CO_2 Capture Project: An Integrated, Collaborative Technology Development Project For CO_2 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, subtask 0.4) records progress towards defining a detailed Work Plan for the CCP 30 days after contract initiation. It describes the studies planned, workscope development and technology provider bid evaluation status at that time. Business sensitive information is provided separately in Appendix 1. Contract negotiations are on hold pending award of patent waiver status to the CCP.

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Section 1

Introduction

Brief overview of document background, aims and relationship with the original DOE work scope submitted in July 2000.

1. INTRODUCTION

This report describes research and development (R&D) workplans developed for studies within the Department of Energy, US regional program, Carbon Dioxide Capture Joint Industry Project (CCP). These workplans focus on R&D topics having the highest potential for achieving step-change reductions in separation and capture costs identified from the results of previous Subtasks, namely:

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.

The results of the above subtasks are described in detail in the Phase 0 report soon to be released. The Phase 0 report includes an in depth description of the rationale for the selection of technologies described in these work plans. Only a brief outline will be included here.

There follows individual team reports covering Subtask 0.4 of the statement of work and where appropriate Subtask 0.5 details (select Technology Developers). The worplans include a comparison with the Subtasks originally proposed in July 2000 to show changes arising from knowledge acquired to date, or alternative funding arrangements.

It should be noted that the continuous screening of technologies throughout project life, to focus on those that have the highest probability of success, requires us to start out with more technologies in the Work Plan than could be accommodated within the total budget if all were successful. The program will be managed to ensure that total expenditure remains within the original budget. Detailed discussions will take place within the CCP and with co-funding agencies concerning the fate of those studies terminated during the project. The process to manage this ‘weeding’ out of technologies to establish our ‘Favored Technology’ is part of our Technology Assurance Process (TAP).

The appendix lists some key documents describing the bid evaluations, the chosen proposals, presentations to the CCP Executive Board and External Technology Advisory Board (of which the DOE is a member) describing the rational for the technologies to be further developed and other relevant material. This documentation is available on request, though some of the information is proprietary in nature.

Section 2

Technology Team Workplans

Individual team workplan reports:

2.1 Post Combustion CO_2 Capture Team

2.2 Pre-Combustion Decarbonisation Capture Team

2.3 Oxyfuel Capture Team

2.4 Storage Monitoring and Verification Team

2. CCP TEAM WORKPLAN REPORTS

The original Statement of Work submitted to the DOE in July 2000 has been modified to take into account increased knowledge acquired during the period July 2000 to August 2001 and to reflect areas where R&D has been funded outside of the DOE program creating additional opportunities for investment. In the following reports the Tasks and Subtasks pertinent to the current workplan have been included to provide context for the individual studies.

A brief introduction to the individual studies is given, together with some background information concerning the technology providers contacted, the selection process and chosen technology provider. In some instances, new items recently added to the list are still at an early stage of development to the point of Statement of Requirement (SOR) preparation, those study costs are supported wherever possible from previous knowledge of similar study costs and will be updated in the near future when a technology provider has been selected for the work.

The capture teams have followed a common process to construct their individual workplans, which are summarized at the end of Section 2.3 (Tables 1-3). The Storage, Monitoring and Verification (SMV) team followed a different process due to the nature and content of their program, so that is described as a freestanding subject in Section 2.4(Tables 6&7) The overall program budget is addressed in Section 3.

2.1 Post Combustion CO_2 Capture

This activity was described as 'Task 1 – Develop Post-Combustion Separation and Capture Technologies' in the original DOE proposal. The underlying text has been modified as follows:

While this area may not have the greatest potential for step-change reductions in separation and capture costs, it has the greatest near-term potential for reducing CO_2 emissions since it can be retrofitted to existing facilities. The most obvious opportunity to achieve technological breakthroughs and material cost reductions will be to make improvements in the conventional solvent separation process. Specific studies will include:

2.1.1 Advanced Solvents (DOE)

Solvents that can absorb larger volumes of CO_2 per unit of solvent, and can be regenerated with a lower energy penalty, will be topics of investigation. Of lower priority will be to investigate solvents that can capture criteria pollutants such as Sox and Nox in addition to CO_2 (i.e., "one box" concepts). Finally, solvents that can withstand impurities such as O_2, water vapor, and hydrocarbons without loss of effectiveness will be sought.

This first subtask will be addressed in a new work package entitled "Radical Chemistry for CO_2 Removal'. This is the latest addition to the current program.

2.1.1.1 Work Package No. 1 Radical Chemistry for CO_2 Removal

Awaiting revised proposal from Stanford Research International

2.1.2 Advanced Absorption System Designs

New packing systems to achieve greater mass transfer efficiencies with lower pressure drop and lower cost will be investigated. In addition, entirely new non-oilfield design concepts that could yield step-change reductions in capital costs will be researched. Such concepts will take account of the non-flammable nature of the solvents and the non-critical nature of the operation, and will include new (to the oil and gas industry) thinking on fire and gas detection, firefighting/protection and equipment sparing. Engineering studies, with possible laboratory work are envisioned for this subtask. There are numerous opportunities for system optimization. For example the pressure drop through the exhaust ducting, direct contact cooler and absorber, will have a direct bearing on the power consumption of the exhaust blower. Another example would be cooling of the exhaust and lean amine, which together represent a significant proportion of the cost of post combustion capture. Optimization opportunities will be identified using the CEM to help quantify the total net costs. Also considered for optimization will be the capture plant's relation to the rest of the power plant including synergies if they can be found.

2.1.2.1 Work Package No. 2 Cost Efficient Design and Integration

Scope

The study will utilise a baseline design and cost estimate for a 350 MW gas turbine combined cycle (CCGT) power plant based around the CCP Norwegian scenario. Part of this baseline design includes a post combustion capture plant added to the flue gas system.

The objective of this programme is to evaluate new and novel design approaches to the design of the capture unit and to optimise the way this is integrated into the overall CCGT power plant design. Capture technology will be based on conventional amine systems, unless system synergies dictate the use of alternate capture mediums e.g. hot carbonate solutions.

Work Tasks

1. Subdivide the capture unit into key cost determining elements by equipment category. Suggested division is:
   - Vessels
   - Heat Exchangers
   - Pumps
   - Piping
   - Control/Inst. (low pressure systems)
   - Civil
   - Electrical
   - General Fire/safety (low pressure systems)

   Establish the cost of each component within each category in the base case proposal.
2. For each of these equipment categories the contractor will evaluate alternate design and construction strategies for equipment in non-hydrocarbon low-pressure service. Ideas for lower cost equipment fabrication and construction techniques and fit for purpose standards will be sought in other industries, e.g. utility, water, food processing, mining,

mineral processing etc. Some ideas to be developed include, substitution of steel piping and vessels with lower cost concrete or plastic constructions, use of novel low cost mass transfer surfaces, substitution of shell and tube exchangers with low cost novel heat exchange designs, selection of pumping equipment built to acceptable, but less stringent, design codes for non-hazardous systems. Low cost instrumentation etc.

3. Develop design concepts for the key elements using alternative construction techniques. Prepare construction drawings and obtain cost estimates for the fabrication and erection of these items.
4. Investigate system integration possibilities for these new/novel items within the overall CCGT scheme and maximise the beneficial use of low-level energy streams produced from the CCGT plant. Evaluate cost saving integration possibilities between the capture plant and power plant, particularly with the final section of the convection section, the exhaust ducting and stack, the steam condensing and cooling systems. This will require close co-operation between the selected contractor and external suppliers of gas turbine, power plant and boiler equipment. Optimise overall capital and operating costs for the system within the overall scenario.

