



IEA Greenhouse Gas R&D Programme Task 1

JOULE-II The Underground Disposal of Carbon Dioxide

Project Summary 001 combined with 005

MARCH 1996

OBJECTIVES

IEA Programme

- To evaluate (on a full fuel-cycle basis) the technologies used for the abatement, control, use and disposal of carbon dioxide (CO₂) and other greenhouse gases derived from fossil fuel use. The technical and feasibility aspects, performance, economics, environmental benefits and impacts of the technologies were also studied.
- To estimate the impact that the implementation of these technologies would have on the economy and energy markets.
- To sponsor or conduct collaborative R&D projects in the field of CO₂ removal, utilisation, transportation and disposal.
- To disseminate results to participants and prepare R&D proposals for the favoured technical options.

JOULE-II Initiative

- To determine the technical feasibility and costs of, and the potential volumes available for, the geological disposal of CO₂ from fossil fuel-burning power stations, both onshore and offshore in the UK and Europe.
- To evaluate the optimum conditions for safe and permanent disposal of CO₂ underground, the quantities of CO₂ that may be disposed of in this way, and the costs that would be involved.

POTENTIAL USERS OF THE TECHNOLOGY

- Electricity generation industry
- Chemical companies
- Coal, oil and gas industries.

CONTRACTORS' REPORTS

IEA Programme

IEA Greenhouse Gas R&D Programme: Phase 1 Summary Report: available from Operating Agent

JOULE-II Initiative

The Underground Disposal of Carbon Dioxide CT92-0031 available from the contractor.

PARTICIPANTS

IEA Programme

Task 1 was sponsored by 14 countries: Australia, Canada, Denmark, Finland, Germany, Italy, Japan, the Netherlands, Norway, Spain, Sweden, Switzerland, the UK and the USA.

JOULE-II Initiative

France, Germany, the Netherlands, Norway and the UK.

OPERATING AGENT/CONTRACTOR

IEA Programme

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JOULE-II Initiative

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COST

IEA Programme

£202,500 funding from the Department of Trade and Industry (DTI) out of a total cost for Task 1 of £1.8 million (1991 money values).

JOULE-II Initiative

£143,544 DTI funding (50% of BGS costs) out of a total cost of approximately £1.25 million.

DURATION

IEA Programme:

May 1991-October 1994.

JOULE-II Initiative:

February 1993-June 1995.



BACKGROUND

Man-made emissions to the atmosphere of greenhouse gases such as CO₂, methane and chlorofluorocarbons (CFCs) risk enhancing the natural greenhouse effect, thereby contributing to global warming and climatic change.

Concern about the effects of such change has stimulated international co-operation in order to develop a better scientific understanding of the processes involved. Many nations have also adopted strategies designed to limit greenhouse gas emissions, mainly by improved energy efficiency and changes in fuels. However, further action may be needed in the future, and one option could be to capture and dispose of the relevant gases as they are produced.

The IEA Greenhouse Gas R&D Programme was initiated in 1991, and its first task (Task 1) was to provide an independent and objective evaluation of a range of technologies for capturing and disposing of (or using) CO₂ the major greenhouse gas. Some 24 studies, involving 14 countries and with additional support from the European Commission, have been undertaken, and the first phase of the programme is now complete.

THE STUDIES AND THEIR FINDINGS

Power Generation Studies

Task 1 of the IEA programme has derived cost, efficiency and emissions data for four types of power generation scheme representing both current and future technology:

- pulverised fuel (PF) plant incorporating flue gas desulphurisation (FGD)
- natural-gas-fired combined cycle (NGCC) generation
- integrated gasification combined cycle (IGCC) generation
- the combustion of coal in an atmosphere of oxygen and recycled CO₂.

In each case a standardised plant size with a net electrical output of 500MW has been assumed, and each system has been evaluated on a consistent basis.

Carbon Dioxide Capture

Task 1 has also assessed a range of existing and novel systems for CO₂ capture. The high energy requirement of all these systems significantly increases the costs of power generation (Table 1), particularly where CO₂ concentrations in the flue gas stream are low. This, to some extent, reduces the efficiency advantage of gas-fired plant.

