially significant.

Once the existing regulations were determined to be outdated, thus permitting lax engineering practices, the Hutchinson accident lost some of its value as a catalyst for regulatory reform outside of the state. If the source of the leak would have been attributed to a failure in the storage facility instead of a damaged pipe, the incident would have had a more substantial ripple effect.

5. Epistemic communities and industry groups are important in disseminating information.

Information about the Kansas incident went around the world in days via TV, internet, professional groups and word of mouth. The Europeans were especially interested in what happened, why it did, and how future occurrences could be prevented. This fact merely illustrates the point that information can be disseminated quickly but rules often change slowly. In this case, the media played an important role on the local and regional level while the NGOs and grassroots organizations were less important in driving regulatory reform.

These important lessons are very tangible in the context of CO_2 storage. In later sections of this thesis, proponents of storage have highlighted the need to study the latent effects of underground gas storage and the potential for migration and re-accumulation. In addition, the political and regulatory response that followed an underground storage accident of this nature adds to our understanding of these processes and will better allow us to develop a regulatory regime and predict its dynamic characteristics over time.

8.0 Lessons Learned

A number of practical lessons can be learned from studying current activities in the oil and gas industry that are directly relevant to geologic storage of CO_2. Some of the key insights that could be immediately implemented include safety and operator training procedures, emergency response plans, automated shutdown systems and important management strategies for public relations and gas processing. These are critical practices now employed in existing operations.

Despite the practical insights gained, a more general theme has emerged from looking into these analogs: similar activities have existed, evolved and have been managed successfully for decades. Three points deserve special attention:

1. Low-volume geologic storage of CO_2 has successfully occurred in the form of enhanced oil recovery since the early 1970s and under the guise of acid gas injection since 1989. The specific knowledge and expertise now exists for effective management and should be exploited for storage activities.

2. All four analogs evolved incrementally into major operations over time. For instance, the first acid gas injection operation injected roughly 10 tonnes per day in 1989. Today, the largest acid gas injection scheme injects nearly 1,400 tonnes per day into a depleted gas field. The development of a geologic CO_2 storage regime would also benefit from the evolution of small-scale operations to a larger more voluminous storage regime.

3. Through research, experience and public outreach, operators and regulators have successfully managed the risks, benefits and public apprehension associated with these activities.

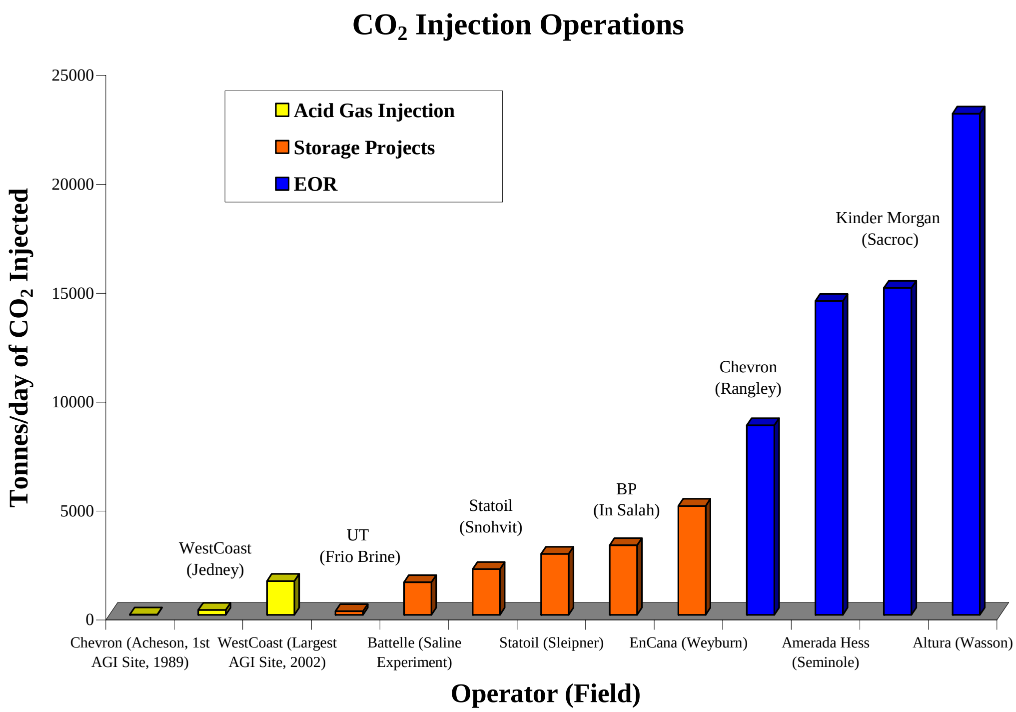

Figure 8.1: Comparison of CO_2 Injection Activities (Data from Hovorka, 2002; Lock 2002; Maldal, T., and Tappel, I.M., 2002; Roche, 2002; Riddiford, F.A., et. al., 2002; Stevens, et. al., 2000)

Based on experiences with acid gas injection, EOR activity, natural gas storage and CO_2 transport, most of the environmental and safety risks associated with the handling and injection of CO_2 seem to be well understood and generally accepted by the local public, at least at the present level and geographical distribution of operation. Figure 8.1 illustrates the current magnitude of CO_2 injection activity in acid gas injection, direct storage activities and enhanced oil recovery projects. The figure shows that storage-related activities are becoming quite substantial and will continue to increase in size in the future especially if a market develops and/or government offers incentives for development. Although both acid gas injection schemes and current storage projects inject volumes below the projected sizes of future commercial storage applications, the largest EOR operations far exceed 10,000 tonnes per day, a reasonable metric for future storage activities. Granted, while most of the CO_2 injected daily in EOR projects is recycled through the process, a single EOR project can sequester around 2000 tonnes per day, which is on the order of acid gas injection and CO_2 storage operations.[85] Although these activities are not totally risk free, the benefits of lower energy prices, reduced emissions, and economic development are likely to outweigh the risks, which have already been greatly reduced through years of experience, public education and proper management strategies. Will CO_2 storage have the same experience? It will depend on how far/fast CO_2 storage increases in size and whether local populations can enjoy similar benefits as in EOR, etc.

This section highlights many of the environmental and safety issues associated with current activity in the oil and gas industry and demonstrates the many similarities to geologic CO_2 storage. Section 9 turns to the mechanisms and implications of various risks specific to geologic CO_2 storage should a scaled-up program arise.

9.0 Risks Associated with Geologic CO_2 Storage

9.1 Identification

This section reviews the risks emerging from the literature on geologic storage of CO_2. Much has been written about the environmental and human health issues related to exposure to CO_2.[86,87,88] In sum, CO_2 is denser than air and can cause asphyxiation if allowed to accumulate and displace oxygen in confined areas without sufficient ventilation. Also, because of its acidic characteristics, CO_2 can in some cases threaten potable water sources and surrounding ecosystems.[89,90] In order for these events to occur, some elements of the storage system must fail in its ability to contain the CO_2.

[85] Stevens, S.H., Kuuskraa, V.A. and J.J. Taber, 2000. pp. 36-58.
[86] Benson, et al., 2002. pp. 13-39.
[87] Holloway, S., "Safety of the underground disposal of carbon dioxide," *Energy Convers. Mgmt*, vol.38, 1997, pp. 241-245.
[88] Smith, Larry, N. Gupta, B. Sass and T. Bubenik, "Carbon Sequestration in Saline Formations-Engineering and Economic Assessment: Final Technical Report," PRDA #: DE-RA C26-98FT35008, Battelle Memorial Institute, July 9, 2002, pp. 42-43.
[89] Benson, et al., 2002. pp. 13-39.
[90] Holloway, 1997, pp. 241-245.

Fundamentally, a CO_2 storage system can be broken down into two general subsystems, namely operational and *in situ*. The operational subsystem is composed of the more familiar components of CO_2 capture, transportation and injection, which have been successfully deployed in the previously discussed applications. Once CO_2 is injected in the reservoir it enters an *in situ* subsystem in which the control of CO_2 is transferred to the forces of nature. Years of technological innovation and experience have given us the tools and expertise to handle and control CO_2 in the operational subsystem with adequate certainty and safety; however, that same level of understanding is largely absent once the CO_2 enters the storage reservoir.

Hawkins and other environmentalists raise key questions (See Appendix A for list of questions) that must be addressed if we are to successfully implement large-scale storage without widespread public opposition. While the answers to many of these questions are relatively uncertain at this point, there is a great deal of effort and research now going on that is attempting to address these critical issues.

Some have suggested that global risks may arise from increases in emissions over time due to the energy penalty associated with capture.[91,92] Because of all the feedbacks involved in our energy systems, it is very difficult to claim with any certainty that total future CO_2 emissions from scenarios with leaky storage reservoirs would be greater vis-à-vis a scenario without CO_2 storage. For example, policies to stimulate storage activity will probably increase the cost of CO_2 emissions. Increasing the cost of emitting CO_2 should lead to smaller market shares for fossil energy. In our view, the suggested "increase in emissions" is more of a policy and economic issue than a direct safety or environmental risk and, therefore, beyond the scope of this thesis.

[91] Wilson, Elizabeth, Tim Johnson, and David Keith, "Regulating the Ultimate Sink: Managing the risks of geologic CO_2 sequestration," submitted for *Environmental Science and Technology*, 2002.
[92] Union of Concerned Scientists, "Policy Context of Geologic Carbon Sequestration," [online article] 2002, [cited September 13, 2002] http://www.ucsusa.org/index.html

The Union of Concerned Scientists and others have raised concerns about the "deep hot biosphere," referring to biological communities within the potential storage formations.[93] Studies conducted over the past two decades have documented that such communities are present deep in the subsurface, including depths where geologic storage of CO_2 is likely to occur. The structure (species of organisms present and how they interact with each other) and function (what they do in these environments) have only been studied in a few locations. However, in general, these deep biological communities are few in number and less active than communities in the comparable near-surface environments. The environmental significance of these communities is not likely to be a serious concern for the following reasons: (1) they are unlikely to play an important ecosystem function, instead they are probably just barely surviving in this environment, and (2) the "foot print" of geological storage is going to be small compared to the total amount of subsurface habitat available for these organisms – so even if these microorganisms are harmed within the CO_2 plume, loss of biodiversity and ecosystem function will be negligible.

The primary concerns we address in this section are direct environmental and human health risks. Researchers are now conducting studies to evaluate the likelihood and potential impacts associated with the key systematic risks as they pertain directly to human health and environment. These risks result from the potential for large catastrophic leaks, slow migration and accumulation, and induced seismicity. The following section will discuss them in more detail.

