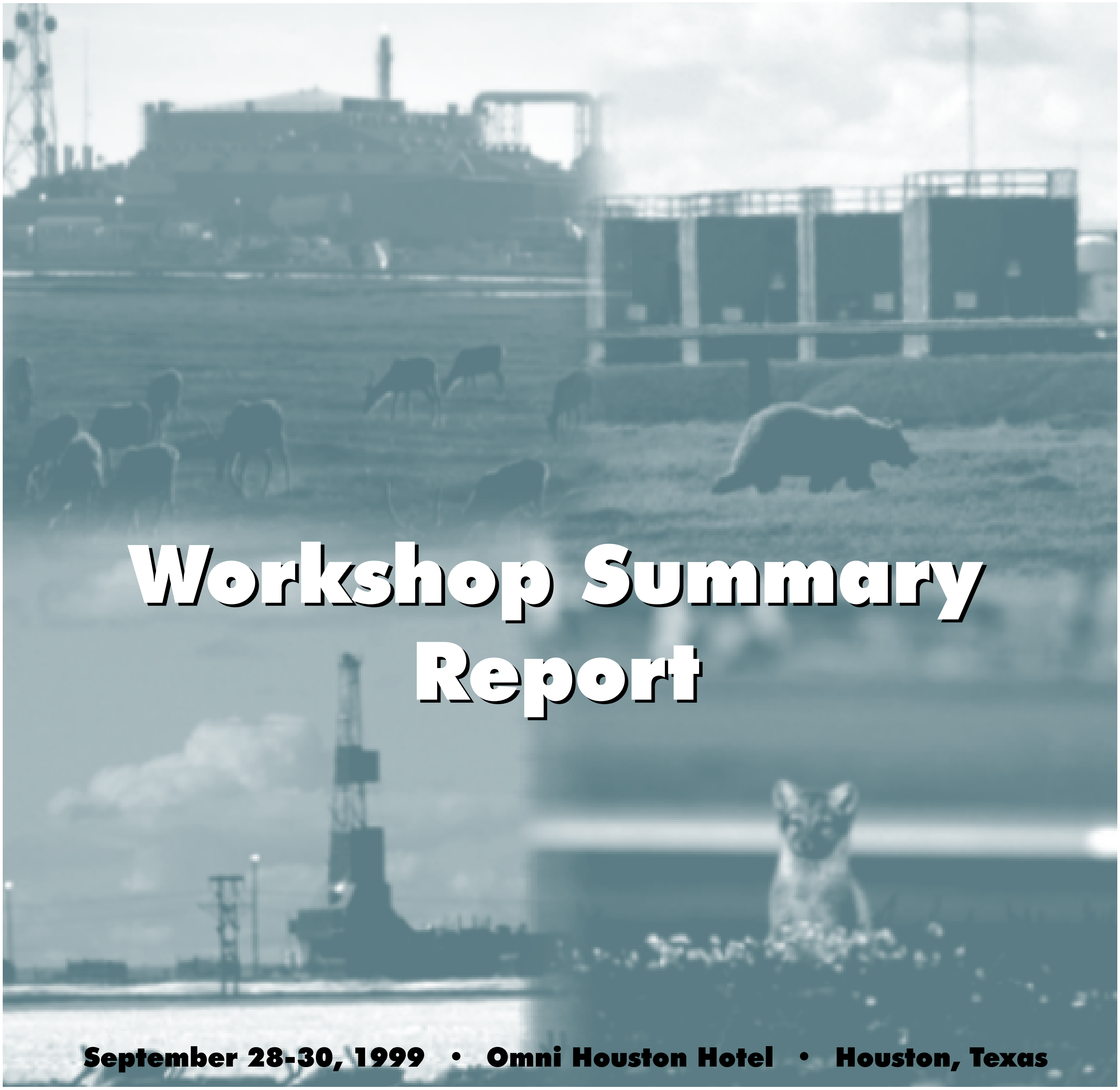
CO_2 Capture and Geologic Sequestration:

Progress Through Partnership



Workshop Summary Report

September 28-30, 1999 • Omni Houston Hotel • Houston, Texas

FETC

BP Amoco

IEA GREENHOUSE GAS R&D PROGRAMME

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I. Introduction

CO_2 Capture and Geologic Sequestration: Progress through Partnership was a collaborative workshop to create new solutions to the challenge of CO_2 capture and geologic sequestration. The workshop was jointly sponsored by BP Amoco, the U.S. Department of Energy's Office of Fossil Energy, and the International Energy Agency's Greenhouse Gas R&D Programme (IEA/GHG). It consisted of:

- International, national, and industry perspectives
- Panel discussions on CO_2 capture and geologic sequestration technologies
- Status reports from ongoing CO_2 sequestration projects
- Working sessions to develop an industry work program leading to breakthroughs in costs and performance

The partnership between BP Amoco, U.S. DOE, and the IEA/GHG was successful in bringing together a diverse group of experts in CO_2 capture and geologic sequestration. Over 140 participants attended the workshop. Seventy-five percent of the participants were from industry, with 30% of the participants coming from outside the United States.

