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A CARBON DIOXIDE POWER PLANT FOR TOTAL EMISSION CONTROL AND ENHANCED OIL RECOVERY

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ABSTRACT

The design of a compact environmentally acceptable carbon dioxide diluted coal-oxygen fired power plant is described. The plant releases no combustion products to the atmosphere. The oxygen for combustion is separated in an air liquefaction plant and the effluent nitrogen is available for use in oil well production. Recycle carbon dioxide mixed with oxygen replaces the nitrogen for the combustion of coal in the burners. The carbon dioxide produced is used in enhanced oil recovery operations and injected into spent wells and excavated salt cavities for long-term storage. The recovery of CO_2 from a coal burning power plant by this method appears to have the lowest energy expenditure and the lowest by-product cost compared to alternative removal and recovery processes.

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INTRODUCTION

The increasing use of the vast coal resources of the United States has become evident for some time. The depletion of oil and gas reserves has made coal one of the most important sources of energy in the near future. However, the environmental problems associated with coal have also made it one of the least desirable energy sources. The problem with sulfur dioxide production from coal fired plants has threatened to turn the lakes of Canada and the northeast United States into relatively sterile acid pools, while the worldwide problem of increasing carbon dioxide content of the air threatens far-reaching climatic changes known as the "greenhouse effect".[1,14]

The CO_2 content of the air is presently 335 ppm and increasing at the rate of approximately 1 ppm per year. The increasing worldwide use of carbonaceous fuels is expected to increase the rate of CO_2 growth in the atmosphere to about 2 ppm per year by the year 2000 and about 3 ppm per year by 2025. The CO_2 concentration would then reach about 435 ppm causing earth surface temperature increases with consequent disturbing climatic effects.[4] An expected global warming of 1 to 2°C in the atmosphere over the next fifty years will not be evenly distributed. There will be less warming in the tropics and more in the moderate and arctic regions reaching to as much as 3 to 4°C. A region that suffers a 30% decrease in rainfall in a crop area that is marginally too dry and too hot, like the high plains of the U.S.A., will have a large human impact. The U.S. National Academy of Science stated recently[2], "A major climatic change would force economic and social adjustments on a world scale, because the global patterns of food production and population that have evolved are implicitly dependent on the climate of the present century. This dependence of the nation's welfare, as well as that of the international community as a whole, should serve as a warning signal that we simply cannot afford to be unprepared for either a natural or a man-made catastrophe." The first measurable effects of CO_2 increases in the atmosphere are expected in the next twenty years, when the background "noise" of the temperature variation will be exceeded.[3]

It is thus prudent to examine environmental control technologies (ECTs) for CO_2 in an attempt to determine whether it is possible to slow the rise in atmospheric content. The following ECTs are some that have been suggested.

The control of carbon dioxide in the atmosphere can be accomplished by removal of CO_2 either from the atmosphere, the surface waters of the oceans, or the smoke stacks of fossil fueled power plants. The removal of CO_2 from exhausts of transportation vehicles and residential heating devices although possible is considered less practical because of their dispersion. The concentration of CO_2 in power plant flue gas is about 500 times greater than in the atmosphere; therefore, its removal from this source point is greatly facilitated. The removal of carbon dioxide from a concentrated effluent source requires the least expenditure of energy.[1,5]

The disposal of captured carbon dioxide has been the subject of several previous investigations.[1,5,7,15] The options include: (1) injection in the deep ocean, (2) terrestrial storage, (3) absorption by photosynthesis in plants and trees, (4) conversion of CO_2 into useful products, and (5) extraterrestrial disposal. Some of the results of these studies are as follows.

(1) Injection into the ocean at 500 to 3000 meters depth where no CO_2 presently exists is feasible mainly for near shoreline power plants. The economic penalty for removal, recovery and disposal is severe.[5,15] Shore pumping stations and long pipelines would be required. There is also some concern of the unknown ecological effects of deep ocean disposal of CO_2.

(2) Terrestrial burial by injection under pressure into abandoned and depleted oil or gas wells or solution mined salt domes although suggested, has not been adequately studied. CO_2 pumped into these wells would be maintained under pressure and would be available at a late date for synthetic fuel and feedstock production using a non-fossil energy source. Further analysis of this interesting disposal method is given in this paper.

(3) Storage by forestation in trees and plants appears feasible. A 1000 MW(e) coal burning plant requires on the average about 1000 square kilometers of forest land dedicated to this plant for photosynthesizing the effluent CO_2. There appears to be little benefit of locating this area adjacent to the plant site. Regional or worldwide forestation could take care of the equivalent CO_2 emission.[7] There is, however, some concern of other environmental side effects due to a change in the earths albedo caused by extensive forestation.

(4) Conversion of CO_2 into useful marketable products is extremely limited compared to the large quantities of CO_2 being produced due to power production. Some of these products include, methanol, formaldehyde, methane and other organic compounds widely used in commerce. These products, however, eventually return CO_2 to the atmosphere. The fixation of CO_2 into recyclable useful plastics although market limited is worth further investigation.

