BNL-27164

CONF - 800309 - - 1/

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ENVIRONMENTAL CONTROL TECHNOLOGY FOR ATMOSPHERIC CARBON DIOXIDE

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ABSTRACT. The impact of fossil fuel use in the United States on worldwide CO₂ emissions and the impact of increased coal utilization on CO₂ emission rates are assessed. The aspects of CO₂ control are discussed as well as the available CO₂ control points (CO₂ removal sites).

The primary factor affecting the practicability of a CO₂ control system is the energy required by the control system. Removal of CO₂ from the atmosphere or from the ocean surface water is energetically not feasible with a fossil energy source. More CO₂ is generated than is recovered. Removal from the stacks of fossil fuel power plants requires the least amount of energy and allows use of a fossil energy source. Estimates of the energy required to capture and recover CO₂ from coal-fired power plant stacks by various processes are presented. The effect on the reduction in overall plant efficiency is determined.

Although capture and recovery of CO₂ are important considerations in the overall scheme of CO₂ control, disposal or reuse of recovered CO₂ is the greatest problem in the CO₂ control chain. Of the several options considered, deep ocean storage appears to be a possibility.

Two control scenarios are evaluated, one based on the absorption of CO₂ contained in power plant flue gas by seawater; the other, based on absorption of CO₂ by MEA. Captured CO₂ is injected into the deep ocean in both cases. The analyses indicate that capture and disposal by seawater is energetically not feasible, whereas capture and disposal using MEA* is a possibility. However, the economic penalties of CO₂

* Mono Ethanol Amine.

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control are significant. At a CO₂ removal efficiency of 50% the power generation efficiency of a conventional coal fired plant would be reduced from 34% to 25% and the cost is expected to double. For 90% removal the efficiency is reduced to between 15% and 6% and the power generation cost would increase by a factor of from 4 to 7.

The use of non-fossil energy sources, such as hydroelectric, nuclear or solar energy is considered as an alternative for limiting and controlling CO₂ emissions resulting from fossil energy usage.

I. INTRODUCTION

(1) Global CO₂ Problem

During the last one hundred years or so, the release of fossil carbon as CO₂ has increased at an exponential rate as shown in Figure 1.[1] As a result, the concentration of CO₂

contained in the atmosphere has grown by about 12%, increasing from about 295 ppm by volume in 1860 (pre-Industrial Revolution) to the current level of 331 ppm. Except for short periods during World Wars I and II and the Depression, the release rate of fossil carbon has increased at the rate of about 4.3% per year.[2] At present, with no CO₂ emission controls, about 5×10^9 metric tons of carbon per year in the form of CO₂ are emitted to the atmosphere by the burning of fossil fuels from worldwide sources. About 50% of this carbon can be accounted for by the increased CO₂ concentration in the atmosphere. The remaining carbon is presumably absorbed by the oceans and by the land biomass; however, the actual quantities of CO₂ absorbed by the land biomass and by the oceans are still undetermined. Deforestation considerations tend to complicate the issue even further.

It is predicted that the concentration of atmospheric CO₂ relative to the pre-industrial value could increase by a factor of from about 2 (low-use case) to about 5 (high-use case) during the next one hundred years.[2] The low-use case corresponds to a fossil fuel growth rate of 2% per year until the year 2025, followed by a symmetrical decrease as alternative and renewable energy sources become more available and the use of fossil fuel is discouraged. The high use case corresponds to an initial annual growth rate of 4.3% with subsequent reductions in proportion to the ultimate fossil fuel supply that has been consumed.

Of primary concern is the warming ("greenhouse effect") which may be produced by these increased CO₂ concentrations due to the absorption by CO₂ of a portion of the infrared radiation returning to space from the earth. The amount of warming produced by a given CO₂ concentration increase is estimated at 1° to 5°K per doubling of the CO₂ concentration. For the low-use case described above, this corresponds to a mean global temperature rise of from about 1° to 5°K over the next one hundred years and from about 2° to 10°K for the high-use case. A temperature rise of 1° or 2°K during this period may be acceptable; however, a rise of 10°K would probably cause catastrophic climatic and environmental effects.

Increased concentrations of particulate matter in the global air mass might produce a cooling effect by backscatter of incoming solar radiation and thus counteract, the warming produced by increasing CO₂ levels. However, uncertainties in this effect and increased reductions in particulate emissions make control by this method of questionable value.

Since there is a chance that naturally occurring and/or anthropogenic opposing factors will not just counter the

effects of increasing CO₂ levels, it may be necessary to limit industrial CO₂ emissions. It is thus of interest to examine the technical feasibility and economic costs of CO₂ control should the need arise for regulating the quantity of CO₂ contained in the atmosphere.

(2) Impact of U.S. Emissions

In order to determine the impact of fossil fuel use in the United States on overall (worldwide) CO₂ emissions, we have superimposed several points on Figure 1, based on U.S. fuel use data for the years 1950 through 1976.[1,3] The points were obtained by subtracting the estimated emissions of carbon (as CO₂) by U.S. sources from the corresponding worldwide emissions for each of the above years, and thus indicate the quantities of carbon that would have been emitted if the U.S. had not burned any fossil fuels during these years. The reduction in carbon (and thus in CO₂) by this hypothetical non-use of fossil fuels in the U.S. ranges from 0.32 ppm in 1950 to 0.64 ppm in 1973 (and in 1976). However, during this period the percentage of the total yearly emissions contributed by the U.S. decreased from 43% in 1950 to 27% in 1976. Furthermore, it is projected that the contribution to global CO₂ production by the U.S. and Canada will decrease to about 8% by the year 2025 due to use of alternative energy sources and lower rate of energy growth demand. Developing nations will account for 36% of the CO₂ production, the USSR and Eastern Europe 27%, Asia 19%, Western Europe 7%, and Japan and Australia 3%.[1] Thus, it appears that a worldwide effort would be required to effectively control the level of atmospheric CO₂.

(3) Impact of Alternative Energy Sources

Table 1 contains the source distribution of the carbon (CO₂) produced from major worldwide sources for 1976.[1] Using heating values of 18,000 BTU/lb of contained carbon for coal, 22,400 BTU/lb carbon for fuel oil and 31,500 BTU/lb carbon for natural gas, and assuming that all fossil energy was produced by the burning of solid coal, the carbon released to the atmosphere would have been roughly 6×10^9 metric tons or about 1.2 times the quantity actually emitted. Energy differences required in mining versus drilling, preparation, transportation, etc. and in combustion efficiencies were not taken into account. If we had assumed that the natural gas and petroleum consumed in 1976 had been replaced by coal derived gaseous and liquid fuels, the quantity of carbon released to the atmosphere would have been greater than 6×10^9 metric tons due to inefficiencies in the gasification and liquefaction processes. Thus, added reliance on coal for energy production tends to compound the atmospheric release rate of CO₂.

