Challenges and Opportunities for Geological Carbon Sequestration in Colorado

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Summary

This report was requested by the State of Colorado as a response to funding provided to the Colorado School of Mines through C.R.S. § 25-1-1303. The timing is ideal to take stock of the carbon sequestration opportunities here in Colorado, because sequestration is becoming a major new growth industry in many parts of the world, and Colorado is well poised to benefit from this trend. Geological carbon sequestration is a technology where concentrated sources of CO_2 can be compressed, injected and stored in depleted oil and gas fields, major deep aquifers ('saline brines'), and coal seems in the subsurface. In light of the historical strength in minerals science and engineering of Colorado's industries and research universities (particularly CSM), and the public determination to reduce atmospheric emissions of CO_2 as a climate change mitigation measure, Colorado has the technical skills and public will to help build a technology foundation to clean up the hydrocarbon energy industry.

More than 30 years of global climate research has proven beyond any reasonable doubt that man-made CO_2 emissions, mostly from the burning of hydrocarbons, have created a pattern of global warming that is beginning to take an enormous toll on the planet's economic infrastructure as well as ecological systems. Consequently, countries like the U.S., Australia, Norway, Japan, Britain and others with advanced hydrocarbon industries are rapidly moving to use relevant skills and experiences to reduce, and some day eliminate, carbon emissions from the burning of hydrocarbon fuels. Colorado is

positioned to ride this new wave, because many companies operating in the Rocky Mountains have sequestered carbon in several oil fields for decades (Rangely, Baroil, Salt Creek). The Colorado Geological Survey has just completed an assessment of the potential for large-scale sequestration and found that the State has a cumulative capacity to store more than 700 billion tons of CO_2, providing several hundred years of carbon storage based on current state emission levels.

The research universities have developed a range of skills including imaging the CO_2 in the subsurface and how it moves over time, modeling and predicting the behavior of the CO_2 when it is injected down-hole, and developing the right materials for use in corrosive subsurface settings.

This year, two major industrial companies, Xcel Energy and Shell Oil Company, are moving rapidly to put in place geological carbon sequestration systems linked to the planned IGCC plant at Brush and the production of shale oil in the Piceance basin on Colorado's western slope. Both of these projects are real 'game changers' in their respective industries and will be emulated worldwide. To the extent that Colorado research universities and specialized new service and consulting companies contribute to the success of these very visible ventures, there will be rapid growth in sequestration-related technology firms in the State.

Moreover, carbon sequestration to mitigate climate change will be a research priority of the U.S. government and many foreign nations for a long time to come. Engagement by the State of Colorado with its research universities to help further develop the 'right' research skills will therefore position the state to compete effectively for growing Federal and private research funds. Finally, as in all other industry transformations, the market will need new entrants with new skills, and students graduating from universities with strong programs in this component of "tomorrow's industries" will have a competitive advantage.

This report represents work done by the lead author as a member of a Department of Energy panel and several recent industrial forums focused on identifying the basic research challenges in carbon sequestration, a new graduate student in the Department of Environmental Science and Engineering at CSM, and a comprehensive new report on the CO_2 sequestration potential of Colorado, prepared by the staff of the Colorado Geological Survey as a member organization of the SW Carbon Sequestration Partnership (Young et al., 2007).

Introduction

Climate change mitigation, meaning proactive change in industrial, community and household processes to reduce emissions of greenhouse gases, is rapidly emerging as a one of the largest, cooperative enterprises on earth. In contrast to some other large technological challenges over the past decades, such as the Manhattan project or the space race, climate change mitigation is not about national competition, it is about global collaboration to invent, deploy and operate large systems of new technologies and processes designed to reduce emissions and sequester (or 'put away') those emissions that cannot yet be eliminated. Emissions must be reduced by everyone, because their effects are felt everywhere.

The challenge ahead is huge, and the responses that are now emerging in technology, policy and trading circles around the world are gradually beginning the grasp the magnitude of the required response. Increased energy efficiency, fuel switch to lower emissions fuels, accelerated deployment of renewable energy generation facilities, emissions trading, carbon taxes and growth in industrial use of some greenhouse gases (such as CO_2 for enhanced oil recovery) are just some of the emerging responses, and they are all useful. The scale of the problem is such that massive long-term storage of greenhouse gases (mostly CO_2) has become a necessity. This carbon sequestration can be seen as a 'bridging technology' till that day in the future when the entire planet has moved beyond a dependence on hydrocarbons for energy.

This bridging technology is already in a rapid phase of growth. CO_2 is being sequestered today in a number of oil and gas fields around the world, and across vast areas in countries that already have implemented farm, ranch and forest management practices designed to increase the storage of carbon in soils and biomass. Yet, much more must be done because CO_2 concentrations in the earth's atmosphere are increasing at an accelerating rate.

A recent influential report by the British economist Nicholas Stern (2006) concluded that the cost of action to mitigate climate change, while expensive, will still be vastly less than the cost of inaction. Inaction implies covering the costs of reconstruction following increased frequencies of extreme storms, forest fires, relocation of resource industries, and global sea level rise with associated coastal flooding. In Stern's review, this cost is found to potentially rise to 5% of Global GDP, or as much 20% if the most extreme climate forecasts turn out to be correct. In contrast, the cost of action – if implemented in a timely fashion may be about 1% of GDP. Because of this realization, and related studies that have reached similar conclusions (Lovell, 2006), policy decisions made across the world are increasingly focused on stimulation of the most effective forms of direct action to reduce the threat.

The State of Colorado is already the home for much of the research that has developed the understanding of climate change – through long-term basic research programs at the State's three research universities and the many prominent national research centers along the Front Range. Now, the door is opening to facilitate growth of new climate-change mitigation industries, because the State has a long history in the extraction of minerals, oil, coal and gas – exactly the industries with the technology and skills to operate subsurface carbon sequestration sites. Ironic perhaps, but the hydrocarbon industry will play a dominant role in leading the world beyond the classic hydrocarbon economy.

Some large international oil companies envision a future carbon sequestration industry on the scale of today's global oil and gas industry. Some of these companies also envision the future use of hydrocarbons not only with reduced emissions but zero emissions. Technologically, this can all be done. Carbon can be separated and sequestered at the production site for hydrocarbon extraction, it can be separated before combustion of coal or after combustion (but more expensively at that stage), and it can be separated at the automobile tail pipe.

Underground sequestration of all this separated carbon is also technologically viable. Industry will capture and transport greenhouse gases from points of origin to suitable storage targets, inject the gases (in supercritical fluid form) into the subsurface, and predict and monitor the migration and ultimate permanent storage of the materials underground. Government agencies will certify the sites and monitor the long-term safety of storage. Industry, government, educational institutions, NGOs and other employers will need recruits with new skills. The service industry must develop new tools and systems management skills. Overall, carbon sequestration will open up a major new sector of economic activity associated with high demand for advanced technology and labor with new skills. Those states that invest in developing the infrastructure for these new technologies the earliest will attract most of the new companies that will serve a range of specialty needs across the globe.

The enactment of the Colorado Climate Change Markets Act in 2006 was a significant first step on the road to a Colorado that could play a leading role in the greatest environmental challenge the world has ever faced. The act was included in the same House Bill that also established the Colorado Renewable Energy Collaboratory (HB 1322). This action expressed a clear understanding on the part of the Legislature that for Colorado to become a leader in the industry of climate change mitigation, it should start by forging links between Colorado's energy research institutions. Looking forward, to have real impact these links have to widen, and also to expand to include State and Federal agencies, industrial operators, NGOs and interested individual citizens.

The climate change mitigation case for geological carbon sequestration

Climate change is part of earth's history. Data from the geological record document that CO_2 has invariably played a major role in climate changes on earth. On 100 million-year time scales, CO_2 concentrations and climates have changed in response to movement of tectonic plates across the earth and resulting variations in the frequency of volcanic eruptions (Robock et al., 2000). On time scales of 10s of thousands to 100s of thousands of years, climate has also changed from glacial to interglacial conditions, dominantly because of astronomical changes in the Earth's orbit around the sun which impact the amount and timing of solar radiation our planet receives. These ice-ages have been a recurrent phenomenon over the past 2 million years and are particularly well recorded in ice cores from existing thick ice sheets, such as those in Greenland and Antarctica. These cores record not only the changes in the rate of snow (which turns to ice on burial) accumulation, but also the composition of the atmosphere when the snow fell. Figure 1 (modified from Petit et al., 1999) is one such record from the Vostok research station near the South Pole, with data on CO_2 concentrations and temperature back through time. The signal documents regular glacials (ice-ages) and inter-glacials just about every 100-thousand years or so for the past 400-thousand years. More surprisingly, the data also document that during every glacial period the atmospheric CO_2 concentrations typically were about 180 ppm and during every interglacial period they stayed pretty close to about 280 ppm. As a natural system, the Earth regulated CO_2 concentrations such that it fell within a well-constrained range. Varying in parallel with these CO_2 concentrations were average temperatures, which typically ranged over a range of 10^{o}C between glacials and interglacials. Humans were around during these 400-thousand years, but left little discernable evidence of climate impact – until very recently.

