SUCCESS STORY

Oil Recovery by Carbon Dioxide Flooding

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DRAFT

It has taken over 30 years for Carbon Dioxide Flooding (CO_2 Flooding) to become a major contributor to the US oil production. The road to the current success of carbon dioxide flooding involved the cooperation of government(ERDA/DOE), universities and industry. Many of the initial problems associated with this process have been solved. New challenges have emerged, which if solved, can greatly the increase the oil recovery from current and future carbon dioxide floods. A brief history of carbon dioxide flooding is show by Table 1.

This flooding process is particularly amenable to deep low permeability reservoirs such as those located in the Permian Basin of West Texas and South Eastern New Mexico. Figure 1 shows the number of CO_2 flooding project from the 1950s until 1996. It was over 12 years from the time the first carbon dioxide paper for oil recovery was published in the late 1950s until the first major field test was started in 1971.

The oil production due to carbon dioxide flooding is over 170,000 barrels per day. There are over 300,000 acres undergoing carbon dioxide flooding. Most CO_2 flooding projects are located in the Permian Basin area. Figure 2 shows the current production due to carbon dioxide flooding in the United States and Canada.

The cumulative revenue from carbon dioxide flooding, using $20 per barrel as an average oil price, is approaching 6 billion dollars as shown by Figure 3. There was no significant production from carbon dioxide flooding until 1980.

The government has played an important part in causing carbon dioxide flooding to become commercial. Table 2 lists most of the wholly or partially funded government projects. If the government's contribution to the total revenue is estimated at only 10%, this amounts to nearly 600 million dollars (Figure 4).

New challenges have emerged, which if solved, can greatly increase the oil recovery from current and future carbon dioxide floods. Current carbon dioxide flood leaves behind a significant amount of oil. The current floods are estimated to recover only about 7.5% of the Original-Oil-In-Place (OOIP is the volume of oil in the reservoir at discovery). Assuming a 30% recovery efficiency for the primary and secondary production, this would correspond to only 11% of the Oil-In-Place (OIP is the volume of oil in the reservoir at the start of the carbon dioxide flood). An increase in the recovery efficiency from 7.5% of OOIP (11% OIP) to 30% of OOIP (43% OIP) would increase the annual production from carbon dioxide floods from 62 million barrels to nearly 250 millions barrels. This is one of the main focuses of the gas flooding research program.

Table 1

An outline of the history of gas flooding and in particular carbon dioxide.

Late 1950s	A paper was published that showed carbon dioxide to be a promising oil recovery agent.
Early 1960s	Research directed toward miscible flooding (enriched natural gas drives, wet natural gas drives, ethane, propane, butane and other solvents). Research directed toward dispersion affects, gravity effects, and miscibility correlations. Carbon dioxide was not considered a viable process due to large amount of carbon dioxide needed for field implementation.
Late 1960s	Most miscible methods were found to be uneconomic due to increased demand for natural gas, ethane, propane, and butane. Interest in using carbon dioxide increased and efforts were started to find large sources of carbon dioxide.
Early 1970s	The amount of carbon dioxide from natural gas plants and power plants was determined. The first carbon dioxide flood implemented was implemented in 1971 with the carbon dioxide source from a natural gas plant. Research focused on determining the Minimum Miscibility Pressure (MMP), effect of impurities, and phase behavior.
Late 1970s	By the end of the 1970s, nearly twenty carbon dioxide pilot and field floods were started. Research areas were Equations-of-State (EOS), reservoir simulators, rock/fluid interactions and corrosion. Pipelines were built from large natural carbon dioxide sources in New Mexico and Colorado to the Permian Basin. Carbon dioxide immiscible flooding field test were conducted.

Table 1 (Continued)

Early 1980s	Pipelines were opened to Permian Basin. Due to the low viscosity of carbon dioxide, the Mobility Control/Sweep Improvement in the field was recognized as a serious challenge. Research was initiated using foams, entrainers, or solvents. It was found Water-Alternate-Gas (WAG) good to reduce gravity segregation and improve CO2 gas handling capabilities.
Late 1980s	Oil price collapsed in the mid 1980 which caused many carbon dioxide floods to be canceled or delayed. There was a major rethinking carbon dioxide field flooding procedures. The field procedures and past research was reviewed to determine what is important to reduce the cost of carbon dioxide floods. Pipelines were not at capacity and carbon dioxide prices dropped. Reduced cost carbon dioxide floods were implemented.
Early 1990s	Relatively Low cost CO2 floods started. The reservoir sweep is still low. Field results show that better Mobility Control/Sweep Improvement and better simulation for fluid placement are needed to reduce the CO2 utilization rate.
Late 1990s	There are currently 64 carbon dioxide floods in the United States. These floods cover nearly 300,000 acres and have almost 170,000 bpd of enhanced oil production. A typical flood is recovering about 7.5% of OOIP (15% of OIP). There is a major need for better sweep improvement/mobility control and carbon dioxide placement. Improvements in sweep and mobility could increase recovery to about 30% of OOIP (43% of OIP) or more.
Early 2000s	The pipelines are nearing capacity and the cost of carbon dioxide is rising. Methods to improve reservoir sweep, mobility control, and placement of carbon dioxide in field floods are needed to decrease the carbon dioxide utilization rate.

Table 2

Listing of Carbon Dioxide Flooding Projects.