TABLE 1

WORLD-WIDE CO₂ EMISSIONS BY SOURCE
ALL ENTRIES IN 10⁶ METRIC TONS CARBON AS CO₂

Source	1976	1976 Distribution %
Coal	1676	33.2
Lignite	260	5.1
Crude petroleum & N.G. liquids	2224	44.1
Natural gas	675	13.4
Natural gas flared	113	2.2
Cement	99	2.0
Total carbon as CO ₂	5047	
Incremental atm CO ₂ conc. (ppm)	2.38	
U.S. emissions contribution	0.64	

depending upon the extent to which coal displaces oil and natural gas and future energy use patterns.

The expected reduction in the U.S. contribution to worldwide atmospheric CO₂ emissions is partially attributed to the development and implementation of alternative energy sources, which includes, nuclear (fission and fusion) geothermal and solar. The impact of these alternatives in the U.S. depends to a great extent on four factors: (1) the demand growth for energy in the U.S. (2) the availability of the technology (3) the capital and production costs and (4) the supply of world petroleum sources and (5) the demand of the developing countries for petroleum and coal resources.

Although uncertainties in all of these factors make it extremely difficult to estimate the impact of substitute energy sources, nevertheless some projections can be made for the U.S. in the next 50 to 100 years as listed in Table 2. Thus, if the energy demand no more than doubles in the next 50 years, and the fossil fractional use decreases in half, the U.S. would then contribute approximately the same amount as at present to the world atmospheric CO₂ emissions, as indicated by the CO₂ Index in the lower half of Table 2. However, the other countries would exceed their present contributions as they develop technologically at a higher rate. Eventually even

TABLE 2

PROJECTED DISTRIBUTION OF ALTERNATE ENERGY SOURCES
FOR THE U.S. IN THE NEXT 50 TO 100 YEARS

Source	Percent of Demand		
	1975	2025	2075
Fossil (coal, oil and gas)	90%	50%	30%
Nuclear (Fusion and Fission)	5	20	30
Solar	0	20	30
Hydro, Geothermal and others	5	10	10
Total	100	100	100

U.S. AND WORLD ENERGY GROWTH AND
DISTRIBUTION OF ALTERNATIVE SOURCES

Region	1975			2025		
	Quads	Fraction Fossil	CO ₂ Index*	Quads	Fraction Fossil	CO ₂ Index*
U.S.	75	0.90	67.5	150	0.50	75
Other Nations	175	1.00	175.0	1100	0.84	925
World (total)	250	0.97	242.5	1250	0.80	1000

*CO₂ index is product of Quads consumed and fossil fuel fraction.

these countries will acquire alternative energy sources and the CO₂ emissions may then become stabilized.

Table 3 shows the quantities of CO₂ produced per unit energy released for various naturally occurring and synthetic fuels. In determining the CO₂ generated by synthetic fuels such as substitute natural gas (SNG), the CO₂ generated in the production process is included. It is noted that natural gas produces about one third the amount of CO₂ per unit energy released in comparison to SNG derived from coal, and less than half the CO₂ from the direct burning of coal. Synthetic liquids and gases from coal generates the largest amount of CO₂ per unit of energy released. Of course there is no CO₂ generation if non-fossil energy sources used to produce hydrogen as a synthetic fuel.

II. CO₂ CONTROL OVERVIEW

Perhaps the most significant difference between the control of CO₂ in comparison to other pollutants is the vast amount of CO₂ generated by the activities of mankind--currently about 20×10^9 tons per year from the use of fossil fuels. Effective control would therefore require an extremely large-scale application of technology and the expenditure of large amounts of energy and capital. Methods for removing and

TABLE 3

CO₂ GENERATION FOR VARIOUS FUELS

Fuel type	Chemical Formula	Higher heating value Btu/lb	CO ₂ generated lb CO ₂ /lb fuel	CO ₂ generated lb CO ₂ /1000 Btu	Energy generated kWh(e)/lb CO ₂ generated ⁽¹⁾
Coke (semiass C)	C	14,000	3.67	0.26	
Bituminous coal	C ₁₀ H ₈ O _{0.1}	12,700	2.59	0.20	0.55 ⁽²⁾
Fuel oil & gasoline (petrol. dist.)	(CH ₂) _n	19,600	3.14	0.16	0.70
Benzene	C ₆ H ₆	18,000	3.38	0.19	
Acetylene	C ₂ H ₂	21,500	3.38	0.16	
Methanol (wood alc)	CH ₃ OH	10,000	1.38	0.14	
Methanol (syn. from coal)	CH ₃ OH	10,000	3.3	0.33 ⁽³⁾	0.34
Biomass (wood, cellulose)	(CH ₂ O) _n	8,000	1.47	0.18	
Carbon monoxide	CO	4,350	1.57	0.36	0.31
Natural gas	CH ₄	24,000	2.75	0.115	0.97
SNG from coal gasification	CH ₄	24,000	7.9	0.33 ⁽⁴⁾	0.34
Synthetic liquid fuels (by coal hydrogenation)	—	—	—	0.34 ⁽⁵⁾	
Synthetic liquid & gaseous fuels (mixed products from SRC-II process)	—	—	—	0.26 ⁽⁶⁾	
ONG coal & non-fossil hydrogen	CH ₄	24,100	2.73	0.11	1.07
Hydrogen generated by:	H ₂	61,000	0	0	
Coal gasification	H ₂	61,000	16.5	0.27	
Natural gas reforming	H ₂	61,000	7.0	0.11	
Non-fossil energy					
Hydro. solar, nuclear-electrolytic	H ₂	61,000	0	0	
Geothermal-electrolytic	H ₂	61,000	2.44	0.04	

(1) Assuming a power plant efficiency of 38%.

(2) For a power plant with FGC, assuming power plant efficiency is reduced from 38% to 35%, the kWh(e)/lb CO₂ generated is reduced to 0.50.

(3) Estimated from ref. 14.

(4) Estimated from ref. 15 and 16.

(5) Estimated from ref. 17.

(6) Estimated from ref. 17 and 18.

recovering CO₂ from gases and liquids have been practiced in industry and are currently available,[4] however, because there was little need for reuse, experience with storage and disposal techniques, are very limited.

Although there are several key factors in assessing the practicability of a prospective control methodology, the most important consideration is the energy required by the control system. As this energy increases, assuming that the energy required to drive the control system is furnished by fossil fuel, overall power plant efficiency decreases and the quantity of CO₂ emitted to the atmosphere per KWH(e) generated increases. A point could be reached where the only effect produced by the CO₂ control system is a decrease in power plant efficiency with no net reduction in CO₂ emissions.

