BNL 51597

I-7662 (1)

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POSSIBLE STORAGE SITES FOR DISPOSAL AND ENVIRONMENTAL CONTROL OF ATMOSPHERIC CARBON DIOXIDE

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DEPARTMENT OF ENERGY AND ENVIRONMENT

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UC-11
(Environmental Control Technology and
Earth Sciences - TIC-4500)

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PROCESS SCIENCES DIVISION
DEPARTMENT OF ENERGY AND ENVIRONMENT
BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.

UNDER CONTRACT NO. DE-AC02-76CH00016 WITH THE
UNITED STATES DEPARTMENT OF ENERGY

Abstract

To control the increasing carbon dioxide in the atmosphere and mitigate its environmental effects, an investigation of possible storage sites for CO_2 as liquid in depleted oil and gas wells and excavated salt domes has been made. The storage capacity versus CO_2 production from the use of fossil fuels in the U.S. for the three types of sites indicates low capacity for oil wells, intermediate for gas wells and high capacity for salt domes. Salt domes appear to provide CO_2 storage for many decades, but at an annual excavation cost in the tens of billions of dollars amounting to a minimum of 13% of the total cost of power production which includes removal and storage of CO_2. The total cost of removal, recovery and storage of CO_2 from power plants could almost double the total conventional cost of power production utilizing fossil fuel.

POSSIBLE STORAGE SITES FOR DISPOSAL AND ENVIRONMENTAL CONTROL OF ATMOSPHERIC CARBON DIOXIDE

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The increasing use of fossil fuels throughout the world as the primary source of energy in today's society can cause an increase in the carbon dioxide concentration of the atmosphere. Although the photosynthesis reaction removes carbon dioxide from the air, the quantity of carbon dioxide entering the air from the combustion of oil, gas, coal, and wood greatly exceeds the worldwide photosynthesis capacity. There is also absorption of carbon dioxide into water on the surface of the world's oceans and lakes which tends to reduce the CO_2 concentration in the atmosphere. As a result, the carbon dioxide concentration fluctuates, rising in the winter and decreasing in the summer[1], however, the average value has been steadily increasing annually since the start of the Industrial Revolution in 1850. The concentration has increased from the pre-industrial level of 290 ppm (parts per million) to a 1982 level of 337 ppm with projections of 400 ppm by the year 2000 due to the accelerating use of fossil fuels[2].

Predictions of carbon dioxide content in the atmosphere beyond the year 2000 vary depending upon the scenario chosen for world energy production. The "worst case" scenario for continued high fossil fuel use predicts a carbon dioxide concentration of 500 ppm by the year 2020. A "best case" scenario predicts about 420 ppm by 2020.

The consequences of the increased content of carbon dioxide are being studied throughout the world[3], and considerable effort is being made in the use of models to apply the data being collected to determine the global effects. The most widely predicted result is the "Greenhouse Effect" in that carbon dioxide is transparent to sunlight but absorbs in the infra-red region, thus the heat loss of the earth to outer space is decreased as the CO_2 content increases. The heat balance of the earth will be disturbed and the average temperature will rise to increase the rate of heat loss.

The magnitude of the temperature rise is predicted to be in the order of one degree celsius around the year 2000 and two or three degrees by 2030. The temperature change itself is not highly important, but the change in climatic patterns portends to be highly significant[4]. Various models[5] indicate that the warming trend would be uneven and that the effect at the poles would be roughly double the average, while in the tropics it would be less than the average.

The most dramatic predicted change would be the melting of the Arctic Sea ice and the West Antarctic ice sheet as the carbon dioxide concentration doubles and quadruples in the twenty-first century. The levels of the world's oceans would rise about ten meters causing dislocations worldwide. The more subtle changes induced by the warming trend would be a change in the amount of seasonal rainfall or a change in the normal wind patterns[3]. There are many marginal areas in the world that would revert to desert conditions over a long-term climate change that ordinarily would not be particularly perceptible in the short-term climatic system. The high plains area of the U.S. is a region that is marginal in terms of heat and rainfall and is, thus, vulnerable to a temperature increase.

As the effects of carbon dioxide in the atmosphere become more apparent and actual measurements confirm the "Greenhouse Effect", the worldwide community may decide to cope with the problem by just maintaining the existing carbon dioxide concentration or reducing the growth of the atmospheric CO_2 concentration. A number of environmental control technologies can be set forth to accomplish this result. This includes (1) reduction in fossil fuel use, (2) removal of CO_2 from fossil fuel power plants and, (3) increased forestations of land areas[6]. In all of these cases, a repository for disposal of the excess carbon dioxide being produced would be needed. One repository would be to put the CO_2 back where some of it originated[7], in abandoned oil and natural gas wells.

Other options would be to dissolve the gas in the ocean at depths below the thermocline[8], or react the gas to form a solid substance for disposal[9]. Proposals have also been made to increase the forested areas of the world to store more of the carbon dioxide in biomass through the photosynthesis cycle[6]. Storage of the gas can also be envisioned in depleted gas and oil wells, in depleted underground mines and in excavated salt domes.