CONTRACTOR	CONTRACT		START	
Early 1970s				
WEST VIRGINIA UNIVERSITY, MORGANTOWN, WV	GRANT G0155014	CARBON DIOXIDE SOURCES	10/01/74	NOTE
GUYAN OIL COMPANY, HUNTINGTON, WV	EF-76-C-05-8024	GRIFFITNSVILLE FIELD, WEST VIRGINIA	08/28/75	1
Late 1970s				
COLUMBIA GAS TRANSMISSION CORP, CHARLESTON, WV	DE-AC05-76ET12015	GRANNY'S CREEK FIELD, WEST VIRGINIA	06/03/76	1
PENNZOIL COMPANY, PARKERSBURG, WV	DE-AC21-76ET12002	ROCK CREEK FIELD, WEST VIRGINIA	06/30/76	1
PULLMAN KELLOGG, HOUSTON, TX	E(49-18)-2515	A STUDY FOR EOR VIA CO2 INJECTION	10/13/76	
SHELL OIL COMPANY, HOUSTON, TX	DE-AC05-77ET12004	WEEK'S ISLAND "S" SAND, IBERIA PARISH, LA	06/10/77	1
WEST VIRGINIA UNIVERSITY, MORGANTOWN, WV	EF-77-S-05-5532	DET OF THE EFFECTS OF SO2 ON CO2 RECOVERY	07/01/77	
AMERON, SANTA ANA, CA {LAWRENCE-ALLISON ASSOC}	EF-77-C-03-1582	TOR BY CO2 FLOODING, LOS ANGELES BASIN	09/12/77	
PULLMAN KELLOGG, HOUSTON, TX	EX-76-C-01-2515/A003	A STUDY FOR EOR VIA CO2 INJECTION PHASE II-SUPPLY	09/29/77	
WEST VIRGINIA UNIVERSITY, MORGANTOWN, WV	EY-77-C-76-8087	DET TEST AND PHASE BEHAVIOR APPALACHIAN CRUDE CO2	06/01/78	
LOUISIANA STATE UNIVERSITY, BATON ROUGE, LA	DE-AS21-78ET13387	ENHANCED OIL RECOVERY THROUGH USE OF CO2	07/07/78	
UNIVERSITY OF SOUTHERN CALIFORNIA, LOS ANGELES, CA	EY-76-S-03-0113	CARBON DIOXIDE DISPLACEMENT OF RESIDUAL CRUDE OIL	08/28/78	
SUMX CORPORATION	EW-78-C-21-8442	CO2 CORROSION PROBLEMS	09/22/78	
UNIVERSITY OF SOUTHERN CALIFORNIA, LOS ANGELES, CA	ET-78-C-05-5785	DATA BASE ON THE CO2 MISCIBLE FLOODING PROCESS	09/28/78	
UNIVERSITY OF ALABAMA, TUSCALOOSA, AL	ET-78-S-01-3250	MICROSCOPIC STUDY OF OIL RECOVERY BY CO2	10/01/78	
GRUY FEDERAL, INC., HOUSTON, TX	DE-AC21-79MC08341	TARGET RESERVOIRS FOR CO2 MISCIBLE FLOODING	02/12/79	
TEXAS A&M RESEARCH FOUNDATION	DE-AC21-79MC10509	OIL FROM SUBSURFACE RESERVOIRS WITH CO2	02/23/79	
GULF OIL EXT AN PROD CO. OKLAHOMA CITY, OK	DE-AC21-79MC08383	LITTLE KNIFE FIELD, BILLINGS COUNTY, ND	07/17/79	1
RENSSELAR POLYTECHNIC INSTITUTE, TROY, NY	DE-AC21-79MC11580	EFFECTS OF POROSITY TYPE ON TERTIARY RECOVERY	08/31/79	
WEST VIRGINIA UNIVERSITY, MORGANTOWN, WV	DE-AT21-79MC11284	PHASE BEHAVIOR HO APPALACHIAN CRUDE - MIXTURES	09/28/79	
NM INSTITUTE OF M & T, SOCORRO, NM	DE-AC21-79MC10689	MOBILITY CONTROL IN CO2 EOR PROCESS	09/29/79	
NEW MEXICO STATE UNIVERSITY, LAS CRUCES, NM	DE-AC21-79MC10865	CO2 FORMATION DAMAGE STUDY	09/29/79	
UNIVERSITY OF KANSAS, LAWRENCE, KS	DE-AC19-79BC10122	DEV OF A METHOD FOR EVALUATING CO2 MISCIBLE FLOODS	10/01/79	
Early 1980s				
NM INSTITUTE OF M & T, SOCORRO, NM	DE-AS19-80BC10331	DISPLACEMENT OF OIL BY CO2	09/01/80	
LOUISIANA STATE UNIVERSITY, BATON ROUGE, LA	DE-AC19-80BC10344	INVESTIGATION OF EOR THROUGH THE USE OF CO2	10/01/80	
NEW MEXICO STATE UNIVERSITY, LAS CRUCES, NM	DE-AC21-78MC03259	EOR BY CO2 FOAM FLOODING	11/01/80	
COLORADO STATE UNIVERSITY, FORT COLLINS, CO	DE-AC19-81BC10640	COMPUTER SIMULATION OF RECOVERY CYCLIC HEAVY OIL	03/01/81	
NM INSTITUTE OF M & T, SOCORRO, NM	DE-AC21-81MC16426	MOBILITY CONTROL FOR CO2 INJECTION	05/20/81	
UNIVERSITY OF ALABAMA, TUSCALOOSA, AL	DE-AC21-81MC16140	DETERMINATION OF MMP BY DIRECT OBSERVATION	07/07/81	
NEW MEXICO STATE UNIVERSITY, LAS CRUCES, NM	DE-AC21-81MC16551	EOR BY CO2 FOAM FLOODING	09/01/81	
NIPER, BARTLESVILLE, OK	METC-6-891	LIGHT OIL GAS MISCIBLE DISPLACEMENT PROJECT	10/01/83	
NIPER, BARTLESVILLE, OK	DE-FC22-83FE60149/OE4	DEV OF IMPROVED IMMISCIBLE GAS DISP - OE4	10/01/83	
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY, SOCORRO, NM	DE-FC21-84MC21136	IMPROVEMENT OF CO2 FLOOD PERFORMANCE	04/01/84	
UNIVERSITY OF WYOMING, LARAMIE, WY	DE-AC21-84MC21207	NEW CONCEPTS FOR IMP OIL RECOVERY IN CO2 FLOODING	09/01/84	