Potential Suppliers/Technology Providers

- Bechtel Corporation
- Foster Wheeler
- Fluor Daniel
- Kellogg Brown and Root
- General Electric
- Nexant
- Siemens
- Alstom Power and Energy

Estimated Timeline and Cost

Phase 1: Establish potential
Duration: 6 months.
Total cost estimated at $400,000.
Phase 2: Possible extension into development/demonstration of new/novel equipment prototype.
No present estimates for duration or cost.

Original Submission

This work programme is an amalgamation of several work programmes included in the original submission. The alternative design/engineering standards approach was omitted originally due to perceived funding limitations.

Application

Any Low Pressure capture scenario.

Applicable Fuel Type; Natural Gas, liquid fuels and coal (gasified or direct fired) for which additional considerations of flue gas treatment to remove contaminant substances detrimental to the selected capture solvent would have to be addressed.

2.1.3 "New and Novel" Concepts

There are several "new and novel" approaches to post-combustion separation and capture that hold promise for achieving material cost reductions. Promising at present is the selective separation of CO_2 that can be achieved by the physical adsorption of the gas on high-surface-area solids. Conventional physical adsorption systems are operated in pressure swing adsorption and temperature swing adsorption modes. These processes are somewhat energy-intensive and expensive, and are therefore not attractive to the capture of low-concentration CO_2 from flue gases.

However, a relatively new but related process, Electric Swing Adsorption, shows considerable promise for being more energy efficient, and its application will therefore be a topic of research. Oakridge National Laboratories in the US have the patent rights. The technology is at a very early stage of understanding and development. Additional studies to improve the performance of the carbon composite substrate packing and to understand the scale up issues for large-scale engineering of the package are also required.

2.1.3.1 Work Package No. 3 Electrical Swing Adsorption Project

General

This document comprises a first outline of the Electrical Swing Adsorption Project, including preliminary cost estimates, execution and procurement plans. The plans are intended as a basis to obtain proposals from different partners in a development project.

The project will be initiated based upon a successful result of ongoing engineering pre-studies with Kvaerner Process Systems, and laboratory work by Oak Ridge National Laboratory.

The project will primarily concentrate on CO_2-removal from exhaust gases, which the pre-studies also are based upon. Parallel development of CO_2-separation from hydrogen in a pre-combustion process will be considered.

Description of the ESA process

The ESA-process utilises a bed of sintered carbon nano-fibres for adsorption of CO_2. The special properties of the carbon material is a key to large potential improvements compared to ordinary adsorption materials:

- A large adsorption area of the highly active carbon material gives a large rate of adsorption.
- Desorption at high rates can be accomplished applying electrical current to the carbon material

Calculations based on available adsorption data indicate that it is possible to make an improved CO_2-separation process compared to existing technology. However, there is need for R&D on a number of critical areas to form a completely new adsorption technology. Some of these areas are:

- Establish reliable adsorption/desorption data and characteristics for CO_2, water and impurities, for actual carbon materials.
- Develop a carbon fibre material with low pressure drop, simultaneous high adsorption capacity, and adequate physical strength..
- Engineering design of an adsorption system including pre-cooling, humidity control, exhaust gas and regeneration gas circulation, and electrical supply.
- Component development including high speed valves, electrical connectors

There are a number of challenges not yet solved. Existing data are only available for significantly higher concentrations of CO_2 than in turbine exhaust. The effect of water content on the adsorption process is unclear. Water may be adsorbed preferentially compared to CO_2. Existing tests have been made on a solid block of the carbon material, resulting in an extensive pressure drop. Short switching times between adsorption and desorption may be required. The electrical power demand is significant, and to lower the power demand a combination with heating or vacuum may be required.

Development strategy

A development strategy has been formed in order to minimize the time and resources required to undertake a development from the laboratory stage to a fully industrialized large-scale plant. The basic steps in the development are:

1. *Pre-evaluation (CCP funded)* comprising necessary laboratory tests and engineering calculations to document the potential of the technology. If this does not show the required potential is there the work will be scaled back considerably.
2. *Phase 1(DOE co-funded). Electrical Swing R&D project*, comprising necessary R&D activities to solve critical problem areas, and sufficient engineering development, to indicate technical feasibility of a total adsorption system.
3. *Phase II (DOE co-funded) Laboratory demonstration and component development,* comprising laboratory tests of the adsorption system in laboratory scale and component development including test in sufficient scale to prepare design of demonstration plant. Feasibility study of a full-scale plant design and pre-engineering of a demo plant.
4. *Phase III . Demonstration plant (not part of this work plan).*

Industrial partners

ORNL is a natural partner to undertake the R&D part of the work in USA. A highly advanced manufacturer of carbon materials, SGL, has contributed in the pre-studies, and is qualified to undertake development of the carbon material, .

One of the key issues of the development is to find an industrial partner that is willing and able to undertake an industrial development of an environmental technology prior to documentation of breakthrough. The CCP-members may be the only companies willing to take this kind of risk, in co-operation with the US DOE or the Norwegian Klimatek/NorCap funding institutions.

The pre-evaluation study contract is presently with KPS (Kværner Process Systems) in cooperation with ORNL, with funding from Klimatek. The results from the pre-evaluation are assumed to be available in December 2001.

Project description

The following project activities included in Phase I are described in Attachment A below.

Phase I. Electrical Swing R&D project

Phase I comprises the following activities:
1. Laboratory testing and scientific work
2. Carbon material development
3. Computer model of an ESA bed
4. Engineering development of the electrical swing adsorption process

An outline design of the electrical swing process will be made in the pre-study, based on preliminary laboratory data.

The major effort in Phase I will be to develop carbon materials with adequate adsorption characteristics for an industrial process. Based on the engineering development the carbon manufacturer will make different designs of the carbon material, to provide high adsorption area and low pressure-drop.

Laboratory testing will provide data on adsorption and desorption characteristics. The effects of impurities as water, Nox and Sox will be investigated. Scientific analysis of the results will be required to formulate theoretical or semi-empirical models of adsorption, desorption and power demand.

With sufficient data available, a suitable carbon material will be selected.

A computer model will be developed to be able to design and optimise the adsorption beds.

Engineering development is executed as a parallel activity. If the carbon material proves to be sensitive to the water content, methods to reduce the humidity of the exhaust have to be investigated.

Execution plan

Based on the present work description preliminary proposals will be obtained from possible development partners. Selected partners will meet with the CCP post combustion group, to agree upon details of the work programme. Proposals can then be updated and included in a joint budget proposal. Then contract negotiations can start.

When the ongoing pre-project has been completed, the main activities of the work programme can start.

The following milestones are suggested:

1.	Clarify position of Klimatek/Kværner	14/09/01
2.	Request for draft proposals, including date of workshop:	07/09/01
3.	Response on draft proposals	21/09/01
4.	Formal confirmation of workshop, selected vendors	28/09/01
5.	Workshop	08/10/01
6.	Request for updated proposal, summary workshop	15/10/01

7. Updated proposals received 30/10/01
8. Contract negotiations 02/11/01 - 15/12/01
9. Award of contracts 04/01/02
10. Earliest start of project execution 07/01/02

The following milestones are suggested for:

1. Laboratory testing
2. Laboratory rig 07.01.02 - 31.03.02
3. Test campaign 1 07.01.02 - 31.05.02
4. Test campaign 2-4 30.09.02
5. Scientific reports 31.10.02
6. Potential final tests on selected material/conditions 15.12.02
7. Carbon material development 07.01.02 - 31.08.02
8. Computer model 07.01.02 - 31.09.02
9. Engineering development 07.01.02 - 31.03.03

Preliminary cost estimate

The total cost of Phase I is estimated to be 1.3 mill USD including CCP cost.

Potential partners

The original proposal came from ORNL a natural partner on development in the US region.

SGL has been identified as a highly advanced partner in US on carbon materials, and has contributed significantly in development of material solution for the present ESA concept.

For computer modeling, we have still not evaluated any vendors. This is an area where cooperation with a Norwegian R&D institution is possible, if it is desirable to maintain cooperation with Klimatek in Norway on co-funding ESA.