The enormous volumes of carbon dioxide[10] being generated continuously throughout the world in power and industrial plants, in transportation vehicles, in commercial and residential heating[11] pose a problem as to how the gas can be captured, separated from air, and disposed of. The most concentrated source of carbon dioxide would be from the flue gases of a power plant. Since in the U.S., 31% of the CO_2 generated[9] comes from electric power plants, it is a significant source point at which control of the gas could be initiated. Therefore, it is proposed that the carbon dioxide separated from the flue gas by one of several available processes, be compressed, cooled and liquefied for insertion into depleted and abandoned gas and oil wells. There are over 12,000 abandoned oil and gas reservoirs in the U.S.[12]

Gas wells are abandoned when their pressure drops to a few hundred pounds and then are capped[13]. The liquefied carbon dioxide at 1000 psi can be pumped into the well against the residual gas pressure. 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 well. The critical temperature of CO_2 is 88.4°F and the critical pressure is 1071 psia at a density of 28.9 lbs/ft^3. If the liquid CO_2 is injected at 1000 psia, 80°F, and a density of 41.9 lbs/ft^3, an increase in temperature of a few degrees will cause it to boil thereby increasing the pressure to the critical pressure and beyond. The final temperature and supercritical pressure will depend upon the depth of the well, as high well temperature and pressures are normal in the oil and gas fields. An increase of 10°F is usual for every 1000 ft of depth; therefore, a 10,000 ft well will heat the CO_2 to 180°F and a final pressure of 3000 psia. A gas well with a bottom well pressure of 4,000 psia is not unusual at this depth. In fact, pressures in excess of 10,000 psi are frequently encountered at greater depth, thus the containment of the CO_2 gas under supercritical conditions is feasible. If the well is not filled with CO_2 at the 42 lb/ft^3 density before its temperature rises, a high pressure pump will be needed to insert the liquid CO_2 against the increasing well pressure.

The total volume available for carbon dioxide storage can be estimated on the basis of the total oil and gas well volume of the known reserves. As the fuels are removed and combusted, the carbon dioxide generated can be returned to the wells. Limiting our concern to the U.S., since the U.S. generates 27% of the world's CO_2[8], the total U.S. reserve volume in natural gas is about 2×10^{12} cubic feet, under gas well pressure conditions (at an average pressure of 2000 psia.) As shown in Table 1, the volume of liquid CO_2 generated from that amount of natural gas combusted as fuel is about 1×10^{12} cubic feet (for liquid CO_2 at 1000 psi and 80^oF). There is, therefore, more than enough volume available to store the CO_2 from natural gas generation.

Storage volume in U.S. oil wells based on volume of oil reserves is about 2×10^{11} cubic feet, an order of magnitude less than that for gas, while the liquid CO_2 generated from oil is 1×10^{12} cubic feet which is five times the oil volume available. The excess CO_2 generated by the oil must be added to the CO_2 generated by the gas and stored in gas wells. This leaves little or no room for CO_2 generated by the use of coal. The volume of CO_2 generated from coal cannot be stored in coal mines because the volume available amounts to only 15% of the liquid CO_2 generated from combustion of the mined coal[14]. Furthermore, coal mines cannot readily hold fluids under pressure which is required for CO_2 storage.

It is evident from the above figures, that gas wells can accommodate the carbon dioxide generated from gas and oil, but not for coal. The use of coal in the U.S. produces 30% of the CO_2 emission and thus requires a significant storage volume. A possibility exists in the use of excavated salt domes. The storage of large gas volumes in salt domes excavated for this purpose has been a routine procedure in the gas industry for years. The salt domes are prominent in the Gulf States region of the U.S.[15] as well as in other parts of the world.

There are 524 known salt domes[16] in the Gulf coastal area which average two miles in diameter[17]. The first salt dome named Avery Island was discovered near New Iberia, Louisiana in 1862 and was used to mine salt (see Figure 1). A topographic map and cross section of this typical salt dome is shown in Figure 2. The salt dome locations in Louisiana, Mississippi, and Alabama are shown in Figure 3, while the offshore salt domes are shown in Figure 4. The location of the Texas onshore salt domes is shown in Figure 5, and the offshore domes in Figure 6.

If only one percent of the salt volume is excavated for gas storage in this area an additional 10^{12} cubic feet of gas volume would be available. This incremental volume is equal to half the natural gas well volume in the U.S. or five times the oil well volume.

A solution mining technique has been used to produce large caverns in salt formations[18] which can hold gas under pressure. The salt is plastic and self-sealing of any cracks. The mining operation (see Figure 7) consists of pumping fresh water down a concentric tube under high pressure and flowing the resultant salt solution from the sump through the center pipe out to some surface or ocean disposal area. Liquid CO_2 will take the place of "diesel oil in" as shown in Figure 7. The mining of multimillion barrel storage volumes are considered routine operations and is being used for the strategic petroleum reserve in the U.S.[18]. The cost of excavation of a salt dome, varies with water availability and accessible disposal areas and is in the range of $1 to $3.50 a barrel (42 gal.) of volume excavated[16,18]. Pumping seawater which has a salt concentration of 3.5% and increasing the salt concentration to 20% should also be a feasible operation. The concentrated seawater would be disposed of by pumping into the ocean.