Carbon Dioxide Storage

A conventional 500MW coal-fired power station produces about 3 million tonnes of CO₂ per year. It is therefore clear that, if CO₂ capture is to be implemented as a method of reducing atmospheric emissions, some form of large-scale storage must be developed. Several storage options have been assessed:

- The oceans, which are the final 'sink' for CO₂, offer the greatest storage potential in the long term. Although not every country has suitable access to deep oceans, the global storage capacity is estimated at more than 1000Gt carbon.
- The planting of forests is, in principle, a feasible approach to CO₂ disposal, with the trees 'fixing' the carbon as they grow. However, about 2000km² is required to absorb the CO₂ produced by a 500MW coal-fired power station during its expected life. Because of the land requirement, more effective management of the world's forests and reforestation are perceived to be more promising options. The short rotation coppicing of trees for the production of wood chip fuel is also attractive in some countries.

- The JOULE-II study on the underground disposal of CO₂ has shown that underground sequestration is a feasible option. The technologies involved are commercially proven, while studies of large, naturally occurring CO₂ accumulations indicate that the gas can be retained in such reservoirs for millions of years.

Depth of storage is an important consideration. Shallow subsurface containment is deemed to be impractical: there is insufficient gas-tight man-made void space to accommodate significant quantities of CO₂, while shallow, porous and permeable reservoirs are important for groundwater supplies. However, storage at depths of 800m or more within porous or permeable reservoir rocks is a practicable option, provided these reservoirs are capped by clays and shales of limited permeability. At these depths the CO₂ would be in a dense supercritical phase, which would greatly increase storage capacity per unit volume of reservoir rock. Furthermore, although structural or stratigraphic traps, including depleted oil and gas reservoirs, are known to be appropriate storage locations, modelling suggests that CO₂ can safely be injected into essentially horizontal structures.

Table 1 Costs of power generation with and without CO₂ capture

Power plant	Cost of power generation (US c/kWh)	Cost of power generation with CO ₂ capture (US c/kWh)
PF/FGD	4.9	7.7
NGCC	3.5	5.3
IGCC	5.3	6.3

Table 2 Underground CO₂ storage capacities, Europe

Storage location	Onshore Gt CO ₂	Offshore Gt CO ₂
Aquifers ¹	57 ¹	716 ¹
Oil fields	0.22	5.94
Gas fields	12.54	14.40

¹ Figures for conventional fluid traps alone are 10.67Gt onshore and 19.51Gt offshore.

Table 3 Potential global CO₂ storage capacities

Storage location	Gt carbon
Oil and gas wells	6-180 ¹
Salt domes/Aquifers	100-3000
Ocean disposal	1,400 – 2 x 10 ⁷
Global forest management	50-100

¹ Literature gives 120-500Gt carbon

The estimated underground storage capacities for Europe estimated in the JOULE-II study are around 800Gt of CO₂ (Table 2).

The cost of the CO₂ underground disposal process is estimated to be only a small proportion of the cost of capture.

IEA estimates of the storage capacities for the various storage options are shown in Table 3. Most of these options could be implemented using current technology, although the environmental impact of large-scale storage, particularly in the oceans, is not yet clear.

Carbon Dioxide Utilisation

CO₂ is already widely used in industry although, in most cases, the gas is not permanently stored in the products but escapes to atmosphere at a later date. It may, therefore, be possible to use captured CO₂ for commercial purposes. There are several possible options:

- CO₂ could be used as a replacement feedstock in the manufacture of chemical products, reducing the demand for other manufactured feedstocks. Although income generated from the sale of the products would help to offset the cost of CO₂ capture, other costs would be incurred during

manufacture. This, combined with high levels of energy consumption, means that the net benefits are limited.

- Naturally-occurring CO₂ is already used commercially in a number of oilfields for enhanced oil recovery. It may also be economic to use CO₂ recovered from power stations for this purpose, because the high costs of capture can largely be offset by the income derived from the sale of recovered oil. Although the injection of CO₂ to improve oil output will greatly increase the CO₂ storage space available, it is not yet clear to what extent subsequent oilfield operations might release the stored CO₂ into the atmosphere.
- A third possibility is to use the CO₂ to grow algae for the manufacture of biofuels. Although this approach is not yet developed sufficiently to judge its technical or economic feasibility on a large scale, it offers the theoretical potential for high rates of carbon take-up and could be an option in certain locations.

