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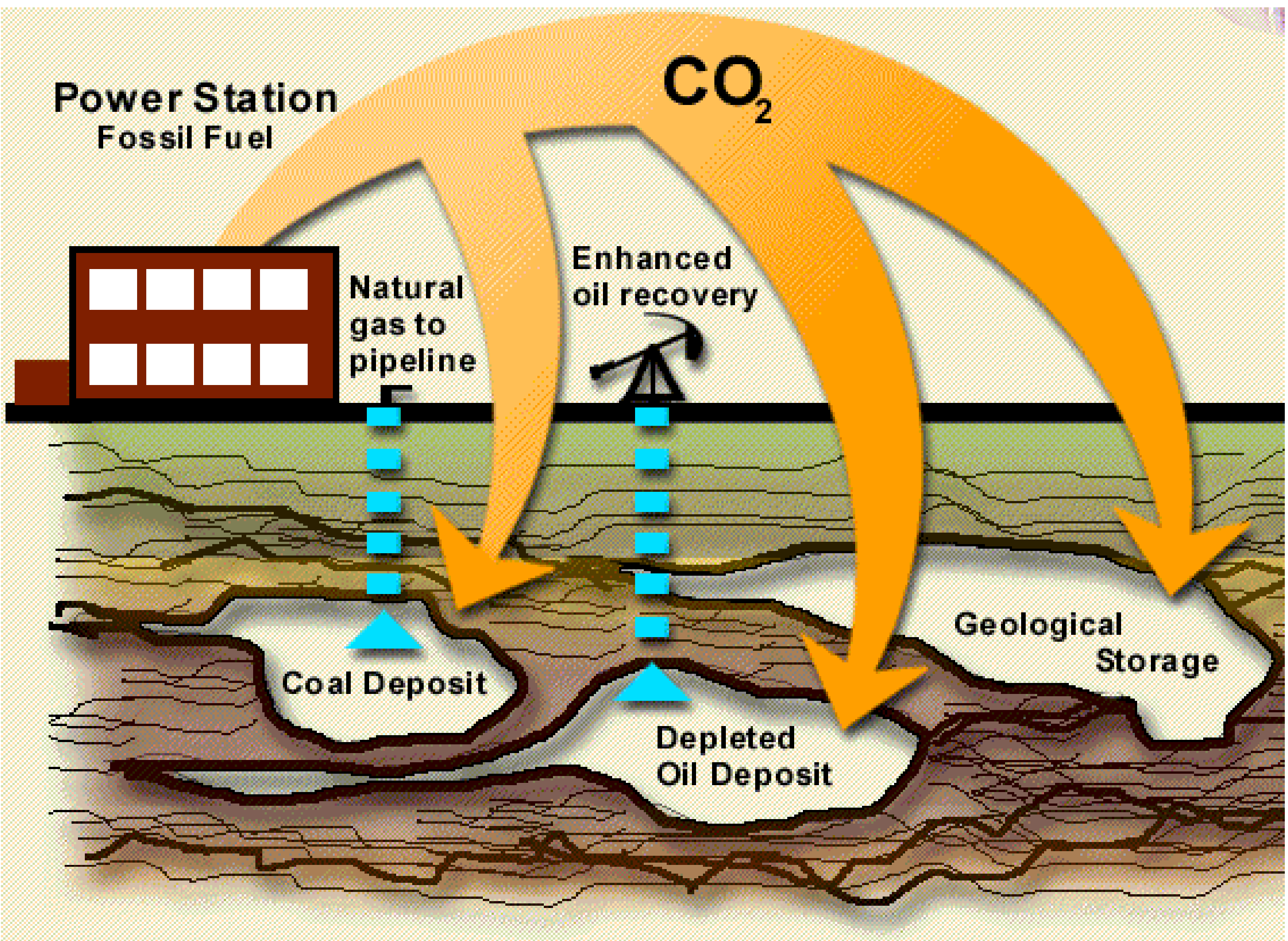
THE CAPTURE AND STORAGE OF CARBON DIOXIDE EMISSIONS

A significant opportunity to help Canada meet its Kyoto targets



Canada

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A significant opportunity to help Canada meet its Kyoto targets

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The Capture and Storage of Carbon Emissions

Executive Summary

This report was prepared to support the carbon dioxide (CO_2) capture and storage option which the October 2000 joint meeting in Québec City of Ministers of Energy and the Environment considered as part of Canada's National Implementation Strategy on Climate Change and the first National Business Plan. The report reviews the current status of CO_2 capture and storage technology development in Canada and the contribution that these technologies could make to greenhouse gas (GHG) mitigation

CO_2 capture and storage represents a further option to decreasing national GHG emissions. Other options include reducing energy consumption, increasing energy efficiency, adopting lower or zero carbon fuels and reducing GHGs from non-energy sources. The technology involves removing CO_2 from large single-point sources such as power station stacks, making use of the CO_2 where applicable, and storing it underground in geological reservoirs. It has particular application in western Canada where large fossil fuel users are located close to suitable underground reservoirs. Similar circumstances may also apply in Atlantic Canada and the adjacent offshore. It is an attractive option because it allows continued use of Canada's fossil fuel resources, while at the same time contributing to GHG mitigation and providing the time required for the transition to lower carbon-intensive technologies.