Besides the Gulf area in the U.S., there are other large salt volumes already in use for gas storage in Kansas, Ohio, Michigan, Pennsylvania, West Virginia and New York which could be used for CO_2 storage. Figure 8 shows location of all underground 1977 gas reservoirs and salt deposits in the U.S.[16]. Most of the U.S. underground storage capacity is in salt strata or salt domes. Of the total 2 x 10^9 ft^3 of storage capacity, 93.5% is in salt reservoirs, and about half of this is in Gulf coast salt domes.[16] In the West there are potential sites in the salt domes of the Paradox Basin of Utah, the Piercement salt masses in Colorado, Salt domes in Supai Basin of Arizona, and also some salt masses in North Dakota[19]. The western sites present a particular problem for this type of excavation technique because solution mining requires large volumes of water which is in short supply in these semi-desert areas. The volume of salt domes available is fifteen times the $10^{14} ft^3$ of Gulf dome volume available and is adequate to store all the CO_2 ($1.3 \times 10^{14} ft^3$) that could be generated from the U.S. coal deposits, (see Table 2). However, the method of excavation to create storage volume requires further study.

A reasonable control goal which might be pursued is to maintain the existing concentration of carbon dioxide in the atmosphere. The amount of CO_2 that would be required to be removed from effluent sources depends on the terrestrial CO_2 balance. Because of uncertainties in the terrestrial CO_2 balance, it is not yet known what emission reduction would be needed to maintain the CO_2 concentration at a constant balance point. Several models involving atmospheric dynamics have been proposed[5] to account for the many complicated exchange mechanisms involved in the carbon dioxide cycle. One estimate for this balancing requirement amounts to about 50% of the current total fossil fuel emissions. Concentrated sources of CO_2 emissions are found at the utilities and industrial plants in the U.S. and accounts for over 50% of the CO_2 released[11]. Therefore, removal and storage of the gas from these sources alone could possibly accomplish the goal of stabilizing the CO_2 concentration in the atmosphere.

In Table 3 the annual consumption of fuels in 1980 is given in metric tons of carbon for the five categories of use: residential, commercial, industrial, electric utilities, and transportation. Three separate storage capacities are considered, (1) the total U.S. oil well volume at depletion, (2) the total U.S. gas well volume at depletion, and (3) 10% excavation of the Gulf Coast salt dome volume. If the total annual production of CO_2 from one of the five categories, i.e. industrial, was injected into spent oil wells the capacity would be useful for only 3.2 years, while the gas well volume would last for 32 years and the salt dome volume would last for 160 years.

A combination of two sources is also shown in Table 3, namely industrial and electric utilities which account for 7.1×10^8 metric tons or 53% of the total carbon consumption. The corresponding storage time would be reduced to 1.3 years for oil wells, 13 years for gas wells and 65 years for salt domes.

The excavation of salt storage volumes to accommodate 50% of the U.S. yearly CO_2 emission would cost somewhere between 22 and 79 billion dollars annually, depending upon the cost of excavating the salt. The cost of excavating salt domes in the Gulf Coast varies from $1.00 a barrel of volume to $3.50 a barrel for the strategic petroleum reserve storage volume[16,18]. CO_2 storage would not require the retrieval system of petroleum storage. It should be noted that CO_2 can be considered a valuable resource for the future. CO_2 stored in salt domes could be available at a later date for possible reconversion to hydrocarbon fuel with the use of a non-fossil energy source, either nuclear or solar.

The use of gas wells can be considerably less costly when abandoned gas wells are available. The cost of piping the carbon dioxide as a liquid or a gas to the storage areas from the areas of high fuel use must also be considered, and is estimated at $1.00 for 100 miles for each thousand cubic feet of pumped volume. The cost to a utility for scrubbing flue gases to remove the carbon dioxide, transporting the CO_2 100 miles to a well, compressing and injecting it into the well excavated for this purpose at a cost of $1.00 per equivalent barrel has been estimated to add 37 mills per killowatt-hour to the cost of electricity as shown in Table 4. The cost of CO_2 recovery by absorption[20] is estimated at 15.5 mills/KWH, the compression and transport add 11.1 mills/KWH and the salt mining another 10.6 mills/KWH for a 1000 MW(e) coal-fired plant. The cost of power from a conventional coal-burning power plant is estimated to be 45 mills/KWH[21] at 1981 costs. The removal, recovery and storage of CO_2 could, therefore, almost double the cost of producing electrical power. It should be noted that the salt excavation costs alone amounts to about 13% of the total power cost with removal and storage of CO_2. The removal, and recovery of CO_2 from the power plant amounts to 32% of the total power cost.