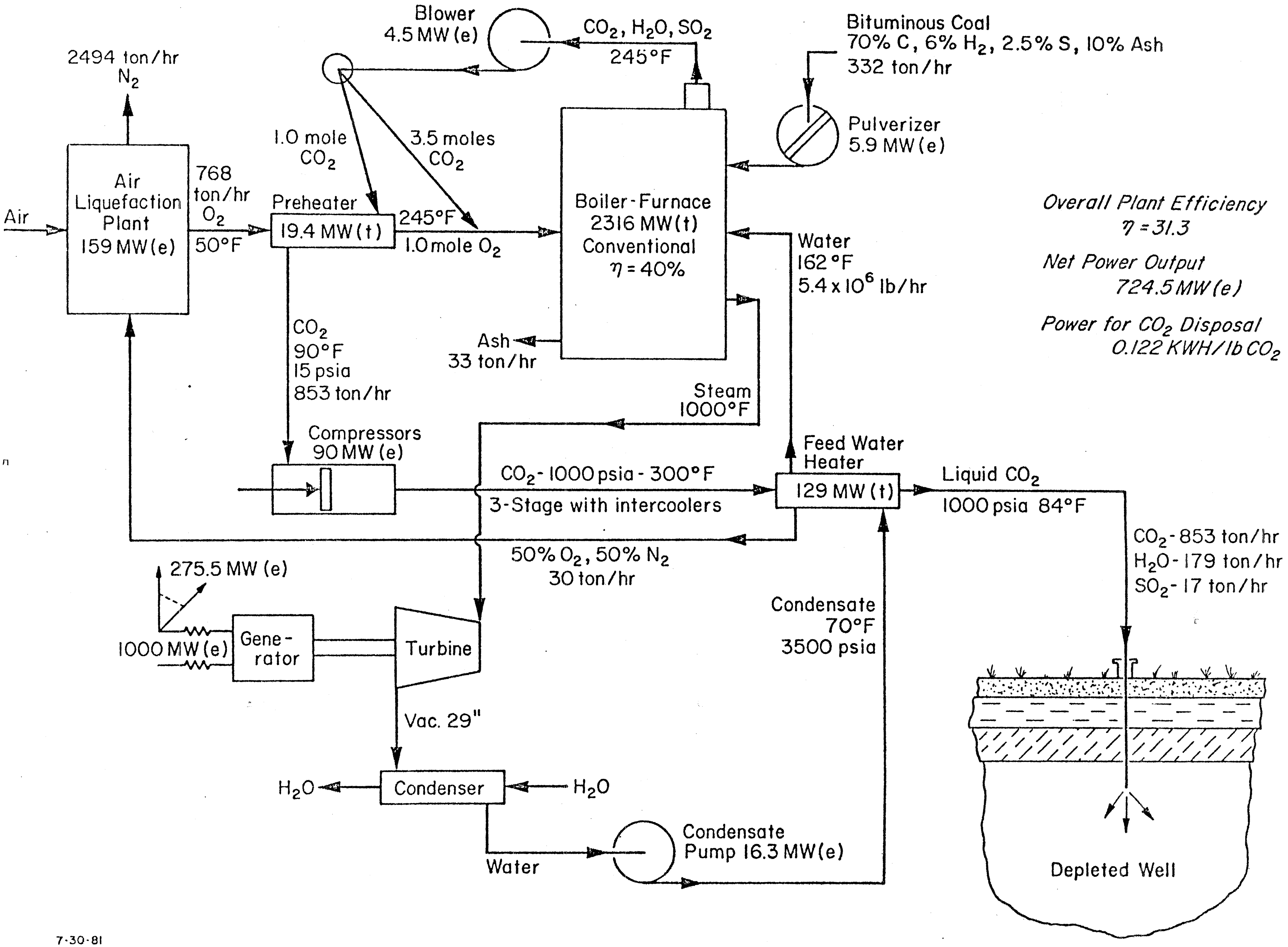
(5) Extraterrestrial disposal is considered impractical because of the large payload to be lifted clear of the earth (900 tons per hour of CO_2 for a 1000 MW(e) plant). The large fuel to payload ratio in conventional fueled rockets would generate much more CO_2 in the atmosphere than disposed of.

Of course there is also always the ECT option converting to a non-fossil energy source (nuclear or solar) thus eliminating the formation of CO_2. However, these alternative sources have their own environmental and economic problems, e.g. radiation from nuclear energy and land resource limitation for solar energy.

A NEW CARBON DIOXIDE POWER PLANT CONCEPT WITH TOTAL EMISSION CONTROL

A new coal burning power plant concept that would meet most control technology criteria is needed. A coal plant that emits no combustion products, thus mimicking the nuclear power reactor, and that still produces competitive power is the concept envisioned. The concept consists of a plant that separates and utilizes only the oxygen portion of the air and utilizes it to convert the carbon in coal to carbon dioxide, which is totally recovered and contained. An embodiment of this coal burning power plant concept is shown in the flowsheet of Figure 1. The plant essentially

CARBON DIOXIDE POWER PLANT WITH WELL DISPOSAL OF EFFLUENT AND FOR E.O.R.