As a potential engineering development partner, four companies have been identified on a short-list: Praxair, Air Products, UOP and Kvaerner.

Detailed Work scope (see Appendix 1)

2.2 Pre-Combustion Decarbonisation CO_2 Capture

This was described as Task 2 - Develop Pre-Combustion Decarbonization (PCDC) Technologies in the original DOE proposal. This approach has the potential to achieve low CO_2 separation and capture costs but due to more "steps" in the process, capital costs are high and overall efficiency suffers. One of the reasons for this is that current plants have been designed for chemical-grade H_2 production. However such purity is probably not necessary. If one adopts an integrated systems view to lowering CO_2 separation and capture costs, substantial cost-reduction opportunities present themselves. The original sub tasks proposed in the original Statement of Work are addressed in the 8 work packages described subsequently.

2.2.1 Gas Turbine Fuels

A required area for study is to evaluate the H_2 concentrations that can be burned in existing gas turbines and boilers/fired-heaters without modification. An assessment of modifications to this equipment, and their cost, for higher H_2 concentrations is therefore required. This will be accomplished via detailed engineering studies.

2.2.1.1 Work Package No. 4 Gas Turbine Retrofit

Aim of Project

To confirm the feasibility of firing gas turbines on hydrogen or hydrogen nitrogen mixtures, to assess the impact of this on emissions including oxides of nitrogen and the effect on power output and operability of the machines.

Scenario Applicability

This work is directed principally at the Alaskan distributed gas turbine scenario but is also applicable to the Canadian IGCC and Norcap CCGT schemes.

Technology

This is evaluation of existing technology for use with decarbonised fuel. The work planned is to:

- Select Gas Turbine Model(s) which represent the Scenario Gas turbine population
- Determine what equipment and control system changes are required for specific gas turbines featuring in the Alaskan scenario.
- Estimate the costs of retrofitting the turbines for use on hydrogen fuel.
- Evaluate efficiency of the gas turbines on a range of hydrogen nitrogen mixtures and with the addition of steam.
- Evaluate the emissions from a gas turbine on a range of hydrogen/nitrogen/steam mixtures.

Program Completion by end 2003.

Vendors: Selected from General Electric; Solar; Rolls Royce; Alstom.

2.2.2 Fuel-Grade Hydrogen Generation

The next topic of R&D for pre-combustion decarbonization will target the reforming/shift-reacting stage. Specific lines of investigation will include combined air blown autothermal reforming/gas heated reforming systems to reduce equipment size, and advanced air separation systems based on membranes for integration into partial oxidation and autothermal reforming designs. Advanced separation systems for CO_2 removal from syngas such as ESA and the Kvaerner absorption contact membrane system will be examined. These options will be evaluated through a combination of laboratory and engineering studies.

2.2.2.1 Work Package No. 5 Very Large Scale Autothermal Reformer

Aims of the Project

To develop and evaluate pre-combustion decarbonisation process design using blown auto-thermal reforming and steam reforming processes which extends the design envelope for the scale of single train plants beyond current levels.

The use of large scale technology or single-train philosophy have in other applications, e.g. methanol or GTL, shown to provide significant cost reductions. The objective of this study is to develop a PCDC plant design at the maximum single-train size.

When deployed on large gas fired CO_2 emitters, the economy of scale and ability to distribute the hydrogen fuel by pipeline offers substantial benefits over the baseline post combustion technology which must be installed in several locations

Scenario Applicability

The system will be developed for the Alaska distributed gas turbines, but could be equally applied to a large integrated refinery or petrochemicals site.

Technology

VLS designs will be developed employing the following technologies.

i. Oxygen blown Autothermal Reforming (ATR) to generate a high-purity H_2 fuel gas stream. Nitrogen from the Air Separation Unit to generate a N_2-diluted, H_2 fuel gas stream
ii. Air blown ATR to generate a N_2-diluted, H_2 fuel gas stream.
iii. Integrated ATR and gas heated reformer (GHR).
iv. Steam methane reforming combined with an air blown secondary reformer to generate a N_2-diluted, H_2 fuel gas stream

Each of the above base technologies are proven at smaller scale but require detailed evaluation to increase the train size and to integrate into pre-combustion flow-schemes.

Program and Technology Provider

The work is anticipated to be complete within nine months of kick-off. The Integrated ATR/GHR work will be undertaken by Synetix Ltd. Working with Jacobs Engineering in the UK. All other tasks will be undertaken by Haldor Topsoe with the work split between Denmark and the US.
Total budget for the work is anticipated to be around $275,000.

2.2.2.2 Work Package No. 6 Oxygen Membrane ATR

Aims of Project

Apply a novel autothermal reformer concept incorporating an oxygen separation membrane to precombustion decarbonisation. This technology is being developed elsewhere to reduce the cost of syngas generation, principally for gas to liquids application, but the benefits of the development will be equally applicable to PCDC. This project is intended to leverage the development effort being made elsewhere by applying the novel technology to CO_2 capture.

Scenario Applicability

The system could be applied to any natural gas fired system, including refineries, boilers and gas turbines.

Technology

The technology involves the use of mixed conducting ceramic membranes with capability to separate oxygen from air at high temperature. These membranes if incorporated into the combustion zone of an autothermal reformer have the potential to reduce the cost of providing an oxygen blown ATR system by eliminating the cryogenic air separation system and reducing the energy consumed in the air separation process.

The development of the membranes and reactor designs is being undertaken as part of another project and is therefore not within the scope of this project. The activities proposed are to establish a 'black-box' operating performance and cost for the O_2 membrane ATR and integrate this item into a precombustion decarbonisation process to determine the overall cost and efficiency. It is envisaged that information relating to the O_2 Membrane ATR will be handled by a contractor under a confidentiality agreement due to possible IP conflicts between the CCP members.

Program

Completion end 2003.

2.2.2.3 Work Package No. 7 Electrical Swing Adsorption

Aims of Project

To develop an electrical swing adsorption system for the removal of carbon dioxide from hydrogen/ carbon dioxide mixtures. This system will be regenerated using electrical current in a cyclic bed operating at a higher pressure than conventional wet removal systems, minimising the cost and energy involved in compressing the captured CO_2. ESA use here may be even more efficient than in the post combustion exhaust gas application as the CO_2 concentrations are much higher in this case.

This system will be developed for application in pre-combustion systems based on autothermal reforming of natural gas and gasification of heavy fuels.

Scenario Applicability

Subject to demonstrating the resistance of the adsorbent material to damage by sulphur or other contaminants, this concept is believed applicable to any pre-combustion capture scheme and hence all the large combustion processes firing gas oil coke or coal.

Technology

The ESA concept relies on the adsorption characteristics of a class of carbon fibre monolith which releases the adsorbed CO_2 when an electrical current is applied. This concept has been demonstrated in laboratory experiments by Oak Ridge National Laboratory.

The current is observed to result in little heating of the carbon but is understood to liberate the carbon dioxide by other mechanisms. This offers the potential for a low energy consumption separation system. It also has the advantage that the carbon dioxide can in principle be removed from the adsorbent at high pressure.

This project will apply this approach to separation of CO_2 from a shifted syngas in a pre-combustion decarbonisation plant based on autothermal reforming or gasification systems.

It is proposed to execute this work in two phases as follows.

Phase 1

Phase 1 work will involve initial laboratory testing to evaluate the performance of the ESA separation system. This will be followed by preliminary techno-economic evaluation.

The performance of the current adsorbent will be evaluated to determine:

i. The removal capacity of the adsorbent under typical operating conditions
ii. The effect of regeneration at three different pressures on system capacity, energy use and adsorbent integrity under cyclic operation
iii. The effect of other trace contaminants on the adsorbent.