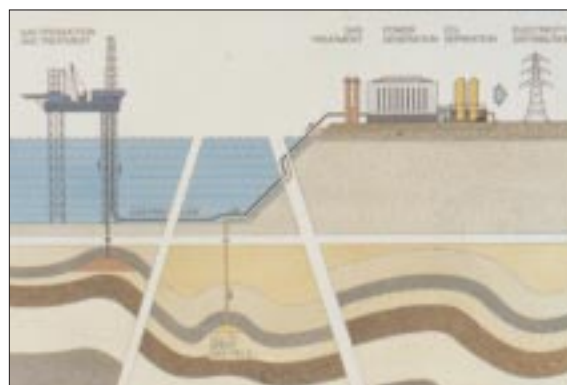
Assessing the Global Impact

Power generation investment decisions are based on well-established procedures that take account of the associated

environmental impact to the extent necessary to comply with legislation on planning and regulations on emissions to air, water and land. A component of Task 1 of the IEA programme has been to develop a methodology for evaluating all the costs, including the environmental (or 'external') costs, associated with power generation, and to test that methodology on three specified fuel cycle/CO₂ disposal options:

- NGCC plant with CO₂ capture followed by disposal in a disused gas well
- IGCC plant with CO₂ capture followed by disposal in the deep ocean
- PF plant with FGD and sequestration of CO₂ in a newly planted forest.

Environmental impacts and costs have been assessed at the local, regional and global levels, for power generation and for CO₂ capture and disposal. All the known effects have been identified for each fuel cycle and, where possible, assessed using the damage function approach. Each impact has been given a monetary value or, where this proved impossible, a qualitative assessment. The levels of confidence assigned reflect the associated degree of uncertainty.



NGCC with gas field storage of CO₂.
Schematic courtesy of CRE Group Ltd.

BACKGROUND (continued)

The JOULE-II project has focused specifically on possibilities for the underground disposal of CO₂ from power plant in Europe. There are three main reasons for this approach:

- *electricity generation contributes about 30% of global CO₂ emissions from fossil fuel consumption*
- *global energy demand will continue to rise for the foreseeable future, with a high proportion of that demand being met from fossil fuels*
- *Europe already has much of the necessary information on geology, power supply and emissions.*

Nevertheless, many of the project findings are applicable at the global level.



Table 4 Private and external costs of power generation

	NGCC + CO ₂ disposal in a disused gas well US c/kWh	IGCC + CO ₂ disposal to the deep ocean US c/kWh	PF + FGD + CO ₂ sequestration in a forest US c/kWh
Total private costs ¹	6.56	8.61	5.66 + (1.3-11.1) ⁴
External costs ²			
Local	0.01	0.22	0.18
Regional	0.10	0.14	0.23
Global ³	0.01	0.01	-0.10
CO ₂ disposal	0.00	0.07	-1.31
Total external costs	0.12	0.44	-1.00

¹ At 10% discount factor ² For those impacts that have been given a value
³ At 1.5% discount factor ⁴ Range of forestry costs, dependent on sequestration period and discount rate

The principal impacts at the local level are occupational accidents. At the regional level, most of the potential impact is associated with damage to building materials and human health as a result of sulphur dioxide (SO₂), nitrogen oxides (NO_x) and particulate emissions, though much of the underlying data is controversial and highly uncertain.

At the global level the emphasis is on climate change, and the assessment varies with the climate change scenario and discount rate applied. The ‘pulverised fuel and forestry’ option shows a particular benefit in climate change terms, as the forest continues to mature beyond the lifetime of the power station, thereby sequestering much more CO₂ than the fuel cycle itself demands.

The main potential impacts of CO₂ capture and disposal have been identified as accidental releases of CO₂, ecological disturbance of the deep ocean in the ocean disposal option,

and underground migration of CO₂ in the gas well disposal option. There is considerable uncertainty as to the likely magnitude of these impacts.

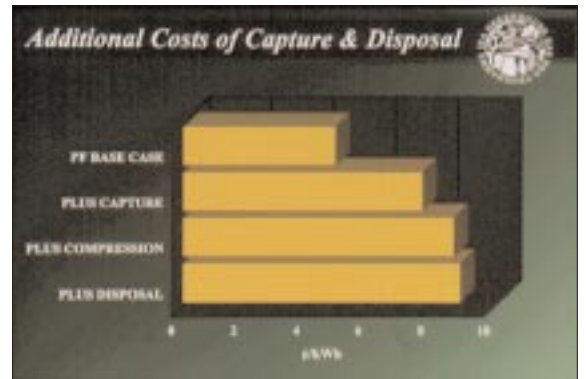
The overall finding is that, as a consequence of adopting measures to capture and dispose of CO₂, the external costs associated with the three fuel cycles are small compared with the generation (‘private’) costs (Table 4). This means that the choice of option is dominated by the private or internal costs of the technologies involved.