In a coal-fired power plant as shown in Table 3 about 0.55 KWH of electricity is produced per pound of CO₂ generated. Table 4 indicates in a general manner, the effect of CO₂ control system energy requirements and CO₂ collection efficiency on the overall power plant efficiency and on net CO₂ emissions.

TABLE 4

EFFECT OF CO₂ CONTROL SYSTEM ENERGY
REQUIREMENTS ON POWER PLANT EFFICIENCY

Energy required by CO ₂ control system kWh(e)/lb CO ₂	CO ₂ removal efficiency, %	Net power plant efficiency %	lbs CO ₂ discharged to atmosphere per net kWh(e) generated
0	100	38.0	0
0.1	100	31.0	0
	75	32.8	0.53
	50	34.5	1.01
	25	36.3	1.44
	0	38.0	1.83
0.2	100	24.1	0
	75	27.6	0.53
	50	31.0	1.12
	25	34.5	1.31
	0	38.0	1.83
0.3	100	17.1	0
	75	22.4	0.78
	50	27.6	1.26
	25	32.8	1.59
	0	38.0	1.83
0.4	100	10.2	0
	75	17.1	1.01
	50	24.1	1.44
	25	31.0	1.68
	0	38.0	1.83
0.5	100	3.2	0
	75	11.9	1.46
	50	20.6	1.69
	25	29.3	1.78
	0	38.0	1.83
0.55	100	0	0
	75	9.5	1.83
	50	19.0	1.83
	25	28.5	1.83
	0	38.0	1.83

Three potential control points (CO₂ removal sites) are available for regulating the concentration of CO₂ in the atmosphere: (1) the atmosphere itself, (2) the surface waters of the oceans, and [3] the stacks of fossil fuel power plants. The latter sites have the advantage of providing a source of relatively high CO₂ concentration, while the first two provide more flexibility for site selection and simpler disposal or recovery and reuse logistics. A choice of control point limits the available choices of CO₂ removal processes and will reflect on the size of operation, the number of required sites, energy requirements, the comparative economics, and the overall feasibility of operation.

The CO₂ concentration ranges of the three control points are listed in Table 5. Since the concentration of CO₂ in flue gas is significantly greater than that in the atmosphere or the oceans, the energy required to remove CO₂ from flue gas should

TABLE 5
CO₂ CONCENTRATIONS AT CONTROL POINTS AND MINIMUM
CO₂ SEPARATION ENERGIES

Control point	CO ₂ concentration		Min. separation energy ⁽¹⁾ kWh/lb CO ₂
	% by vol	% by wt	
(1) Atmosphere	331x10 ⁻⁴	502x10 ⁻⁴	0.0570
(2) Ocean	—	100x10 ⁻⁴ (2)	0.0570
(3) Fossil fueled power plant stacks	7-20	11-28	0.0259-0.0179

(1) Minimum energy based on free energy of mixing:

$\Delta F = RT \sum n_i \ln(P_i/P_i^0)$, where P_i^0 and P_i are the initial and final partial pressures of the i^{th} species, respectively. R is the gas constant, T is temperature in degrees absolute, and n_i is the number of moles of the i^{th} species.

(2) ECO_2 (total carbon dioxide content) = $\text{CH}_2\text{CO}_3 + \text{CCO}_2(\text{aq}) + \text{CHCO}_3(\text{T}) + \text{CCO}_3(\text{T})$.

be appreciably lower than for the other two control points. The minimum theoretical energy (the thermodynamic free energy) to separate CO₂ from each of the three sources are also listed in Table 5. Based on these theoretical values, it would take about three times more energy to separate CO₂ from the atmosphere than from flue gas.

Although removal or capture of CO₂ from a particular source is an important consideration in devising a CO₂ control system, CO₂ disposal (storage) and reuse potentials are equally or perhaps more important, for unless a control scenario produces a net near term decrease in the rate of buildup of atmospheric CO₂ it will be of no value. This means that the captured CO₂ must be stored or recycled until large scale non-fossil energy sources become available.

A block diagram showing the relationship between the various aspects of CO₂ control is presented in Figure 2.

III. CO₂ REMOVAL AND RECOVERY

(1) Atmosphere and Oceans

The present concentration of CO₂ contained in the atmosphere is about 331 ppm by volume. Therefore, in order to

FIGURE 2. LOGIC DIAGRAM FOR CO₂ CONTROL

remove one mole of CO₂ from the atmosphere a minimum of 3021 moles of air must be processed. This is equivalent to about one pound of CO₂ per 2000 pounds of air. The equation for calculating the air horsepower of a fan can be expressed, as follows[5]

$$\text{Air h.p.} = 157 \times 10^{-6} Q P ,$$

where Q is the volume handled in cfm and P is the pressure drop across the fan in inches of water. For air at standard conditions, this reduces to:

$$\text{Air h.p.} = 34.9 \times 10^{-6} W P ,$$

where W equals the mass flow rate of air in pounds per hour. Assuming a fan efficiency of 75%, and converting to kilowatts yields

$$\text{kW fan} = 34.7 \times 10^{-6} W P = 34.7 \times 10^{-6} (m/) P .$$

Dividing by pounds of CO₂ and substituting 2,000 pounds of air per pound of CO₂ for m yields the following equation:

$$\frac{\text{kWh(e)}}{\text{lb CO}_2} = 0.0694 P .$$

Assuming an overall power plant efficiency of 38% and a coal heating value of 18,000 Btu per pound of contained carbon, the pounds of CO₂ produced per KWH(e) generated amounts to 1.83. Setting $1/1.83$ (0.5464) equal to the latter equation P is found to equal 7.9 inches of water. Thus, if the pressure drop across a CO₂ absorption or adsorption unit is equal to about 8 in. of water (assuming a 100% removal efficiency and electricity generation by the combustion of coal), as much CO₂ will be generated in supplying electricity to the air-handling fan as will be removed from the atmosphere by the CO₂ removal system. For electricity generation by the combustion of natural gas instead of coal, P maximum calculates to 14 in. of water. Since a maximum allowable pressure drop of from 8 to 14 in. of water is a rather stringent constraint to impose on such equipment (actually the pressure drop would have to be much less than the calculated maximum allowable for the process to be of value), and since there are other system energy requirements to satisfy, e.g., sorbent pumping energy in absorption systems, it is unlikely that a practicable system can be designed for removing CO₂ from the atmosphere, using a fossil energy power source. Note that Steinberg and Dang[6] determined that the energy required to remove CO₂ from the atmosphere by refrigeration techniques was greater (9.4 kWh(e)/lb CO₂) than that required for removal by atmospheric absorption or adsorption processes (0.4 kWh(e)/lb CO₂). It was also determined that the energy required to remove CO₂ from the ocean was at a minimum equal to or greater than that required for removal from the atmosphere. It is concluded that for the removal of CO₂ from the atmosphere or the ocean, a non-fossil fuel source would be necessary.