LEWIN AND ASSOCIATES, INC., WASHINGTON, DC	DE-AC21-84MC21138	DEVELOPMENT OF A MODIFIED BLACK OIL SIMULATOR		09/26/84
NIPER, BARTLESVILLE, OK	DE-FC22-83FE60149/BE05A	GAS FLOODING	- BE05A	10/01/84
NIPER, BARTLESVILLE, OK	DE-FC22-83FE60149/BE05B	MOBILITY CONTROL AND SWEEP IMPROVEMENT IN GAS FL	- BE50B	10/01/84
METC, MORGANTOWN, WV	9-891	EOR GAS FLOODING AT METC		01/01/85
METC, MORGANTOWN, WV	9-891/SA-13	ENHANCED OIL RECOVERY SYSTEMS ANALYSIS		01/01/85
METC, MORGANTOWN, WV	9-891/WT	EOR MODEL DEVELOPMENT AND VALIDATION		01/01/85
METC, MORGANTOWN, WV	9-891/TF	ENHANCED OIL RECOVERY RESEARCH LABORATORY		01/01/85
WEST VIRGINIA UNIVERSITY, MORGANTOWN, WV	DE-AC21-85MC22044	IMPROVED CO2 EOR MOBILITY CONTROL - IN-SITU PREC.		09/01/85
STANFORD UNIVERSITY, STANFORD, CA	DE-AC21-85MC22042	RESERVOIR CHARACTERIZATION FOR CO2 FLOODING		09/17/85
Late 1980s				
UNIVERSITY OF ALASKA, FAIRBANKS, AK	DE-FG21-86FE61114	DEVELOPMENT OF EFFECTIVE GAS SOLVENTS - CO2		09/06/86
LOUISIANA STATE UNIVERSITY, BATON ROUGE, LA	DE-FG22-89BC14204	CYCLIC CO2 INJECTION FOR LIGHT OIL RECOVERY		11/21/88
STANFORD UNIVERSITY, STANFORD, CA	DE-AC21-89MC26253	SCALE-UP OF MISCIBLE FLOOD PROCESSES		07/20/89
TEXAS A & M UNIVERSITY, COLLEGE STATION, TX	DE-FG22-89BC14444	OII REC ENHANCEMENT FROM FRACTURED LOW K RESERVOIR-	ANNEX IV	09/01/89
JOHNS HOPKINS UNIVERSITY, BALTIMORE, MD	DE-AC22-89BC14200	STAT DESIGNED STUDY OF THE VAR AND PARM OF CO2 EOS		09/29/89
NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY, SOCORRO, NM	DE-AC21-89MC26031	FIELD VERIFICATION OF CO2-FOAM		09/30/89
Early 1990s				
STANFORD UNIVERSITY, STANFORD, CA	DE-FG22-92BC14852	SCALE-UP OF MISCIBLE FLOOD PROCESSES		09/30/92
TEXACO EXPLORATION AND PRODUCTION, HOUSTON, TX	DE-FC22-93BC14960	POST WATERFLOOD CO2 MISCIBLE FLOOD IN A LO FLUVIAL RESERVOIR		06/01/93 2
K&A ENERGY CONSULTANTS, TULSA, OK	DE-FG03-93ER81550	TRANSPORTING MOBILITY CONTROL AGENTS TO HIGH PERM ZONES		09/08/93
BDM-OKLAHOMA, BARTLESVILLE, OK	DE-AC22-94PC91008/15034	MOBILITY CONTROL, PROFILE MODIFICATION AND SWEEP	- TASK 2.4	01/01/94
BDM-OKLAHOMA, BARTLESVILLE, OK	DE-AC22-94PC91008/15034	GAS FLOODING PERFORMANCE PREDICTION IMPROVEMENT	- TASK 2.3	01/01/94
TEXACO EXPLORATION AND PRODUCTION, HOUSTON, TX	DE-FC22-93BC14986	CO2 HUFF-N-PUFF PROCESS		02/10/94 3
BDM-OKLAHOMA, BARTLESVILLE, OK	DE-AC22-94PC91008/95-A03	EXTRACTION RESEARCH - IMPROVED RECOVERY PROCESSES -	SUB	02/28/94
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY, SOCORRO, NM	DE-FG22-94BC14977	IMPROVED EFFICIENCY OF MISCIBLE CO2 FLOODS		03/31/94
FINA, USA, MIDLAND, TX 79705	DE-FG22-93BC14989	APPLICATION OF INTEGRATED RESERVOIR MANAGEMENT FOR INFILL		06/13/94 3
PHILLIPS PETROLEUM COMPANY, BARTLESVILLE, OK	DE-FC22-93BC14991	CO2 FLOOD UTILIZING ADVANCED RC AND HW INJECTION WELLS		06/30/94 3
OXY USA, INC., MIDLAND, TX 79710	DE-FG22-93BC14990	APPLICATION OF RESERVOIR CHARACTERIZATION AND ADVANCED TECH		08/03/94 3
BDM-OKLAHOMA, BARTLESVILLE, OK	DE-AC22-94PC91008/95-A03	EXTRACTION RESEARCH - IMPROVED RECOVERY PROCESSES -	TASK 9	10/01/94
PARKER & PARSLEY DEVELOPMENT, MIDLAND, TX 79701	DE-FG22-95BC14942	ADVANCED RESERVOIR CHARACTERIZATION AND CO2-GRAVITY DRAINAGE		07/24/95 4
BDM-OKLAHOMA, BARTLESVILLE, OK	DE-AC22-94PC91008/95-A03	EXTRACTION RESEARCH - IMPROVED RECOVERY PROCESSES -	TASK 5	10/01/95
Late 1990s				
CHEVRON USA INC., BAKERSFIELD, CA	DE-FG22-95BC14938	ADVANCED RESERVOIR CHARACTERIZATION IN THE ANTELOPE SHALE		02/12/96 4
STANFORD UNIVERSITY, STANFORD, CA	DE-FG22-96BC14851	GAS INJECTION PERFORMANCE FOR HETEROGENEOUS RESERVOIRS		09/30/96
BDM-OKLAHOMA, BARTLESVILLE, OK	DE-AC22-97PC91008/97-A03	EXTRACTION RESEARCH - IMPROVED RECOVERY PROCESSES -	TASK 5	10/01/97
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY, SOCORRO, NM	DE-FG22-97BC15047	MISCIBLE CO2 FLOOD EFFICIENCY IN HETEROGENEOUS RESERVOIRS		0X/XX/97