The insert in the top right of Figure 1 (Etheridge et al. 1998) documents CO_2 variations over the past 1000 years. From year 1000 CE till 1750 CE, the CO_2 concentrations varied with small amplitude around a mean of about 280 ppm. Since 1750 there has been a dramatic increase in concentrations, at an accelerating rate, coinciding with the rapid increase in use of fossil fuel across the world starting with the 'industrial revolution' in the late 1700s. Today the average atmospheric CO_2 concentration stands at 380 ppm.

Figure 1. Variations in atmospheric CO_2 concentrations (top graph) and temperatures (by proxy) recorded in continuous drill cores from the Antarctic ice cap, near the South Pole. Modified from Etheridge et al. (1998).

This correlation of historical CO_2 and temperature variations does not prove cause and effect. Yet, it does not contradict it either. In this case, the patterns shown in Figure 1 are consistent with the predictions of fundamental physics of the greenhouse effect, which was first understood by Tyndall in England in the 1840s and reaffirmed by numerous experimental and theoretical studies since. The Academies of Science in 10 major nations concurred in their reports to the G8 meeting in Gleneagles, Scotland in 2006 that the earth's climate is currently warming because of man-made CO_2 emissions, and the summary of the 4th IPCC (Intergovernmental Panel on Climate Change) report (2007), concluded "with 90% certainty" that the observed changes in Earth's climate are man-made.

The challenge ahead to stabilize atmospheric CO_2 concentrations is enormous, regardless of which target level one might aim at. The IPCC has for some time operated with the assumption that the Earth could tolerate a doubling of CO_2 concentrations relative to the pre-industrial level of 280 ppm, or about 550 ppm. Reports on accelerating rates of ice-sheet deterioration in Greenland and Antarctica, however, are raising increasing concerns as to whether that level of CO_2 concentration is too high. If CO_2 levels are to be kept at significantly lower levels, then emissions must be reduced at a faster pace than called for in current plans, or the industrial capacity for capturing or storing CO_2 underground must be increased. A recent calculation on the rate of CO_2 storage needed to cap concentrations at today's level is quite sobering: Socolow et al (2004) proposed that getting a handle on reductions in CO_2 emissions would be easier if we broke it down into parts. Each of 7 parts could be addressed by separate approaches, including increase energy efficiency, carbon sequestration, and so on. If we were to do one wedge (1/7th of the problem) through geological carbon sequestration, it would require building an infrastructure to inject 125 million bbl/d at the end of 50 years. Current oil production is some 82 million bbl/d so that is about a 50% increase over current global oil production. (C. Christopher, BP, personal communication, 2007).

The case for pro-active climate mitigation is clear to scientists, policy makers and industry leaders. Given the magnitude of the industry needed to deal with the problem through sequestration, it is clear that one must pursue all available business opportunities to generate the level of investments needed to bring about a change. This report will focus on one such industry opportunity, CO_2-enhanced oil recovery, which opens great economic possibilities for Colorado.

The business case for geological CO_2 sequestration – a: the world

The large-scale use of CO_2 for industrial purposes began in the Permian basin of west Texas in the 70s and 80s because of the oil price spike that followed the Arab oil embargo (1973-74) and the Iranian revolution (1979). Here in the Rocky Mountains region, CO_2-EOR took off at the same time at the Rangely oil field in the Piceance basin of northwest Colorado (operated by Chevron), and at Baroil in Wyoming (then operated by Amoco). The source of CO_2 for the west Texas operations were natural CO_2 fields in southern Colorado and northern New Mexico (McElmo Dome, Bravo Dome and Sheep Mountain; Fig. 2). The Colorado and Wyoming EOR fields obtained CO_2 from the La Barge gas field in western Wyoming (Fig. 2).

Once the oil price collapsed in the mid-80s, only minor new investments were made in the use of CO_2 for enhanced oil recovery, until very recently. Currently, there is a very rapid expansion of CO_2-enhanced oil recovery around the world. Also, because climate mitigation now has become a business driver, which it was not in the 70s, there are now a number of new CO_2-EOR projects in which the potential value of sequestered CO_2 enters into the financial project feasibility analysis. The projects listed in the following paragraphs are all commercial projects. In addition to these, there are also a number of R&D tests, pilot projects and sequestration technology demonstrations going on around the world.

One of the most 'visible' CO_2-EOR projects at present is the one at EnCana's Weyburn field in Saskatchewan, Canada. At Weyburn, EnCana has injected 3,000 to 5,000 tons of CO_2 per day for increased oil production since year 2000, and they expect to store a total of 20 million tons of CO_2 once the commercial production comes to an end. The Weyburn project is 'visible' because it was the site for a major 'joint industry project' earlier in this decade, the Carbon Capture Project (CCP). The CCP was a joint R&D effort between nearly a dozen major international oil and gas companies, the Canadian government, the provincial government of Saskatchewan and the U.S. Department of Energy.

The Weyburn field is one of the largest oil fields in Canada (estimated 1.4 billion barrels of original oil in place) and was discovered in 1954. At the end of its water-flooding stage, the field was thought to have produce 30 percent of total reserves, and with the new CO_2 project now underway the expectation is to increase that to a total recovery percent of 46. Peak daily production is expected to reach 30,000 barrels (BOPD) per day in 2008, as compared to only 10,000 BOPD if water flooding had been continued. These numbers are a dramatic illustration of the value of CO_2 flooding in oil reservoirs, and help drive home the magnitude for the CO_2 market in the oil industry once anthropogenic CO_2 truly becomes a viable industrial resource through capture and separation. An excellent technical summary of the CCP project is included in http://www.co2captureproject.org/Phase1Index.htm.

Close to Weyburn is the Midale oil field, now operated by the Apache Corporation. This is also an old field, discovered in 1953. CO_2 injection started in 2004 and they expect production of an additional 45 MMBOE, out of the original estimated oil in place of 515 MMBOE, or about 9% additional recovery. For this EOR operation, Apache is injecting a total of 2100 tons of CO_2 per day, for a cumulative storage of 8.75 million tons for the 30-year life-time of the project.

To bring these two Canadian projects into the context of the emissions reductions needed on a global scale, it is worth pointing out that Weyburn and Midale together will at the end of their lifetimes (30 years) have locked away the equivalent of more than six years worth of all carbon emissions from the province of Saskatchewan.

The Postle Field in Oklahoma is an example of a major trend of reservoirs that produce oil from the thick, coarse sandstones of the Morrow Formation. A large number of such fields underlie the panhandle of Oklahoma and adjacent Colorado and Kansas. There is significant upside potential using CO_2 to enhance oil recovery from many of these fields, and perhaps as much as an additional 50 to 75 million barrels of oil can be recovered (http://www.pttc.org/solutions/207.htm).

SACROC (Scurry Area Canyon Reef Operators Committee) Unit in the Permian Basin of West Texas represents North America's seventh largest oil field with about 3 billion bbl of original oil in place. It is also the first CO_2-EOR project in North America (started operating in 1972) and currently the world's largest CO_2 sequestration site. Another quite interesting 'factoid' about SACROC is that in the early years (1972-1984) Chevron fed it CO_2 from produced gas streams at four gas plants in the southern part of the Permian basin, and dehydrated and transported that gas 220 miles to SACROC for injection. This was all prior to the construction of pipelines from southern Colorado to the Permian basin (Fig. 2). Since year 2000, the field has been operated by Kinder Morgan CO_2 Company ($KMCO_2$).

At In Salah in Algeria, BP with its partners Statoil and Sonatrach, has been running a commercial CO_2 enhanced oil recovery and sequestration operation since 2004. The project is comparable in scale to Weyburn, with injection of 3,000 to 4,000 tons per day and an expected ultimate storage volume of 17 million tons upon project completion.

The Sleipner field in the Norwegian sector of the North Sea is the earliest pure commercial sequestration project, driven by Norway's passage of a tax of $100 per ton of CO_2 emissions, way back in 1995. They have been injecting about 3,000 tons of CO_2 per day since 1996 into a shallow subsurface aquifer, well above the production reservoir below. At completion, the Sleipner field is also expected to store about 20 million tons of CO_2. Sleipner also has become on of the world's foremost laboratories for monitoring what is actually happening to the CO_2 once injected underground. Since 2006, this monitoring effort has become another joint industry project, termed "CO_2 remove". Figure 3, courtesy of the "CO_2 remove" project, demonstrates very clearly how the CO_2 has migrated upward from the initial injection point till it hit an impermeable layer, or 'cap rock', and then migrated laterally underneath that sealing layer. Later in this report we will return to the many scientific questions related to this type of fluid migration. This example is included here to demonstrate that the technologies needed to 'track and verify' where the injected fluid moves over time, are well in hand.

Sequestration of CO_2 in deep saline brine formations is also about to become an available commercial technology. At Snohvit in northern Norway, Statoil began injecting 2,000 tons of CO_2 per day in 2006. Chevron is planning a very large commercial sequestration project at their Gorgon field of the NW coast of Australia, injecting as much as 10,000 tons of CO_2 per day into a saline brine formation, starting in 2009.

Figure 2. Map of the Southwest Region (Allis and others, 2003).