(2) Flue Gas

The concentration of CO₂ in fossil fuel power plant flue gas is about 500 times greater than its concentration in the atmosphere, therefore, CO₂ removal should be greatly facilitated. Furthermore, commercial processes, i.e., absorption/desorption processes, are currently available for removing CO₂ from flue gas and other gaseous mixtures. For example, in the manufacture of liquid CO₂ and dry ice, CO₂ resulting from the burning of a carbonaceous material is absorbed from flue gas with sodium carbonate, aqueous potassium carbonate, or amines. CO₂ removal systems are also employed in the production of synthesis gases for ammonia, methanol, and in hydrogen production.

Estimates of the energy requirements for removing CO₂ from flue gas are given in Table 6. Values range from 0.15 kWh(e)/lb CO₂ for 50% absorption with monoethanolamine (MEA) to 0.8 kWh(e)/lb CO₂ for 90% absorption with seawater. The most

TABLE 6

ENERGY REQUIRED TO REMOVE AND RECOVER
CO₂ (GASEOUS) FROM FLUE GAS

Process	CO ₂ removal efficiency %	kWh(e)/lb CO ₂ ^(1,2,3) recovered
1. Amine (MEA) absorption/Stripping	50 90	0.15 0.27
2. Potassium carbonate absorption/stripping	90	0.32
3. Molecular sieves	90	0.40
4. Refrigeration	90	0.40
5. Seawater absorption ⁽⁴⁾	60 90	0.60 0.80

- (1) Energy required to recover CO₂ (as a gas) from flue gas of coal-fired power plant subsequent to SO₂ removal. Inlet conditions to CO₂ removal process are 120°F and 14.7 psia, assuming flue gas is saturated with water vapor and free of SO₂. Reheat of flue gas accounted for by SO₂ system.
- (2) All energy requirements have been converted to the equivalent amount of electrical energy.
- (3) To liquefy the recovered CO₂ gas, an additional 0.05 kWh(e)/lb CO₂ is required; to solidify the CO₂ gas, about 0.17 kWh(e)/lb CO₂ is required.
- (4) Including deep ocean disposal of captured CO₂.

effective solvent appears to be MEA; however, even the use of MEA will significantly reduce overall power plant efficiency.

It should be pointed out that only about 30% of the total CO₂ released by the U.S. today is located at central stationary electric power plants. The rest comes from smaller stationary industrial and residential boiler and heating systems and from transportation sources (automobiles and railroads).

IV. CO₂ DISPOSAL (STORAGE)

Four ways of disposing of captured CO₂ have been considered: (1) injection in the deep ocean, (2) terrestrial burial (3) storage in plants and trees, (4) conversion of CO₂ to useful products and (5) extraterrestrial disposal. The latter method is considered impractical because of the large fuel to payload ratio to lift a unit mass into earth orbit, thus generating more CO₂ than can be disposed of.

(1) Injection in the Deep Ocean

In the two-box model, the world ocean is represented by two reservoirs, separated by a thermocline. One reservoir consists of surface layers to a depth of about 100 meters; the

other, of deeper layers from the 100-meter depth to the ocean floor. Mixing is assumed to occur rapidly within each box or reservoir, but exchange between the two boxes proceeds slowly. Thus, the deep ocean is a potential sink for CO_2 since there is no direct exchange between the atmosphere and deep ocean waters. Only the surface layers are in CO_2 equilibrium with the atmosphere. The main discrepancy between the simple two-box model and the real ocean is that in some regions (e.g., Arctic, Antarctic, and Gibraltar) convection currents extend from the ocean surface to the ocean bottom.

One proposal for disposing of collected CO_2 is to inject it into the sea at the Strait of Gibraltar.[7] Presumably, the current would carry it to the deeper ocean waters where it would remain for centuries. Another proposal is to inject liquid CO_2 into the deep sea at a density greater than that of deep sea water via a long pipe.[24] The CO_2 would sink to the bottom of the ocean forming a liquid CO_2 lake within the ocean. CO_2 could also be injected into the deep ocean as a gas, provided the injection depth is deep enough to permit dissolution of the CO_2 before it rises to the upper layers.

The current release rate of fossil carbon to the atmosphere is about 5×10^{15} g/yr, whereas the current carbon content of the deep ocean is estimated to be at 0.373×10^{20} g. Therefore, if all this fossil carbon was captured and deposited in the deep ocean, its carbon content over a one year period, would increase by only about 0.013%. However, the effects of this injected carbon on the deep ocean ecosystem have not been assessed.

(2) Terrestrial Burial

Storage in abandoned mine shafts or wells and fixation in natural clays are two options in this category which can be considered. The latter has been dismissed as impractical because of the large quantities of clays that would have to be handled, even if they were available and effective in fixing CO_2 . In the case of below ground storage the rate at which CO_2 would re-enter the atmosphere is an important consideration as well as the available storage capacity of the below-ground cavities. A related disposal scheme is to use captured CO_2 for enhanced oil recovery, in which case, the CO_2 would be injected into depleted oil wells to effect additional oil recovery. Captured CO_2 would thus have an economic value. However, the effectiveness of such a method in controlling atmospheric CO_2 does not only depend on economics but upon (1) the energy requirements of the CO_2 removal and disposal system, (2) how much CO_2 can be injected into depleted wells, and (3) the length of time the CO_2 would remain underground. These factors

have not been studied in enough detail to draw any firm conclusions.

(3) Storage in Plants and Trees

It has been suggested that in the event of a CO₂ worldwide emergency, corrective measures to halt or reverse the growth of atmospheric CO₂ could be instituted by planting fast-growing long-lived trees which are left unharvested and/or by growing short-lived plants which are converted to humus or allowed to accumulate in artificial peat bogs. However, this action would be limited by the availability of fertilizer.[8] Furthermore, additional CO₂ would be generated by the reforestation activities and in supplying energy for increased fertilizer production, which would reduce the effectiveness of the method. Further analysis is required to rationalize this method.

(4) CO₂ Conversion to Useful Products

Although a number of commercial CO₂ products can be made for the economy, e.g., dry ice, or soda ash, the quantity of these products consumed yearly is extremely limited in comparison to the quantity of fossil CO₂ emitted to the atmosphere. Therefore, atmospheric CO₂ levels will not be significantly affected by the way in which these products are made. Furthermore, these products eventually return the CO₂ back to the atmosphere.