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consists of separating oxygen from air in a liquefaction plant at the head-end of the plant, burning the coal with oxygen in the furnace diluted with recycled CO_2 to temper the flame, and liquefying the effluent CO_2. The sulfur dioxide (SO_2) formed from the coal would dissolve in the carbon dioxide and the liquid waste CO_2 product transported by pipeline to a well site for disposal or for use in enhanced oil recovery operations. The effluent nitrogen from the liquefaction plant is available for useful purposes or is merely vented to the atmosphere. Because there is no nitrogen in the combustion flame except for trace amounts in coal there will be no formation of polluting nitrogen oxides (NO_x). The coal ash is returned for burial or used in marketable products.

Conventional power plant flue gas contains about 15% CO_2, 5% H_2O and 75% nitrogen. The elimination of nitrogen greatly reduces the volume of gas to be processed; therefore, the use of oxygen in the power plant furnace can reduce the size of the plant and more importantly produces a stream which essentially consists of 100% CO_2. However, burning coal in pure oxygen causes extremely high temperatures. In order to lower the combustion temperature, CO_2 must be recycled to the oxygen fed to the furnace to temper or lower the temperature of the flame. The resultant flue gas is nearly all CO_2 and is thus in a form that can be readily recovered and removed. Limiting the flame temperature to about 1650^oC (3000^oF) by adjusting the oxygen concentration provides the furnace conditions necessary for generation of high pressure steam. Because of the increased heat capacity of CO_2 compared to nitrogen, it is estimated that 3.5 moles of CO_2 per mole of oxygen are needed to burn the coal in 2% excess oxygen at 3000^oF. The volume of combustion gases handled is about 10% lower than for burning with air containing the nitrogen. When temperatures in excess of 3000°F are encountered, the theoretical flame temperature is decreased due to the dissociation of carbon dioxide and any water vapor present. Radiation losses also reduces flame temperature. The actual recycle quantity of carbon dioxide will be adjusted so that the proper burning temperature is maintained.

The liquid carbon dioxide recovered from the plant can be disposed of by storage in spent oil and gas wells, or injected deep in the ocean[5] or can be effectively used for enhanced recovery of oil from depleted oil wells. If mainly disposal of the CO_2 is considered, the sulfur dioxide formed from burning coal along with any water vapor can be left unseparated in the carbon dioxide. The SO_2 and H_2O can be condensed and disposed of together with the CO_2 as a liquid, since SO_2 and H_2O are soluble in CO_2 and will be dissolved under pressure at ambient temperature in the effluent liquid CO_2. Any trace NO_x should also be dissolved in the CO_2. The bulk of the water vapor can be removed by condensation during CO_2 pressurization. The ash from the furnace will be removed from the furnace and disposed of in the conventional manner. If an SRC (Solvent Refined Coal) product is used, there will be no ash and less sulfur and the plant could then become cleaner and easier to construct and operate. However, SRC fuel may not be available in the future and in any case, will be more expensive than coal, so that a trade off assessment is necessary.

The disposal of CO_2 into abandoned oil and gas wells is considered a possible disposal solution because there are available 12,000 abandoned wells throughout the U.S.A.[8] The abandonment oil and gas well pressure is usually in the range of 100 to 500 psia,[9] so that CO_2 at 1000 psia can be readily injected into an abandoned well. The carbon content of a well filled with liquid CO_2 at 1000 psia is 30% greater than the carbon content of the same well filled with natural gas at 3000 psia. However, the liquid CO_2 will not remain at its liquefaction temperature of 80°F, but will be slowly heated to the temperature of the surrounding earth. Its final temperature will depend upon the depth of the well and could rise to 200°F or more. At this temperature the CO_2 will be supercritical and the pressure will rise to 3000 psia or more. If the pressure is kept at 1000 psia the CO_2 will expand to five times it original volume at 200°F, thus reducing the equivalent carbon storage capacity of the well. There should be no problem in holding the pressure in gas wells because drilled gas wells are presently capped off at high pressures and contain the natural gas without leakage.

Oil wells normally contain gas under thousands of pounds pressure, increasing in direct relationship to the depth. The carbon content of liquid CO_2 is about 25% of that of liquid petroleum thus requiring more storage volume for CO_2 when replacing oil on a carbon for carbon basis. In Table 1, the relationship between the volumes of CO_2 produced by electrical power production using gas, oil, and coal and the storage volumes of their wells is compared. The CO_2 produced from coal can be recycled for storage back into the numerous spent gas or oil wells or it can be stored in solution mined salt caverns. Salt caverns presently planned for the strategy petroleum reservoir[16] can be formed by solution mining in geological formations at an additional cost of a few mills per KWH(e) to the overall power production cost. A medium sized well with a 200 million cubic foot capacity would provide storage of CO_2 at 3000 psia

TABLE 1

VOLUME OF CO_2 PRODUCED FROM POWER PLANTS

Fuel Type	Natural Gas		Petroleum Oil		Bituminous Coal	
Fuel specifications	95% CH_4		24° API		70% C	
Heating value Btu/lb	21,000		19,000		14,000	
Fuel quantity needed for power[1] lbs/KWH(e)	0.41		0.45		0.61	
CO_2 produced lb/KWH(e)	1.15		1.32		1.57	
Initial well pressure psia	3000	6000	3000	6000	0[6]	0[6]
Initial temperature °F	200	400	200	400	50	50
Fuel volume used for power ft^3/KWH(e)	0.0432	0.0354	0.0090	0.0108	0.0073	0.0073
CO_2 volume at well pressure ft^3/KWH(e)	0.0346	0.0367	0.0398	0.0421	0.0472[2]	0.0499[2]
Fraction of CO_2 volume that can be stored in well	1.24	0.96	0.27	0.26	0.15[3]	0.15[3]
CO_2 storage in empty wells[4] in terms of MW-yrs operation	660	622[a]	574	542[b]	484	458[c]
No. of wells used for a 30 yr lifetime of a 1000 MW(e) plant[5]	34	36	39	41	46	49