9.1.1 Subsystem: Operational

Human health and environmental risks associated with operating CO_2 storage activities are no different in character, if not in quantity, than the risks in other ongoing operations in the oil and gas industry. As far as the processing, transporting and injecting of CO_2 are

[93] ibid.

concerned, the risks are well understood and the risk management strategies are well developed.

Some of the most common risks are a consequence of well and pipeline failure. According to the US Office of Pipeline Safety, pipeline damage most often occurs from external activities (e.g. unrelated construction operations or farming activities).[94] Corrosion is also a concern, but these issues seem to be more relevant to older wells and pipelines than newer ones. The newest materials and technologies are sufficiently corrosion resistant. Other damage to a well can occur when it is reopened for uses other then its original intention. State regulations often dictate which practices are employed. For example, some states prohibit well re-openings while others do not. Further, states with laxer regulatory requirements and enforcement do not always ensure the best engineering practices are in use.

Although many problems arise from operator error, a significant number of accidents can be prevented if safety recommendations are followed. Other causes of pipeline and well failure include well leakage between the casing and wall of the bore hole from a poor seal and pack, venting from poorly abandoned or forgotten wells, improper deployment of shut-off capability, and insufficient leak detection or pressure monitoring systems.

None of the operational issues are new to industry and thus should not be major obstacles in the development process of a geologic CO_2 storage regime. The capture, processing, transport and injection of CO_2 are proven practices using established technologies.

9.1.2 Subsystem: *In Situ*

Unlike the operation subsystem, we have less experience storing CO_2 in geologic reservoirs. This section will take a closer look at some of the key issues associated with the *in situ* subsystem.

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[94] Office of Pipeline Safety, Research and Special Programs Administration, [online document], 2001, [cited August 2002] http://ops.dot.gov/stats.htm

Formation Leakage to the Surface

Carbon dioxide occurs naturally in literally thousands of CO_2 and hydrocarbon reservoirs around the world. Therefore, it would seem that we have more experience with storage than some might think. Nevertheless, storing CO_2 in geologic formations, especially near populated areas, raises concerns about CO_2 venting slowly or even catastrophically to the surface and creating unwanted hazards. Diffuse CO_2 releases occur continuously in the form of earth degassing, biological respiration, and organic matter decomposition. Volcanic releases, while more profound in terms of the volume of CO_2 released, have occurred in the past, but they are not all that common. Despite their low frequency, for some, risks of this nature bring to mind a few of the more catastrophic events involving uncontrollable CO_2 releases. Notwithstanding the dreadfulness of these events, their relevance to furthering our understanding about the risks associated with storage activities is debatable. Although the technical estimates of these catastrophic-type risks are likely to be quite low, the degree of dread associated with events such as Lake Nyos and Mammoth Mountain have heightened risk perceptions. In Lake Nyos, Cameroon, an estimated 100,000 – 300,000 kg of concentrated CO_2 erupted from a volcanic crater killing 1700 people.[95] On Mammoth Mountain, a volcano in eastern California, approximately 1200 tonnes per day of CO_2 emitted through the soil and killed over 75 acres of trees.[96]

While catastrophic CO_2 releases from a formation are a legitimate concern, they are not all that likely to occur for a few reasons. Instances of large catastrophic releases of CO_2 from volcanic activity are not that analogous to geologic storage of CO_2. By nature, CO_2 pressurizations from volcanic activity, such as occurred in Lake Nyos, are very different than injection into a hydrocarbon reservoir engineered for CO_2 storage. Lake Nyos concentrated the CO_2 coming from the volcano. Eventually it had to erupt because CO_2 continued to build-up in a lake of finite volume. In a similar fashion, one can only expect to blow up a balloon so far before it bursts. For CO_2 storage reservoirs, natural forces

[95] Holloway, 1997, pp. 241-245.
[96] ibid.

will act to diffuse the CO_2. Also, these reservoirs can be managed to avoid pressure buildup that could lead to a large release.

Although storage reservoirs are engineered to contain a certain volume of CO_2, design factors do not preclude relatively low volumes of CO_2 from escaping. These releases can occur through cracks in the formation or venting through an abandoned well, but again substantial leaks are presumably rare if proper practices are employed during abandonment. In fact, drilling operators take special measures to ensure that wells are sealed tightly and equipped with safety features such that gases cannot escape back up through the well or between the rock and casing. Further, pressure tests used to evaluate a formation's containment ability are well developed and used frequently before initiating large-scale injection operations in industry. Nevertheless, these risks do shape public debate and perception.

In sum, CO_2 releases to the surface occur continuously and are usually relatively harmless primarily because they are diffuse. However, once in a while, large concentrated releases can occur that pose greater risks to humans. Thus, the nature of release, terrestrial and weather conditions, proximity to humans and the opportunity to accumulate are all important factors in assessing the risks associated with CO_2 leakage. If effective containment can be achieved and verified in the subsurface and opportunity for accumulation can be reduced, the risks of CO_2 storage can be substantially mitigated.

Leakage within the Geologic Formation

Although engineers, etc. have made significant advances in understanding fluid behavior and formation integrity in the subsurface, there is still some degree of uncertainty involved. While various tests and models can be developed to fairly accurately predict key variables, there is always the potential for CO_2 leakage from the intended storage formation. For example, hydrocarbon and groundwater contamination can occur if CO_2 migrates to other zones in the subsurface. This problem may be compounded by an inability to control fluid movement in the subsurface over the long-term. As mentioned in the EOR section, some operators speculate that CO_2 may be lost through the oil-water contact zone. This would not likely pose a danger to humans or potable water zones due to the depth of the reservoir, but nonetheless could be a pathway for CO_2 to move out of the intended zone. Researchers at Princeton University are looking into the possibilities and mechanisms by which CO_2 can carry lead and other contaminants into potable waters or other undesirable areas.[97] Also, the safety and stability of underground storage of CO_2 depends on the geochemical or biochemical compatibility between the CO_2 and the geologic characteristics.[98]

The uncertainty associated with leakage in the *in situ* subsystem is compounded by the extended time periods involved. EOR operators have not experienced significant losses of CO_2 to other zones in the subsurface, nor have they been concerned with leaching effects or incompatibility with the formations. However, EOR has only occurred for 30 years, a relatively short time period in the context of CO_2 storage. Risks that have longer latency periods, such as the risk of CO_2 gradually migrating and re-accumulating into other shallower zones over time are not fully understood. This phenomenon can present a number of human health concerns. For instance, there is the possibility of CO_2 migrating near or under residential areas creating a potential hazard for anyone attempting to drill or excavate in an area. Thus the latent effects of underground storage should be more thoroughly understood as geologic storage moves ahead.

Seismic Events

At present, most acid gas injection, EOR and underground natural gas storage operators are not overly concerned with inducing seismic events, primarily due to the low volumes of fluids being injected. However, larger volumes of injected fluid would increase reservoir pressure, displace other fluids and might then induce seismic events.[99] Reservoir Induced Seismicity (RIS) is primarily a potential environmental and dam safety-related concern. The mechanism by which seismic activity is induced is generally

[97] Wilson, Elizabeth, Tim Johnson, and David Keith, 2002.
[98] Holloway, S., et al., 1996, pp. 1-24.
[99] Holloway, et al, 1996, pp. 1-24.

understood, however the means to reliably predict such events are limited. One of the first recorded instances of induced seismicity occurred in 1966 as a result of storage of contaminated fluids at the Rocky Mountain Arsenal in Denver, Colorado. Interestingly, the Canadian Induced Seismicity Research Group (CISRG) reported,

> *Not all seismic activity was proved to be connected with the fluid disposal, but awareness and social sensitivity brought the operation to an end because of environmental concern associated to increased social sensitivity rather than real threats.*[100]

CISRG argued that induced seismicity might be more of a concern in areas of low natural seismicity because induced events may have a greater impact than naturally occurring ones. Nevertheless, careful siting, design, pressure monitoring and placement of wells and pipelines can significantly reduce the risk coupled with seismic activity.

Indeed, the uncertainties characterizing human health and environmental risks resulting from the operational and *in situ* subsystems are compounded by the extended time scales involved. As a result, further understanding is needed to develop the credibility necessary to bring this technological approach to fruition in a manner that is politically and socially acceptable. One way to aid and prepare this process is by explicitly identifying the risks that are likely to be the most difficult to manage, regulate, communicate, and ultimately gain public acceptance. The following section attempts to characterize the risks in this manner in order to better inform the process for moving forward.

[100] Vladut, Thomas, "Induced Seismicity and Earthquake Prediction," Canadian Induced Seismicity Research Group, [online document], 1999, [cited September 10, 2002] available at http://www.cadvision.com/retom/predict.htm

9.2 Risk Characterization

In general, the level of CO_2 concentration within a particular confined space is more of a contributor to harmful effects than the sheer volume of CO_2 emitted or the source. Hence, CO_2 releases, even large ones, which are quickly dispersed into the atmosphere, do not have particular relevance to potential leaks that take place over long periods of time from underground storage reservoirs – a more likely scenario in the case of geologic storage.[101,102]

The literature concerning risks and uncertainty provides a great deal of valuable insights here. There is not one clear or correct model for making decisions about risk. Risk perceptions and valuations depend on the values and experiences of individuals and society. For instance, risks are not defined exclusively by the number of deaths or injuries over a specific period of time. Risk evaluation depends on how well the process in question is understood, how well people can manage their exposure and whether the risks are voluntary and distributed fairly.[103] Morgan has used these characteristics to develop a "risk space" in order to help identify how people are likely to respond to certain events. Figure 9.1 is a modified risk space that has been developed to help assess and predict possible responses to various risks associated with geologic CO_2 storage. Many different attributes could be used to compare risks, but characteristics such as the level of understanding and the ability to mitigate adverse effects seem to be most relevant for geologic CO_2 storage at this early stage. In addition, the figure also indicates how perceived risks are likely to increase as understanding and controllability decreases. As proponents move ahead with geologic storage projects, it will be important not to dismiss the perceived risks held by the public. Proponents and policy makers need to recognize and communicate the "objective" (i.e. what the experts know) and perceived risks (what the public anticipates) with equal attention.

