CO₂ Capture Project: An Integrated, Collaborative Technology Development Project For CO₂ Separation, Capture And Geologic Sequestration

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ABSTRACT

This report (which forms part of the requirements of the Statement of Work Task 0, Subtasks 0.1 to 0.3 and 0.5) describes how technologies were evaluated for inclusion in the program and the current status of the contracting process as of July 2002.

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1.0 INTRODUCTION

This report describes the results of Subtasks 0.1 to 0.3 and 0.5 listed under Task 0 in the Statement of Work agreed under contract in July 2001.

Subtask 0.1 The identification of relevant separation, capture and sequestration (storage) scenarios.

Subtask 0.2 The establishment of state-of-the-art (SOA) separation and capture technology.

Subtask 0.3 The development and application of a common economic model.

Subtask 0.5 Select Technology Developers

The sub tasks are rolled up into one Phase 0 Technology Selection Processes Report first prepared for the CCP in November 2001 and modified to meet the Task 0 contract requirements. Specifically this involved removing some confidential proprietary material. The report is attached as Appendix 1.

The Phase 0 report includes an in depth description of the rationale for the selection of technologies described in the program work plans, submitted in the first Semi-Annual Project Report (issue date September 2002).

Work under Subtask 0 continues within the program as the search goes on for new technology and our knowledge concerning current SOA is revised. As new ideas and proposals become known to the project they are evaluated for inclusion in the program.

Refinement of the economic model used to evaluate our progress against cost reduction baseline targets is also ongoing. These baselines are real life scenario based on large point source CO₂ emission sites. The baselines give the cost of uncontrolled CO₂ capture and the cost of CO₂ capture with the best available CO₂ capture technology (amine scrubbing) available today incorporated. Detailed process flow designs and cost estimates have been prepared for the baselines. To those costs are added both transportation and storage costs to complete the cycle.

The program will continue to focus down onto favored technologies which meet our CO₂ capture cost reduction targets, namely a 50% cost reduction for retrofit applications over the base case and a 75% cost reduction for new build applications (where full advantage may be taken of both new technology and 'know how' integration). The best performers in our program will ultimately also be subjected to detailed process flow design and cost estimation to demonstrate success.

The Phase 0 Report in Appendix A shows how we will focus the program through the application of our Technology Assurance Process (TAP). TAP involves a thorough review of performance for each technical study against project objectives as they reach key stage gates. Those that fail to pass through the stage gate review process will be dropped from the program. Decision support material collected at the stage gate will be used to justify all decisions.

The targets set out for this project are stretch targets designed to take technology development and CO₂ capture cost to a significantly different place from where it is now. The risked portfolio selected to date is likely to reduce in size over project life as technologies fail to meet expectation. The contract status spreadsheet as of July 2002 (Table 1) thus contains more technologies than can be fully funded under the DOE program. Funds have been requested for release sufficient to enable these technologies to proceed to their first stage gate review. Some will be eliminated at that point

and in this fashion the program will be managed to meet the agreed Phase 1 budget. When needed funds will be re-distributed amongst those studies remaining in the program or for new projects. Those technologies that are eliminated will be agreed with the Co-funder (DOE technical manager for the program) and the CCP Executive Board based on the technical team recommendations.

The CO₂ Capture Project, is an International collaborative project co-funded by the US DOE, The European Union Departments of Transport & Energy and Research, and The Norwegian Government Klimatek Program. This has avoided the need for duplication of research activities and enabled all parties to best leverage their research funds. Should there be no justification to eliminate studies within the DOE program after the first stage gate reviews, then where appropriate some studies may be moved into another regional program to enable work to continue without exceeding the DOE contracted budget.

Work has started on many of the program tasks and progress on all tasks will be the subject of the next Semi Annual Report, January 2003.

TABLE 1 - CONTRACT STATUS SPREADSHEET JULY 2002

*CO2 Collection Project
Contract Status Spreadsheet - Department of Energy*

Technology	Description of Technology Provider Proposal	Technology Provider/Selected	Contractor Type	DOE APPROVAL	2001 \$K	2002 \$K	Amt Deferred	2003 \$K	Amt Deferred
SMV	HSE Probabilistic Risk Assessment Methodology	Idaho National Lab (Idaho)	National Lab	12/21/2001	0	244	0	196	0
SMV	Investigation of Novel Geophysical Techniques for Monitoring of CO2 Migration	Lawrence Berkeley National Lab (Berkeley)	National Lab	12/21/2001	30	115	0	35	0
SMV	Probabilistic Health, Safety & Environmental Risk Assessment for CO2 Leakage	Lawrence Berkeley National Lab (Berkeley)	National Lab	12/21/2001	63	197	0	200	0
SMV	Hyperspectral Geobotanical Remote Sensing for CO2 Containment	Lawrence Livermore NL (Livermore)	National Lab	12/21/2001	0	200	0	100	0
SMV	Noble Gas Isotopes for Screening and Monitoring Long Term Migration	Lawrence Livermore NL (Livermore)	National Lab	12/21/2001	0	301	0	152	0
SMV	Risk Assessment, Reactive Transport Modeling of Integrity of Caprocks & Faults (Johnson)	Lawrence Livermore NL (Livermore)	National Lab	12/21/2001	0	186	0	120	0
SMV	Leveraging Nuclear Storage; RA Framework, Public Perception, etc.	Monitor Scientific (Sci Monitor)	Business	1/17/2002	0	35	0	0	0
SMV	HSE Risk Assessment Methodology Development	Netherlands Institute of Applied Geosciences	National Lab	1/17/2002	0	445	0	445	0
SMV	CO2 Optimum Monitoring Methodologies	Netherlands Institute of Applied Geosciences	National Lab	12/21/2001	0	35	0	0	0
SMV	Long Term Sealing Capacity of Steel Wellbore Tubulars & Cement	SINTEF	National Lab	1/17/2002	0	110	0	0	0
SMV	Long Term Monitoring & Verification Using Satellite Radar Interferometry	Stanford University (Stanford)	University	12/21/2001	0	123	0	216	59
SMV	Use of Depleted Gas Reservoirs for Storage; Studies on Increased Condensate Rec.	Texas Tech University	University	12/21/2001	0	123	0	92	0
SMV	Screening Tool for Miscibility Pressure Calculations; Tradeoffs of Impure CO2	Tie-Line Technology (Tie-Line)	Business	1/17/2002	0	103	0	0	0
SMV	Reservoir Characterization, Fault Leakage Analysis, and Synthesis of Leaky Systems	Utah State University (Utah State)	University	12/21/2001	0	35	0	52	0
SMV	Leveraging and Characterization of CO2/H2S Acid Gas Disposal/AB	Alberta Energy & Utilities Board	Business	N/A	0	0	0	100	0
Pre Combustion	Sorption Enhanced (SEER)	Air Products & Chemicals, Inc.	Business	12/21/2001	0	773	0	200	194
Pre Combustion	Develop Supported Copper Palladium Alloy	Colorado School of Mining (CSM)	University	12/21/2001	0	119	0	0	0
Pre Combustion	Develop Electro-ceramic membranes	Eltron Research	Business	21/21/01	0	209	0	0	0
Pre Combustion	Develop Silica Membranes and Provide Mathematical models	Energy Resource Centre of the Netherlands	Business	1/17/2002	0	178	0	378	205
Pre Combustion	Develop Flowsheet & Design	Fluor Daniel	Business	1/17/2002	0	240	0	170	0
Pre Combustion	Reactor Design, scale up and cost assessment	McDermott Technology, Inc.	Business	1/17/2002	0	19	0	279	0
Pre Combustion	Copper Palladium Membrane Research	TDA Research, Inc. (TDA)	Business		0	95	0	0	0
Pre Combustion	Develop Supported Silicalite (zeolite) membranes	University of Cincinnati	University	12/21/2001	0	200	0	597	0
Pre Combustion	Gasification CO2 Separation Development	Fluor Daniel	Business	N/A	0	377	0	0	0
Pre Combustion	Gas Turbine Retrofit	General Electric (GE)	Business	N/A	0	0	0	150	0
Pre Combustion	Compact Reformer Membrane Contactor	Kvaerner	Business	N/A	0	150	50	100	0
Pre Combustion	Distributed Gas Turbines (VLS ATR)	Jacobs	Business	12/21/2001	0	65	0	0	0
Pre Combustion	Distributed Gas Turbines (VLS ATR)	Haldor Topsoe	Business	1/17/2002	0	210	0	0	0
Post Combustion	Radical Chemistry: Part 1 Review State of Art Opportunities	SRI	Business	N/A	0	200	0	0	0
Post Combustion	Radical Chemistry: Part 2 Technical Studies	Unknown	Business	N/A	0	0	0	200	200
Post Combustion	Technology cost estimating	Fluor Daniel ?	No Tech Prop	N/A	0	0	0	300	300
Post Combustion	ESA development for CO2 removal from low pressure flue gas	Oakridge, APCI, SGL	Business	N/A	0	300	0	400	0
Post Combustion	Cost Efficient Design Integration	NEXANT	Business	N/A	0	175	187	0	0
Oxyfuel	Oxyfuel boilers and heaters recycle	Air Products & Chemicals, Inc.	Business	N/A	0	170		169	0

APPENDIX 1 – TECHNOLOGY SELECTION PROCESS

CO₂ Capture Project

Cooperating
for a better
Environment

CO₂ Capture Project Technology Selection Processes 1 November 2001

Presented to the

CO₂ Capture Project Partners

BP
ChevronTexaco
ENI
Norsk Hydro
Pan Canadian
Shell
Statoil
Suncor

And

Funding Agencies

European Union
Klimatek
U.S. DOE

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Executive Summary

The CO₂ Capture Project (CCP) brings together scientists and engineers from different technical disciplines, corporate cultures, and national cultures. A rigorous and fair, but readily understood, process for technology selection was needed to ensure that diverse technical and political stakeholder needs were considered. This document describes the technology selection process used to gather input, shape the technology development program and to ensure that appropriate technologies for further development were chosen. It also serves as an archive of information about the program and its processes.

The CCP technology selection process began with the September 1999 Informational Conference sponsored by BP, the IEA-Greenhouse Gas Program, and the US Department of Energy. Attendees were encouraged to describe technologies that could be used to separate and capture carbon dioxide from combustion sources and to raise other issues and concerns. The conference highlighted the need for broad cooperation between stakeholders (industry, government researchers, technology developers, academics, and policy makers.) Policy and public acceptance issues were raised as major issues not adequately addressed. The proposed technology program was generally endorsed and significant improvements were made as a result of the conference.

Participants who joined the CCP sponsored a detailed review and evaluation of the public input, past industry work, government and academic research, and their proprietary research studies. The Review and Evaluation (R&E) Phase focused the program on capture techniques, combustion processes, geologic storage, and public acceptance issues. The evaluation teams recommended that industrial application designs (scenarios) be used as the basis for technology development. Scenarios include the unit operations and integration common to industrial plant design and ensure that technology is not developed in isolation. Public acceptance potential was gauged through two CCP sponsored conferences with environmentally focused non-governmental organizations (NGO.) The results of those conferences make the CCP cautiously optimistic that its work will meet with NGO acceptance.

While the R&E Phase focused the program, specific research activities and government funding discussions led the CCP to carry out a detailed Analysis Phase that included scoping studies to further sharpen the direction of the program. The teams agreed to use four scenarios as the framework for further technology development. These scenarios are based on common industrial operations that represent a substantial fraction of business applications. They include:

- **Refinery** – gas and oil fired heaters commonly found in refinery and chemical plant service for direct heating of process units, process steam, and electricity generation service with both steam and direct fired gas turbines.
- **Very Large Gas Turbines** – Natural gas fired turbines with electricity generation capacities greater than 300 MW intended to provide electricity to public power grids.
- **Distributed Gas Turbines** – Natural gas-fired turbines with electricity generation capacities less than 100 MW intended for direct shaft power or smaller electricity

generation service. The scenario includes multiple installations distributed around a major site.

- **Gasification** - Steam, electricity cogeneration, and hydrogen production fueled by gasified solid fuel (petroleum coke). The main applications would be in chemical plants and refineries to service those plant needs. Electricity might be sold into the public power grid.

Compression and transportation of carbon dioxide to storage sites was reviewed and found to be commercially available technology and not in significant need of enhancement. As noted above, public acceptance issues, monitoring, and verification of safe storage were deemed to be the dominant geologic storage issues and will be studied thoroughly. Technologies to carry out geologic storage are either already in commercial service or readily derivable from current oil field technologies and will not be heavily studied in the CCP. Geologic storage will be dominated by enhanced oil recovery opportunities where an economic incentive to use the carbon dioxide exists. Aquifer storage was viewed as a viable option that uses similar technologies to commercially available enhanced oil recovery technologies. Coal-bed storage with associated methane production is of interest but is not a central theme of the CCP.

Each technology development team has chosen areas on which to concentrate their activities in support of CCP goals. **Oxyfuel** activities are centering on gas turbines with flue gas recycle, boilers and heaters with flue gas recycle, and on chemical looping for oxygen separation. **Post-combustion** will concentrate on combining membrane contactor technology with improved sterically hindered amines, cost reduction through simpler design standards for conventional amine processes, electrical swing adsorption of CO₂, and a novel in-pipe separation technology. **Pre-combustion decarbonization** will concentrate on water gas shift membrane reactors, membrane reformers, the compact reformer with carbon dioxide membrane contactors, very large scale auto thermal reactors, sorption enhance water gas shift, and novel approaches in solid fuel gasifiers to separate carbon dioxide from the hydrogen rich stream. Several other technologies needing long-term development that will be encouraged are ion transport membranes, electrical swing adsorption, ElectroPOX, and IFEs MeO power process. As noted above, the **Storage, Monitoring, and Verification** team will concentrate on addressing monitoring, verification, and public acceptance issues.

The Technology Development Phase is underway with approximately 40 contracts in place or in final negotiations as of September 2001. The Appendices to this report include details about the technology selection and assurance process along with archival materials pertinent to the technologies selected.

Introduction

The CO₂ Capture Project (CCP) brings together scientists and engineers from different technical disciplines, corporate cultures, and national cultures. A rigorous and fair, but readily understood, process for technology selection was needed to ensure that diverse technical and political stakeholder needs were considered. The complexity and schedule made it necessary for the selection process to rapidly identify desirable technologies and to allow the teams flexibility to encourage new technologies.

The CCP technology selection process began at the September 1999 Informational meeting when attendees were encouraged to describe technologies that could be used to separate and capture carbon dioxide from combustion sources. After the CCP began operations, the selection process intensified and was managed by a stage-gate decision-making process and technology assurance process. Each technology team used similar processes to ensure that a valid comparison could be made. The teams developed a technology selection process that is used by all. The decision-making process uses tools developed by the Common Economic Model Team. This report describes the technology selection work done and processes used by the teams.

This document is organized to discuss the processes, actions, and results of each step in the Technology Selection Process up to September 2001. As shown in Figure 1, it follows the Technology Assurance Process and adheres to stage-gate decision-making. It provides the assurance that prudent technology development choices are being made.

Figure 1

Public Forum

Overview:

“CO₂ Capture and Geologic Sequestration: Progress through Partnership”

sponsored jointly by BP, the US DOE, and the IEAs Greenhouse Gas Program, was held in September 1999 to gauge interest and gather ideas for carbon dioxide mitigation technology development.¹ BP led the meeting and provided most of the background information and structure.

Over 150 people attended the conference and gave their advice freely. It became clear that carbon dioxide mitigation is viewed as a public awareness and policy issue as well as a technical problem. Selected and paraphrased viewpoints of attendees were:

- Action is needed now to meet the very long-term challenge.
- A long-term view on carbon capture and sequestration technology development is critical. We must look past near-term projects toward creating carbon emissions reduction options for scenarios in which global anthropogenic carbon emissions must be reduced by 60-90%.
- If we want to make real progress towards a carbon dioxide emission future, we must start doing experiments now!
- Legislative and policy initiatives to provide incentives for research and technology development where the primary technology driver is a public benefit are needed.
- Government involvement through incentives and investment in technology development is needed for broad-based application of carbon sequestration. Existing carbon sequestration projects have unique circumstances (e.g., Sleipner, natural gas product specifications and the Norwegian carbon tax; Weyburn – royalty agreements and nearby CO₂ source).
- Public perception and acceptance is critical. Engage stakeholders such as environmental groups early.
- Widespread carbon dioxide mitigation will not occur without an economic driver for business. There must be a business or regulatory environment that gives business the opportunity to develop a competitive advantage through participation in carbon sequestration.
- Systems integration (i.e., putting existing components together in an optimal way) is critical to cost reduction, perhaps reducing costs by 50%.
- A major opportunity for systems integration is carbon dioxide separation from combustion streams because of the large energy and pressure losses.
- Injecting CO₂ into oil reservoirs and coal beds (for methane recovery) early in the productive life, rather than later, is a promising sequestration concept.
- Assuring that CO₂ stays in the storage area through monitoring will be a significant technical challenge and cost.
- Our ultimate challenge is changing the shape of the marginal cost curve.

The conference gave an opportunity for wide-ranging discussions of both technical and policy issues. Summary reports from each breakout session were prepared and published to the attendees.

Policy Context

- U.S DOE:** Fossil fuels represent 85% of world energy use 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 anthropogenic energy consumption threefold or more. In 1992, the United States and 160 other countries ratified the Rio Accord, in which they agreed 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 large growth in energy consumption that is anticipated, and because of 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 low-cost options for reducing carbon dioxide emissions such as improvements in energy efficiency, niche renewable energy applications, and combined heat and power. However, such no-regrets options will become fully applied after aggregate emissions reductions of 10-20% below business-as-usual.²

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 their own 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 – enabling prosperity and growth in a carbon-constrained economy.

- BP:** BP decided that, as an energy company, CO₂ emissions are a business issue to be addressed. In 1998, BP announced a target of reducing its greenhouse gas emissions to 10% below 1990 levels by 2010. The target reduction changes as the corporate asset base changes, however the 10% reduction target does not. Based on expected growth in exploration and production, chemicals, and refining of clean fuels, a reduction of about 30% from business-as-usual BP emissions in 2010 are needed to meet this objective. 2010 is not that far in the future for such a significant goal and BP has begun taking steps to reduce its CO₂ emissions. Specific actions include: establishing emissions metrics in business unit performance, expanding solar programs, and initiating an in-house greenhouse gas emissions trading program. BP has identified a number of projects that both reduce greenhouse gas emissions and give a good return on investment (e.g., reduced flaring, sealing methane leaks). The portfolio of financially attractive mitigation projects will produce around half of needed reduction. BP is investigating geologic storage as one option for achieving the remaining reduction at the lowest cost.³
- IEA:** The IEA Greenhouse Gas R&D Program, 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. In the world there is a growing interest in carbon sequestration and recognition of its importance. The governments of some

countries have taken proactive action with respect to the greenhouse gas issue, either through ratifying the Kyoto Protocol and/or promulgating carbon taxes or other incentives for greenhouse gas emissions reduction.

IEA has identified four key issues for carbon sequestration: reducing the cost of CO₂ capture, minimizing the risk of CO₂ storage, demonstrating the reliability of CO₂ storage, and verifying the amounts of CO₂ stored. The IEA program conducts several “practical R&D” activities, including monitoring of the Sleipner project and investigations into O₂/CO₂ recycling and pre-combustion decarbonization.⁴

- **EPRI:** The Electric Power Research Institute (EPRI) has performed an analysis of the domestic and global electricity supply market over the next fifty years. EPRI expects U.S. electricity demand to grow in that time frame, but for 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 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 needs acceleration to prove that it is a viable carbon management option – thus enabling a wise transition strategy and policy towards a sustainable U.S. energy system.⁵

Ongoing Carbon Dioxide Storage Activities

Saline Formation: CO₂ from natural gas produced at Statoil’s Sleipner Field is captured using an amine separation system to meet natural gas product specifications. The pure CO₂ stream is compressed and injected into the Utsira sandstone, a saline formation under the North Sea. The incremental cost of compressing and injecting the CO₂ stream is about \$20/tonne CO₂ compared to \$40/tonne CO₂ for the amine separation stage. Statoil injects roughly 1 million tonnes CO₂ / year at Sleipner. The developers estimate the cost of compression and injection for a 4 million-tonnes/year project would be around \$7/tonne CO₂. A European Union funded project led by Statoil, **SACS**, is studying the Sleipner project to verify that storage of CO₂ in geologic formation is safe and to validate models for geology, geophysics, and reservoir tools. In cooperation with IEA, a large amount of geophysical data has been gathered. A report that provides interpretations of the data gathered thus far will be published soon.⁶

Enhanced Oil Recovery: CO₂ extracted from process streams at the Dakota Gasification Plant will be used for enhanced oil recovery in the Weyburn Oil Field in Canada. The project will sequester 1.8 million tonnes CO₂/year beginning in 2000. The Weyburn field, discovered in 1954, has been produced through primary and water flood production. CO₂-EOR is being used to extend field life while increasing recovery. Pan Canadian Petroleum believes that they will gain incremental recovery of 7% OOIP while sequestering carbon dioxide. The Weyburn project was facilitated by negotiation of a favorable royalty agreement and availability of a nearby low-cost CO₂ supply from Dakota Gasification, a lignite-to-natural gas facility built with U.S. DOE support in the

1980s. Field infrastructure is in place and the largest additional investment was a 200-mile pipeline. The developers reported that several electricity generators submitted bids to be the supplier of CO₂ for the Weyburn project and their costs were only 30% above the level to make the project economically viable.⁷

Coal Bed Methane (CBM): Methane production from dewatered coal formations is an established commercial process. Enhancement of that process by injection of nitrogen is underway as a commercial-scale pilot program at BP's Tiffany Field in Colorado. Research has shown that flue gas injection enhances methane production while adsorbing carbon dioxide onto the coal. There are several research projects underway to extend the concept to CO₂ sequestration. Among others, Alberta Research Council investigators are studying the use of mixtures of CO₂ and nitrogen in CBM recovery. The concept is that flue gas from an electricity generation plant could be injected without processing into a CBM reservoir. The recovered mixture of methane and CO₂ could be fed directly to a combustion turbine in an integrated electricity generation / CBM recovery process. Preliminary model studies have shown that CO₂/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 CO₂ to nitrogen is economic. Economic analysis to determine the carbon emissions reduction credit necessary to make the process economically viable is needed.⁸

Work Group Reports

A major objective of the Informational and Public Forum meeting was to gather ideas and suggestions for further development by CCP.⁹ Breakout sessions challenged the workshop participants with 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 CO₂ capture and geologic sequestration by 2006.

The Work Groups addressed the following topics:

- CO₂ Capture and Separation via Post-Combustion Methods
- CO₂ Capture and Separation via Oxyfuel
- CO₂ Capture and Separation via Pre-Combustion Decarbonization
- Maximizing Sequestration in Oil Reservoirs
- Measurement and Verification of Safe Storage
- Incentives, Emissions Trading, and Public Policy

CO₂ Capture and Separation via Oxyfuel

This Work Group considered gas and steam turbines in new and retrofit applications. They identified the following concepts that could be developed in the next 1-3 years.

- O₂/CO₂ Boiler is a boiler system burning natural gas or oil that uses oxygen for combustion tempered by recycling flue gas to maintain furnace temperatures at acceptable levels.
- Pressurized boiler with CO₂ Turbo expander: A pressurized boiler generating steam operating on O₂/CO₂ firing with a CO₂ turbo expander to recover energy

from the hot exhaust gas which can be used to drive the compressor or produce electricity.

- Retrofit Heat Recovery Steam Generator (HRSG) with supplemental oxygen firing to raise flue gas CO₂ concentration: retrofit concept for existing gas turbines with waste exhaust heat recovery in a Heat Recovery Steam Generator (HRSG). Additional gas is fired, using O₂/CO₂ combustion to provide a flue gas that is essentially CO₂ and water vapor.
- Direct oxyfuel fired high-pressure steam generator: This concept burns gas directly with oxygen and uses water injection to cool exhaust gas and to generate steam at high pressure so that the resulting steam/CO₂ mixture can be expanded through a turbine to generate electricity. The steam is condensed leaving the CO₂ ready for injection.

Two concepts requiring long-term development were suggested. These include an O₂/CO₂ turbine and an oxygen generation system based on an ion transport membrane rather than the conventional cryogenic oxygen separation process. It was estimated the development of an O₂/CO₂ turbine would cost \$1 billion. The near-term options have low fuel efficiency (and as a result low net carbon sequestration) compared to the longer-term options.

CO₂ Capture and Separation via Post-Combustion Methods

This group limited its considerations to carbon dioxide separation in the combustion product composition range (3% - 12% by volume) and did not consider sulfur or other flue gas components. The Work Group believes that improvement of amine separation technology should be a near-term focus. Specific R&D areas include:

- Optimization and integration
- Contactors,
- Improved solvents.

Integration of combustion processes with amine separation is seen as an opportunity to take advantage of the waste heat of combustion to provide energy for the amine-CO₂ separation. A full system scenario was recommended to facilitate investigation of the full benefits of systems integration. It was also asserted that significant cost savings could be realized by choosing design specifications appropriate to the operation and to not over-design the equipment. For example, a low-pressure operating environment requires less stringent standards for welds.

Contactors are the largest cost and size item in the separation plant. Reduction of column size or changes in the type of contactor used will have significant impact on capital and operating costs.

Improved solvents with lower energy per tonne of carbon dioxide captured are needed. These might allow flash separation versus steam stripping) while providing less solvent loss per tonne through reduced sludge formation and fugitive emissions. Reduced corrosivity in an oxidative environment would also be a great benefit. Better solvent stability that allows higher temperature operation would provide a cost savings through reduced flue gas cooling requirements. IGT, Mitsubishi (MHI), ABB and others have

performed extensive research into new adsorbents and have new products with improved performance.

The Work Group recommended R&D on advanced CO₂ capture and separation systems such as electric swing adsorption, membrane separation, carbon dioxide hydrates, and cryogenic condensation.

Several hybrid combustion and separation concepts were suggested. Exhaust gas recycle or partial oxygen firing gas turbine system to raise the CO₂ concentration would decrease the flue gas volume handled dramatically. On the other hand, it was noted that only the absorber size would be affected while the desorber and amine circulation system costs are controlled by the amount of CO₂ captured. A multi-stage capture process in which a membrane system followed by an amine system to increase recovery was suggested.

An integrated separation/sequestration concept was proposed. CO₂ is separated from flue gas by forming carbon dioxide hydrate. Bechtel is investigating CO₂ capture from flue gas via hydrate formation. The concept is amenable to the North Slope because of the low Arctic temperatures. The hydrate would be slurried in water for injection into the reservoir where they decompose and release the CO₂ to enhance oil recovery and be sequestered underground.

CO₂ Capture and Separation via Pre-Combustion Decarbonization

Pre-combustion decarbonization produces a hydrogen-rich stream that is fed to an electricity conversion process. The hydrogen-rich stream would be produced by reformation or gasification of a fossil fuel. There is some overlap with the oxyfuel approach because both would benefit from an advanced oxygen generation technology (e.g. ITM).

In the near term, the Work Group recommended flow-scheme optimization and integration. Specifically, the reformer and HRSG could be heat integrated. Separation of CO₂ from the hydrogen-rich stream is a markedly different separation task than in post-combustion systems. The process should be optimized with respect to CO₂ pressure and percent CO₂ recovered.

In the long term, the largest cost impact could be achieved by replacing combustion turbines with fuel cells for electricity generation. Medium impact, long term areas for R&D include: gas turbines specifically designed hydrogen firing, advanced CO₂ removal processes, high-efficiency reformer systems, inorganic membranes, and compact heat exchangers.

Maximizing Sequestration in Oil Reservoirs

This topic seeks to maximize CO₂ sequestration in oil reservoirs while maintaining or enhancing oil production. This is the opposite of the current imperatives in EOR applications. CO₂ is a purchased commodity so operators seek to maximize the production of oil per unit of CO₂ injected which minimizes the amount of CO₂ sequestered.

The Work Group identified some short timeframe projects that could have high impact.

Improve the fundamental understanding of the sequestration process by conducting laboratory evaluations to optimize purity and composition requirements in the target reservoirs. Background information should also be gathered from existing EOR floods and naturally occurring CO₂ reservoirs.