The following deliverables will be provided upon the completion of Phase 1:

- Determination of the size, preliminary cost, energy consumption and performance of ESA equipment specified for inclusion in the two scenarios.
- Identification of development needs and performance targets for the adsorbent and equipment for Phase 2.
- Preliminary evaluation of the performance of the overall decarbonisation process including efficiency and CO_2 recovery and purity.

It is anticipated that Phase 1 will have a duration of 4 to 6 months.

Phase 2

Phase 2 involves undertaking a development program to take the system to proof of concept. This would require the key uncertainties in applying the technology to be resolved and could include:

1. Development of an adsorbent material for optimal performance in CO_2 removal from syngas and resistance to degradation.
2. Demonstration of an extended cycle operation in laboratory tests under realistic operating conditions.
3. Optimization of the conditions of operation and cycle time of the ESA system
4. Development of a mathematical model of the adsorbent system for predictive and design use
5. Evaluation of large scale adsorbent preparation and cost.
6. Preparation of detailed large scale adsorption system design and estimate costs
7. Development of process flow diagrams incorporating the ESA system
8. Development of major equipment lists for both scenarios. These lists will be used by the CCP to determine capital costs and performance for comparison with competing technologies.

Phase 2 is scheduled for completion at the end of 2003.

Technology Providers and Budget

Oak Ridge have been invited to submit a detailed proposal to undertake this work and have proposed to do so in conjunction with the supplier of the carbon monolith, SGL Hitco, together with a US Gas Separation Technology Company.

2.2.3 Systems Integration and Optimization

Systems optimization and integration will be the next task. Here, the results of Subtasks 2.2.1 and 2.2 will be combined in the framework of the common economic model (CEM) to establish the lowest-cost total separation and capture system configuration. Heat and pressure optimization and integration will also be performed via engineering studies. Special focus will be on integration between the hydrogen generation side and the gas turbine side.

2.2.3.1 Work Package No. 8 Gasification Separation Development

Aims of the Project

The objective of this section of the project is to evaluate and develop several technologies for the capture of CO_2 from an Integrated Gasification Combined Cycle (IGCC) power generation plant with co-production of steam and hydrogen (Tri-generation).

Scenario Applicability

The work will be based on the Canadian scenario but the separation systems evaluated are all applicable to CO_2 capture from any gasification scheme using any hydrocarbon feedstock including coal or oil and would also have potential for improvement of pre-combustion systems based on steam reforming or ATR.

The following systems will be evaluated in phase 1 by incorporating them into pre-combustion designs, simulating the system performance using data provided by the individual technology vendors. A preliminary ranking process using assessments of system efficiency and capital cost will be used to select the best one or two technologies for further development. The development needs of each technology will be assessed in the Phase 1 work and will define the detailed program.

The development program will therefore be specific to those technologies selected, those to be evaluated together with potential providers are:

i. CO_2 permeation membrane, Medal Inc.

ii. H_2 permeation membrane (including polymeric and possibly molecular gate)
Air Products, Medal or UBE

iii. Cryogenic CO_2 separation (possibly combined with membranes)
Air Products or Linde

iv. High pressure CO_2 liquefaction
Fluor Daniels

v. Hot gas sulfur removal
Triangle Research

vi. Oxygen separation using ion transport membranes
Air Products or Praxair

The activities proposed for the project are listed in Tables 5a and b.

The project will include the development of a baseline capture cost estimate to assess the performance of the new technology. This baseline work comprises estimating costs for the ICGG facility without CO_2 capture and using current best available technology.

Table 5a Phase 1

Define Technology	Collate information about each technology performance and operating envelope
Develop Process Design	Incorporate novel technology into PCDC flowsheet
Identify Development needs	Identify current and required performance, identify changes required for performance gap closure and develop outline programs
Rank Technology	Assess efficiency, cost and other factors such as risk, development cost and time
Select technologies for Phase 2	Identify top one or two for further development

Table 5b Phase 2

Development Program	Undertake development activities for the 1 or two technologies selected
Precombustion process optimization	Optimise the PCDC design exploiting the novel technology for maximum cost and efficiency benefit.
Cost Estimates	Develop estimates

Program

The work will be co-ordinated by Fluor Daniels working with each of the providers listed above.

Phase 1 is anticipated to be around 9 months duration, with Phase 2 having total duration of 15 months.

2.2.4 "New and Novel" Concepts

Finally, new and novel H_2 generation schemes will be researched. Specifically, a water gas shift membrane reactor will be evaluated and modifications assessed for low-cost H_2 production, i.e. technology that combines several process steps (e.g., Steam Methane Reforming and purification or shift and CO_2 removal).

2.2.4.1 Work Package No. 9 Membrane Water Gas Shift Reactor for a Refinery Gasification scheme

Aims of the project

To develop a combined reaction and separation system employing high temperature hydrogen permeation membranes which will be integrated into a gasification process to produce a hydrogen rich fuel gas and a high pressure concentrated CO_2 stream suitable for sequestration.

Scenario Applicability

The technology will be developed with the refinery scenario using fuel oil and refinery fuel gas feed as the basis for design, but will be applicable to CO_2 capture from a wide range of combustion processes, and any hydrocarbon fuel ranging from natural gas to coal.

Technology

Membrane reactors combine reaction with separation of a product. They are therefore able to increase the conversion of an equilibrium reactor complying with le Chatelier's principle. The water gas shift (WGS) equilibrium reaction (1) converts carbon monoxide to hydrogen and CO_2. The reaction is exothermic and favoured by lower temperatures. It is not possible to achieve high conversion in a conventional reactor in a single reaction step so several reactors in series are typically deployed and the CO conversion is still limited to around 90%.

$CO + H_2O \;\; <> \;\; CO_2 + H_2$ (1)

By removing hydrogen from the reacting mixture it is possible to achieve near perfect conversion with the two product gas streams at the required quality to allow the fuel to be burned with minimal CO_2 emissions and the CO_2 pure enough to dry and compress for sequestration.

There are additional savings if the reaction can be conducted without having to cool the feed gas and remove sulphur from it by scrubbing with solvents. This requires that the membrane developed is not affected adversely by the presence of sulphur or other components in the reacting mixture, conventional palladium membranes for example are rapidly poisoned by hydrogen sulphide.

Program and Technology Providers

To achieve the CO_2 recovery target and a CO_2 stream above 97 mol% purity, novel membranes are required with improved properties. Four membrane types have been identified with the potential to perform this service and all four are to be assessed for suitability and performance. Proposals have been selected from four leading developers of these hydrogen permeable membranes each with programs defined to improve the membrane characteristics required to achieve the necessary performance, stability and resistance to poisoning. Each of these membranes will be developed and characterised in Phase 1 of the development program which is scheduled for completion at the end of 2003. These characteristics will be measured under identical defined conditions to permit the most promising membrane to be selected at the end of phase 2.

Table 7 Technology Developers

Developer/Subcontractor	Principle Investigator	TP Role in Project	Location
Colorado School of Mines (CSM) with TDA Research Inc.	Doug Way	Develop Supported Copper-Palladium alloy	US
University of Cincinnati with Ohio State University	Jerry Lin	Develop Supported Silicalite (zeolite) membranes	US
ECN Dutch Energy Efficiency Institute		Develop silica membranes and provide mathematical models	Netherlands
Eltron Research Ic.	Tony Sammells	Develop Electro-ceramic membranes	US
Fluor Daniels	TBC	Process flowsheeting and design	US/EU
Mc Dermott Technology Inc.	TBC	Reactor design, scale-up and cost assessment	US/EU

Fluor Daniels will develop simulations of the overall process incorporating a model of the membrane reactor, supplied by ECN.   Several process configurations will be screened to determine the most efficient, lowest cost arrangement. Each membrane will be simulated in turn in the reactor model integrated into a complete gasification scheme.   The preferred membrane will be that which shows acceptable stability and poison resistance and has the potential for lowest cost of CO_2 capture.