Figure 3. Time series of reflection seismic signatures of the CO_2 plume at the Sleipner field in the North Sea. Injection began in 1996 and three years later the difference from pre-injection conditions are clearly observed. The CO_2 plume had already reached an impermeable layer at the top of the reservoir, but lateral spreading beneath that seal is still limited. By 2006 there was a significant lateral spreading beneath the cap rock. Also, there is no indication that the CO_2 is penetrating the cap rock, even 10 years after commencement of the injection.

Also in Norway, Shell Oil and Statoil have announced two very large CO_2-EOR projects at the closely juxtaposed Heidrun and Draugen fields. These projects are scheduled to be operational by 2010 and inject about 6,000 to 7,000 tons of CO_2 per day. CO_2 will be captured from a methanol plant and from an 860 MW gas fired power station to be constructed on the coast of mid-Norway (Tjeldbergodden). The power plant will provide offshore power to Draugen, Heidrun, and the gas export facility for Ormen Lange and Nyhamna. In addition it will provide a secure regional onshore power supply. Some 2.5 million tons of CO_2 will be injected annually for EOR and sequestration, initially at Draugen and then subsequently at Heidrun, with potentially further candidates for CO_2-EOR beyond these fields. This is the largest proposed offshore CO_2-EOR project. Shell is actively leveraging its Permian Basin experience in the feasibility study of Draugen. Successful development will require a substantial economic contribution from the Norwegian authorities. The investment decision is scheduled for end-2008, with expected startup in 2010-2011.

Finally, Monash Energy and Shell are planning a very large combined CO_2-EOR and saline brine sequestration project in Australia, designed to inject as much as 35,000 tons of CO_2 per day.

Perhaps the most interesting planned CO_2 sequestration projects in the world are those tied to coal power plants with carbon capture, designed to generate 'carbon-free' electricity from hydrogen. There are two such commercial projects already underway, both headed up by BP. The first such plant was announced in June, 2005 and is to be built on the coast of Scotland and will use natural gas combined with hot steam to produce pure hydrogen, H_2, and pure CO_2. The H_2 will be used to fuel a turbine for electricity and the CO_2 will be piped to the Miller oil field in the North Sea, 240 km offshore for use in enhanced oil recovery operations. At the Miller oil field they are schedule to inject 2000 tons of CO_2 per day, for a total storage capacity over the project life of 1.3 million tons. This is the world's first such industrial scale project.

The second project, announced in February, 2006, will be built in Carson, California at BP's large refinery there. Jointly with the Edison Mission Group, BP will build a 500 MW hydrogen power plant, with the H_2 generated by gasification of petroleum coke, an abundant byproduct of the oil refining process. The CO_2 that is produced in the same reaction will be used for oil field CO_2-EOR (at a field yet to be determined). The plant is designed to capture 90% of the CO_2 emissions, and the CO_2 separation train has the capacity to deliver 10,000 tons of CO_2 per day to a potential customer.

The Japanese Ministry of Economy, Trade and Industry recently announced that they intend to set up facilities worldwide to capture carbon dioxide from industrial operations and store it underground. Their goal is for this program to reduce emissions of CO_2 to the atmosphere by 200 million tons per year. This is the equivalent of ten times as much CO_2 as what a sequestration site like Sleipner will store at the end of its expected operation time span. Nevertheless, it is still equivalent to only about 1% of the total annual global emissions rate. The Japanese intend to store half of the CO_2 in the country and half abroad.

This brief review of the broad global picture of to carbon sequestration with and without CO_2 enhanced oil recovery, tells a powerful story: large integrated oil companies all over the world are committing themselves to a future fossil energy industry that is inexorably tied to carbon capture and sequestration. In their minds and – more importantly – in their business plans, the issue is settled. The future survival of an energy industry based on hydrocarbons is dependent on developing cost-effective technologies and engineering systems to capture CO_2 emissions.

The business case for geological CO_2 sequestration – b: Colorado and Wyoming

Historical and current trends in the CO_2 enhanced oil recovery industry here in the central Rocky Mountains may position Colorado to become a major player in the emergence of a clean hydrocarbon industry.

CO_2 storage in Colorado began with Chevron's project at Rangely in 1986. The CO_2 for this EOR operation is purchased from ExxonMobil's plant at Shute Creek in Wyoming (Fig. 4) and transported via pipeline to Rangely. As an EOR project, this operation has been quite successful and estimated to have recovered an addition 6% of the original oil in place (Young et al., 2007). Also, as a sequestration site it is quite significant: by the time the project is schedule to close down (in 2010) it will have sequestered a total of 29 million tons of CO_2 (Young et al., 2007), more than the Sleipner and Weyburn fields discussed previously. Soil gas flux measurements by Ron Klusman (2003) also document that the Weber Sandstone reservoir into which the CO_2 is being injected is also quite well sealed, making this oil field a high-quality long-term sequestration site.

The pipeline from Shute Creek forks in SW Wyoming and also provides CO_2 to Baroil in Wyoming, where EOR operations began in 1987 and 1989 at the two separate fields that make up this complex. The field was operated by Amoco when EOR began and is now operated by Merit Resources. The cumulative CO_2 storage at field life completion (2008?) is expected to be about 5 million tons.

After nearly 20 years of dormancy in new CO_2-EOR projects in the central Rockies, Anadarko decided in 2004 to extend the CO_2 pipeline from Shute Creek to reach the Salt Creek field, Wyoming's largest oil field (Fig. 4). At the current operations level, the field receives between 5,000 and 6,000 tons of CO_2 per day, and is estimated to store a total of 27 million tons at the end of its operational life, making it a storage field of about the same size as Rangely. On its way to Baroil, the Shute Creek pipeline also connects to the Patrick Draw field in SW Wyoming (Fig. 4). In 2004 Anadarko also put the Monell unit of this field on line for CO_2-EOR.

The revival of the CO_2-EOR industry in Colorado and surrounding states is mostly driven by today's high oil prices. However, the interest is also stimulated by the expectations that evolving regulatory regimes might help build a strong economic foundation for a range of sequestration industries.

CO_2 enhanced oil recovery works very well as a method to increase the total amount of recoverable reserves from an oil field. Fig. 5 shows the principles of the operation. CO_2 is injected under high pressure to a reservoir at a depth of several thousands of feet. For best results, the pressure should be above the 'minimum miscibility pressure' to achieve complete dissolution of CO_2 in the oil. Once this is achieved, the viscosity of the oil is reduced, surface tension is reduced, and the diluted oil flows more easily through the rock matrix to adjacent well bores hence increasing oil production. Because oil companies pay for the CO_2 used in EOR, they recycle as much of it as possible. As oil with dissolved CO_2 moves back up the production well bore, the pressure is released at a separation unit (Fig. 5) where CO_2 is removed from the oil and re-injected into the formation. After successive cycles of CO_2 migration through the reservoir, an increasing net amount of CO_2 is permanently stored in the subsurface in a mixture of oil and supercritical CO_2 that fails to find its way to the production wells and is left as unrecoverable. The net amount of purchased CO_2, therefore, is less than the total volume that circulates through the field during the lifetime of a field's operation (by a factor of 2 to 3).

Figure 4. Distribution of CO_2 transport pipelines, CO_2-EOR fields, oil and gas fields and power plants through the three-state region of Colorado, Wyoming and Utah. From Nummedal et al., 2003.

The production history for all Rocky Mountain oil fields that have been subject to CO_2-EOR demonstrates very clearly the success of the method as a means of stimulating recovery. Figure 6 presents data from the two fields that make up Baroil in Wyoming: Wertz and Lost Soldier. Injection of CO_2 at Wertz field commenced in early 1987 and at Lost Soldier in 1989. In each field, immediate post-injection production increased by about a factor of 3.

Because of this historical success, Colorado and the surrounding Rocky Mountain States are poised to expand the use of CO_2 for enhanced oil recovery. Currently, growth in this industry is supply-limited, because all current CO_2 comes from 'natural' subsurface reservoirs, specifically the ExxonMobil field at LaBarge, Wyoming. As the map in Fig. 4 also shows, this pipeline goes directly past a number of very large coal-burning power plants, which emit large amounts of CO_2. Moreover, these plants sit dispersed across sedimentary basins of the Rocky Mountains region that contain literally thousands of individual oil reservoirs (gray patches in Fig. 4) that would, in principle, benefit from access to CO_2 for enhanced recovery.

There is a major irony in this, that the Rocky Mountains region finds itself in a situation where the lack of CO_2 is a barrier to domestic oil production, while the world struggles to sequester more of this greenhouse gas. Efforts to resolve this impasse must include: 1) better technology development to capture of CO_2 from these coal-burning power plants at low cost to make if affordable in EOR operations, 2) development of an integrated regional structure of pipelines, power plants and EOR/sequestration facilities, and 3) trading schemes that offer incentives for companies to include CO_2 into their long-term business plans for increased oil and gas recovery. With these factors in place, Colorado would probably experience a growth in service industries handling CO_2 storage, start-up companies developing new tools for CO_2 injection, monitoring and verification, and a thriving R&D sector pursing cost and efficiency improvements at every step in this complex, integrated industrial sector.