Minimizing the amount of water injected into the reservoir before starting CO₂ injection. Water and CO₂ compete for space in a reservoir. The conventional reservoir management approach is to follow primary production with a waterflood and finally CO₂ flood. It is speculated that initiating CO₂ injection in the earlier stages of a reservoir production could improve production and also sequester much more CO₂. It is possible that enhanced imaging technologies could enable better characterization of the reservoir and enable early injection of CO₂.

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, public, and NGO’s must be engaged early on in the development of measurement and verification systems.

The Work Group also suggested a focus on carbon dioxide sweep improvement through the reservoir by viscosifiers, miscibility enhancers, and enhanced CO₂ 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 long-term area.

Measurement and Verification

There are many different stakeholders associated with carbon dioxide capture and sequestration projects. The repository operator, regulators, scientific community, and the public have different views on what is important with respect to monitoring and verification of safe storage. Stakeholders will undoubtedly question the amount of CO₂ that is actually captured and stored. Credible, traceable, and standardized measurements are essential to satisfy these groups. Further, an emissions trading credit system will require auditable measures for material transferred between seller and buyer. Challenges include defining net sequestration (accounting for losses and emissions associated with capture and sequestration activities) and monitoring leaks from both surface facilities and subsurface structures.

A firm understanding of the potential subsurface migration of CO₂ and communication of that understanding to the public is essential to address concerns about the safety and long-term stability of injecting a buoyant gas, CO₂, underground. It is important to be able to predict the impact of CO₂ 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 CO₂ and coal, brine, and minerals as well as better subsurface property measurements.

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 CO₂ 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 things change. Other areas where industry can get involved in incentives-related policy are to engage politicians and others to gain favorable recognition of voluntary CO₂ emissions reductions actions and to provide input to analyses of various tax incentive options.
- **Barriers:** There are few regulations pertaining to carbon dioxide sequestration in geologic structures 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 CO₂ repositories is consistent with the degree of risk they pose.
- **Direct R&D Funding:** There are high-risk / long-term R&D concepts within the carbon 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.
- **Crosscutting:** Industrial companies that are 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. 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.

Participant Focus

The CCP formally began in March 2000 with seven members and has grown to nine. The Executive Board authorized simultaneous activities to bring the project together quickly. A key action was to narrow the focus to ensure that participant business needs were met and that the program could be accomplished.

Technology Selection Process

The Public Forum and Participant activities generated numerous ideas for examination in the Review & Evaluation Phase that fed into the Analysis Phase that has just been completed. This evaluation process (Figure 2) reduced the number of topics for further study in the Technology Development Phase. Each technology selection decision reduces the number of options to be studied. Unique to this process is the continual re-evaluation of dropped technologies over time. The team members are keenly aware that the carbon dioxide mitigation technology is embryonic and growing rapidly. As our knowledge matures, technologies that didn't appear to have merit may become important as new information becomes available.

Figure 2 - Technology Selection Process Decision Flow

Ultimately, the CCP hopes to identify a small number of full system-based technologies that will serve in many different industrial applications. Ideally, there would be a single favored technology that could be applied broadly with enormous economy of scale and reduction of costs for carbon dioxide mitigation. Realistically, we believe that each of the combustion technologies we are evaluating will have application in niche markets. The technology selection process initially expanded the universe of ideas and then reduced them to manageable levels in succeeding stages. Figure 3 shows the effect of each stage in the CCP on the technology selection process.

Figure 3 - Selection of Technology Options

Narrowing the Scope

Carbon dioxide sequestration will affect all human activities. The U. S. DOE recently completed a road mapping study of carbon sequestration that details all known mitigation technologies and anthropogenic carbon dioxide sources. World governments are addressing many of these technologies through research and development activities.

We recognize that there are many potential pathways to mitigating carbon dioxide emissions and believe that all viable methods will be necessary to meet the challenge. The CCP cannot address all potential technologies so the scope of CCP was narrowed to meet the business needs and to use the expertise of participants.

The focusing process attempts to answer these questions:

- What is already known? – *The Review & Evaluation Phase*
- What will be further developed? - *The Analysis Phase*
- What technologies or tools are needed? - *The Technology Development Phase*
- Where and how will a technology be applied? – *Favored Technology Design*
- What are the objectives – what does success look like? *Goals set.*
 - 50% reduction in costs for retrofit applications from a current baseline.
 - 75% reduction in costs in new builds from a current baseline.

Figure 4 summarizes carbon-based combustion processes used in industry and highlights the full cycle of carbon management. A carbon-based fuel (gas, oil, wood, coal, etc.) is combusted to produce heat energy for use. Carbon dioxide must be separated from the other waste products, processed, transported, and ultimately stored.

Figure 4 - Carbon Management Cycle

CCP has chosen to limit its work to the areas in which the participants have expertise and can contribute strongly. Initial estimates suggest that about 75% of the costs will be in separation and capture operations. Compression and transportation of large quantities of carbon dioxide are commercially available and are well developed. Geologic storage is believed to hold the greatest potential for carbon dioxide storage in

the short (years) to medium (decades) term and is a focus for continued development. Our public forum showed that public policy and regulatory framework needs development. Biofixation, food industry uses, chemical feedstock development and ocean storage are outside the expertise of the participants and outside the scope of CCP.

Scenario Development

Most studies concentrate on part of the carbon management cycle not the whole system necessary to capture, separate, transport, store, and monitor carbon dioxide safely. Reports from the literature are sometimes confusing because they are not directly comparable and don't allow generalizations to be made on the potential of technologies. This view led the CCP to develop the common economic model concept that includes all the carbon dioxide mitigation steps in business-based scenarios. A complete scenario for a particular fuel/oxidant system will include all the operations necessary to:

- Capture the carbon dioxide from the combustion process,
- Separate it from other stream components (water, particulates, and other gases,
- Process it for further handling (cooling and compression)
- Transport it to a storage site (pipeline, truck, ship, etc.)
- Process it for long-term storage or use (distribution, injection, etc.)
- Provide for monitoring to assure the public and regulators that the carbon dioxide is safely stored for the required period.

The scenarios are controlled by fuel type, combustion method, and availability of suitable storage sites. Fuel choice affects both the combustion and separation technology choices. The scenarios were chosen to account for the common industrial fuels: natural gas, liquefied petroleum gases (propane, etc.), liquid hydrocarbons (fuel oil), petroleum coke, and coal. Other fuels such as wood or waste material make up a small fraction of industrial fuels and hence were not specifically considered.

Separation technologies can be matched to the fuel type and plant configuration. The program will evaluate the logical separation technologies to work with the fuel type and equipment configuration. Direct and indirect fired heaters, steam generation, and turbines are represented. Stationary internal combustion engines for shaft power or electricity generation are a relatively small fraction of power units used within our industry.

CCP is limiting its studies to geologic storage of carbon dioxide rather than other storage options. The participants are familiar with handling carbon dioxide in geologic environments and believe that geologic storage holds the greatest promise for safe storage in the short to middle term. Suitable reservoir types include oil reservoirs, depleted gas reservoirs, coal beds, and saline aquifers. Some are already in use for EOR and for carbon dioxide storage. CO₂ EOR has the greatest potential because of the revenue stream that may offset the costs of carbon dioxide capture and transportation through enhancement of oil recovery from the reservoir. Carbon dioxide injected into coal beds is believed to enhance production of natural gas adsorbed on the coal. Saline aquifers have great potential as storage sites because of their size and availability; however, in the absence of financial incentives, saline aquifers have lower priority in CCP.

The CCP participants proposed twelve scenarios that represent their operations in which they could be expected to mitigate carbon dioxide. The twelve scenarios are summarized in an Appendix to this report. CCP has maintained the principle of applicability to real operations as a critical criterion for selection. Four scenarios (Table 1) were selected to represent participant operations.

Table 1 - CCP Scenarios

Scenario	Fuel Source	CO ₂ Source	Geologic Sink	Location
Refinery	Hydrocarbon Gas & Liquids	Heaters & Boilers	Offshore EOR	European Refinery
Very Large Gas Turbines	Natural Gas	Large Electric Power Generation (CCGT)	Saline Aquifers Offshore EOR	Western Norway
Distributed Gas Turbines	Natural Gas	Small Distributed turbines	Onshore EOR	Alaska North Slope
Gasification	Solid gasification	Steam, H ₂ & Electricity Cogeneration	Onshore EOR	Western Canada

The scenarios continue to be refined to meet the business needs of the participants and the interests of the funding agencies. A fifth scenario based on coal and coke firing of steam boilers for electricity generation with coal bed storage was seriously considered because of its importance to the electricity generation industry. Participants decided that CCP did not have sufficient resources to manage five major scenarios and that the technologies being developed for other scenarios should be applicable to the solids-firing industry.

Common Economic Model

“The trouble with economics is the need for accurate information for investment decisions in the absence of experience.” Business decisions hurdles are set to account for the perceived investment risks. Carbon dioxide mitigation faces extreme challenges because there are few commercial markets and there is a highly uncertain regulatory environment. High quality estimates of carbon dioxide mitigation costs are necessary for commercial scale implementation. The Common Economic Model (CEM) is intended to provide comparisons of diverse technology options on a consistent basis.

The CEM is a rigorous spreadsheet-based tool written in Microsoft Excel and available to CCP participants for their use. The CEM Team will oversee its use for making decisions regarding CCP objectives to maintain integrity of the model and ensure consistent use among the various scenarios and technologies. The main purposes for the CEM are to:

- **Measure progress towards achieving CCP cost reduction goals.** The CCP has established a goal of reducing the cost of capture and geologic storage of CO₂ by a factor of 50% for existing facilities and 75% for new-build facilities

relative to the cost of currently available (amine scrubbing) technology. To do this, cost and performance estimates will be prepared for uncontrolled, baseline (amine scrubbing), and new CO₂ capture technologies for the scenarios agreed-to by the CCP Participants. For each of these discrete cases, the CEM will compute capture economic metrics such as:

- . \$/MW-hr
- . Tonnes CO₂/MW-hr

Figure 5 shows how the 'percent reduction in cost' is computed. The 'cost per tonne of CO₂ avoided' is the slope of the line between a control case and an uncontrolled case.

- **Identify the most leveraging factors to focus R&D investment.** Many factors influence the 'cost per tonne of CO₂ avoided'. Input to the CEM includes capital and operating cost components, fuel consumption, plant availability, and operating efficiencies. The model will be able to perform sensitivity analysis to see which input variables have the greatest influence on the economic metrics. This will give the technical teams important feedback on where they should focus their efforts to achieve the greatest cost reductions.
- **Evaluate impact of policies and incentives.** The CCP may wish to evaluate the impact tax policies and other incentives have on the cost of geologic storage. The CEM enables modeling of taxes, tax credits, and trading credits to see how changes in these variables impact relative economic performance. Currently, the CEM models the cost of CO₂ capture from combustion sources.

Figure 5 - New Technology Comparison

The CEM is also a decision making tool to guide technology selection decisions in the context of the Technical Assurance Process (TAP) and to measure and report progress towards goals. It is not an optimization tool designed to select the best technology for a particular application. Currently, the CEM models the cost of CO₂ capture from combustion sources using the schematic shown below in Figure 6. It does not yet include the impacts of storage (which include additional costs and/or income from ECBM or EOR). Storage will be incorporated into the model in 4Q2001.

Figure 6 - Common Economic Model Schematic Basis

The model compares a specified combustion plant in three configurations:

- **Uncontrolled:** The basic combustion system with **NO** carbon dioxide controls or collection systems.
- **Baseline:** The specified combustion system with a baseline amine separation and capture system attached to the unmodified system flue gas exhaust.
- **New Technology:** The specified combustion system with the modifications and expected performance of the technology being evaluated.

The model inputs include: capital expense (CAPEX), operating expenses (OPEX), plant performance efficiency, income streams from sale of any products generated, taxes, and incentive effects. Table 2 shows the detailed inputs used in the CEM model. The results are consolidated and presented in graphic form (Figure 6) and in tabular form (Table 3).

Table 2 - Hypothetical Example Input Information

	Units	Uncontrolled	Baseline	New Technology
Net Present Value	\$MM	(\$0)	\$0	(\$0)
Net Power/Heat Exported	MW-hr	17,664,000	13,248,000	14,352,000
Net CO ₂ Emissions	Tonnes	6,624,000	1,218,816	900,864
Cost of Electricity/Shaft Horsepower	\$/MW-hr	41.4	74.5	62.5
CO₂/MW-hr Emissions to Atmosphere	Tonnes/MW-hr	0.375	0.092	0.063
CAPEX:				
Fuel Conditioning CAPEX	\$MM			
O ₂ Generation CAPEX	\$MM			
H ₂ Generation CAPEX	\$MM			
Power/Heat Generation CAPEX	\$MM	(50)	(50)	(50)
CO ₂ Capture and Separation CAPEX	\$MM		(20)	(10)
CO ₂ Compress. CAPEX	\$MM		(10)	(9)
Amine Regen. CAPEX	\$MM		(4)	(2)
CO ₂ Treating CAPEX	\$MM			
CO ₂ Metering CAPEX	\$MM			
Plant Performance				
Gross Power Imported (1)	MW-hr/yr			
Gross Elect. /Shaft Power Generated (2)	MW-hr/yr	800,000	800,000	800,000
Gross Elect. /Shaft Power Consumed in Plant (3)	MW-hr/yr		(200,000)	(150,000)
Heat Exported (5)	MW-hr/yr			
CO ₂ from Heat/Power Generation (8)	Tonnes CO ₂ /yr	300,000	300,000	300,000
ant Heat Rate	Mmbtu /MW-hr	9.0	9.0	9.0
CO ₂ Capture Efficiency (% CO ₂ Removed)		0%	85%	90%
Availability of CO ₂ Capture Plant		96%	96%	96%
Availability of Power Generation Plant		96%	96%	96%
OPEX:				
Fuel Cost	\$/mmbtu	(2.00)	(2.00)	(2.00)
Imported Electric Power Cost	\$/MW-hr	(41)	(75)	(62)
Value of Exported Heat	\$/MW-hr	40	40	40
Utilities:				
Water	\$MM/Yr			
Instrument & Plant Air	\$MM/Yr			
Other	\$MM/Yr	(1)	(3)	(2)
Catalyst, Chemicals, and Consumables:				
Fuel Conditioning, H ₂ and O ₂ Generation	\$MM/Yr			
Power/Heat Generation	\$MM/Yr			
CO ₂ Capture, Compression, Treating, Metering	\$MM/Yr		(2)	(1)
Operating Labor:				
Fuel Conditioning, H ₂ and O ₂ Generation	\$MM/Yr			
Power/Heat Generation	\$MM/Yr	(5)	(5)	(5)
CO ₂ Capture, Compression, Treating, Metering	\$MM/Yr		(1)	(1)
Maintenance (labor, equipment, parts):				
Fuel Conditioning, H ₂ and O ₂ Generation	\$MM/Yr			

	Units	Uncontrolled	Baseline	New Technology
Power/Heat Generation	\$MM/Yr	(5)	(5)	(5)
CO ₂ Capture, Compression, Treating, Metering	\$MM/Yr		(1)	(1)
Miscellaneous:				
Emissions Imported Power	Tonnes CO ₂ /MW-hr	0.375	0.092	0.063
Discount Rate (Real)		10.0%	10.0%	10.0%
Tax:				
Tax Rate		40%	40%	40%
Investment Tax Credit		0%	0%	0%
Property Tax		1%	1%	1%
CO ₂ Emissions 'Tax'	\$/tonne			

Table 3
Hypothetical Example Results

Case Summary	Tonnes CO ₂ /MW-hr	\$/MW-hr
Uncontrolled	38	\$41
Baseline	0.09	\$75
New Technology	0.06	\$62

Cost of Abatement		\$/Tonne CO ₂
Uncontrolled -> Baseline		\$(117)
Uncontrolled -> New Technology		\$(67)
Cost Reduction Achieved		-42.4%

Notes:

- *Cost reduction is the percentage difference in Cost of Abatement.*
- *Negative is a cost reduction, positive is a cost increase*

The current CEM model was brought to its current level of development to address capture and separation as a first priority in the CCP project. The next steps in CEM development are:

- Engage recognized CO₂ economic evaluation experts as CEM advisors to:
 - Provide assurance that the model is technically correct
 - Improve model interface and integrity
 - Compare to other methodologies.
- Incorporate carbon dioxide storage costs / benefits.
- Review value of an optimization model for capture and storage projects and recommend the way forward

Review & Evaluation Phase (March – July 2000):

The Review and Evaluation Phase was established immediately after the formation of the CCP and ran concurrently with the Participant Focus work. Four **R&E teams**, comprising staff members from the seven founding Participant companies, investigated the following areas:

- Post-combustion capture of CO₂
- CO₂ capture via the Oxyfuel route
- Pre-combustion decarbonization
- Sequestration, Monitoring and Verification of CO₂

The R&E Phase did groundwork for **Technology Teams**, which would then execute the technology development through the rest of the project. Thus the **R&E teams** had the following objectives:

- Define the state of the art for each area
- Develop statements of requirement for each Technology Team
- Develop a process to identify novel technologies
- Assess resource requirements for each Technology Team
- Involve technology providers
- Review Participants' offerings for applicability to the work of the CCP
- Make recommendations to the Board on the above

Their report¹⁰ is summarized below:

R&E Phase Recommendations:

The Executive Board approved these recommendations:

- An Analysis Phase should commence immediately.
- Four Technology Teams be established in addition to the existing Common Economic Model team.
 - Oxyfuel combustion & capture
 - Post-combustion capture of CO₂
 - Pre-combustion decarbonization
 - CO₂ Storage

R&E Phase Technology Selection Processes

This section presents the technology selection processes used by the four R&E teams, which include:

- Ranking of technology in each study area
- Ranking of technologies across team boundaries
- Novel technology selection

The work of the teams was presented with the caveat that it was not a perfect view of the status of the technologies. However, it was a solid enough foundation for the Technology Teams to start with. The CO₂ capture teams are agreed that no one capture technology area can be shown to be inherently superior to the others and that all three areas should be pursued until enough information can be assembled to allow a clear choice.

CO₂ Capture Technology Ranking

Towards the end of their work the R&E capture teams began to grapple with the issue of comparing technologies and developed a Boston Square process. The ranking considered the following factors:

- Potential capture cost reduction
- Materiality: the extent to which the technology would have significant impact on CCP objectives and that the technology could be applied to the proposed CCP Scenarios
- Likely cost to the CCP
- Timescale for development, which reflected complexity.

Each team used the ranking criteria to priorities their particular technologies but there was not time to develop the process sufficiently to allow cross technology area comparisons.

Novel technologies

The R&E teams were able to find and analyze data on “what we know.” They agree that more effort was needed in the area of “finding out what we don’t know.” CCP needs to stimulate novel technology development. To facilitate this, a four-pronged approach was proposed:

- A workshop for technology providers to encourage novel thinking.
- An ideas competition with cash prizes.
- Announcements in trade and learned journals
- Novel Idea Page on the CCP website

Technology Team Reports

Oxyfuel

The **principle of CO₂ capture by oxyfuel** technologies is to burn fuel with oxygen instead of air, so that the flue gas consists mainly of CO₂ and water with few contaminants. These processes usually propose recycle of part of the flue gas to the burner to act as a substitute for nitrogen from air. Other approaches such as higher temperature designs or recycled water injection may be possible. Earlier studies, including pilot scale testing on coal, indicate that oxyfuel combustion with flue gas recycle could be retrofitted to boiler and other heating plants with no major technical obstacles. However gas turbines would require relatively costly development of new combustors, compressors to handle the change in working fluid. These studies showed that the major additional capital and operating costs in the oxyfuel route are

associated with oxygen production. Development costs for modified boilers, heaters, and gas turbines would add to the capital cost as the vendors recover their development costs.

CCP should support development of lower cost oxygen production methods, relevant combustion retrofit boiler and heater technologies and integration of the new oxygen technologies directly with combustion systems. Other opportunities seek to take advantage of the distinctive oxyfuel characteristics to conceive power plants with higher efficiency and/or lower capital cost that offsets oxygen separation costs. One technology proposed, chemical looping, is a novel, potentially energy saving, process that combines air separation with fuel oxidation.

No oxyfuel technologies have been demonstrated on a commercial scale for CO₂ capture and therefore there is no existing oxyfuel technology against which to assess cost reductions for new approaches. However, most studies suggest that overall capture costs for the oxyfuel flue gas recycle techniques would be comparable with those for existing post-combustion capture methods. While oxyfuel combustion is not currently used for CO₂ capture, it should be noted that combustion in pure oxygen or in oxygen enriched air in special high temperature furnaces is widespread in the metallurgical, glass and other industries, and therefore the operational and safety issues of oxygen combustion are well understood.

The Oxyfuel Review and Evaluation Team identified the following technologies as having the potential to offer reduced CO₂ capture costs. Detailed discussions of the technologies and their potential are reported in the Oxyfuel R&E Phase report published separately. In provisional priority order:

- A. **Advanced high efficiency gas turbine cycles with water injection.** Long term development that exceed CCPs timescale but may have high potential benefits.

Application: New-build plant in both gas turbine scenarios.

Possible capture and compression cost reduction: 65%.

Timescale: Critical technology developments 2003.

Full-scale prototype 2010.

CCP cost: ~\$1million.

Potential developers: Boeing Rocketdyne

ANO

SINTEF

- B. **Boilers/heaters with flue gas recycle.** Lower risk technology with wide potential application to furnace equipment. Cost savings will come from process integration and from new oxygen separation processes.

Application: Retrofit or new-build in both the refinery and the solid-fuel boiler scenarios.

Possible capture and compression cost reduction: 25%.

Timescale: Enabling technology developments 2002. Demonstration plant 2003.

CCP cost: <\$250k.

Potential developers: Mitsui Babcock (UK)

Air Products (UK/US)

C. Ceramic membrane oxygen production – integration with combustion.

Concepts for boilers and gas turbines integrate ceramic membranes with combustion to reduce oxygen separation costs still further with high potential benefits.

Application: New-build plant in the gas turbine and refinery scenarios (possibility of retrofit with one gas turbine proposal).

Possible capture and compression cost reduction: 40-60%.

Timescale: Critical technology developments 2003.

Full scale demonstrations 2010.

Cost to CCP: ~\$2m.

Potential developers: Praxair (US)

Alstom Power (Europe/US)

Norsk Hydro (Norway)

D. Chemical looping. Novel technology in the laboratory stage. Worth evaluating as the efficiency gains could be high.

Application: New-build plant in the gas turbine and refinery scenarios.

Possible capture and compression cost reduction: 45% or more.

Timescale: Concept development and engineering 2003.

Full scale demonstration 2007.

Cost to CCP: <\$250k initially. ~\$1m if progressed.

Potential developers: Chalmers University, Sweden (Europe)

E. Combined cycle gas turbine with flue gas recycle. This technology would benefit from reduced oxygen costs but requires costly gas turbine development.

Application: New-build plant in the gas turbine scenarios.

Possible capture and compression cost reduction: 25%.

Timescale: Full-scale demonstration 2004 if progressed quickly.

Cost to CCP: <\$1m (turbine development much greater – would need separate funding).

Potential developers: Aker Maritime

Gas turbine vendor

Oxygen vendor

F. Zero or low recycle boilers. Capital cost reductions likely from the reduced boiler size are not clear; however, the concept is being promoted by at least one boiler vendor.

Application: New-build plant in the refinery and solid-fuel boiler scenarios.

Possible capture and compression cost reduction: 35%.

Timescale: Demonstration plant 2005.

Cost to CCP: ~\$1m.

Potential developers: Alstom Power (US/Europe)

Praxair (US)

G. High-pressure boilers. The cost savings from reduced boiler size and reduced CO₂ compression costs are not yet clear.

Application: New-build in the refinery and solid-fuel boiler scenarios.

Possible capture and compression cost reduction: 35%.

Timescale: Demonstration plant 2004.

Cost to CCP: ~\$1m.

*Potential developers: Mitsui Babcock (UK)
SINTEF (review) (Norway)*

Technology ranking used criteria common to all the capture teams. These were:

- Potential capture cost reduction.
- “Materiality”, i.e. the extent to which the technology could be applied to the proposed CCP scenarios.
- Likely CCP development cost
- Timescale for development and complexity.

The evaluation was confined to technical and cost issues. It did not address intellectual property issues although these are noted where raised. Some technologies cannot be fully evaluated until confidentiality agreements are signed.

Post-combustion capture of CO₂

State of the art: Post-combustion capture of CO₂ has been practiced on a commercial basis for over twenty years. However, when compared to the scale envisioned for commercial CO₂ storage the existing plants are too small by 10 to 100 times. The successful processes are based upon chemically absorbing CO₂ into primary amines with subsequent heating to release it. Based upon 1999 studies by Statoil and BP, two vendor processes could be regarded as state of the art – Fluor Daniel’s Econamine FG process and Mitsubishi’s KS-1 process.

Technologies for further development: The team has grouped its recommendations into those which are improvements on existing processes, where the benefit is quite well understood, and those where it is thought there will be good benefits.

Three improvements to existing post combustion separation technologies are recommended in priority order:

1. Kværner membrane contactor technology, enhanced by sterically hindered amines, with a potential 50% cost reduction. Development cost \$2 to 4 million.
2. Development of Mitsubishi Heavy Industries (MHI) technology, combined with extensive simplification of design standards, with a potential reduction cost of 45%. Cost \$1 to 2 million.
3. Development of Fluor Daniel (FD) technology, enhanced with MHI technology and simpler design standards. Potential cost reduction – 40%. Cost \$1 to 2 million.

New technologies for which the team has not yet estimated benefits or development costs are recommended:

1. Oak Ridge National Laboratories (ORNL) electrical swing adsorption (ESA) technology.
2. Norsk-Hydro’s radical exhaust channel treatment technology.

Discussion:

Chemical post-combustion separation using amine solutions is currently the commercial CO₂ capture process for food and chemical use. The current cost of post-combustion CO₂ capture and compression is high. An estimate given in a recent IEA Greenhouse Gas R&D Programme (IEA GHG) report estimates that the electricity cost from a 663 Mwe Combined Cycle Gas Turbine (CCGT) power station would increase by 45%, if CO₂ were to be captured and compressed to 110 bar. Post-combustion capture of CO₂ costs for the oil and gas industry are difficult to estimate because they are highly dependent on local conditions. The Post-combustion R & E team pooled its own knowledge and obtained information from a long list of technology providers. The following recommendations for further study are based on the knowledge available and must be reviewed continuously. The top 3 existing post combustion separation technologies are recommended in the following sequence according to priority:

Significant reductions in global CO₂ emissions will require step change technologies that radically reduce the costs, reduce the parasitic energy requirements, and solve problems related to undesirable side effects such as degradation of monoethanolamine. The R&E Post Combustion report, published separately, includes three main sections: - a Technology Overview, Existing Technology with suggestions on improvements, and Novel Technology. Each section includes detailed recommendations for further study by the technology teams. The R&E report appendices include details on technology providers, letters sent to existing and new technology providers, their responses, technology evaluations, Boston squares for new and existing technologies and estimates of resource requirements required to carry out the proposed program.

Technology Overview

Separation, capture, and compression of CO₂ are estimated to represent about 75% of the total cost of geologic sequestration. Among the largest point sources of CO₂ are: power plants (coal-fired and natural gas-fired), production of pipeline-quality natural gas, and industries such as oil refining, iron/steel plants, and lime/cement plants. Many options for CO₂ capture exist, although none has yet been applied at the scale needed for sequestration (billions of tons/year by 2025).

Chemical and physical absorption are the most common technologies used because CO₂ is usually recovered from dilute gases at low to moderate pressure. Only chemical methods (aqueous solutions of MEA) are currently used for CO₂ removal post-combustion. Companies currently selling commercial plants are Fluor Daniel, ABB Lummus and MHI. Combustion gases containing CO₂ also include other components include H₂O, NO_x, N₂, O₂, and SO_x that must be considered. The CO₂ purity requirement for sequestration is uncertain and may represent an area for cost improvement.