This report summarizes the insights and information from the CO_2 Capture and Geologic Sequestration workshop.

II. Background

Without reducing world population and/or economic activity, there are three options to decrease anthropogenic CO_2 emissions: 1) reduce the carbon content of energy systems either through the use of renewables and nuclear power, or by switching to lower carbon fuels; 2) reduce the energy intensity of economic activity either by improving the efficiency of motors, furnaces, and other energy conversion devices or finding ways to use less energy; and 3) sequester carbon, either directly, through capture and storage, or indirectly, by enhancing natural sinks. The first two options are important but would be prohibitively expensive in a scenario where deep reductions in carbon emissions are required. Carbon sequestration provides an alternative to expensive changes in energy infrastructure and allows continued economic prosperity from low-cost fossil fuels without compromising the environment–an important policy option.

In 1997, the President's Committee of Advisors on Science and Technology (PCAST) published a report Federal Energy Research and Development for the Challenges of the Twenty-first Century that called for a "much larger science-based CO_2 sequestration program." In 1998, the U.S. Department of Energy and the Massachusetts Institute of Technology jointly hosted a *Stakeholder Workshop on Carbon Sequestration* with participants from industry, universities, and government. The goal was to solicit stakeholder input on research and development priorities for carbon sequestration, and identify possible industry/government/university partnerships. Earlier this year, the Department of Energy's

Office of Science and Office of Fossil Energy released a draft report, Carbon Sequestration: State of the Science, containing a comprehensive and detailed discussion of R&D activities needed to advance carbon dioxide sequestration. Carbon dioxide capture and sequestration is a very broad topic encompassing many scientific disciplines and these initial efforts were appropriately broad in scope.

With the foundation set, the focus turns to specific technology areas and promising projects. This was the goal of the recent workshop on CO_2 capture and geologic sequestration. Industry and government professionals from diverse backgrounds came together to discuss carbon dioxide capture and geologic sequestration, both in general terms and in relation to an interesting sequestration project that BP Amoco has identified at their oil field on the North Slope of Alaska. Focused workshops provide ample opportunities for experts to present new information, discuss potential applications, and identify fruitful research areas. This particular workshop had the benefit of bringing together chemical engineers, reservoir engineers and geologists to discuss integration of the capture and sequestration system components and identify possible technology implementation barriers.

III. Progress Through Partnership—The Path Forward

The workshop was a clear success in sharing information and opportunities for collaboration.
BP Amoco will use the information and contacts from the workshop to help in its efforts to form a Joint Implementation Project (JIP) that sequesters CO_2 in Alaska's North Slope. The Federal Government and IEA will apply the information from the workshop to the management of their R&D activities. Together all the parties can exploit areas of common interest identified during the workshop to work collaboratively in the area of geologic carbon dioxide sequestration.`

IV. Agenda

Workshop Agenda

	Tuesday September 28, 1999
7:30 am	Registration and Welcoming Continental Breakfast - Colonnade Salon
8:30 am	Session Welcome
	International Perspective *Dr. Kelly Thambimuthu, IEA Greenhouse Gas R&D Programme*
	U.S. National Perspective *Rita Bajura, U.S. DOE*
10:00 am	Break
	Presentation: **Sleipner Storage Project** *Torre Torp, Statoil*
	Presentation: **CO_2 Sequestration in Deep Unmineable Coal Seams** *Bill Gunter, Alberta Research Council*
	Presentation: **CO_2 from Coal Gasification and EOR Use at the Weyburn Field in Canada** *Malcolm Wilson, Saskatchewan Department of Energy* *Ray Hattenbach, Dakota Gasification Co.* *Ken Brown, PanCanadian Resources*
	Discussion Groups
12:30 pm	Lunch served in workshop
1:30 pm	Panel Discussion: **CO_2 Capture - Technology and Applications** Moderator: *Howard Herzog, MIT* Panelists: *Eivind Aarebrot, Statoil* *Harry Audus, IEA GHG R&D Programme* *Lars Ingolf Eide, Norsk Hydro* *Malcolm McDonald, TransAlta*
3:00 pm	Break
	Panel Discussion: **Geologic Sequestration - Technology and Applications** Moderator: *Vello Kuuskraa, ARI* Panelists: *Neeraj Gupta, Battelle Columbus Laboratory* *Daryl Erickson, BP Amoco* *Chuck Fox, Shell CO2 Supply Co.*
	Discussion Groups
5:30 pm	Adjourn
6:00 - 8:00 pm	**Reception** *Hosted by BP Amoco*