The selected membrane developer for Phase 2 will construct a laboratory scale membrane reactor and undertake experiments to determine the optimal reactor arrangement and operating conditions. Further development of the membrane will be undertaken during this phase. The experimental data will be used to tune a detailed reactor mathematical model, which will be used in the design of a full-scale reactor. Details of the tasks to be undertaken and the overall schedule is shown in Figure 1 below.

A specialist engineering company McDermott Technology Inc. will undertake the detailed reactor design with input from the membrane developer and ECN who will provide the model. A detailed evaluation will be undertaken of the mechanical aspects of the design covering large scale membrane production, reactor assembly and sealing, reliability and maintenance. McDermott will also estimate the costs of producing the reactor system.

Fluor Daniels will use simulation to optimise the flowsheet for the selected membrane, estimate efficiency and utility consumption and undertake detailed equipment sizing and specification. This information together with the cost estimate for the novel equipment supplied by McDermott will form the basis for an overall system cost estimate to be undertaken by the CCP common cost estimator. The Phase 2 work is to be completed at the end of 2003.

2.2.4.2 Work Package No. 10 Compact Reformer Membrane Contactor

Aims of the Project

To develop a pre-combustion decarbonisation process employing novel compact steam reforming and CO_2 removal technologies to reduce the size and cost of key equipment and increase the efficiency of the decarbonisation process. This system to be developed to decarbonise gaseous fuels, specifically natural gas and offgases from refinery and petrochemical processes.

Scenario Applicability

The system is particularly well suited to refinery and petrochemical units but can also be applied to gas turbine schemes potentially including distributed turbines and large CCGT's.

The membrane contactor is applicable to any CO_2 removal system and could be appied with a range of solvents to combined acid gas removal (CO_2 and H_2S) from a gasifier product gas from oil or coal feeds.

Technology

BP and Kvaerner Process Technology have developed a highly efficient compact steam reformer which employs high intensity heat transfer to minimise the heat exchange surface and hence dramatically reduce the equipment size compared with conventional designs. In a conventional steam reformer, the combustion air and process gas typically leave the unit at more than 850°C, with this sensible heat used to generate steam with significant loss of efficiency to a pre-combustion process. The heat exchange approach allows that heat to be largely recovered, reducing fuel usage within the process increasing efficiency of the reformer and hence the overall process. The first large scale unit is under construction in Alaska as part of a Gas to Liquids (GTL) test facility, but the benefits of incorporating this arrangement into a large scale pre-combustion process are not yet evaluated.

The Kvaerner membrane contactor developed with WL Gore and Associates is a novel gas/liquid contactor system which allows significant reduction in the size of amine absorber and stripper systems for CO_2 removal from a shifted syngas with 65-70% reduction in unit weight and footprint achievable. It has been tested on separation of CO_2 from natural gas and flue gas, but has not yet been evaluated in hydrogen production, where it offers similar benefits.

Program and Technology Provider

The work scope is as follows:

1. Process Design
   i. Process Design
   ii. Heat and Mass balance for the overall process (Noting proprietary equipment is to be treated as a “black-box”, requiring only inlet and outlet data to specified).
   iii. Equipment specification for non-proprietary items, including size, type, material of construction and any special features or design considerations.
   iv. Estimated cost for Kvaerner Proprietary Equipment.
   v. Plot plan
   vi. Indication of capacity for suspected largest single train.

2. Membrane Laboratory tests:
   Goal: Verify the calculations
   Split of work: Kværner in cooperation with SINTEF or GTI
   Delivery: Input to report
   Duration: Initial testing / start up: 2 weeks
   Tests: 3 weeks
   Theoretical work follow up: 2 weeks

KPT will be responsible for the overall Kvaerner input although development of the basic process design for CO_2 removal section will be by Kvaerner in Norway.

Budget

Cost excluding the membrane tests is One Hundred and Eighty Three Thousand Pounds Sterling £183000.

The membrane test work is estimated to cost Five Hundred and Sixty Thousand Norwegian Kroner 560000 NOK.

Life Test Work (dependent initial study results)

Depending on the duration of tests we would expect membrane life tests to cost between £50 and £100,000.

2.2.4.3 Work Package No. 11 Sorption Enhanced Water Gas Shift Reactor

Aims of the Project

To develop and evaluate a combined shift reaction and CO_2 separation system employing high temperature adsorbents to selectively remove carbon dioxide from a reacting gas mixture thereby increasing the conversion and providing two gas streams requiring minimal further purification. This system is proposed for integration into a natural gas reforming process to produce a hydrogen rich fuel gas which is at high-pressure, high temperature and contains significant quantities of steam, making it highly suitable for direct firing in a gas turbine with high efficiency.

Scenario Applicability

The technology will be developed with a base case of gas turbine firing using natural gas feed. It is anticipated that a successful system could with moderate additional development work to tailor the adsorbent and catalyst be applied to gasification systems, particularly for Integrated Gasification Combined Cycle (IGCC) fed with oil or coal yielding similar cost and efficiency benefits.

Technology

The concept of Sorption Enhanced Reforming (SER) has been developed by Air Products and Chemicals Inc. with support from the US DOE.

This system has many advantages for small-scale hydrogen production, but significant technical challenges remain to apply the system at the extremely large scale envisaged for decarbonisation of fossil fuel. The large heat input required for SER necessitates a significant heat exchange surface area. At large scale this is anticipated to result in unacceptable equipment size and cost.

Sorption enhanced water gas shift (SEWGS) reaction has been identified as a better fit for pre-combustion decarbonisation for the following reasons.

The shift reaction is mildly exothermic and is normally operated adiabatically so potentially needs no heat exchange. The reactor system is therefore simpler. The products from the reactors will be a high temperature (around 400 ^oC) hydrogen rich stream with excess steam and depending on the syngas generator a significant nitrogen content. This mixture can be fired directly on a gas turbine system with low NO_X emissions and high efficiency, avoiding the need to cool and separate the steam, saving considerably on heat exchange area and avoiding efficiency loss. The second product stream will be a low pressure CO_2 stream, which with an appropriate de-sorption cycle can be sufficiently pure for to be cooled, dried and compressed for sequestration without further purification, again minimising the cost of separation.

This concept has already been demonstrated at lab scale as a step in the SER development program, the development needs are to apply the system to CO_2 capture and optimise the adsorbent and cycle for large scale use in this application. The process incorporating the SEWGS reactor needs to be optimised for gas turbine fuel processing.

The technology addressed by this proposal concerns the precombustion decarbonization of hydrocarbon feedstock that has been gasified by reaction with steam and/or oxygen with or without a catalyst to produce an $H_2/CO_2/H_2O/CO$ gas mixture with trace contaminants, depending on feedstock, such as methane, inert gases (N_2 + argon), H_2S, and COS.

The gas mixture must have its CO content converted to H_2 by reaction with steam over a shift catalyst. The CO_2 would conventionally be separated at ambient temperature in an amine scrubbing system such as MDEA. The resulting hydrogen-rich gas, substantially free of CO_2, would then be used to fuel a gas turbine combined cycle power system. An alternative process would involve the operation of the shift reactor with a mixture of conventional shift catalyst mixed with a high-temperature CO_2 adsorbent. The effect on the shift reaction would be to swing the product composition completely to hydrogen:

$$\begin{array}{c} CO + H_2O \rightarrow CO_2 + H_2 \\ \downarrow \\ \text{removed} \\ \text{by adsorption} \end{array}$$

The reaction would take place in one of a number of identical vessels that would be switched in sequence to allow regeneration of the adsorbent and the removal of a substantially pure CO_2 product stream at close to atmospheric pressure.

Air Products has substantial experience in the design and operation of adsorption separation systems in which two pure components are separated from a gas mixture with very high recovery of valuable syngas. Our objective would be to achieve better than 95% recovery of CO_2 free hydrogen gas turbine fuel.