Critical steps in the technology, especially CO_2 capture from dilute exhaust gas streams, must still be demonstrated on a large scale and costs are generally high at the current stage of technology development. These costs can be offset when the captured CO_2 has an economic value, e.g. to increase recovery from existing oil reservoirs. If capture costs can be reduced to $20 per tonne from the current level of $35-50 or higher, there is potential to deploy the technology widely such that volumes of CO_2 could be stored in Canada to reduce the projected 2010 emissions over the Kyoto target.

The potential for this contribution has already been recognized in Canada's National Implementation Strategy for Climate Change and is included as an action plan in the first National Business Plan on Climate Change. CO_2 removal from coal-fired power plants is also a centre-piece of the 10-year $1 billion R,D&D plan proposed by the recently-formed Canadian Clean Power Coalition. Activities with international exposure are underway in Canada, including monitoring of the CO_2 budget in an enhanced oil recovery (EOR) project and pilot-scale CO_2 capture projects. The *ad hoc* national coordinating committee on CO_2 capture and storage has developed an enhanced R,D&D plan which outlines preliminary projects and work plans for further development of the technology.

Further consultations are required to confirm S&T priorities and to finalize the national R,D&D program designed to lead to large-scale technology demonstration projects and first commercial plants. The plan then needs to be implemented through partnerships between the private sector, the federal government, the provinces and academia.

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Background

Canada signed the Kyoto Protocol in December 1997, committing the country to work toward the ratification of a binding greenhouse gas (GHG) reduction target for the period 2008-2012. This target is to reduce annual GHG emissions to a level of minus 6% in 2010 relative to the 1990 level, estimated to have been equivalent to 526 megatonnes of CO_2[1]. However, a business-as-usual emissions projection to the year 2010 incorporating existing government policies indicates emissions could be as high as 764 megatonnes equivalent, leaving a gap of over 200 megatonnes of CO_2 equivalent (about 26%) between predicted emissions and Canada's Kyoto goal. CO_2 will comprise about 78% of these emissions.

In early 1998, the Energy and Environment Ministers of Canada and the provinces began work on a national climate change strategy with a mandate to develop a plan to meet the Kyoto target. Sixteen "Tables" or consultative groups, with approximately 450 government and stakeholder members in total, investigated an economic sector or cross-cutting policy area. The mandate of the Tables included the task of developing "options" for GHG mitigation policy and to indicate the level of support for these options among the Table members. By spring of 2000, all of the Tables had prepared their final reports, containing well over 100 options in total. Three of these Tables, covering the areas of technology development, the electricity generation industry and the upstream oil and gas industry, independently concluded that capture of CO_2 from large emission point sources, usually fossil fuel-fired systems, and its subsequent sequestration or storage could have a significant impact on reducing Canada's GHG emissions.

A *National Implementation Strategy on Climate Change* has been developed under the auspices of the National Air Issues Coordinating Committee. This strategy will recommend further consideration of the capture and storage option as a means to CO_2 mitigation. Canada's first National Business Plan on Climate Change takes the recommendations one step further and proposes concrete action items on capture and storage. By way of an example of emerging private sector interests, CO_2 capture from coal-fired power plants is also the centre-piece of a 10-year, $1 billion R,D&D plan proposed by the recently-formed Canadian Clean Power Coalition, an alliance of western Canadian coal-based electric utilities and coal producers.

Canada is not alone in recognizing the potential of this mitigation option. Activities in other countries will be reviewed later in this report. In several aspects of the development of this option, however, Canada is already playing an international leadership role, including chairing the Executive Committee of the International Energy Agency (IEA) Greenhouse Gas R&D Programme. High-profile Canadian projects, supported by the federal and provincial governments, industry and academia, as well as offshore partners, will also be summarized later in the report.

[1] Greenhouse gases have different warming potentials. In order to make comparisons possible, all emissions are converted to equivalent CO_2 emissions.

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Already, scientists and managers from Canadian industry, governments and academia have formed a network to stimulate and organize the development and deployment of technologies for the large-scale economic and environmentally-acceptable capture, use and geological storage of CO_2. This *ad hoc* national coordinating committee on CO_2 capture and storage held two major workshops in 1999, in Calgary and Regina respectively. The outcome of these workshops was a preliminary master plan which:

- identified candidate technologies for capture, transportation, and geological use and storage of CO_2 and what needs to be done to further develop these technologies;
- assessed the barriers and issues that will influence the further deployment of these CO_2 capture and storage technologies in Canada; and
- identified what additional work needs to be done to better address deployment-related concerns.

The federal government, through the Program of Energy Research and Development (PERD) at Natural Resources Canada, and in partnership with other players, funds a national research and development program on CO_2 capture and storage. This program is funded at a level of $1.018 million in 2000/2001, with industry adding a further $4.5 million. Other federal, provincial and industry expenditures on related projects are given later in the report. However, collective S&T investments in Canada are inadequate given the size of the opportunity and the role S&T must play to capture the prize.