Estimates[11] of the increasing production rate of CO_2 due to increase of fossil fuel use for the years through 2020 are shown in Table 5 for industrial and utility emissions in the U.S. The number of years of CO_2 storage volume available from oil wells, gas wells, and salt domes, separately, is tabulated. As the CO_2 production increases, the storage time available decreases rapidly. This is shown in graphical form in Figure 9 for the total CO_2 production in the U.S., as well as combined industrial and utilities production of CO_2.

Conclusions

Limiting the emission of CO_2 to the atmosphere from fossil fuel power plants is technically feasible. At the current rate of production, the use of gas wells for storage offers a short term solution (several years duration) to the steadily increasing CO_2 content of the atmosphere. A combination of fractional storage in all three storage volumes, oil and gas wells and excavated salt domes is a possible means of extending the lifetime of these sites for storage and controlling the CO_2. The intermediate term, from the year 2000 to 2050, requires the storage of larger volumes of CO_2 and would use excavated salt domes as possible storage sites. The cost of CO_2 scrubbing, compression, transporting and storage is relatively high because of the large volumes of gas involved. It is estimated that the cost of electrical power production would nearly double if this means of controlling CO_2 would be implemented.

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Table 1

U.S. Reserve Volumes of Gas, Oil and Coal with the Volume of CO_2 and Generated Compressed into Liquid Form

	Natural Gas	Petroleum Oil	Bituminous Coal
Approx. U.S. Fuel Reserve Volume ft^3	2×10^{12}	2×10^{11}	2×10^{13}
Volume of CO_2 generated ft^3*	1×10^{12}	10×10^{11}	13×10^{13}
Fraction of CO_2 Volume that can be stored in each reserve	2	0.2	0.15

*Liquid CO_2 at 1000 psia and 80°F

Table 2

Salt Dome Volume Available Compared to Total Volume of CO_2 Generated from All Fossil Fuel Sources in the U.S.

	Vol. 10^{14} ft^3
Gulf Coast Salt Dome Volume*	1.0
Other U.S. Salt Basin Volumes*	15.0
Total	16.0
Volume of Liquid CO_2 Generated from Total U.S. Fuel Reserve	
Natural Gas	0.01
Petroleum Oil	0.01
Bituminous Coal	1.30
Total	1.32

*Based on excavation down to 10,000 ft in salt domes and 100 foot depth of a single rock salt layer covering the basin area.

Table 3

Duration of Well and Dome Capacity for Carbon Dioxide Storage, from Various Source Sectors in the U.S.A. in 1980

Source Sector	Annual Carbon Consumption 10^8 Metric Tons	Duration of Storage Capacity[3]		
		Oil Wells yrs	Gas Wells yrs	Salt Domes[1] yrs
Residential	1.5	6.3	63	315
Commercial	0.9	10.2	102	510
Industrial	3.0	3.2	32.0	160
Electric Utilities	4.1	2.3	23	115
Transportation	3.8	2.5	25	125
Total	13.3	0.72	7.2	36
Combined Industrial and Electrical Utilities[2]	7.1	1.3	13.0	65

Assumptions:

1) 10% of total Gulf States Salt Domes volume (0.1×10^{14} ft^3) excavated for storage.

2) Assume removal and storage of only concentrated sources of CO_2 from Industrial and Electric Utilities effluent which represents about 50% of the total U.S. carbon consumption.

3) Stored as liquid CO_2: 42 lb/ft^3 at 1000 psia and 80^oF.

Table 4

Cost of CO_2 Removal and Storage* from the Flue Gas of a 1000 MW(e) Coal-fired Power Plant

	mills/KWH
CO_2 absorption by MEA or K_2CO_3	15.5
Compression and liquefaction of CO_2	6.0
Pipeline Transport of CO_2 for 100 miles to storage site	5.1
Excavation of Salt Cavern for Storage of CO_2 (at $1/bbl)	10.6
Total Cost for Removal and Storage	37.2
Cost of Power Produced in a Conventional Power Plant with No Environmental Control Technology (1981)	45.0
Total Power Cost with Environmental Control Technology	82.2

*Assumptions used in calculations: 15% depreciation per year on capital equipment; 80% Power Plant Operating Factor; Maintenance and Labor at 20% of Depreciation; Solution Mining of Salt at a minimum cost of $1 per barrel of volume.

Table 5

Estimated Capacity for Storage of Liquid CO_2 from Industrial and Utility Emissions in Oil and Gas Wells and Excavated Salt Domes

Year	1980	1985	1990	2000	2020
Annual Production Rate of CO_2 in 10^8 metric tons C	7.1	8.1	8.9	10.9	18.3
	Number of Years of CO_2 Storage Capacity				
Total U.S. Oil Well Volume	1.3	1.2	1.1	0.9	0.5
Total U.S. Gas Well Volume	13.1	12	11	9	5
Gulf Coast Salt Domes*	65	60	55	45	25
Excavation Cost for Salt*	$\$22 \times 10^9$	$\$30.3 \times 10^9$	$\$33.2 \times 10^9$	$\$40.9 \times 10^9$	$\$68.4 \times 10^9$

*Assumes 10% of salt dome volume excavated for storage at a minimum excavation of $1 per barrel.