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[101] Holloway, S., "Safety of the underground disposal of carbon dioxide," *Energy Convers. Mgmt*, vol.38, 1997, pp. 241-245.
[102] Benson, et al, 2002, pp. 66-68.
[103] Morgan, Granger, "Risk Analysis and Management," *Scientific American*, July 1993. pp. 32-41

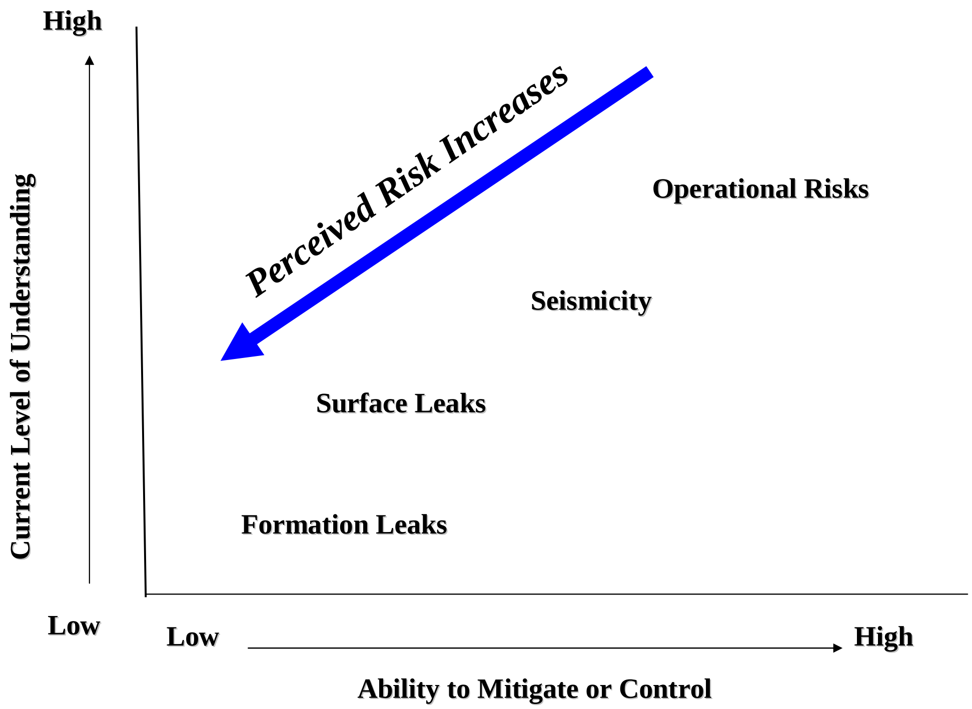

Figure 9.1: Relative Risk Space

The risk space attempts to make relative risk comparisons by combining our current degree of understanding (i.e. level of uncertainty) with our ability to manage a particular risk in an acceptable manner akin to what we now see in other industries. As the figure tries to illustrate, risks associated with daily operations are largely understood and can be controlled in a manner that is now socially acceptable in the form of CO_2 transport, EOR operations, and acid gas injection activities. On the other hand, most of our ignorance and lack of knowledge is connected to the ability of the geologic formation to adequately contain large volumes of CO_2 over extended time periods. This suggests more research and experience is needed to better understand the behavior of CO_2 once it is sequestered in the geologic formation (i.e. the *in situ* subsystem).

It is also likely that risks in the lower left space will encourage more stringent government regulation in order to provide a higher level of protection against adverse consequences, because operational risks are already controlled by OSHA-type regulations. For example, one of the most dread-inducing risk perceptions involves the catastrophic release and migration of large concentrations of CO_2. It is important to acknowledge the possibility that a CO_2 storage reservoir could experience a catastrophic release or accumulate in a basement or other low-lying area creating a hazard for those exposed. For example, a worker making a restaurant delivery was asphyxiated when CO_2 leaked and collected in a stairwell where the worker was standing.[104] Although this type of risk is of great concern, measures can be employed to manage and mitigate risks to acceptable levels. A related risk analog to this scenario may perhaps be radon, a gas known to increase the chance of lung cancer, but one that is accepted as an ordinary (e.g. not dread-inducing) risk and effectively mitigated once detected.

Risks characterized by high levels of uncertainty and high controllability require greater emphasis on understanding the nature of the risk. For instance, uncertainty about formation fracturing and migration of resident fluids as the reservoir pressure increases can be offset by carefully chosen storage sites, conservative pressure profiles and diligent reservoir monitoring. Storage risks identified in the upper right portion of the risk space are generally well understood and largely controllable due to previous experience and regulation in the oil and gas industry. For that reason, management strategies are also fairly well developed to deal with incidents as they occur.

An additional point the figure illustrates concerns the level of risk perceived by the public. The public's perceived risks are quite likely to be different than the more scientifically informed views which are based on technical measures of probability and consequence. In addition, the general public is probably more risk averse. Identifying which risks are perceived to be the most concerning is a critical task for project developers and policy makers moving forward. Without a keen understanding of the perceived risks and a strategy for dealing with them, proponents will face a tougher task scaling up to commercial level geologic storage regimes. These barriers will likely surface in the siting, permitting and development stages.

In previous sections, we have identified the most salient risks associated with geologic CO_2 storage and have fundamentally attempted to characterize them by our current level

[104] Smith, et al., 2002, p. 42.

of understanding and our ability to control the risk. These attributes can inform us on how some of these risks and uncertainties might be dealt with in the regulatory and political processes moving forward. As a result, better science and further understanding is needed in order to bring this technological approach to fruition. The following section provides an overview of the current attempt to develop this understanding.

10.0 Current Research

At the start of the 1990s, the field of carbon capture and storage consisted of a handful of research groups working in isolation. Finding funding was difficult, as this field was not one of the research priorities of traditional funding sources. This has all changed over the last decade. Today, there is an interconnected research community, with a high level of collaboration and increased funding sources. Equally as important, industry is taking a major role in analyzing and developing these technologies.

Perhaps the most significant development has been the Sleipner project, the first commercial application of emissions avoidance through the use of carbon capture and storage technologies. In addition, many other research level and commercial-scale CO_2 storage projects are being studied for their efficacy in containing CO_2 in geologic formations. Most notably, Encana's Weyburn EOR project is now being studied to assess the long-term implications of CO_2 storage and monitoring. Other new and significant storage activities include BP's In Salah Gas Project in Algeria, Statoil's Snøhvit gas operation and proposed experiments by the University of Texas and Battelle Memorial Institute. These projects and others around the world are focusing on health, safety and environmental assessments, reservoir characterization and modeling, as well as monitoring and verification.

In order to meet internal firm emissions commitments, BP and Sonatrach have designed an integrated emissions mitigation plan for the In Salah gas project that has allowed them to capture and sequester CO_2 in the subsurface. In order to export the produced natural gas, operators must first remove a high concentration of CO_2 from the produced gas stream. It is estimated that over the life of the project, over 450 billion cubic feet of CO_2 will be extracted from the produced natural gas stream.[105] During the design phases, project leaders considered a variety of storage options by evaluating the reservoir's demonstrated seal integrity, capacity, reservoir properties and pressure. As a result, the aquifer region of the Krechba Carboniferous reservoir was selected because of the extensive characterization operators had of the reservoir as a result of other well penetrations and a 3-D seismic image that provided them with a sound understanding of the geology in the prospective storage reservoir. While many lessons will be learned about reservoir selection and predicting CO_2 behavior in the reservoir, BP and Sonatrach could also take steps to design an effective monitoring and evaluation system that continues well beyond the life of the project. A longer-term approach would ensure that emissions reductions are achieved permanently and not just during the profitable life of production.

A project also involving the extraction and storage of CO_2 from a natural gas stream is Statoil's Snøhvit project. Again, high concentrations of CO_2 must be removed before the gas is sold to market. Over the 30-year life of the project, the CO_2 removed will represent nearly 2% of total Norwegian emissions.[106] During the design phase, developers considered 1) releasing CO_2 into the atmosphere, 2) ocean storage, 3) underground storage and 4) injection for EOR. Once the underground storage option was chosen, operators evaluated four possible storage formations and selected the Snøhvit Tubåen Formation because the formation had already been characterized from a previous operation. Reservoir modeling predicted a low probability of vertical CO_2 migration due to a thick gas water contact zone between the producing and storage formations. However, the model predicted lateral migration is more likely through the sand-sand contact zones. During the project life, CO_2 monitoring has been proposed by deepening a producing well and using it for observation. In addition, a feasibility study of 3D Seismic

[105] Riddiford, F.A., et al. "A Cleaner Development in the In Salah Gas Project, Algeria," presented at the GHGT-6 Conference, Kyoto, Japan, October 2002.
[106] Maldal, T., and Tappel, I.M., "CO_2 Underground Storage for Snøhvit Gas Field Development," Statoil, presented at the GHGT-6 Conference, Kyoto, Japan, October 2002.

monitoring is scheduled, as this type of monitoring has proven effective for CO_2 monitoring in saline aquifers. The Tubåen Formation located 60 meters below the producing formation is expected to store 23 million tons of CO_2.[107]

Additional field tests currently being designed include the Frio Brine project on the Texas Gulf Coast and a Battelle Memorial Institute field assessment in the Ohio River Valley. Sponsored by the University of Texas, the Frio Brine experiment is designed to produce a great deal of technical information based on monitoring and modeling small-volume CO_2 injection and storage over a shortened time period (on the order of 3500 tonnes over 3 weeks).[108] The experiment will be permitted as an Underground Injection Control (UIC) Class 5 experimental well. However, project planners were permitted to submit the shorter application for a Class 5 well in addition to a report detailing project and engineering practices usually included in a UIC Class 1 well permit. Although no impact is anticipated, project leaders will also work with the Texas Railroad Commission to assess the impact on oil production. Due to the experimental nature of the project, the Bureau of Economic Geology, the state survey, is planning to host public informational meetings, rather than conducting them through the traditional channels of the Texas Commission on Environmental Quality (TCEQ), which requires a lengthier process. Project leaders anticipate that future schemes will either require a Class 2 well permit, where injection occurs into a productive reservoir for EOR or Enhanced Gas Recovery, or a Class 1 well for injection into a brine formation away from producing areas.[109] Due the scientific nature of the project, there will be a significant opportunity to gain additional information from the measurements and instrumentation employed.

With support from the Department of Energy and other major energy companies, Battelle Memorial Institute will conduct exploratory field tests at a power plant in West Virginia by late 2003. The scope of this project includes site assessments, seismic surveys,

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107 ibid.

108 Hovorka, Susan and Paul Knox, "Frio Brine Sequestration Pilot in the Texas Gulf Coast," Bureau of Economic Geology, University of Texas at Austin, presented at the GHGT-6 Conference, Kyoto, Japan, October 2002.

109 Email correspondence with Susan Hovorka, Bureau of Economic Geology at the University of Texas at Austin, October 11, 2002.

drilling, testing, deep well development, reservoir modeling and preparation of regulatory permits for a potential CO_2 storage and monitoring facility.[110]

On the international level, the International Energy Agency set up an implementing agreement to establish the IEA Greenhouse Gas R&D (IEA GHG) Programme. Launched in November 1991, the IEA GHG Programme currently has 17 member countries plus 8 industrial sponsors. This international collaboration aims to identify and evaluate technologies for reducing emissions of greenhouse gases arising from the use of fossil fuels. From the outset, the primary technical focus of the IEA GHG Programme has been carbon capture and storage.