Workshop Agenda

	Wednesday September 29, 1999
8:00 am	Coffee and Muffins - Colonnade Salon
8:30 am	Session Welcome
	Oil and Gas Industry Perspective *Bernie Bulkin, BP Amoco*
	Power Industry Perspective *Hank Courtright, EPRI*
	Presentation: **Technology Roadmap for Carbon Capture and Sequestration** *Sally Benson, U.S. DOE, Office of Science* *David Beecy, U.S. DOE, Office of Fossil Energy*
10:15 am	Break
	Presentation: **The Alaska CO_2 Sequestration Project** *Gardiner Hill, BP Amoco*
12:30 pm	Lunch served in workshop
1:30 pm	**Work Groups** A. CO_2 Capture and Separation via Post-Combustion Methods B. CO_2 Capture and Separation via Oxyfuels C. CO_2 Capture and Separation via Pre-Combustion Decarbonization D. Maximizing Sequestration in Oil Reservoirs E. Measurement and Verification F. Incentives, Emissions Trading, and Public Policy
3:45 pm	Break
	Work Groups Consolidate Reports
5:30 pm	Adjourn

	Thursday September 30, 1999
	Coffee and Muffins - Colonnade Salon
8:30 am	Session Welcome
	Work Group Reports
10:15 am	Break
	The Way Forward
12:30 pm	Workshop Ends

V. Participant Insights

After each discussion session during the workshop, the facilitator, David Sawyer, invited participants to stand up and summarize key points for the whole group in a sentence or two, so called "laser outs." The following are notable "laser out" comments (with some editing and combining of similar thoughts).

- If we want to move along, we must start doing experiments.

- Public perception is important; engage environmental groups and other public entities early.

- A significant cost may be monitoring and verifying whether CO_2 stays in the ground.

- Does participation in carbon sequestration now give a company a competitive advantage? It well could.

- Systems integration (i.e., putting existing components together in an optimal way) is critical to cost reduction, perhaps reducing costs by 50%.

- Separation is a big energy loss and a big pressure loss, thereby providing opportunity for systems integration improvements.

- Existing carbon sequestration projects have special environmental and economic circumstances (e.g., Sleipner, natural gas product specifications, carbon tax; Weyburn - royalty agreements, nearby CO_2 source in Dakota Gasification). Government involvement through incentives and investment in technology development is needed for more broad-based application of CO_2 sequestration.

- There is an emerging need for legislative and policy initiatives i.e., incentives for breakthroughs and support for demonstrations where the primary technology driver is a public benefit.

- Injecting CO_2 into oil reservoirs and coal beds (for methane recovery) early in the productive life rather than later is a promising sequestration concept.

- It is critically important to maintain a long-term view toward carbon capture and sequestration technology development, looking past near-term projects toward creating carbon emissions reduction options for scenarios where global anthropogenic carbon emissions must be reduced by 60-90%.

- Our ultimate challenge is changing the shape of the marginal cost curve.

- Industry is serious about CO_2 sequestration; it is here to stay.

VI. A Policy Context for the Technology Discussions

U.S. DOE Fossil fuels represent 85% of world energy use today and are expected to be the dominant source of energy for the foreseeable future. Over the next 100 years, a combination of population and economic growth is expected to increase the rate of global energy consumption threefold or more. In 1992, the United States and 160 other countries ratified the Rio Accord, in which they agree to stabilize the concentration of carbon dioxide in the atmosphere at levels that will not be harmful to human health and the environment. Because of the anticipated large growth in energy consumption, and the anticipated continued reliance on fossil fuels (when one considers coal and methane hydrate resources the supply of fossil fuels is virtually inexhaustible), stabilizing the concentration of carbon dioxide at 550 ppm will require cutting emissions of carbon dioxide by 60-90% below business-as-usual over the next 50-100 years. There are some low-cost options for reducing carbon dioxide emissions, for example, improvements in energy efficiency, niche renewable energy applications, and combined heat and power. However, such “no-regrets” options do not have the aggregate capacity to provide deep reductions in carbon emissions. Achieving deep reductions in carbon emissions with nuclear power and renewable-based power systems would be expensive, would not provide the convenience and reliability of energy consumption upon which the world economy is based, and would come with its own set of environmental issues. The role of carbon dioxide capture and sequestration can be seen as keeping the marginal cost of carbon emissions reductions low in the event that deep reductions in anthropogenic emissions are required—providing a policy option that enables prosperity and growth in a carbon-constrained economy.

BP Amoco As an energy company BP Amoco has decided that it must get involved in the CO_2 issue. In September 1998 Sir John Browne, CEO of BP Amoco, announced that BP would set for itself the target of reducing its greenhouse gas emissions to 10% below 1990 levels by 2010. Since the merger with Amoco on 1 January 1999, this target now extends to the whole BP Amoco group. Based on the current company assets, the target is to reduce company-wide carbon and carbon-equivalent emissions to 70 MM tonnes per year of CO_2 by 2010. (Note the emissions target will change with “material” changes in the corporate asset base, however the 10% reduction target will not change.) Based on expected growth in 1) exploration and production, 2) chemicals, and 3) refining of clean fuels, the business-as-usual BP Amoco emissions in 2010 are expected to be roughly 100 MM tons of $CO_{2.}$ Thus a reduction of 30 MM tonnes of CO_2 per year is required.