Existing technologies for CO₂ capture are tabulated below:

TECHNOLOGY	TYPICAL CO ₂ FEED	CRITICAL ISSUES	FUTURE R&D NEEDED TO FILL GAPS	EXAMPLES OF INDUSTRIAL USE
Absorption, Chemical (E.g. MEA)	Partial pressure 3.5-17 kPa	Energy penalty for regeneration Need pretreatment for other acid gases	Novel solvents with high capacity for CO ₂ And low desorption energy requirements. New contacting devices	Removal of CO ₂ to upgrade nat. gas Removal of CO ₂ from flue gas
Absorption, Physical (E.g. cold methanol, glycols)	Partial pressure > 525 kPa	Need to optimize regeneration (e.g., number of flash stages)	(Same as above)	
Adsorption, PSA/VSA (zeolites)	High pressures	Adsorbents tend to have low capacity/selectivity Restricted to low temperature CO ₂ product is impure, and delivered at low pressure	New adsorbents that adsorb CO ₂ in presence of water vapor New adsorbents / desorption methods to get pure CO ₂ product	Removal of CO ₂ for H ₂ production Removal of CO ₂ to upgrade nat. gas
Adsorption, TSA		Energy penalty for regeneration Long cycle times (hours)	(Same as above)	
Cryogenic Distillation	High pressure and purity (90+%)	Refrigeration < 0°C needed Pretreatment for impurities that freeze above operating temp. (E.g., H ₂ O)	Integration with sequestration processes Efficient refrigeration cycles	CO ₂ liquefaction from gas wells
Membranes, Inorganic (ceramic, Pd)	High pressure	Much lower area per unit volume than polymeric membranes	Develop membrane devices for fuel reforming with simultaneous H ₂ /CO ₂ separation	
Membranes, Polymeric	High pressure	Low CO ₂ selectivity (selectivity vs. permeability tradeoff) Degradation issues	New synthesis methods Modeling efforts to establish CO ₂ removal potential	

Emerging Technologies

Below are examples of new technologies that have potential for CO₂ capture. Among these, electrical swing adsorption (ESA) appears to be the most promising in terms of economics and energy-efficiency.

Technology	Description	Critical Issues
Chemical-Looping Combustion (a.k.a., Sorbent Energy Transfer)	Fossil fuel transfers energy to reduce a regenerable metal oxide, producing steam and high-pressure CO ₂ . Being studied by Oxyfuel team.	Barriers to new combustion system are "legion"
CO ₂ Hydrate Formation	CO ₂ is trapped in ice-like solids by injection into water at high pressures (0°C, 1-7 Mpa)	Pressures (1-7 Mpa) are too high for CO ₂ separation from exhaust gases (~1 atm)
Electrical Swing Adsorption (ESA)	Gases adsorbed onto activated carbon fiber, desorbed by low-voltage current with little pressure or temperature change	CO ₂ affinity appears low at gas turbine exhaust pressure. Need estimates of bed size, energy requirements, and cost

Existing Technology and Improvements

Two main technologies are available for separation of CO₂ post combustion: absorption and adsorption. Absorption systems for CO₂ from exhaust gas have been installed at about 10 locations. Most of these applications are on coal fired boilers, and one is on a gas turbine system. The capacity range is typically 200-800 te./day. Refrigeration technology is also applied in a few cases, freezing out CO₂ from exhaust gas.

[refer to Supplemental Appendix – Limited Rights Data]

Pre-combustion decarbonization (PCDC)

No commercial process or technology fulfils the requirements set for PCDC; therefore no baseline state-of-the art(SOA) exists. The PCDC team formulated criteria to qualify a technology as a SOA candidate. These principles are widely accepted when applying technology for major process plant based on proprietary technology.

- Technology providers give process guarantees without risk sharing to show that the provider has confidence in the technology offered.
- The technology provider should, to some extent, be able to provide references. This gives the client confidence in the feasibility of the technology.
- The technology shall generally be accepted by consensus of partners.
- The technology shall generally be acceptable to international financing partners. In some cases, the financing partner is a member of the ownership and must have confidence in the technology.

The consequence of the above is that improvements operate in a very narrow frame and that SOA moves very slowly. These criteria usually limit innovation because the unit has to be proven in a similar operation and the maximum allowable scale up is 50%.

CCP has an outstanding position in PCDC technologies. CCP participants operate plants with a total capacity exceeding 4,000,000 Nm³/h of hydrogen. Some participants provide technology as part of their core activity. Some partners are part of technology alliances where they have a large technology contribution. Finally, most CCP participants have in-house engineering experience in project implementation; execution; cost estimation and technology development for PCDC type plants.

Technologies for further development: The following logical groupings have been identified:

1. Advanced syngas generation
 - An engineering /flow sheeting study to which auto thermal and compact reforming options offers greatest CO₂ recovery cost savings.
 - Topsoe catalyst coated tubes and the Shell Flameless Distributed Combustion should be evaluated as novel concepts.
2. Very large scale POX/ATR
 - Limits of single train design should be studied with an experienced vendor
 - Lessons learned through recent substantial increases in GTL & methanol plants applied to both POX and ATR.
3. Combined syngas generation and CO₂ separation
 - A targeting study to determine the required performance of membrane reactors to achieve the target cost reduction to provide a research goal for those working in the field.
 - A directed search for researchers in this field should be undertaken to allow those with most promising developments to be identified and contacted.
4. Improved CO₂ separation techniques
 - Hydrogen membranes could radically alter the separation process by condensing CO₂ from a membrane separation stage with ammonia absorption refrigeration that uses waste heat from the syngas process.
5. Hydrogen utilization
 - Catalytic combustion offers the potential to overcome Nox generation in hydrogen combustion and should be studied. Catalytica Combustion Systems offers their 'Xonon ' catalytic combustion technique for gas turbines that can burn fuels at lower temperatures avoiding NO_x formation.
 - Determine the feasibility of retrofit of existing turbines for hydrogen fuelling through vendor studies.

Within these groupings the qualitative benefits of 22 technologies have been identified and a high, medium or low priority for CCP funding been assigned. However, the team wishes to highlight their belief that one technology – membrane reactors – is seen as having potential for significant cost reduction and recommend that this be treated as top priority.

State of the Art (SOA) – Precombustion Decarbonization Technology (PCDC).

PCDC can operate as non-integrated stand-alone PCDC hydrogen plants providing fuel for distributed needs or as an integrated PCDC/power plant. Non-integrated PCDC plants would be those in which the fuel preparation and fuel users are completely separate with hydrogen piped to users for use in steam boilers, refineries, distributed gas turbines etc. An integrated PCDC/power plant operates in an Integrated Reforming Combined Cycle (IRCC). HydroKraft and IGCC (Shell and Texaco are technology providers) are two examples. Air and fuel systems are integrated across the turbine, fuel processor and heat recovery/steam generation sections.

In general a PCDC plant can be divided into three unit operations: hydrocarbon conversion, CO-conversion, and CO₂ removal.

Hydrocarbon Conversion generates H₂, CO, and CO₂ from a hydrocarbon fuel. Steam reforming, partial oxidation, or a combination of both usually does conversion. The technology chosen depends on the feedstock type.

Technology	Description	Fuel Type	References
SMR	Steam Methane Reforming	Natural Gas, Naphtha	Hydrogen, Ammonia
ATR	Autothermal Reforming	Natural Gas	Ammonia, GTL
POX	Partial Oxidation	All types	IGCC, Ammonia, GTL
SMR+ATR	Two-step reforming	Natural gas, Naphtha	Ammonia, Methanol

CO-conversion is the step in which the CO generated in the hydrocarbon conversion section is converted into hydrogen and CO₂ by water gas shift reaction. The predominant method is a two-step approach in which the major conversion takes place at high temperature called high temperature shift (HTS) and final conversion takes place at low temperature called low temperature shift (LTS).

CO₂ removal: The process gas mainly consists of hydrogen and carbon dioxide at the end of the CO-conversion and hydrocarbon conversion steps. Large amounts of nitrogen will be present if air was the oxidant. Traces of unconverted CO and methane will also be present. CO₂ is normally removed by chemical or physical absorption systems, e.g. BASF's aMDEA, Selexol, UOP's Benfield process and Giammarco-Vetrocoke's hot potassium process. These technologies are used in ammonia plants and in combination with gasification plants.

Fuel Users: The consequence of PCDC is a change in fuel characteristics from hydrocarbons to hydrogen. The PCDC team collected information about the use of hydrogen as fuel. In general, steam boilers and fired furnaces can combust nearly 100% hydrogen; gas turbines can accept high concentrations of hydrogen but will generate high amounts of NO_x in the combustor. Up to 60% hydrogen mixtures can be used in gas turbines and still have low NO_x emissions.

Novel Pre-combustion Decarbonization Technologies with potential to reduce the total cost of capture of CO₂ by the pre-combustion route were identified through discussions with vendors, literature search, reference to the Houston Meeting notes, the DOE sequestration technology road-map and from participant in-house knowledge. These technologies are focused on the key process steps for hydrogen production and use, particularly syngas generation and CO₂ separation.

There are a number of developments in both these areas and some which combine both syngas generation and CO₂ /hydrogen separation. The ability to substitute hydrogen for existing fuels is an essential requirement for the precombustion route. Effective utilization without adversely affecting NO_x or other emissions and the reliability of hydrogen gas turbine has not been proven for high purity (>70%) hydrogen.) Opportunities to more effectively use the hydrogen in fuel cells could also be considered.

Novel technologies have therefore been grouped under the following five headings: -

- Advanced Syngas Generation
- Very Large Scale Hydrogen Production
- Combined Syngas generation and CO₂ Separation Systems
- Improved CO₂ separation
- Hydrogen Utilization

Table 4 provides an overview of the technologies considered under each heading, outlining the potential vendors and researchers in the field.

Table 4 - Novel PCDC Technologies

REF	TECHNOLOGY	PROVIDER	LOCATION OF VENDOR (S)	TECHNOLOGY DESCRIPTION AND BENEFITS
ADVANCED SYNGAS GENERATION				
1	ATR/Gas Heated Reformer	ICI/Uhde/ Kellogg/HT	UK/ Germany / Denmark	Combining a Heat Exchange Reformer with ATR to improve efficiency- cuts size of air compressor and all downstream plant
2	ATR/GHR +F/E Heat Exchanger	ICI/Uhde/ Kellogg/HT	UK/ Germany / Denmark	Enhancement of above- with higher efficiency but risk of metal dusting attack due to high CO content of syngas
3	ATR/EXPANDER	AC. /NUOVO PIGNONE	Sweden/Italy	Improves efficiency by generating power or work from syngas expansion – metallurgy questions on the expander
8	PLASMA SYNGAS	SYNGEN TECHNOLOGIES & MIT	USA	Syngen developed a plasma reactor for air partial oxidation of gas or liquid fuels in an electric arc, designed for FT gas to liquids process. – Benefits over conventional ATR are not clear – electrical power consumption
10	COMPACT REFORMER	TOPSOE / BPA-KPT	Denmark, UK or USA	Higher intensity heat exchange in fired reformers giving compact designs and increased efficiency. Offer reduced size and weight of reformer, saving in high alloy steel. Mass produced standardized modular design – cost benefits & for difficult locations
11	CAT COATED TUBES- CR	TOPSOE	Denmark or USA	Potential to further reduce the size of compact reformer designs by increasing heat transfer rates.
12	HIGH PRESSURE ATR	HT/FW	Denmark/USA/UK	Potential equipment size and cost reduction
23	Flameless Distributed Combustion	Shell/Raytheon (Washington Group International)	USA	Novel combustion technology- flexible geometry, can provide a tailored profile of heat flux, and has extremely low Nox emissions, potential for use in partial oxidation and for reformer heating.
VERY LARGE SCALE HYDROGEN PRODUCTION				
4	V LARGE SCALE ATR/(GHR)	ICI/ TOPSOE /FW	Denmark/USA/UK	Achieves capital cost benefit through large scale.

REF	TECHNOLOGY	PROVIDER	LOCATION OF VENDOR (S)	TECHNOLOGY DESCRIPTION AND BENEFITS
18	V LARGE SCALE POX	SHELL TEXACO DESTECH	USA/Holland	POX reactors scale well to large throughput with significant cost advantage over says steam reforming. Single train throughput limits in other equipment e.g. air separation, shift reaction and CO2 separation equipment need to be determined
COMBINED SYNGAS GENERATION/CO2 SEPARATION				
5	MEMBRANE REFORMER	TOPSOE	Denmark, USA	Steam reforming combined with separation of pure hydrogen- favors the equilibrium reaction by removing product achieves high conversion at lower temperature. This eliminates shift stage and reduces the size of the CO2 separation step.
6	MEMBRANE WG SHIFT	PRINCETON, BEND RESEARCH, LOS ALAMOS LABS	USA,	Combined water gas shift reactor and hydrogen separation- similar to membrane reforming but at lower severity – lower benefit as reformer is still required, but lower development cost/risk. Could be developed as a step to membrane reforming.
7	SORBENT ENHANCED REFORMING	AIR PRODUCTS	USA	Uses a mix of high temperature adsorbent and catalyst to combine reforming and CO2 removal into a single stage. The separation favors the equilibrium and allows lower temperature of operation- the unit runs cyclically as a PSA.
9	OTM/ITM OXYGEN TRANSPORT MEMBRANE	AP/PRAXAIR	USA	Membrane air separation system, with potential to deliver oxygen for POX schemes at significantly lower cost. Can be readily integrated into a Gas Turbine scheme using extraction air, giving plant size reduction and efficiency benefit compared to air ATR
9A	ELECTROPOX	PRAXAIR	USA	Integrating ITM into a POX or ATR reactor, where the O2 permeates directly into the reacting zone. The low O2 pp on the process side- maximizes flux/ minimizes air compression requirement. Use of O2 Vs air minimizes downstream equip size & cost
IMPROVED CO2 SEPARATION SYSTEMS				
13	MEMBRANE CO2 CONTACTOR	KVAERNER	Norway	Has been demonstrated in other applications to reduce size and cost of contactor for CO2 absorption.
14	ELECTRICAL SWING ADSORPTION	Oak Ridge	USA	High temperature CO2 Adsorbent – regenerated by electrical ohmic heating
15	CO2 SELECTIVE MEMBRANE	OAK RIDGE	USA	Work on selective membranes for CO2 permeation from syngas, believed to be preliminary – could offer benefit against conventional separation- leaving H2 at higher pressure for CCGT use but at early stage in development – high risk and uncertain benefit
16	HYDRATE CO2 SEPARATION	SIMTECHE	USA	Cooling of syngas to 34 °F at 650-1500 psig is predicted to give CO2 hydrate/ water slurry, allowing 80-92% CO2 recovery by gas/slurry separation. Claimed 50% cost reduction Vs amine system but significant refrigeration & other equipment costs
20	H2 PERMEATION MEMBRANE	UOP, AP , UBE, AL , Praxair	USA	Combining conventional H2 permeation membranes with high press ATR/POX leaves high concentration CO2/H2 mixture that could be combined with cryogenic or other purification methods. Liquid CO2 can be pumped to high pressure, reducing compression cost
HYDROGEN UTILISATION				
21	FUEL CELLS	Shell, Ballard, Westinghouse	USA/Canada/various	Fuel cells could be used to substitute for power generation gas turbines in a distributed turbine scheme with big efficiency benefits, but the capital cost relative to firing H2 is high
22	TURBINE – RETROFIT	Catalytica GE , ALSTHOM, SIEMENS	USA/Germany	This is key to scenarios B and D (and included in A) and is a pre-requisite for pre-combustion decarbonization

There is a wide range of activity in the hydrogen production field. Many researchers and technology suppliers are actively working on systems for hydrogen supply for fuel cells (on-board vehicles and fixed installations), syngas for GTL, methanol and other applications. There are many opportunities for the CCP to incorporate and extend this technology. Many of the developments such as OTM/ITM are already well funded (in some cases partly by CCP participants.) Although the technology is relevant and has high potential, there is little incremental benefit by CCP providing additional research support, but there is a good opportunity to optimize integrated process designs for the new technology at relatively low cost.

There are some areas which are at early stages of development but have considerable potential to simplify the hydrogen generation process by combining reaction and separation, particularly membrane reactors. There is considerable work in the field, but it is widely dispersed and there should be scope to support promising research on the topic. A number of the novel technologies identified in Table 4 have been applied for other processes such as ammonia, methanol or GTL (gas-to-liquids,) but will offer significant benefits in a PCDC scheme, particularly in the syngas generation and CO₂ removal areas. These systems need to be compared on common basis using the CEM in a screening study to select the lowest cost combination of syngas generation and CO₂ removal system. Determination of the benefits of larger scale POX or ATR can be determined in the same exercise, indicating whether work on identifying and overcoming bottlenecks in the single train plant designs should be undertaken.

Table 5 gives an indication of the development needs for each technology showing where any JIP participation should be focused.

Table 5 - Pre Combustion Decarbonization Technology Development Needs

	TECHNOLOGY	DEVELOPMENT AND RESEARCH NEEDS	VENDOR CONTACT STATUS	PRIORITY FOR JIP
ADVANCED SYNGAS GENERATION				
1	Auto thermal Reformer /Gas Heated Reformer (ATR+GHR)	Develop and cost flow schemes for comparison with SOA and other schemes	Topsoe signed up to EU proposal with 15% contribution. Uhde Invited to discuss participation.	HIGH –SCREEN
2	ATR/GHR plus Feed/Effluent Heat Exchanger	Develop and cost flow schemes for comparison with SOA and other schemes- consideration of metal dusting	Topsoe signed up to EU proposal with 15% contribution. Uhde Invited to discuss participation.	HIGH –SCREEN
3	ATR/EXPANDER	Develop and cost flow schemes for comparison with SOA and other schemes	Texaco have some experience	HIGH-SCREEN
8	PLASMA SYNGAS	Demonstration plant currently being commissioned	BP have links with Syngen & MIT but not yet invited to participate	LOW
10	COMPACT REFORMER	Need evaluation in a decarbonization scheme	Kvaerner agreed to participate Topsoe - EU	HIGH –SCREEN
11	CAT COATED TUBES/HIGH SV COMPACT REFORMER	No data yet available from vendor beyond patent- IP concerns but Topsoe have signed up for EU project and this option can be pursued when IP issues resolved & data is available	Topsoe did not offer this technology yet, IP issues to resolve	MED
12	HIGH PRESSURE ATR	Part of flow sheet optimization.	Topsoe	HIGH-SCREEN
23	Flameless D. Combustion	Develop conceptual reactor designs to determine potential benefits	Shell (Not decided if FDC will be available to JIP)	MED – SCREEN
VERY LARGE SCALE HYDROGEN PRODUCTION				
4	V LARGE SCALE ATR/(GHR)	Develop and cost flow schemes for comparison with SOA and other schemes- identify limits to throughput of key equipment items and study debottlenecking techniques to extend single train throughput.	Topsoe, also Kvaerner are willing to participate	HIGH –SCREEN
18	V LARGE SCALE POX	Cost benefits of large scale by engineering study. Study of limitations in single train throughput limits for the key equipment items, with more specific engineering study to show feasibility of larger scale equipment for key items if necessary	Texaco Involved	HIGH-SCREEN
COMBINED SYNGAS GENERATION/CO2 SEPARATION				
5	MEMBRANE REFORMER	Conceptual reactor and flow sheet designs –based on vendor data. Membranes use palladium metal or alloys on ceramic support- need to minimize use of palladium, demonstrate mechanical resilience and develop fabrication method fore large scale.	Topsoe signed up	HIGH – VENDOR EVALUATION
6	MEMBRANE WG SHIFT	As for Membrane reforming	Topsoe signed up to EU proposal with 15% contribution	AND TARGET PERFORMANCE DEFINITION
7	SORBENT ENHANCED REFORMING	Considered by the vendor as more applicable to smaller scale, the adsorbent and conceptual design is done through a DOE funded project, but AP highlight serious valve problems as a barrier to the designs and have played down potential for decarbonization.	AP signed up to EU but are not keen to include SER	MED
9	OTM/ITM OXYGEN TRANSPORT MEMBRANE	Development is fully supported by the two competing consortia; only work required by JIP is study of cost benefits of integration of the technology into decarbonization scheme. Clear overlap with Oxyfuel activities. – See also 9A	AP and PRAXAIR signed up to EU	HIGH

	TECHNOLOGY	DEVELOPMENT AND RESEARCH NEEDS	VENDOR CONTACT STATUS	PRIORITY FOR JIP
9A	ELECTROPOX	Flow sheet evaluation for cost/performance of black-box reactor system. There are gaps –membrane mechanical integrity and fabrication but the program is well funded through GLT consortium.	Praxair signed up but no discussions on Electropox –IP & confidentiality issues	HIGH
IMPROVED CO2 SEPARATION SYSTEMS				
	TECHNOLOGY	DEVELOPMENT AND RESEARCH NEEDS	VENDOR CONTACT STATUS	PRIORITY FOR JIP WORK
14	ELECTRICAL SWING ADSORPTION	No work proposed as system seems to offer little benefit over conventional absorption systems- will be studied in more detail by Post Combustion Team	Post Combustion have approached	LOW
15	CO2 SELECTIVE MEMBRANE	Determine state of development.	No Approach yet on this technology	LOW
16	HYDRATE CO2 SEPARATION	No experimental data available on syngas mixtures until Dec 2000. All the system performance predictions so far are based on model predictions. System could be benchmarked against other separation systems when this data is available to determine benefits	Simteche agreed to collaborate via engineering study	LOW
20	H2 PERMEATION MEMBRANE	This approach is application of proven technology in an engineering evaluation/cost estimation-combination with other systems such as refrigeration/liquification or oxyfuel combustion of residue should be considered	AP & Praxair have proposed membrane work	HIGH – SCREEN
HYDROGEN UTILISATION				
19	HIGH H2 GAS TURBINE	Requirement for this depends on outcome of fuel processor work and should be decided on later in the project	No Approach yet – Hydro have worked extensively with GE	MED
21	FUEL CELLS	Large effort already being made by others, option to replace smaller GT in a distributed scheme could be evaluated at low cost	No approach to date	LOW
22	TURBINE – RETROFIT	Determine limits of operation (hydrogen purity) within emissions (Nox limits); consider Nox abatement techniques where appropriate. Determine any mechanical/metallurgical effects of hydrogen firing and any efficiency loss.	No approach to date	HIGH

Sequestration, Monitoring & Verification (SMV) of CO₂

The SMV Team found:

- There is significant activity outside the CCP that can be leveraged and steered.
- The Team is already actively leveraging several key efforts.
- The Team is not engaged with all the opportunities and new efforts are needed.
- The Team found that SMV efforts outside of the CCP were addressing roughly 80% of the technology gaps.

Key Conclusions of the Team are:

1. Health, Safety & Environmental (HSE) Risk Assessment R&D is inadequate and is a critical need.
2. Critical Long-Term Monitoring & Verification R&D strategies were not being addressed.

3. The Team identified several medium importance level gaps from the following areas:

- a. Understanding Geological Storage
- b. Maximizing Sequestration
- c. Monitoring & Verification

The SMV Technology Team considers HSE Risk Assessment as the key area to address with the objective of convincing stakeholders that the underground storage of CO₂ is effective, efficient and safe. The SMV Team recommended that the resources allocated to the SMV technology challenges be distributed as shown in Table 6.

Table 6 - SMV Recommended Technology Investment Strategy

Section Description	Tech. Maturity	Industry Skills	External Skills	Recommended JIP Investment Strategy
Understanding Geologic Storage	Medium	High for EOR Low for Brines & Coals	Medium	·Leverage External Efforts ·10% of overall SMV funding ·CCP funds for 1-2 key gaps
Maximizing Sequestration	Low	Low	Low to Medium	·Leverage External Efforts ·20% of overall SMV funding ·CCP funds for 1-3 key gaps
Monitoring & Verification	Low	Low	Low to Medium	·Leverage External Efforts ·20% of overall SMV funding ·CCP funds for 1-3 key gaps
HSE Risk Assessment	Low	Low	Low to Medium	·Roughly 50% of SMV funding ·Possible leverage of significant experience in groundwater, hazardous waste, and nuclear waste industries ·Likely will require new R&D ·Heavy emphasis on long-term monitoring and verification R&D

Analysis Phase (July 2000 – March 2001)

The Analysis Phase built on the results of the R&E Phase. The Technology Teams have completed their analysis and are negotiating contracts for the Technology Development phase. Analysis Phase goals were to:

- Screen and rank technologies relative to CCP Key Success Criteria
- Select technologies for further development and spending
- Decide budget allocations by:
 - Technology theme (pre-, post-, oxyfuel) for total CCP
 - Technology theme for each Scenario/Regional work program
- Agree slate of potential technology developers
- Agree process to access novel technologies

Technology Ranking and Selection Methodology

Rigorous selection criteria updated for each phase of the project are needed because participants do not know what the best options are or whether a breakthrough might occur. Costs of potential winning technologies are very uncertain and not well enough known to allow participants to make investment decisions. Numerous concepts being promoted by technology developers, researchers, and entrepreneurs must be screened for their potential. The criteria and processes must be clear, rigorous, and fair to give confidence to external funding agencies that the CCP is worthy of their support.

Each team agreed upon Analysis Phase success criteria against which each technology was ranked.

- **Achieve target cost reductions** relative to existing (baseline) technology. *CCP targets are to reduce costs of:*
 - *Retrofit to existing operations by 50% over the baseline amine process*
 - *New installations by 75% over the baseline amine process.*
- **Materiality and applicability to Participants' emission sources.** *The technologies must be scaleable to Participant operations with sufficient size to compete commercially. The technologies must work with the real operational combustion streams without hampering commercial operations.*
- **Health, Safety, and Environmental performance requirements met with good operability.** *The technologies must be safe for workers and the environment. Operation in commercial service must not put undue constraints on other processes. The technology must be robust to ensure that the plant will operate efficiently and have high availability for use.*
- **Able to meet CCP's schedule.** *The technologies must be sufficiently well advanced to prove that the concept will work by the end of 2003. The preferred technology must be developed enough to be ready for full scale implementation by 2010.*
- **Acceptable to government and public stakeholders.** *Public acceptance and confidence is key to success. A technology viewed with suspicion and alarm by stakeholders will not be successful.*

The Analysis Phase selection process was designed to be simple, rational, and consistent. It had to be useable by virtual teams and adaptable to a variety of situations and confidence levels. It had to be quick and inexpensive so that decisions are not delayed and that it didn't consume scarce resources. Above all it had to be focused on the needs and opportunities of the Participants.

The selection process shown in Figure 2 was updated for the Analysis Phase to address several issues. Resource allocation is complicated by the needs of co-funding agencies and the need for balance between the technology themes. Novel or high-risk, technologies may not score well in the selection process because of their immaturity.

The CEM Team served a facilitating role in the Analysis Phase technology selection process. Recognizing the difference between the Combustion teams and the SMV teams, the process was applied somewhat differently. The Combustion teams are comparing radically different technologies head-to-head with the goal of choices

between the technologies. The SMV Team's mandate is to develop modifications to commercial technologies (enhanced oil recovery, enhanced gas recovery, coal bed methane recovery, natural gas storage, and waste injection) for use in carbon dioxide mitigation.

Combustion Team Process

The combustion technology teams developed a technology screening methodology recognizing the constraints discussed here. The principles behind the selection tool are:

- A scoring process combining objective and subjective analysis
 - Relies heavily on experience, judgment, and prior work
 - Risk based – Score = Quality * Likelihood
 - Option A compared to Option B by comparing total score
- Criteria to be scored
 - Show stoppers -- i.e. >10 year development time, too costly
 - Agreed objective and subjective categories and subcategories for each CCP success criteria. Weighting factors for each.
- Input requirements
 - Budget and resource constraints
 - Project cost estimates
 - Specific economic success criteria

The concepts described above were applied to the technologies being analyzed. The teams used the criteria to score each technology/scenario against both subjective and objective criteria using a spreadsheet tool provided by the CEM Team. The ranking system gives priority to those technologies with high potential to meet CCP objectives with broad application in multiple scenarios. Each technology was ranked between 5 (High Importance, High Probability, High Potential, or Great Relevance) to 0 (Unimportant, Low probability, No Potential, or Irrelevant). A four level hierarchy of weighting factors was used to balance the technology's potential contributions to CCP's objectives. Figure 7 shows the scoring criteria interrelationships.