Other projects around the world in the process of addressing the key questions and uncertainties associated with storage include the CO_2 Capture Project, GEO-SEQ led by Lawrence Berkeley National Lab, Alberta Research Council projects, Geological Disposal of CO_2 (GEODISC), Saline Aquifer CO_2 Storage (SACS), and the RECEPOL Project. A one-page summary of each of these projects can be found in Appendix B.

Current research activities and proposed experiments are continuously adding to our level of knowledge and understanding about the environmental and human safety issues attributed to geologic storage. A well-funded and active community is working hard to address many of the critical questions and uncertainties laid out by many other experts and observers of the field. Although progress is being made, more research is needed, particularly with regards to the *in situ* subsystem, in order to ensure the safe and effective use of geologic storage technology.

[110] Gupta, N., et al., "Engineering and Economic Assessment of CO_2 Sequestration in Saline Aquifers," Battelle Memorial Institute, presented at the GHGT-6 Conference, Kyoto, Japan, October 2002.

11.0 Policy Recommendations and Needed Approaches

Geologic CO_2 storage has the potential to be an effective complement to other greenhouse gas abatement strategies now being pursued, but its success will depend on the proper alignment of the economic, political and social elements. Importantly, the two major international agreements concerning the issues associated with climate change, the Framework Convention on Climate Change (FCCC) and subsequently the Kyoto Protocol, espouse the need for further research and development in the area of CO_2 storage. The Climate Convention is the overarching and most widely agreed upon framework for addressing the problem of climate change and anthropogenic emissions of greenhouse gases. The Convention explicitly recognizes the role and importance in terrestrial and marine ecosystems of sinks and reservoirs of greenhouse gases.[111] The Convention specifically mentions the need for using sinks and reservoirs as one component of a more comprehensive portfolio of strategies for reducing greenhouse gas emissions. Article 4.1.d of the Convention notes:

> *Promote sustainable management, and promote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems;*

Likewise, the Kyoto Protocol emphasizes the

> *…development and increased use of, new and renewable forms of energy, of carbon dioxide sequestration technologies and of advanced and innovative environmentally sound technologies.*[112]

To pursue the broader goals set out in the international agreements, the United States must adopt policies that encourage the development and evolution of CO_2 storage technologies. Specifically, the policy needs include action by federal and state government to establish the appropriate incentives for industry. Such actions could

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[111] United Nations Framework Convention on Climate Change, 1992, Article 4.1.d, http://unfccc.int/
[112] The Kyoto Protocol to the United Nations Framework Convention on Climate Change, 1996, Article 2.1.a.(iv), http://unfccc.int/

include promoting voluntary emission reduction programs, restricting or taxing CO_2 emissions or encouraging new technologies through tax incentives. The Department of Energy should take the lead in coordinating with other federal and state agencies in developing an effective and consistent regulatory regime specific to CO_2 storage. Leading CO_2 storage proponents should continue to address public safety concerns and educate the public by leveraging expertise from existing operations and knowledge bases. Researchers in academia and industry as well as the operators in the field should continue to develop a better understanding of the environmental and human safety risks while developing the expertise and criteria for site selection. The development of clear and consistent policy signals designed to promote CO_2 storage is critical to the successful adoption of storage as one component of a larger portfolio of strategies to mitigate climate change. This section examines some of the policy issues and needed approaches most salient to understanding, managing and communicating the environmental and human safety risks associated with CO_2 storage in the United States.

For each of the three policy recommendations discussed below, the willingness, opportunity and capacity of the key stakeholders involved (i.e. industry, government, research community, public) to take the necessary steps toward a storage regime will be evaluated. Stakeholder willingness refers to their attitudes toward change, understanding of the problem and knowledge of solutions. Opportunity refers to the possibility for economic gain, the ability to capture advantage in the marketplace or to generate public and societal benefits. Willingness and opportunity are closely related because a party's willingness to take action may depend on the opportunity available. However, it is still insightful to distinguish between the two so that public policies can be more focused at overcoming the critical barriers to implementing a commercial-scale storage regime. Finally, stakeholder capacity refers to the available knowledge and expertise of each group to influence the problem at hand. Evaluating the willingness, opportunity and capacity of such large and internally diverse groups of stakeholders will necessarily require a large degree of generalization; yet despite the simplification, useful insights can be gained.

Policy Recommendation #1: Government should encourage the continued development and scaling up of technologies and expertise now employed in oil and gas operations by enhancing the willingness and opportunity of industry through market-based and regulatory incentives.

Key Stakeholders: Industry, Government

Willingness

Industry and government, the key stakeholders, have already been active in developing the core technologies and expertise necessary for storage. In Alberta, government imposed air emission standards encouraged industry to pursue alternatives to H_2S flaring and coincidentally releasing CO_2. Industry has also been more willing to appear green by making certain efforts to reduce their environmental impacts. Although industry is still reluctant to accept binding obligations and more stringent regulatory controls, the increase in industry willingness has been a result of greater awareness about the problem, gaining intangible public relations value, and due to their direct ability to influence the solutions. Nevertheless, greater industry willingness to adopt storage schemes will depend on other economic opportunities, regulatory controls, public acceptance of storage as a viable strategy and ultimately the bottom line. The willingness to widely adopt storage techniques needs to be increased by public pressures and government imposed incentives that includes stricter emissions regulations, enforcement and sanctions.

Increased global recognition and more intense debate over climate change have in part served to increase the willingness of industry to adopt new measures aimed at climate change. Voluntary emissions controls are examples of mechanisms that can lead industry to pursue CO_2 storage technologies. As mentioned in the Current Research section of the thesis, BP's In Salah gas project was developed directly as a result of internal emission control requirements voluntarily adopted by the firm.

Government willingness, at least at the federal level in the US, to impose any kind of restrictions or added costs on CO_2 has been extremely low and not likely to change in the near future. On the other hand, there may be a greater willingness at the state level to impose tighter restrictions on CO_2 emissions and encourage CO_2 storage development. Figure 11.1 illustrates that the states in the Midwest and Central part of the US, where a large number of oil fields and power plants are in close proximity to each other, may benefit from creating incentives for EOR using CO_2 from point sources. Such regulations or incentives could generate increased tax revenues, create employment and further develop the technologies, expertise and willingness of industry to pursue CO_2 storage.

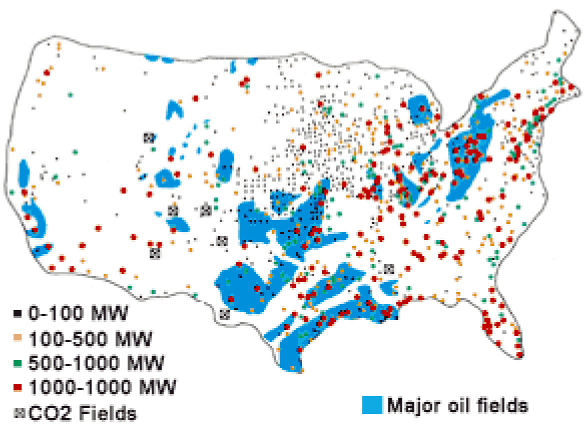

Figure 11.1: Locations of major U.S. oil fields, power plants and CO_2 fields.[113]

Opportunity

Operators in the oil and gas industry have been developing technologies and experience in order to exploit the opportunity to capture profit via EOR and reduce costs through acid gas injection. EOR technologies have allowed operators to maximize production capability while acid gas injections schemes have proven to be a cost effective alternative to sulfur recovery. CO_2 pipeline networks and underground natural gas storage operations have also increased in scale to meet user demands for CO_2 and energy. Government action in Norway has helped to create opportunity for industry by taxing

[113] Preuss, Paul, "Storing CO_2 Underground One Option for Greenhouse Gases," *Science Beat*, Lawrence Berkeley Labs, [online document] February 1, 2001[cited November 6, 2002] available at http://www.lbl.gov/Science-Articles/Archive/terr-sequ.html

CO_2 emissions from extraction activities. These actions led to the world's first major CO_2 storage initiative in the North Sea. Although a carbon tax would meet substantial resistance, similar economic incentives are needed in the US to induce storage activity.

One way to enhance the opportunities industry faces in the marketplace is to continue to look for value-added schemes involving CO_2 such as EOR from industrial sources. Greater availability of stable and reliable CO_2 sources would drive down the price of CO_2 and encourage more EOR development in areas where it is now too costly to pursue. This would be a valuable economic driver for industry and local economies. On the other hand, environmentalists may see this as a way to prolong dependency on fossil fuels. This aspect of CO_2 storage may generate increased opposition because EOR is a way to produce more oil and at least in part more oil could produce more potential CO_2 emissions.

Other incentives can be created by government in the form of tax breaks, stricter regulations and tradable permits. Generally, the opportunity for industry to move toward a storage regime on a smaller scale is now available; however, the opportunity for scale-up is now limited by markets that have not internalized the true cost of production and by the lack of scientific understanding and experience with the risks involved with long term storage of CO_2. The research community will play a significant role in creating these opportunities for storage.

Capacity

The applicable skills and capacity to conduct CO_2 storage have been developed over several decades. Some of the key insights, especially from EOR and acid gas injection schemes, were that operations began at relatively small scales and expanded over time into larger and more complex systems. This is an important lesson that should be adopted in the evolution of CO_2 storage systems. In the short term, proponents of CO_2 storage should continue to encourage oil and gas producers to utilize their available capacity and take advantage of the opportunity to reduce greenhouse gas emissions by capturing and storing CO_2 in nearby reservoirs.

> **Policy Recommendation #2:** Government and industry should work together with public input to develop a regulatory framework to ensure health and safety by using existing analogs and frameworks as a model.
>
> Key Stakeholders: Industry, Government, Public

Willingness

The willingness of industry and government to accept and implement new regulatory requirements is not an easy matter to assess. Generally, industry would oppose more restrictions and requirements, which in their view only serve to increase costs. Proposals designed to incorporate CO_2 storage into existing regulatory regimes (e.g. Underground Injection Control) governing underground injection and waste storage would likely be more acceptable than a completely new set of regulations and permits specific to CO_2 storage. Governmental willingness is generally determined by the political ideologies and allegiances of elected officials, namely the legislative and administrative branches of government. Historically, the US government has not been overly proactive and willing to implement strict health and safety standards designed to protect workers, consumers and residents. Such policies usually come about after an incident occurs or as a result of activity in the tort system. Furthermore, governmental willingness to implement new regulations at the agency level is often a function of their existing capacity to enforce and verify compliance. If governmental agencies would be required to monitor and verify compliance over extended time periods, they may be less willing to implement adequate controls if they lack the personnel and technical capacity to enforce them.