2010 is not that far in the future for such a significant goal, and BP Amoco has begun taking steps in earnest to reduce CO_2 emissions. Specific actions include 1) establishing emissions metrics as a part of the performance contracts with the company’s various business units, 2) expanding solar programs, and 3) initiating an in-house greenhouse gas emissions trading program. BP Amoco has identified a large number of projects that both reduce greenhouse gas emissions and give a compelling return on investment (e.g., reduced flaring, sealing methane leaks). Such no-regrets projects have the capacity to provide BP Amoco with 18 of the 30 MM tonnes of reduced emissions, leaving a 12 MM tonne per year gap. BP Amoco is investigating geologic carbon sequestration as well as other advanced technology options with the goal of achieving the remaining 12 MM tonnes of emissions reduction at the lowest cost possible.

IEA The IEA Greenhouse Gas R&D Programme, an organization jointly funded by 17 countries and several major corporations, serves as an international nexus for thinking on carbon sequestration, as well as a convenient forum for collaborative efforts among different nations.

There is a growing worldwide interest in carbon sequestration and a recognition of its importance. This factor is particularly important for the continuing use of fossil fuels and the infrastructure currently in place for the distribution and use of some 90% of the world's primary energy consumption. The governments of some countries have taken proactive action regarding the greenhouse gas issue, either through ratifying the Kyoto Protocol and/or promulgating carbon taxes or other incentives such as emissions trading and joint implementation (JI) projects for greenhouse gas reduction.

The IEA/GHG Programme conducts an extensive agenda of studies and assessments and has identified four key issues for carbon sequestration: reducing the cost of CO_2 capture, minimizing the risk of CO_2 storage, demonstrating the reliability of CO_2 storage, and verifying the amounts of CO_2 stored. The Programme also facilitates several practical R&D projects, including monitoring of the Sleipner project, a coal seam sequestration project operated by the Alberta Research Council, and investigations into O_2/CO_2 recycling and enriched air (oxy-fuel) combustion conducted by the CANMET Energy Technology Center in Canada. The Programme is currently also looking into the establishment of additional projects on pre-combustion decarbonization and enhanced oil recovery with CO_2 sequestration in Weyburn, Saskatchewan. Where and when feasible, the Programme is willing to facilitate a number of other practical R&D collaborations among interested parties.

The Programme is hosting the GHGT-5 conference in Cairns Australia in August of 2000. Persons who are interested in attending should visit the IEA/GHG Programme website at www.ieagreen.org.uk for more information.

EPRI EPRI (formerly the Electric Power Research Institute) recently developed an Electricity Technology Roadmap to explore opportunities and threats for electricity-based innovation over the next 25 years. In the chapter on the "Energy/Carbon Challenge," EPRI identifies carbon sequestration as a key technology, stating that "Economical carbon capture and safe, long-term storage technologies will be needed to extend the environmental lifetime of fossil fuels within a global carbon emissions budget."

EPRI has performed an analysis of the domestic and global electricity market over the next 50 years. EPRI expects U.S. electricity demand to grow in that time frame, but expects the demand for electricity to grow much faster in the developing countries. The United States and the world rely on an increasingly diverse portfolio of energy sources, which is good because it provides stability. It is important to recognize the strong link between environmental and energy policies. Environmental policies, such as limits/taxes on carbon emissions, could have a profound effect on the mix of energy sources. In the U.S. electricity supply industry, carbon constraints could cause a switch from coal to natural gas-based generation, resulting in both stranded coal-fired generation assets and the demise of U.S. coal infrastructure prior to the introduction of clean coal technologies, including carbon sequestration. Carbon capture and sequestration R&D should be accelerated to prove that it is a viable carbon management option, thus enabling a wise transition strategy and policy toward a sustainable U.S. energy system.

VII. Establishing a Technology Baseline: Panel Discussions

Two panel discussions brought the participants up to date on the latest technology developments. The first, on CO_2 capture, was moderated by Howard Herzog of the Massachusetts Institute of Technology. It was comprised of the following four speakers.

- *Eivind Aarebrot from Statoil* spoke about post-combustion separation. He stated that an economical CO_2 separation solution had not yet been found and that Statoil was looking for a system with 30% lower capital cost and 20% lower energy consumption than a state-of-the-art amine absorption system.

- *Malcolm McDonald from TransAlta* spoke about CO_2 capture and separation via oxyfuels and emphasized that one could retro-fit oxygen/CO_2 recycle combustion technology to existing plants in the near term. Transalta's evaluation of the power plant retrofit was based on the results obtained from R&D on oxyfuel combustion undertaken by the CANMET Energy Technology Center in Ottawa.

- *Lars Ingolf Eide from Norsk Hydro* spoke about pre-combustion decarbonization, noting that the viability of decarbonization depended largely on the development of utilization systems, either fuel cells or combustion systems with low-cost NO_x controls (e.g., controlling concentration of steam).

- *Harry Audus from the IEA/GHG Programme* gave a comparative assessment of the various options for carbon dioxide separation. He stated that options available in the near term for CO_2 capture from fossil fuel-based electricity generation systems represented an energy penalty of roughly eight percentage points and a cost increase of 1.5 cents/kWh. He concluded that at present no capture and separation system is clearly superior and the preferred option would depend on project-specific factors.