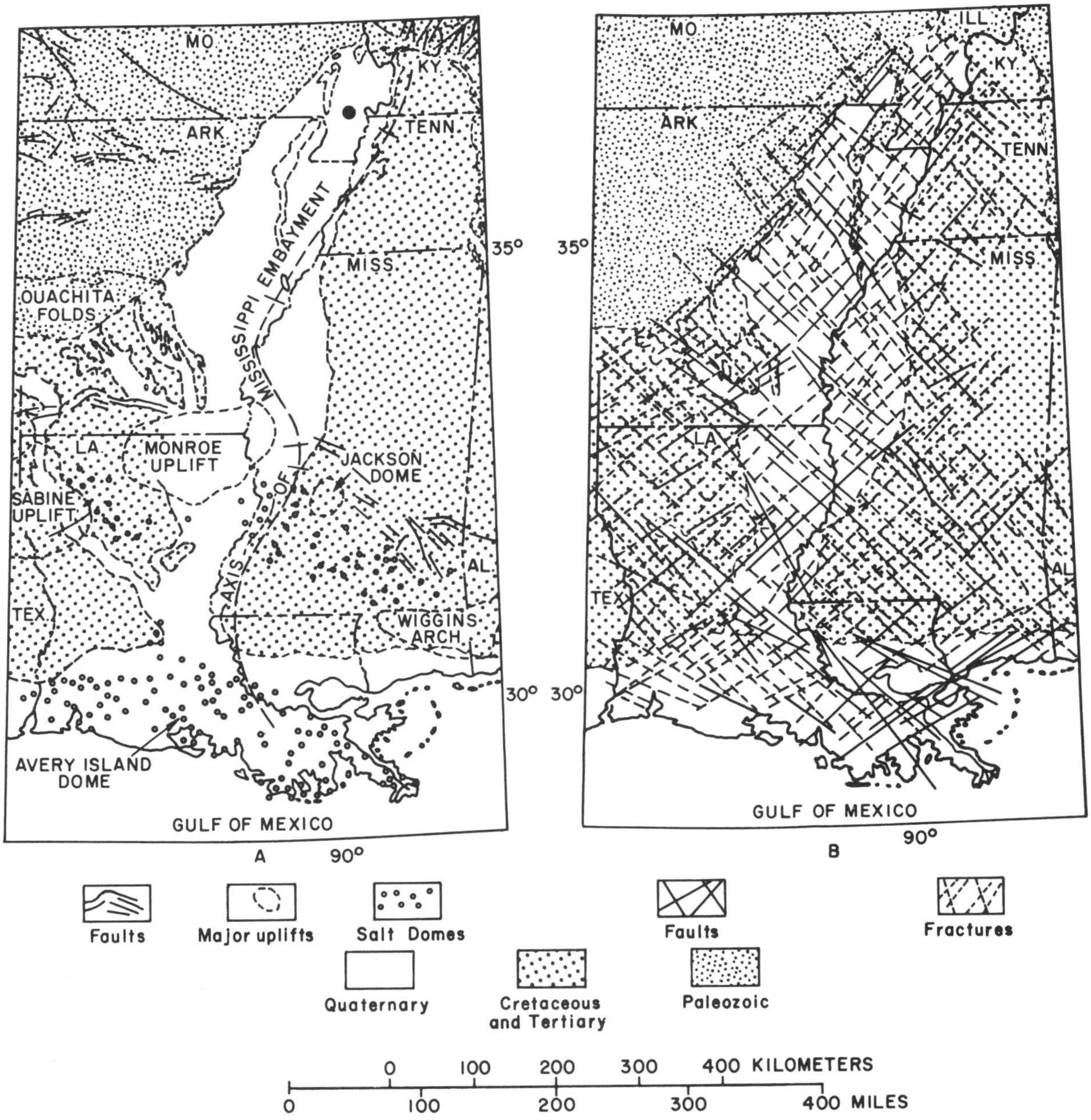

Figure 1. Maps of south-central part of Middle North America showing structures in Mississippi Embayment and Mississippi Delta. A: Structures in Tertiary and older rocks. B: Fault and fracture pattern in Quaternary and older rocks. After Fisk (1944, Figs. 5, 6, and 71).