1) 8530 Btu equivalent to one KWH(e).
2) CO_2 disposal at gas and oil well pressures and temperatures in salt caverns.
3) Equivalent storage volume of coal mined; CO_2 storage in cavities produced by underground coal gasification.
4) a) A medium sized gas well produces an approximate total of $50 \text{x} 10^9$ SCF of natural gas, and has a volume of $2 \text{x} 10^8$ ft^3 or 40 million barrels.
   b) A depleted oil well of $40 \text{x} 10^6$ bbl capacity has an equivalent volume of $2 \text{x} 10^8$ ft^3.
   c) A salt cavern designed for storage of $40 \text{x} 10^6$ bbl or a volume of $2 \text{x} 10^8$ ft^3.
5) 74% plant factor used.
6) Coal mine pressure.

and 200°F for 484 MW-yrs(e) hours of plant operation. A total of 46 such wells would be needed over the thirty-year lifetime of a 1000 MW(e) coal-fired plant.

Pressurized carbon dioxide is presently a much sought after commodity[10] in the oil well areas of the world for enhanced oil recovery (EOR) operations. If the CO_2 from the power plant is desulfurized it can be transported and marketed as a liquid or gas for use in extracting more oil from depleted wells, or used as a liquid to transport coal in a liquid/slurry pipeline.[15] Primary oil extraction removes about a third of the oil, while EOR removes another third before a well becomes uneconomical to operate. Secondary and tertiary treatment of oil wells employs CO_2 not only because of its displacement value but also because it is highly soluble in oil which markedly reduces its viscosity and density thereby making the oil more mobil in the broken rock and sand formations.[10] The volume of CO_2 gas used varies from approximately one to six thousand cubic feet per barrel of oil recovered. At current prices, the CO_2 treatment can be valued equivalent to as much as $10 additional cost of producing a barrel of oil.[10] The sale of carbon dioxide from the carbon dioxide power plant can be taken as a credit in reducing the cost of electrical power to the ratepayer.

An important item in this unconventional power plant is the production of oxygen. For purposes of this study we chose a standard air liquefaction/distillation technique for production of oxygen because it is the most efficient and highly developed oxygen separation process available today. Other less developed but potentially more efficient methods of oxygen production are possible e.g. membrane or even magnetic separation could be the subject of future plant developments.

PROCESS DESIGN

The nearly complete elimination of nitrogen from the combustion gas simplifies the gas removal and recovery problem, and allows disposal scenarios that use a minimum of energy. The flowsheet shown in Figure 1 for the carbon dioxide power plant with well disposal of CO_2 utilizes all conventional equipment that is currently available. These include the air liquefaction plant, the steam boiler-electric generator power plant, and the carbon dioxide reciprocating compressors with heat exchangers. The flow rates, power consumption, and heat exchanger duties are given in Table 2.

The air liquefaction plant consumes the major portion of auxiliary power used, 159 MW(e), and produces oxygen of 98% purity. The 98% oxygen production plant assumes a Linde 2000 ton per day unit with a specific energy consumption of 203 KWH(e) per ton of oxygen.[11] This is accomplished with high efficiency heat exchangers and the use of expansion turbines to conserve energy. The 2% nitrogen and 2% excess oxygen will be separated from the liquefied CO_2 and recycled to the oxygen plant, and any nitrogen oxides and sulfur oxides formed along with water vapor will be compressed to 1000 psia condensed along with the CO_2 and transported and injected along with the carbon dioxide into the depleted wells. The SO_2, H_2O and residual NO_2 dissolve in the liquid CO_2 and exert a lower vapor pressure than CO_2. The oxygen is preheated by the hot (245°F) carbon dioxide issuing from the furnace, recovering 19.4 MW(t). The carbon dioxide is thereby cooled to 100°F where it is fed to a three-stage compressor with intercoolers. The CO_2 is compressed from atmospheric to 60 psia and 300°F and cooled to 90°F by condensate water, recompressed to

TABLE 2

CARBON DIOXIDE POWER PLANT
Nominal Power Plant Capacity = 1000 MW(e)
Net Electrical Power Output 724.5 MW(e)

MASS FLOW RATES

Fuel

Bituminous Coal	-	332 Tons/hr
O_2	-	752.5 Tons/hr

Effluent

CO_2	-	853 Tons/hr
SO_2	-	17 Tons/hr
H_2O	-	179 Tons/hr
Ash	-	33 Tons/hr
Steam Rate	-	5.4×10^6 lb/hr