There is now an immediate need to refine and take steps to implement the plan developed by the *ad hoc* national coordinating committee on CO_2 capture and storage. There is also a need to assess the opportunities and funding implications of large-scale projects involving retrofits, technology demonstrations and deployment, as well as to provide answers to outstanding economic and technological issues.

What does CO_2 capture and storage include?

CO_2 capture and storage firstly involves the separation of CO_2 from (a) fossil fuel-fired power plant or heating plant flue gases, (b) the effluents of industrial processes such as petrochemicals (ethane purification and ethylene production) and cement manufacture, and (c) hydrogen production by the steam reforming of natural gas (the decarbonization of methane). Separation from these point sources can be accomplished by absorption after contact with amine-based solvents (the most common method), adsorption on activated carbon or other materials, by passing the gas stream through special membranes, or by cryogenic separation. However, costs are high and significant technical problems remain unsolved.

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As well as separation from stack gases after fossil fuels have been combusted in electricity generating station boilers, it is also possible to remove the CO_2 prior to emission. For example, this can be achieved by gasifying coal using an integrated gasification combined-cycle (IGCC) system, or to concentrate it by recycling CO_2 while burning the fuel in oxygen. This latter technique, known as O_2/CO_2 combustion, is under development by an international consortium led by the CANMET Energy Technology Centre at Natural Resources Canada.

Secondly, CO_2 capture and storage involves transportation of the separated CO_2 to the use or storage site. CO_2 pipelines are already in operation in the U.S. to transport the gas, often from natural CO_2 reservoirs, to oil fields where it is used to enhance oil production. A 325-kilometre pipeline has recently come on stream, delivering 5 000 tonnes per day of CO_2 from a coal gasification plant in North Dakota to PanCanadian's CO_2-based enhanced oil recovery project at Weyburn, Saskatchewan.

Thirdly, CO_2 capture and storage involves sequestration of the transported CO_2 in geological reservoirs or in the oceans. Canada participates in an international consortium studying environmental aspects of the injection of liquid CO_2 in the ocean off Hawaii. However, because of the high potential for geological storage in Canada, e.g. in the Western Canada Sedimentary Basin (WCSB), only this option is considered in this report.

Three principal types of geological formation could be used:

- active and uneconomical or depleted oil and gas reservoirs
- deep and unmineable coal formations, and
- deep saline aquifers.

About 70 oil fields worldwide use injected CO_2 for enhanced oil recovery, including the Weyburn field in Saskatchewan. The purity of the CO_2 injected can affect capture costs. It may be possible to reduce costs by injecting CO_2 mixed with other gases, e.g. flue gases containing sulphur and nitrogen oxides, but this would necessitate the study of reservoir reactions to such mixtures.

Canada has led an international effort to evaluate the displacement of methane from coal seams with CO_2, the methane then being available as a fuel for heating or electricity generation. Since two volumes of CO_2 are sequestered for each volume of methane produced and the adsorption is largely irreversible, this storage option looks promising in terms of the economics of electricity generation.

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CO_2 sequestration in a sub-seabed saline aquifer is already being practised in the North Sea off Norway (the Sleipner Project). Results from a Canadian three-year study on the aquifer disposal of CO_2 were published in 1996. This study was done by the Alberta Research Council and funded by a consortium comprising the Alberta Department of Energy, Environment Canada, Natural Resources Canada, TransAlta Utility Corporation and Edmonton Power, as well as the Alberta Research Council. The work demonstrated that both hydrodynamic trapping (no reaction between CO_2 and formation water and aquifer minerals) and mineral trapping (reactions occur and minerals are precipitated or dissolved) are viable processes for the storing of CO_2 in the subsurface, depending upon the reservoir properties.

Why does CO_2 capture and storage represent a significant opportunity to help Canada meet its Kyoto targets?

The CO_2 capture and storage climate change mitigation option is particularly applicable in Alberta and Saskatchewan where coal-based electricity generation is a major source of GHG emissions. They also have geological reservoirs available as storage sites close to point source emitters. Emissions associated with oil and gas production, processing and transportation to markets are also significant in these provinces. Electric power generation is also the largest point source of emissions in New Brunswick and Nova Scotia and, again, there is access to geological reservoirs for CO_2 storage, including aquifers and deep coal seams. Although aquifers exist in Ontario which could be used to store CO_2 captured from fossil-fired electricity generation plants, interest in that province may be focused on technology development and the establishment of markets for the technologies both in Canada and abroad. Other provinces, including British Columbia, Manitoba and Quebec, make extensive use of hydro-electricity and, therefore, have low emissions of CO_2.

Options for decreasing GHG emissions include reducing energy consumption, increasing energy efficiency and use, adopting lower or zero carbon fuels and reducing GHGs from non-energy sources. A further option for reducing CO_2 emissions from energy production is capture and storage, permitting the production of CO_2 but preventing its emission. This option offers Canada the continued use of its immense and cheap fossil fuel reserves without the associated negative climate change impact. It should remain viable in the context of western Canada as long as coal for electricity generation can continue to be supplied at close to $2.00 per barrel oil equivalent. Also, extension of the lifetime of existing fossil-fired plants may be the most cost-effective way to maintain power supplies at the current time.