A more variable possibility for reducing the buildup of CO₂ in the atmosphere, is to recover and convert CO₂ to synthetic liquid and gaseous carbonaceous fuels using a non-fossil energy source such as nuclear, solar or hydro energy.[6,9,10] Another alternative is to combine a non-fossil energy source with coal to produce synthetic fuel. This would tend to reduce the rate of increase of CO₂ emissions by a factor of up to 3 compared to producing hydrocarbon synfuels from coal alone. The latter is a step toward complete substitution of fossil with non-fossil energy.

V. REMOVAL AND DEEP OCEAN DISPOSAL OF FLUE GAS CO₂ USING SEAWATER

(1) System Description

In light of the previous considerations, control point 3 (power plant stacks) has been selected as the initial control point of interest. Accordingly, a scenario based on the absorption of CO₂ generated by coal-fired power plants has been

FIGURE 3. FLOWSHEET FOR CO₂ ABSORPTION DISPOSAL FROM POWER PLANT FLUE GAS USING SEAWATER.

formulated. A process diagram of the system is presented in Figure 3. Seawater from the surface of the ocean is pumped to the top of a CO₂ absorber (packed tower). The seawater flows downward through the packing by gravity, absorbing CO₂ from the power plant flue gas which flows countercurrent to the seawater. The water exits at the bottom of the absorber and is pumped to the deep ocean while the treated flue gas is discharged to the atmosphere. The flue gas is fed to the absorber, subsequent to SO₂ removal, by an auxiliary blower. Such a system is perhaps the simplest for one step absorption and disposal of CO₂. No CO₂ desorption step is required and no additional handling of recovered CO₂; the captured CO₂ is discharged directly into the ocean reservoir. Furthermore, seawater is readily available in large quantities at no cost. However, the scenario does impose constraints on power plant location.

In evaluating this subject, it was assumed that the power plant under consideration has a capacity of 200 MWe, an efficiency of about 34% (subsequent to SO₂ removal), is located near the U.S. coastline at sea level, and that deep ocean waters are accessible at a distance of about 10 miles from the power plant site.

FIGURE 4. EQUILIBRIUM PARTIAL PRESSURE OF CO_2 VERSUS MOLE FRACTION IN WATER AND IN SEAWATER (3.5% SALINITY)

(2) Process and Absorber Design

Flue gas composition was determined assuming 20% excess combustion air. A calculation of the design of the absorption tower was based on CO_2 solubility data from Riley and Skirrow[12] and the transfer unit method described by Sherwood and Pigford.[13] Two cases were determined; one for a CO_2 removal efficiency (R) of 0.6 (60%) and the other for a removal efficiency of 0.9. Figure 4 shows the plots of CO_2 partial pressure versus mole fraction for pure water and for seawater with the two absorber operating lines indicated. The absorber tower size was determined from the liquid to gas mass flow ratio and the pressure drop correlation for two inch Raschig Ring packing. A summary of the design and operating characteristics for the two removal efficiency cases are given in Table 7. It is seen that the pressure drop in 15 inches and 70 inches water respectively. The system would require between 84 to 90 and 100 to 107 towers of 20 ft diameter each for each of the cases. For the 60% removal case the packed height is 23 ft while for 90% efficiency the tower height is 130 ft. The equipment and consequently the capital investment becomes formidable.

TABLE 7
SUMMARY OF CO₂ ABSORBER DESIGN DATA
AND RESULTS FOR CO₂ REMOVAL EFFICIENCIES
OF 60 AND 90 PERCENT
SEAWATER ABSORPTION/DISPOSAL

	CO ₂ removal efficiency	
	60%	90%
x ₁ , mf *CO ₂ in outlet seawater	70x10 ⁻⁶	80x10 ⁻⁶
x ₂ , mf CO ₂ in inlet seawater	0.2x10 ⁻⁶	0.2x10 ⁻⁶
y ₁ , mf CO ₂ in inlet gas	0.1340	0.1340
y ₂ , mf CO ₂ in outlet gas	0.0536	0.0134
N _{OL} , number of overall liquid-phase transfer units	3.3	16.3
m, slope of equilibrium line	1620	1620
L _m /G _m , molar ratio of liquid to gas	1217-1493	1533-1981
L/G, mass ratio of liquid to gas	754-927	949-1271
G, mass velocity of gas, lb/(sec) (ft ²)	0.020-0.018	0.017-0.014
H _{OL} , height of overall liquid-phase transfer unit, feet	7	8
h, packing height, feet	23	130
ΔP/foot packing, inches water	0.5	0.5
ΔP/tower, inches water	15	70
Tower diameter, feet	20	20
Overall tower height, feet (approx.)	42	150
No. towers	84-90	100-107

*Mt = mole fraction

(3) Energy Requirement

A summary of energy requirement is given in Table 8. The major energy requirement, as would be expected, is due to the seawater pumping load. A relatively minor quantity of energy is required to pump the flue gas through the absorbers. It should be mentioned that the high horsepower and thus energy requirements of the seawater pumps are due to the large quantities of seawater (about 3x10⁶ gpm) that must be supplied to and exhausted from the CO₂ absorption towers (because of the limited solubility of CO₂ in seawater). Friction loss (for the selected pipe sizes) and static head requirements are not excessive (about 100 psi overall). Furthermore, static head is dictated by absorber height and not by the depth to which the spent seawater must be pumped because the head against which the spent seawater is pumped is balanced by the static head gain of the spent seawater in flowing from sea level to the deep ocean. However, the deeper the injection point the greater the friction loss (for a given pipe size and flow rate) because a greater length of pipe is required.

TABLE 8
SUMMARY OF ENERGY REQUIREMENTS FOR CO₂
REMOVAL EFFICIENCIES OF 60 AND 90 PERCENT
SEAWATER ABSORPTION/DISPOSAL

	Energy requirements, kWh(e)/Lb CO ₂ captured 60%	90%
Seawater pump #1	0.2235	0.4839
Seawater pump #2	0.3688	0.3087
Flue gas exhaust blower	<u>0.0045</u>	<u>0.0136</u>
Total	0.5968	0.8062

For each of the CO₂ removal efficiencies considered, more CO₂ would be produced in supplying electricity to the control system (assuming coal derived power and electrically driven equipment) than would be extracted from the power plant flue gas. For the 60% efficiency case, about 0.6 kWh(e)/lb CO₂ captured is required and for the 90% case, about 0.8 kWh(e)/lb CO₂ captured. At an overall power plant efficiency of 34% and a coal heating value of 18,000 BTU per pound of contained carbon, only 0.5 kWh of electricity is produced per pound of CO₂ generated. Thus for a fossil fueled power source more power is required to remove CO₂ than is generated. Therefore, this system is not feasible. The only alternative is to use a non-fossil energy source to produce the power for CO₂ removal. However, it can be argued that the non-fossil source could replace the fossil fuel plant in the first place.