POWER CONSUMPTION INCLUDING CO_2 RECOVERY

		HP	MW(e)
Condensate Pump	-	21,930	16.3
Coal Pulverizer	-	7,882	5.9
CO_2 Blower	-	5,987	4.3
CO_2 Compressors (80% efficient)	-	120,054	90.0
Air Liquefaction Plant	-	213,280	159.0
Total			275.5

HEAT EXCHANGER DUTIES

O_2 - Preheater	-	66.2×10^6 BTU/hr
Feed Water Heater	-	439×10^6 BTU/hr

250 psia and 300°F and cooled to 90°F, and finally compressed to 1000 psia and 275°F and cooled to 84°F. The final condensation to liquid CO_2 at 84°F in a heat exchanger is accomplished with 70°F condensate water flowing at 5.4 million pounds per hour. The excess oxygen and nitrogen are separated at this point for recycle. The condensate water picks up a total of 129 MW(t) and enters the boiler at 162°F thus decreasing the coal consumption and furnace heat generation to 2316 MW(t). A conventional Rankine cycle steam turbine generator produces the 1000 MW(e).

The air liquefaction plant[11], carbon dioxide compressors and blowers use 254 MW(e) of the power output, yields a net power output of 724.5 MW(e) and thus reduces the overall plant efficiency to 31.3%. A modern conventional plant runs as high as 40% efficiency. Table 3 summarizes the power balance of the main components of the entire plant. The disposal of liquid CO_2 is accomplished by pumping into empty or spent wells. The volume available in a spent well[8] would typically accept the 1000 MW(e) power plant effluent for periods ranging from 6 months to 3 years. The energy required equivalent to the energy reduction of the power plant amounts to 0.12 KWH(e) per pound of carbon dioxide stored. This penalty can be written off as a cost for environmental control or the additional cost for this power can be more than recovered if the carbon dioxide can be sold for stimulating the recovery of oil in spent wells.

If low sulfur CO_2 for EOR is required, there are several ways of adjusting the SO_2 content. The carbon dioxide can either be scrubbed with potassium carbonate solutions prior to compression, or more economically the liquid CO_2 can be run through a limestone trap to remove the SO_2. The energy requirement is estimated to be 0.5 MW(e) for full SO_2 removal

TABLE 3

CARBON DIOXIDE POWER PLANT
Nominal Power Plant Capacity = 1000 MW(e)
Power Balance

CO_2 Power Plant Operating Without CO_2 Recovery and Disposal

Condensate Pump - 16.3 MW(e)
Coal Pulverizer - 5.9 MW(e)

Power Consumption - 22.2 MW(e)

Boiler Output - 2316 MW(t) (85% eff)
Feed Water Heater Output - 129 MW(t)

Total Output - 2445 MW(t)

Net Electric Power Output = 1000 MW(e) - 22.2 = 977.8 MW(e)

Plant Efficiency $\eta_c = \frac{977.8 \text{ MW(e)}}{2445 \text{ MW(t)}} = \underline{40.0\%}$

CO_2 Power Plant Operating with CO_2 Recovery and Disposal

Additional Power Plant Consumption for CO_2 Disposal:

Air Liquefaction Plant - 159.3 MW(e)
Carbon Dioxide Blower - 4.5 MW(e)
Carbon Dioxide Compressors - 89.5 MW(e) (80% eff)

Power Consumption - 253.3 MW(e)

Net Electrical Power Out = 1000 - 22.2 - 253.3 = 724.5 MW(e)

Net Plant Efficiency $\eta_c = \frac{1000 - 22.2 - 253.3}{2316} = \underline{31.3\%}$

(<0.1%) and proportionally less for partial SO_2 removal, which is, in any case, a negligible amount, compared to the power plant output.

PRELIMINARY ECONOMIC ANALYSIS

The capital cost estimate of a nominal 1000 MW(e) power plant given in Table 4 is compared to one with desulfurization and one with flue gas recovery of CO_2 using monoethanolamine (MEA)[5] and finally with the carbon dioxide plant. Table 4 also gives a breakdown of the additional capital equipment needed for the CO_2 plant above the conventional plant. The power production costs in mills per KWH(e) are given in Table 5 for each of the cases mentioned. Table 6 and Table 7 give a cost comparison, between conventional plant operations and the CO_2 power plant operation with and without the sale of CO_2 for EORs. When the CO_2 cannot be sold and there is no disposal site immediately available for the CO_2 it can be vented to the atmosphere so there will be no power interruption. The power cost in this case would be 55.6 mills/KWH(e) which is only 8.6 mills/KWH(e) more than for a conventional 1000 MW(e) plant.

If the CO_2 can be sold at a price of one dollar per thousand standard cubic feet, the cost of electricity is about equal to a conventional plant, 47.0 mills/KWH(e). Any increase in the sale price of CO_2 will make the cost of electricity that much less and would benefit the ratepayer.

Monoethanolamine (MEA) absorption/stripping is one of the more energy efficient methods of recovering CO_2 from a conventional power plant by stack gas scrubbing, according to recent studies.[5] Compared to a conventional plant that recovers 90% of its CO_2 by MEA absorption, the CO_2 Power Plant can sell its CO_2 at about two-thirds the price ($1.00/mscf) of a conventional plant, ($1.50/mscf) to breakeven at the same net electric and power generation cost of (46.7 to 48.0 mills/KWH(e)).