The second panel, on geologic sequestration, was moderated by Vello Kuuskraa of Advanced Resources International, Inc. It was comprised of the following three speakers.

- *Chuck Fox of Shell CO_2 Supply Company* spoke about the use of CO_2 in enhanced oil recovery (EOR). He views CO_2 as a product that can be put to use if the cost of recovery is low enough. Regarding economics, he estimated that the price an oil producer could pay for CO_2 for an EOR application ($/tonne) equals 50% to 100% of the price of oil in dollars per barrel. Based on today's oil prices, a carbon emissions tax of 10-20 \$/tonne CO_2 could make CO_2 from flue gas economical for EOR applications.

- *Daryl Erickson of BP Amoco* spoke about the use of CO_2 in the recovery of coal bed methane. He emphasized the potential benefits of starting CO_2 injection at the beginning of the productive life of a reservoir, as opposed to the conventional approach of injecting CO_2 only in the later stages. This concept applies to both enhanced oil recovery and coal bed methane applications.

- *Neeraj Gupta of Battelle Columbus Laboratory* spoke about saline formations. He has performed a study showing a very large capacity for CO_2 storage in saline reservoirs in the mid-western U.S., a region with significant coal-fired generation assets.

The presentation materials from the panel discussions contain more detailed information and are found in Appendix A. Also many of the fundamental points from the panel discussions were reiterated by the Work Groups and have been incorporated into Section X, Work Group Reports.

VIII. Reports from Ongoing Sequestration Activities

Workshop participants heard presentations from persons involved in real-world CO_2 sequestration projects. Those presentations covered the three major types of geologic CO_2 sequestration: saline formations (Sleipner), enhanced oil recovery (Weyburn), and coal bed methane (Alberta, Allison and Tiffany pilot projects). In addition to demonstrating technologies, these projects provide insights into the innovative cooperative relationships that are and will be needed for large-scale sequestration projects.

Saline Formations Statoil and its partners operate a natural gas recovery platform above the Sleipner natural gas reservoir off the coast of Norway. CO_2 must be removed from the natural gas to make it marketable. The separation is conducted by an amine absorption process housed on a nearby platform. The cost of the amine separation is \$40/tonne of CO_2 removed. Statoil and its partners, with funding from the European Union (EU), formed a Joint Implementation Project (JIP) to compress the CO_2 gas from the amine absorber unit and inject it into a saline formation under the North Sea. The incremental cost of compressing and injecting the CO_2 stream is 20 \$/tonne CO_2 compared to 40 \$/tonne CO_2 for amine separation. Further, Statoil has identified significant economies of scale associated with the compression and injection of recovered CO_2. The Sleipner project injects roughly 1 million tonnes of CO_2 per year. For a project with a capacity of 4 million tonnes per year, Statoil estimates the cost of CO_2 compression and injection would be 7 \$/tonne $CO_{2.}$ Statoil estimates the cost of amine separation would decrease only marginally for the bigger system, based on current technology.

The operational goals of the Sleipner project were to verify the safety of CO_2 storage in a geologic formation and to validate models for geologic, geophysics, and reservoir tools. Significant adjustments must be made to existing hydrocarbon-based models to account for the fact that CO_2, unlike hydrocarbons, is soluble in water. In cooperation with the EU and IEA, a large amount of geophysical data has been gathered. A report that provides interpretations of the data gathered thus far will be published in the near future.

Enhanced Oil Recovery A major project in the Weyburn Oil Field in Canada will use CO_2 for enhanced oil recovery. The project is slated to begin in the year 2000 and will ultimately result in 350 billion cubic feet of CO_2 being sequestered. The Weyburn field has been through primary and water flood production, and CO_2 is being used to further extend production. The reservoir has many characteristics that indicate that a CO_2 flood will be successful and the developers are hopeful for a large amount of incremental recovery. The recovery to date is 23%, and the goal using CO_2 is 30%. The Weyburn project was aided by two conditions: first the developers were able to negotiate favorable agreements with government and other parties, and second, a nearby low-cost CO_2 source exists in Dakota Gasification, a lignite-to-substitute natural gas facility built with U.S. DOE support in the 1980s. With most of the injection infrastructure in place, the largest investment required was a 200 mile pipeline from Dakota Gasification to Weyburn. A notable aspect of the Weyburn project is that it is international, in that a gasification facility in the United States is supplying CO_2 across the border to an oil reservoir in Canada. Interestingly, the developers reported that several electricity generators submitted bids to be the supplier of CO_2 for the Weyburn project and their costs were only 30% above the level that would make the project economically viable.

Coal Bed Methane (CBM) Coal beds typically contain large amounts of CBM, methane-rich gas that is absorbed onto the surface of the coal. In some cases, CBM can be recovered economically. The current practice for recovering it is to depressurize the bed, typically by pumping water out of the reservoir. An alternative approach is to inject CO_2 and/or nitrogen into the reservoir, which, in addition to recovering CBM, can result in CO_2 being sequestered in the coal bed.