VI. REMOVAL OF CO₂ FROM FLUE GAS USING MEA, FOLLOWED BY DEEP OCEAN DISPOSAL

(1) MEA Absorption/Stripping

Of the several processes evaluated for removing CO₂ from stack gases (Table 6), monoethanolamine (MEA) absorption/ stripping requires the least amount of energy per unit of CO₂ recovered. MEA absorbs CO₂ rapidly and efficiently at low partial pressures and is therefore well suited for removing CO₂

from power plant flue gas. Impurities such as COS, CS₂, HCN and SO₂ react non-regenerably with MEA so SO₂ must be removed from the flue gas prior to treatment with SO₂. Flue gas does not normally contain COS, CS₂ or HCN.

A flow sheet of the MEA process for CO₂ absorption and recovery from power plant flue gas is shown in Figure 5.[19,20]

FIGURE 5. FLOWSHEET FOR CO₂ ABSORPTION RECOVERY FROM POWER PLANT FLUE GAS USING MEA.

removal is fed to the suction of a blower which compresses the flue gas to about 16 psia and feeds it to the MEA absorber. As the flue gas passes through the absorber CO₂ is removed by reaction with lean MEA solution, flowing countercurrent to the flue gas, in accordance with the following reaction:

The reaction takes place to the right (forward direction) at temperatures between about 100 and 175°F.

Spent MEA solution is pumped from the bottom of the absorber through a filter, for removal of solid impurities, to the top of the regenerator. Before entering the regenerator, the cold spent MEA solution is heated by heat exchange with the hot regenerated (lean) solution from the bottom of the regeneration. Carbon dioxide is stripped from the MEA as the solution flows downward through the regenerator. A steam heated reboiler supplies the necessary heat for regeneration. The bottom of the regenerator is maintained at about 250°F. Elevated temperature combined with steam stripping favors the reverse of the absorption reaction.

The stripped carbon dioxide exits the regenerator at the top and flows to a condenser for removal of water vapor. Most of the condensed water is returned to the generator as reflux, a portion of the remainder is pumped to the top of the absorber to reduce MEA losses. Excess water is pumped to disposal.

Regenerated MEA solution from the bottom of the stripping tower is first cooled by heat exchange with spent MEA solution flowing to the stripper and then by water. The cooled lean solution is then fed to the top of the absorber tower.

A reclaimer for recovering MEA which has reacted with residual flue gas SO_2 is shown at the bottom of the regenerator. A sidestream of MEA is withdrawn from the regenerator reboiler and cooled by heat exchange with the reclaimed solution returning to the reboiler. Sodium carbonate is added to the stream to liberate MEA. The sidestream is then cooled and filtered to remove precipitated sodium sulfate and sulfite and other degradation products. Purified MEA solution is returned to the reboiler. The reclaiming system is speculative at the present time and further development work is required before a final design can be prepared.[20]

(2) Deep Ocean Disposal of Recovered CO_2

Three methods of disposing of the recovered gaseous CO_2 from the MEA absorption/stripping process were considered (a) gaseous disposal via a deep ocean pipeline, (b) liquid disposal via a deep ocean pipeline and (c) deep ocean solid disposal.

(a) Gaseous disposal. In gaseous disposal, CO_2 recovered by the MEA process is compressed and fed to the deep ocean via a pipeline. A 500 meter injection depth was assumed even though ocean surface layers usually extend to a depth of only about 100 meters. The additional 400 meters was provided to allow for dissolution of the injected gas in the deep ocean. Any injected CO_2 which reaches the well mixed surface layers will eventually equilibrate with the atmosphere and thus reduce the effectiveness of disposal. Ocean depths of 500 meters are

accessible at distances of about 100 miles from the shoreline of the northeast United States (approximate width of the continental shelf), therefore, a pipeline of about 100 miles in length was assumed (no allowance was made for inland distance).

For 90% recovery of the CO_2 generated by a 200 MWe coal fired power plant an 18 inch line was selected; for 50% recovery, a 14 inch line was selected. Most of the energy required by the CO_2 compressor is expended in overcoming the seawater static head between the CO_2 injection point and the surface of the ocean. A compressor discharge pressure (third stage) of about 800 psia is required.

A block diagram of the overall absorption/recovery/disposal system is shown in Figures 6. and 7.

FIGURE 6. ENERGY REQUIREMENTS FOR MEA ABSORPTION AND DEEP OCEAN DISPOSAL OF FLUE GAS CO_2 FROM 200 MW(e) COAL FIRED POWER PLANT

Case 1 ($\eta = 0.5$)

A. Gaseous Disposal

B. Liquid Disposal

C. Solid Disposal

Note:

(1) Equivalent energy requirement in KWH(e) per pound of CO_2 recovered.

FIGURE 7. ENERGY REQUIREMENTS FOR MEA ABSORPTION AND DEEP OCEAN DISPOSAL OF FLUE GAS CO_2 FROM 200 MW(e) COAL FIRED POWER PLANT

Case II ($\eta = 0.9$)

(b) Liquid disposal. In order to produce liquid CO_2 product of the MEA system, the gaseous CO_2 must be compressed, cooled and dried. This is done in a three stage compression system equipped with coolers, water knockout drums, and a dryer. The gas is compressed to 920 psia in the third stage, passed through a cooler, and liquefied in a condenser at about 27°C [22] (the critical pressure and temperature of CO_2 are 1073 psia and 31°C). For deep ocean disposal, the liquefied CO_2 would then be piped to an appropriate location in the deep ocean.

In order to store CO_2 as a liquid pool in the deep ocean it must be injected to a depth where the density of CO_2 , at the pressure corresponding to the seawater static head and the prevailing seawater temperature, is greater than the density of the seawater at the injection point. The specific gravity of CO_2 is approximately equal to 1 at pressures between 150 and 300 atmospheres and temperatures between 3 and 15°C . An injection depth of 3000 meters was selected which corresponds to a pressure of about 300 atmospheres; the temperature of the ocean at this depth is about 3°C . The specific gravity of CO_2 (liquid) at these conditions is 1.05.