TABLE 4

CAPITAL COST ESTIMATES
1981 Dollars

Conventional Coal-Fired Power Plant, 978 MW(e)	-		$650,000,000
Conventional w/Flue Gas Desulfurization, 978 MW(e)	-		750,000,000
Carbon Dioxide Plant, 724 MW(e) net output	-		951,500,000
Additional Capital Equipment for CO_2 plant			
Linde Oxygen Plants, 18,000 Tons per Day	-	$202,500,000	
Carbon Dioxide Compressors, 1049 Tons per Hour	-	60,000,000	
Heat Exchangers for Feed Water, 5.4×10^6 Lb per hour	-	25,000,000	
Oxygen Preheater, 753 Tons per Hour	-	12,000,000	
Carbon Dioxide Circulation Blower, 4750 tons per hour	-	2,000,000	
Total additional capital for CO_2 plant			301,500,000

TABLE 5
PRODUCTION COSTS* OF POWER PLANTS
1000 MW(e) Nominal Capacity

1. Conventional Plant, No Desulfurization:	
978 MW(e) net output	
Fuel Expense:	15.2
Depreciation:	18.5
Operating and Maintenance Labor	10.0
Total	43.7
2. Conventional Plant with Flue Gas Desulfurization:	
978 MW(e) net output	
Fuel Expense:	15.2
Depreciation:	21.3
Operating and Maintenance Labor:	10.5
Total	47.0
3. Conventional Plant with Desulfurization and Flue Gas Recovery (90% removal) of CO_2 using MEA absorption and disposal in a well:	
443 MW(e) net output	
Fuel Expense:	33.5
Depreciation:	59.5
Operating and Maintenance Labor:	11.5
Total	104.5
4. Carbon Dioxide Plant with SO_2 and CO_2 Disposal to a Well	
725 MW(e) net output	
Fuel Expense:	19.2
Depreciation:	36.5
Operating and Maintenance Labor:	11.0
Total	66.7

*Assumptions
Depreciation: 18% per year
Fuel: Coal at $42/ton
Plant Factor: 74%

TABLE 6

ELECTRIC POWER PRODUCTION COST*
FOR
A CONVENTIONAL 1000 MW(e) COAL-FIRED POWER PLANT
WITH BY-PRODUCT RECOVERY OF CO_2

		Net Cost of Power mills/KWH
1.	Power plant without flue gas desulfurization	43.7
2.	Conventional power plant with flue gas desulfurization (FGD)	47.0
3.	Conventional power plant with desulfurization and flue gas recovery (90% removal) of CO_2 using MEA absorption and disposal in a well.(1	104.5
4.	Conventional power plant with flue gas desulfurization and by-product sale of CO_2.	
	Selling Price(2 of CO_2 $/mscf	
	0.00	104.5
	0.75	75.6
	1.00	66.0
	1.50**	46.7**
	2.00	27.4

*Assumptions:
Depreciation: 18% per year.
Fuel: Coal at $42/ton.
Maintenance and Labor: 10.0 to 11.5 mills/KWH for 1000 MW(e) plant
Plant factor: 74%

1) well assumed available at power plant site at no extra cost.
2) CO_2 sold F.O.B. at power plant.

**Selling price of CO_2 for breaking even with net power production cost from a conventional plant with FGD.

TABLE 7

ELECTRIC POWER PRODUCTION COST*
FOR
CARBON DIOXIDE POWER PLANT
WITH BY-PRODUCT RECOVERY OF CO_2

	Selling Price(2 of CO_2 \$/mscf	Net Cost of Power mills/KWH
1. CO_2 Power Plant and with flue gas SO_2 removal.		55.6
2. CO_2 Power Plant with CO_2 and SO_2 recovery and disposal in a well(1		66.7
3. CO_2 Power Plant with SO_2 removal from CO_2 prior to disposal in a well.		68.3
4. CO_2 Power Plant w/sale of CO_2 after SO_2 removal		
	0.00	68.3
	0.75	53.0
	1.00**	48.0**
	1.50	42.9
	2.00	27.7

*Assumptions:
Depreciation: 18% per year.
Fuel: Coal at $42/ton.
Maintenance and Labor: 10.5 to 11.5 mills/KWH for 1000 MW(e) plant
Plant Factor: 74%

1) well assumed available at power plant site at no extra cost.
2) CO_2 sold F.O.B. at power plant.

**Selling price of CO_2 for breaking even with power production cost for a conventional plant with FGD.

A 725 MW(e) plant produces enough CO_2 (15,000 T/D) to obtain enhanced oil recovery (EOR) from spent wells equivalent to 43,000 to 262,000 bbl/day of oil based on 1000 to 6000 CO_2 SCF barrel of oil. At a $1.00/mscf for CO_2, this adds $1 to $6/bbl of oil to the cost of oil recovery at the wells. The plant size can be scaled down or adjusted to the needs of EOR, thus if less CO_2 is needed in an area for oil recovery a proportionately smaller size power plant can be built. Normally, the power plant would be sized for the power production requirement to meet the demands in the area. The CO_2 would then be used wherever it is economically feasible in the oil fields. Like every dual purpose plant, a parametric optimization study must be performed. If the CO_2 is sold for 75 cents per mscf, its approximate operating cost of recovery, the average income to the plant from EOR would be $196,000 per day, which is equivalent to 15.3 mills/KWH, bringing the power cost down to 53 mills/KWH(e). In all these estimates no dollar credit has been taken for environmental control.