CO_2 Sequestration versus EOR

The traditional CO_2-EOR industry is, of course, very aware of how emissions constraints are changing the parameters surrounding their industry. This became

quite apparent in the opening of this winter's (2006) CO_2 conference in Houston/ Midland when Texas Railroad Commissioner Michael Williams told a conference of oil professionals that "knowledge of CO_2 sequestration is important because we are moving toward a carbon-managed world". He also pointed out that Texas (and other states) is facing a shortage of CO_2 to keep up with the production of the more than 160,000 barrels per day of oil currently produced in the state. He estimated that the current shortage is about 0.5 billion cubic feet per day with the industry in the state consuming about 1.5 billion cubic feet per day (http://www.oaoa.com/news/nw120506d.htm).

One way to increase the supply of CO_2 to the EOR industry is to provide long-term fiscal regimes that assign value to the CO_2 that is sequestered underground as long as it is

Figure 5. Schematic illustration of the CO_2-EOR process, modified by Young et al. (2007), from the National Energy Technology Laboratory

produced by anthropogenic sources. Industry is working hard, therefore, to have carbon capture and storage (CCS) recognized for earning credits under the evolving set of domestic and international trading schemes (see corresponding report by CU for in-depth discussion of this issue).

Sequestration is not the same as EOR, and combined projects, in particular, do present a series of very special technical and managerial challenges. For example, it takes a significant volume of recycled CO_2 to maximize EOR production. Also, energy is used for gas separation at the well head and re-compression for injection. Finally, the minimum miscibility pressure of CO_2 (limit for the formation of a supercritical fluid and full miscibility for viscosity reduction) depends on the methane contents of the reservoir.

All these additional operations in an EOR field also lead to increased emissions, so a complete life-cycle CO_2 budget really needs to be generated at the outset of combined EOR/sequestration operations.

It is particularly important to recognize that the time history of injecting CO_2 also will differ between EOR operations and sequestration. EOR operations are optimized with respect to oil yield, and sometimes that requires reducing CO_2 injection rates to keep 'balance' with the internal reservoir pressure build-up. In contrast, for sequestration, one wants to have a high, continuous rate of injection. All this may require more complex commercial as well as engineering structures. Linking several sources of CO_2 with several sinks may, in part, generate the flexibility to meet the complex demands of the sequestration industry to ensure availability of injection capacity.

Finally, in a combined EOR and sequestration project, the regulatory framework needs to be clearly established, in terms of any additional requirements over and above the monitoring that would be deployed purely for EOR purposes and the ownership of the liability for ensuring the integrity of CO_2 sequestration after field production and EOR operations have ceased at conventional field abandonment.

Overall, there clearly are a number of additional value elements in a combined CO_2-EOR and sequestration program. These include: 1) the increased production of oil from domestic reservoirs and therefore improved energy security, 2) a first and important step on the way to cleaner (greener) fossil fuel supplies, 3) a very large and immediately available sink for CO_2 emissions, and 4) increased knowledge about the behavior of CO_2 in the subsurface, helping set the stage for sequestration in other, and even larger, reservoirs such as regional saline aquifers.

The Carbon Sequestration Potential in Colorado - a Brief Summary of Work Completed by the Colorado Geological Survey

The Colorado Geological Survey is a partner in the Southwest Regional Partnership on Carbon Sequestration, one of seven partnerships established by the U.S. Department of Energy's National Energy Technology Laboratory in 2003. These partnerships form a nationwide network for the purpose of evaluating optimum strategies for minimizing greenhouse gas intensity via suitable carbon sequestration methods. The Southwest Partnership is led by the New Mexico Institute of Mining and Technology and comprises a large, diverse group of expert organizations and individuals specializing in carbon sequestration science and engineering, as well as public policy and outreach.

In 2000, CO_2 emissions were more than 92 million short tons in Colorado and are projected to increase by 2.4 percent per year through 2025 (Young and others, 2007). Nearly 76 percent of these emissions result from activities in the utility and transportation sectors. Power generation in the state relies primarily on coal and as a result, 42 million short tons of CO_2 or 46 percent of the total emissions in Colorado are emitted from power plants in the utility sector (U.S. Environmental Protection Agency, 2004). These stationary point sources afford the possibility of capture and separation of CO_2 for transport to and storage at nearby "sinks". Figure 4 shows the locations of the States' major power plants, as well as the distribution of oil fields in the major sedimentary basins.

Figure 6. Production of oil as a function of time in the two fields that make up the Baroil complex in Wyoming. Injection of CO_2 at Wertz field commenced in early 1987 and at Lost Soldier in 1989. In each field, immediate post-injection production increased by about a factor of 3. From Nummedal et al., 2003.

Although CO_2 sink potential is widely distributed across the state, characterization efforts conducted by the Colorado Geological Survey focused on seven "pilot study regions" defined on the basis of maximum diversity in potential sequestration options relatively close to large CO_2 sources (Young and others, 2007). Utilizing both geologic and mineralization options, the Colorado Geological Survey estimates 720 billion short tons of carbon storage capacity within these regions (Young and others, 2007). With the availability of suitable technology, the pilot areas have the potential of providing a long-term storage solution based on 2000 CO_2 emission levels. The Colorado Geological Survey estimates that the highest CO_2 sequestration capacity potential for Colorado lies within the oil, gas, coalbed, and saline aquifer reservoirs of the Denver, Cañon City Embayment, Piceance, and Sand Wash basins (Young and others, 2007). Further site-specific investigations are required to determine both the technical and economic feasibility of implementing carbon storage projects in any one of these areas.

Colorado CO_2 Sources and Sinks

In the report by Young et al. (2007), the Colorado Geological Survey has screened the oil and gas reservoirs data base for reservoirs that may have the potential to store relatively large volumes of CO_2. Three screening criteria were used to identify favorable reservoirs. These were: production volume, reservoir depth, and proximity to a relatively large source of anthropogenic CO_2.

The preliminary screening step involved selecting reservoirs that had cumulatively produced either 1 MMBbls of oil or 10 Bcf of gas, or both. These larger-volume reservoirs were considered by the Southwest Partnership to be more attractive for storing carbon due to the capital investment costs associated with project startup. A minimum reservoir depth of 3,000 feet, at the mid-point of the reservoir, was used to ensure the reservoir could maintain CO_2 at supercritical (liquid) conditions (88 ^oF and 1,070 psia). The final screen was a distance of about 30 miles between the mid-point of the field and a relatively large point source of CO_2 such as a coal-fired power plant. This distance represents an investment of about \$2.5 to \$3.5 million in a CO_2-grade 4- to 6-inch diameter pipeline between a source and a single injection site (Mike Hirl, KinderMorgan CO_2 Company, L.P., oral communication, 2004).

In Colorado, 223 fields have individually produced 1 MMBbls of oil or 10 Bcf of gas. There are 181 Colorado oil and gas reservoirs in 117 fields that not only passed the production volume screen but also occur at a depth amenable to maintaining supercritical CO_2 and are located within 30 miles of a relatively large source of anthropogenic CO_2.

A candidate list of 247 oil and gas reservoirs are identified in six of the seven pilot study regions as having potential for carbon storage. (This list was combined on the basis of commingled production into 180 reservoirs for capacity calculations.) Each of these reservoirs screened successfully for production volume, depth, and proximity to an anthropogenic source of CO_2. The total carbon capacity estimated for these candidate reservoirs is 1.886 GT. Sixty-eight percent of the total oil and gas carbon capacity is associated with Rangely and Denver pilot study regions.

The EOR-related storage numbers for Colorado are quite impressive: 1.886 GT of carbon translates into about 25% of current annual global emissions. Storage of carbon in Colorado oil and gas fields, therefore, could have major impact on the reduction of global atmospheric CO_2.

Science and Technology Challenges for Reliable and Cost-effective Geological Carbon Sequestration

As a consequence of the background work made possible by funding from HB 1322, CSM scientists and engineers with the appropriate skill sets are positioning themselves to play a growing role in the many R&D programs that are emerging in Colorado and throughout the world to develop an emissions-free fossil fuel industry. A significant part of that vision centers on capture of carbon – at all stages in the life cycle of hydrocarbon fuels – from the first stage of production to emissions capture at the power plant smoke stack and the automobile tail pipe. Technically this is all feasible, but a lot of research and testing is needed before it all becomes economically viable. Geological carbon sequestration will play a huge part in this vision for a future of clean hydrocarbon fuels, but it is of course not the whole picture.