Opportunity

Although a regulatory regime governing oil and gas injection operations is well established at both the federal and state levels, a new framework to govern the long term management of storage reservoirs is needed to ensure the lowest levels of risks to humans and the environment. In moving forward with developing a regulatory framework, insights can and should be gained from the study of some of the key drivers influencing the development of other regulatory regimes that have similarities to CO_2 storage. The natural gas case study presented in this thesis showed that accidents can and do drive regulatory change. Additional insights can be learned from studying similar operations in EOR, hazardous waste disposal, high and low level nuclear waste, petroleum reservoirs, and acid gas injection. Researchers at MIT have begun studying the application of the aforementioned analogs to CO_2 storage by using criteria such as public and occupational health risks, timescales for management, public acceptance, applicability of pre-existing regulations, spillover effects into other jurisdictions and credibility of solutions.[114]

Capacity

Although the US government's ability to implement and enforce regulations exists today, the current reservoir monitoring, verification and accounting capabilities required are relatively less developed. These deficiencies would create a barrier to the adoption and effectiveness of regulations. Monitoring does occur through pressure testing at the injection wellhead and through seismic readings, but the specific capabilities to trace CO_2 in the reservoir are relatively immature – though rapidly evolving. Further, in terms of national climate policy, there is a need for a standardized accounting system. Few countries have even thought about an accounting system that includes geologic sinks at the international or national level. Specifically how this verification and accounting system should evolve is beyond the scope of this thesis, but the capacity for developing a global standard, which is essentially required, is lacking.

Most likely, a regulatory regime designed to mitigate risks will evolve in parallel with the commercialization of CO_2 storage. Thus, it is vitally important that regulators, industry and the research community work together to ensure the use of the most diligent site

[114] Reiner, David and Howard Herzog, "A Search for Regulatory Analogs to Carbon Sequestration," Massachusetts Institute of Technology, presented at the GHGT-6 Conference, October 2002.

selection criteria in developing and testing the storage reservoirs. Careless site selection could lead to accidents that could create significant insurmountable obstacles to further deployment.

Suitable formations will have, among other characteristics, sufficient volume, porosity and cap rock. Usually, these characteristics are known or can be tested with portable injection devices. Especially in the early stages of CO_2 storage, practitioners should focus on developing sites where containment has been proven. In other words, geologic CO_2 storage projects should probably be first tested in depleted oil and gas reservoirs. Further, initial CO_2 storage should not occur in just any "suitable" depleted oil or gas reservoir. Practitioners will benefit by developing CO_2 storage activities in areas where local populations are already familiar with and benefit from oil and gas exploration, production and processing. Not to mention, subsurface areas are better characterized where hydrocarbon operations have occurred for many years. For instance, subsurface knowledge is probably more substantial in Midwestern parts of the United States and Canada than in other parts of the two countries. Restricting CO_2 storage projects to these areas, at least in the emergent stages, will provide some needed confidence and added capacity while additional operating, monitoring and public management experience is gained. In addition, resources would be well spent on training geologists and equipping them with the specific skills and knowledge needed to locate and characterize depleted reservoirs for their suitability.

Policy Recommendation #3: Researchers and government should commit resources to better understand both perceived and objective risks while developing targeted strategies to communicate and mitigate them.

Key Stakeholders: Public, Industry, Government, Research Community

Willingness

The willingness of industry, regulators and the research community to understand perceived as well as objective risks and communicate mitigation strategies needs to be enhanced. Targeted public outreach campaigns are often outside the expertise of the technologist and scientist conducting the objective risk assessments. Often, technical researchers and operations personnel fail to understand that public risk perception is influenced by factors such as age, gender, personality, experience, culture, ideology and existing mental models of the hazard.[115] Other barriers to effective communication occur because the source of information must be trusted for a risk message to be effective. Generally, the public does not trust industry on matters related to the environment. Trust is associated with believing the source of information is an expert, unbiased and disinterested. To maximize effectiveness, risk communications must be understandable and able to influence the mental models. It must be clear, definitive and easily interpretable.[116] This is especially difficult when risks are plagued by a high degree of scientific uncertainty. Further, risk communication can initiate social processes that are rarely controllable. All these factors reduce the willingness of the scientific community and industry to communicate these risks to the public. Nevertheless, the unwillingness of industry, regulators and the research community to recognize and respond to the perceived risks must be overcome for commercial applications of geologic CO_2 storage to succeed.

[115] Slovic, Paul, Baruch Fischoff and Sarah Lichtenstein, "Facts and Fears: Understanding Perceived Risk", in R. Schwing and W.A. Albers, Jr (eds), Societal Risk Assessment: How Safe is Safe Enough? New York, Plenum, 1980, pp. 181-214.
[116] Breakwell, Glynis M., “Risk Communication: Factors Affecting Impact,” British Medical Bulletin, 2000, 56(1) pp. 110-20.

Opportunity

Possibly more than any other factor, the success or failure of geologic CO_2 storage will depend on proponents' ability to educate the key stakeholders. This task will require the design and implementation of both a strategic and tactical public outreach plan. Such a plan should be handled with both a top-down as well as a bottom-up approach. A top-down strategy designed to educate the general public should be influenced by the academic and environmental community and implemented at the highest levels of industry and government. A bottom-up includes educating the local population about the operations, opportunities and risks involved, establishing mechanisms for effective communication, and responding quickly to concerns and complaints. Hiring the right personnel and maintaining positive public relationships are crucial components. The combination of the two approaches will serve to establish trust and communication among all stakeholders. As CO2 storage grows in size and geography, the communication strategies and tactics will need to be adapted to parallel the changing notions and compositions of the public and other stakeholder groups.

Capacity

The capacity to evaluate the risks is now available to the stakeholders involved. From an operational point of view, these risks can come about as a result of unanticipated releases of CO_2 from transportation, processing, injection or storage systems. Over the years, risk management strategies and improved technologies have been employed to make these risks more manageable especially during transport, processing and injection. The long-term effects associated with storage are less understood and should be studied using acid gas injection, hazardous waste disposal and EOR schemes as laboratories in addition to using sophisticated geologic reservoir and gas dispersion modeling techniques.

The lack of industry and government capacity to communicate the risks involved often creates obstacles to successful implementation. Communicating risks and educating the public can be overwhelming and out of the operator's or regulator's area of expertise.

These problems are compounded by the fact that the risk management strategies, communication tactics and emergency plans employed should be specific to each operation, practiced on a regular basis, and coordinated with emergency response units, nearby operators and local residents. Coordination among operators and regulators can be a critical step to initiate the process. Educating the public, communicating on a regular basis and quickly responding to public concerns have been critical to acid gas injection and EOR operations. Operators should look for ways enhance their capacity by combining their response plans with other operators in the nearby area. These synergies can reduce costs, create efficiencies, reduce response times and facilitate a mutual commitment to ensuring the best possible risk reduction strategies.

A combination of all three general policy prescriptions proposed in this section is necessary in some form for geologic storage of CO_2 to become a mainstream strategy to address climate change. The three policy recommendations: 1) create incentives to scale up technologies, 2) develop a regulatory framework to ensure public health and safety, and 3) understand public concerns and develop targeted risk communication strategies, are closely linked. For instance, the capability and familiarity of the technologies determine public acceptance and regulatory standards. Conversely, concerns about risks stimulate the development of new technologies and more stringent regulatory controls, which may in turn reduce the public's perceived risks. The intent of the aforementioned policy recommendations is to provide a framework in which the key stakeholders can work toward the wider adoption and acceptance of CO_2 storage. The goal is not to advocate specific market-based or command-and-control policies, but rather to draw attention to the most salient obstacles and needed approaches that could affect the willingness, opportunity and capacity for the stakeholders to change in important ways.

12.0 Conclusions

Geologic storage of CO_2 is a promising strategy for climate change mitigation because it can build upon the knowledge and experience gained in the oil and gas industry. The analogs presented in this thesis, which include acid gas injection, enhanced oil recovery, underground natural gas storage and CO_2 transport, provide some useful insights into developing a storage regime as part of a broader portfolio of strategies designed to mitigate climate change. Specifically, 3 lessons were identified from the analogs:

1. Low-volume geologic storage of CO_2 has successfully occurred in the form of enhanced oil recovery and acid gas injection for many years. The specific knowledge and expertise now exists for effective management and should be built on for carbon storage activities.

2. All four analogs evolved incrementally into major operations over time. The development of a geologic CO_2 storage regime would also benefit from the evolution of small-scale operations to a larger more voluminous storage regime.

3. Through research, experience and public outreach, operators and regulators have successfully managed the risks, benefits and public apprehension associated with these activities.

In the second part of the thesis, the risks associated with geologic CO_2 storage were identified and characterized into two subsystems, namely the operational and *in situ* subsystems. Essentially, the operational subsystem refers to the handling and transportation of CO_2 above ground, while the *in situ* subsystem refers to the storage of CO_2 in a suitable geologic reservoir. The operational risks associated with CO_2 storage are generally well understood and controlled using existing management strategies, engineering practices and technologies. On the other hand, less is known about the risks associated with the *in situ* subsystem primarily because of our lack of experience in this area. Risks associated with the *in situ* subsystem can result from three general activities: 1) leakage to the surface, 2) leakage within the subsurface and 3) induced seismicity. As was demonstrated by the Yaggy Field study in Section 7, gas leakage, migration and re-accumulation within the subsurface is arguably the most important area of uncertainty and in need of further research. Although risks are present, it appears that they can be mitigated to acceptable levels with increased experience, proper site selection, and the best engineering and monitoring practices.

Before large-scale storage activities come to fruition, a better understanding of the long-term implications and behaviors of CO_2 in the *in situ* subsystem is needed. Opportunities to study these issues are now available in Western Canada at the many acid gas injection sites and in the United States at the more than 70 CO_2 flooding operations. Newly designed experiments and existing CO_2 capture and storage operations will also play a role in furthering our knowledge and understanding about the risks involved.

Finally, this thesis attempts to develop a policy framework by recommending specific approaches that the United States should pursue in encouraging the development of a commercial scale CO_2 storage regime. For each policy recommendation, the willingness, opportunity and capacity of the key stakeholders to make the changes necessary were evaluated. The policy recommendations include the following:

1. Government should encourage the continued development and scaling up of technologies and expertise now employed in oil and gas operations by enhancing the willingness and opportunity of industry though market-based and regulatory incentives.

2. Government and industry should work together with public input to develop a regulatory framework to ensure health and safety by using existing analogs and frameworks as models.

3. Researchers and government should commit resources to better understand both perceived and objective risks while developing targeted strategies to communicate and mitigate them.