OUTSTANDING ISSUES

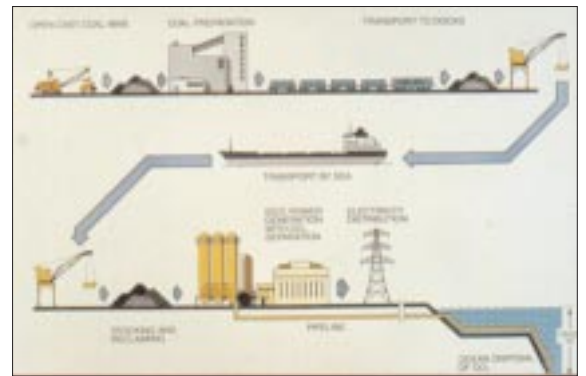
IEA Programme

A number of key questions remained at the end of Task 1 of the IEA programme:

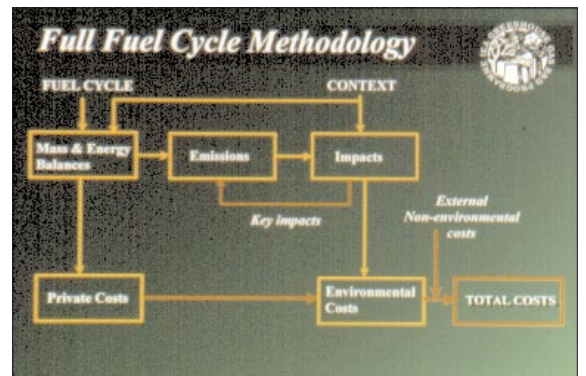
- Can the costs of CO₂ capture be substantially reduced?
- How can the risks of CO₂ disposal be reduced?
- Are the options for utilising CO₂ able to make a substantial net reduction in emissions?



Courtesy of CRE Group Ltd.



IGCC with ocean storage of CO₂. Schematic courtesy of CRE Group Ltd.



Courtesy of CRE Group Ltd.



- What are the full fuel cycle costs of other CO₂ emissions-mitigation technologies?
- How effective are the techniques used to mitigate emissions of other greenhouse gases?
- What research is needed to make significant progress in the various technologies?

JOULE-II Initiative

Further research is required in three areas:

- Geochemical modelling and reservoir simulation for CO₂ disposal in offshore formations that lack a conventional fluid trap
- Geochemical experiments and modelling to determine more precisely the effects of CO₂ on the permeability, porosity and stability of reservoir and cap rocks
- Construction of a one-dimensional two-phase flow reaction-transport reservoir simulator for simulating the migration of supercritical CO₂ and water through the reservoir and predicting likely geochemical change.

IEA PHASE 2 ACTIVITIES

The major elements of Phase 2 of the IEA Greenhouse Gas programme include:

- Assessment of other power generation technologies, particularly those that provide the basis for a radical approach to the capture of CO₂, for example fuel cells
- Investigation of advanced capture techniques
- Further consideration of ocean storage
- The potential for using CO₂ for chemical manufacture
- Full fuel cycle studies, including further consideration of global impact
- Assessing the emissions-mitigation techniques available for other greenhouse gases, beginning with methane.

FURTHER INFORMATION

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CONCLUSIONS

- *The sequestration of CO₂ from the combustion of fossil fuels is technically feasible. Various options are available, including the use of physical and chemical solvents and, for IGCC applications, cryogenic processes.*
- *The energy needed to operate most CO₂ capture systems significantly reduces the efficiency of power generation.*
- *CO₂ capture would increase the cost of electricity generation by at least 40-50%.*
- *It is technically feasible to use the deep oceans, depleted oil and gas reservoirs, and deep horizontal aquifers for storage. However, there is still considerable uncertainty about the long-term effectiveness and environmental impact of such storage.*
- *The planting of forests is a feasible approach to CO₂ disposal. Although the initial costs can be relatively high, the long-term advantages of continued sequestration beyond the life cycle of the generating plant can be substantial, assuming the continued existence of the forest.*
- *The use of captured CO₂ for enhanced oil recovery and for the manufacture of chemical products is a possible way forward, particularly if the costs of capture are reduced.*
- *Application of a new methodology has shown that, where NGCC, IGCC and PF+FGD plant incorporate some means of CO₂ capture and storage, the estimated levels of associated external costs are very small when compared with the private costs.*