NOTES:

1 Field Demonstration
2 Class 1 Project
3 Class 2 Project
4 Class 3 Project

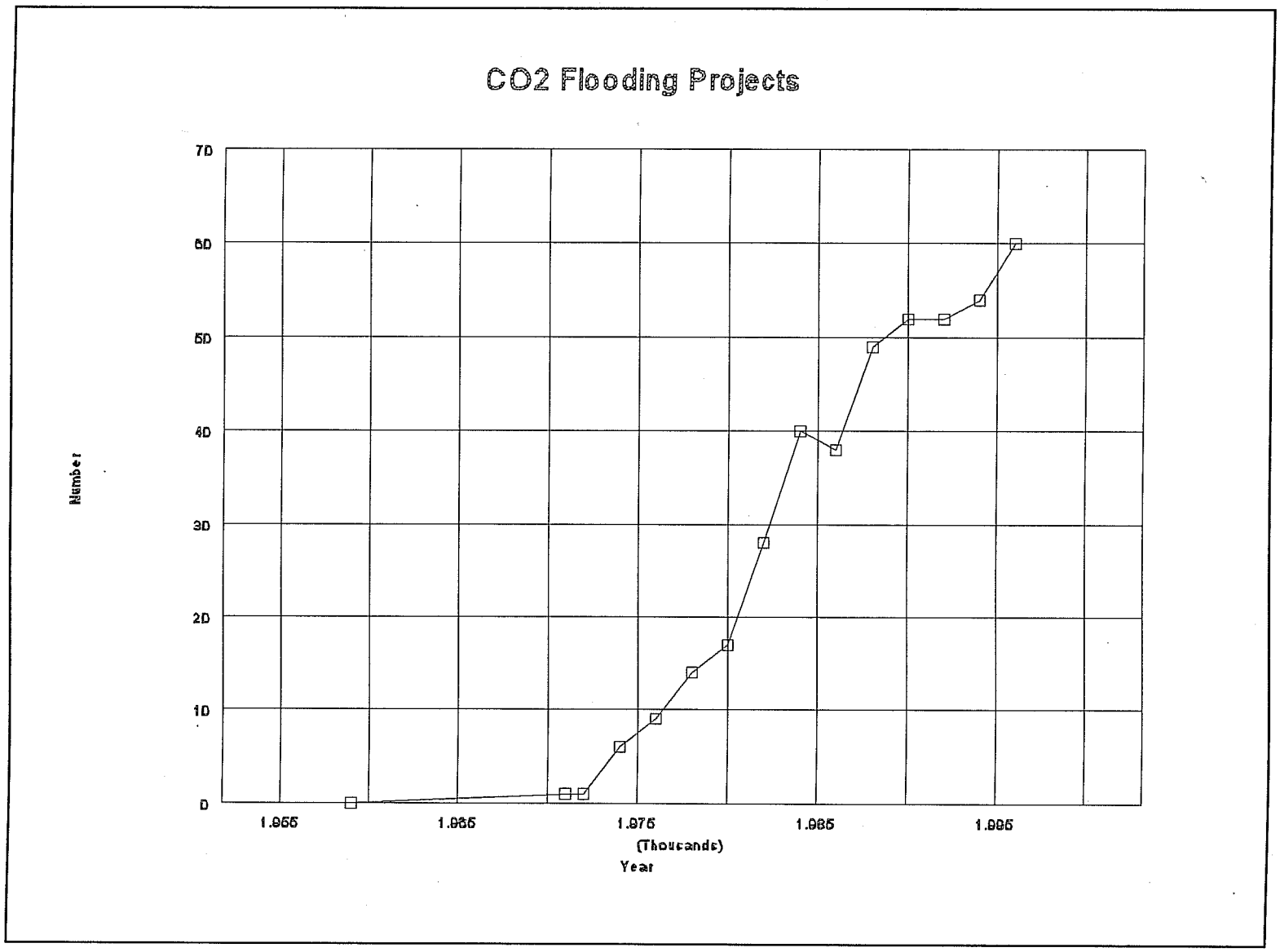


Figure 4

The number of Carbon Dioxide Projects is Increasing

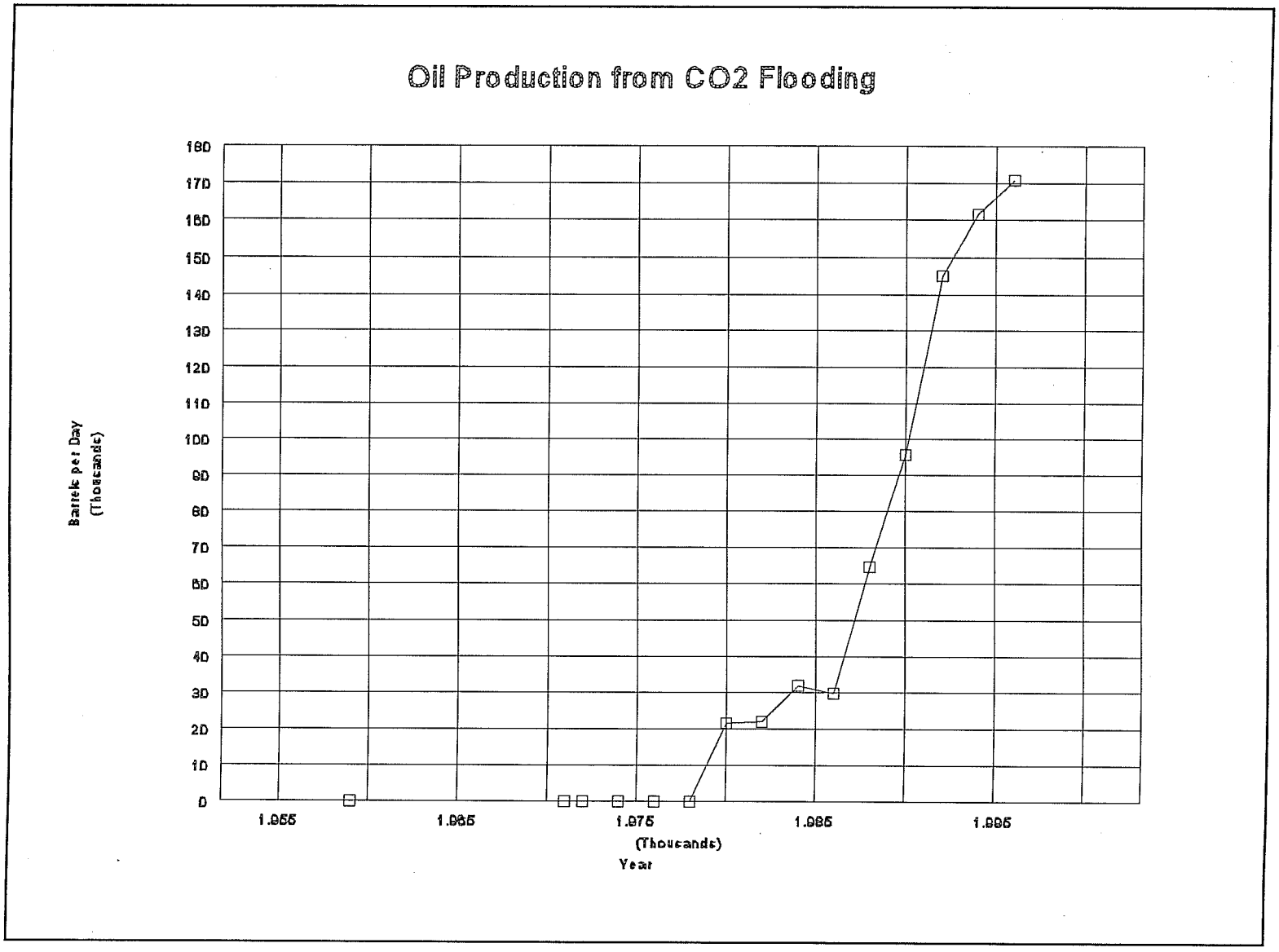