In designing these risk communication strategies, we should take measures to ensure the most critical science and work to improve the transparency and conduct of the scientific debate. Further, we should work to encourage robust and independent media reports while encouraging business and government participation and at the same time restraining their influence on the debates.

The potential for extrapolating from the analogs or scaling up existing CO_2 storage projects to commercial operations depends on a number of factors including, but certainly not limited to, the technical aspects. The viability of CO_2 storage will no doubt be determined by the complex linkages between environmental, economic, technical and political forces. Therefore, design choices need to be based on qualitative as well as quantitative risk attributes.

CO_2 storage proponents must strike the proper balance between overestimating and underestimating its potential. Overestimating can lead to possible adverse consequences, while underestimating can reduce the benefits at stake. Obstacles to measuring the risks of CO_2 storage are significant including unavailable data, a general lack of experience and the absence of agreed upon criteria for assessing the magnitude of the consequences. Nevertheless, analogs are available to help inform these questions and reduce the obstacles.

The Kyoto Protocol may also have implications for scaling up CO_2 storage activities in other parts of the world, most notably in Europe and Japan. In order to meet emissions reductions targets, CO_2 storage technologies and expertise may develop outside the US at a more rapid pace. On the other hand, ideological opposition, in the form of green politics, which is more prevalent in Europe, may work to prevent the wider adoption of CO_2 storage activity. Non-scientific views of risks and the desire to substitute renewable energy for fossil fuels may limit the ability of CO_2 storage to gain broader public acceptance both in the US and in other parts of the world.

Storage is not a substitute for other CO_2 mitigation strategies. Rather, it is a necessary component of a broader portfolio of methods designed to reduce the effects of CO_2 on the global climate. Fossil fuels will be around for many more years; therefore, storage techniques can play a useful role in reducing their impact while we transition to less CO_2-intensive technologies and energy sources.

Can we know the risks CO_2 storage will bring now or in the future? Can we measure these risks better? The answer will often depend on who *we* is. Storage proponents should continue to work to produce better science in order to help reduce some of the uncertainties we face moving forward. Science and technological progress has given us the confidence to think realistically about CO_2 storage and has given us the tools to develop it in a safe and effective way. We can learn a great deal from the analogs in the oil and gas industry and will continue to improve our ability to manage the risks by pursuing and encouraging sound and open research in this area.

Appendix A – Environmental Questions

Critical Questions for CO_2 Storage
David Hawkins, National Resource Defense Council

- Do scientists have a complete inventory of unanswered technical issues?
- Do they have a research program to address them?
- What are the timelines for research deliverables and how do those match up with plans to conduct demonstrations?
- What are the remedies if leak rates are greater than design assumptions?
- How will we know if leaks are greater than design criteria?
- How long will the cement in well casings last? How do we know the answer is accurate?
- What are other pathways for carbon to reach the surface?
- Do I have to worry about CO_2 collecting in my basement like radon?
- What will happen if there is an earthquake near a repository?
- What is the probability of detecting and locating significant leaks?
- How large must a local leak be to be detected using currently contemplated monitoring methods?
- Who will keep track of how well the entire system is performing on a global basis?
- What are the robust monitoring schemes? How much will they cost? To whom will costs and operational responsibility be assigned?
- Who is responsible for maintaining a repository if the original companies go out of business?
- How will we design systems to inform population hundreds of years from now of the locations of carbon storage reservoirs so they do not accidentally penetrate them?

Key Issues and Risks
Union of Concerned Scientists

Environmental Risks:

- Given the energy penalty associated with capture and storage, if stored CO_2 is re-released over long times scales, atmospheric concentrations will increase

- Continued reliance on fossil fuel and environmental impacts at fossil fuel extraction sites

- Environmental impacts associated with pipeline development

- Unknown impacts on the biological communities in the storage sites

- Insufficiently understood contamination of "sweet-water" aquifers overlying brine formations into which CO2 is being dumped

- Unknown impacts on biological communities that live in deep saline formations and other storage sites

Direct Risks to Humans:

- Catastrophic venting from storage sites

- Potable water contamination

- Induced Seismicity

Appendix B – Major Geologic Storage Projects

CO_2 Capture Project

The CO_2 Capture Project (CCP) is an international effort funded by a consortium of 8 energy companies, led by BP. The project objectives of the CCP are:

- Achieve major reductions in the cost of CO_2 Capture and Storage:
  - 50% reduction when applied to a retrofit application
  - 75% reduction when applied to a new build application
- Demonstrate to external stakeholders that CO_2 storage is safe, measurable, and verifiable
- Progress technologies to:
  - At least one large scale application in operation by 2010
  - 'Proof of concept' stage by 2003/4

To do this, they established working groups on the key topics, including Post-Combustion Capture Technologies; Pre-Combustion Capture Technologies; Oxyfuels Capture Technologies; Storage, Monitoring, and Verification (SMV) for Geologic Sequestration; and Economic Modeling.

Sponsors: *Industrial partners* – BP, ChevronTexaco, Eni, Norsk Hydro, Encana (formerly PanCanadian), the Royal Dutch Shell Group of Companies, Statoil and Suncor Energy; *Government Co-Funding* – U.S. DOE, the European Union's Energy and Transport Directorate (DG TREN), and the government of Norway (Klimatek programme).

Contractors: 25 individual contracts covering 31 principal investigators in the SMV group alone.

Budget: The overall budget for all working groups is $28 million/3yrs.

Focus: The primary focus of the SMV working group is on geologic storage and EOR projects.

Goals: Proof of concept by 2003/4 and one large-scale application in operation by 2010.

Approach: Multiple contracts, initially with a broad scope, and later focusing on the most promising approaches.

Web Reference: http://www.co2captureproject.org

The Weyburn CO_2 Project

The Weyburn CO_2 Project is a monitoring project coupled with an EOR project. Injection of CO_2 into a carbonate oil reservoir in southeastern Saskatchewan, Canada, began on September 22, 2000. Prior to the start of injection, substantial baseline data (3D-seismic, VSP, cross-well, single-well seismic and geochemical sampling) were obtained from the field. The monitoring project will occur over a four-year period and will be evaluating the distribution of CO_2 in the carbonate reservoir and will determine the chemical reactions that are occurring within the reservoir between the CO_2 and the reservoir rock and fluids. The ultimate goal of the monitoring project is to verify the long-term storage capacity of an oil reservoir, with particular emphasis on reservoir integrity. The Weyburn Project is divided into 4 categories with the following purposes:

- Fluid Studies
    - Establish the changes in fluid properties within the reservoir over time
- Short-Term Simulation
    - To provide an integrated reservoir simulation
- Long-Term Simulation
    - To provide a model to assess long-term performance of sequestration process
- Technology Development
    - To develop technologies to improve mobility control and detection of CO_2

Sponsors: PanCanadian, Saskatchewan Petroleum Research Incentive Program, and the Canadian Government's Climate Change Action Fund.

Contractors: *Canada* - Saskatchewan Energy & Mines, Saskatchewan Research Council, University of Alberta, University of Calgary, University of Saskatchewan, University of Regina, Alberta Research Council; *Europe* - British Geological Survey (Britain), Bureau de Recherches Geologiques et Minieres (France), Institut Francais du Petrole (IFP) (France), Danish Geological Survey (Denmark); *USA* - Lawrence Berkeley National Laboratory, Colorado School of Mines, Monitor Scientific (Colorado)

Budget: U.S. $14.8 million/4yrs (Canadian $23.3 million/4yrs).

Focus: The primary focus of the monitoring project is monitoring injected CO_2 of an EOR project in the Weyburn Field.

Goals: Verify long-term storage capacity of an oil reservoir

Approach: The use of seismic characterization and geochemical studies

Web Reference: http://www.ptrc.ca/projects/weyburn.htm

GEO-SEQ

The GEO-SEQ Project is a broad-focused sequestration project with the goal of developing the "technology and information needed to enable the application of safe and cost-effective methods for geologic sequestration of CO_2 by the year 2015." The three broad goals of the program are:

- Reducing the cost of sequestration.
- Decreasing the risk of sequestration.
- Decreasing the time to implementation.

To achieve these goals, nine individual subtasks are currently underway:

- Development of methods to co-optimize EOR and sequestration.
- Development of carbon-sequestration-enhanced gas production from natural gas reservoirs.
- Evaluation of the effects of SO_X and NO_X on geochemical reactions between CO_2, water, and reservoir rocks.
- Identification of geophysical techniques for monitoring CO_2 migration in the subsurface.
- Field testing of geophysical-monitoring techniques.
- Development of tracer techniques for monitoring the interaction between CO_2, water and reservoir rocks.
- A reservoir simulation-code comparison study for predicting the fate of CO_2 in the subsurface.
- Enhancement of simulation models for carbon- sequestration-enhanced coal-bed methane recovery.
- Improved capacity assessment for brine formations.

Sponsors: *Industrial partners* – ChevronTexaco, Pan Canadian Resources, BP-Amoco, Statoil, Alberta Research Council Consortium; *Government Co-Funding* – U.S. DOE (National Energy Technology Laboratory).

Contractors: Three National Labs (LBNL, LLNL, ORNL), Stanford University, US Geological Survey, Texas Bureau of Economic Geology, Alberta Research Council (ARC), UC Berkeley, UC Davis, the University of Texas, the University of Tennessee, and the University of Calgary.

Budget: The overall budget is $14.25 million/3yrs.

Focus: This project has a broad focus within the area of geologic sequestration including lowering sequestration costs and risks, decreasing time to implementation, and addressing the issue of public acceptance.

Goals: Developing the technology and information needed to enable safe and cost-effective geologic sequestration by the year 2015.

Approach: Multiple studies such as sequestration optimization methods, monitoring technologies, simulations, and capacity assessment.

Web Reference: http://esd.lbl.gov/GEOSEQ/

Alberta Research Council (ARC) Projects

The ARC consortium sequestration program is three fold and includes the following research topics:

- CO_2 Enhanced Coalbed Methane Recovery (ECBM)
    - Pilot site at Fenn-Big Valley, Alberta
    - 5-spot, full-scale pilot in planning
- Geologic Sequestration of CO_2 – EOR and Aquifers
    - Monitoring of aquifer disposal
    - Geochemical modeling
    - Mineral and hydrodynamic trapping
- Acid gas reinjection
    - Waste stream from sour gas plants (~90% CO_2)
    - Examining net CO_2 emissions on 31 possible sites

Numerical models for sequestration in coal beds are in development and examination of the best regional areas for storage is in progress. Phase property distributions of CO_2 are being developed in the P-T space of the reservoirs in Alberta. In addition, the ARC is involved as a research contractor on the GEO-SEQ and Weyburn projects.