- **Level 1** ranks the technology in its importance to CCP's main objectives of cost reduction, emission reduction, and probability of technology development being successful within the time constraints of CCP for each of the scenarios and technologies.
- **Level 2** evaluates the technology's effect on emissions reduction and overall environmental performance. It weights the technology development potential and likelihood of meeting CCP objectives within the time constraints. It also makes an estimate of the importance of CCP participation in development of the technology, the availability of willing technology providers to develop and commercialize the technology, and finally whether there are commercial markets for the technology outside the membership of CCP.
- **Level 3** addresses the applicability of the technology to the four CCP scenarios. It also weights the maturity of the technology and its likelihood of reaching Proof of Concept within 3-5 years and Commercialization within 10 years.
- **Level 4** addresses the technology's applicability to New Build or Retrofit options in CCP participant businesses.

The total score for each technology was calculated by summing the contribution of each scenario option and success criterion together to generate a score normalized to 100 for a “perfect” technology. The score for each technology was calculated using the weighting factors and the subjective score given by team members. The overall weighting factors and scores were calculated using these equations:

$$\text{Option Overall WF} = \text{Level 1 WF} * \text{Level 2 WF} * \text{Level 3 WF} * \text{Level 4 WF}.$$

$$\text{Total Score} = 20 * \text{Summation of (Option Overall WF} * \text{Team Ranking of Technology)}$$

This ranking process generated the weighted ranking of each technology shown in Table 7. This ordering was used along with the needs of participants and co-funding organizations to generate the recommended combustion technologies for development in the Technology Development Phase of the project.

Figure 7

CO2 Capture Project
Analysis Phase Selection Scoring Criteria
March 2001

Table 7 - Combustion Technology Ranking Results

	Emissions Reduction Potential & Applicability to Scenario						Technology Development					Total Score
	Grangemouth	Norway	Alaska	Canada coke	Env Perf.	Proof of Concept	Development Horizon	CCP Influence Dev?	Tech. Developer Available?	Market Potential Outside CCP	Cost Abatement Potential	
Scoring Criteria	Retro	New	Retro	New	Retro	New	Comm?					
Level 1	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.5	
Level 2	0.8	0.8	0.8	0.8	0.8	0.8	0.3	0.25	0.3	0.15	1	
Level 3	0.25	0.25	0.25	0.25	0.25	0.25	0.5	1	1	1	1	
Level 4	0.5	0.5	0.5	0.5	1	1	1	1	1	1	1	
Scenario Weighting Factor	0.03	0.03	0.03	0.03	0.05	0.04	0.04	0.06	0.08	0.04	0.5	
Oxyfuel												
Membrane Boiler	-	5	-	-	-	-	4	3	4	4	3	76
Membrane with GT	-	-	4	5	4	5	4	3	2	4	4	71
Gas Turbine with Flue Gas Recycle	-	-	-	5	-	-	3	3	4	5	4	67
GT with Water Injection	-	-	-	5	-	-	3	3	4	5	3	57
Boilers and Heaters with Recycle	5	5	-	-	5	5	5	5	4	5	2	55
Chemical Looping	2	5	2	2	2	2	3	2	3	3	3	55
High Pressure Boiler	-	5	-	-	-	-	4	4	3	4	-	28
Zero or low recycle boiler	-	5	-	-	-	-	3	3	4	2	-	26
Postcombustion												
ESA	5	5	5	5	5	5	3	4	5	4	4	85

Emissions Reduction Potential & Applicability to Scenario										Technology Development						
	Grangemouth			Norway		Alaska		Canada		Env Perf.	Development Horizon	CCP Influence Dev?	Tech. Developer Available?	Market Potential Outside CCP	Cost Abatement Potential	Total Score
	Retro	New		Retro	New	Retro	New		Retro	New						
Scoring Criteria	Retro	New		Retro <td>New</td> <td>Retro<td>New</td><td></td><td>Retro<td>New</td><td>Proof of Concept</td><td>Comm?</td><td></td><td></td><td></td><td></td></td></td>	New	Retro <td>New</td> <td></td> <td>Retro<td>New</td><td>Proof of Concept</td><td>Comm?</td><td></td><td></td><td></td><td></td></td>	New		Retro <td>New</td> <td>Proof of Concept</td> <td>Comm?</td> <td></td> <td></td> <td></td> <td></td>	New	Proof of Concept	Comm?				
MHI/Kvaerner Amine Scrubbing	5	5		5	5	5	5	-			5	5	5	4	4	82
Norsk Hydro In-Pipe Technology	5	5		4	4	4	4	3	3	4	3	4	5	3	3	69
Reduced Standards	1	1		1	1	1	1	1	1	5	5	5	5	5	3	64
ABB TSA	4	4		4	4	4	4	3	3	4	2	3	3	4	2	57
Precombustion																
WGS Membrane	5	5		5	5	5	5	5	5	5	4	4	5	3	5	86
ESA	5	5		5	5	5	5	5	5	5	3	3	5	2	3	81
IFE CaCO3	5	5		5	5	5	5	5	5	5	2	1	5	2	5	80
ElectroPOX / WGS																
Membrane	-	5		5	5	5	5	-	-	5	4	4	5	3	5	68
ITM-OTM	5	5		3	3	2	2	3	5	2	5	5	2	4	4	66
Membrane Reformer	-	5		5	5	5	5	-	-	5	3	2	5	3	5	66
Standardized PCDC Design	2	5		4	5	3	4	4	5	2	5	5	5	5	2	62
MembraneCO2 Contactor	5	5		5	5	5	5	5	5	4	5	5	5	5	1	59
Electropox	-	5		5	5	5	5	-	-	3	5	4	2	4	2	55
Sorbent Enhanced Reforming																
CO2 Selective	-	5		3	3	3	4	-	-	4	3	2	5	2	4	49
	5	5		5	5	5	5	5	5	4	2	2	3	2	5	48

	Emissions Reduction Potential & Applicability to Scenario						Technology Development								
	Grangemouth		Norway		Alaska		Canada		Env Perf.	Development Horizon	CCP Influence Dev?	Tech. Developer Available?	Market Potential Outside CCP	Cost Abatement Potential	Total Score
Scoring Criteria	Retro	New	Retro	New	Retro	New	Retro	New		Proof of Concept	Comm?				
Membrane															
Hydrogen Permeation Membrane	5	5	-	-	3	3	5	5	3	4	4	5	4	1	46
Hydrate CO ₂ Separation	5	4	4	4	4	4	5	5	4	2	2	2	3	1	45
Compact Reformer	-	5	3	3	5	5	-	-	2	5	5	3	5	1	42
Advanced ATR	-	5	5	5	5	5	-	-	2	5	5	5	5	-	36
VLS ATR	-	5	-	-	5	5	-	-	4	5	5	5	5	-	35
High Hydrogen Gas Turbine	-	-	5	-	5	5	-	5	2	2	1	5	3	-	30
Plasma Syngas	-	5	3	3	2	2	-	-	2	5	5	2	5	-	28
VLS POX	5	5	-	-	3	3	-	-	3	5	5	-	3	-	26
Turbine															
Recuperation Blade Cooling	-	-	-	5	-	5	-	-	2	2	1	4	4	-	23
Fuel Cell Integration	-	-	-	3	-	5	-	-	3	2	1	4	5	-	22
Metallurgical Reactor	-	5	2	2	2	2	-	-	2	-	-	5	1	-	20

Storage, Measurement, and Verification (SMV) Process

The challenges facing the SMV team are different than those facing the combustion teams. The technologies believed to be useful in carbon dioxide storage are modifications of conventional oil industry technology that can be applied to carbon dioxide with minor changes. The SMV team objectives were to:

- Develop technology assessments and identify key gaps
- Recommend CCP R&D investments to fill those gaps
 - Avoid duplication of other research
 - Collaborate closely with other research initiatives
- Close the key technical gaps identified by CCP
- Work closely with stakeholders to demonstrate that Geologic Storage can be safe and effective.

The team devised a “funnel” process to gather information, ideas, and current knowledge. They led an international workshop attended by over 50 experts from nuclear, hazardous waste, natural gas storage, risk analysis, technology providers, and the petroleum industry. The process generated 61 proposals for technology development that were reviewed to generate a recommended program. The ability of successful completion of the proposed work to answer key questions about geologic storage was a primary selection criterion.

- Is geologic storage acceptable to the public and regulatory agencies? What are the safety and environmental risks?
- Can injection offer long-term permanent storage of carbon dioxide? If not, what are the leakage rates and will they be acceptable?
- How much carbon dioxide can actually be stored, monitored and verified? How can monitoring and verification costs be minimized?
- How much will it cost? What are the economic drivers? What are the most cost effective methods?
- Where are formations with the right properties to provide carbon dioxide traps?
- What are the right geologic properties?
 - What are the geochemical and geotechnical responses of faults and caprocks to large quantities of carbon dioxide?
 - What chemical reactions and products of rock-water-carbon dioxide interactions are expected? What is their impact on carbon dioxide storage?

Each proposal was evaluated using the following process:

- A primary reviewer for each proposal was selected from the team
- Held weekly teleconferences to review on-going evaluations and prioritize effort.
- Developed these selection criteria
 - **Proof-of-Concept** - Is the technology far enough along, and the technical risk low enough, to produce viable results no later than yearend 2003?
 - **Potential Applications / Reward / Commercial Viability** - Are the potential applications & sinks large enough to make it attractive?

- **Importance of CCP Investments** – Is the R&D critical, and is CCP key to developing the technology?
- **Provider Track Record / Core Competencies / Staff Availability** - Can the contractor deliver the goods?
- **Collaboration Capability** - How well does the proposal have synergistic links with other R&D, contacts, interest levels, etc?
- Proposals grouped by Key Technology “Buckets”
 - HSE Risk Methodology proposals/CCP Tech Gaps
 - Long-Term Monitoring & Verification proposals / CCP Tech Gaps
 - Other Key Gap Areas – How well are CCP Tech Gaps Addressed?
- Proposals reviewed for overlap and gaps.
- Looked for overall balance and geo-diversity
- If Proposal did not address SMV Key Tech Gaps, overlapped with other, better proposals, comments noted but not passed through.

Analysis Phase Results

Oxyfuel

Oxyfuel methods will require extensive redesign of existing equipment or novel concepts for combined unit operations. The major technical hurdle in oxyfuel technology is the air separation process to produce the required oxygen stream. Air separation remains the largest single cost component of oxyfuel combustion systems. Oxygen transport membrane based systems seem to have the greatest potential to lower air separation costs. Best cycle efficiency will be gained by close integration of the air separation process with combustion. We believe that doing so will increase turbine cycle efficiency and reduce boiler size and cost through process integration.

Two technologies are being funded by government agencies and will require little from the CCP beyond surveillance and cost studies to gain independent insight into their potential. The **Praxair membrane** boiler that may be applicable to the CCP refinery scenario is being funded by the US DOE. The **AZEP membrane** gas turbine that may be applicable to the CCP Gas Turbine scenarios is to be supported by the European Union

The Oxyfuel team commissioned several Analysis Phase studies to critically evaluate novel concepts for their feasibility. Studies commissioned and their results were:

- **Advanced oxyfuel gas turbine cycles (SINTEF):** The Clean Energy Systems Cycle promoted by Boeing could not give the claimed efficiency. Do not support. Boeing later agreed and is now promoting a simpler cycle like Aker Maritime’s HiOx concept.
- **High Pressure Boiler (Mitsui Babcock/Air Products).** Potential efficiencies of high-pressure operation are offset by high capital costs. Do not pursue.
- **Zero recycle boiler (Alstom Power/Praxair and Mitsui Babcock/Air Products).** Benefits too small to justify development. Do not pursue.

The following technologies were recommended for Technology Development Phase (Define Stage) study to develop preferred technologies:

- **Gas turbine with flue gas recycle:** Aker Maritime is leading a multi-partner project to develop their **HiOx** system. They have just completed their own R&E phase work and are proceeding into their Design Phase. CCP and Klimatek will join their Design Phase if a gas turbine vendor joins to provide a source for needed gas turbine development. Alstom Power, a turbine vendor, is negotiating with Aker Maritime to join the consortium. Certain features of a cycle proposed by Graz University researchers could improve the efficiency of the basic HiOx cycle and consideration should be given to incorporating their ideas.
- **Boilers and heaters with flue gas recycle:** Earlier studies on oxyfuel refinery combustion systems using conventional air separation technology showed that 52% of the capital cost and 68% of the auxiliary power were required for air separation. Effective oxyfuel systems will require breakthroughs in air separation costs that we believe may come from the oxygen transport membrane technologies. An engineering study to determine applicability to a Refinery scenario and the cost reduction potential of process integration and of emerging oxygen production technologies will be done beginning 2002 when definitive oxygen transport membrane technology costs will be available.
- **Chemical looping:** Chemical looping uses chemical reactions between a metal and oxygen to generate the metal oxide with subsequent combustion reaction to generate useful heat and the metal for recycle. It is early in the development cycle but has substantial potential for efficiency and cost reduction through process integration. It will be studied in the CCP EU GRACE project for application in refineries.

Post-Combustion

Improvements to existing post-combustion separation technologies are being evaluated:

- **Kværner membrane contactor technology enhanced with Mitsubishi Heavy Industries (MHI) sterically hindered amines** to produce a potential 50% cost reduction. Project objectives are to establish and document the feasibility of the Kvaerner Membrane System in combination with MHI amine solvent for carbon dioxide separation for the CCP scenarios. Discussions with MHI & Kværner are underway.
- **Development of appropriate simpler design standards for conventional amine processes like MHI & Fluor-Daniel Econamine.** Potential cost reduction – 40%. Cost \$1 to 2 million. Project objective is to significantly reduce the cost of post combustion capture of carbon dioxide by applying minimum, non-oilfield, standards. The work will recognize that the carbon dioxide separation plant will contain no hydrocarbons and does not need to be as operationally reliable as an oil or gas production plant. Work is planned to begin in late 2001.
- **Oak Ridge National Laboratory (ORNL) electrical swing adsorption (ESA) technology.** Project objectives are to verify the potential for significant benefit from the electrical swing adsorption in the CCP scenarios. A contract is being reviewed by ORNL to support this work.
- **Norsk-Hydro In-Pipe Separation technology.** Project objective is the establish the feasibility of this technology for heat recovery and exhaust cooling within the exhaust duct and to establish the feasibility of the compact wheel desorber technology for use in regenerating carbon dioxide from rich amine

solutions. A recommendation to progress this project from a preliminary study is awaiting team comments.

- **Radical New Chemistry for Separations.** Project objective is to stimulate new technology development in carbon dioxide separation from flue gases through novel technologies. The goal is to generate one, or more, project on novel chemistries.
- **Baseline studies for conventional amine systems.** Project objective is to provide carbon dioxide separation plant baseline costs for comparison with new technologies. Development of the statement of requirements is underway.

Pre-combustion Decarbonization (PCDC)

The Review & Evaluation Phase identified a broad range of hydrogen generation technologies with potential for substantial cost reduction. It found that about ten first-rate technology providers control commercial technologies worldwide. These technology providers have no incentive to share new technologies or intellectual property rights with CCP and are willing to bring forward only commercial technologies. The planned \$5 million budget for PCDC is less than 1% of worldwide hydrogen generation technology development spending. *Consequently, the PCDC team is concentrating on long-term opportunities that go beyond commercial technologies.* The only significant activity with conventional technology will be an engineering evaluation of the cost reduction benefits of standardizing PCDC plant designs.

An advanced syngas screening study with the objective of establishing schemes for a 350-400MW plant was completed. The base case was conventional auto-thermal reforming technology. The alternatives were:

- Gas heated reformer,
- Feed-product gas heat exchanger,
- Optimized carbon dioxide removal,
- High pressure operation with physical solvent separation,
- High pressure syngas generation with hot syngas expander,
- Reduction of overall carbon dioxide recovery specification from 90% to 80%.

None of the six showed any significant benefit over conventional technology. The study also concluded that **conventional ATR** could provide the fuel for air-blown combined cycle gas turbines and that a **very large scale ATR** could be used with multiple distributed turbines. The study also highlighted the potential of standardization for cost reduction in the near term.

Sorption enhanced reforming technology was identified above as having cost reduction potential through reduced reforming temperature and fewer processing steps. This system has significant implementation challenges in the very large scale anticipated for CO₂ capture because of heat input requirements of the endothermic reforming process and of its limitation to gas fired combustion processes. The team, along with the technology provider, determined that a sorption enhanced water gas shift process in conjunction with an auto thermal reformer would be a lower risk approach for CO₂ capture that could be subsequently developed for use with syngas. This approach was included in the program.

Ten of the original nineteen technologies identified in the R&E phase have been selected for further study. These will be the core CCP program efforts. Those with short to mid-range objectives are:

- WGS (water gas shift) membrane reactors,
- Membrane reformers,
- Compact reformer with carbon dioxide membrane contactors,
- Very large scale auto thermal reactors (VLS ATR)
- Sorption Enhanced Water Gas Shift Reaction
- Novel approaches to CO₂ separation from hydrogen produced in solid fuel gasifiers including CO₂ and H₂ permeation membranes, adapted PSA cycles and CO₂ liquefaction at high pressure or low temperatures.

Technologies needing long-term development that will be encouraged are:

- Ion transport membrane – oxygen transport membrane (ITM OTM)
- Electrical swing adsorption (ESA)
- ElectroPOX
- IFE MeO Power process.

Storage, Monitoring & Verification (SMV)

Carbon dioxide storage in geologic formations is the most likely method to store large amounts of carbon dioxide in the medium term (decades). The techniques and tools to transport and inject carbon dioxide are commercially practiced in the petroleum industry to enhance oil production from existing oil reservoirs. This process has been in use for over 30 years and currently consumes about 25 million tonnes of carbon dioxide per year. Extension of that technology into long-term storage is a major objective of CCP. The main objectives of the SMV team are to:

- Develop the health, safety and environment (HSE) risk assessment methodology needed and is seriously lacking today
- Perform site-specific and generic studies to show public and governments that geologic storage can be safe and effective. Identify what generic and site-specific areas and what kinds of storage attributes are needed.
- Develop the tools to understand CO₂ migration, and develop methodologies for monitoring and verification of storage.

The Review & Evaluation (R&E) Phase produced state-of-the-art descriptions of the technologies, technical gaps needing additional work, and investment strategy recommendations to carry on into the Analysis Phase. The technologies were organized into the following areas:

1. **Understanding Geologic Storage** – Understanding trapping mechanisms, potential for migration, potential negative impacts on caprock and fault integrity.
2. **Maximizing Storage** – How can CO₂ storage be maximized?
3. **Short-Term Monitoring & Verification Tools** – Tools available or close to commercialization.
4. **Long-Term Monitoring & Verification Tools** – Tools that may have the potential to cover larger areas and at much lower cost (e.g. 4D seismic is currently very expensive and must be done on a field scale – LandSat technology shows great promise, for example)

5. Risk Assessment Methodology – How to evaluate risk in probabilistic terms, how to mitigate risk, and how to remediate risk if something goes wrong.

A survey of 50 external R&D efforts showed that technical gaps in Areas 1-3 are being addressed and need little funding from the CCP. The investment strategy recommendation is to focus about 50% of the budget on Area 5 because risk assessment is not being studied at all and is a critical tool to demonstrate to the public and governments that geologic storage is safe and effective. Area 4 was to receive about 25% of the SMV budget, with the remainder going to areas 1-3.

The SMV Team engaged potential technology providers; such as national laboratories, university researchers and consultants; in a 2-day workshop to explore technology needs. The breakout sessions focused on learning about nuclear waste, deep well industrial waste injection, and groundwater contamination issues. The workshop generated 61 proposals that were evaluated and ranked. The evaluation process produced a project portfolio that addressed primarily Areas 4 and 5. Table 8 shows the list of selected projects and Appendix xxx gives a short description of each project.

Table 8

SMV Technology Providers and Work Summary Description

Technology Organization	Principal Investigator	Project Descriptions
<u>CCP funding</u>		Subtotal
ARI	Stevens	Leveraging Natural Analogs – 4 Field Case Studies
Berkeley NL	Benson	HSE Risk Assessment Literature Search; Synthesis of Findings
Cal Tech	Tang	Literature Search on CO ₂ Detection Technologies
GFZ Potsdam	Borm	Influence of Injection on Physical Properties of Reservoirs & Caprocks
HyMap Ace.	Pickles	Hyperspectral Geobotanical Remote Sensing for Rangely Field
NM Tech	Grigg	Leveraging EOR Studies – Long Term Storage in Mature Basins
TP Workshop 1	Jan01WkShop	Process to Engage Technology Providers & Solicit Proposals
TP Workshop 2	WkShops	Annual Workshops to Encourage Collaboration Among Technology Providers
<u>EU / NGCAS</u>		Subtotal
AEAT	Naylor	Optimization of storage and risk assessment methodology
BGS	Holloway	Methodology for assessment of storage options
BP	Espie	Management, risk assessment, monitoring and mitigation
GEUS	Christensen	Basin model development
IFP	Brosse	Basin modeling and geochemistry
IEA GHG Pgm	Gale	Technology transfer
Statoil	Berger	Technology transfer
<u>NORWAY</u>	<u>(NorCap)</u>	Subtotal
IFE	Seiersten	Understanding materials & corrosion issues, costs, rules of thumb
Reinertsen		Understanding critical phase behavior at high temps & pressures
University of Oslo		Understanding the Legal Issues including the London Convention
<u>US DOE</u>		Subtotal
CC Central	Bachu	Leveraging and Characterization of CO ₂ /H ₂ S Acid Gas Disposal/AB
Berkeley NL	Hoversten	Novel Geophysical Techniques for Monitoring of CO ₂ Migration
Berkeley NL	Oldenburg	Coupling Ground Leakage & Atmospheric Transport Models; Probabilistic RA
Idaho NL	Rateman	HSE Probabilistic Risk Assessment Methodology of Coalbed Storage
LLNL	Pickles	Hyperspectral Geobotanical Remote Sensing for CO ₂ Containment
LLNL	Nimz	Noble Gas Isotopes for Screening & Monitoring Long Term CO ₂ Migration
LLNL	Johnson	Risk Assessment; Reactive Transport Modeling of Integrity of Caprocks & Faults
Sci Monitor	Stenhouse	Leveraging Nuclear Storage; RA Framework, Public Perception, etc.

Technology Organization	Principal Investigator	Project Descriptions
Sintef	Lindeberg	Long-Term Sealing Capacity of Steel Wellbore Tubulars & Cement
Stanford	Zebker	Long-Term Monitoring & Verification Using Satellite Radar Interferometry
Texas Tech	Frailey	Use of Depleted Gas Reservoirs for Storage; Studies on Increased Condensate Rec.
Tie Line Tech	Stenby	Screening Tool for Miscibility Pressure Calculations; Tradeoffs of Impure CO ₂
TNO-NITG	Wildenborg	HSE Risk Assessment Methodology Development
TNO-NITG	Arts	White Paper on Optimum Monitoring Technologies
Utah State	Evans	Reservoir Characterization, Fault Leakage Analysis, and Synthesis of Leaky Systems
Parking Lot		
PCM Technical	Moschovidis	Fracture Mechanics Approach to Seals Evaluation
U of Texas	Pope	Integrated Reservoir Simulation
Livermore NL	Knauss	Risk Assessment; Caprock & Seal Integrity & Impact of Containment
Livermore NL	Viani	Predictive Model for Assessing Long-Term Caprock Integrity
Sintef	Zweigel	Assessment of CO ₂ Leakage Risk & Rates by Simulation of Various Scenarios
U of Alberta	Chalatumyk	Performance Assessment Methodology

CO₂ Capture Project Peer Review

A Peer Review of the CCP Review & Evaluation and the Analysis Phase was held. The Peer Review Team included:

- Vello Kuuskraa (Advanced Resources International)
- Maarten van der Burgt (Independent Consultant)
- David Beecy (U.S. Department of Energy)
- Dale Simbeck (SFA Pacific)

Reviewers were asked to answer six questions, as well as make recommendations:

- Have the technical teams reviewed all relevant technology?
- Have we followed a reasonable process to select technologies for investment?
- Have we got the correct mix of technologies to meet our goals (short/long term, high/low risk,)?
- Are our goals appropriate?
- Are we spending the correct proportion of funds in each of the technical areas?
- Have we reached a reasonable set of conclusions?

The Peer Review Team found that the Technical Teams had conducted a very thorough and technically impressive planning and technology selection process. The criteria used by the Teams for the selection were clear and intuitively rigorous. Except for a few modest additions or expansions, the Teams had reviewed all of the relevant technologies.

The Peer Review Team commended the Technical Teams for setting aggressive, breakthrough goals, providing promise that the costs of capture could be reduced substantially. The technologies are also matched with a robust set of scenarios that provide further insight on the targeted markets for CO₂ capture and the technologies that are essential in each of these markets.

The technology selection process identified a robust portfolio and strategy that includes a favorable mix of high and low risk technologies and a mix of short term and long-term efforts. While many of these technologies will be dropped in future years based on their competitiveness and likelihood of being ready by 2010, the broad based strategy adopted by the Teams will increase the success potential of the CCP.

The distribution of project funds among the technical areas was deemed appropriate. The Peer Review Team offered two broad recommendations:

- Consider establishing a cross-cutting Team that maintains dialog between the Technical Teams and the Advanced Gas Turbine Industry, as the availability of advanced and new turbines is central to many of the technologies being considered by the Technical Teams
- In the scenarios, examine the applicability and performance of each technology with both existing heat systems (e.g. boilers) and as well as with future heat and power systems (e.g. combined cycle) that may be in place by 2010.

Technology Development (March 2001 – March 2003)

The Executive Board approved the outlined technology programs recommended by the technology teams after a Technology Advisory Board peer review of March 8-9, 2001. The CCP leadership worked aggressively to gain funding for the entire program by soliciting new members and competing for funding from Norway's Klimatek, the European Union, and the U.S. DOE. Each of these competitions has been successful with support from all the Participants and their home governments.

The technology teams continued to refine their plans and to recruit resources from universities, research institutes, and technology vendors. A total of seventy research contracts worth \$17 million are signed or in final stages of negotiation. Contracts have been agreed with the funding agencies and final work packages are being agreed. A list of the contracts and their status is included below as Table 9

The results of these researches will be reported as they are completed. This report section gives the status as of September 2001.

Technology Scenarios

The scenarios have evolved into those described schematically below. The Participants believe that these scenarios will represent the majority of industrial applications. These scenarios have been used as the basis for the technology development contracts being agreed and worked. The starting point scenario table (Table 1) is reproduced as a reference to the basic conditions being considered. Each scenario diagram includes more detail on the fuels and operating conditions envisioned.