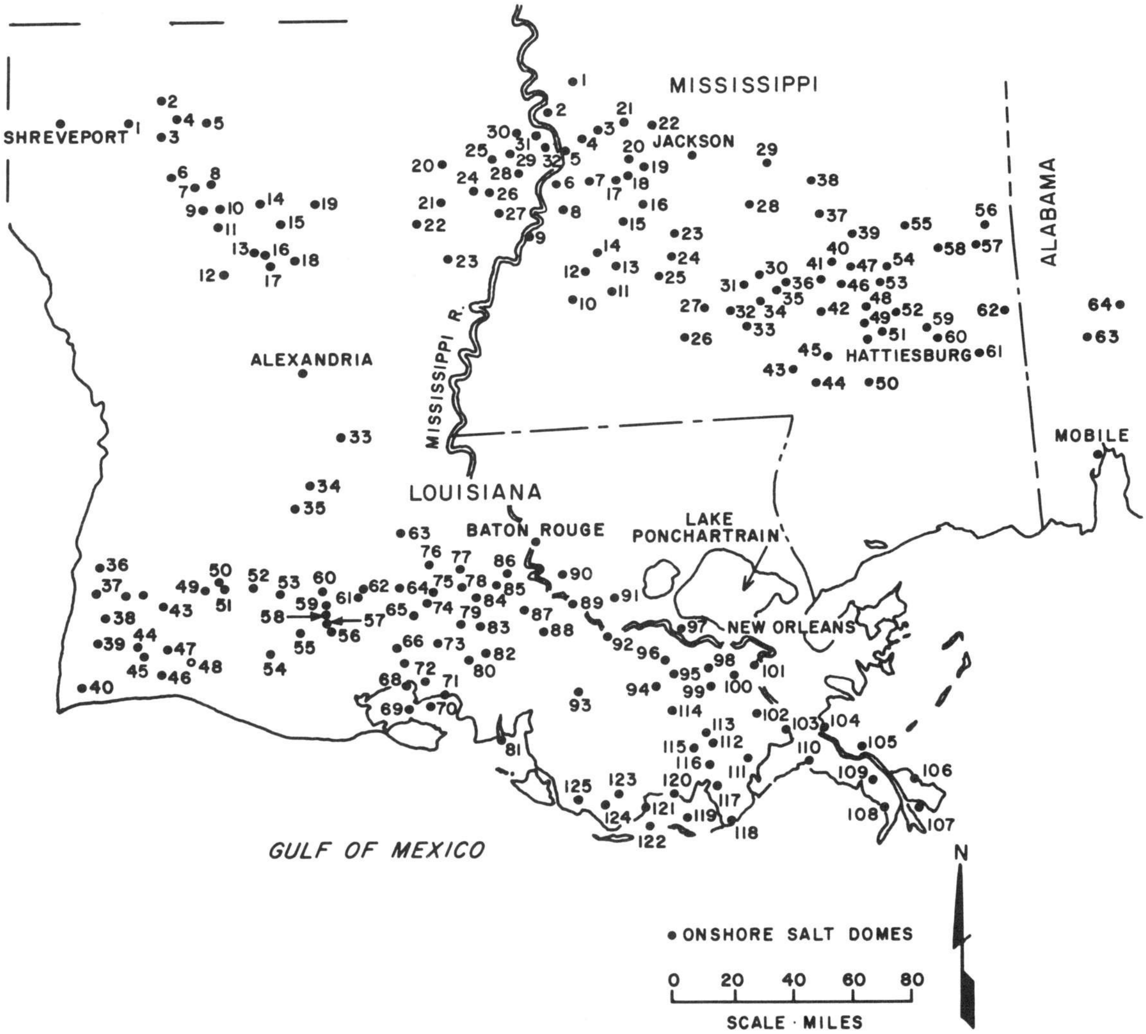

Figure 3. Location of Louisiana, Mississippi, and Alabama Salt Domes.