Figure 5

Daily Oil Production from Carbon Dioxide Flooding

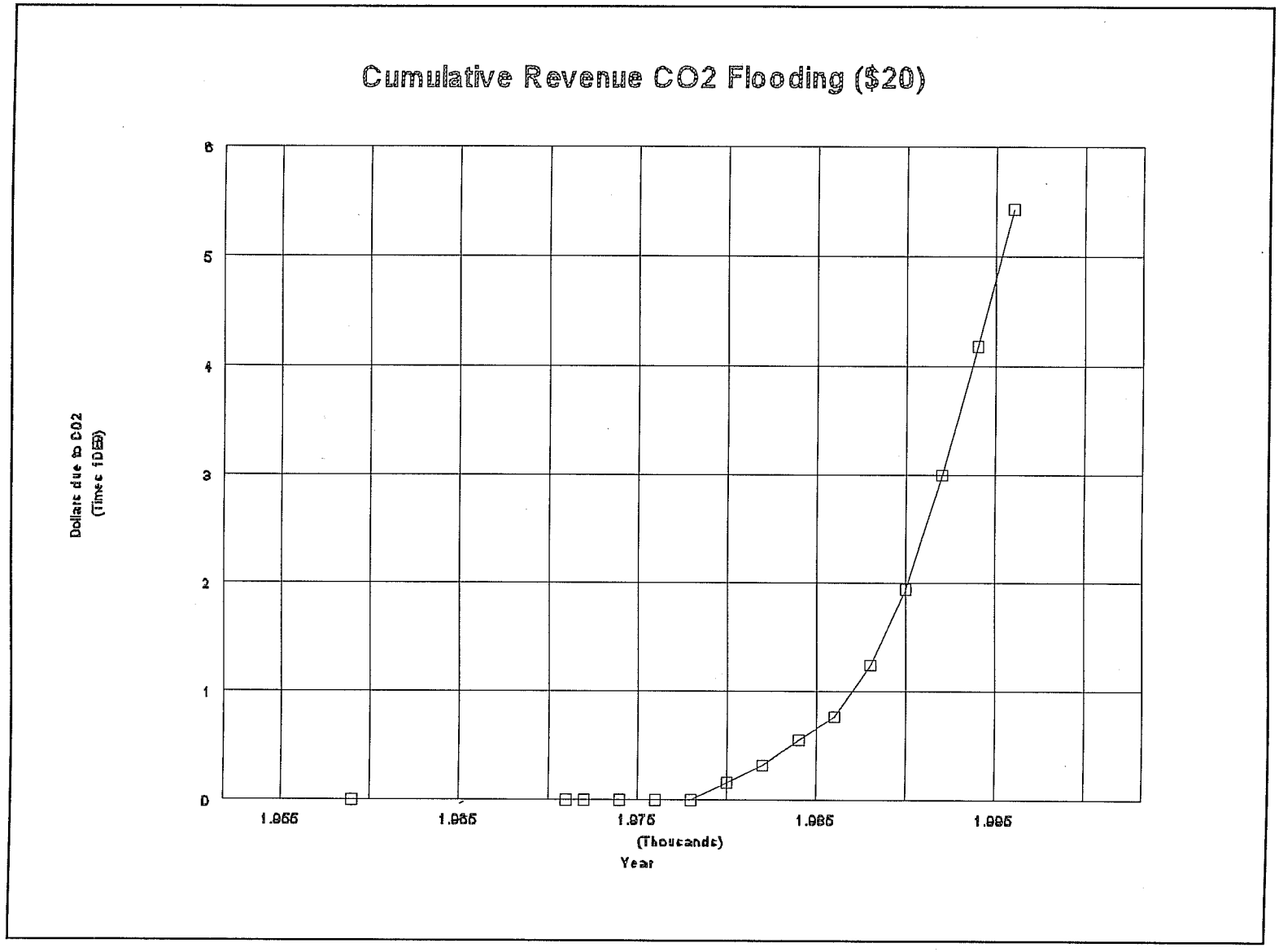


Figure 6

Cumulative Revenue from Carbon Dioxide Flooding at $20 per Barrel from 1955-1996.