Table 1
CCP Scenarios

Scenario	Fuel Source	CO ₂ Source	Geologic Sink	Location
Refinery	Hydrocarbon Gas & Liquids	Heaters & Boilers	Offshore EOR	European Refinery
Very Large Gas Turbines	Natural Gas	Large Electric Power Generation (CCGT)	Saline Aquifers Offshore EOR	Western Norway
Distributed Gas Turbines	Natural Gas	Small Distributed turbines	Onshore EOR	Alaska North Slope
Gasification	Solid gasification	Steam, H ₂ & Electricity Cogeneration	Onshore EOR	Western Canada

Refinery Scenario

GRANGEMOUTH SITE SCENARIO PRELIMINARY DEFINITION
TARGET : CAPTURE 50% OF CO₂ EMISSION FROM HEATERS & BOILERS

SOURCE A

CO ₂ EMISSION BY FUEL TYPE	
	ktpa CO ₂
FUEL OIL	
FUEL GAS	
NAT GAS	
TOTAL	1633

SOURCE B

CO ₂ EMISSION BY FUEL	
	ktpa CO ₂
FUEL OIL	
FUEL GAS	
NAT GAS	
TOTAL	1192

STACK	A	B & D	C	E
TPA CO ₂	97.7	152.6	189.5	34.6
No Htrs	2	4	2	1
STACK	F	G&H	I	J
TPA CO ₂	215.8	292.0	170.5	40.5
No Htrs	5	4	1	2

SOURCE C

FUEL GAS

SOURCE D

FUEL GAS

Distributed Gas Turbines

Very Large Gas Turbines

Gasification

Technology Development Contract Summary

Table 9 - Technology Development Contract Status (September 26, 2001)

Area Num	Description	Technology Provider	CCP Contact	Funding Source	Principal Investigator	Work Location	Total	Contract Signed?	Start Date
Oxy									
1	Chemical Looping Combustion-Preliminary Work Proposal for Alstom Power Boilers	Chalmers University of Technology (Chalmers)	Wilkinson	EU GRACE	Leckner	Sweden	548	Yes	11/01/2001
2	Study Reactor Design Solid Properties, and Particle Size on the Solids' Circulation Rate	Vienna University of Technology	Wilkinson	EU GRACE		Austria	164	Yes	11/01/2001
3	Study Bubbling Fluidized Bed Combustion & Cold Circulating Fluidized Bed Test Rig	Consejo Superior de Investigaciones Cientificas (ICB-CSIC)	Wilkinson	EU GRACE		Spain	360	Yes	11/01/2001
4	Feasibility Study & Economic Model for Chemical Looping Technology	Alstom Power Boilers (AV)	Wilkinson	EU GRACE		France	92	Yes	11/01/2001
5	Study Membrane Activities Including Processes for Oxygen Separation from Air	Uni. Of Twente-AMK	Wilkinson	EU GRACE		Netherlands	226	Yes	11/01/2001
6	Membrane Reformer, Permeation Membrane and Reactor Design	Inst. Membrane & Modeling of Chem. Reactors (IRMERC)	Wilkinson	EU GRACE		Italy	229	Yes	11/01/2001
7	Production and Design of Prototype Equipment	Triton Engineering	Wilkinson	EU GRACE		UK		Yes	11/01/2001
8	Zero Recycle Oxyfuel Boiler	Alstom Power Boilers	Wilkinson	EU GRACE		UK		Yes	11/01/2001
9	Refinery	Kvaerner	Wilkinson	EU GRACE		Norway		Yes	11/01/2001
10	Advanced Retrofit Boiler Design			DOE		US		No	
11	Oxyfuel boilers and heaters recycle	Alstom Power, Praxair, Babcock, Air Products, B&W, Foster Wheeler, Jacobs Engineering, Fluor Daniel,		DOE		US	500	No	
						Subtotal	2119		

Area Num	Description	Technology Provider	CCP Contact	Funding Source	Principal Investigator	Work Location	Total	Contract Signed?	Start Date
PCDC									
1	Develop Silica Membranes and Provide Mathematical models	/Energy Resource Centre of the Netherlands (ECN)	Lowe, Middleton, Assink	DOE	Alderletsen	Netherlands	356	No	
2	Develop Supported Copper Palladium Alloy	/Colorado School of Mining (CSM)	Lowe, Middleton, Assink	DOE	Way	US	200	No	
3	Develop Flow sheet & Design	/Fluor Enterprises Limited (Fluor)	Lowe, Middleton, Assink	DOE	Stupin	US/EU	410	No	
4	Reactor Design, scale up and cost assessment	/McDermott	Lowe, Middleton, Assink	DOE	Rowley	US/EU	319	No	
5	Develop Electro-ceramic membranes	/Eltron Research	Lowe, Middleton, Assink	DOE	Sammells	US	209	No	
6	Develop Supported Silicalite (zeolite) membranes	/University of Cincinnati	Lowe, Middleton, Assink	DOE	Lin	US	200	No	
7	Hydrogen Membrane Technology Ceramic Material, Reactor and Process Design	/Norsk Hydro	Wilkinson	EU GRACE		Norway		Yes	11/01/2001
8	Membrane Reformer	Norsk Hydro, Statoil, BP, Sintef	Bjorn	Norcap		Norway/UK	574	No	
9	IFE MeO Process	Institute for Energy Technology (IFE)	Bjorn	Norcap		Norway/UK	31	No	
10	Investigation of High Temperature Hydrogen Membrane	/SINTEF	Wilkinson	EU GRACE		Norway		Yes	11/01/2001
11	Use of Pd/Zelite Composite Membranes for Selective Hydrogen Permeation	/Universidad de Zaragoza (UNIZAR)	Wilkinson	EU GRACE		Spain		Yes	11/01/2001
12	Radical chemical engineering, step change technologies research	/University of Newcastle Upon Tyne (CPII-NU)	Wilkinson	EU GRACE		UK		Yes	11/01/2001
13	Distributed Gas Turbines (VLS ATR)	/Haldor Topsoe, Synetix, Jacobs Engineering	Henrik	DOE		US/UK	300	No	
14	Standardized PCDC	Topsoe, Kellot, Uhde, Lurgi, McDermott, Praxair, Jacobs, Fluor Daniel, Parsons	(Various)	Norcap	(Various)	US/EU		No	
15	Compact Reformer Membrane Contractor	Kvaerner/		DOE		US/UK	300	No	

Area Num	Description	Technology Provider	CCP Contact	Funding Source	Principal Investigator	Work Location	Total	Contract Signed?	Start Date
16	Sorption Enhanced WGS	/Air Products	Lowe, Middleton, Assink	DOE		US	100	No	10/16/2001
17	Gasification CO2 Separation Development			DOE		US/EU	800	No	
18	Oxygen Membrane ATR			DOE		US	200	No	
19	Electric Swing Adsorption	Oakridge National Lab. (Oakridge)		DOE		US	250	No	
20	Gas Turbine Retrofit	GE		DOE		US/EU	50	No	
						Subtotal	4299		
Post									
1	Electrical Swing Adsorption	Oak Ridge National Lab		DOE		US	1400	No	
2	Adsorbents for ESA	SGL		DOE		US			
3	Engineering Scale-Up Study for ESA	Various Engineering Companies		DOE		US			
4	MHI Amine Scrubbing/Membrane Contactor	Norsk Hydro, MHI, BP	Bjorn	Norcap		Norway	1954	No	
5	Hydro in Pipe Absorber	Norsk Hydro, NNTU, Prototek	Bjorn	Norcap		Norway	689	No	
6	Radical Chemistry	Triton, NNTU, Sintef	Bjorn	Norcap		Norway/US	103	No	
7	Radical Chemistry: Part 1 Review State of Art Opportunities			DOE		US		No	
8	Radical Chemistry: Part 2 Technical Studies			DOE		US			
9	Analysis Phase Study	Oak Ridge National Lab	C. Lewis	CCP	Burchell	US	50	No	
10	Cost Efficient Design Integration	Bechtel, Foster Wheeler, Fluor, Kellogg, GE, AV, Siemens/		DOE		US	400	No	
						Subtotal	4596		

Area Num	Description	Technology Provider	CCP Contact	Funding Source	Principal Investigator	Work Location	Total	Contract Signed?	Start Date
SMV									
1	Leveraging Natural Analogs – 4 Field Case Studies	Advanced Resources Int'l (ARI)	C. Lewis	CCP	Stevens	US	154	Yes	
2	HSE Risk Assessment Literature Search, Synthesis of Findings with Roadmap	Berkeley NL	C. Lewis	CCP	Benson	US	50	Yes	
3	Literature Search on CO2 Detection Technologies	Tang Associates	C. Charles	CCP	Tang	US	20	Yes	
4	Influence of Injection on Physical Properties of Reservoirs & Caprocks	/GFZ Potsdam	Charles & Bjorn	CCP	Borm	Germany	350	Yes	
5	Leveraging EOR Studies	/New Mexico Tech	J. Woliver	CCP	Grigg	US	73	Yes	
6	Optimization of Storage & Risk Assessment Methodology	/AEA Technology (AEAT)	T. Espie	EU NgCas	Naylor	UK	178	Yes	10/01/2001
7	Methodology for Assessment of Storage Options	/British Geological Survey (BGS)	T. Espie	EU NgCas	Holloway		100	Yes	10/01/2001
8	Management, Risk Assessment, Monitoring & Mitigation	/BP	T. Espie	EU NgCas	Espie	UK	331	Yes	10/01/2001
9	Basin Model Development	/Geological Survey of Denmark & Greenland (GEUS)	T. Espie	EU NgCas	Christensen	Denmark	100	Yes	10/01/2001
10	Basin Modeling and Geochemistry	/Institute Francais du Petrole (IFP)	T. Espie	EU NgCas	Brosse	France	100	Yes	10/01/2001
11	Technology Transfer	/IEA Greenhouse Gas R&D Program (IEA)	T. Espie	EU NgCas	Gale	UK	99	Yes	N/A
12	Technology Transfer	/Den Norske Stats Oljeselskap a.p (Statoll)	Bjorn	EU NgCas	Berger	Norway	20	Yes	N/A
13	CO2 Corrosion and Membrane for Selective Hydrogen Permeation	/Institute for Energy Technology (IFE)	Bjorn	Norcap	Seiertsen	Norway	270	Yes	
14	CO2 Transportation Process Optimization	/Reinertsen Engineering (Reinertsen)	Bjorn	Norcap	Solligard	Norway	330	No	
15	Legal Aspects of CO2 Underground Storage	/Nansen Institute	Bjorn	Norcap	Bugge	Norway	77	No	
16	Leveraging and Characterization of CO2/H2S Acid Gas Disposal/AB	/Climate Control Central (CCC)	S. Das	DOE	Bachu	US	145	No	
17	Novel Geophysical Techniques for Monitoring of CO2 Migration	/Lawrence Berkeley NL (Berkeley)	C. Lewis	DOE	Hoversten	US	230	No	

Area Num	Description	Technology Provider	CCP Contact	Funding Source	Principal Investigator	Work Location	Total	Contract Signed?	Start Date
18	Coupling Ground Leakage & Atmospheric Transport Models	/Lawrence Berkeley NL (Berkeley)	C. Lewis	DOE	Oldenburg	US	280	No	
19	HSE Probabilistic Risk Assessment Methodology	/Idaho National Lab (Idaho)	C. Charles	DOE	Rateman	US	440	No	
20	Hyperspectral Geobotanical Remote Sensing for CO2 Containment	/Lawrence Livermore NL (Livermore)	C. Charles	DOE	Pickeles	US	300	No	
21	Noble Gas Isotopes for Screening and Monitoring Long Term Migration	/Lawrence Livermore NL (Livermore)	C. Charles	DOE	Nimz	US	275	No	
22	Risk Assessment, Reactive Transport Modeling of Integrity of Caprocks & Faults	/Lawrence Livermore NL (Livermore)	Wolf & Charles	DOE	Johnson	US	305	No	
23	Leveraging Nuclear Storage; RA Framework, Public Perception, etc.	/Scientific Monitor (Sci Monitor)	Rick	DOE	Stenhouse	US	35	No	
24	Long Term Sealing Capacity of Steel Wellbore Tubulars & Cement	/SINTEF	Bjorn	DOE	Lindeberg	Norway	110	No	
25	Long Term Monitoring & Verification Using Satellite Radar Interferometry	/Stanford University (Stanford)	Woliver	DOE	Zebcker	US	400	No	
26	Screening Tool for Miscibility Pressure Calculations; Tradeoffs of Impure CO2	/Tie-Line Technology (Tie-Line)	C. Charles	DOE	Stenby	US	215	No	
27	HSE Risk Assessment Methodology Development	/Netherlands Institute of Applied Geosciences (TNO-NITG)	Lars & Wolf	DOE	Wildenberg	Netherlands	891	No	
28	White Paper on Optimum Monitoring Technologies	/Netherlands Institute of Applied Geosciences (TNO-NITG)	Bjorn	DOE	Arts	Netherlands	35	No	
29	Reservoir Characterization, Fault Leakage Analysis, and Synthesis of Leaky Systems	/Utah State University (Utah State)	C. Lewis	DOE	Evans	US	87	No	
						Subtotal	6000		
ON HOLD	Fracture Mechanics Approach to Seals Evaluation	PCM Technical	Charles	Deferred	Moschovidis			Deferred	
	Integrated Reservoir Simulation	U of Texas	Charles	Deferred	Pope			Deferred	
	Risk Assessment; Caprock & Seal Integrity & Impact of Containment	Livermore NL	Charles	Deferred	Knauss			Deferred	

Area Num	Description	Technology Provider	CCP Contact	Funding Source	Principal Investigator	Work Location	Total	Contract Signed?	Start Date
	Predictive Model for Assessing Long-Term Caprock Integrity	Livermore NL	Charles	Deferred	Viani			Deferred	
	Assessment of CO2 Leakage Risk & Rates by Simulation of Various Scenarios	Sintef	Bjorn	Deferred	Zweigle			Deferred	
	Performance Assessment Methodology	U of Alberta	Swapan	Deferred	Chalatumyk			Deferred	
	Hyperspectral Geobotanical Remote Sensing Rangeley Field	AIG-HyMap	C. Lewis	Deferred	Pickles				

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2. Rita Bajura, FETC, presentation summarized. Reference 1, page 6.
3. Bernard Bulkin, BP, presentation summarized, Reference 1, page 6.
4. Kelly Thambimuthu, IEA GHG, presentation summarized, Reference 1, page 7.
5. Hank Courtright, EPRI, presentation summarized, Reference 1, page 7.
6. Torre Torp, Statoil, presentation summarized, Reference 1, page 9.
7. Malcolm Wilson, Saskatchewan Energy Resources and Ken Brown, Pan-Canadian, presentation summarized, Reference 1, page 9.
8. Daryl Erickson, BP, presentation summarized. Reference 1, page 10.
9. Work Group Reports, Reference 1, pages 12-16.
10. CCP: Report of the Review and Evaluation Phase: April to July 2000, Michael B. Wilkinson (editor), BP Amoco, 20 July 2000.

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Technology Selection Appendices

These appendices to the ***CO₂ Capture Project Technology Selection Processes Report*** dated ***1 November 2001*** provide background and archival material used by team members during the technology selection process. As such, they are to be used for informational purposes and may represent approaches and technologies not carried forward to development. The critique and decisions made using the material represent the best information at the time and the teams' view of the technology's fitness for carbon dioxide separation and storage. The comments made do not reflect upon the value of the technology for other purposes nor on the ability of any technology or research provider but represent the judgment of the working groups in context of their deliberations.

Technology Assurance Process Overview

CCP's technology development activities are governed by a stage-gate project management method. The Technology Assurance Process (TAP) is a business process with a structured and integrated approach to project selection and cost efficiency. The decision making process used is the core of the technology assurance process. Many companies use similar stage-gate decision-making processes to manage their businesses and this kind of process should be familiar to most industry participants. Below is summarized the main features of the state-gate process modified to suit technology development projects. The technology assurance process has four stages ending with "execute the project."

Technology Assurance Process Overview

The Technology Assurance Process (TAP) is a tool for the delivery of results and value through improved decision quality and spending efficiency. TAP improves performance by:

- Providing a better basis for decision making based on continuous challenge
- Promoting an early and sustained integration of business/technical disciplines into projects
- Providing a consistent structured methodology for driving improvements in project management
- Providing greater discipline to achieve consistently better levels of front-end activity and the application of value improving practices
- Enabling better transfer of learning

TAP Description

The TAP is a structured process based on the following features:

- TAP consists of four stages each corresponding to a distinct phase in the project life cycle and timed to match the pace of other activities.

Appraise the current state of technology and identify broad ranging technology solutions that may have the potential for meeting project objectives.

The Review & Evaluation Phase carried out in CCP during 2000 provided the basis for technology choices for further development.

Select those technologies that the team believes have potential for meeting project objectives and carry out basic and exploratory studies to determine the technology's potential.

The Analysis Phase to critically examine and evaluate a reduced range of technologies so that decisions to select candidate technologies for detailed study can be made.

Define the favored technologies that the team believes will meet project objectives and carry out detailed engineering studies to assure the participants that the costs are well understood and the technologies will work as planned.

The Technology Development Phase to critically examine and develop candidate technologies so that decisions on most favored technologies can be made.

Execute full integration of the favored technologies into an engineering plan that could be taken forward to demonstration and commercialization.

Preparation of detailed engineering designs that could lead to demonstration or commercial plans after CCP has finished its work.

- TAP includes the following roles:

Gatekeeper - the individual responsible (the CCP Executive Board) and accountable for the decision made at the end of each stage, and for securing resources and funds for the next stage of the project

Single Point Accountability (SPA) – the individual (technology project leader) with accountability who leads the project team in its goal to maximise project effectiveness by optimising the mix of project drivers affecting economics and risk in a changing environment

Technology Assurance Board (TAB)– the external review and assurance team that is responsible for providing advice and oversight of the projects to the Executive Board. A key role is to provide assurance that the technology development is in keeping with the Project goals and desired results.

- Between each stage is a **Gate** at which the Gatekeeper decides, in consultation with the Technology Advisory Board, based on the technology team's recommendation to:
 - Proceed to the next stage,
 - Kill the project,
 - Place the project on hold, or
 - Recycle through the current stage

The preferred decision choices are: to **proceed** to the next stage or to **kill** the project. A decision to put a project on **hold** or **recycle** it through the current stage should be very rare.

Principles

- TAP is a business process owned by the technology teams.
- The TAP has the flexibility to adjust its application to all types of projects based on the size and/or complexity of each project
- An essential element of the process is constructive **challenge**. Though incremental development has its place only a step change in project management, technology or engineering innovation will deliver distinctive performance.
- TAP will be continuously improved and enriched based on learning experiences.
- Successful implementation of TAP relies on **Supporting Behaviours** such as beginning with the end in mind and rewarding the cancellation of projects no longer aligned with project objectives.

Technology Advisory Board (TAB)

The Technology Advisory Board is an independent body made up of recognized experts in the field. They are accountable to the Executive Board to provide assurance that the technology teams are completing their work in a technically sound and scientific way. Their effort is an integral part of the CCP program management process and serves to assure the funding government organizations that the CCP leadership is proper stewards of the public funds in addition to providing assurance to the Executive Board on the technical soundness of the projects.

Their roles include providing:

- Advice and oversight of the projects to the Executive Board.
- Assurance that the technology development work is in keeping with the Project goals and desired results.
- Independent challenge to the technology directions of the teams.
- Assurances that best technical practices have been used in delivery of the project.
- Review of a High Level Plan for the process/
- Selection of Peer Review participants
- Advice on external benchmarking that will serve to give assurance that the technology work is at the forefront of technology.

The Board is made up of a core membership that adds other expert members on an as needed basis. Each funding agency will also be invited to designate a representative to participate on the TAB.

Technology Project Cost Estimation

CCP uses a technology project cost estimation process develop the overall funding requirements for the project. A high level stepwise description of the process follows. Overall project costs are estimated by rolling up the costs for each work package and work plan. Verification of costs allocated to each funding group is the responsibility of the Program Manager and is done by collecting both the chargeable costs and the cost-sharing costs not directly billed to the funding agency. In this way, the balance between co-funder expense and participant expense is maintained.

The Executive Board and Program Manager provide oversight of the project development process and hold accountability for stewardship of the budget. They determine resource and fund allocation for the projects. Contract negotiation and final project costs are the accountability of the Program Manager, Contract Team, and Technology Team Leader. Work plan development and development of specific tasks for technology providers is the responsibility of the technology team and the single point accountability (Responsible Technology Team member.)

Project Cost Estimation Process:

1. Strategic direction, scope, and objectives set by Executive Board in consultation with the technology teams.
2. Technology teams develop a working plan to meet the objectives. They make a high level estimate of costs for review and approval of the Executive Board.
3. After approval, the work plan is divided into logical work packages that address one or more technology objectives.
4. Team members outline the specific tasks in the work packages and make estimates of the resources required to complete the task. The Program Manager and technology team leadership review a more detailed cost analysis.
5. Third party technology providers (engineering firms, contractors, universities, and institutes) are pre-qualified for their capabilities and probability of successful and timely delivery of the technology. They are then asked to bid on the tasks or work packages.
6. The bids received are reviewed and discussed with the third party technology providers to ensure that the basis for their cost estimates are clearly understood and that the expected result will meet project objectives.
7. Estimates of the Participant costs are made and ratio of cost-sharing with the co-funding agency for the project are verified.
8. Project costs for each work package and plan are consolidated and reviewed for accuracy and consistency. Executive Board approval for the revised budget and work plan is sought.
9. After review and approval by the Executive Board the Contract Team and Technology Team negotiate final details of third party contractor agreement.
10. Contract details are verified against the requirements of the CCP participants and the co-funding agency.
11. The signed agreement is entering into the BP or Statoil accounting system. Payment of invoices and auditing of expenditures is the responsibility of the lead company (BP or Statoil.)

12. Verification of overall project performance against the budget and cost control is part of the project management process and is the responsibility of the Program Manager and Technology Team Leader.

Public Forum (September 1999) Comments

The September 1999 Information Meeting and Public Forum held in Houston, Texas included several workshop sessions in which knowledgeable experts provided their suggestions for work needed to meet CCP objectives. This section reports their comments with little editing for archival purposes.

Post-Combustion Separation

Improved Contactors

- Develop Gas/Liquid contactors with low differential Pressure
- Cost effective materials to facilitate CO₂ recycle systems
- Develop spray contactor
- Improved adsorber/stripper (e.g., membrane contactor)

Eliminate Pre-treatment of Flue Gas

- Develop simultaneous CO₂/SO₂ removal. Take out SO₂ as SO₃/Ca SO₄
- Remove need to separate components of exhaust flue gas before any type of sequestration
- Use alloys to get around solvent limits from corrosion.

Better Solvent

- Promoted Na or K carbonate
- Use “next-generation” amine systems
- Select optimum amine solution
- Advanced solvent systems (amines and others)
- Examine alternative adsorption chemicals (alternative to MEA) to find those with lower stripping energy
- Amines with low heat of reaction, higher reaction rate
- Amines stable to oxidation
- High-resistance, long-life solvents
- Slurry systems or 2 phase liquids

Alternative Separation Technologies/Membranes

- Look at other industries for analogies of this process
- Low-pressure, high-temperature membranes for CO₂ separation
- Reduce pressure requirements for CO₂ separation/capture
- Improved CO₂ stack enrichment by the removal of part of the N₂ component via membrane
- Development of low-temperature (compatible with stack gas temp) membrane to separate CO₂ from the flue gas

Distillation/Cryogenics

- Low temperature distillation
- Gas/solid adsorbents
- Mineralization and biomineralization with CO₂ separated from flue gas

Optimize Process

- Optimize Stripper pressure
- Isothermal absorber/stripper
- Reduced CO₂ removal and absorber contacting
- Look at the cost changes as a function of the purity. End product may not have to be pure.
- Need to define the end-use purity requirements, including trace impurities.
- Increase the capacity of CO₂ capture process. Maximum size of boiler is 1000 MW capacity, which can recover CO₂ up to 1000 tons /day of CO₂
- Develop best practice of an amine plant for CO₂ capture. Maximum use of low-cost solutions suitable for exhaust gas. Reduce cost factors.

Integration

- Increase CO₂ concentration of in gas turbine exhaust - reduce capital cost
- Integrated systems including heat recovery
- Examine ways to achieve better heat integration of systems
- Inexpensive steam to regenerate amines
- Using other less-expensive energy sources for compression
- Direct heat recovery from gas turbines
- Integration with power production
- Energy integration of combined cycle system and amine system
- Use existing limestone scrubbers as MEA scrubbers\

Flue gas for EOR-O₂ removed

- Sequesters CO₂ but large compression duty
- Coal bed methane-used ok
- Not suitable for oil

Increase CO₂ by supplemental firing

- Adds heat to flue gas- more power
- Reduces absorber size
- More CO₂ production
- Remove N₂ from flue gas by membranes
- Depends where CO₂ goes (low pressure or high pressure)

Remove CO₂ by hydrate formation

- Requires cooling flue gas toward freezing - refrigeration
- Forms pumpable liquid
- Heat releases CO₂ at pressure
- CO₂ product requires dehydration

Swing adsorption process - electrical

- Higher pressure reduces unit size
- CO₂ desorbed at adsorption pressure

- CO₂ purity not well established
- Not applicable to large point sources, e.g., 300 MW PCB
- Process lab-scale at present

Solvent Systems

- Super sorbent, resistant to oxidation degradation
- High pressure CO₂ desorption
- Super chilled water stripper with combustion turbine waste heat - somewhat like old FLAKT process
- Low cost structure packing, reduced pressure drop
- For north slope temps - chilled methanol adsorber/stripper
- Stripping tower, easy to discharge CO₂ (less heat), less carryover
- Absorption tower, less draft loss
- Better solvents
- Low solvent circulation
- Low cost for absorb medium and small size of equipment
- Low corrosion, less degradation
- Flue gas for removing oxygen catalytically and inject CO₂ and N₂
- Combustion turbine exhaust heat directly used for stripping and gas/liquid reboiler
- Increase CO₂ concentration in flue gas stream; CO₂ recycle, membrane N₂ removal, supplemental firing
- Amines with high pressure regeneration

Adsorption

- High selectivity in CO₂ absorb/adsorb
- Temperature swing absorbent
- Metal oxide absorbents

Process equipment

- More efficient heat exchangers for cooling exhaust gas streams
- Apply fit-for-purpose materials to eliminate/reduce corrosion, weight
- Less expensive materials, configuration
- Maximum utilization of waste heat for power production
- Low power consumption pumping, compressor

Cryogenic processing

- Pre chilling (super cooled inert gas)
- Cryogenic to eliminate compression and dehydration

Miscellaneous

- Cryogenic CO₂ removal - innovative cycles
- Absorb or adsorb CO₂ at low pressure and regenerate at high pressure
- Biomemisis (does not reduce concentration of CO₂, enzyme)
- Membranes with vacuum
- Conventional membranes
- Improve the osmosis for CO₂ separation
- Membranes, better work at lower pressure differential
- Efficient membranes for air separation
- Capture CO₂ as liquid or hydrate, low cost compression

- Carbon nanotube adsorption better adsorber pressure/temperature
- Discover new solvent for CO₂ capture
- Discover new material for CO₂ capture
- PSA, TSA, ESA
- CO₂ sponge
- Novel very high temperature adsorbents
- Adsorption-based systems for smaller CO₂ sources

Source

- Establish CO₂ specification for sequestration
- Consider all CO₂ sources (large and small)
- Complete knowledge of gases other than N₂ and CO₂, i.e., O₂, trace constituents and variants

Oxyfuel

- High pressure combustor and recuperator
- O₂ ceramic membranes
- Pretreatment
- Pressure drop
- Lifetime/reliability
- Product purity
- Scale up
- Type of membrane
- Remote location
- Water/steam recycle
- Integration (retrofit, greenfield)
- Pure O₂ boilers
- Down hole combustion
- CO₂ GT (new/retrofit)
- O₂ improve cryo
- Low purity CO₂

Turbines

- Turbines compatible for CO₂ recycle, retrofit applications - existing infrastructure is huge
- Investigate use of smaller gas turbines (less than 5 MW) which have “disposable” interval (similar to microturbines)
- Trace element issues
- Solar panels to provide power to the gas turbines to reduce parasitic losses

Purity

- Low purity CO₂ to save costs (70-90%)
- Variability in NG composition - an issue? Or is there technology in place to cope?
- Need to define purity of CO₂ needed for EOR @ Prudhoe Bay - greatly affects technical solution

O₂ membranes

- Development of ion transport membrane module for integration with gas turbine
- Membranes for “impure” O₂ feedstock

High temperature boilers (o₂)

- High temperature oxyfuel boilers (once through)
- Robust control system for oxyfuel boiler
- In-leakage in boiler is significant problem for oxyfuel in that it results in need for downstream cleanup

H₂O recycle

- Water/steam injection rather than CO₂ recycle
- For new GT, CH₄, O₂, steam to control firing temperature rather than flue gas recycle

Integration

- Improve economics by retrofit of HRSG, steam use to either process or EOR
- Oxygen/turbine exhaust feeding HRSG with CO₂ recycle combines with back end separation technology for CO₂ enrichment
- Use of low level heat (i.e. Condensed water from recycle circuit)
- Integration of CO₂ compression with O₂ plant refrigeration/energy cycle
- O₂/ CO₂ boiler for amine regeneration
- Integrate oxyfuel and post combustion capture
- Integration of an ITM O₂ system with a CO₂ recycle gas turbine (need to heat air to 800 C with an economizer)
- Advanced O₂/CO₂ CO₂ recycle combustion gas turbine integrated with an ion membrane based O₂ separation technology