A 1981 study[12] made at the University of West Virginia on the recovery of CO_2 from flue gas indicates, with the use of a potassium carbonate flue gas process, the CO_2 costs 88 cents/mscf at one atm and the MEA flue gas process costs $1.07/mscf. The difference in cost was not considered significant. For comparison, the carbon dioxide plant cost is equivalent to $1.00/mscf CO_2 delivered at 1000 psia. The compression and drying of flue gas CO_2 in the University of West Virginia study is estimated to add another 20 to 30 cents/mscf; therefore, the total cost will approach the $1.50/mscf estimated above for the MEA absorption recovery process. The difference in cost (~$1.50 versus $1.30) is due to the capital charges assumed, e.g. \$140/KW(e) versus \$200/KW(e) for the higher cost CO_2 plant. The West Virginia study used \$28,300,000 (December, 1979) for the capital investment and our study uses \$40,000,000 (August, 1981) based on a 200 MW(e) plant size.

If the CO_2 is just stored with SO_2 in it and not sold, the cost of electricity is 66.7 mills/KWH without taking any credit for environmental control.

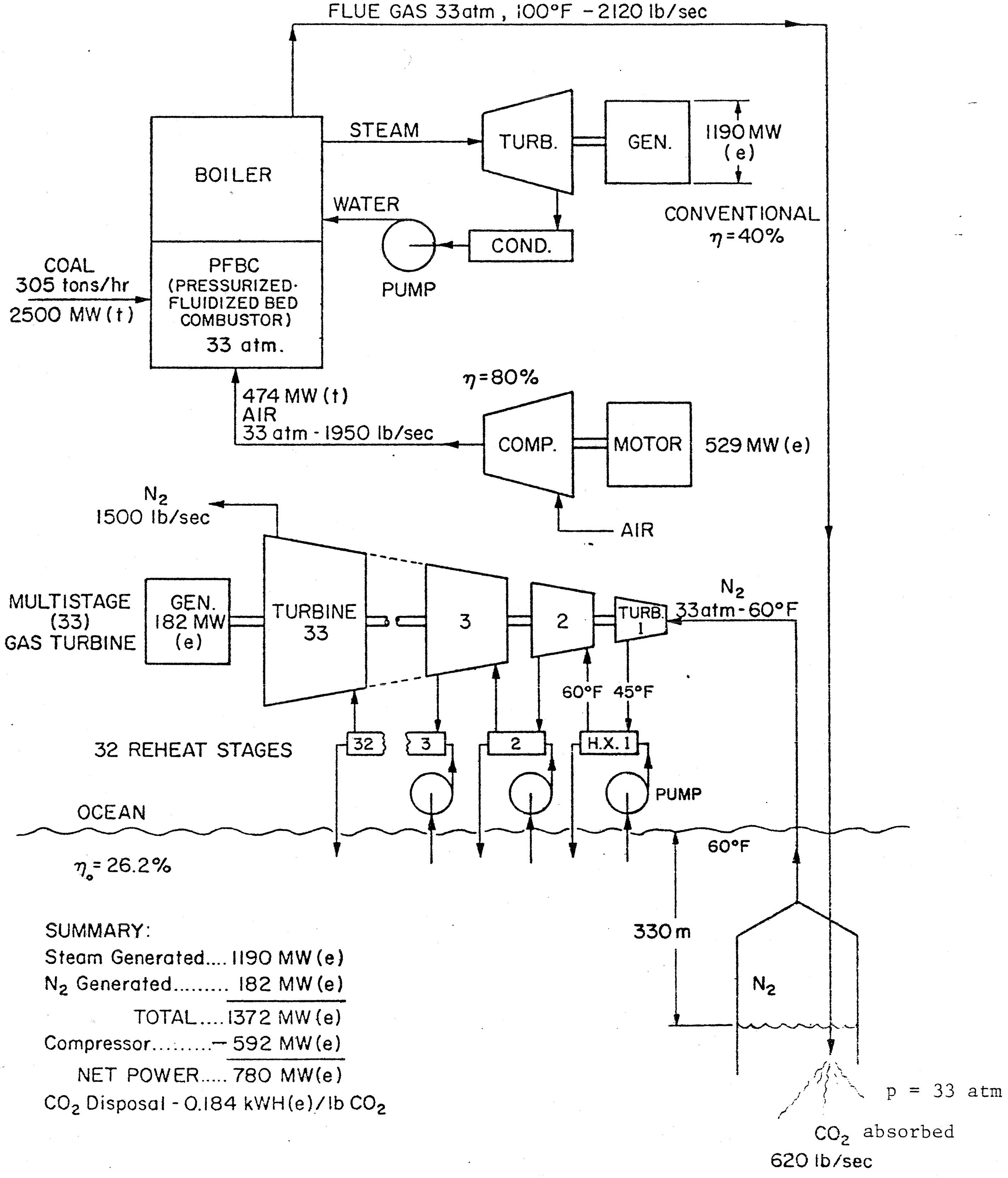
Large quantites of nitrogen are produced by the air liquefaction plant, (60,000 tons/day), but no credit has been taken for its use, although it is available for enhancing oil and gas field recovery. Nitrogen is considered of much less value than the CO_2 in the oil and gas fields, however, the nitrogen value should not be overlooked especially if there is a need to inert large volumes or can be used for other industrial purposes.