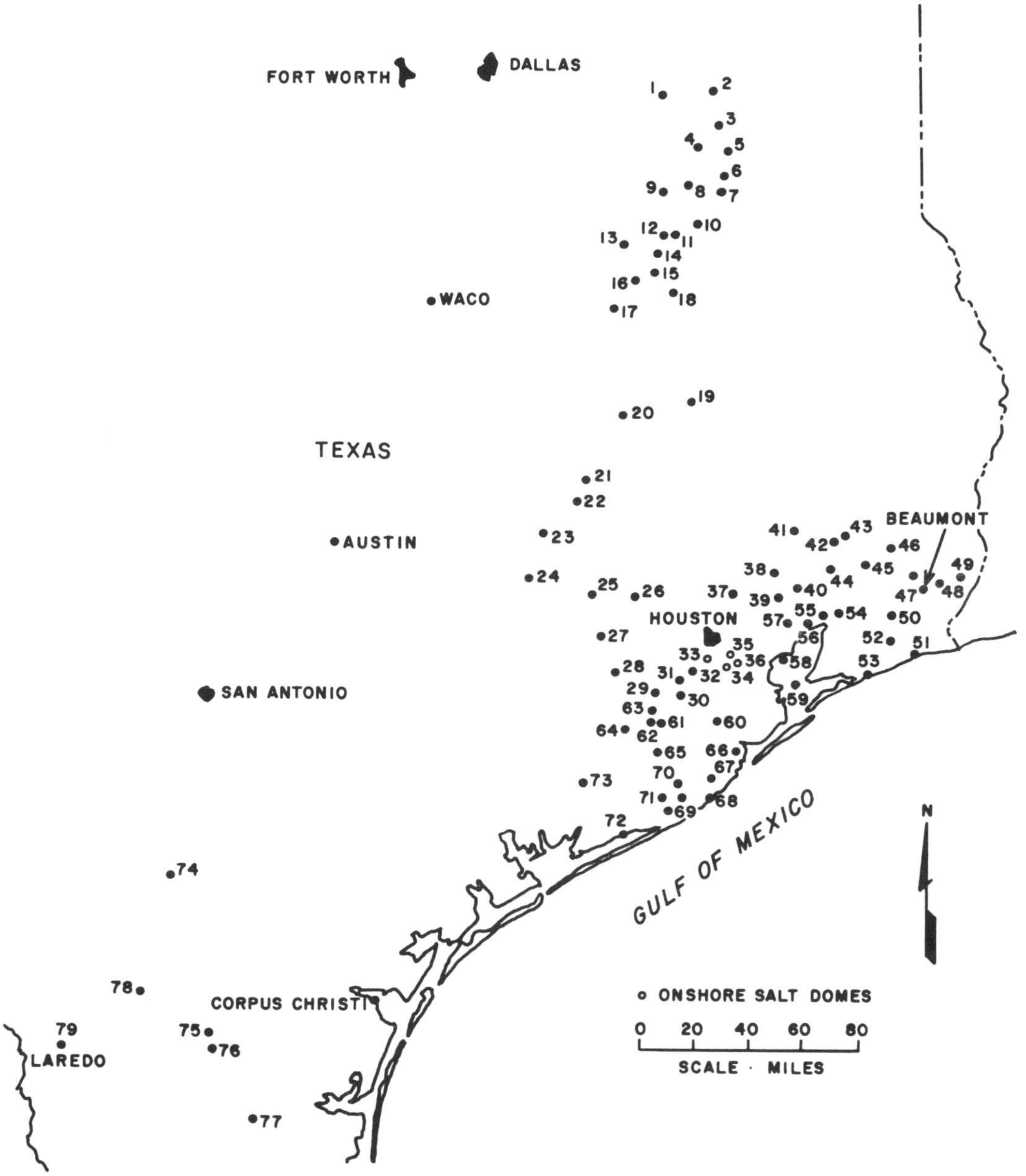

Figure 5. Location of Texas onshore salt domes.