Air Products has carried out research over the last 5 years to demonstrate sorption enhanced reaction to produce CO or H_2 product gas by reverse water gas shift reaction or steam/natural gas reforming. In the course of this program, we have looked briefly at shift reactions, but our primary interest was in the steam – natural gas reforming reactions to produce hydrogen in a one-step process:

$$\begin{array}{c} CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \\ \downarrow \\ \text{removed} \\ \text{by adsorption} \end{array}$$

Part of the work was funded by the U.S. Department of Energy under cooperative agreement DE FC 3695G010059.

Program and Technology Provider

The rights to this technology reside with Air Products and Chemicals Inc. through their earlier work, the concept of applying this arrangement in a precombustion scheme was conceived jointly with CCP, APCI are the only technology provider considered for this project.

The program will be executed in three phases with a decision point at the end of phase 1 to determine whether to progress to the development phase.

Phase 1: Feasibility Study Duration 3 Months

Task 1.1: Conduct SER design study with various synthesis gas systems and determine technical feasibility

Task 1.2: Investigate existing Air Products absorbent database and technical literature for potential CO_2 adsorbents

Task 1.3: Evaluate potential economic advantages of the SER approach

Task 1.4: Management and reporting

Milestone 1 Decision Point: Go/No Go based upon Phase 1 Feasibility

Phase 2: Experimental Study Duration 12 Months

Task 2.1: Experimentally screen potential CO_2 absorbents

Task 2.2: Modify Cyclic Process Unit

Task 2.3: Scale up production of best adsorbent and conduct adsorption performance testing in packed bed

Task 2.4: Experimentally evaluate performance of the cyclic SER process

Task 2.5: Management and reporting

Phase 3: Design Performance and Cost Estimation Duration 3 Months

Task 3.1: Generate SER process flow sheet and define equipment specifications by scaleup of laboratory data

Task 3.2: Evaluate economics of SER process and compare with current practice

Task 3.3: Management and reporting

Total project Costs estimated at $1.2mm

2.3 Oxyfuel CO_2 capture

This program was described as 'Task 3 - Develop Oxyfuel Technologies' in the original DOE proposal. Oxyfuel possesses significant challenges and potential for technology breakthroughs and step-change reductions in CO_2 separation and capture costs. This approach requires substantial capital investments for oxygen production, modified boilers/turbines, and post-combustion CO_2 drying and compression. However, in certain cases, such as boilers and fired-heaters, retrofits to existing facilities are possible. R&D in this area will include:

2.3.1 Oxyfuel Boilers/Heaters

Development and costing of an optimised oxyfuel combustion scheme for a refinery scenario requires an engineering study to identify and resolve the technical issues over application of oxygen firing with flue gas recycle to the boilers and process heaters. The CCP is in the advantageous position that studies completed in the Analysis Phase have shown that the high pressure and zero recycle oxyfuel boiler concepts proposed in the original submission would not offer sufficient cost advantages to justify their development. Therefore the study can concentrate on areas with greater potential. The aim will be to minimise costs through plant integration and through incorporation of emerging lower cost oxygen generation technologies such as the ceramic membranes described below.

2.3.2 Integration of Membrane Air Separation

New air separation processes using high temperature oxygen-ion-transport ceramic membranes are being developed by several consortia. For oxyfuel combustion applications there are further potential advantages in the integration of these membranes with the combustion process. These benefits could come from (a) increasing the oxygen driving force across the membrane by contacting low-oxygen-content flue gases with the downstream surface of the membrane and thus reducing or eliminating the pressure difference required and/or (b) thermal integration between the high temperature membrane process and the combustion process. Thus the two main sources of operating cost in a ceramic membrane process can be minimized. Although such a development for boilers is likely to take place independently of the CCP, it is hoped to include engineering and comparative cost studies of its application to the refinery scenario. An SOR will shortly be issued to appropriate vendors .

2.3.2.1 Work Package No. 12 Oxyfuel Boilers and Heaters with Flue Gas Recycle

Statement of Requirements (SOR)

Introduction

This document requests proposals for a Development Phase Engineering and Cost study on one of the selected oxyfuel technologies: Oxyfuel Boilers and Heaters with Flue Gas Recycle.

Technologies selected by the CCP will be assessed against the requirements of one or more application scenarios using a common economic model. The technology described here will be assessed for the CCP's oil refinery scenario, details of which are provided.

Background

A number of studies and pilot scale tests have been published demonstrating that conversion of existing boilers to oxyfuel firing is feasible and can usually be carried out with little or no changes to the costly pressure parts and often with a gain in performance. Projected costs have generally been comparable with those for current post- and pre-combustion capture technologies, the major additional costs compared with air firing being associated with the production of the oxygen and the compression and treatment of the CO_2 product.

Therefore further experimental development is not being proposed for this phase. Instead the CCP requests an engineering study of the application of this technology to the boilers and process heaters in the CCP Refinery Scenario, sufficient to provide the cost data required by the CCP's Common Economic Model. It is a key requirement that the study should include the impact on costs of any new oxygen generation technologies likely to be available for commercial application by 2010. The foreseeable potential for cost reduction of integration between the oxygen generation, combustion and CO_2 treatment/compression plant should also be covered. It is not anticipated that the study will include major changes to the principle of firing existing plant with oxygen and recycled flue gas in place of air, but if the contractor is able to propose any adaptations of the concept which could reduce CO_2 capture costs, these should be included in the study.

Three new approaches to oxyfuel firing, mainly applicable to new rather than existing plant, have been rejected following pre-studies carried out for the CCP. These were a combustion system operating at elevated pressure, and two approaches to combustion in oxygen without flue gas recycle. These options should not be considered in the present study.It is expected that the preferred technology will include recirculation of a proportion of the flue gases after the final convective heat transfer stage but before separation of water from the CO_2 product. However, other options such as recirculation of CO_2 after water separation may be proposed for discussion if desired.

Technical developments are also taking place in the production of lower purity oxygen or enriched air. An additional element of this study will be to review whether these could allow an enriched air combustion scheme to be designed with lower CO_2 capture costs than the oxyfuel schemes described above.

Scope of Work

Phase 1

1. Process description, process flow diagrams and heat and mass balances for the retrofit of the boilers and heaters of the CCP Refinery Scenario for oxyfuel operation with flue gas recycle, to include cryogenic oxygen production and CO_2 treatment and compression. See Appendix B for details of the existing plant and conditions in the Scenario.
2. Preliminary study of the engineering feasibility of the conversion, including any additional sealing of the combustion plant against air in leakage, uncertainties in combustion performance, any duty losses and materials and corrosion issues. If it is considered that any aspect of the scenario is not amenable to conversion, such as any individual combustion plant or current fuel, this should be stated. It is not expected that detailed (e.g. CFD) modelling of each combustion plant will be undertaken as part of this study. Instead, performance predictions and optimisation should be the best that can be achieved on the basis of published information, engineering models if appropriate and the contractor's experience.
3. CO_2 emissions before and after conversion. CO_2 captured. Composition of CO_2 product stream (A specification for the CO_2 product is in Appendix C).
4. Specification of plant modifications and new plant, to the level required for capital cost estimation to ±30%.
5. Layout and land requirement of new plant.
6. Any critical safety issues with oxyfuel operation.
7. Capital costs on the basis specified in Appendix C.
8. Operation and maintenance costs on the basis specified in Appendix C.
9. Additional utilities, including electric power for air separation, recycle blowers and CO_2 treatment and compression, on the basis specified in Appendix C.
10. Any recommendations for further work needed to prepare for a plant demonstration on a boiler or heater.