Several pilot-scale injection projects are aimed at examining CO_2 injection for CBM recovery from the perspective of CO_2 sequestration. The Alberta Research Council leads a consortium of over 15 countries and government bodies in a JIP that has established a pilot site at Fenn-Big Valley in Alberta, Canada, on Gulf Canada properties. Also, BP Amoco and Burlington Resources are conducting field tests in the San Juan Basin in the Southwestern United States.

Investigators are studying the use of mixtures of CO_2 and nitrogen in CBM recovery with the idea that flue gas from an electricity generation plant could be injected (without processing) into a CBM reservoir. The recovered product, a mixture of CBM, nitrogen, and CO_2, could be fed directly to a combustion turbine in an integrated electricity generation/CBM recovery process. Preliminary model studies have shown that CO_2/nitrogen injection mixtures give lower rates of CBM production than injecting pure nitrogen; more work is needed to identify conditions in which the addition of CO_2 to nitrogen is economic. Also, sensitivity studies are needed to determine the degree to which possible future CO_2 emissions reduction credits could affect the economic attractiveness of CO_2 versus nitrogen in CBM recovery.

When assessing the use of CO_2 in recovering coalbed methane, it is important to consider that nitrogen can also be used to recover CBM and has many favorable properties when compared to CO_2. First, 1 scf of nitrogen injection immediately recovers 1 scf of methane, whereas 2-3 scfs of CO_2 are required per 1 scf of methane recovered. Second, the mechanism (inert gas stripping) by which nitrogen removes methane from coal provides a much quicker response at recovery wells than does the CO_2 mechanism (displacement desorption process). Although ultimately CO_2 provides a greater percent of recovery of methane, the time value of money causes nitrogen to provide a more valuable revenue stream than CO_2, all else being equal. Ultimately, it is expected that some mixture of the two gases will provide the best overall results.

IX. The Opportunity on Alaska's North Slope

The opportunity on Alaska's North Slope stems from the fact that a number of large point sources of CO_2 emissions (albeit at low concentration, 3%) are located near a large, undeveloped viscous oil reservoir. The characteristics of the reservoir indicate that it could be amenable to a CO_2 flood. The concept is to capture the CO_2 from the point sources and inject it into the viscous oil reservoir where it will decrease the viscosity of the oil and thus increase the productivity of the wells to the point where they are economical to operate. The potential scale could be material, 2-4 million tonnes of CO_2 sequestered per year against 9.1 million tonnes of CO_2 emitted per year.

Based on current technology, the sequestration concept is not economical on its own merits. Although given that BP Amoco is committed to reducing CO_2 emissions by 30 million tonnes per year by 2010, sequestration may be attractive compared to other options for emissions reductions. Key challenges include the low concentration of CO_2 in the combustion turbine flue gas (3%), the expense of corrosion inhibition, and the timing of expenditures versus revenues. To improve the project economics, BP Amoco seeks to 1) reduce the cost of CO_2 capture and gas treatment plants, 2) increase sequestration efficiency and EOR recovery (i.e., the amount of gross CO_2 emissions that end up sequestered (currently 60%) and the effectiveness of CO_2 injection), 3) reduce the rate of corrosion and/or the cost of dealing with it, 4) utilize the economies of scale from broad application, and 5) participate in emissions trading programs and other incentives.

Significant advances are needed and BP Amoco seeks to reduce the overall project costs by more than 50%. BP Amoco is on a tight schedule with the goal of commercial-scale operation by 2010. Meeting the schedule will require a successful pilot-scale demonstration by 2006 and completion of the necessary technology development by 2002-2003.

X. Work-Group Reports

The workshop participants divided into work groups to address the following charge: Define a work program to develop, test, and demonstrate next generation technologies that can deliver a 50% reduction in the cost of CO_2 capture and geologic sequestration by 2006. Six pairs of Work Groups (roughly 12 persons per group) addressed the following topics:

A. CO_2 Capture and Separation via Post-Combustion Methods
B. CO_2 Capture and Separation via Oxyfuels
C. CO_2 Capture and Separation via Pre-Combustion Decarbonization
D. Maximizing Sequestration in Oil Reservoirs
E. Measurement and Verification
F. Incentives, Emissions Trading, and Public Policy

The results from each of the Work Groups are summarized below.

A. CO_2 Capture and Separation via Post-Combustion Methods

The Work Group limited its discussion as follows: it did not consider sulfur removal and other flue gas preparations required for coal-based systems. Also, the range of concentrations considered for capture was 3% (gas turbine) to 12% (steam turbine).

The Work Group saw amine technology enhancement as a near-term focus. Specific R&D areas include optimization and integration, contactors, and improved solvents.

Integration is seen as an opportunity because amine separation is an energy sink, whereas other unit operations (e.g., electricity generation) produce waste heat. Several persons emphasized that a tangible project is needed in order to investigate and realize the benefits of systems integration. They also asserted that significant cost savings could be realized by *not* over-designing a system (e.g., heat treatment of welds not required for atmospheric pressure systems).