ALTERNATE PROCESS DESIGN

A number of variations and alternatives to the basic flowsheet can be considered. (1) The oxygen from the air liquefaction plant can be used at 50 psi and higher in a pressurized fluidized bed (PFBC) power generation furnace; (2) the air liquefaction plant can be eliminated and the flue gases compressed to remove the carbon dioxide and the nitrogen expanded through a turbine to recover the energy and (3) a proposal by Garwin[13] to use a pressurized fluidized bed (PFBC) at 33 atmospheres to generate power with deep sea disposal of the pressurized flue gases. In the latter scheme, sketched out in Figure 2, the carbon dioxide is dissolved in the sea water at 330 meter ocean depth which pressure equalizes the power plant at that depth. The pressurized nitrogen after being scrubbed of its

FIGURE 2

PFBC POWER PLANT PRESSURE EQUALIZED BY SEAWATER DISPOSAL OF CO_2



CO_2 content at the 330 meter depth, is piped back to the ocean surface and expanded through a turbine to recover and generate electric power. A CO_2 disposal energy cost was calculated to be equivalent to 0.18 KWH(e) per lb CO_2, or 50% higher than for the carbon dioxide power plant flowsheet described above. No pipeline or pumping power was included for the sea disposal which would further increase the energy requirement for CO_2 disposal. The efficiency of this plant is 26.2% which is lower than the 31.2% for the CO_2.

The energy required to remove and recover CO_2 from flue gas with at least 90% efficiency by conventional methods shown in Table 8 varies from 0.27 KWH(e)/lb CO_2 for MEA absorption, to 0.32 KWH(e)/lb for potassium carbonate absorption, to 0.40 KWH(e)/lb for molecular sieves and refrigeration to 0.80 KWH(e)/lb for sea water absorption. The Garwin proposal reduces the sea water disposal energy to the lowest of the air-fired plants - 0.18 KWH(e)/lb. However, the carbon dioxide recycle plant proposed in this report reduces the energy requirement to a minimum value of 0.12 KW(e)/lb and thus energy-wise is the most economical.

CONCLUSIONS

An oxygen-coal fired power plant diluted with CO_2, referred to as a carbon dioxide recycle plant designed to contain all environmentally unacceptable combustion products has been evaluated to be energy and cost effective. The carbon dioxide and sulfur dioxide as well as any trace nitrogen oxides are condensed and injected into depleted oil or gas wells or solution mined salt caverns. The plant is environmentally acceptable for total emissions control which include sulfur oxides, nitrogen oxides and carbon dioxide. The cost effectiveness of the plant can be further

TABLE 8

ENERGY REQUIRED TO REMOVE AND RECOVER CO_2 FROM COAL FIRED POWER PLANT

Process	CO_2 removal efficiency %	KWH(e)/lb CO_2[a] recovered
1. Amine (MEA) absorption/stripping	90	0.27
2. Potassium carbonate absorption/stripping	90	0.32
3. Molecular sieves	90	0.40
4. Refrigeration	90	0.40
5. Seawater absorption(b)	90	0.80
6. PFBC Seawater Pressure Equalized(b)	99	0.18
7. Carbon Dioxide Power Plant(c)	100	0.12

(a) Energy required to recover CO_2 (as a gas) from flue gas of coal-fired power plant subsequent to SO_2 removal.

(b) Including deep ocean disposal of captured CO_2.

(c) Includes CO_2 liquefaction energy.

increased by using the carbon dioxide for enhanced oil recovery (EOR) operations and the income can be accrued to the ratepayer by significantly reducing the net cost of power. This plant appears to be the most economically and ecologically acceptable method for controlling carbon dioxide as indicated by the minimum energy consumption used for disposal, 0.12 KWH(e)/lb CO_2, compared to the other more conventional methods which require from 50 to 100% higher energy expenditures. The capital equipment investment appears to be in a reasonable range at $951,500,000 for a net 725 MW(e) plant with zero emissions.

A 1000 MW(e) plant can sell 725 MW(e) of electricity and 853 tons per hour of CO_2 for enhanced oil recovery (EOR) operations, which at $1/mscf will produce an average income of $262,000 a day equivalent to a credit of 20.4 mills/KWH. The quantity of CO_2 available for EOR is equivalent to producing 43,000 to 262,000 bbl/day of oil at an additional $1 to $6/bbl above the cost of conventional recovery of oil at the wells. The cost of electricity for the plant would be about 48 mills per KWH which is about equal to the cost of electricity from a conventional plant. The availability of depleted oil, aged gas wells, as well as solution mined salt caverns allows the long term storage of CO_2 from coal burning power plants for either environmental reasons or for conversion to carbonaceous fuels using a non-fossil energy source at a future date. The economic and environmental potential of this conceptual power plant and CO_2 disposal system appears highly attractive.

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