A number of large volume single-point sources of CO_2 have been identified, particularly in western Canada. Three-quarters of these sources are from electricity generation and it is estimated that they could total as much as 62 megatonnes per year by 2007 in Alberta alone. The capacity of geological sites in Alberta for long-term CO_2 storage has been estimated to exceed 60 000 megatonnes, thus in theory providing storage for all of Alberta's emissions for the foreseeable future.

Storage capacities available in other provinces are not as well documented. However, the Geological Survey of Canada is leading a modest program to characterize the storage potential of geological reservoirs across Canada, especially specific sites in the vicinity of major CO_2 point sources located in sedimentary basins.

Considerable economic benefits could accrue from the adoption of CO_2 capture and storage. CO_2 delivered to an oil field for enhanced recovery is a commodity that commands a price, offsetting capture and transportation costs. The same situation would also apply to supplying CO_2 to projects for coal-bed methane recovery, enhanced gas recovery, enhanced in-situ bitumen recovery, and the in-situ upgrading of bitumen and heavy oils, as long as the delivered price of the CO_2 is sufficiently attractive.

This technology could also limit the overall costs of Canada's greenhouse gas mitigation strategy. Recent modelling results indicate that over 1.5 megatonnes per year of CO_2 could be stored in oil reservoirs (EOR) in the Western Canada Sedimentary Basin at a net cost of $13.00 per tonne. A further 40 megatonnes per year could be stored in deep coal seams or aquifers at cost of $38.00 per tonne. These estimates also underline the important conclusion that deployment of CO_2 capture and storage technologies could ultimately account for a significant proportion of Canada's greenhouse gas mitigation needs by the year 2010.

It should be noted that the physical storage capacity of deep coal seams and aquifers is many times larger than the above estimate, but the above-mentioned storage rates were limited by the amount of CO_2 available for storage, competing mitigation options and other constraints. Only CO_2 emissions from the electricity sector were made available for storage in the model. Estimates by the Energy Resources Branch of Natural Resources Canada indicate that an additional 8 megatonnes of CO_2 from natural gas and various industrial plants could be stored at a net cost of less than $17.00 per tonne. Reduction of capture costs by $10.00 per tonne would reduce the above cost figures by the same amount.

Deployment of CO_2 Capture and Storage Technologies – Strategic Considerations

Although geological reservoirs in western Canada have sufficient capacity to store all of the CO_2 that will be emitted for the foreseeable future, parts of the technology require further development and first-plant demonstration prior to multi-plant deployment. Several strategic considerations surround defining a path forward to such deployment:

- Capture technology is available but is costly and inefficient. Costs of removing and treating CO_2 from stack gases represent probably two-thirds or more of the overall costs of capture and storage. In addition, there is an energy penalty associated with CO_2 capture that reduces overall power generation capacity. These costs are the most important barrier to the commercialization of CO_2 capture and storage technologies in Canada.

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- Flue gases account for about 80% of the CO_2 available in western Canada but there is little experience in large-scale separation. Coal-based power plants have the highest CO_2 emissions of all fossil fuel units but often are the lowest cost electricity generators. If these plants are to continue operating in the competitive market, retrofit requirements for stringent environmental control must be available at an acceptable cost. Current technology has not been tested beyond pilot scale and many problems have yet to be solved.

- It is important to know whether geological storage of CO_2 emissions from large coal-fired power plants is feasible at a commercial scale and, if so, at what cost. This information is also important in terms of decisions for new plants when capital-stock turnover occurs.

- The environmental acceptability of large-scale geological storage needs to be confirmed, especially from the point of view of public perception and acceptance. For example, will sequestered CO_2 slowly leak out of some reservoirs? Further research is needed on the long-term chemical and physical impacts of CO_2 on reservoir rocks and fluids.

- If capture and storage technologies are to be deployed to achieve deep reductions in Canada's CO_2 emissions, policy guidance is needed so that both a realistic development program and a timeline for work to develop and demonstrate new and cost-effective technologies can be defined.

- Because parts of CO_2 capture and storage technologies require further development, multiple approaches are warranted, and significant breakthroughs can be expected. Under these circumstances, the federal government is an appropriate sponsor up to the first commercial plant, but in partnership with provincial governments and industry.

- Overall costs for this support will be high. For example, costs to retrofit CO_2 capture facilities to an existing point source could be up to $300 million and costs of a new technology demonstration could be up to $700 million. A broadly-based group of non-government stakeholders in Alberta has submitted a report to Alberta's Climate Change Central which puts a high priority on extensive provincial S&T support including basic, applied and demonstration efforts relating to CO_2 capture and storage technologies. Proposed funding is about $2.5 billion over 10 years.

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- High interest in CO_2 capture and storage technologies has developed in other countries. Japan, the Netherlands, Norway and the U.S. all have national research programs in progress. Through its already recognized leadership role in several technology areas, Canada can now capitalize on partnerships in international projects when these apply to Canadian needs.

- Commercial and regulatory issues should also be addressed. A principal commercial barrier is likely to be optimization of petroleum production with CO_2 storage. The regulatory framework must be modified to allow this activity to be routinely performed and monitored.