A thriving geological sequestration industry in Colorado would benefit from a solid scientific and engineering foundation at the State's research institutions, including the Colorado School of Mines. To help develop an understanding of the needed expertise, this report summarizes the key science challenges this 'incipient' industry currently is facing. Two specific industrial carbon sequestration projects are currently at the planning stage for Colorado: the "Brush project" related to Xcel's plans for an IGCC plant with carbon capture and sequestration, and the "Piceance basin project" related to Shell's plans for emissions-free production of shale oil in that basin. The report will therefore conclude with a discussion of the relevance of these 'scientific challenges' to the success of the two projects. The key challenges are:

1. GIS data management for assessment of economically viable storage options.
2. Subsurface geological mapping and qualification of alternative sequestration targets.
3. Prediction of sealing capacity for injection targets.
4. Modeling to predict the fate of the injected fluids down-hole (geochemical changes)
5. Modeling to predict geo-mechanical and geo-microbiological changes in the subsurface in response to injection of large volumes of man-made fluids.
6. Evaluation of all potential leakage mechanisms, in particular the possibility of CO_2 migration to the surface through cemented and abandoned oil and gas wells.
7. Testing and development of materials with properties to last in a corrosive subsurface environment.
8. Monitoring, measuring and verification (MMV) of the movement and ultimate stabilization of CO_2 in the subsurface.
9. Surface monitoring of potential CO_2 leakage into the air.
10. Education and information exchange with the public and policy makers to build mutual trust and confidence in the sequestration industry.

1a: Building an ArcGIS Geodatabase of Geologic Sequestration

ArcGIS software by Environmental Systems Research Institute (ESRI) holds incredible potential for storing, analyzing, and representing spatial data of all kinds. Very broadly, it combines the features of an Access database with Geographic Information System (GIS) technology, and puts them within an interactive framework that is relatively easy to manipulate, view, and query based on any data field entered. In the specific case of Colorado sequestration projects, ArcGIS data previously compiled by the Colorado Geological Survey (CGS) provides an excellent starting point for a geodatabase specific to the sedimentary basin in the state. For this data set, one can aggregate and convert the various data tables compiled for the 2007 CGS study into one geo-database that is specific to each basin and the data requirements of the specific sequestration issues. The geodatabase can be continuously updated and populated by reservoir and aquifer data from CGS and from records kept by the Colorado Oil and Gas Conservation Commission (COGCC).

The completed CERI geodatabase will contain some of the following parameters aggregated from the CGS databases for each oil and gas field and deep saline aquifer: field name, field location, field status, county(ies), producing zones and formation, produced oil, produced gas, produced water, production by formation, enhanced oil recovery (EOR) operations, average reservoir depth, saline aquifer properties, and other data as necessary or available.

1b: Screening for Oil and Gas Fields with Carbon Sequestration Potential for Specific CO_2 Sources

Once populated, the CERI geodatabase will allow extensive geospatial analysis of all potential geologic sequestration options in Colorado. Queries, or screens, could be applied for any number of attributes of interest within the list of reservoirs to obtain a short list of reservoirs and saline aquifers meeting the specified criteria. The CERI study will screen for production volume, average reservoir depth, distance from CO_2 sources, as well as other attributes to arrive at a list of geologic sequestration possibilities tailored for any given CO_2 source. Data specific to EOR will allow searches to identify oil and gas reservoirs that may be strong candidates for EOR operations.

2: Subsurface geological mapping and qualification of alternative sequestration targets

Fundamentally, identifying and qualifying (i.e. determining the volume of injected CO_2 that the site may hold) the sequestration target is the reverse of generating 'prospect maps' in the oil and gas industry. In the latter, one tries to determine where and how large the subsurface oil and gas accumulation is; in the case of sequestration one needs to map the location of a trap and identify its volume. Because supercritical CO_2 is lighter than water, and hence is driven upwards by buoyancy just like oil, the same trapping mechanisms that contain hydrocarbons are also likely to contain injected CO_2. Also, just like oil, CO_2 will travel upwards till it hits an impermeable seal (as in Fig. 3) and it may also travel vertically through fractures and faults or laterally along high-permeability paths, often associated with paleo-erosion surfaces embedded in the stratigraphic record. Ideally, for cost effective injection and low risk of CO_2 leakage, one wants to inject in deep targets with several vertically stacked zones of both reservoirs and seals.

Throughout the sedimentary basins in Colorado, there are many high-permeability sandstones and carbonates, ideal for CO_2 storage. Also, in light of the structural complexity of Colorado's basins, there are numerous trap configurations including basal onlap geometries that provide basin-margin stratigraphic traps in addition to such traditional structural traps as anticlines and sealing faults.

CO_2 can also be sequestered in deep aquifers, the so-called 'saline brines', at depths well below any aquifers tapped for agricultural or urban water supplies. The trapping mechanisms there may be different in that slow migration of the dissolved CO_2, together with slow-moving groundwater, may be acceptable in many settings. Also, CO_2 can be sequestered in underground, non-minable coal seams, a storage target of potentially great value in Colorado because of thick and widespread coal seams in many basins.

3: Prediction of sealing capacity for injection targets

The strength and lateral and vertical integrity of the storage target seals are critical components in determining storage volumes, potential gas migration over time, and quantification of risk. For carbon storage, seal effectiveness can be described by the effectiveness of three components: wells, faults, and cap-rocks. Wells represent a unique risk, and a potentially large one due to the extensive set of well-bores that penetrate the sedimentary basins of the Rocky Mountains. Many of these wells are now abandoned, and the leakage risk today is therefore directly related to the stability of the cement that was used when they were plugged and abandoned. Because of this uniqueness, well bore leak potential must be given special attention and it is discussed below in terms of cement stability.

Fault and cap-rock leakage characteristics and thresholds must also be qualified and quantified to provide clear understanding of local risks. Fault seal analysis in the context of juxtaposition of permeable strata across the fault throw, as well as the potential of leakage through the fault gauge, will also be addressed using advanced subsurface geology software developed for reservoir seal integrity appraisals. In the context of faults, it is generally thought that fault leakage thresholds can be predicted by fault reactivation and failure criteria (e.g., Wiprut and Zoback 2002). This analysis requires understanding of fault geometry and the stress tensor, both stress orientation and magnitude). This analysis can predict a number of important parameters:

- The maximum injection pressure for a given location.
- The CO_2 column height that may be supported at a given site.
- The threshold for substantial induced seismicity.

All of these parameters provide a quantitative basis for risk assessment, and can help to provide information for operators, regulators and other stakeholders concerned about such risks. In particular, the risks associated with induced seismicity are of special note in Colorado due to the history of induced seismicity at Rocky Mountain Arsenal; as such, correct and convincing predictions will be required for permitting and approval of large-scale CO_2 injection in Colorado's sedimentary basins.

To understand cap-rock leakage risk, a minimal amount of information is required. By far, the most important constraints are continuity and thickness of sealing rock units and these are fairly readily identified during the stratigraphic reconstruction of the regional geomodel. However, there are also concerns regarding the capillary properties of sealing facies and the dilation of micro cracks in cap-rocks (e.g., Johnson et al. 2004). The first can be characterized with conventional laboratory analyses of capillary entry pressure. The second could be quantified through advanced reactive transport simulation.

4: Modeling to predict the fate of the injected fluids down-hole

It should be noted that more than a hundred millions of CO_2 have been injected in the

Permian basin of west Texas since the 1980s, and over 25 million tons have been injected in total into Colorado's Rangely field since 1984, all without any detectable reservoir damage or leakage. In addition, injection at Weyburn included 1 to 2% of the sour gas H_2S, yet the field has suffered no leakage or damage to wells. Therefore, the CO_2 sequestration is starting from a solid base: for more than 30 years, industry has injected large amounts of fluids into subsurface reservoirs without any significant environmental problems. Nevertheless, the anticipated volumes of CO_2 to be sequestered if this technology is to be used as a major climate change mitigation tool, require an even higher level of understanding and predictability of how this fluid behaves in the subsurface.

A critical science issue prior to injecting CO_2 into any target zones is to model the fluid flow to evaluate CO_2 storage potential and migration in the reservoirs, and to investigate potential changes in injectivity of CO_2 with time. There are a number of issues related to the interactions of the injected CO_2 both with other fluids ('brines') in the potential target zone and with the various minerals in the rocks.

The specifics of formation brine compatibility with CO_2 and other potentially injected fluids depend on a number of factors. The most important of these are brine composition and rock composition. For example, relatively little is know about the phase behavior of the mixture of CO_2, H_2S and saline brines at different temperature and pressure regimes. The critical values for CO_2 are 31ºC and 74 bars. For higher values than that, CO_2 forms a supercritical fluid. The phase behavior for a mixture of the multiple fluids, however, is much less constrained. The approach chosen at CSM to address the phase behavior of these multi-fluid systems will involve molecular based modeling and simulation coupled with parameter optimization based on selected experimental data.

These science problems are best addressed through combined field, laboratory and simulation experiments. Fluid sampling should be done before injection for baseline characterization, during injection to track break-through, and after injection to document fluid composition changes and investigate leakage into overlying strata. Execution of such work should be considered as basic to the evaluation of the CO_2 storage suitability for Colorado reservoirs. Toolkits such as "geochemists workbench" and modified by reactive transport continuum codes such as NUFT and TOUGH2, are available and will be used in such modeling.