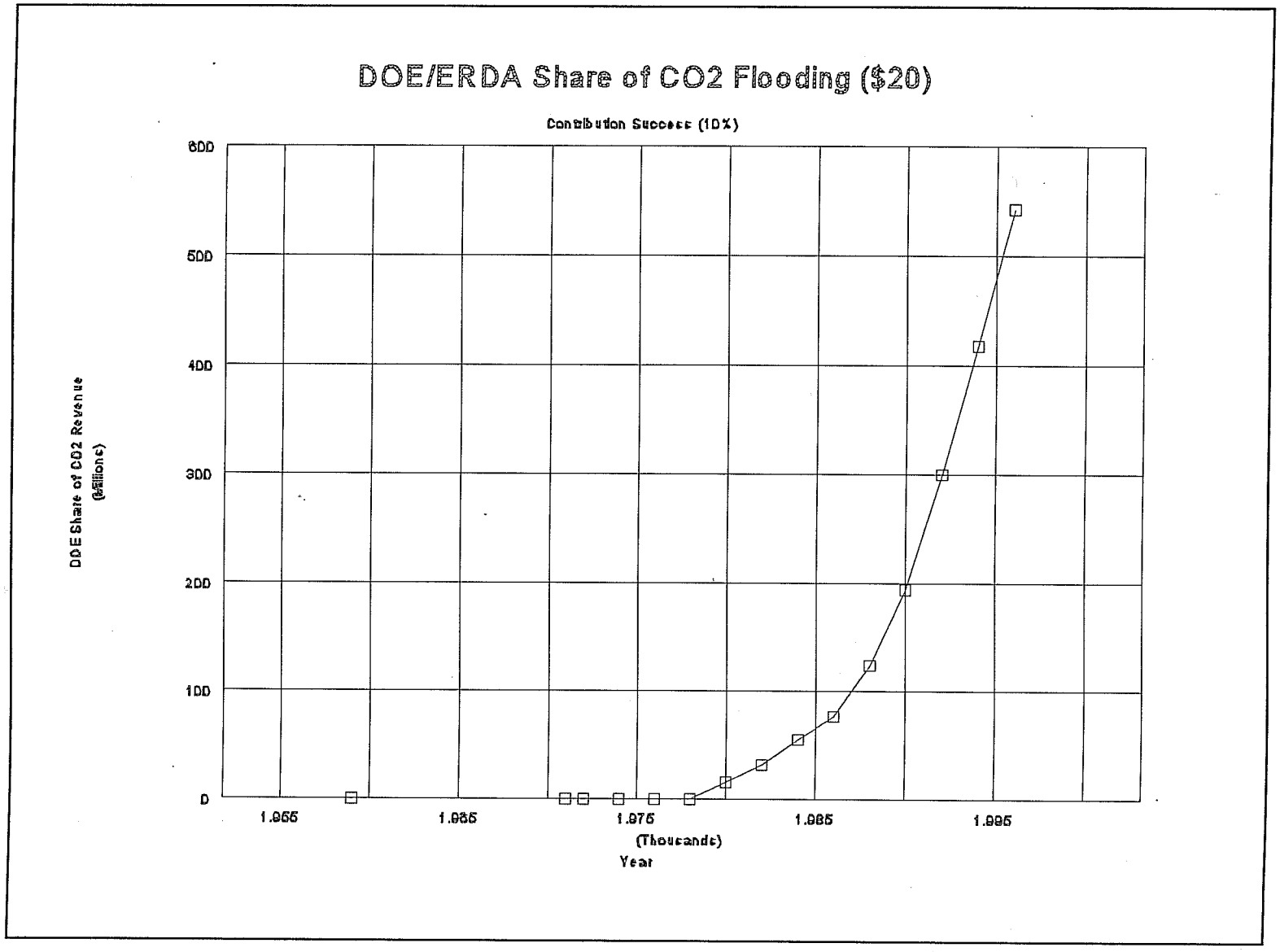


Figure 7

DOE contribution to Carbon Dioxide Flooding