The "make or break" issues for uptake by industry and commercial deployment of CO_2 capture and storage technologies are risk and cost, in particular the cost of capture and compression prior to pipelining. For sequestration in a reservoir, e.g. an oil field, where the owner pays for the CO_2 to enhance the efficiency of a process, the delivered costs at the plant gate must be economically attractive. It is this route to storage, where the CO_2 product has commercial value, that has the highest chance of immediate application. If there is no market for the CO_2 and it must be stored, the substitution of natural gas for coal in power generation may be favoured, at least until the price of natural gas rises to a sufficiently high level or until the cost of CO_2 capture is sufficiently low. CO_2 capture and storage for natural gas-fired systems may be introduced before coal but, worldwide this technology is likely to play a critical role in fossil systems for the next 30 or 40 years.

It seems that current capture technology could probably produce CO_2 at the plant gate at about $35 per tonne but costs as low as $25-27 per tonne are possible. The goal for a national program would be to refine existing technologies by reducing capital requirements and improving capture process integration to reduce costs to about $20 per tonne CO_2 within the Kyoto timeframe or soon after. Transportation costs add an estimated $1.00 per 100 km per tonne and storage adds approximately $2.00 per tonne. Further reduction of capture and supply costs would increase the amount of CO_2 sequestered.

Current CO_2 Capture and Storage Activities in Canada

There are several projects underway in Canada which are making significant contributions to the knowledge and practical application of CO_2 capture and storage. These projects encompass:

- reduction of CO_2 capture costs;
- monitoring of CO_2 behaviour after injection into an oil field;
- enhanced recovery from an abandoned oil field using CO_2 injection;
- increased CO_2 concentrations in flue gases using O_2/CO_2 combustion;
- injection of CO_2 into deep coal beds to enhance methane recovery; and
- assessment of CO_2 storage capacity of Canadian sedimentary basins and coal seams.

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International Test Centre for CO_2 Capture

The International Test Centre in Saskatchewan was announced on December 17, 1999. It has two main components: a pre-commercial scale chemical absorption technology demonstration pilot plant at the Boundary Dam power plant near Estevan, and a technology development pilot plant at the Petroleum Technology Research Centre (PTRC), University of Regina. It will examine refinements to current technology and ways of reducing the costs of capturing CO_2 from stack gases emitted from fossil fuel-fired electricity generating stations.

The original Boundary Dam pilot plant was built in 1987 at a cost of $2.5 million under the sponsorship of SaskOil, Amoco Canada, Shell Canada, and the governments of Canada and Saskatchewan. An earlier absorption separation plant operated in Alberta for about 18 months in the early 1980s at the Sundance power plant. However, the cost of separation of the CO_2 for use in enhanced oil recovery projects was prohibitively high and solvent degradation was a severe operating problem.

The technology demonstration pilot plant at the Boundary Dam power station will be an updated and refurbished version of the 1987 unit. It will improve the already commercial chemical absorption process using a variety of solvents. The smaller pilot plant at the PTRC will be used for both the development of new technology and technology screening.

Contributors include Natural Resources Canada, Saskatchewan Energy and Mines, the Government of Alberta, and the Canada/Saskatchewan Western Economic Partnership Agreement. Industry partners include Sask Power, Fluor Daniel, Luscar, BP Amoco, EPCOR, TransAlta Utility Corporation, Canadian Occidental and PanCanadian Petroleum. Other governments and corporations have also expressed interest.

IEA CO_2 Monitoring Project at Weyburn, Saskatchewan

This project builds upon the $1.1 billion PanCanadian Weyburn CO_2 enhanced oil recovery project in which CO_2, pipelined from the Dakota (coal) Gasification Company in Beulah, North Dakota, will be pumped into the Weyburn field to reduce the viscosity of the oil and thereby increase its recoverability. An incremental 120 million barrels of oil will be recovered over the next 15 to 20 years, at the same time storing about 14 million tonnes net of CO_2 underground.

The International Energy Agency (IEA) CO_2 Monitoring Project is focussed on assessing the long-term integrity of CO_2 storage. This four-year research project is starting with a pre-injection reservoir baseline study. The project will develop a comprehensive understanding of the storage integrity, migration and fate of CO_2 injected into an oil-bearing geological structure.

Total project cost will be $35 million. Partners to date include PanCanadian Resources Ltd., Saskatchewan Energy and Mines, the Petroleum Technology Research Centre and the Government of Canada through the Climate Change Action Fund. SaskPower, BP Amoco, Dakota Gasification Company and TransAlta Utility Corporation plan to participate in the project. The European Union has also committed funding with more anticipated from other European sources.

This project will include researchers from Canada, the United States and Europe under the auspices of the *IEA Greenhouse Gas R&D Programme.* This IEA activity, chaired by Canada and with offices in the U.K., brings together the interests of 16 countries and the Commission of European Communities. As well, BP Amoco, DMT-FP, EPRI (Electric Power Research Institute, California), Mobil Oil, RWE AG and Shell International are sponsors.