Several hybrid concepts were set forth. For example, in the gas turbine retrofit application the 3% CO_2 concentration drives the cost by creating an enormous amount of gas that must be processed per unit of CO_2 captured. It was suggested that a recycle or partial oxygen-firing system could be used to raise the concentration of CO_2 in the flue gas. On the other hand, it was noted that in an amine system, only the size and cost of the adsorber is affected by the concentration of CO_2 in the flue gas; the cost of the desorber and amine circulation systems are related to the amount of CO_2 captured. A multi-stage CO_2 capture process was also suggested. For example, a membrane could be used as a first stage to capture the bulk of the CO_2 with an amine system as a polishing step.

Improved solvents would have lower energy requirements per unit of CO_2 capture (i.e., flashing versus steam stripping), less attrition per unit of CO_2 capture (both sludge formation and fugitive emissions), and reduced corrosivity in an oxidative environment. It was also suggested that an adsorbent operating at a higher temperature could provide a cost savings through reduced flue gas cooling requirements.

IGT, Mitsubishi, ABB and others have performed extensive research into new adsorbents and have new products with improved performance.

Beyond amines, the Work Group recommended R&D into advanced CO_2 capture and separation systems including electric swing adsorption, membranes, hydrates, and cryogenic condensation.

The Work Group proposed an interesting integrated separation/sequestration concept, as follows. CO_2 is separated from flue gas by forming a water hydrate. (DOE recently funded Bechtel to investigate CO_2 capture from flue gas via hydrate formation; the concept is particularly amenable to the North Slope due to the availability of cold ambient air and/or sea water.) Once formed the hydrates are made into a water-based slurry and injected in the reservoir. The hydrates decompose underground, releasing the CO_2. Once released in the reservoir, CO_2 enhances oil recovery and ultimately becomes sequestered underground. The idea has not been fully vetted. Issues raised include the amount of water per CO_2 injected downhole and the permeability of the hydrate slurry through the reservoir. In a larger context, the concept points to opportunities that lie in the integration of capture and separation systems with downhole activities.

B. CO_2 Capture and Separation via Oxyfuels

The Work Group considered both gas turbines and steam turbines and new and retrofit applications. The Group identified the following products that could be ready for a demonstration project in 1-3 years.

> O_2/CO_2 Boiler is a boiler system burning natural gas or oil. Oxygen is used in the boiler for combustion tempered by recycling flue gas to maintain furnace temperatures at acceptable (lower) levels.
>
> Pressurized boiler with off-the-shelf CO_2 Turboexpander: This concept uses a pressurized boiler (generating steam) operating on O_2/CO_2 firing, with a CO_2 turboexpander to recover energy from the hot gas which can be used to drive the compressor or produce electricity. Really a "poor man's" O_2/CO_2 gas turbine.
>
> Retrofit HRSG with supplemental oxy-firing to raise CO_2:   This is a retrofit concept for the existing gas turbines. Waste exhaust heat is recovered in a Heat Recovery Steam Generator (HRSG). Additional gas is fired, using O_2/CO_2 combustion to provide a flue gas that is essentially CO_2 and water vapor.
>
> Direct oxyfuel fired HP steam generator: This concept burns gas directly with oxygen and uses water injection to cool the gas and generate steam. It is done at high pressure so that the

resulting steam/CO_2 mixture can be expanded through a turbine to generate electricity, and the steam can be condensed, leaving the CO_2 ready for injection into the formation. This concept was developed in Germany about 10 years ago.

For the longer term, the Work Group recognized two products: 1) an O_2/CO_2 turbine and 2) an oxygen generation system based on an ion transport membrane (ITM) instead of the conventional cryogenic process. Development of an O_2/CO_2 turbine would be costly. The near-term options have low fuel efficiency (and as a result low net carbon sequestration) compared to the longer-term options.

C. CO_2 Capture and Separation via Pre-Combustion Decarbonization

This approach produces a hydrogen-rich stream that is fed to an electricity conversion process. The hydrogen-rich stream can be produced by either reforming or gasifying the fossil fuel, and there is some technology overlap with the oxyfuels approach in that both would benefit from an advanced oxygen generation technology (e.g., ITM).

In the near term, the Work Group recommended flowscheme optimization and integration. Specifically, the reformer and HRSG could be heat integrated. Also, separation of CO_2 from the hydrogen-rich stream, a markedly different separation task than is required in the post-combustion systems, should be optimized regarding CO_2 pressure, percent CO_2 recovered, and other metrics. Finally, value-added co-products from gasification can be used to improve the economics.

In the longer term, the largest cost impact could be achieved by replacing combustion turbines with fuel cells as an electricity generation process, removing the need for both CO shift conversion and CO_2 removal from the hydrogen-rich stream. Medium impact, long term areas for R&D include developing gas turbines specifically designed for the unique combustion properties of hydrogen, advanced CO_2 removal processes, high-efficiency reformer systems (e.g., flame-less distributed combustion being developed by Shell, inorganic membranes), and compact heat exchangers (something different than shell and tube).