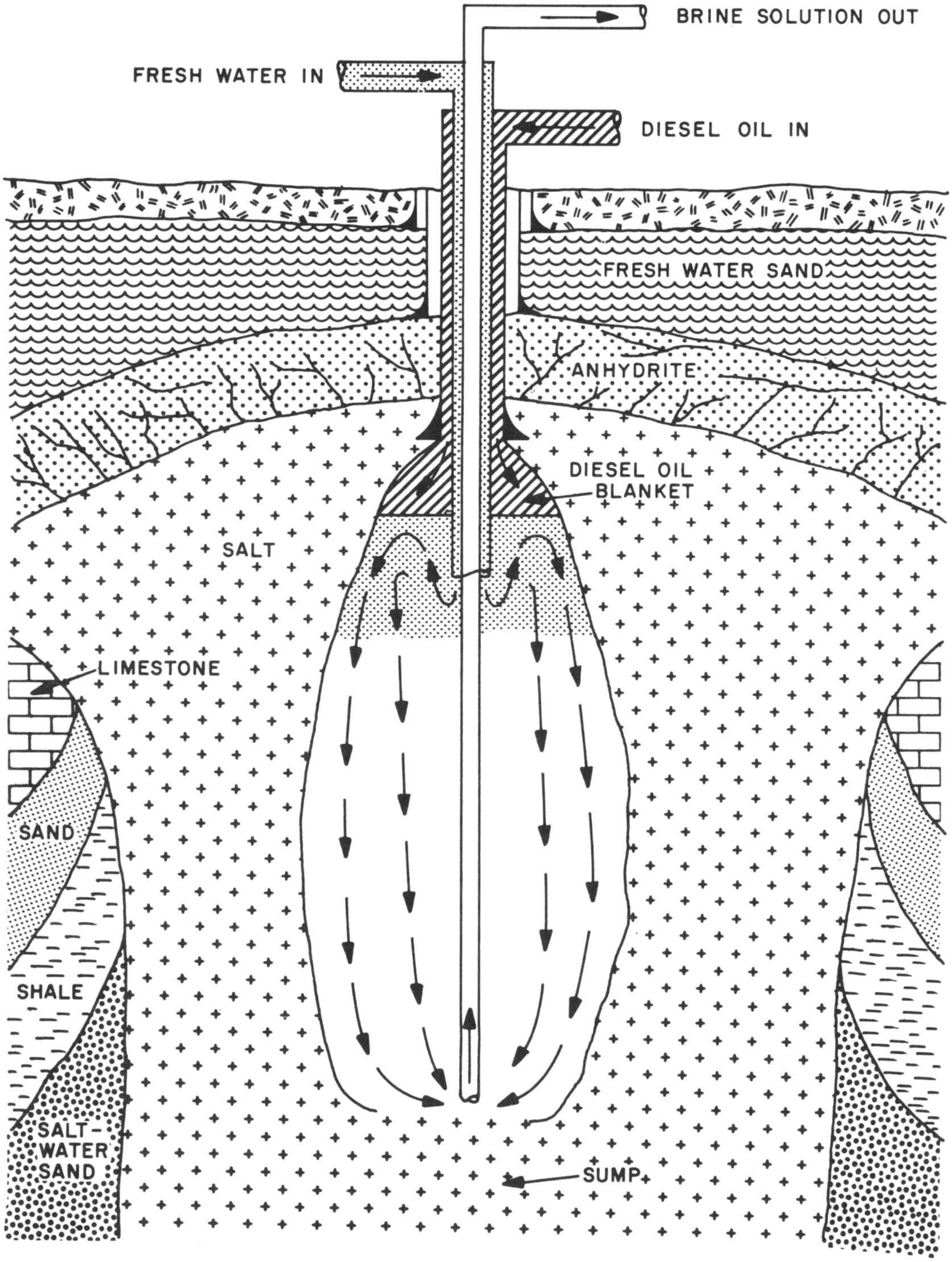

Figure 7. Schematic of a salt cavern leaching operation.

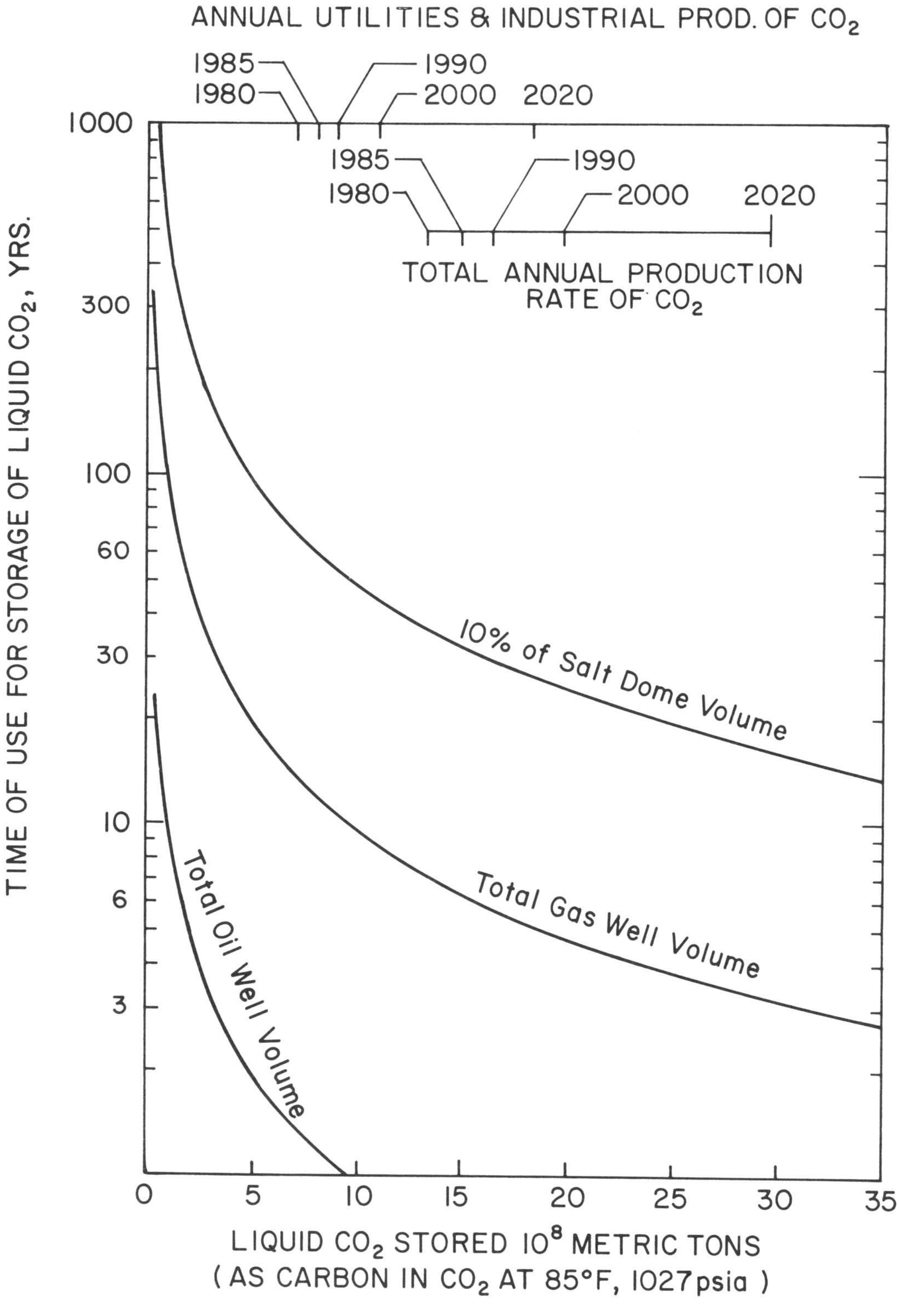

Figure 9. Storage time for liquid CO_2 in three types of reservoirs.

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