One example of the value of such fluid sampling before injection and after breakthrough is the Frio sequestration pilot north of Houston. In this experiment, Kharaka et al., (2006) documented rapid decrease in pH upon breakthrough of injected CO_2, and attendant increase in potential for dissolution of carbonates and iron oxyhydroxides. This potential dissolution might ultimately cause pathways for CO_2 migration through seals or well cements and needs to be well understood in all new sequestration target units. Also, dissolution of minerals such as oxyhydroxides could mobilize toxic trace metals and toxic organic compounds, if available (such as in hydrocarbon residues). Also, even subtle changes in gas concentration or rock composition can have surprising results regarding rates of gas and mineral dissolution, precipitation kinetics, and mobilization of metals in the reservoir (e.g. Knauss et al. 2006). These may affect injectivity, long-term effectiveness of CO_2 storage, and overall risk. In order to better understand the sequestration potential of a reservoir, the two-phase (water and CO_2) relative permeability of the reservoir must also be understood. Recent modeling (Kumar et al, 2005) indicates that storage of CO_2 as a residual phase in the pores may be a significant factor in the long term sequestration of CO_2.

5a: Prediction of geo-mechanical changes in the subsurface in response to injection of large volumes of man-made fluids

Modeling of volume reduction in the ground due to outflow of fluid is a classical area of geotechnical analysis called consolidation theory, that enables surface settlements and rates of settlement to be predicted in response to heavy surface loading. Conversely, similar theories can be adapted to estimate the potential for volume increase in the ground due to injection of fluids or gases. Computer modeling offers great potential for understanding the physics of problems such as these in view of the complex boundary conditions and non-uniformity of the rock properties. A key issue for modelers is the prediction of leakage from the system in view of the undesirable consequences of acidification that may ensue.

5b: Prediction of coupled subsurface processes

The complexity of interactions ('coupled processes') in a subsurface geologic system is one of the biggest challenges to be encountered in a growing carbon sequestration industry. To develop confidence in predictions of the subsurface response to injection of a 'foreign' fluid, one needs to understand links such as: 1)geophysical signals from biologic and chemical processes, 2) biogeochemical links to porosity, permeability, mineralogy, fluid fluxes; 3) geomechanical causes/consequences of biogeochemical activity; 4) chemical and fluid impacts on faulting, fracturing, and seismicity;

6: Evaluation of the possibility of CO_2 migration to the surface through cemented and abandoned oil and gas wells

Wells present a specific risk to CO_2 leakage because they are permeable "fast paths" to the surface – that is why we drill them. Even when properly completed and plugged, they represent a specific set of leakage risks (Gasda et al., 2004). Cement corrosion represents a special concern due to the acidification of deep brines after CO_2 injection (see Frio experiment summary, above) and the role that cement plays in proper completion, plugging, and abandonment. As such, understanding short and long-term cement response to CO_2 injection is central to proper quantification of risk.

Again, this is a problem that requires an integrated experimental and numerical approach. Reactive-transport simulation can approximate real-world subsurface processes and make discrete predictions of the long-term response. However, such models rely on proper knowledge of the system's equations of state and the kinetics of multiple chemical reactions. In particular, the kinetic data can be best determined in laboratory experiments. Moreover, such experiments should be conducted at elevated temperatures and pressures, in order to characterize the system response to static and dynamic conditions. Information from these experiments is needed to calibrate reactive transport simulation on wells and cements, which would serve as the basis for predictions of the long-term behavior of the cement in contact with injected CO_2.

7: Testing and development of materials with properties to last in a corrosive subsurface environment.

The materials used in CO_2 sequestration and/or EOR operations must be tough. Based on the long-term experience of the corrosion group in Metallurgical & Materials Engineering at the Colorado School of Mines, however, the expertise exists to assess the compatibility of materials selection for harsh environments, both aqueous and high-temperature. To perform such research on the specific problems related to CO_2 sequestration in Colorado, we need to prepare a testing facility where pipe segments can be examined in the aggressive environment of acid gas, sour, CO_2, brine, and their combinations at various temperatures, pressures and recirculation modes that simulate the environment at the sequestration site environment. Evaluation of coatings is particularly important because coated products, as opposed to uncoated material, will allow for great economic advantage over the potential alternative of using high-alloy corrosion resistant materials. A common and fairly inexpensive stainless steel, alloy 410, could be covered with refractory corrosion resistant coatings and become a more suitable material for downhole operations than some of the very expensive alloys.

8: Monitoring, measuring and verification (MMV) of the movement and ultimate stabilization of CO_2 in the subsurface.

CO_2 sequestration fundamentally differs from enhanced oil recovery in that successful storage of CO_2 requires monitoring and verification of injection. This is needed to demonstrate safe storage, recognize leakage, validate simulations and reservoir models of storage, and to account for CO_2 storage for (future) trading or crediting purposes. There are many technology options of variable resolution, validity and cost, but it appears that some combination of subsurface and surface tools is needed to satisfy most stakeholders. We focus here on a few key technologies including seismic, micro-seismic, tomography, and laser detection methods.

Several active seismic experiments have amply documented that CO_2 flow fronts can readily be imaged in the subsurface. The Weyburn experiment is a good example where CO_2 dispersal from horizontal injector wells can easily be contrasted with the ambient fluids in the reservoir (Fig. 7). Multi-component shear wave seismic tools proved invaluable in the Weyburn experiment. Operational monitoring of CO_2 migration during long-term injection would require a 4D (or 'time lapse') multicomponent seismic program.

In addition, there is merit in pursuing two other monitoring techniques which may be well suited to the conditions of a future sequestration project in Colorado sedimentary basins. The first is electrical resistance tomography (ERT), which measures resistance changes between downhole electrodes. In some cases, existing well casings can serve as electrodes; in other cases, electrodes are added to new casing. In all cases, it is cheap, non-invasive, and very fast. While recent studies have shown the success of this technology (Ramirez et al., 2006), the technique is best served through formal integration with other techniques (e.g., seismic, microseismic).

Microseismic methods have served for years as a means of observing hydrofractures. Recently, it has been suggested that it would serve as an excellent means of tracking CO_2 plumes in the subsurface. This approach works best when a microseismic array is deployed down-hole, ideally in nearby abandoned wells or monitoring wells. Given Colorado's history of induced seismicity, microseismic monitoring would have two additional advantages. First, it would help to allay stakeholder concerns about risk of induced seismicity. Second, it would quantify and detect the maximum possible seismic hazard from CO_2 injection into permeable strata (e.g. Rangely in 1969).

Figure 7. Dispersal of CO_2 away from two horizontal, branching injectors in the Weyburn field. Higher CO_2 saturation corresponds to warmer colors on the map. From Tom Davis, CSM, 2005 personal communication.

To ensure accuracy in the inversion of seismic data to saturation values for CO_2 and H_2S in the sequestration targets, geophysical measurements must be linked to rock physics measurements on a suite of target rocks with different CO_2 saturations. A fully equipped laboratory for such measurements is in place at the Colorado School of Mines, and ready to be deployed in sequestration research once this becomes a significant activity here in the state.

9: Surface monitoring of potential CO_2 leakage into the air

Detection of CO_2 gas leaks to the surface can readily be measured directly through soil gas flux measurements (Klusman, 2003) – but only at pre-determined sites where the gas flux chambers are set up. There are also tools for laser-based surface monitoring. Differential adsorption LiDAR (DiAL) and FTIRs both have the potential for high precision measurements and unique fingerprinting of CO_2, but may require long time series and high energy and data management requirements. There is even a potential for direct CO_2 detection using airborne measurements from laser or hyperspectral imaging technologies. However, it is not certain yet under what conditions these tools will operate, how to configure a monitoring array to maximize detection capability, and how to integrate monitoring data sets with other kinds of geological, geophysical, atmospheric, and operational data. Before CO_2 leak detection becomes 'standard operating procedure', there are several challenges related to testing and evaluation of these and potentially new pieces of detection equipment.

Simultaneous use of multiple monitoring techniques would help validate the results of any one of them, and help elevate public and industrial confidence in the final technologies that the State may want to have employed to ensure injection safety during the long life time (40-yrs?) of industries like coal gasification plants or oil shale production. After completion of a particular injection project, the sequestration site moves into a much longer-term, post-injection monitoring phase with its own set of technology challenges, as well as environmental and public policy concerns.

To ensure that changes in conditions at the sequestration sites can muster potential future scrutiny by public interest groups, it is invaluable to compare conditions to pre-injection baseline data. Establishment of the appropriate baseline data at targeted sequestration sites should be a high priority for the State.

10: Education and information exchange with the public and policy makers to build mutual trust and confidence in the sequestration industry.

George Bernard Shaw reportedly once said: "The single biggest problem in communications is the illusion that it has taken place". So it is, indeed, with much communication between the science and technology community and the public to whom policy makers, environmental analysts, scientists and engineers are all ultimately accountable. Therefore, the program that the Colorado Department of Health and Environment has initiated under C.R.S. § 25-1-1303 is a great first step: it has opened communication between "the State" and the technology and legal communities at the three State research universities as well as between these university groups themselves. Hitherto, communication between our three university groups about carbon sequestration was quite limited.

Communication between these research and industry groups and the public at large is more difficult, partly because of the fairly complex technical issues, and partly because public knowledge about many technology issues is based on news accounts of the occasional project failure or problem, rather that the accounts of the multitude of projects that operate as designed. This is not the place to propose a particular mechanism for better communication with the public, but it needs to be recorded that developing the right communications tool should be an integral part of the State's role in guiding the growth of this new industry.