assuming a 10% Rate

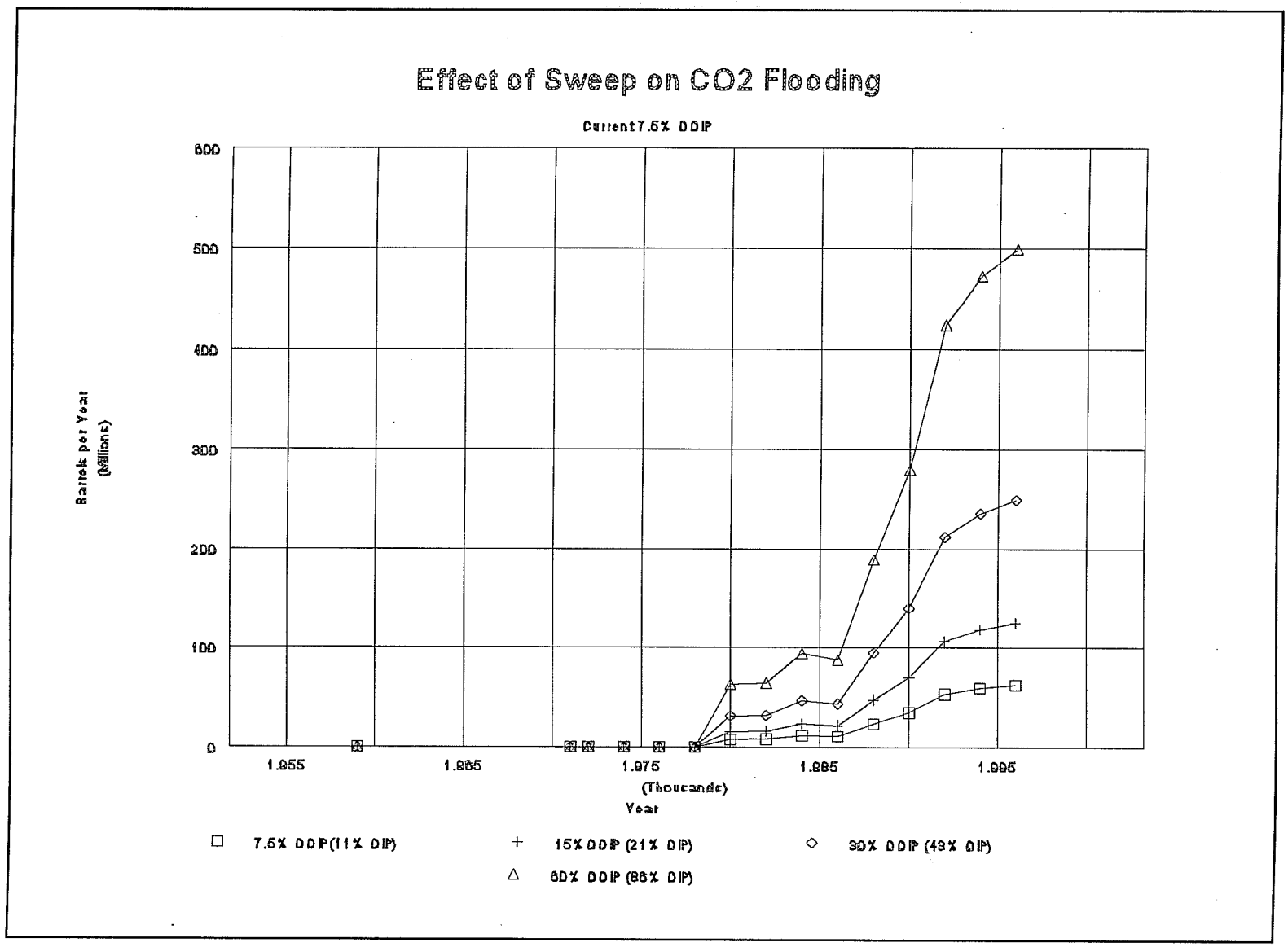
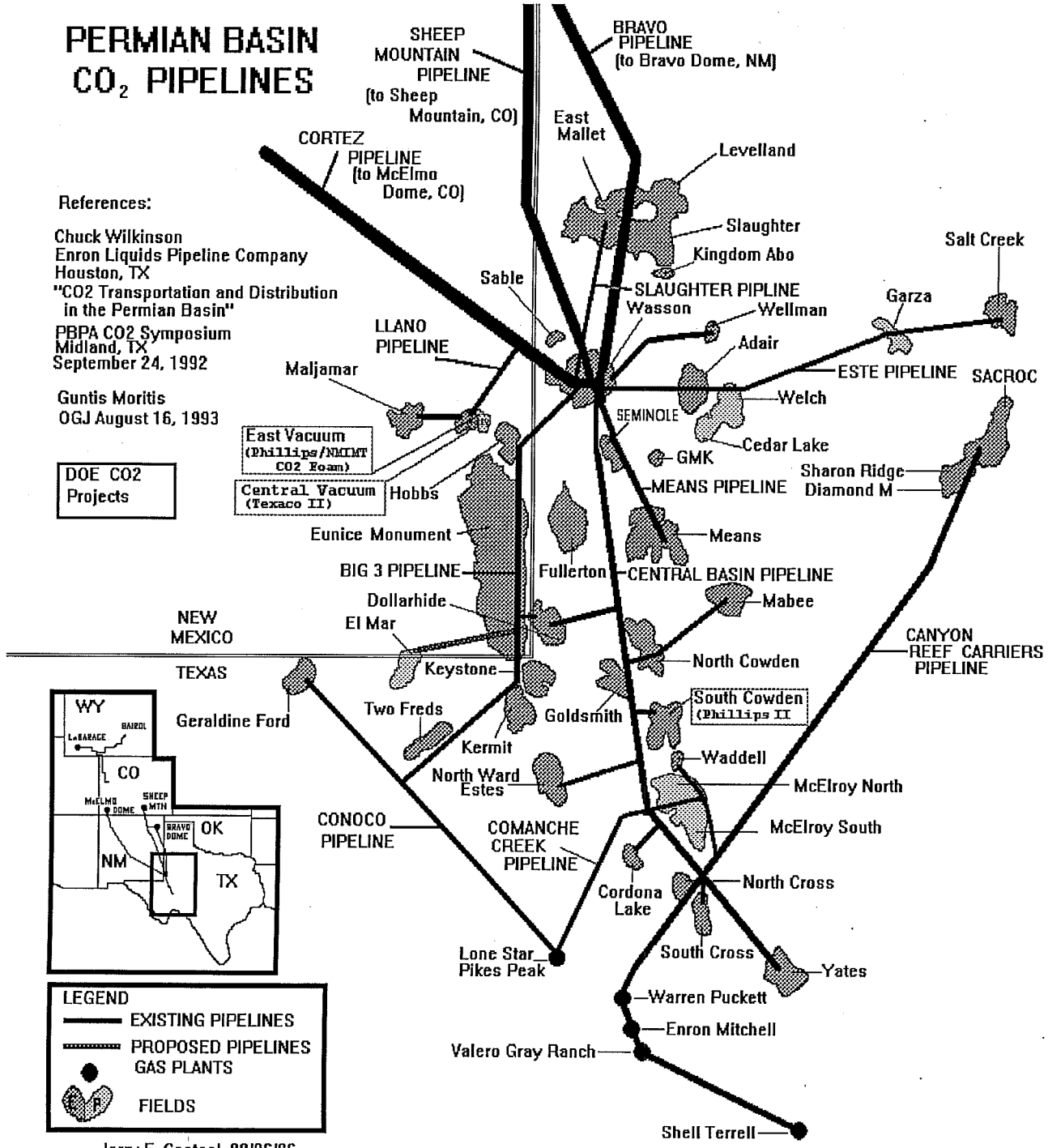