Phase 2

1. As phase 1, but designing the retrofitted system to use, for oxygen production, oxygen ion transport mixed conducting membrane technology (or any other technology expected to produce large tonnage high purity oxygen at lower cost than cryogenic plant and to be commercial by 2010).
2. To review whether any new technologies for lower purity oxygen (enriched air), such as novel adsorbents or membranes could lead to an enriched air combustion scheme with lower CO_2 capture costs for this scenario.
3. Deliverables
   Two final reports detailing and discussing the above outputs.
4. Timing
   Phase 1: 3 months starting 4Q 2001.
   Phase 2: 3 months starting 4Q 2002.
5. Work process
   Monthly summary progress reports and telephone conferences. Meetings with CCP team members to initiate the programme and to present the draft final report.

2.4 CO_2 Storage Monitoring and Verification

This program was described in the original DOE work statement as ' Task 4 - Establish Key Geologic Sequestration Controls and Requirements'

An important aspect of this project will be to understand the key controls on efficiency for each geologic sequestration option, such that the total cost of separation, capture, and sequestration can be minimized in an integrated manner. It is also important to understand the geological and engineering requirements of a sequestration project to ensure that long-term sequestration can be maximized in a safe manner, measured and verified, and that risks can be adequately identified and mitigated.

2.4.1 Understanding Geologic Storage

A first step in defining geologic sequestration requirements is to understand the fundamental aspects of geologic storage. Specifically, natural analogs can provide a great deal of information on the integrity of cap rocks, natural leakage, and storage capacity. These analogs include both naturally occurring CO_2 sources, and oil reservoirs undergoing CO_2 injection for EOR. A large knowledge base of operating experience also exists within the gas storage industry. However, storage of CO_2 is different from these analogs in a number of important ways. First, the changes of pH and chemical reactivity of CO_2 mean that the long term integrity of steel, cement and the reservoir seal can no longer be taken for granted. Second, the time period for storage is much longer than the normal hydrocarbon field cycle – periods of about 100 years upward may be necessary. Finally, the solubility of CO_2 in water means that any hydrodynamic gradients causing dynamic water flow through a trap can transport substantial volumes of CO_2 out of the trap. This portion of the project will therefore focus on gathering relevant information that can be used to improve our understanding of geologic storage of CO_2.

2.4.2 Flexibility in CO_2 Purity

As discussed previously, the overall cost of CO_2 separation, capture, and sequestration can be substantially reduced if the sinks are tolerant to lesser-purity CO_2. To study this issue, a combination of literature search, laboratory and modeling studies will be performed. Much of this information may be available from other R&D projects (e.g., GEO-SEQ). Public-domain literature will also be searched to understand the potential reservoir impacts of impurities in the CO_2. Using this information, reservoir models will be employed to establish broad relationships between CO_2 purity, incremental oil and/or coalbed methane recovery, and CO_2 sequestration.

2.4.3 Maximizing CO_2 Sequestration

Different from typical EOR strategies, the objective of CO_2 sequestration is to maximize CO_2 volumes retained in the reservoir. Modeling studies will be performed to identify the general operating strategies needed to achieve this goal, not only for EOR, but also for coals.

2.4.4 Measurement and Verification

The viability of long-term geological storage of CO_2 must be established for public acceptance and assurance that it is safe. For long-term storage, such issues as leakage of CO_2 through old wellbores, through reactivated faults, through drift out of the formation, or through the seal after long-term chemical reactions need to be addressed. Measurement of sequestered CO_2 that will withstand audit and verification by third parties will also be an important need for commercial CO_2 sequestration activities. Many tools exist or are contemplated for monitoring the geologic sequestration of CO_2. This subtask will seek to identify effective monitoring tools and technologies, which hold high potential for improving our ability to characterize the location, quantity, and condition of sequestered CO_2.

2.4.5 Risk Assessment and Mitigation Options

The subtask will examine the risks associated with safe sequestration of CO_2 in geologic formations, and what mitigation options are available to minimize them. The first step in this assessment will include identifying potential subsurface leakage modes. Once potential leakage routes are identified, the next question is how likely they are to actually leak, at what rate over time, and what are the long-term implications for safe sequestration. Diagnostic options will be developed for assessing leakage potential on a quantitative basis.

2.4.6 Executive Summary of Sub Task 2.4 - SMV Work Programs

2.4.6.1 Introduction

The CCP Storage, Monitoring and verification (SMV) Technical Team coordinated a CCP-sponsored workshop in Washington D.C. in January 2001, which attracted 53 representatives from around the world. As a result, this workshop generated 61 technical proposals to address critical technical gaps that need to be, and must be researched in the areas described in sub tasks 2.4.1-2.4.5 above. This R&D must be conducted before industry, in partnership with governments, will be able to demonstrate that geologic storage of CO_2 can be safe and effective.

Since February 5, 2001, the deadline for the technology development proposals, the SMV Team expended significant time to read, analyze, evaluate, rank and select those technical proposals of the 61 proposals which best address the R&D gaps and needs as defined by the SMV Team. Although the majority of funding necessary is planned to go to USA National Labs, which DOE is very familiar with, some funding will be needed by non-National Lab organizations such as Universities, and organizations east of the Atlantic.

CCP Executive Board approval to proceed with contract negotiations was given in March 2001, and the technical negotiations for the R&D proposals (workplans, scope, funding, etc.) were mostly completed in May. Due to the late award of the CCP contract by the DOE and further discussions concerning patent waivers, at this point in time only one contract has been awarded.

Tables 6 (a &b) and 7 (a&b) (see Attachments) list the projects recommended for DOE co-funding with the brief descriptions and associated funding. Table 8 provides a brief description of each project that will not be co-funded by the DOE. Table 9 lists those same projects with the recommended funding by time periods.

Sections 2.4.6.2 provide some background to the activities that led us up through engaging technology providers, in what we believe was an open, fair and transparent process. Section

8 covers the “Proposal Selection Process”. The remaining sections cover recent activity and “The Way Forward”.

2.4.6.2 Recommended SMV Portfolio of R&D Projects

2.4.6.2.1 Background

The SMV Team has 10 representatives from all nine CCP participants. The team meets face-to-face two to three times per year, and also convenes almost every week by teleconference. The team’s kickoff meeting occurred in Oslo in April 2000.

The SMV Team has key core competencies in geoscience (geology, geophysics, geohydrology, geomechanics, geochemistry, geophysics), various engineering disciplines (petroleum and natural gas engineering, chemical engineering), and heath, safety and environmental (HSE) risk assessment methodology.

2.4.6.2.2 Review & Evaluation (R&E) Phase

The objective of the kickoff meeting was to map out the plan for the R&E Phase, which was to conclude in July 2001. Specific products delivered to the CCP Executive Board were state-of-the-art (SOTA) descriptions of the technologies, technical gaps needing additional work, and investment strategy recommendations.

The SMV Team extremely heavily relied on the DOE Roadmap developed in 1999 as the basis of the SMV analysis. On balance, the SMV Team thought that the DOE Roadmap was an excellent piece of work and well described the technology SOTA as well as the key gaps. There were a couple of gaps, however, that the team felt needed articulation and technology development in order for geologic storage to be deemed safe and effective. The SOTA descriptions were organized into the following areas:

- Understanding Geologic Storage – Understanding trapping mechanisms, potential for migration, potential negative impacts on caprock and fault integrity, etc.
- Maximizing Storage – Since supercritical CO_2 has very low viscosity and will “finger” through the strata, how can CO_2 storage tonnage be maximized?
- Short-Term Monitoring & Verification Tools – tools available or close to commercialization.
- 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).
- 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 some 50 external R&D efforts showed that technical gaps from Areas 1 through 3 above were being well addressed and researched, and needed only nominal funding from the CCP. Examples of this effective research being conducted are GEOSEQ (DOE/LBNL), SACS (Sleipner Field, Offshore Norway), Weyburn (Canada), GESTCO (EU), GEODISC (Australia), and many others as well.