Membership also provides access to information from other international projects, for example the Sleipner CO_2 capture and storage project of Statoil, the Norwegian state oil company. This project removes CO_2 from natural gas in the North Sea using an amine absorption process. The CO_2 is then compressed and injected into an aquifer 1 000 m below the seabed. The Sleipner project is the largest CO_2 capture and storage project in the world, sequestering about 1 million tonnes of CO_2 per year.

O_2/CO_2 Combustion Technology

This project is being conducted at the pilot plant facilities of the CANMET Energy Technology Centre (CETC) in Ottawa. The CANMET consortium includes five Canadian utility companies (TransAlta Utility Corporation, EPCOR, SaskPower, Ontario Power Generation and Nova Scotia Power), two industry companies (Air Liquide Canada and the McDermott Corporation), the government of Alberta through AOSTRA and the U.S. Department of Energy.

The principle of O_2/CO_2 combustion of fossil fuels is that the CO_2 concentration in the flue gases can be increased to more than 95% by displacing air with oxygen in the combustion process, thereby minimizing the complexity of CO_2 capture from these gases. Nitrogen is separated from the combustion air and the CO_2 combustion product is recirculated through the combustor with the oxygen. The use of CO_2 recycle allows for proper control of boiler performance in retrofit situations. This technique also shows promise for the clean-up of other emissions such as nitrogen oxides, sulphur dioxide and particulates.

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This project is now in its fifth phase. Pilot-scale O_2/CO_2 combustion trials are continuing and the techniques learned will be applied to a commercial burner design. As well as the opportunity to retrofit this technology to existing fossil-fired power plants, the possibility for a field demonstration project in conjunction with the coal-bed methane project, described below, has been discussed. In this application, O_2/CO_2 combustion would provide a CO_2-rich flue-gas stream sequestered in deep unmineable coal beds while simultaneously recovering the methane trapped in the coal. The economic value of the methane recovered would offset the cost of sequestering the CO_2.

As part of this project, "virtual plant" models have been developed to simulate the effect of various CO_2 capture technologies on overall plant performance and to optimize system integration to reduce energy losses.

CO_2 Enhanced Recovery of Coal-bed Methane

The objectives of this project are to reduce greenhouse gas emissions by injection of CO_2 into deep coal beds and to enhance coal-bed methane recovery factors and production rates as a result of CO_2 injection. This project is led by Environment Canada with expertise from the Alberta Research Council. It is sponsored by the governments of Alberta, Canada, the U.S., the U.K., Australia and the Netherlands as well as a group of more than 15 oil producers, utility companies and other interests.

A single-well pilot was successfully tested in Fenn-Big Valley, Alberta in1999/2000 and a two-well pilot injection test is in the design stage for implementation in 2001.

CO_2 Storage Capacity of Canadian Coal Seams

This modestly-funded project ($38,000 in 2000/2001) is being carried out from the Calgary office of the Geological Survey of Canada. It seeks to understand the adsorptive capacity for CO_2 of representative coal samples from coal seams in Canada using laboratory isotherm experiments. Detailed studies are required on the areas in Canada, including the east coast, with the highest potential for storage but current funding is inadequate for this.

Canadian Clean Power Coalition

This activity is still at the proposal stage. An association of leading Canadian coal and coal-fired electricity producers, known as the Canadian Clean Coal Power Coalition, has proposed a program with the aim of "securing a future for coal-fired electricity generation, within the context of Canada's multi-fuelled electricity industry, by proactively addressing environmental issues in cooperation with government and our stakeholders". Current members of the Coalition are EPCOR, Luscar Ltd., SaskPower, the Alberta Research Council and TransAlta Utility Corporation. The proposal includes:

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- construction and operation of a full-scale demonstration project for the removal of greenhouse gas and all other emissions of concern from an existing coal-fired power plant by 2007;
- development of low-emission technology for new power plants; and
- an integrated air-quality covenant that tackles the entire portfolio of air quality issues related to coal-fired power generation.

Costs over the next 10 years for the full-scale demonstration project and demonstration of low-emission technology for new power plants are estimated to be nearly $1 billion.

International CO_2 Capture and Storage Activities of Interest to Canada

As well as the above projects currently underway in Canada, there are other activities abroad of particular interest to Canada. They were reported upon at the Fifth International Conference on Greenhouse Gas Control Technologies in Cairns, Australia, August 13-16, 2000. Total attendance at this conference was 380 with 37 countries represented. Seven papers authored by Canadians were presented in the sessions on capture and geological storage.

Zero Emission Anaerobic Hydrogen or Electricity Production from Coal

The heart of this concept is to transform coal by means of the high-temperature chemical reaction of steam with coal, producing hydrogen and CO_2. No combustion takes place. The hydrogen could then be used as fuel in a high-temperature solid-oxide fuel cell to make electricity. The CO_2 is removed by reacting it with lime, CaO, forming a mineral, calcium carbonate ($CaCO_3$). The $CaCO_3$ is subsequently calcined at high temperatures releasing a concentrated stream of CO_2 and the CaO is recycled.

The released CO_2 would be reacted with naturally-occurring serpentine, a magnesium silicate. The product of the reaction is magnesium carbonate, which is benign and could be stored at the serpentine mine.