Figure 8

Improvement in Oil Recovery due to Improving Sweep Efficiency

PERMIAN BASIN CO_2 PIPELINES



References:

Chuck Wilkinson
Enron Liquids Pipeline Company
Houston, TX
"CO2 Transportation and Distribution in the Permian Basin"
PBPA CO2 Symposium
Midland, TX
September 24, 1992

Guntis Moritis
OGJ August 16, 1993

DOE CO2 Projects

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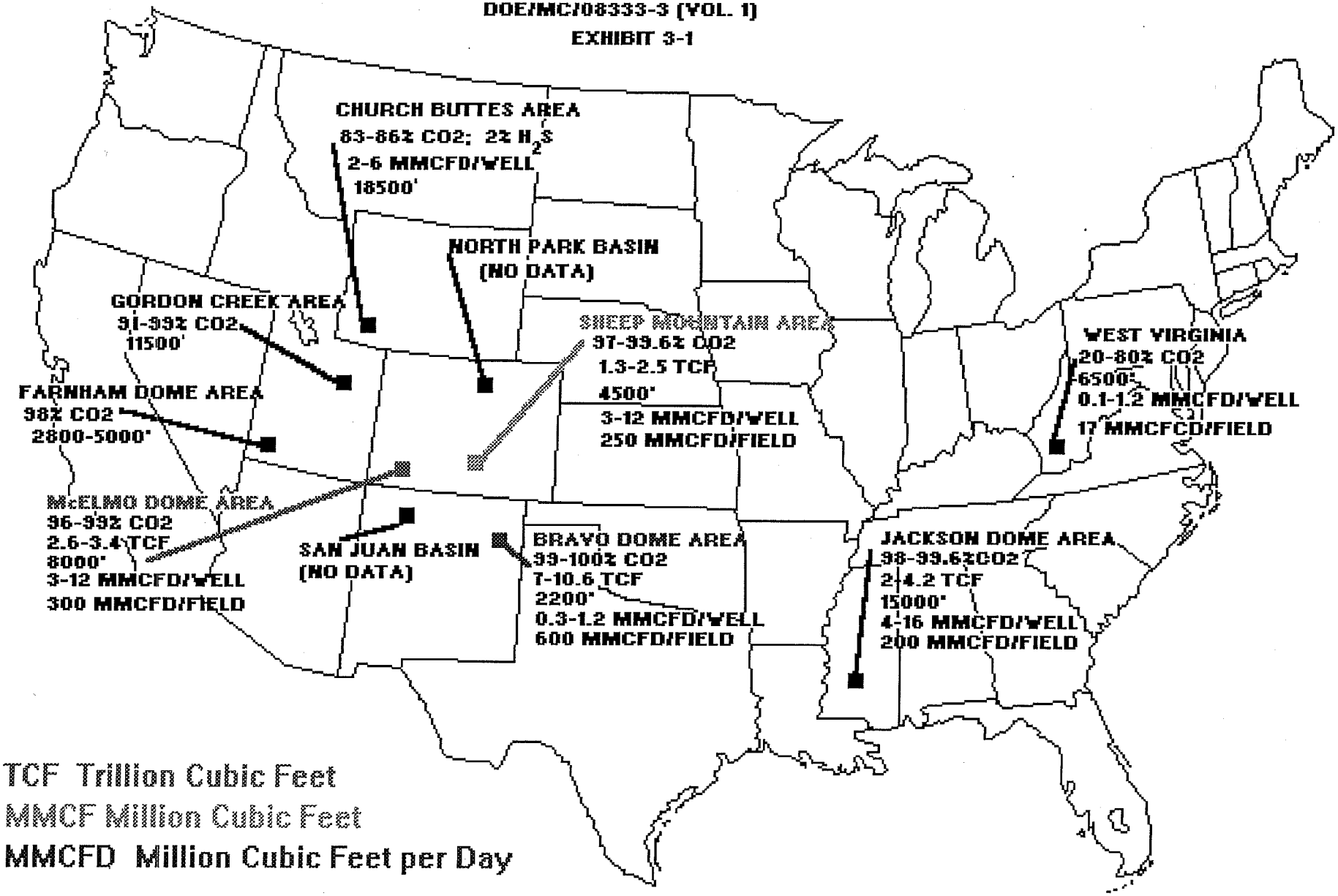
Natural Carbon Dioxide Sources

DOE/MC/08333-3 (VOL. 1)

EXHIBIT 3-1



TCF Trillion Cubic Feet

MMCF Million Cubic Feet

MMCFD Million Cubic Feet per Day

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