Ocean depths of 3000 meters are accessible at distances of about 200 miles from the shoreline of the northeast United States and thus a pipeline of about 200 miles in length is required (no allowance is made for inland distance since the required offshore distance is quite variable with respect to the U.S. coastline). For 90% recovery of the CO₂ generated by a 200 MW(e) plant a 12 inch line was selected; for 50% recovery, a 10 inch line. For these line sizes, the liquid CO₂ will flow to the deep ocean under the influence of the CO₂ liquefaction pressure. Pumps are not required. In the subject evaluation it was assumed that the liquid would be cooled from about 27°C to the temperature of the deep ocean injection point during its journey to the deep ocean. If this is not the case, additional cooling of the liquid CO₂ will be required.

A block diagram of the overall absorption/recovery disposal system is shown in Figures 6 and 7.

(c) Solid disposal. In the production of commercial solid CO₂, the liquid CO₂ produced by compression and cooling, as described above, is expanded through a nozzle, forming "snow", and fed to a press. The vapors given off during expansion are used to precool the liquid carbon dioxide prior to expansion. The gas is then recompressed and reliquefied. The "snow" is compressed into 220 pound blocks and then quartered by band saws. The 55 pound blocks are wrapped in Kraft paper and either stored or shipped in insulated cars.[22] The density of the blocks is about 100 lb/ft³. The temperature of saturated CO₂ ice at 1 atmosphere pressure is -78.5°C.

Since the density of the CO₂ blocks is much greater than that of seawater, they should readily sink to the ocean bottom when dropped into the surface waters of the ocean. The settling velocity of a 10 inch cube of solid CO₂ in seawater is roughly estimated at 5 ft/sec. For a disposal depth of 500 meters (the depth selected for gaseous CO₂ disposal) it would take about 5.4 minutes for a block to reach bottom; for a disposal depth of 3000 meters (the depth selected for liquid CO₂ disposal) it would take about 32 minutes. Based on the phase diagram for CO₂ and assuming the blocks are heated by the seawater to prevailing ocean temperatures, the final state of the blocks for both the 500 and 3000 meter disposal depths, is liquid. The liquid formed for the 3000 meter disposal depth will have a density greater than that of seawater and therefore should remain at the bottom of the ocean. For the 500 meter depth, the liquid will be less dense than seawater and would therefore tend to rise. Upon rising, some of the liquid CO₂ may dissolve in the seawater and some may flash into vapor which in turn will rise and dissolve. Depending upon the relative rates of heat and mass transfer and the rate of ascent

of the CO₂ liquid droplets and gaseous bubbles, some CO₂ may reach the surface layers of the ocean. CO₂ reaching these layers may eventually end up in the atmosphere. Losses may also occur as the blocks descend to the ocean bottom as a result of gas and liquid formation and dissolution. Without experimental data or a detailed analysis of the physics of deep ocean disposal of solid CO₂ it is not possible to confidently predict the fate of the solid CO₂ blocks or accurately determine the extent of losses.

The energy required to transport the solid CO₂ blocks a distance of 100 miles offshore (500 meter disposal depth) by barge is estimated at 0.005 kWh(e)/lb CO₂ and for 200 miles (3000 meter depth) at 0.010 kWh(e)/lb CO₂. The energy to produce solid CO₂ blocks from gaseous CO₂ is about 0.17 kWh(e)/lb CO₂. Therefore, barging distance does not have a significant effect on the overall energy requirements of the system, assuming no CO₂ losses during transport, however, disposal costs for the 200 mile distance would be almost twice that of the 100 mile distance.

(3) Energy Requirements

Total system energy requirements for CO₂ recovery efficiencies of 50 and 90% and for gaseous, liquid and solid disposal are summarized in Figures 6 and 7, respectively. At 50% efficiency, gaseous or liquid disposal require the equivalent of about 0.20 kWh(e)/lb CO₂ recovered and at 90% efficiency about 0.32 kWh(e)/lb CO₂. For solid disposal at 50% recovery, assuming no sublimation losses during handling and transportation, about 0.33 kWh(e)/lb CO₂ are required, whereas, about 0.45 kWh(e)/lb CO₂ are needed at 90% recovery.

Assuming a power plant efficiency of 34% after sulfur dioxide removal, 0.49 kilowatt-hours of electricity is produced per pound of CO₂ generated. With no CO₂ removal, 2.04 pounds of CO₂ are discharged to the atmosphere per net kilowatt-hour of electricity produced. At 50% recovery and gaseous or liquid disposal, overall power plant efficiency would be reduced to 27% and for 90% recovery to 14%. The corresponding pounds of CO₂ discharged to the atmosphere per net kWh(e) generated are 1.3 and 0.5, respectively. For 50 and 90% recoveries and solid disposal, power plant efficiency would be reduced to 23% and 6%, respectively. The corresponding pounds of CO₂ discharged per net kWh(e) produced are 1.5 and 1.1.

(4) Investment and Power Generation Costs

Rough estimates of the required fixed capital investments for 50% and 90% CO₂ recovery using MEA and for gaseous, liquid

and solid disposal are summarized in Table 9. Based on these estimates and estimates of the capital and operating costs of a 200 MWe coal fired power plant with flue gas desulfurization (FGD), electricity generation costs have been calculated and are included in Table 9 along with an estimate of the cost of generation without CO₂ control.

TABLE 9
COSTS OF GENERATING ELECTRICITY
WITH AND WITHOUT CO₂ CONTROL
FOR INITIAL POWER PLANT CAPACITY
OF 200-MW(e)

	SO ₂ removal with no CO ₂ control	SO ₂ Removed Gaseous disposal	Plus 50% CO ₂ Control Liquid disposal	Solid disposal	SO ₂ Removed Gaseous disposal	Plus 90% CO ₂ Control Liquid disposal	Solid disposal
Net Capacity, ⁽¹⁾ MW(e)	200	161	159	134	86	93	37
Capital investment, M\$							
(a) Power plant ⁽²⁾	160	160	160	160	160	160	160
(b) CO ₂ control system ⁽³⁾	—	152	216	46	194	290	68
Total	160	312	376	206	354	450	228
Operating costs, ⁽⁴⁾ M\$S/year							
(a) Coal @ \$30/ton	18.9	18.9	18.9	18.9	18.9	18.9	18.9
(b) O&M	4.8	5.8	5.8	7.2	5.8	5.8	7.2
(c) Barging costs ^(5,6)	—	—	—	5.0	—	—	5.0
(d) Capital charges @ 15% of Capital investment	24.0	46.8	56.4	30.9	53.1	67.5	34.2
Total	47.7	71.5	81.1	62.0	77.8	92.2	65.3
Electricity generation costs, Mills/kWh (revenue requirements)	30	56	64	58	113	139	221

(1) Electrical energy to drive the CO₂ control system is assumed to be obtained from the electrical output of the power plant, therefore: $e_{net} = e_{gross}(200 \text{ MWe}) - e_{control}$.