Pressure Combustion

- Down hole combustion for thermal benefit
- CO₂, a small percent of O₂ to promote CO₂ and thermal enhanced oil recovery
- Develop pressurized boiler with turboexpander integrated with air separation unit
- Pressurized boiler/GT to reduce compression cost
- Direct condensation of CO₂ against air/seawater
- High pressure combustion of natural gas in CO₂/O₂ mixture
- High temperature, high pressure recuperative heat exchanger for advanced gas turbine cycle

Pre-Combustion Decarbonization

- Waste heat from nuclear plant to drive steam/CH₄ reform, CO₂ shift, CO₂ removal to H₂
- In situ COAL partial oxidation (POx coal or POx heavy oil to make CO and H₂)
- Hydrogen manufacture pre-reforming
- HRSG reforming
- Catalytic partial Ox
- Develop methane thermal cracking for H₂ with CO₂ produced by air regeneration
- Indirect reforming of methane by CH₄, C + H₂ reaction, i.e., cracking
- Better process for conversion CH₄ → H₂/CO biofermentation
- Use enriched air for POx or CPO → H₂/N₂ mixture

- Turbine designed for hydrogen at high efficiency
- Improved CO₂ recovery process generating CO₂ at high pressure
- Justify CO₂ production by use of H₂ for high value usage (e.g., fuel cells in cars)
- Turbine exhaust to drive steam/CH₄ + □□.to H₂
- Do something with heat rejected in shift - it equals reduced efficiency
- Integration of reformer and GT exhaust
- Low-cost adsorbent
- Low losses?
- Easier/cheaper regeneration
- SMR example - use Mr. Watson's Idea - burn CH₄ to drive SMR. So what about the CO₂ in that operation
- Reverse PEM operation to make O₂ and H₂: elect from solar or nuclear
- Enriched O₂ for SMR, POx via membrane
- Bulk H₂ CO₂ separation to download final purification
- Removal of CO₂ before CO₂ shift
- LT shift @ HT retain H₂ @ pressure

Syngas Production

- Flameless distributed combustion as POx and or SMR
- Syngas production with simultaneous h₂ removal (inorganic membrane)
- Simple compact SMR
- Isothermal SMR
- Isothermal h₂ combustion
- Cheap reactor
- Improve existing steam reforming
- Isothermal Pox
- New reforming catalysts
- Scalable SMR

CO₂ recovery

- New amine/solvents
- Increase pressure of CO₂/H₂
- Solvent for CO₂ removal
- Inorganic membranes
- Develop membrane separators
- Membrane H₂ separation (no water gas shift)
- Operate at high pressure

Power block

- Optimize fuel vs. power
- Improve combustion efficiency
- Advanced GTS
- Fuel cell combined cycle

CO Production

- Share costs with products other than co₂ (e.g., H₂ MeOH, FT liquids transport fuel)
- Make other products off-peak (e.g., pumped water, MeOH, compressed air)

Oxidant

- Air, electric motor or GT compressor
- O₂, cryogenics, membranes, PSA
- Half O₂, half air, polymer membrane
- System Integration
- Optimize functions that fit together
- Combine functions into one

Miscellaneous

- Integrate all components
- Solar arc heating of inputs
- Optimize CO₂ reduction
- Pre-heat CH₄/steam with waste heat of other industrial processes
- Integrate functions
- Integrate technologies

Maximizing sequestration in oil reservoirs**Key Points Unedited**

- Maximize CO₂ by reducing volume of H₂O injected, technology for mobility control
- Utilize water saturation of hydrocarbon leg for CO₂ storage
- Maximize sweep of hydrocarbon to provide max volume for CO₂ storage (also recover most oil)
- Optimize EOR vs. carbon sequestration by operational practice
- Late-life soaking
- Balance of risk of early CO₂ flood vs. standard water flood and WAG
- High pressure abandonment of CO₂ storage
- Economics - fully integrated with source, pipeline, CO₂ flood
- Optimize CO₂ composition, EOR vs. separation cost
- Monitoring/validation of historic CO₂ floods, where CO₂ has gone

Modeling

- Surface, sub (C+M + H + T)
- Integration of multiple existing models
- Validation
- What is accuracy requirement?
- Understand key parameters (simplify)
- Collaborative team - new vs. existing (JIP)

Process Understanding

- Field sampling, analysis
- Lab studies
- Modeling studies
- Seal integrity

Sensing/Monitoring

- Effective/affordable
- Scout existing technologies
- Real-time reservoir visualization

- Test case
- Other JIPs? Consider CO₂ sequestration, influence their work
- Imaging through wells

Pilot Test

- 5 wells minimum
- Minimum drilling, costs
- Known properties
- CO₂ cost/availability
- Instrumentation?
- Timing - when to do for conclusive results?
- What to measure?

Old Field Tests

- Screen sites
- How much can you sequester
- The other bookend from EOR
- Multiple pilots?
- Study/understand existing CO₂ source fields

Collaboration (how?)

- Workshops
- Govt facilitation
- Access to private data
- Note to Sir John, divulge data, confidentiality issues
- Universal/individual links
- “JIP” participation by nonprofits
- Work-in-kind
- Royalty
- IEA involvement
- Intellectual property rights
- Look for models from other industries
- Advisory boards

Measurement and Verification

Subsurface Measurements

- How are techniques used together?
- Need for small scale pilots
- Important to learn from early projects. Assume that measurement requirements will be less as experience is gained.
- Detailed chemical analysis - filling porespace vs. Chemical reactions.
- Core analysis for certain forms of geological sequestration
- Losses to EOR to water, other areas?
- Inexpensive geological tracers for evaluating solubility and mineral trapping
- Fluid flow tracer studies
- Need experimental data, not just models

Implementation/Technology Transfer

- How can we best use the knowledge from CO₂ flooding and natural CO₂ field characterization to validate the verification of CO₂ sequestered?
- Definition of method of sequestration. (Trapping, conversion to solids, dissolution)

Geochemical Measurements

- Consistency in measurement and verification. Industry methods & international variations
- Work on subsurface monitoring
- Geology of reservoirs
- Upgrading measurement techniques. As new techniques become available what will be the effect on current systems and sequestration figures.
- Coal characterization. Measurements to generalize predictive models.
- A large number of methods and techniques can be employed now, with needed incremental improvements.
- Reservoir engineering methods, pressure transient analysis, modeling, history matching
- Electrical methods (logging etc)
- Modeling & simulation of CO₂ sequestration. Basic measurement to calibrate models
- Maintaining CO₂ in a hydrodynamic trapping environment. Where does it go - issue in subsurface property rights.
- Monitoring can also impact economics of sequestration if incorporated into decisions for injection strategy
- Fundamental measurements of sequestered volumes.
- Mass measurement of tonnes of CO₂
- Need for integration of monitoring data
- Development of in-place monitoring devices needs to be carried out
- Need for basic work to better interpret geophysical measurements
- Need to look at tools like: surface displacement, tiltmeter, altitude changes
- Seismic methods including 2, 3, 4D and cross well
- Resolution of geophysical techniques - present seismic and electric are insufficient
- Leak detection requires higher resolution. Seismic tool is needed for resource assessment

Verification and Audit

- Don't over complicate. This is just custody / title transfer. Specs, exchange location, physical measurements, audit issues.
- Standardize verification based on capture and sequestration methods
- Time period for implementation of measurement. How long will development take? Base date is getting further back in time.
- Who is generating the data?
- Too much cost will be shed to industry. Governments are making the pledge while industry is responsible for achieving the results.
- New world! How do we measure leaks?
- How do we evaluate and compare the efficiency of various monitoring methods? We need templates to do that.
- We must give thought to how people could commit fraud.
- Who will do the verification?

- How do we make sure that we have good information transfer between various monitoring projects? Avoid wheel reinvention.
- Trading verification & reporting
- Cost of verification

Cost of Verification

- Focus on leaks from existing wells. Preemptive capping possible?
- Well performance CO₂, oil, gas, water in and out of wells
- Establish an industry bond - performance instrument so that by meeting a standard you in effect self-insure performance that creates value to the buyers.
- Add to the team - audit, accounting, and transactional skills. Bring in EY, AA, ECT, to then create an acceptable third party marketplace
- Use natural gas measurement technology as a starting point.
- Need economic model for verification of costs and reduction potential
- Reporting requirements, standards, and value/cost of sequestration?
- Define rules, volumes or storage period. Who is making the rules?
- Use NYMEX natural gas trading rules as an example for turning CO₂ into a tradable item.
- Forecasting sequestration leads to trading futures?
- Apply different weights to various sequestration methods depending on the risk of capture and chance of leakage.
- Need to include the CO₂ produced by equipment and processes of sequestration
- NGO views
- Net sequestration is main issue
- Cost of measurement, continuous monitoring versus periodic measurements
- Is labor a major component of costs?
- Remote unmanned monitoring sessions. Transition from PhDs to technicians
- Measurement and verification accuracy should not exceed the value transferred.
- Two levels (safety & accounting). For accounting there is an optimum expenditure on measurement (could assume some losses, take less credit, and measure less)
- Measurement cost likely to have big economies of scale
- Use systems approach - net CO₂ sequestered by activity

Public and Regulatory Perception

- Tracers for different types of flow - through seals, through wellbores, through wellbores to fractures for lateral movement
- CO₂ is not that hazardous except in very high concentrations
- CO₂ is not like a hazardous waste but the models and predictions will be viewed skeptically by public given the history of the petroleum industry and DOE. How can we more effectively educate the public and regulators
- Magnitude of impact on potable water? CO₂ & formation water, others. Prevent being blindsided.
- State agencies & conservation commissions charge is to maximize resource recovery. How can they be stimulated to develop compatible rules to maximize CO₂ sequestration?
- Type of storage important? 100% "fixed."
- Retention in our property. Royalty & landowner issues?
- Keep an eye toward an end result that can be easily applied to accountants, lawyers, and commercial transactions. Rules of thumb, charts with assumptions.

- Public, non-scientists must understand verification methods. Outreach - how?
- Bridging the gap between technical results and public perception? The waste isolation analogy.
- Property owners as stakeholders
- Methods must be transparent and easy to understand

Field Geology – Physical Properties

- Seal integrity - performance to what level?
- Volume, physical measurements (pressure, temp, time)
- Rock properties, permeability, porosity, density?
- Phase behavior measurements and modeling for: gas adsorption on coal, CO₂/saline aquifers including reduction kinetics
- Unintended consequences - the MTBE analogy
- How much space for interaction is there?
- Need system to detect and locate micro-seismic events related to CO₂ injection into the reservoir
- Who owns the aquifer
- Geologic - mineral rights. Ownership and international border issues.
- Proposal 100 years may be sufficient. Similar to global warming political base
- Public education
- Public perception, far from population centers. Would reduce public relations issues?
- Areal sensing for CO₂ leaks.
- Real time remote sensing techniques to verify estimation methods (short term)
- Assessment of leakage from cap-rock into the surface
- Seismic & electrical geophysical methods (including logging)
- High resolution seismic imaging techniques for tracing CO₂ migration
- Earth science, seismic containment & movement
- Monitor wells (logging)
- Need system to make time lapse images of CO₂ in reservoir
- For quantitative interpretation. Establish fundamental relationships between geophysical measurements (electrical & seismic) to properties of interest (CO₂ concentration/phase)
- Reservoir-scale electrical imaging
- 4-D seismic
- Seismic techniques for fluid fronts
- Role of seismic. Cost effective? How to make it cost effective?
- Reservoir models for performance assessment, optimization, and verification
- Modeling of CO₂ injection, migration, sequestration, and storage
- Dynamic reactive transport models for predictions of behavior. Design input for measurement and observations. Timeframe for monitoring.
- Advanced reservoir modeling techniques
- Reliable models for predicting and verifying CO₂ migration in the subsurface
- Atmospheric transport models for evaluating dispersion of CO₂
- Geology: structure, rock type, flow units
- Compilation of existing relative available data for a common data base
- Assessment of reservoirs for potential capacity for CO₂ storage.
- Assessment of available reservoirs that have the integrity to sequester CO₂.

- Assessment of existing reservoirs that are presently in permitting category for injection (CO₂ N₂, waste, etc.)
- Priority ranking of reservoirs with numerous wells which could be used for monitoring wells
- Priority ranking of reservoirs that need additional basic data for use as CO₂ storage site. Core data, permeability, porosity, faulting) well logs, seismic, etc.
- Assessment of relative existing available data in coal, oil/gas, and saline reservoirs.
- Assessing natural fractures

Framework for Commodity Trading

- More than gauges and meters. Need framework for quality and quantity of sequestration. Discounting?
- How do you respond to an individual who proclaims that he/she contributes to CO₂ sequestration by planting trees?
- How to make verification and measurement methods agreeable internationally?
- Commodity exchange development
- Develop a standard for sequestration like used in the oil industry for reserves (Proven, probable, Possible)
- Do we need any penalties associated with false declaration of capture & sequestration?
- Sequestration capacity assessment

CO₂ Accounting Framework

- Knowledge of fuels and carbon content
- Consistent estimation methods for industry sectors
- Verify containment - volumetric & material balance
- Efficiency of CO₂ recycling from CO₂ rich gas streams
- CO₂ cogeneration rates for different compression configurations
- Need baseline data of high quality and low costs
- Traceability of estimation methods
- Prepare reports
- Energy balance accounting
- Net or gross sequestration - financial statement parallels
- Instrumentation and measurements
- Metering of injection and withdrawals
- Establish CO₂ monitoring program of injection and leakage
- Instrument quality assurance
- In-line sensors for pressure, temperature, and chemistries
- Fast analytical techniques for reliable determination of CO₂ and methane in presence of higher hydrocarbons
- In-situ sensors (not really available for all needs)
- Compositional analysis of injectants
- Leakage rates for delivery systems
- CO₂ leakthrough rates for Oil and gas reservoirs
- Monitoring of CO₂ concentrations at the surface
- Inexpensive surface CO₂ monitoring for leaks in surface facilities and from subsurface

Integrity of Engineered Subsurface Structures

- Well design
- Records of old plugged wells
- Mechanical integrity tests on wells
- Well monitoring, sampling, pressure measurements
- Monitor annulus pressure of injection wells
- Quick and easy reservoir pressure and testing methods
- Smart wells
- Studies on effects of CO₂/water on wellbore cements and casing
- Wellbore integrity
- Fracture testing

Incentives, Emissions Trading, and Public Policy**Incentives**

- Cabinet/presidential level recognition
- DOE or other government recognition - CO₂ award
- Royalty provisions
- State EOR royalty release
- Buydown programs
- Industry cost-sharing to enhance achieving matching federal funds
- Cost sharing of first of a kind projects
- Incentive pricing a la section 29
- Demonstrate corporate profits
- Expensing/accelerated depreciation
- Obtain tax credits for industry R&D
- Tax incentive
- Tax credits for “qualifying” investments
- Tax credits for early action
- Tax incentives for “novel”/new capture and sequestration technologies
- R&D tax credit for geo sequestration (climate or oil supply rationale)
- Investment tax credits tied to the value of CO₂ avoidance
- Develop model tax incentives (e.g., add valorum, sales, capital equipment, power severance carbon)
- Tax credit for military use/application (defense has established goals for emissions reduction)
- Credits
- Targeted volume program with available guaranteed credit with cap on total
- Be an umpire, develop mechanism for recognition/credit of CO₂ capture and sequestration

Barriers

- Develop information on low-cost capture/sequestration options
- Be proactive in establishing rational monitoring and verification standards and model regulations (for injection/sequestration, transmission)
- State level actions to develop measurement and verification standards
- Interstate transport issues need to be addressed (Kentucky CO₂ emissions sequestered in CBM in Ohio, gas burned in Michigan)
- Need emissions trading! (Commercialize CO₂)

- Defuse possible opposition by broadening technology applications to include all GHG emitters (i.e., landfill)
- Determine “playing rules” e.g., emission ceilings, baselines, etc.
- Ensure geo-sequestration included in international policy development (through home country)

Direct R&D funding

- Highlight importance of R&D investments in GHG issues
- Tax credits for R&D
- Advanced appropriation (CCT)
- Targeted program with separate appropriation
- Ensure a legislative champion (Murkowski, Stevens, Young)
- Sponsorship of projects in developing countries
- Funded technology transfer linked to JIPs
- Revolving fund
- Cost-sharing funding of RD&D to produce info for design of incentives and market based mechanisms
- Science R&D support linked to JIP
- Identify critical technology gaps and
- Development of policy and impact assessment tools
- Develop technologies appropriate to independents, capture, and sequestration
- Monitoring and verification to form a basis for permitting, emissions trading, and CO₂ credits

Cross-cutting

- Develop partnerships with NGOs, including environmental (this will be a big challenge)
- Develop industry coalition (majors, independents, utilities, suppliers, transportation companies, royalty owners)
- Public education (K-16, general public, community)
- Develop mechanisms for tech transfer, show importance of JIPs in developing technology

CO₂ Capture and Sequestration Scenario Candidates

CCP technology development work is being carried out in the context of reasonable scenarios that fit real industrial operations. Each participant proposed scenarios that they believed best fit their needs and that had general application in their industries. The proposed scenarios were reviewed, modified, and agreed by the technology teams and leadership. This section describes the candidate scenarios for archival purposes. The four scenarios selected for further development were:

CCP Selected Scenarios

Scenario	Fuel Source	CO ₂ Source	Geologic Sink	Location
Refinery	Hydrocarbon Gas & Liquids	Heaters & Boilers	Offshore EOR	European Refinery
Very Large Gas Turbines	Natural Gas	Large Electric Power Generation (CCGT)	Saline Aquifers Offshore EOR	Western Norway
Distributed Gas Turbines	Natural Gas	Small Distributed turbines	Onshore EOR	Alaska North Slope
Gasification	Solid gasification	Steam, H ₂ & Electricity Cogeneration	Onshore EOR	Western Canada

Candidate Scenarios by Location

USA

1. Distributed gas turbines, viscous oil EOR - BP (Alaska)
3. Coal fired power plant, coalbed disposal - Chevron (mid West US)
4. Gas fired Steam Gen/CoGen, EOR in San Joaquin Valley - Chevron (US)
5. Power plant, onshore EOR - Shell (US or Canada)

Europe

2. Refinery/chemicals complex, offshore EOR or onshore coal - BP(UK)
7. Gas fired power plant, offshore EOR - Statoil (Norway)
8. Gas fired power plant with offshore disposal in saline formation - Statoil (Norway)

Canada

9. Petroleum coke fired boiler with distant onshore EOR - Suncor (Alberta)
10. Gas fired steam generation with onsite disposal in heavy oil - Suncor (Alberta)

Unspecified Location

6. Refinery/gas processing plant with non-EOR Disposal - Shell
11. Gas fired power plant with onshore EOR - Texaco
12. Solid fired industrial boiler with onshore EOR - Texaco

Candidate Scenarios by Application

Shaft Power / Electricity Generation

1. Distributed gas turbines, viscous oil EOR - BP (Alaska)
3. Coal fired power plant with coalbed disposal - Chevron (mid West US)
5. Power Plant With Onshore EOR - Shell (US or Canada)
7. Gas fired power plant with offshore EOR - Statoil (Norway)
8. Gas fired power generation with offshore disposal in saline formation - Statoil (Norway)
11. Gas fired power plant with onshore EOR - Texaco (no location given)

Heat / Steam Generation

2. Refinery / chemicals complex onshore coalbeds or offshore EOR – BP (UK)
4. Gas fired Steam Gen/CoGen with EOR in San Joaquin Valley - Chevron (Cal., US)
6. Refinery / Gas Processing Plant With non-EOR Disposal - Shell (no location given)
9. Petroleum coke fired boiler with distant onshore EOR - Suncor (Alberta)
10. Gas fired steam generation with onsite disposal in heavy oil - Suncor (Alberta)
12. Solid fired industrial boiler with onshore EOR - Texaco (no location given)

Candidate Scenario Descriptions

1. Distributed Gas Turbines
Sponsor: BP
Concept: Retrofit to existing distributed gas turbines used for compression and power generation. Capture via post-combustion or pre-combustion decarbonisation methods.
Size: Combination of 20 - 60 MW turbines with combined emissions > 2 Mte/year.
Parameters: CO₂ ~3% by volume in flue gas
 Pressure - Atmospheric
 Limited heat recovery
 Longer term option to supplement CO₂ supply from gas treatment
Sequestration: Onshore EOR (large undeveloped viscous oil reservoir within 30 miles.
Location: North Slope, Alaska
2. Refinery Complex
Sponsor: BP
Concept: Retrofit to existing refinery / chemicals complex - power plant with steam boilers and fired heaters. Capture via post-combustion, pre-combustion decarbonisation or oxyfuel methods.
Size: Power plant steam boilers ~ 2 Mte/year Fired heaters ~ 2 Mte/year.
Parameters: CO₂ ~10 - 12 % by volume in flue gas
 Multiple processes generating CO₂ give opportunity to optimise
Sequestration: Offshore EOR (requires 250 km pipeline)
 Onshore or offshore coalbeds
 Offshore saline formations
 Opportunity to optimise storage characteristics
Location: CO₂ capture: Grangemouth refinery, Scotland

Storage: Forties field, North Sea

3. Coal Fired Power Plant
Sponsor: Chevron
Concept: Retrofit to large existing coal-fired power plants.
Size: 1000 MWe power plant
Parameters: CO₂ ~10-14%
 Atmospheric pressure with limited heat recovery
Sequestration: Local deep unmineable coal seams or very large aquifers
Location: Midwest US
4. Gas Fired Steam Generation/CoGenerated Electricity
Sponsor: Chevron
Concept: Distributed gas turbines, large boilers, cogen plants
Size: 20 MWe to 300 Mwe
Parameters: Light oil in diatomite formations
Sequestration: EOR
Location: San Joaquin Valley, California
5. Gas Fired Power Plant
Sponsor: Shell
Concept: New build
Size: 100 - 500 MW
Parameters: 100-300 km pipeline to EOR sites
Sequestration: Onshore EOR
Location: US or Canada oil fields
6. Refinery/Gas Processing Plant
Sponsor: Shell
Concept: Refining, gas processing plants with potential for easy capture of CO₂ particularly during upgrading of processes. Disposal to saline aquifer or other nearby non-EOR related sink.
Size: Not specified
Parameters: Not specified
Sequestration: Not specified
Location: Not specified
7. Gas Fired Power Plant
Sponsor: Statoil
Concept: 400 MW natural gas fired combined cycle power plant at Kårstø (onshore gas terminal) Pre- or post combustion CO₂ removal of approx. 1 Mt CO₂/year. Gullfaks EOR using 1.5Mt/y NGL & 1 Mt/y CO₂
Size: 400MW natural gas >1 million tonnes CO₂/ year
Parameters: 2-3% CO₂ in exhaust gas. Gas processing plant via pipeline offshore for sequestration.
Sequestration: EOR at Gullfaks
Location: Norway onshore plant to offshore fields
8. Gas Fired Power Plant
Sponsor: Statoil

Concept: Provide power for gas compression and transport. Gas turbines with CO₂ recovery placed onshore with power transmitted by cable to offshore sites or placement of gas turbines with CO₂ recovery offshore.

Size: 40 MW in 2005 and 40 MW in 2008

Parameters: 2-3% CO₂ in exhaust gas. CO₂ storage in the Utsira formation or in combination with the Gullfaks scenario. CO₂ tax for offshore applications is approx. 35 US\$/tonne.

Sequestration: Saline formation (Utsira) or EOR Gullfaks.

Location: Kollsnes Onshore Plant to Troll Field, Norway

9. Coke Fired Boilers

Sponsor: Suncor

Concept: Existing coke boilers retrofit for post combustion capture via amines or other process. As an option could consider coke gasification with H₂ boilers or gas turbine

Size: 3 boilers @ 900 klbs/hr steam. 320 Tonne/hr CO₂ (2.8 Mte/year)

Parameters: CO₂ ~15% by volume in flue gas. Pressure - Atmospheric
Temperature: 140 F. Gas exiting flue gas desulphurizer that has removed SO₂.

Enhancement available by combining with H₂ plant offgas which is 92% CO₂ (dry basis) and has 35 Tonne/hr CO₂ available at 15 Psig (0.3 Mte/year)

Sequestration: Onshore EOR (300-500 km pipeline to multiple EOR sites)

Location: Extraction - Fort McMurray, Alberta
EOR - Central Alberta

10. Mixed Fuel Steam Generation / Electricity Cogeneration

Sponsor: Suncor

Concept: Petroleum asphaltenes gasifier with O₂ plant & H₂ burning cogen. Greenfield steam and electricity co-generator for heavy oil development. Options could include coke gasification from nearby oil sands plant.

Size: 100,000 B/d heavy oil production

1000 MW of low-pressure steam generation for steam flood

500-600MW of Electric Power export

Parameters: Asphaltene custom distilled from heavy oil on site to suit thermal needs. CO₂ separated after gasifier for offsite EOR. Steam generation at high pressure for efficiency and let down to injection pressure through power generating turbines.

Sequestration: Onshore EOR. Needs 500 km pipeline to multiple EOR options.

Location: Extraction - Firebag SAGD Project near Fort McMurray
EOR - Central Alberta

11. Gas Fired Power Plant

Sponsor: Texaco

Concept: A new technology that would replace a large-scale turbines that are currently used to supply electrical power for a private or commercial grid and waste heat or other secondary energy recovery technology. The fuel would be natural gas, but precombustion carbon extraction should be considered. Oxyfuel and postcombustion extraction should also be considered as an alternative.

Size: 4 GE Frame 7 or 2 GE 7F gas turbines (350 MW total)

Parameters: Land-based although offshore injection is a possibility. A Break-through technology is sought for new development opportunities that would be implemented in the next 6 to 10 years.

Sequestration: EOR in light oil (50 mile pipeline required)

Location: Not specified.

12. Coke Fired Steam Generation

Sponsor: Texaco

Concept: A technology that would utilize coke, coal or other high carbon content fuel as the energy source for an industrial scale boiler or steam generator. A major goal of the sequestration portion of this project should be directed to the definition of the most favorable reservoirs setting for geological carbon sequestration given all opportunities.

Size: Large enough to provide economy of scale for the carbon capture operation.

Parameters: Land based operations should be the focus for carbon capture with the opportunity of offshore injection. The sequestration portion should focus on reservoir characteristics for most economical storage. A break-through technology is sought for new development opportunities for utilization of our depleted oil and gas reservoirs for storage purposes

Sequestration: EOR (50 mile pipeline required)

Location: Not specified

Work Packages Considered in Analysis Phase

Oxyfuel Project Descriptions

Work Package Description			Oxyfuel Team		
Work Package No: 1	Start Month:	End Month:	Cost: (\$) 1 000 000		
Work Package Title: Advanced Gas Turbine Cycles with Water Injection (CES)					
	Work Package Leader	Other Partners With Major Involvement			
Partner Name		Boeing Rocketdyne (CES)	SINTEF		
Person Months					
Cost per Partner					
Other Significant Cost Items (Subcontractors plus costs)					

Objectives

Description of Work

New Advanced cycles dispense with flue gas recycle and instead use water injection to control flame temperatures. The system becomes a hybrid gas/steam cycle that has the potential for higher efficiencies than a pure gas turbine cycle. Cycles generally incorporate multiple turbine stages, often with reheat, with the high temperature characteristic of gas turbines and the high pressures found in steam turbines to produce the higher efficiencies.

Deliverables

Milestones and Expected Results

Scenario Fit Norwegian Onshore CCGT Power Generation – new build. Alaska Dispersed Gas Turbines – new build.					
Screening Score		Cost Metric Result (\$/tonne CO₂ avoided)	\$XXX	Suggested Regional Fund	
Risk to Delivery New combustion and turbine technology. Multiple turbines.					
Development Horizon Full Scale Demonstration – 2010.					