The investment strategy recommendation to the Executive Board was to focus about 50% of the SMV Team's budget on Area 5. Area 5 is an area that essentially was not being addressed at all and would be a critical piece in demonstrating 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 through 3.

2.4.6.2.3 SMV R&D Objectives

The ultimate value of the work fall into some key areas:

- Develop the health, safety and environment (HSE) risk assessment methodology that is seriously lacking today
- Perform site-specific and generic studies to show public and governments that geologic storage can be safe and effective, and in what generic and site-specific areas and with was kinds of storage attributes
- Continue to develop the tools to understand CO_2 migration, and develop methodologies for monitoring and verification of storage.

2.4.6.2.4 The "Final Deliverable"

The final deliverable late in 2003 will be a reader friendly, integrated summary of all 30 projects. This will be done by a professional editor because it needs to be a seamless, integrated, and hopefully compelling story of the work done and the degree to which CO_2 storage can be safe and effective. We envision that there will be more than one version so that we can effectively reach various audiences, such as the public, governments, the technical community, and so on.

2.4.6.2.5 Analysis Phase

This phase began in August 2000 and ended in early February 2001. During this phase the SMV Team engaged potential Technology Providers, such as National Labs, Universities and Consultants. A key event in this process was a 2-day workshop, wherein we explained our technology needs. This workshop was held January 16-17, 2001, in Washington D.C. Several breakout sessions focused on what we can learn and leverage from the nuclear waste, deep well industrial waste injection, and groundwater contamination issues.

53 people from as far as Australia participated. Although we were hoping for 20 to 30 technology development proposals, the event generated 61 proposals that took the team quite some time for evaluation and ranking. The total face value of the 61 proposals was $17 million USD.

2.4.6.2.6 Technology Selection Phase

From early February through March, the SMV Team had the very large task of reviewing, evaluating, ranking, and selecting the best proposals which addressed the high priority technical gaps identified by the team. The Proposal Evaluation Process used was:

- Selected one or two team members to evaluate each proposal
- Weekly teleconferences to review and prioritize
- Developed Selection Criteria
- Grouped by Key Technology "Buckets"

A. Identify best HSE Risk Assessment Methodology proposals
B. Identify best Long-Term Monitoring and Verification proposals
C. Identify best proposals, which address key gaps not in Buckets A & B above

- Scored by 5 Technology Buckets
- Looked for Overlaps and Gaps
- For key proposals selected, searched for ways to shrink budgets, re-scope, stretch out, etc.
- Provided for overall balance and "geo-diversity"

The 5 Selection Criteria used by the SMV Team were:

- 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 - Is the potential application and geologic sink large enough to make it attractive to fund?
- Importance of CCP Investments - Is the R&D critical to demonstrating storage can be safe and effective, and is the CCP key to providing funding to develop the technology? (i.e. would the R&D be funded elsewhere if CCP did not fund?)
- Provider Track Record / Reputation / Track Record / Core Competencies / Staff Availability - Will the Technology Provider deliver the goods on time and on budget?
- Collaboration Capability / Ongoing Activity / Links with other Key R&D - How well does the proposal have synergistic links with other R&D, contacts, interest levels, etc?
- Other Considerations

There are 3 groups of proposals as follows:

- Proposals to be funded by Norway / Klimatek
- 7 proposals to be funded by the EU / NGCAS
- 61 proposals generated as a result of the January 2001 Workshop in Washington, D.C.

From the list of 61 proposals, the end product was a portfolio of some 15 proposals that addressed key technical gaps primarily Areas 4 and 5 described above in Section 4. Approval from the CCP Executive Board to proceed with these 15 proposals was received in late March, 2001. These 15 proposals were called the **"**Short List**"** proposals.

The Board was also informed that in addition to the 15 proposals on the Short List, there were 10 proposals of very high quality, but which could not be funded in 2001 due to the SMV Budget allocation. These 10 proposals were called the **"**Parking Lot**"** proposals.

2.4.6.2.7 Technical Work Plan Negotiations

From April through June, the team's focus was to re-scope and downsize several of the 15 proposals so that all 15 could be funded within the approved SMV budget for 2001. It was important to fund all 15 proposals as each addressed a key technical gap.

2.4.6.2.8 Recommended SMV Portfolio Modifications

Upon further technical analysis, the SMV Team in a face-to-face meeting in Oslo in July, concluded that there were an additional 5 proposals which needed to be funded to address additional gaps in 2001. Due to delays, total funding for the SMV Team would only grow nominally by $100,000 USD.

2.4.6.2.9 The Way Forward

The immediate action that must occur quickly is for the Contracts Team to execute all of the technology development contracts. After all of technology Providers (TPs) get their work underway, we will hold another workshop in November. The purpose of this workshop is for each TP to share what they are doing, the challenges they face, and where each TP could use some help from the others. The goal is to enhance the international collaboration, and increase the value and leveraging to the CCP and government co-funding partners by identifying overlaps and gaps.

Each TP's progress is being managed by one or two SMV team member depending on the size of the project. Our goal is to aggressively manage each TP, to provide work direction and industry support, regularly review progress reports, cut lower value projects if deemed appropriate later, and add new attractive R&D opportunities, if available, on a semi-annual basis.

The recommended SMV Team portfolio can efficiently spend $1.45 million in 2001. The $3.01 million for 2002 and the $2.26 million for 2003 currently exceed the SMV Team budget allocation. It is anticipated that several projects will need to be phased out prior to completion, or the budget allocation will need to be increased, or both.

The final deliverable late in 2003 will be a reader friendly, integrated summary of all 30 projects. This will be done by a professional editor because it needs to be a seamless, integrated, and hopefully compelling story of the work done and the degree to which CO_2 storage can be safe and effective. We envision that there will be more than one version so that we can effectively reach various audiences, such as the public, governments, the technical community, and so on.

Section 3

Budget

3. DOE BUDGET

Table 10 shows a program and cost summary of the DOE workplan which will run from October 2001 through to December 2003. The budget reflects the total program costs assuming all elements run through to the end of 2003. As we move through Phase 1 of the workplan the program will be focussed on to fewer favored technologies. i.e. non-performing projects will be dropped from the program. This process enables us to manage the program costs to stay within the overall agreed budget. At the end of Phase 1 (December 2002), a revised program of favored technologies together with updated costs will be provided for approval for Phase 2.

4. ATTACHMENTS

4.1 Tables and Figures

4.2 EU Program Summary

4.2.1 EU GRACE

(NB. Work packages 2& 3 now funded in the Klimatek Norcap project)

<u>Work package 1</u> Membrane Reactor for Hydrogen Production

Total Cost Euro 1,640,000

Partners (see Table 11: - P6 (Lead), P8, P9, P10, P1, P7, P13)

- **Membrane materials**
  - Evaluation of existing membrane materials.
  - Development of improved materials.
- **Reactor designs**
  - Development of membrane reformer designs.
  - Engineering studies conducted to determine the performance, cost and feasibility

    of such designs.
- **Process Designs**
  - Integration of the membrane reactor concepts into an optimized pre-combustion

    flow sheet.

<u>Work packages 4 to 8</u> Capture and Separation by Chemical Looping Combustion

Total Cost Euro 1,414,000

WP 4	320,000
WP 5	279,000
WP6	205,000
WP7	485,000
WP8	125,000

Partners: - P1 (Lead), P2, P3, P4, P5

- **Oxygen carrier particles**

  - Selection of a wide range of materials for testing
  - Manufacture and screening of particles
- **Comprehensive particle testing**
  - Reactivity and integrity data
- **Fluidization testing**
  - Determination of optimum fluidization conditions
- **Bench-scale chemical looping combustor**
  - Verification of oxygen carrier particle performance
  - Demonstration of technology
- **Engineering and cost studies**
  - Configuration and economic modeling of an industrial plant