(2) Total capital investment @ \$800/kW(e) including FGD.

(3) Total capital investment @ 1.2 times fixed capital investment.

(4) Based on 8000 hours of operation per year.

(5) Dry ice barging costs @ \$15,000 per day; costs for transporting dry ice from power plant to barge are not included.

(6) Barging costs are based on a 1000-mile barging distance (3000-meter disposal depth); for a 200-mile distance (3000-meter disposal depth), barging costs are estimated at 9 million dollars per year.

Revenue requirements in mills/kWh were calculated on the basis of net electricity output assuming an initial plant capacity of 200 MWe (after SO₂ removal) and assuming that the electricity required to drive the CO₂ control system is supplied internally by the subject power plant. Thus, the net output of the power plant (e_{net}) is equal to gross output (e_{gross} = 200 MWe) minus the electricity consumed by the control system ($e_{control}$). A schematic of the overall system is presented in Figure 8.

FIGURE 8. SCHEMATIC OF SELF-CONTAINED POWER PLANT WITH FGD AND CO₂ CONTROL

For a CO₂ removal efficiency of 50%, the costs of generating electricity for gaseous, liquid and solid disposal are approximately equal. The net power generated and yearly operating costs for gaseous and solid disposal are about the same, and therefore, so are power generation costs. Solid disposal requires more energy but less capital. For 50% removal of CO₂, these two factors balance one another and the cost of power generation for solid disposal turns out to be about the same as for gaseous and liquid disposal.

For 90% CO₂ removal, in comparison to 50%, the cost of power generation roughly doubles for both gaseous and liquid disposal whereas it increases by a factor of about 4 for solid disposal. This marked increase in generation costs for the solid disposal case is due to excessive control system energy requirements at the 90% CO₂ removal efficiency.

If the above analysis had been based on a net power plant output of 200 MWe rather than a gross output of 200 MWe the costs of power generation, particularly at the higher CO₂ removal efficiencies, may have been somewhat lower because of economies of scale.

(5) Discussion

Based on the above results, removal and recovery of flue gas CO₂ using MEA is technically and energetically feasible, however, economic penalties are significant. Disposal also appears to be feasible provided the effects of injected CO₂ on the deep ocean ecosystem are not prohibitive.

MEA absorption/stripping in combination with either gaseous or liquid disposal requires appreciably less energy than an MEA-solid disposal combination. On the other hand, the capital investments required by the former combinations far exceed those of the latter offsetting, to some degree, the economic benefits of the lower energy requirements. For gaseous or liquid disposal, the major portion of the capital investment is due to pipeline costs, which may be understated in the cost estimates.

A possible way to reduce the capital investment for a liquid disposal system is to barge liquid CO₂ to the required offshore distance (of about 200 miles) and then inject the liquid into the deep ocean via a pipe extending from the ocean surface to the injection point. With this arrangement the required length of injection piping would be substantially reduced (from about 330,000 meters to about 3000 meters) as well as the required pipe size. However, CO₂ would have to be shipped under pressure and below the critical temperature (31°C) to maintain it in the liquid state.

For direct gaseous or liquid deep ocean injection (via pipeline), essentially no losses of recovered CO₂ would be incurred during transport. For solid disposal by barging, losses during handling and transportation could be significant. For 10 inch cube blocks of about 55 pounds each, shipping losses (based on transport by truck) may be as high as 8 pounds during the first 24 hours in summer.[23] To reduce handling losses and improve handling logistics for inland power plants it may be better to pump the flue gas to the dock site and remove/recover and solidify at that point.

VII. CONCLUSIONS

1. The contribution by the United States to worldwide CO₂ emissions has been decreasing during the last 25 years and it is projected that it will decrease even further during the next 50 years. Therefore, a worldwide effort will be required to control the buildup of atmospheric CO₂.

2. Increased utilization of coal for producing heat, electric power and/or synthetic gaseous and liquid fuels will increase the rate of CO₂ emissions. The magnitude of this increase may or may not be significant depending upon the extent to which coal displaces oil and natural gas, and future energy use patterns.

3. Direct capture of CO₂ from the atmosphere or capture from the surface waters of the oceans does not appear to be feasible when using a fossil energy source to drive the CO₂ control system. More CO₂ is generated than is recovered.

4. For 60% to 90% absorption of the CO₂ contained in the flue gas of a coal fired power plant using seawater and deep ocean disposal, more CO₂ would be generated in supplying energy to the control system than would be recovered from the flue gas.

5. Removal and recovery of CO₂ from the stacks of fossil fuel plants by commercially available processes is feasible, e.g. by absorption/stripping with MEA. However, large quantities of energy are required which will substantially reduce the efficiency of power generation. For 50% CO₂ removal, the power plant efficiency decreases from 34% to 27 to 23% depending on whether gaseous liquid or solid CO₂ is disposed of in deep ocean. For 90% CO₂ removal the efficiency decreases to between 15% and 6%.

6. Disposal of captured and recovered CO₂ will be a problem. Of the disposal/reuse options considered, deep ocean disposal appears to be a possibility. However, the costs of disposal are substantial. Also the effects of injected CO₂ on the ocean ecosystem have not as yet been assessed.

7. Of the processes considered, absorption by MEA is the least energy intensive. For a 50% CO₂ removal efficiency, the equivalent of 0.15 kWh(e)/lb captured CO₂ is required; and for 90% removal, 0.27 kWh(e)/lb CO₂. Gaseous or liquid disposal of the captured CO₂ requires an additional 0.05 kWh(e)/lb CO₂ whereas solid disposal requires about 0.18 kWh(e)/lb CO₂ (discounting transportation and handling losses). The required capital investments for gaseous and liquid pipeline disposal are substantially greater than for solid disposal. Low energy consumption and high capital investment have offsetting effects on the cost of power generation.

8. For effective control of atmospheric CO₂ by removal from flue gases, it would be advantageous and perhaps necessary to centralize the use of fossil fuels, such as in an all electric economy, since it would be almost impossible to

remove, recover and dispose of CO₂ from the numerous small sources, i.e., from the flues of home heating units, process plants and from automobile exhausts. In the U.S. about 30% of the total CO₂ released originates from central fossil fueled power plants. For direct removal of CO₂ from the atmosphere or from the surface layers of the ocean, centralized use of fossil fuels is not required. However, removal of CO₂ directly from the atmosphere or from the oceans does not appear to be feasible unless the energy required to drive the CO₂ system is supplied by a non-fossil energy source.

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