D. Maximizing Sequestration in Oil Reservoirs

The goal of this area is to maximize the sequestration of CO_2 in oil reservoirs while maintaining oil production. Importantly, this is the opposite of the current incentives in EOR applications. Because CO_2 is a commodity that must be bought, operators seek to maximize the production of oil per unit of CO_2 injected, essentially minimizing the amount of CO_2 sequestered.

The Work Group identified a number of short timeframe projects that could have a high impact. First is to improve the fundamental understanding of the sequestration process, by conducting laboratory experiments to optimize solvent purity and composition and characterizing reservoirs. The Work Group also suggested that information could also be gleaned from existing EOR floods and naturally occurring CO_2 reservoirs.

Another near-term R&D area is minimizing the amount of water injected. Water and CO_2 compete for space in a reservoir. The conventional approach to oil production is to first perform primary production, followed by a water flood, and finally a CO_2 flood. It is speculated that initiating CO_2 injection in the earlier stages of a reservoir production could improve production and also sequester much more CO_2. One drawback is that early water injections are often used to characterize a reservoir, and it would be expensive to learn with CO_2. More than water, CO_2 seeks out high permeability channels. It is possible that enhanced imaging technologies could enable better characterization of the reservoir and enable early injection of CO_2. The Work Group stressed that in the near term it is important to "learn as you go," using staged development coupled with integrated economic modeling. Regulators, the public, and non-government organizations (NGOs) must be engaged early on in the development of measurement and verification systems.

The Work Group also suggested a focus on improving the sweep of CO_2 through the reservoir through the use of viscosifiers, miscibility enhancers, and enhanced CO_2 solubility. In the longer term, an integrated sequestration model and effective 4D fluid imaging could have a high impact. Developing an abandonment strategy is also an important longer term area.

E. Measurement and Verification

Many different stakeholders are associated with CO_2 capture and sequestration projects (e.g., the repository operator, regulators, the scientific community, NGOs). Each has a somewhat different view of what is important regarding monitoring and verification. Therefore it is a broad topic area with many different aspects.

Unlike nuclear and renewable-based energy systems, carbon sequestration involves the generation of CO_2, a portion of which is captured and sequestered. Persons and organizations will undoubtedly question the amount of CO_2 that is actually captured and stays in the ground. Credible, traceable, and standardized measurements are essential to satisfy such persons/groups. Further, an emissions trading credit system will require dependable estimates of performance. Challenges include defining the net sequestration (i.e., taking into consideration efficiency losses associated with capture and sequestration) and monitoring leaks from both surface facilities and subsurface structures.

A firm understanding of the potential subsurface migration of CO_2 and communication of that understanding to the public is essential to address concern over the safety and long-term stability of injecting a buoyant gas, CO_2, underground. Also, it is important to be able to predict the impact of CO_2 injection on mining, drilling and other subsurface activities that may be conducted in the vicinity of the sequestration reservoir. Such understanding could be gained through multiple subsurface techniques including seismic and electrical geophysics, geochemical methods, logging, and pressure testing. Needed improvements include higher spatial resolution, lower cost, and improved quantification. Reservoir models can be improved by more rigorous treatment of the interactions between CO_2 and coal, brine, and minerals as well as better subsurface property measurements.

F. Incentives, Emissions Trading, and Public Policy

Cost-effective sequestration will require a close working relationship between government and industry. The objective of this Work Group was to explore mechanisms and opportunities for providing industry input to public policy related to CO_2 capture and geologic sequestration. The work group identified a number of activities to be implemented over the near, mid, and long term to meet the objective.

> Incentives The closest form of government/industry cooperation and the one with the highest potential impact is collaboration in cost-shared projects. Such projects enable industry and government to share the risks of technology development that could both prove to return profits and serve the public good. It is important to give proper consideration to the structure of contracts through which industry and government are tangibly involved in a long-term project and incorporate the flexibility that is required as the technology evolves and other factors change. Other areas where industry can get involved in incentives-related policy are to engage politicians and others to gain favorable recognition of voluntary CO_2 emissions reduction actions and to provide input to analyses of various tax incentive options.
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> Barriers There are few regulations pertaining to CO_2 sequestration in geologic structures, mostly because it is such a new idea. There is an opportunity for industry to proactively influence the regulatory development process to ensure that the rigor associated with measurement and verification standards for underground CO_2 repositories is consistent with the degree of risk they pose.
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> Direct R&D Funding There are high-risk/long-term R&D concepts within the sequestration arena where it is appropriate for government entities to provide all or most of the funding. Such activities complement near-term sequestration projects where industry plays an equal or leading role, and a robust R&D program provides an incentive for industrial companies to get involved in near-term activities. Industry could encourage government funding for sequestration-related R&D by recruiting legislative champions and/or explore innovative funding mechanisms for industry/government partnerships that will enable industry participation in longer-term high-risk R&D activities.
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> Cross-cutting Industrial companies involved in carbon sequestration activities can serve as liaisons to entities that are not directly involved in sequestration technology development but are interested and influential nonetheless. Activities could include informing policy decision-makers of the benefits of carbon sequestration (not preaching to the choir), developing industry coalitions, and engaging environmental groups and other NGOs.