Work Package Description				Oxyfuel Team			
Work Package No: 2		Start Month:		End Month:		Cost: (\$) 250 000	
Work Package Title: Boilers/Heaters with Flue Gas Recycle							
	Work Package Leader	Other Partners With Major Involvement					
Partner Name		Mitsui Babcock	Air Products				
Person Months							
Cost per Partner							
Other Significant Cost Items (Subcontractors plus costs)							

Objectives**Description of Work**

A boiler or heater is fired with fuel (gas, oil, or solid) and oxygen instead of air. Flue gas is largely carbon dioxide and water. In order to moderate the combustion temperature, and so allow conventional combustion equipment to be used, a proportion of the flue gas is recycled back to the combustor. The flue gas is dried and the CO₂ is compressed for sequestration and storage.

Deliverables**Milestones and Expected Results**

Scenario Fit European Refinery – retrofit or new build. US Coal Boiler Power Generation – retrofit or new build.					
Screening Score		Cost Metric Result (\$/tonne CO₂ avoided)	\$XXX	Suggested Regional Fund	
Risk to Delivery Slight. Mostly proven technology.					
Development Horizon Full Scale Demonstration - 2004					

Work Package Description					Oxyfuel Team		
Work Package No: 3		Start Month:		End Month:		Cost: (\$) 1 000 000	
Work Package Title: Ceramic Membrane ASU–Integration With Combustion–Advanced Boiler							
	Work Package Leader	Other Partners With Major Involvement					
Partner Name		Praxair	Alstom Power	Norsk Hydro			
Person Months							
Cost per Partner							
Other Significant Cost Items (Subcontractors plus costs)							

Objectives**Description of Work**

Integration of high-temperature oxygen-ion-transport ceramic membranes within the combustion process will offer significant reductions in the cost of oxygen production. Contacting low oxygen-content combusting, or recycled, flue gases with the downstream surface of the membrane reduces, or may even eliminate, the pressure difference required for oxygen production. The thermal integration between the high temperature membrane and the combustion process further enhances process efficiency.

Deliverables**Milestones and Expected Results**

Scenario Fit European Refinery – new build. US Coal Boiler Power Generation – new build.					
Screening Score		Cost Metric Result (\$/tonne CO₂ avoided)	\$XXX	Suggested Regional Fund	
Risk to Delivery Significant amount of new technology development.					
Development Horizon Full Scale demonstration – 2010.					

Work Package Description				Oxyfuel Team			
Work Package No: 4		Start Month:		End Month:		Cost: (\$) 1 000 000	
Work Package Title: Ceramic Membrane ASU – Integration With Combustion – Gas Turbine							
	Work Package Leader	Other Partners With Major Involvement					
Partner Name		Norsk Hydro	Alstom Power				
Person Months							
Cost per Partner							
Other Significant Cost Items (Subcontractors plus costs)							

Objectives

Description of Work

Integration of high-temperature oxygen-ion-transport ceramic membranes within the combustion process will offer significant reductions in the cost of oxygen production. Contacting low-oxygen-content combusting, or recycled, flue gases with the downstream surface of the membrane will reduce, or eliminate, the pressure difference required and result in an increased oxygen driving force across the membrane. This thermal integration of the combustion process and the membrane allows for efficient attainment of the membrane operating temperature. In addition, a reduced pressure drop of the recovered oxygen can be achieved by using pressurized combusting gases or recycled flue gases as sweep gas for the downstream surface of the membrane.

Deliverables

Milestones and Expected Results

Scenario Fit Norwegian Onshore CCGT Power Generation – new build or retrofit (AZEP). Alaska Open Cycle Gas Turbines – new build or retrofit (AZEP).					
Screening Score		Cost Metric Result (\$/tonne CO₂ avoided)	\$XXX	Suggested Regional Fund	
Risk to Delivery Significant amount of new technology development.					
Development Horizon Full Scale demonstration – 2010.					

Work Package Description				Oxyfuel Team			
Work Package No: 5		Start Month:		End Month:		Cost: (€) 1 414 000 CCP Funding: €320 000	
Work Package Title: Chemical Looping Combustion							
	Work Package Leader	Other Partners With Major Involvement					
Partner Name	BP	Chalmers University	TU - Vienna	ICB - CSIS	Alstom Power		
Person Months	6	68	36	72	6		
Cost per Partner	150 000	594 000	180 000	390 000	100 000		
Other Significant Cost Items (Subcontractors plus costs)							

Objectives

To develop the knowledge and technology required allowing for the construction of a demonstration plant. This includes work in four distinct fields.

- Manufacture and comprehensive testing of oxygen carrier particles.
- Fluidizing conditions and solids recirculation.
- Demonstration and evaluation of this new combustion technology and verification of the oxygen carrier particles in a bench-scale chemical looping combustor.
- Completion of a feasibility study and economic model for the next stage demonstration plant.

Description of Work

Chemical cycles separate oxygen from air and deliver it to the combustion process. Oxygen in air is reacted with, for example, a metal to produce an oxide. This, in effect, plays the role of an air separation unit. The oxide is then reacted with the hydrocarbon fuel resulting in carbon dioxide, water, and the metal again. The process would be carried out in a circulating fluid bed system, analogous to CFB combustors, in which the two reactions take place in separate beds. The metal/metal oxide, deposited on a suitable substrate, is transported between the two reactors.

Deliverables

Data on reactivity and particle integrity for a large number of oxygen carrier materials. A selection of the best candidates for testing.

Experimental results from particle testing including solid conversion rates, particle integrity, and the effect of temperature, fuel, and particle size on reactivity.

Design and operation of a bench-scale chemical looping combustor.

Basic engineering of an industrial plant including main process flow diagrams and main Chemical Looping Combustion equipment sizing. Estimates of equipment and operating costs. Preliminary conclusion on plant feasibility.

Milestones and Expected Results

Experimental particle testing results.

Selection of best oxygen carrying particles.

Design and manufacture of Cold Flow Model for the fluidized beds.

Design and construction of Chemical Looping Combustor (CLC).

Demonstration of a bench-scale CLC.

Basic Feasibility Study for the next stage demonstration plant on a semi-industrial scale.

Scenario Fit European Refinery – new build. US Coal Boiler Power Generation – new build.					
Screening Score		Cost Metric Result (\$/tonne CO₂ avoided)	\$XXX	Suggested Regional Fund	European Union
Risk to Delivery Significant new technology development.					
Development Horizon Full Scale demonstration – 2010.					

Work Package Description				Oxyfuel Team			
Work Package No: 6		Start Month:		End Month:		Cost: (\$) 1 000 000	
Work Package Title: CCGT with Flue Gas/Steam Recycle (HiOx/Graz)							
	Work Package Leader	Other Partners With Major Involvement					
Partner Name		Aker Maritime	Alstom Power	TU Graz			
Person Months							
Cost per Partner							
Other Significant Cost Items (Subcontractors plus costs)							

Objectives

Description of Work

Instead of air, recycled flue gas is used as the working medium in the gas turbine. Pure O₂ is mixed with fuel in the combustor and a portion of flue gas recycled back to the combustor controls the reaction temperature. Since the combustion product contains mainly CO₂ and water, more advanced gas turbine cycles may be developed that could improve the energy efficiency compared to the use of the more conventional gas turbine cycle.

It is felt that the additional integration of a steam recycle will result in further cycle efficiencies. It is proposed that components of a natural gas fired Graz cycle be integrated into the existing HiOx program currently under review by the CCP.

Deliverables

Milestones and Expected Results

Scenario Fit Norwegian Onshore CCGT Power Generation – new build Alaska Open Cycle Gas Turbines – new build					
Screening Score		Cost Metric Result (\$/tonne CO₂ avoided)	\$XXX (HiOx) \$XXX (HiOx/ Graz integrtrion)	Suggested Regional Fund	
Risk to Delivery A new gas turbine using carbon dioxide as the working fluid needs to be developed.					
Development Horizon Full Scale demonstration – 2004.					

Work Package Description				Oxyfuel Team			
Work Package No: 7		Start Month:		End Month:		Cost: (\$) 1 000 000	
Work Package Title: Zero or Low Recycle Boiler							
	Work Package Leader	Other Partners With Major Involvement					
Partner Name		Alstom Power	Praxair				
Person Months							
Cost per Partner							
Other Significant Cost Items (Subcontractors plus costs)							

Objectives**Description of Work**

For new plant builds, oxyfuel boilers can be redesigned to take advantage of the lower combustion gas flows and higher heat fluxes possible if flue gas recycle is reduced or eliminated. The technology involves flameless combustion with oxygen. The oxidant and fuel are added separately into a combustion chamber that behaves like a well-stirred reactor. The low oxygen concentration in the diffuse combustion zone results in low NO_x emissions, more uniform temperature and heat flux distributions, and lower peak temperatures.

Deliverables**Milestones and Expected Results**

Scenario Fit European Refinery – new build. US Coal Boiler Power Generation – new build.					
Screening Score		Cost Metric Result (\$/tonne CO₂ avoided)	\$XXX	Suggested Regional Fund	
Risk to Delivery The theory is not complex but the technology is unproven.					
Development Horizon Full Scale demonstration – 2010.					

Work Package Description				Oxyfuel Team			
Work Package No: 8		Start Month:		End Month:		Cost: (\$) 1 000 000	
Work Package Title: High Pressure Boiler							
	Work Package Leader	Other Partners With Major Involvement					
Partner Name		SINTEF	Mitsui Babcock				
Person Months							
Cost per Partner							
Other Significant Cost Items (Subcontractors plus costs)							

Objectives**Description of Work**

Operation of an oxyfuel boiler combustion system at an elevated pressure would significantly reduce the cost of compression of the CO₂ product and may also make result in a more compact boiler design. It is envisaged that the optimum pressure would be below that at which the CO₂ becomes dense phase to facilitate the physical separation of the water content and to avoid the most energy intensive part of CO₂ compression. (200 kPa – 3000 kPa)

Deliverables**Milestones and Expected Results**

Scenario Fit European Refinery – new build. US Coal Boiler Power Generation – new build.					
Screening Score		Cost Metric Result (\$/tonne CO₂ avoided)		Suggested Regional Fund	
Risk to Delivery Relatively simple but unproven technology.					
Development Horizon Full Scale demonstration – 2010.					

Post-Combustion Project Descriptions

Work Package Description			Post-combustion		
Work Package No: 1	Start Month: 01.04.2001	End Month: 01.04.2002	Cost: (\$) 600 000 2001: (\$) 500 000		
Work Package Title: Kvaerner/MHI Amine Scrubbing					
	Work Package Leader	Other Partners With Major Involvement			
Partner Name	SL (MS)	Kvaerner	MHI		
Person Months (2001)	6				
Cost per Partner					
Other Significant Cost Items (Subcontractors plus costs)					

Objectives

Establish and document the feasibility of the Kvaerner Membrane System in combination with MHI amine solvent for CO₂ separation for the CCP scenarios. Verify the potential for significant operational benefits and cost reductions.

Description of Work

Task 1. - Run the MHI solvent in the SINTEF/Kvaerner laboratory test unit (approx. 5 weeks).

Task 2. - Verify task 1 results by pilot testing at Karsto (approx. 15 weeks).

Task 3. - Carry out a pre-engineering study for a full scale onshore CO₂ separation unit, using the Norwegian Scenario as a design basis (approx 10 weeks).

Deliverables Reports on the testing and study described above.

Milestones and Expected Results

Successful completion of laboratory testing, with no showstoppers identified, followed by pilot testing at Karsto using existing membrane module designs, or low cost modifications. Delivery of a pre-engineering report, utilizing the MHI process design and membrane contactor, showing a substantial reduction in cost, compared to the baseline.

Scenario Fit

All scenarios with the exception of the Canadian. The Kvaerner membrane contactor is expected to be applicable to the Canadian scenario, utilizing a different solvent eg. BASF's activated MDEA.

Screening Score	75	Cost Metric Result (\$/tonne CO ₂ avoided)	\$XXX	Suggested Regional Fund	Norway
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Risk to Delivery

Low risk – failure of MHI and Kvaerner to co-operate, KS-1 solvent incompatibility with the ePTFE membrane.
Medium risk - failure to achieve the expected cost reductions.

Development Horizon

Proof of concept possible this year. Demonstration project start as early as 2002 could be possible.

Work Package Description				Post Combustion			
Work Package No: 2		Start Month: 01.08.2000		End Month: 31.12.2003		Cost: (\$) 4 500 000 2001: (\$) 300 000	
Work Package Title: Electric Swing Adsorption							
	Work Package Leader	Other Partners With Major Involvement					
Partner Name	EA (DE)	KPS	ORNL	SGI	ARI		
Person Months (2001)	5						
Cost per Partner							
Other Significant Cost Items (Subcontractors plus costs)							

Objectives

Establish and document the feasibility of the Electric Swing Adsorption System for CO₂ separation for the CCP scenarios. Verify the potential for significant operational benefits and cost reductions.

Description of Work

Task 1 – Development and laboratory testing of the carbon material.

Task 2 – Pilot testing.

Task 3 – Engineering development of the adsorption system.

Task 4 - Carry out a design study and cost estimate for a full scale onshore CO₂ separation unit, using the Norwegian Scenario as a design basis.

Deliverables Reports on the testing, adsorption system and study described above.

Milestones and Expected Results

Complete laboratory testing by mid 2002. Carbon structure optimized for pressure drop, adsorber size and CO₂ removal capacity, amount of power required. Complete pre-engineering by the end of 2001.

Complete pilot plant design by end Q3 2002. Pilot plant to be operational by end Q1 2003. Proof of concept by end Q4 2003.

Scenario Fit

All scenarios.

Screening Score	85	Cost Metric Result (\$/tonne CO₂ avoided)	\$XXX	Suggested Regional Fund	Norway
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Risk to Delivery

High risk – aggressive schedule, too low adsorption capacity, too high regeneration power, costs.

Development Horizon

Has potential for full scale application by 2010.

Work Package Description				Post Combustion			
Work Package No: 3		Start Month: 01.01.2002		End Month: 01.10.2002		Cost: (\$) 500,000 2001: (\$) 0	
Work Package Title: Minimum Standards							
		Work Package Leader	Other Partners With Major Involvement				
Partner Name		DC	To be bid				
Person Months (2002)		8					
Cost per Partner							
Other Significant Cost Items (Subcontractors plus costs)							

Objectives

To significantly reduce the cost of post combustion capture by applying minimum, non oilfield standards. The work will recognize that the plant contains no hydrocarbon, and does not need to be as reliable as oil and gas production plant. Equipment sparing will be minimized/eliminated.

Description of Work

Task 1 - Document list of cost saving ideas.
Task 2 - Apply value analysis/engineering to screen out the best candidates.
Task 3 - Determine cost savings related to the Alaska Scenario.

Deliverables

A report on the study

Milestones and Expected Results

At the end of task 1, we would expect to have an agreed list of ideas to work on. At the end of task 2 we would expect to be able to identify those ideas which will be developed in the scenario estimate. Finally, a report on the engineering study and cost estimate.

Scenario Fit

Applicable to all the scenarios.

Screening Score	57	Cost Metric Result (\$/tonne CO₂ avoided)	\$XXX	Suggested Regional Fund	USA
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Risk to Delivery

Medium risk that the expected cost reduction will not be achieved.

Development Horizon

Study completed in 2002. Applicable thereafter.

Work Package Description				Post-combustion			
Work Package No: 4		Start Month: 01.01.2002 (?)		End Month: 31.12.2003		Cost: (\$) 1,400,000 2001: (\$) 0	
Work Package Title: Norsk Hydro in pipe technology – Heat Exchanger							
	Work Package Leader	Other Partners With Major Involvement					
Partner Name	MS (EA)	Norsk Hydro	Univ. of Newcastle	Triton			
Person Months	?						
Cost per Partner							
Other Significant Cost Items (Subcontractors plus costs)							

Objectives

To establish and document the feasibility of this technology being used for heat recovery and/or cooling of exhaust, in the exhaust duct.

Description of Work

Task 1 - Continue development engineering of the rotating heat exchanger, including building a mechanical model (pilot). The fan effect of the rotation serves to compensate for the implicit pressure loss across the heat exchanger. Engineer a means of transferring boiler feed water, steam and cooling medium between the heat exchanger and steam users etc.

Task 2 - Carry out experimental work in a hot gas stream and mathematical modelling to prove the concept, and provide design information.

Task 3 - Design a heat exchanger and produce a cost estimate for a Grangemouth Refinery boiler/heater exhaust duct.

Deliverables

Construction and assembly drawings, a working model (pilot) and report on the testing. Pre-engineering report and demo. plant cost estimate.

Milestones and Expected Results

Determined the optimum design and arrangement of fan/heat exchange elements. Produce drawings, construct and install a working model. Demonstrate the concept by operating the model. Design and estimate the cost of a device for a boiler/heater duct, showing a considerable saving on a fan and direct water cooler combination.

Scenario Fit

All scenarios. Potential for to use for combined cycle steam generators, as well as in simple cycle turbines and boiler/heaters

Screening Score		Cost Metric Result (\$/tonne CO₂ avoided)		Suggested Regional Fund	Europe
Risk to Delivery This is at a very early stage of development. Risk of failure is therefore high.					
Development Horizon Possible full-scale implementation by 2010, if substantial work can be done this year.					

Work Package Description				Postcombustion			
Work Package No: 5		Start Month: 01.01.2002 (?)		End Month: 31.12.2003		Cost: \$900,000 2001: \$0	
Work Package Title: Norsk Hydro in pipe technology – desorber							
	Work Package Leader	Other Partners With Major Involvement					
Partner Name	MS	Norsk Hydro	Univ. of Newcastl e	Triton			
Person Months	?						
Cost per Partner							
Other Significant Cost Items (Subcontractors plus costs)							

Objectives

To establish and document the feasibility of this compact rotating wheel desorber technology to be used for regeneration of CO₂ from rich amine. The intention is that the wheel periphery will contain the reboiler and the condenser will be located in the eye of the wheel. Mass transfer will take place between these two parts. Residence times will be very short minimizing solvent degradation.

Description of Work

Task 1 - Integrate a reboiler and condenser into previously developed Higee type technology. Produce a working pilot.

Task 2 - Carry out performance trials and mathematical modeling to enable demonstration plant design.

Task 3 - Design a desorber wheel and estimate the cost of such a unit for full scale demonstration at Grangemouth.

Deliverables

Assembly and construction drawings. A working model (pilot) and report on the testing and mathematical modeling. A report on the design and cost estimate for a full-scale demonstration.

Milestones and Expected Results

Proof of concept followed by an engineering design and cost estimate, showing a considerable saving when compared to a conventional packed column, reboiler and condenser combination.

Scenario Fit

Applicable to all scenarios.

Screening Score		Cost Metric Result (\$/tonne CO₂ avoided)		Suggested Regional Fund	Europe
Risk to Delivery This is at a very early stage of development. Risk of failure is therefore high.					
Development Horizon Possible full-scale implementation by 2010, if substantial work can be done this year.					

Work Package Description				Post combustion			
Work Package No: 6		Start Month: 01.04.2001		End Month: 31.12.2003		Cost: (\$) 2,900,000 2001: (\$) 600 000	
Work Package Title: Norsk Hydro in pipe technology – Absorber							
	Work Package Leader	Other Partners With Major Involvement					
Partner Name	MS	Norsk Hydro	To be chosen				
Person Months (2001)	5						
Cost per Partner							
Other Significant Cost Items (Subcontractors plus costs)							

Objectives

To establish and document the feasibility of this compact rotating absorber technology to be used for CO₂ removal from the exhaust duct.

Description of Work

Task 1 - Continue development work of the rotating absorber, including building a working model (pilot). The fan effect is designed to compensate for the implicit pressure loss across the absorber. It will also be necessary to design a means of transferring amine in and out of the rotor (see work package 4).
 Task 2 - Carry out performance trials and mathematical modeling to prove the concept and enable demonstration plant design.
 Task 3 - Design a rotating absorber and estimate the cost of such a unit for full scale demonstration within the Norwegian Scenario.

Deliverables

Assembly and construction drawings for a working model. A working model (pilot) and report on the testing and mathematical modeling. A report on the design and a cost estimate for a full scale demonstration.

Milestones and Expected Results

Proof of concept followed by an engineering design and a cost estimate showing a significant saving on the cost of a conventional packed column absorber and fan combination.

Scenario Fit Applicable to all scenarios.					
Screening Score		Cost Metric Result (\$/tonne CO₂ avoided)		Suggested Regional Fund	Norway
Risk to Delivery This is at a very early stage of development. Risk of failure is therefore high.					
Development Horizon Possible full-scale implementation by 2010, if substantial work can be done this year.					

Work Package Description								Post combustion	
Work Package No: 7		Start Month: 01.05.2001		End Month: 31.10.2001		Cost: (\$) 500,000 2001: (\$) 500 000			
Work Package Title: Base line studies									
	Work Package Leader	Other Partners With Major Involvement							
Partner Name	DC	CEM team	Fluor Daniel	?					
Person Months (2001)	4	3							
Cost per Partner									
Other Significant Cost Items (Subcontractors plus costs)									

Objectives

To establish base line costs for CCP scenarios.

Description of Work**Deliverables****Milestones and Expected Results****Scenario Fit**

Applicable to all scenarios.

**Screening
Score****Cost Metric Result
(\$/tonne CO₂ avoided)****Suggested Regional
Fund**

CCP

Risk to Delivery

Low risk.

Development Horizon

Work Package Description				Post-combustion	
Work Package No: 8		Start Month: 2001/3	End Month: 2001/12		Cost: (\$) 100 000
Work Package Title: Radical CO ₂ chemistry					
	Work Package Leader	Other Partners With Major Involvement			
Partner Name	NH(DE)	Norsk Hydro	NTNU, SINTEF	UiO, SINTEF	UiB
Person Months	2	4	1	1	1
Cost per Partner					
Other Significant Cost Items (Subcontractors plus costs)					

Objectives

Produce 1-4 project proposals for new ways of separating CO₂ from flue gas based on radical CO₂ chemistry.

Description of Work

Task 1. - Analyse results of first lateral thinking session in Feb 2001.

Task 2. - Develop the results further.

Task 3. - Formulate project proposals.

Deliverables Project proposals.

Milestones and Expected Results

Project proposal(s).

Scenario Fit

All scenarios.

Screening Score	Not done	Cost Metric Result (\$/tonne CO₂ avoided)		Suggested Regional Fund	Norway
Risk to Delivery					
High risk, limited costs.					
Development Horizon					
Project proposals within 2001 if successful, but these will probably have long development horizon(s).					

Pre-combustion Decarbonization Work Packages

Work Package Description Work Package No: Start Month: June 2001 End Month: Sept 2002 ¹ Expected Cost: (\$) 500K Work Package Title: Compact Reformer-Membrane Contactor Team : Pre-Combustion Work Package Leader : Jan Assink Partners With Major Involvement : Kvaerner Process Technology, GTI, (Sintef) Person Months 25 Other significant cost items; Laboratory testing costs and if progressed to task 6 Engineering of the slip stream test using existing contactor module. Objectives : Develop a combination of compact low cost syngas generation and CO ₂ Capture systems. These technologies are low risk, both being at the threshold of commercial application in pother applications, the objective here is to establish through experimentation and engineering design the feasibility and cost benefits of application to pre-combustion decarbonisation schemes. Each component can be used in conjunction with other technologies being developed under the program, giving wide applicability to the scenarios. The scenario forming the base case is a natural gas/refinery gas fed refinery fuel decarbonisation scheme.	
Description of Work Task 1. Laboratory Tests to confirm suitability of membrane contactor for HP Syngas use Task 2. Develop Process Design for Membrane contactor for syngas separation Task 3. Develop optimised PCDC flowscheme incorporating Compact Reformer and Membrane contactor Task 4. Undertake detailed cost estimation for construction of a PCDC scheme based on CR + Membrane contactor for Refinery (or Alaska) Scenario Task 5. Screen alternate compact and ultra compact designs (including microchannel types) for use in similar flowsheets Task 6. Subject to results of Tasks 1-4, Use Sage Module as slip-stream test unit on an existing syngas plant.	
Deliverables i. Confirmation of feasibility of membrane contactor in syngas operation ii. Development of a combined low cost syngas generation/CO ₂ capture process. iii. Estimated savings over baseline technology in Refinery (or Alaska) Scenario Milestones and Expected Results i. Q4 2001 Laboratory Work Complete ii Q2 2002 Flowsheets developed iii Q3 2002 Process cost estimates completed iv. Q3 2002 Screening of ultra compact SMR designs complete v. Q4 2003 Slip-Stream testing of Membrane Contactor Complete Potential Technology Providers and Geographic Location Kvaerner Process Technology in UK (Lead Contractor) and Kvaerner Oil & Gas in Norway Potential Sub-Contractors GTI - US (Sintef -Norway) Scenario Fit Combination of CR and Membrane Contactor fit Refinery and Alaska Membrane Contactor can be used in ALL scenarios Screening score TBD Cost Metric result 2 Risks to delivery Low – both component technologies at commercial stage in alternate applications – low cost easy hit. Suggested regional fund DOE Note 1. End date excludes Task 6 which would extend programme to end 2003.	
Work Package Description Work Package No: Start Month: 2002 End Month: 2003 Expected Cost: (\$) 0.1K Work Package Title: Electropox with best novel CO ₂ separation (Membrane WGS Reactor or ESA) Team : Pre-Combustion	

<p>Work Package Leader : Deferred Activity Partners With Major Involvement Norsk Hydro; SINTEF; Person Months 6 Other significant cost items</p> <p>Objectives Establish suitability of the Electropox concept (OTM/ITM incorporated into an autothermal reformer) for combination with the best CO₂ separation process being studied by CCP, ie. Membrane WGS, ESA and Membrane contactor by flowsheet development, simulation and cost estimation.</p>
<p>Description of Work</p> <p>Task 1. Establish process performance for an autothermal reformer process using OTM ceramic membrane technology combined with best CO₂ capture option identified from other workpackages, selecting from Membrane WGS reactor, ESA, Membrane contactor.</p> <p>Task 2. Estimate the costs for the process and economics of CO₂ capture for gas fed scenarios including refinery and gas turbine cases .</p>
<p>Deliverables Evaluation of performance and cost for the combined scheme, using data generated in other workpackages.</p> <p>Milestones and Expected Results Selection of best CO₂ capture system Electropox /novel separation system performance evaluation Economic evaluation</p> <p>Potential Technology Providers and Geographic Location</p> <p>SINTEF Norsk Hydro Praxair? Potential Sub-Contractors</p> <p>Scenario Fit Refinery; Alaska Gas Turbines; Norway CCGT Screening score 68 Cost Metric result 5 Risks to delivery IP issues for OTM ATR Suggested regional fund DOE</p>

Work Package Description	
Work Package No: Start Month: Q4 2001 End Month: Q4 2001 Expected Cost: (\$) 300 K Work Package Title: Electrical Swing Adsorption Team : Pre-Combustion Work Package Leader : Jan Assink Partners With Major Involvement Oak Ridge; Air Products; SGL Hitco Person Months 6 Other significant cost items Experimental evaluation of High Pressure capture of CO ₂ from Syngas Objectives: Determine feasibility, operating performance and costs of an electrical swing adsorption system for the separation of CO ₂ from syngas streams. Determine the feasibility of regenerating the system at elevated pressure to reduce the costs of compression of the CO ₂ Incorporate into most appropriate syngas generation scheme and recovery CO ₂ at maximum pressure.	
Description of Work	
Phase 1 Feasibility Assessment. 4-6 Months	
Task 1. Evaluate by experimental measurement the performance of a the existing carbon fibre material, establishing the CO ₂ removal capacity, regeneration energy requirement, the effects of regeneration at a range of pressures and the effects of probable contaminants on the adsorbent material and system performance. Use two model gas streams representing syngas from steam reformed natural gas and gasified heavy fuel. Task 2. Determine the equipment size and performance for an ESA system based on the measured experimental performance, undertake a preliminary feasibility assessment for pre-combustion system incorporating on ESA. Identify development needs for Phase 2.	
Phase 2 Development and Proof of Concept	
Task 3. Develop optimised adsorbent material to achieve acceptable separation efficiencies, resistance to degradation and manufacturing cost. Task 4 Undertake extended cycle trials and optimize the adsorption/regeneration cycle, developing a mathematical model of the process. Task 5. Develop a design for a large scale CO ₂ separation system and determine the costs for the system and production of the adsorbent. Task 6 Develop low cost pre-combustion schemes incorporate ESA and prepare equipment data to allow cost estimates to be prepared by the CCP common cost estimator.	
Deliverables	
Preliminary evaluation of the system for use in syngas	
Milestones and Expected Results	
Experimental results on syngas and feasibility assessment	
end Q2 2002	
Adsorbent development and system design/optimization	
end Q2 2003	
ESA System Cost and PCDC Scheme design	
end Q4 2003	
Potential Technology Providers and Geographic Location	
Oak Ridge Laboratory US; Air Products US; SGL Hitco US	
Scenario Fit	
ALL (gasification, steam reforming or ATR)	
Screening score	
81	
Cost Metric result	
4	
Risks to delivery	
Need for co-operative gas company	
Suggested regional fund	
DOE	