Two Planned Large Colorado Geological Sequestration Projects

The documentation of rapid growth in CO_2 sequestration across the world and in the Rocky Mountains region, with or without additional benefits of enhanced resource recovery, makes a strong case for initiating action on carbon sequestration here in Colorado. Two potential near-term projects are the storage of CO_2 at or near Xcel's proposed IGCC (Integrated (coal) Gasification Combined Cycle) plant at Brush, and Shell's plans for sequestration in the Piceance basin, as a critical element in the possible production of shale oil in that basin. These two projects will be analyzed in some detail, because they might be the 'pioneers' in an emerging carbon sequestration industry in the State.

The Brush project

The Denver-Julesburg basin

The Colorado Geological Survey has identified the Denver-Julesburg (D-J) Basin as one of the most promising basins for geologic carbon sequestration within Colorado based on estimated carbon storage capacity (Young and others, 2007; Fig. 8). With the town of Brush located near the center of the basin, and as the possible site of an IGCC power

Figure 8. Distribution of carbon storage capacity for oil and gas reservoirs in the Denver and Fort Morgan study regions. MT is million tons, (No. of fields) is the number of fields statewide with the indicated carbon storage capacity. From Young et al., 2007.

plant, the D-J Basin is an ideal setting for detailed assessment of geologic sequestration options for a specific CO_2 source location. The Colorado Energy Research Institute (CERI) at the Colorado School of Mines (CSM) has just initiated this study, and will complete it between now and May 2008.

The research project

The CERI study will consist of three phases. Phase 1 is currently underway and anticipated to conclude in May 2007. It consists of building an ArcGIS geo-database of all oil and gas reservoirs, as well as deep saline aquifers within the D-J Basin of Colorado. It will build upon data previously compiled by the Colorado Geological Survey (CGS) and presented in CGS Resource Series 45, *CO_2 Sequestration Potential of Colorado* (Young and others, 2007). The database will enable flexible querying of D-J Basin reservoirs and saline aquifers for sequestration criteria specific to the Brush site. The completed geo-database can be adapted to fit the evolving informational needs of CERI, CGS, and the State of Colorado. The content of the geo-database will depend on the accessibility of reservoir and aquifer data within the basin.

<u>Phase 1</u>. This phase of the CERI study will differ from the 2007 CGS study in four ways. First, the geodatabase will focus only on the D-J Basin of Colorado instead of all basins within the state. Second, all reservoirs and saline aquifers within that basin will be considered instead of only those falling within the CGS pilot study regions as defined by a 30-mile radius around all major CO_2 sources. Third, field production and enhanced recovery (EOR) data will be updated to extend from 2004 (end date of the CGS study) through June 2006. And fourth, the CERI geodatabase will attempt to compile more extensive parameters specific to deep saline aquifers. The data base will also incorporate a 'distance from Brush' field as well as other reservoir data not included in the CGS databases due to reservoir location outside of the Denver and Fort Morgan pilot study regions of the D-J Basin.

<u>Phase 2</u>. This phase of the project, with is contingent on sufficient funding, will involve a detailed geologic study of one or more of the most promising potential carbon storage targets relative to the Brush site. Candidate reservoirs will be identified by a geo-database query using criteria of interest such as reservoir volume or depth. The emphasis of Phase 2 will be on understanding the subsurface geology of the candidate reservoir(s) and locating geologic traps, or CO_2 confining structures, within the subsurface. Based on data provided by the Colorado Geological Survey (Young and others, 2007), Figure 9 shows 35 of 965 reservoirs within the D-J Basin that match the specified criteria of location within 25 miles of Brush and with cumulative oil production of at least 1.5 million barrels and cumulative gas production of at least 1.5 billion cubic feet.

Phase 2 will build directly on the result of the Phase 1 geodatabase query for reservoirs and aquifers best suited to the Brush, Colorado site. Once the most suitable fields are selected, a detailed assessment of the subsurface geology of these fields will commence through an extensive literature review. The objective will be to identify the geologic formation thicknesses and properties above, below, and within the target zones for CO_2 injection. Emphasis will also be on determining the location, nature, and extent of subsurface traps, both of structural and stratigraphic nature. The integrity of seals, whether fault seals or cap rocks – or both – will be a major focus of study since it is critical to the long-term safe storage of the CO_2. All reservoirs and deep aquifers can be expected to possess some kind of trapping mechanism since they have already long contained the fluids within them. However, fully understanding these features and their effectiveness and reliability will be of utmost importance in selecting any site for geologic CO_2 sequestration.

Phase 3. This final phase, concluding in May 2008, will involve modeling the injection of fluids down-hole (see "challenge no. 4", above) and its reactive subsurface transport in one or more of the candidate D-J Basin reservoirs or saline aquifers based on the detailed geologic assessment performed in Phase 2. Phases 2 and 3 will serve as an M.S. thesis project for CSM student Jason Deardorff, and will end in publication of the results.

Phase 3 will incorporate the detailed geologic information compiled in Phase 2 into a model or simulation of fluid flow aspects of CO_2 injection. This could be a model of

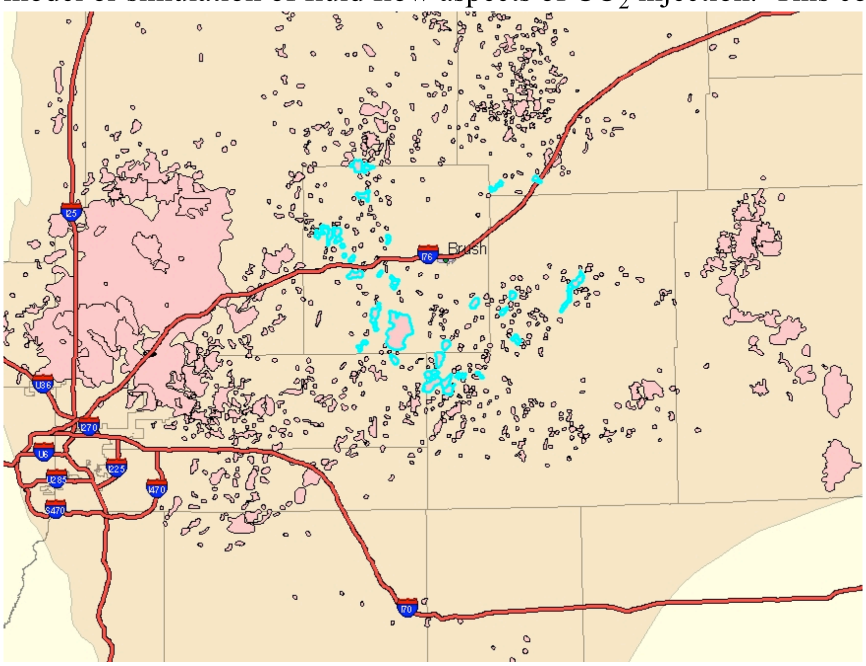


Figure 9: Reservoirs matching the user specified criteria of location within 25 miles of Brush and at least 1.5 million barrels of produced oil or 1.5 billion cubic feet of gas production, as queried within ArcGIS software, are shown highlighted in green. (Reservoir data from Colorado Geological Survey; Young and others, 2007).

injection into a depleted oil or gas reservoir, CO_2 use in an EOR project, or sequestration within a deep saline aquifer, or several of these options. The exact nature of the model or simulation has yet to be determined since final data and results from Phases 1 and 2 are not yet available. Some examples of potential modeling projects and results for Phase 3 of the CERI geologic study include the following:

- Model how injected CO_2 will migrate through a reservoir and determine how long it can be expected to remain sequestered.
- Determine how much additional oil or gas can be expected to be recovered from a reservoir in a CO_2-EOR project.
- Model CO_2 injection into a deep saline aquifer to determine how the CO_2 will migrate within the aquifer or change the chemical properties of the water and interact with containing formation rock.
- Determine how much brine will be produced and handled at the surface from sequestration in a saline aquifer.
- Assess the potential for injection-induced seismic activity within the D-J Basin.
- Determine potential vertical CO_2 migration pathways.

This three-phase CERI geologic sequestration study would determine the best site(s) for geologic sequestration for an anthropogenic source of CO_2 near Brush, Colorado, model an aspect of CO_2 injection into geologic media, and serve as a conceptual model for assessing geologic sequestration options for specific source locations within the State of Colorado and elsewhere.

The Piceance Basin Project

The Piceance basin in western Colorado was also identified by Young et al. (2007) as a very promising basin for geologic carbon sequestration within Colorado (Figure 10). The basin is also of interest to several oil companies conducting feasibility studies for future production of shale oil from the Green River Formation. The Green River Formation has long been a target for shale oil production (since the late 1800s) but attempts at establishing large-scale industrial oil production have repeatedly failed, due to sudden drops in oil price as well as concerns about the severe environmental impact of the traditional shale mining operations (Boak et al., 2007, Oil Shale Symposium Proceedings). Since the last shale oil bust (1982) till today, however, the technologies and issues surrounding shale oil have changed dramatically. Shell Oil Company and others have pushed the development of an entirely new approach to shale oil production, based on in-situ conversion of shale to high-quality crude oil, which can then be pumped to the surface with wells comparable to those in conventional oil fields, although the well heads will be more closely spaced. Also, there is somewhat greater confidence in industry that oil prices will remain high for a longer period of time, making the large investments in this new technology feasible.