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This concept was originally proposed by the Los Alamos National Laboratory in New Mexico. It is now being pursued through the mechanism of a consortium, known as the Zero Emission Coal Alliance (ZECA). Currently, ZECA has underway a $550,000 (U.S.) techno-economic feasibility study of the proposal, to be completed by early 2001. Membership in ZECA includes eight U.S. coal producers, utilities and manufacturers and the Los Alamos National Laboratory. It also includes a number of Canadian participants: EPCOR, SaskPower, Ontario Power Generation, TransAlta Utility Corporation, AFL Venture (ATCO, Fording Coal and Luscar Ltd.), the Coal Association of Canada, AOSTRA and Natural Resources Canada.

BP Amoco Joint Industry Project (JIP)

Six global energy companies have joined with BP Amoco to develop advanced CO_2 separation and geological storage technology: Chevron, Norsk Hydro, Statoil, Shell, Suncor Energy and Texaco. While each member company is actively working to manage its own greenhouse gas emissions through a portfolio of initiatives, this project demonstrates their joint commitment to address the climate change issue through advanced CO_2 capture and storage.

Canadian O_2/CO_2 combustion technology may play a role in this project. BP Amoco is considering a major natural gas decarbonization project for the Alaska North Slope in which CO_2 would be removed from gas turbine exhausts and used for enhanced oil recovery.

U.S. Department of Energy Greenhouse Gas Sequestration R&D Program

The importance of CO_2 capture and storage research as an attractive potentially low-cost option has now been recognized in the United States where about 85% of energy is derived from fossil fuels. This importance was underscored by the President’s Committee of Advisors on Science and Technology in a report entitled “Federal Energy Research and Development for the Challenges of the Twenty-First Century, November 1997” which recommended a much larger science-based CO_2 capture and storage program. It was recognized that this high-risk, long-term R&D would not be undertaken by industry alone. Key areas for research and development that could lead to an understanding of the potential for future use of carbon dioxide sequestration as a major tool for managing CO_2 emissions were identified in a 1999 U.S. Department of Energy report entitled “Carbon Sequestration Research and Development”.

The goal of the U.S. program is to “reduce the cost of carbon sequestration to $10 or less per net ton of carbon emissions by 2015”. Costs in this range would add less than $0.01 per kWh to the average electricity bill in the U.S., making CO_2 capture and storage one of the most affordable options for addressing climate change.

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With this goal in mind, the U.S. Department of Energy has made a transition from funding early exploratory ventures to committing $13.7 million over the next three years to new projects. However, this funding level is only regarded as preliminary until the direction of the program becomes clearer. Partners from private research institutions, industries and universities will contribute an additional $10 million. The first of two phases of this program comprising 13 projects was announced in July 2000. The closing date for the second round of proposals has already passed.

Of these 13 first-round projects, two deal with CO_2 capture (development of a high-temperature membrane for CO_2 capture in coal gasifiers and development of a reusable sodium-based absorbent) and four deal with geological storage (one on storage in coal seams, one on storage in deep saline reservoirs and two on reservoir characterizaton). The remaining projects deal with ocean and terrestrial sequestration and advanced concepts and modelling.

Canadian technology such as O_2/CO_2 combustion, via a U.S. partner, could form part of a future proposal to the program.

A Path Forward for Canada

The Canadian projects currently being supported comprise relatively modest pilot-scale development as well as reservoir characterization and monitoring studies. They are important and useful in providing new knowledge for the next stages in technology development. They also have a high profile on the international stage. However, if CO_2 capture and storage is to make the significant contribution to greenhouse gas mitigation that is promised and envisaged possible, a much more ambitious program approach is required.

As already noted, an *ad hoc* national coordinating committee on CO_2 capture and storage has made significant progress in identifying the needs for such a program. The committee considered the following technologies:

Capture:
- chemical (amine) absorption, coal and natural gas plants
- decarbonization of methane (reaction with steam to produce hydrogen)
- decarbonization of solid fuels (coal gasification)
- O_2/CO_2 combustion
- as CO_2 hydrates from flue gases
- membrane and cryogenic separation
- anaerobic (zero emission) coal gasification

Storage:
- enhanced oil recovery
- enhanced coal-bed methane
- deep saline aquifers
- mineral trapping
- resource characterization and inventory

S&T needs and approximate timetables to the first commercial plant were mapped out by the committee and are summarized in Table 1. Early estimates of costs for development and, in some cases, pilot and demonstration plants are included in the table. Further refining of these figures is needed. However, even though all options would ultimately not go forward, it can be assumed that overall development of technology options would cost in the hundreds of million dollars. As previously noted, large demonstration and first commercial plants would cost well in excess of this figure, probably close to $1 billion.

The national coordinating committee also considered possible partners for these projects and where Canadian expertise already exists. An initial consideration of the present states, critical issues and barriers to deployment of capture technologies was done, based on current knowledge. These observations are summarized below.