Sponsors: Various Industrial and government sponsors.

Contractors: Alberta Research Council.

Budget: U.S. $5 million/2yrs (Canadian $8 million/2yrs).

Focus: The work of the Alberta Research Council is focused mainly on end-use projects.

Goals: Three EOR demos in the next 3 yrs, full-scale ECBM pilot.

Approach: Field work in addition to some simulation models.

Web Reference: http://www.arc.ab.ca/envir/Greenhouse.asp

Geologic Disposal of Carbon Dioxide (GEODISC)

GEODISC is a program underway by the Australian Petroleum Cooperative Research Center (APCRC), a collaborative petroleum research organization consisting of members from industry, government, and research institutions. The purpose of the GEO-SEQ project is to:

- Lower the cost of geologic sequestration by:
  - Developing innovative optimization methods for sequestration technologies with collateral economic benefits (such as enhanced oil recovery (EOR), enhanced gas recovery (EGR), and enhanced coalbed methane production).
  - Understanding and optimizing trade-offs between CO_2 separation and capture costs, compression and transportation costs, and geologic sequestration alternatives.
- Lower the risk of geologic sequestration by:
  - Providing the information needed to select sites for safe and effective sequestration.
  - Increasing confidence in the effectiveness and safety of sequestration through identifying and demonstrating cost-effective monitoring technologies.
  - Improving performance-assessment methods to predict and verify that long-term sequestration practices are safe, effective, and do not introduce any unintended environmental effects.
- Decrease the time to implementation of geologic sequestration by:
  - Pursuing early opportunities for pilot tests with our private sector partners.
  - Gaining public acceptance.

The ten research modules include: (1) regional analysis, (2) specific studies at 2-4 locations, (3) experimental studies on the CO_2-water/brine-rock systems, (4) petrophysical studies, (5) development of a coupled chemical-dynamic-kinetic model, (6) monitoring CO_2 injection, (7) risk assessment, (8) economic model, (9) international cooperation, and (10) natural analogs.

Sponsors: BHP Billiton, BP, Chevron, Shell, Gorgon Australian LNG, Woodside, and the Australian Greenhouse Office.

Contractors: *APCRC Core Participants* – Australian Geological Survey Organization, Australian Petroleum Production and Exploration Association, CSIRO - Petroleum, Curtin University, National Centre for Petroleum Geology and Geophysics, and the School of Petroleum Engineering at the University of New South Wales; *Research Providers* - Alberta Research Council, British Geological Survey, TNO - Netherlands, Australian National University Department of Applied Math, Batelle Memorial Institute.

Budget: U.S. $5 million/4yrs (Australian $10 million/4yrs).

Focus: Broad focus over many areas of research.

Goals: Document feasible areas and model and monitor stored CO_2 behavior.

Approach: Multiple studies including experimental, monitoring, and modeling.

Web Reference: http://www.apcrc.com.au/Programs/geodisc_res.html

Saline Aquifer CO_2 Storage (SACS)

The Sleipner project is the world's first commercial-scale storage of CO_2. Statoil injects the CO_2 into a large, deep saline reservoir, the Utsira formation, 800m below the bed of the North Sea. Geologic data around the injection point is being gathered and simulations are being developed on the reservoir. Various experiments and simulations are examining the geochemistry of the reservoir as well. Data will be collected for three years to model and verify the distribution of the injected CO_2. The goals of the Sleipner CO_2 injection and the SACS project include:

- Verification under what circumstances CO_2 storage in an aquifer is safe and reliable
- Validation models for geology, geochemistry, geophysics and reservoir tools
- Initiation new R&D related to above topics
- Development of "Manual of Good Practice"

The project is split into 5 areas:

- Description of the reservoir geology
- Reservoir simulation
- Geochemistry
- Assessment of need and cost for monitoring wells
- Geophysical modelling

Sponsors: *Industrial* – Statoil (lead), BP, ExxonMobil, Norsk Hydro, TotalFinaElf, and Vattenfall; *Government Co-Funding* – The European Union and national authorities in Denmark, The Netherlands, Norway, and the United Kingdom.

Contractors: British Geological Survey, BRGM, Geological Survey of Denmark and Greenland (GEUS), Institut Français du Petrole, NTIG-TNO, SINTEF Petroleum Research, and the Nansen ERS Centre.

Budget: U.S. $4.6 million/3yrs.

Focus: Monitoring of the Utsira Formation in the Sleipner field during and after CO_2 injection.

Goals:

1. Verify under what circumstances CO_2 storage in an aquifer is safe and reliable.
2. Validate models for geology, geochemistry, geophysics and reservoir tools.
3. Initiate new R&D related to above topic.
4. Start development of "Manual of Good Practice".

Approach: Seismic monitoring.

Web Reference: http://www.ieagreen.org.uk/sacshome.htm

The RECOPOL Project

The RECOPOL project is an ECBM-CO_2 research and demonstration project funded by the EU to investigate the possibility of permanent subsurface storage of CO_2 in coal. RECOPOL stands for "Reduction of CO_2 emission by means of CO_2 storage in coal seams in the Silesian Coal Basin of Poland" and it is the first field demonstration experiment of it's kind outside Northern America. The RECOPOL project is scheduled to start at the end of 2001 and the duration of the project is 36 months (duration of the field experiment is 18 months).

The main questions to be answered by the RECOPOL project are:

- Is subsurface storage of CO_2 in coal, while simultaneously producing CBM, a technically viable option under European conditions?
- Is subsurface storage of CO_2 in coal a safe and permanent solution?
- How much CBM is produced for each tonne of injected CO_2?
- Can subsurface storage of CO_2 in coal be applied on a larger scale in an economical and social acceptable way?
- What are the main criteria (geological/technical/economical/social) for any coal basin, in or outside Europe, to be suitable for this technique?

The seven work packages laid out by the RECOPOL Project are:

- Geological Model (Site evaluation)
- Laboratory work (standard and advanced)
- Simulation I (Data integration and model assessment)
- Feasibility test (Design – Operation – Data Gathering)
- Simulation II (History Matching)
- Socio- Economical and Future-Technological evaluation
- Dissemination of results, summary of results, and reporting

Sponsors: The European Union 5th Framework Programme (50%), 10 partners (50%).

Partners: TNO-NITG (Netherlands), Aachen Univ. of Tech. (Germany), Delft Univ. of Tech. (Netherlands), Central Mining Institute (Poland), Institut Français du Petrol (France), CSIRO (Australia), DBI-GUT (Germany), Gaz de France (France), Gazonor (France), IEA GHG

Budget: U.S. $3.1 million/3yrs (3.5 million EURO/3yrs).

Focus: Investigating the possibility of permanent subsurface storage of CO_2 in coal. The project is located in the Upper Silesian Basin, Poland (best location for ECBM-CO_2 in Europe).

Goals: The main objective of this project is to evaluate the feasibility of greenhouse gas emission reduction by CO_2 sequestration in subsurface coal seams under European conditions. This main objective will be reached by answering the five main questions listed above.

Approach: System modeling and demonstration of a full-scale field experiment.

Web Reference: http://www.nitg.tno.nl/eng/appl/g_resources/natural/recopol.shtml

Battelle Memorial Institute Projects

The sequestration research underway at Battelle focuses on the injection of CO_2 in deep saline sandstone formations, in conditions typical of the Midwestern United States. One phase of the work is the review of the status of existing technologies for handling CO_2 and the development of a preliminary engineering concept and the estimation of the costs for sequestration in the Mt. Simon Aquifer. Another aspect of Battelle's work is the evaluation and examination of factors that affect chemical reactions in underground saline formations. Another area of interest is the study of issues of seismic activity induced by CO_2 injection in deep saline aquifers.

Sponsors: U.S. DOE.

Contractors: Battelle Memorial Institute.

Budget: U.S. $600,000/3yrs.

Focus: Cost analysis and characterization of the Mt. Simon Sandstone.

Goals: Estimate cost of capture and sequestration.

Approach: Engineering studies.

Reference: Smith, Larry, Neeraj Gupta, Bruce Sass, and Thomas Bubenik, *Carbon Dioxide Sequestration in Saline Formations – Engineering and Economic Assessment*, Final report for DE-RAC26-98FT35008, US DOE, National Energy Technology Center, July 9 (2001).

Appendix C – Definitions and Conversion Factors

Definitions

CO_2	Carbon Dioxide
bbl	Barrels of Oil per day
EOR	Enhanced Oil Recovery
EUB	Alberta Energy and Utilities Board
H_2S	Hydrogen Sulfide
IL	Informational Letter
MMBO	Million barrels of oil
MMcf	Million Cubic Feet
TCEQ	Texas Commission on Environmental Quality
Tcf	Trillion Cubic Feet

Conversions

18,000 standard cubic feet (scf) = 1 tonne CO_2

Bibliography

Alberta Energy Utilities Board (EUB) Guide 60: Upstream Petroleum Industry Flaring Requirements, [Online Document] [cited September 24, 2002], available at http://www.eub.gov.ab.ca/BBS/requirements/Guides/guides.htm

Beck, Ulrich, *Risk Society, Towards a New Modernity*. Trans. by Mark Ritter, 1992. pp. 260.

Bennion, D. B., Brent Thomas, Douglas Bennion, Ronald Bietz, "Formation Screening to Minimize Permeability Impairment Associated with Acid Gas or Sour Gas Injection/Disposal," Paper No. CIM 96-93, Presented at the 47th Annual Technical Meeting of the Petroleum Society of CIM, Calgary, Alberta, June 1999. pp. 1-6.

Benson, Sally, John Apps, Robert Hepple, Marcelo Lippman and Chin Fu Tsang, "Health, Safety and Environmental Risk Assessment for Geologic Storage of Carbon Dioxide: Lessons Learned from Industrial and Natural Analogues," Lawrence Berkeley National Labs, 2002 available at http://www.co2captureproject.org/reports/reports.htm.

Breakwell, Glynis M., "Risk Communication: Factors Affecting Impact," British Medical Bulletin, 2000;56(1):110-20.

"Burning: Lost storage gas flares on in Kansas," *Gas Utility Manager*, April 2001," [online document] cited May 2002 available at www.gasindustries.com/articles/giapr01b.htm.

Interview with Maurice Bezinett, EnerPro Midstream Inc, Acheson Field, Alberta, August 28, 2002.

Bosch, Neil, EnerPro Midstream Inc., "Acid Gas Injection: A Decade of Operating History in Canada," presented at the Canadian Gas Processors Conference, Calgary, Alberta, April 5, 2002.

Interview with Maurice Bezinett, EnerPro Midstream Inc, Acheson Field, Alberta, August 28, 2002.