Concurrent with these changes in the business fundamentals, there is also the new realization that for a new, large hydrocarbon industry like this to get started today in a 'carbon constrained world' it is imperative that it be totally emissions free. The future of the shale oil industry in the Piceance basin, therefore, depends on designing production systems that are economically viable to the operator, have minimal impact on the ecosystems and groundwater of the basin, and emit NO carbon dioxide. This latter constraint is the issue in this report. It is hugely important. Large scale shale oil production from Colorado could go a long way towards the much desired "energy independence" for the U.S.A. Also, since oil shale exists in many other places across the globe as well, the emergence of such an industry would help reduce the global pressure on the Middle East as the dominant supplier of oil.

Figure 10. Distribution of carbon storage capacity for oil and gas reservoirs in the Palisade and Rangely study regions. MT is million of tons; (No. of Fields) is the number of fields statewide with the indicated carbon storage capacity. From Young et al. (2007).

Piceance basin sequestration targets

Mesozoic and upper Paleozoic rocks of different lithologies and permeabilities underlie the oil shale production zone (Green River Formation) in the Piceance basin, providing several zones of high injectivity for gas storage, alternating with sealing strata (Fig. 11). Also, the basal onlap geometry provides basin-margin stratigraphic traps in addition to such traditional structural traps as anticlines and sealing faults. One of the potentially attractive injection targets is the Jurassic Entrada Sandstone (Fig. 11), an eolian unit of generally high injectivity, but several other targets are also worthy of evaluation. Near the center of the Piceance basin, this Entrada target lies at a depth of 12,200 ft. Only 5 miles farther west, however, the same horizon shallows to about 9,000 feet. The westward shallowing continues onto the Douglas Creek arch. The Entrada is generally overlain by fine-grained, sealing facies of the Morrison Formation. Sandy members of the Morrison Formation, at shallower depths than the Entrada, are also potentially viable injection targets, as are deeper Paleozoic rocks (which of course would be more expensive targets to reach).

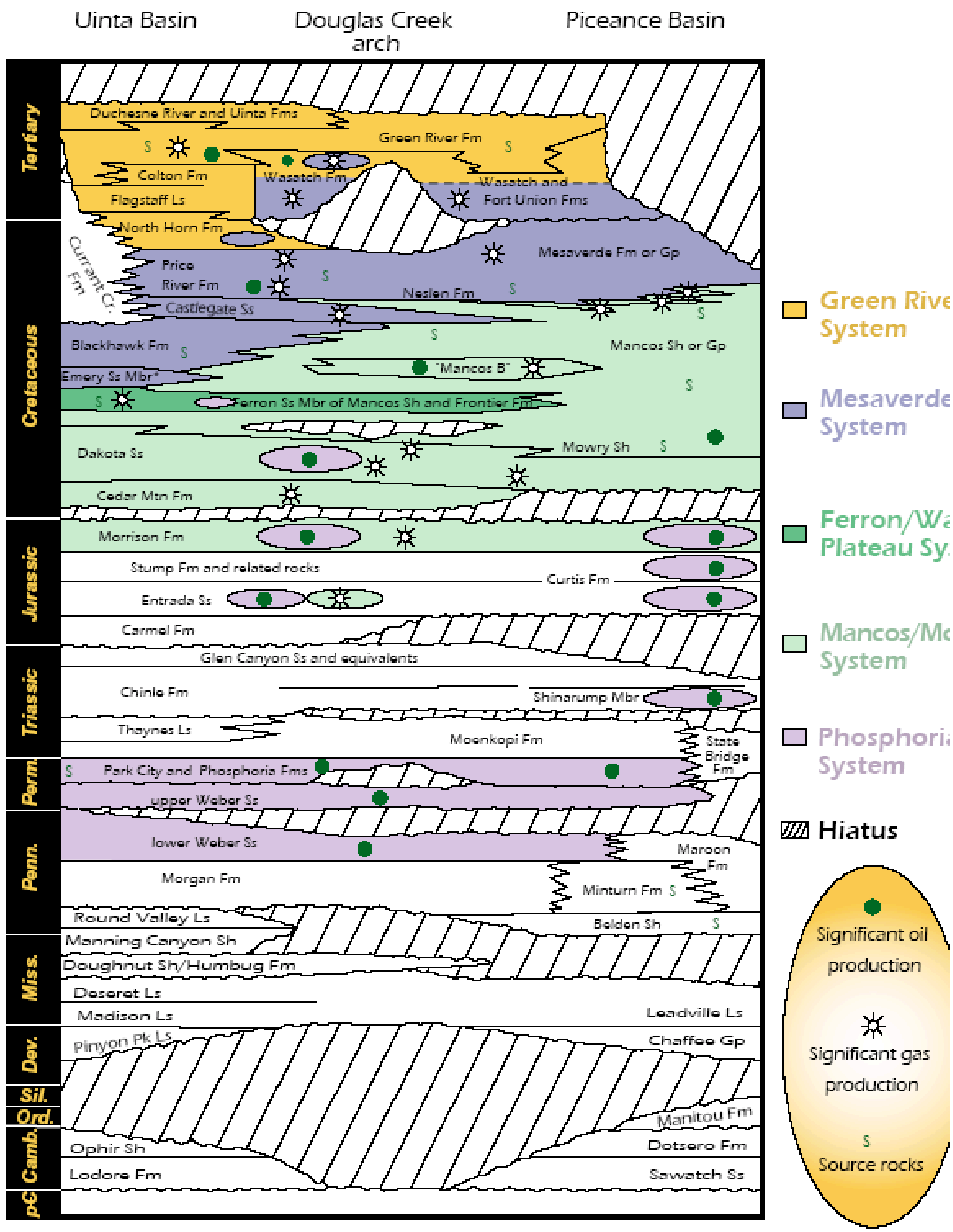
The Piceance basin has been extensively drilled for hydrocarbon production (mostly for gas in the Upper Cretaceous Mesaverde Group, but also locally at small Entrada and Morrison oil pools; see Fig. 11), so the potential for CO_2 escape through abandoned wells needs to be assessed. There are very few deep wells in the basin, however, so we are reasonably confident that storage reservoirs without access to man-made escape paths can be identified. There is sufficient geological information for the basin to assess the potential for gas migration through natural open fractures, faults and other migration fast-paths and to quantify the associated risk.

Conclusions

This study of carbon sequestration in Colorado concludes that the state has all the needed industrial, academic and policy skills to become one of the leaders in the emerging industries to reduce carbon emissions from fossil fuels. In fact, the state is one of very few (the only one?) with the right combination of relevant industrial skills and awareness of the environmental 'paradigm shift' to find ways work together to create a new vibrant industry focused on mitigating global climate change.

The business of CO_2 enhanced oil recovery has been evolving for more than 30 years, and it is currently in a major growth spurt around the world because of the dual drivers of high oil prices and pressures to reduce carbon emissions. The report highlights 12 of the best known such combined CO_2-EOR and carbon sequestration projects around the world, and the four that currently operate here in Colorado and Wyoming. All are highly profitable ventures, and jointly sequester large amounts of carbon. None of the CO_2-EOR projects currently qualify for carbon credits, and few of them use significant anthropogenic sources of carbon, however. Because of the high demand for oil, there is currently a shortage of CO_2 for many high-quality EOR opportunities across the country (and the world), a situation that is highly ironic in light of the climate change issue. Major R&D efforts are needed to learn to separate CO_2 from coal burning power plants and other man-made point sources, at a cost that will make such CO_2 attractive for industrial CO_2-EOR/sequestration projects.

Two major geological CO_2 sequestration projects are about to emerge in Colorado, one in conjunction with Xcel's plans to build an IGCC (integrated gasification combined cycle) power plant with carbon capture and separation at Brush, and another probably linked with Shell Oil Company's plans for shale oil production in the Piceance basin of western Colorado. Both industrial sites are surrounded by a large number of highly suitable sites for geological carbon sequestration. Colorado should engage with these two corporations, through research and enlightened public policy, to help them develop these two new fossil energy facilities into the world's first true emissions-free generators of energy from fossil fuel – and open the door for a domestic clean energy infrastructure where both renewable and fossil primary sources play their proper roles.



* Emery Sandstone Member of the Mancos Shale

Figure 11. Generalized stratigraphic column for the Piceance Creek Basin near Cathedral Bluffs area (From: Johnson, 2003).

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Acknowledgments

The authors acknowledge financial support from the State of Colorado through C.R.S. § 25-1-1303. Leadership by the staff at the Colorado Department of Health and Environment (Jill Cooper and Rachel Wilson-Roussel) was invaluable to the timely completion of the project, and also to the establishment of good collaboration with the other universities in Colorado. Discussions with our colleagues at CSU (Rich Conant, Dennis Ojima and Keith Paustian) and at CU (Robert Keating, Douglas Vilsack, Kevin Doran and Lakshman Guruswamy) have been instrumental in formulating many of the ideas and interpretations set forth in this report. Finally, a sincere thanks to our many friends in the oil and gas industry, too many to list individually here.