Work Package Description Work Package No: 7 Start Month: June 2001 End Month: Dec 2001 Expected Cost: (\$) 30,000 Work Package Title: IFE MeO Process Team : Precombustion Decarbonization Work Package Leader : Eline Vangden Jossang Partners With Major Involvement: IFE Person Months 2 Other significant cost items Objectives: Pre-evaluation of heat-and mass balances for the IFE MeO Process
Description of Work Task 1. Develop heat-and mass balances Task 2. Task 3. Task 4.
Deliverables : Study report Milestones and Expected Results : Report Potential Technology Providers and Geographic Location IFE : EU (Norway) Potential Sub-Contractors Scenario Fit: All Screening score: 80 Cost Metric result: 4 Risks to delivery : Low risk – only heat-and massbalances shall be provided Suggested regional fund : Work Package Description

Work Package Description Work Package No: Start Month: June 2001 End Month: Q4 2003 Expected Cost: (\$) EU \$5Million Work Package Title: Membrane Reformer Team : Pre-Combustion Work Package Leader : Henrik Andersen Partners With Major Involvement EU SINTEF; Univ. Twente; KTH; IRMERC; Univ. Zaragossa, FW Work Package Description Norsk Hydro Sintef, (ECN, Topsoe, Siemens,) Person Months EU 75 Work Package Description 70 K DOE 90K Other significant cost items Experimental Objectives Develop membrane reformer designs for use in precombustion decarbonisation of natural gas fuels for refinery, distributed gas turbine and CCGT applications. Incorporate these designs into integrated flowschemes for each scenario.
Description of Work Task 1. EU Develop and evaluate improved microporous and metallic membranes, test in experimental reactor systems develop a mathematical model of the reactor. Develop a reactor design for use in large scale CO₂ capture plant for a gas fuelled refinery scheme. Task 2. Klimatec Develop and evaluate a ceramic hydrogen transfer membrane (HTM) for membrane reformer service. Study combinations of OTM and HTM reactor systems and alternate fired reactor designs for use within the combined cycle gas turbine scenario, selecting the most economic arrangement.
Deliverables Membrane reactor schemes based on the three available membrane types and applied to an integrated combined cycle gas turbine and non-integrated combustion sources such as refinery or distributed gas turbines. Milestones and Expected Results Improved membranes developed and evaluated for performance and stability Mathematical model of membrane reformer tuned to experimental results Reactor designs developed for fired and integrated OTM/HTM reformer designs Potential Technology Providers and Geographic Location EU SINTEF; Univ. Twente; KTH; IRMERC; Univ. Zaragossa, FW Work Package Description Norsk Hydro Sintef, (ECN, Topsoe, Siemens,) Potential Sub-Contractors Scenario Fit Refinery, Alaska Gas Turbines, Norway CCGT. Screening score 66 Cost Metric result 3 Risks to delivery Significant technical challenge, IP issues for OTM, Suggested regional fund EU & Work Package Description

Work Package Description									
Work Package No: Start Month: Oct 2001 End Month: Dec 2003 Expected Cost: (\$) 2M Work Package Title: Membrane Water Gas Shift Reactor Team : Pre-Combustion Work Package Leader : Cliff Lowe Person Months Other significant cost items Lab testing & Materials Objectives : Develop membrane materials and reactor designs for application in pre-combustion scheme with fuel oil, and develop optimized process designs employing this technology.									
Description of Work									
<p>Phase 1. Develop and evaluate four membrane types suited to sour shift reaction systems base on palladium alloy; Zeolite; mixed conducting ceramic and microporous silica. Develop a gasification scheme employing membrane reactors and model the system performance. Identify the membrane with the highest overall performance and select for Phase 2 development work.</p> <p>Phase 2. Continue membrane development to optimise performance in the reacting system. Build and operate a laboratory scale membrane shift reactor under realistic conditions using the selected membrane type. Develop detailed mathematical model of the membrane reactor system. Apply the experimental results and mathematical model to develop a large scale reactor design. Undertake studies of the mechanical aspects of the design including membrane fabrication, reactor assembly, catalyst deployment and reliability. Develop an optimized gasification flowsheet incorporating the reactor design, estimate the costs and performance of fuel oil decarbonisation and CO₂ capture using this system.</p>									
<p>Deliverables : Improved membranes suited to water gas shift operating conditions operating in sulphur contaminated syngas conditions. Reactor designs which incorporate these membranes to achieve simultaneous CO conversion and CO₂ separation, greatly simplifying precombustion decarbonisation processes for all fossil fuel feed types. Milestones and Expected Results</p> <table> <tr> <td>Improved membranes for experimental evaluation</td><td>Q 4 2002</td></tr> <tr> <td>Membrane performance evaluation</td><td>Q 4 2002</td></tr> <tr> <td>Experimental demonstration and mathematical model</td><td>Q2 2003</td></tr> <tr> <td>Process Designs and cost estimates for decarbonisation scheme</td><td>Q 4 2003</td></tr> </table>		Improved membranes for experimental evaluation	Q 4 2002	Membrane performance evaluation	Q 4 2002	Experimental demonstration and mathematical model	Q2 2003	Process Designs and cost estimates for decarbonisation scheme	Q 4 2003
Improved membranes for experimental evaluation	Q 4 2002								
Membrane performance evaluation	Q 4 2002								
Experimental demonstration and mathematical model	Q2 2003								
Process Designs and cost estimates for decarbonisation scheme	Q 4 2003								
<p>Technology Providers (All US except where stated) Colorado School of Mines; Cincinnati University; Eltron Research Inc., ECN (Netherlands); McDermott Technology Inc., Fluor-Daniels.</p> <p>Sub-Contractors TDA Research Inc. Colorado; Ohio State University</p> <p>Scenario Fit All</p> <p>Screening score 86</p> <p>Cost Metric result 4</p> <p>Risks to delivery Significant membrane improvements required</p> <p>Proposed Regional funding DOE</p>									

Work Package Description Work Package No: Start Month:Q3 2002 End Month: Q4 2002 Expected Cost: (\$) 100K Work Package Title: ITM/OTM Oxygen separation system for gasification or ATR Team : Pre-Combustion Work Package Leader : Deferred Activity Partners With Major Involvement Air Products Person Months 6 Other significant cost items Objectives : Establish the performance and costs of an Oxygen Transport Membrane (OTM) aka ionic Transport Membrane (ITM) for the separation of oxygen for use in a gasification or autothermal reforming plant.
Description of Work Task 1. Undertake techno-economic evaluation of an OTM oxygen plant integrated into a gasification process.
Deliverables Current costs/ performance estimates for the technology to be used if economic in the Refinery oil fed scheme, the Canadian IGCC scenario and potentially in the gas fed schemes in Norway and Alaska. Milestones and Expected Results Evaluation of the system against cryogenic separation Q 4 2002 Potential Technology Providers and Geographic Location Air Products or Praxair US Potential Sub-Contractors Jacobs, FW or other contractor familiar with gasification IGCC schemes. Scenario Fit ALL Screening score 66 Cost Metric result 3 Risks to delivery IP issues Suggested regional fund DOE

Work Package Description Work Package No: 7 Start Month: June 2001 End Month: June 2002 Expected Cost: (\$) 500,000 Work Package Title: Standardized PCDC Scheme Team : Precombustion Decarbonization Work Package Leader : Henrik Andersen Partners With Major Involvement: From - MW Kellogg, Haldor Topsoe, Foster-Wheeler, Technip, IEA, Air Products, GE, Alstom, Siemens Person Months 60 Other significant cost items Objectives Develop a standardized ATR based scheme for a 400 MW power plant. Test the design in the different scenarios, e.g. Alaska, NorCap.
Description of Work Task 1. Identify optimum solution based on cost and efficiency Task 2. Value-engineering of best solution Task 3. Study manufacture processes and design Task 4. Estimate cost of standardized PCDC design
Deliverables : Report on standardized PCDC design Milestones and Expected Results : Report on standardized PCDC design Potential Technology Providers and Geographic Location MW Kellogg, Haldor Topsoe : US Technip, FW, Haldor Topsoe, MW Kellogg : EU Potential Sub-Contractors Scenario Fit: NorCap, Canada, Alaska, Grangemouth Screening score: 62 Cost Metric result: 2 Risks to delivery : Low risk – all component technologies commercial available Suggested regional fund : DOE

Work Package Description Work Package No: 7 Start Month: June 2001 End Month: June 2002 Expected Cost: (\$) 500,000 Work Package Title: Very Large Scale ATR Team : Precombustion Decarbonization Work Package Leader : Eline Vangden Jossang Partners With Major Involvement: MW Kellogg, Syntex, Lurgi, Haldor Topsoe, Foster-Wheeler, Technip Person Months 60 Other significant cost items Objectives: Develop a ATR based PCDC scheme based single-line philosophy. The anticipated scale will be 4-6 times above current scale.
Description of Work Task 1. Develop optimum flowsheet Task 2. Vendor study of equipment and package units design for scale constraints and economy-of-scale effect Task 3. Refine design with vendor input Task 4. Estimate cost of very large scale ATR based PCDC scheme
Deliverables : Report on a very large scale ATR based PCDC scheme Milestones and Expected Results : Report on a very large scale ATR based PCDC scheme Potential Technology Providers and Geographic Location MW Kellogg, Haldor Topsoe : US Technip, FW, Haldor Topsoe, MW Kellogg, Lurgi, Syntex : EU Potential Sub-Contractors Scenario Fit: Alaska, Grangemouth Screening score: 35 (55-65) Cost Metric result: 0 (2-3) Risks to delivery : Low risk – all component technologies commercial available, but a bigger scale Suggested regional fund : DOE

Storage, Measurement and Verification Project Descriptions

HSE Risk Assessment Literature Search

PI: Dr. Sally Benson, Lawrence Berkeley NL, California

Recommended CCP Cost: \$50K US in 2001

Key SMV Contact(s): Craig Lewis, Chevron

Internal time required: One day per month to follow, manage & leverage 5 man-days to process results (Statoil, Shell, Norsk Hydro, bp, Shell Canada)

Contract Status: Already approved by EB & Executed

Project Objectives: Provide "jump start" for SMV team on HSE risk assessment methodology gaps & suggested approaches.

Key Deliverables

- HSE Risk Assessment Literature Search (SOTAs, Key Gaps, etc.)
- Recommended prioritization for CCP SMV to address Gaps
- Recommended "Road Map" for CCP SMV Team

Product Deliveries

- 1st Draft - March, 2001
- Final Draft - May, 2001

Site-Specific HSE Risk Assessment Model

PI: Dr Oldenburg, Lawrence Berkeley NL, California

Recommended CCP Cost

\$60K US in 2001; \$100K in 2002

Key SMV Contact(s): Craig Lewis, Chevron

Internal time required: One day per month to follow, manage & leverage

Contract Status: Recommending to Board

Project Objectives: Develop and test a coupled model (ground leakage & atmospheric transport) to evaluate HSE risk for a range of scenarios and develop probabilistic estimates for consequences of leakage

Key Deliverables

1. Dec 2001 - Report on modeled surface leakage rates
2. Dec 2001 - Interim report describing requirements and design for coupled model
3. Jun 2002 - Report on atmospheric dispersion from scenarios in Task 1
4. Dec 2002 - Report on coupled model, methodology structure & validation studies
5. Jun 2003 - Report on case studies that use model for HSE RA
6. Dec 2003 - Final report summarizing all aspects of RA using coupled models

Safety Assessment Methodology Development

PI: Dr. Wildenborg, TNO-NITG, Netherlands

Recommended CCP Cost: \$297K US in 2001; \$297K in 2002; \$297K in 2003

Key SMV Contact(s): Hans Aksel Haugen, Norsk Hydro; Bjorn Berger, Statoil

Internal time required: 3 man-weeks in April to **re-scope** & negotiate contracts; 1.5 man- weeks in May to finish negotiations & execute. 9 additional man-days from Shell, bp, Chevron in April for face-to-face meetings in Holland 3 days per month thereafter to monitor, steer, leverage and manage R&D

Contract Status: Need EB approval to re-scope proposal & negotiate contract

Project Objectives:

- Develop methodology and computational tools for HSE risk assessment for the North Sea or Onshore Europe
- Application of the methods & tools in a generic performance assessment for 2 European scenarios - one defined by CCP and the other by TNO-NITG
- Results will provide building blocks for site characterization, risk mitigation & remediation

Key Deliverables:

- Features, Events and Processes analysis
- Scenario development; detailed modeling/collaboration with SACS, NASCENT, GESTCO, and Weyburn JIP
- Development of performance assessment models; quantifying HSE risks of individual scenarios; risk assessment methodology & computational tools

Product Deliveries: YE 2003 Final Report; annual & quarterly progress reports

Probability Risk Assessment Methodology

PI: Dr. Raterman, Idaho National Environmental & Energy Lab (INEEL), Idaho

Recommended CCP Cost: \$100K US in 2001, \$150K in 2002; \$150K in 2003

Key SMV Contact(s): Hans Aksel Haugen, Norsk Hydro; Charles Christopher, bp

Internal time required: 2 man-weeks in April to **re-scope** & negotiate contracts; 1 man-week in May to finish negotiations & execute. 3 days per month thereafter to monitor, steer, leverage and manage R&D

Contract Status: Need EB approval to re-scope proposal & negotiate contract

Project Objectives: Methodology to conduct detailed probabilistic risk assessment, mitigation and remediation methodology in coal beds

Key Deliverables:

- Identification of CO₂ release scenarios; lab evaluations of coal/ CO₂ interactions
- Simulation of Tiffany (bp field in Colorado) reservoir, including risk scenarios
- Quantification of risks & identification of risk mitigation processes

Product Deliveries: YE 2003 Final Report; annual & quarterly progress reports

CO₂ Injection and Physical Properties of Reservoir & Caprocks

PI: G. Borm, Geo-Research Center (GFZ) Potsdam, Germany

Recommended CCP Cost - \$100K US in 2001; \$125K in 2002; \$125K in 2003

Key SMV Contact(s): Wolf Heidug, Shell; Bjorn Berger, Statoil

Internal time required: 2 man-weeks in April to re-scope & negotiate contracts; 1 man-week in May to finish negotiations & execute. 2 days per month thereafter to monitor, steer, leverage and manage R&D

Contract Status: Need EB approval to re-scope & negotiate contract

Project Objectives: Laboratory study of fluid/rock interaction relevant for storage of CO₂ with insights as to safety & effectiveness of CO₂ storage

Key Deliverables:

- Long-term flow experiments to gain insights into irreversible changes of rock properties due to chemical alteration of rock framework
- Experimental simulation of CO₂ dissolution due to decreasing pore pressures

Product Deliveries: YE 2003 Quantitative Assessment; annual & quarterly progress reports

Hyperspectral Geobotanical Remote Sensing

PI: Dr. William Pickles, Lawrence Livermore NL, California

Recommended CCP Cost: \$100K US in 2001; \$100K in 2002; \$100K in 2003

Key SMV Contact(s): Charles Christopher, bp

Internal time required: 1 week in April to re-scope & negotiate contracts; 1 week in May to finish negotiations & execute. 2 days per month thereafter to monitor, steer, leverage and manage R&D

Contract Status: Need EB approval to negotiate contract

Project Objectives: Demonstrate the potential of advanced hyperspectral geobotanical remote sensing methods for assessing leakage rates

Key Deliverables:

- Tests of calibration options & assessment, & imagery data of minimum detectable CO₂ emissions
- Minimum detectable amounts of CO₂ and mapping accuracy based on Mammoth Mountain data sets
- Reports on analysis of new overhead data

Product Deliveries: YE 2003 Final Report including satellite imagery data; quarterly progress reports

Hyperspectral Imaging Over Rangely Field

PI: Dr. Pickles, Livermore NL, California

Recommended CCP Cost: \$60K US in 2001

Key SMV Contact(s): Charles Christopher, BP

Internal time required: One day per month to follow, manage & leverage)

Contract Status: Recommending to Board

Project Objectives: Imaging of known Leaky Systems such as Mammoth Mountain; Rangely gives us (hopefully) ground-truthing on non-Leaky Systems; complimented by DOE/School of Mines work with soils/isotopes to provide “compelling” story of how monitoring & verification can work

Key Deliverables

1. Airborne survey over Rangely Field, Colorado

Long-Term M&V Using Noble Gas Isotopes

PI: Dr. Nimz, Lawrence Livermore NL, California

Recommended CCP Cost: \$75K US for 2001; \$100K for 2002; \$100K for 2003

Key SMV Contact(s): Charles Christopher, bp

Internal time required: 1 week in April to **re-scope** & negotiate contracts; 1 week in May to finish negotiations & execute. 2 days per month thereafter to monitor, steer, leverage and manage R&D

Contract Status: Need EB approval to negotiate contract

Project Objectives:

- Test for long-term leakage of CO₂ from aquifers and oil reservoirs

- Establish screening criteria for selecting locations; test EOR reservoirs for CO₂ leakage
- Create long-term monitoring methodology

Key Deliverables:

- Field experiments with tracers in relevant aquifers & EOR sites
- Develop screening criteria; field monitoring strategies, & development of models

Product Deliveries: YE 2003 Feasibility Reports on using noble gas isotopes for screening & testing sites

Novel Geophysical Techniques to Monitor Movement

PI: Dr. G Michael Hoversten, Lawrence Berkeley National Lab, Berkeley, California

Recommended CCP Cost: \$150K US in 2001; \$100K in 2002

Key SMV Contact(s): Craig Lewis, Chevron

Internal time required: 1 week in April to **re-scope** & negotiate contracts; 1 week in May to finish negotiations & execute. 2 days per month thereafter to monitor, steer, leverage and manage R&D

Contract Status: Need EB approval to re-scope & negotiate contract

Project Objectives:

- Review of past experiences & numerical modeling to assess monitoring capability of many techniques used both in isolation & in combination.
- Initial candidates are a) streaming potentials, b) gravity & gravity gradiometry, c) sea-borne magnetotellurics, d) passive seismic monitoring, and e) production/injection history inversion

Key Deliverables:

- Survey of all applications of geophysics, remote sensing & hydrology, both inside & outside industry
- Development of a set of target specs for cost and capabilities for an optimal monitoring system
- Potential technology assessment; operating plan for the cost-effective monitoring of CO₂ Storage

Product Deliveries: YE 2002 Final Report for above deliverables; annual & quarterly progress reports

Characterization of Acid Gas Disposal Sites

PI: Dr. Steven Bachu, Alberta Geological Survey, Alberta

Recommended CCP Cost: \$45K in 2001; \$100K in 2002

Key SMV Contact(s): Swapan Das, Suncor

Internal time required: 1 week in April to **re-scope** & negotiate contracts; 1 week in May to finish negotiations & execute. 2 days per month thereafter to monitor, steer, leverage and manage R&D

Contract Status: Need EB approval to negotiate contract

Project Objectives:

- Study all 31 acid gas (CO₂ & H₂S) disposal sites in Alberta Basin;
- Characterize geology mineralogy, reservoirs & seals, geochemistry, hydrogeology, pressure, geothermals, rock properties, injection streams & operations;
- Leverage the lessons learned for CO₂ Storage.

Key Deliverables:

- Site capacity determinations; caprock integrity evaluations;
- Screening criteria
- Effect of CO₂ purity on rocks

Product Deliveries: Final Report YE 2002 with quarterly progress reports during research

Long-Term Sealing Capacity of Wells

PI: Dr.Erik Lindeberg, SINTEF, Norway

Recommended CCP Cost: \$55K US in 2001, \$55K in 2002

Key SMV Contact(s): Björn Berger, Statoil

Internal time required: 4 days in April to re-scope & negotiate contracts; 3 days in May to finish negotiations & execute. 1 day per month thereafter to monitor, steer, leverage and manage R&D

Contract Status: Need EB approval to negotiate contract

Project Objectives: Verify integrity & avoid leakage of wells penetrating sealing caprock for CO₂ storage

Key Deliverables:

- Study long-term degradation or erosion and cross effects of 2 materials and caprocks
- Evaluate CO₂ transport into well and possible leakage due to degradation
- Study remedies to avoid leakage (degradation, special cementing, etc.)
- Recommendations for well plugging, abandonments; recommendations for further study

Product Deliveries: Progress Report YE 2001; Final report July 2002

Long-term CO₂ Storage Using Petroleum Industry Experience

PI: Dr. Reid Grigg, Petroleum Recovery Research Center, New Mexico Tech

Recommended CCP Cost: \$80K US in 2001

Key SMV Contact(s): Jeff Woliver, Texaco

Internal time required: 1 week in April to scope & negotiate contracts; 1 week in May to finish negotiations & execute. 2 days per month thereafter to monitor, steer, leverage and manage

Contract Status: Need EB approval to negotiate contract

Project Objectives:

- Analyze ~100 Permian Basin oil & gas reservoirs that have been under CO₂/EOR for their long-term CO₂ storage potential
- Leverage EOR lessons learned to help demonstrate effectiveness & safety of CO₂ storage

Key Deliverables:

- Assembled reservoir data & EOR project information
- Reservoir Engineering analysis;
- Comparison of reservoirs; CO₂ storage go-bys, etc.

Product Deliveries: YE 2001 Final Report; quarterly progress reports

Natural CO₂ Field Analogs; 2 Field Studies

PI: Dr. Scott Stevens, Advanced Resources Inc, Arlington, Virginia

Recommended CCP Cost: \$78K US for 2001; DOE (Dave Beecy) has also pledged additional \$50K co-funding

Key SMV Contact(s): Craig Lewis, Chevron

Internal time required: 4 days in April to scope & negotiate contracts; 3 days in May to finish negotiations & execute. 1 day per month thereafter to monitor, steer, leverage and manage R&D

Contract Status: Need EB approval to negotiate contract

Project Objectives:

- Extract maximum information from Natural Analog Partners to address many of the fundamental geologic sequestration issues
- Show how that information might demonstrate that injected CO₂ for storage can be safe & effective, based on McElmo Dome & St. Johns CO₂ Fields

Key Deliverables:

- Establishment of CO₂ storage as a “natural process”;
- Documentation of the long-term impacts of storage;
- Assessment of surface & subsurface CO₂ handling technologies & costs

Product Deliveries: Final Report by 12/15/01; quarterly progress reports; presentations to industry

Synthesis of Nuclear Waste Disposal Experience

PI: Dr. Michael Stenhouse, Scientific Monitor, Denver, Colorado

Recommended CCP Cost: \$35K US in 2001

Key SMV Contact(s): Rick Weidel, Shell Canada

Internal time required: 2 days in April to negotiate contracts; 2 days in May to finish negotiations & execute. 1 day per month thereafter to monitor, steer, leverage and manage R&D

Contract Status: Need EB approval to negotiate contract

Project Objectives:

- Inform CCP on key issues relevant to CO₂ storage already addressed by nuclear waste industry
- Specifically risk assessment framework, public perception & involvement, gas migration modeling, concerns to facilitate the transfer of knowledge to CCP.

Key Deliverables:

- Risk assessment framework review; public perception & involvement; lesson learned from nuclear industry
- Lessons learned from Sweden, France & USA relevant to CO₂ storage

Product Deliveries: 11/2001 Final Report; quarterly progress reports

Atmospheric CO₂ Monitoring Systems

PI: Dr. Tang, Cal Tech, California

Recommended CCP Cost: \$20K US in 2001

Key SMV Contact(s): Charles Christopher, bp

Internal time required: 3 days in April to re-scope & negotiate contracts; 2 days in May. 1/2 day per month thereafter to monitor, steer, leverage and manage R&D

Contract Status: Need EB approval to negotiate contract

Project Objectives: Perform a critical, technical review of appropriate literature, and identify local experts for investigating attractive monitoring methods

Key Deliverables:

Assemble relevant information and develop literature search
Develop and contact relevant groups & experts
Product Deliveries: Final Report 12/2001; quarterly progress reports

Why Leaky Geologic Systems Leak

PI: Dr. Evans, Utah State

Recommended CCP Cost

\$35K US in 2001; \$35K in 2002

Key SMV Contact(s): Craig Lewis, Chevron

Internal time required: One day per month to follow, manage & leverage)

Contract Status: Recommending to Board

Project Objectives: 10 CO₂ leaks identified in Utah - one is a geyser which blows twice daily. The objective is to understand the "critical success factors" for leakage and attributes for systems less likely to leak.

Key Deliverables

1. 2001/2002 - Reservoir Characterization; fault leakage analysis & data synthesis into a form to be used for reservoir engineering modeling
2. 2002/2003 - Reservoir modeling & sensitivity analysis

Use of Depleted Gas Reservoirs for Storage

PI: Dr. Frailey, Texas Tech University

Recommended CCP Cost

\$50K US in 2001; \$110K in 2002

Key SMV Contact(s): Jeff Woliver, Texaco

Internal time required: One day per month to follow, manage & leverage

Contract Status: Recommending to Board

Project Objectives: Investigation and computer simulation of using depleted gas reservoirs for CO₂ storage; determine EOR benefits of storage in retrograde condensate reservoirs

Key Deliverables

1. 2001 - Project planning, data collection, computer simulation
2. 2002 - Simulation, lab work, analysis, economics, documentation

RA, Reactive Transport Model; Caprock Integrity

PI: Dr. Johnson Livermore NL, California

Recommended CCP Cost

\$50K US in 2001; \$100K in 2002

Key SMV Contact(s): Charles Christopher, BP; Wolf Heidug, Shell

Internal time required: One day per month to follow, manage & leverage

Contract Status: Recommending to Board

Project Objectives: Methodology and simulation capability for quantitatively assessing relative long-term performance of potential caprocks; improved understanding of various mechanisms by which CO₂ can penetrate caprocks; time-frame of caprock failure

Key Deliverables

1. 2001 - Define parameter values; begin simulation and interpretive assessments

2. 2002 - Lion's share of simulations and interpretative assessments; begin simulations to evaluate natural analogs
3. 2003 - Complete performance ranking of caprocks based on prior simulations; complete simulations to evaluate natural analog concept

Optimum Monitoring Technology

PI: Dr. Arts, TNO-NITG

Recommended CCP Cost

\$35K US in 2001; \$60K in 2002

Key SMV Contact(s): Bjorn Berger, Statoil

Internal time required: One day per month to follow, manage & leverage

Contract Status: Recommending to Board

Project Objectives: Provide state-of-the-art report on optimum monitoring technology

Key Deliverables

1. State-of-the-art monitoring report

Satellite Radar Interferometry

PI: Dr. Howard Zebker, Stanford

Recommended CCP Cost

\$35K US in 2001

Key SMV Contact(s): Craig Lewis, Chevron

Internal time required: One day per month to follow, manage & leverage)

Contract Status: Recommending to Board

Project Objectives: Imaging of ground surface changes (either subsidence or swelling) can be measured down to 1 cm or smaller. If the technical issues can be further development, this may be a very cost-effective monitoring tool when compared to other tools such as seismic monitoring.

Key Deliverables

1. Year 1: Feasibility Study (how much CO₂ must be injected to produce a measurable signal, impacts of atmospheric water vapor, ground cover issues, acquire InSAR data over areas of known gas production)
2. Years 2-3: Modeling & observations of potential inflation/deflation from gas production & storage; supplement with ground measurements at a few known tie-points; resolve issues tied to limitations of the InSAR technology.