Chemical (amine) absorption, at coal-fired generation plants and natural gas plants:
- lack of long-term experience
- difficulties of integration into existing plant
- a high solvent loading contributes to separation costs

Decarbonization of methane (e.g. reaction with steam to produce hydrogen):
- CO_2 avoidance by this technology in a new plant may be more expensive than adding other capture technologies to existing fossil fuel-fired power plants

Decarbonization of solid fuels (coal gasification):
- coal gasification technology coupled with combined-cycle power generation is very expensive (a 550 MW facility would cost an estimated $1 billion)
- technology integration into existing plants is expensive and potentially problematic
- Canada is not a major player in development of this technology

O_2/CO_2 combustion:
- lack of Canadian boiler manufacturing companies
- large oxygen separation plants are required
- this combustion technology could reduce the reliability of downstream electricity generation facilities

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Capture as CO_2 hydrates:

- early stages of technology development
- costs are currently higher than those of competing technologies
- costs of flue gas compression are high

Membrane and cryogenic separation:

- membranes: extraction costs (\$/tonne CO_2) are unknown; materials need further development
- cryogenics: engineering studies required; system difficulties caused by the formation of CO_2 hydrates

Anaerobic (zero emission) coal gasification:

- anticipated high funding requirements for the R&D
- the concept has still to be demonstrated
- developing a practical process given the thermodynamic constraints
- large volumes of solid wastes generated and large volumes of minerals needed

Table 1: Preliminary Canadian S&T needs for the further development, demonstration and deployment of CO_2 capture and separation technologies

TECHNOLOGY	DEVELOPMENT TIMELINE SUMMARY (2000 – 2005 – 2010 – 2015 – 2020)	ESTIMATED OVERALL COSTS (millions)
CAPTURE		
Absorption (coal and natural gas)	Int'l Test Centre; Coal Demo; Natural Gas Demo	40
Decarbonization of methane	Development; Demo	38
Decarbonization of solid fuels	Systems and Design Studies; Natural Gas Demo	200
O_2 / CO_2 Combustion	Pilot Scale; Demo; Commercial	110
CO_2 Hydrates	R&D and Pilot; Demo	63
Membrane and Cryogenic Separation	R&D; Pilot Units	10
Anaerobic (zero emission) coal gasification	R&D and Pilot; Demo	100-500
STORAGE		
Enhanced oil recovery	CO_2 Monitoring (Weyburn); More Field Projects	100
Enhanced coal bed methane	Reservoir Assessment; Demo	25
Deep saline aquifers	Identify Formations	0.25
Mineral trapping	(Associated work anaerobic coal gasification)	0.20
Resource characterization and inventory	Reservoir Characterization	15.5

Other Actions Needed for Technology Deployment

The *ad hoc* national coordinating committee on CO_2 capture and storage also considered other actions needed to pave the way toward technology deployment, including policy levers available to governments and actions that may be taken by industry. The committee recognized that, in the short term and in the absence of a mechanism which attributes a price for greenhouse gas emissions avoidance, most of the CO_2 capture and storage opportunities would not be viable. Thus, industry is not likely to deploy these technologies without explicit government action based on a public policy mandate. In order to assess the issues that have a bearing on the widespread deployment of CO_2 capture, use and storage, the committee recommended that the following actions be taken:

- existing federal and provincial regulations (health and safety, environmental and economic) which may affect the deployment of CO_2 capture and storage technologies should be reviewed;
- existing federal and provincial fiscal frameworks (taxes and royalties) should be reviewed;
- existing studies of federal and provincial tax and royalty programs designed to promote R,D&D and which would cover CO_2 capture and storage technologies should be identified;
- a generic financial model should be developed to help decision-makers gain a better understanding of the net costs to investors of CO_2 capture and storage;
- an inventory of potential Canadian sources and storage sites should be developed;
- the export potential of Canadian CO_2 capture and storage technologies should be developed;
- a CO_2 capture and storage network should be established to promote enhanced communication and sharing of publicly-available information; and
- a CO_2 capture and storage consortium should be established to promote a broader engagement of companies in this initiative.

The national coordinating committee on CO_2 capture and storage estimated costs of $400 000 to undertake these reviews.

Next Steps

The importance and potential impact of CO_2 capture and storage technologies in helping Canada meet its Kyoto greenhouse reduction commitments have been recognized.

An informed community of scientists and engineers in industry, academia and government has developed. Projects in Canada have attracted international participation.

A national coordinating committee has developed a preliminary roadmap toward the demonstration and deployment of candidate technologies, as well as defining other studies needed to pave the way forward.

Confirmation at the highest level and support for the continued development and demonstration of these technologies is now required. The national coordinating committee should be instructed to undertake further consultation to identify S&T priorities and to finalize the R,D&D plan. The funding for current projects, which only extends to modest initial monitoring and pilot-scale studies, needs to be enriched. Also, further funding is required to enlarge Canada's S&T capacity in this area and for basic research, applied science and demonstrations. Decisions must be made regarding where to support international work and where to establish a Canadian lead.

Because this funding requirement will be high due to the complexities of late-stage technology development, demonstrations and first commercial plants, funding sources should be identified, e.g. the Sustainable Development Technology Fund (SDTF).

The national plan would then be best implemented through partnerships with the provinces and the private sector.

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