Phone interview with Charles Chabennes, Duke Energy, March 14, 2002.

Carroll, John, and James Maddocks, "Design Considerations for Acid Gas Injection," Presented at the Laurance Reid Gas Conditioning Conference, Norman, Oklahoma, February 1999.

Chakma, Amit "Acid Gas Re-Injection – A Practical Way to Eliminate CO_2 Emissions from Gas Processing Plants," *Energy Conversion Management*,1997 Vol. 38, Suppl. pp. S205-S209

Congressional Budget Office, REV-37, “Repeal the Tax Credit for Enhanced Oil Recovery Costs and Expensing of Tertiary Injectants,” [online document], February 2001, [cited October 4, 2002] available at http://www.cbo.gov/bo2001/bo2001_showhit1.cfm?index=REV-37

Department of Energy, “Carbon Sequestration Research and Development,” Report # DOE/SC/FE-1, available at www.ornl.gov/carbon_sequestration/, December 1999.

Department of Energy, “Oil and Gas Reservoir Life Extension,” [online oocument], http://www.fe.doe.gov/oil_gas/life_extension/, [cited September 4, 2002]

EPA, Underground Injection Control Program, [online document], 2002, [cited July 2002] http://www.epa.gov/safewater/uic/whatis.html

Energy Information Administration, “Table 14: Activities of Underground Natural Gas Storage Operators, by State, August 2002,” [online document] cited August 2002 available at http://www.eia.doe.gov/pub/oil_gas/natural_gas/data_publications/natural_gas_monthly/current/pdf/table_14.pdf

Energy Information Administration, “The Value of Underground Storage in Today’s Natural Gas Industry,” March 1999, DOE/EIA-0591(95), Appendix A, p. 43.

“Enhanced Oil Recovery Scoping Study,” EPRI, Palo Alto, CA. Tech. Rep. 113836, 1999.

Federal Register: July 10, 1997 (Volume 62, Number 132) http://www.epa.gov/fedrgstr/EPA-GENERAL/1997/July/Day-10/g17722.htm.

Gale, John, “Geological Storage of CO_2 – Safety Aspects Related to Transmission of CO_2,” IEA Greenhouse Gas R&D Programme, January 11, 2001.

Gale, John and John Davison, “Transmission of CO_2 – Safety and Economic Considerations,” IEA Greenhouse Gas R&D Programme, presented at the GHGT-6 Conference, October 2002.

Gupta, N., et al., “Engineering and Economic Assessment of CO_2 Sequestration in Saline Aquifers,” Battelle Memorial Institute, presented at the GHGT-6 Conference, Kyoto, Japan, October 2002.

Hattenbach, R.P., Wilson, M. and K. Brown, “Capture of carbon dioxide from coal combustion and its utilization for enhanced oil recovery,” in *Greenhouse Gas Control Technologies*, Elsevier Science, New York, 1999, pp. 217-221.

Hawkins, David, "Passing Gas: Policy Implications of Leakage from Geologic Carbon Storage Sites," Natural Resources Defense Council, Washington DC, 2002.

Herzog, Howard, "Carbon Sequestration: Analysis of Research Activities," report on research activities to EPRI, Palo Alto, CA, April 2002.

Holloway, S., et al. "The Underground Disposal of Carbon Dioxide: Summary Report," JOULE II Project No. CT92-0031, British Geological Survey, 1996

Holloway, S., "Safety of the underground disposal of carbon dioxide," *Energy Convers. Mgmt*, vol.38, pp. 241-245, 1997.

Hovorka, Susan and Paul Knox, "Frio Brine Sequestration Pilot in the Texas Gulf Coast," Bureau of Economic Geology at the University of Texas at Austin, presented at the GHGT-6 Conference, Kyoto, Japan, October 2002.

Email correspondence with Susan Hovorka, Bureau of Economic Geology, University of Texas at Austin, October 11, 2002.

Interview with Carl Johnson, Williams Energy Services, Conway, Kansas, August 23, 2002.

Kansas Geological Survey, "Hutchinson Response Project" [online document] cited June 2002 available at www.kgs.ukans.edu

Klara, Mike, National Energy Technology Laboratory, "Carbon Sequestration: The Path Forward," presented at a meeting with the IOGCC and the U.S. Department of Energy (DOE), Alta, Utah [online document] July 17-19, 2002 [cited September 15, 2002] http://www.iogcc.state.ok.us/ISSUES/CO2%20Sequestration/co2sequestration.htm

Kinder Morgan CO_2 Company, "Rules of Thumb," [Online Document], 2001, [cited September 4, 2002], http://www.kindermorgan.com/co2/flood.cfm

Kinder Morgan CO_2 Company, "Transportation," [Online Document], 2001, [cited September 18, 2002], http://www.kindermorgan.com/co2/transport_canyon_reef.cfm

Klins, M.A. and C.P. Bardon, "Carbon dioxide flooding," In *Basic Concepts in Enhanced Oil Recovery Processes*, M. Baviere, Eds. Elsevier Applied Science, 1991, pp. 215-240.

Interview with Brad Lock, Vice President of Operations, EnerPro Midstream Inc, Calgary, Alberta, August 27, 2002.

Longworth, H.L., G.C. Dunn and M. Semchuck, "Underground Disposal of Acid Gas in Alberta, Canada: Regulatory Concerns and Case Histories," Society of Petroleum Engineers 35584, 1995.

Interview with Jim Maddocks, P. Eng., Gas Liquids Engineering, Calgary Alberta, August 27, 2002.

Maldal, T., and Tappel, I.M., "CO_2 Underground Storage for Snøhvit Gas Field Development," Statoil, presented at the GHGT-6 Conference, Kyoto, Japan, October 2002.

Marle, C.M., "Oil entrapment and mobilization," in *Basic Concepts in Enhanced Oil Recovery Processes*, M. Baviere, Eds. Elsevier Applied Science, 1991, pp. 3-39.

Morel, D., "Miscible gas flooding," In *Basic Concepts in Enhanced Oil Recovery Processes*, M. Baviere, Eds. Elsevier Applied Science, 1991, pp. 185-214.

Morgan, Granger, "Risk Analysis and Management," *Scientific American*, July 1993. pp. 32-41.

Moritis, G., "Future of EOR & IOR: New companies, infrastructure, projects reshape landscape for CO_2 EOR in U.S.," *Oil & Gas Journal*, May 14, 2001.

National Energy Technology Laboratory, U.S. Department of Energy, "Transmission, Distribution and Storage Natural Gas Infrastructure – Pipeline Reliability," [online document] 2002 [cited October 17, 2002] available at http://www.netl.doe.gov/scng/trans-dist/ngi/pipeline.html

Office of Pipeline Safety, Research and Special Programs Administration, [online document], 2001, [cited August 2002] http://ops.dot.gov/stats.htm

"Officials Working to Plug Natural Gas Leak," *Jefferson City News Tribune Online Edition*, January 20, 2001, available at http://newstribune.com/stories/012001/wor%5F0120010007.asp

"OGJ Special – Worldwide EOR survey 2000," *Oil & Gas Journal*, pp. 44-61, Mar. 20, 2000.

"OGJ Special – Worldwide production," *Oil & Gas Journal*, pp. 126-157, Dec. 24, 2001.

Preuss, Paul, "Storing CO_2 Underground One Option for Greenhouse Gases," *Science Beat*, Lawrence Berkeley Labs, [online document] February 1, 2001[cited November 6, 2002] available at http://www.lbl.gov/Science-Articles/Archive/terr-sequ.html

Ratigan, J., Sofregaz USA, Inc., Testimony to the Kansas Senate Utilities Committee, February 27, 2001.

Reiner, David and Howard Herzog, "A Search for Regulatory Analogs to Carbon Sequestration," Massachusetts Institute of Technology, presented at the GHGT-6 Conference, October 2002.

"Report Links Gas Leak to Explosion," *Topeka Capital Journal*, July 30, 2002.

Riddiford, F.A., et al. "A Cleaner Development in the In Salah Gas Project, Algeria," presented at the GHGT-6 Conference, Kyoto, Japan, October 2002.

Roche, Pat, "Deep Disposal," *New Technology Magazine*, March 2002, pp. 36-39.

Phone interview with Michael Schumacher, Cargill Salt Division, March 13, 2002.

Slovic, Paul, Baruch Fischoff and Sarah Lichtenstein, "Facts and Fears: Understanding Perceived Risk", in R. Schwing and W.A. Albers, Jr (eds), Societal Risk Assessment: How Safe is Safe Enough?, New York, Plenum (1980): 181-214.

Smith, Larry, N. Gupta, B. Sass and T. Bubenik, "Carbon Sequestration in Saline Formations-Engineering and Economic Assessment: Final Technical Report," PRDA #: DE-RA C26-98FT35008, Battelle Memorial Institute, July 9, 2002.

Stevens, S.H., Kuuskraa, V.A. and J.J. Taber, "Barriers to overcome in implementation of CO_2 capture and storage (1): Storage in disused oil and gas fields," IEA Greenhouse R&D Programme, Cheltenham. Tech. Rep. PH3/22, Feb. 2000.

Tobin, James, "Natural Gas Transportation – Infrastructure Issues and Operational Trends," Energy Information Administration, October 2001available at http://www.eia.doe.gov/oil_gas/natural_gas/info_glance/pipelines.html.

Tobin, J., and James Thompson, "Natural Gas Storage in the United States in 2001: A Current Assessment and Near-Term Outlook," Energy Information Administration, 2001 available at http://www.eia.doe.gov/oil_gas/natural_gas/info_glance/storage.html.

Troy, Alan, Technology "A Comparison of Drilling Incentives in Louisiana, Mississippi, Oklahoma and Texas," Assessment Division Louisiana Department of Natural Resources, January 14, 1991 available at http://www.dnr.state.la.us/SEC/EXECDIV/TECHASMT/lep/drilling/compare.htm, cited September 29, 2002.

Union of Concerned Scientists, "Policy Context of Geologic Carbon Sequestration," [online article] 2002, [cited September 13, 2002] http://www.ucsusa.org/index.html.

Vladut, Thomas, "Induced Seismicity and Earthquake Prediction," Canadian Induced Seismicity Research Group, [Online Document], 1999, [cited September 11, 2002] available at http://www.cadvision.com/retom/predict.htm

Interview with Scott Wehner, Kinder Morgan CO_2 Company, Midland, TX, August 22, 2002.

Interview with Colin Wilson, EnerPro Midstream Inc, Acheson Field, Alberta, August 28, 2002.

Wilson, Elizabeth, Tim Johnson, and David Keith, “Regulating the Ultimate Sink: Managing the risks of geologic CO_2 sequestration,” submitted for *Environmental Science and Technology*, 2002.