DOE/EIA-0183/11
DIST.CAT.UC-92

Technical Report

Projections of Enhanced Oil Recovery 1985-1995

TR/ES/79-30

September 1979

Prepared by: Joan Heinkel
Oil and Gas Analysis Division
Office of Energy Source Analysis

U.S. Department of Energy
Energy Information Administration
Assistant Administrator for Applied Analysis
Washington, D.C. 20461

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PREFACE

This report was prepared to support the EIA Annual Report to Congress 1978, and the National Energy Plan II concerning oil recovery from enhanced recovery methods.

The projections presented in this paper were developed using the Enhanced Oil Recovery model developed by Lewin and Associates.

The author wishes to thank Vello Kuuskraa, John Muller and Edgar Hammershaimb of Lewin and Associates for the support provided in developing these estimates. Secretarial support was provided by Patricia Foreman and Monica Bradley.

Further Information and Comments

Richard O'Neill
Director, Oil and Gas Analysis
Office of Energy Source Analysis
Room 4447
12th and Pennsylvania Avenue, NW
Washington, DC 20461
(202) 633-9108

For copies of this report contact:

National Energy Information Center
1726 M Street, NW
Room 850
Washington, DC 20461
(202) 634-5694

EXECUTIVE SUMMARY

Currently, oil production using enhanced oil recovery (EOR) methods supplies 373,000 barrels per day or about 5 percent of total U.S. production. Approximately 250,000 barrels per day of the production is obtained using steam drive and steam soak, processes which are being commercially applied. The remaining 123,000 barrels per day are from techniques which are still in the initial stages of development. The purpose of this paper is to provide estimates of the production potential from thermal recovery methods, miscible and immiscible gas flooding and chemical flooding methods used in the Energy Information Administration Annual Report to Congress 1978: Volume 3 (ARC).

There are three major types of uncertainties surrounding projections of EOR potential. First is the level of development of EOR technology, secondly, the level and changes in the price of crude oil and finally, environmental restrictions and material supply contraints. For this report, a level of technology was assumed in which existing EOR technology becomes conventionally applied requiring a 10 percent real after tax rate of return similar to that assumed for conventional recovery method. Using these assumptions as the basis, five alternative price paths for world supplies of crude oil were investigated.

Supply possibilities from these enhanced methods are estimated as .9 million barrels per day in 1985 and show no variation despite the $6 range in price among the scenarios. This is due principally to the long lead time required for these projects. However by 1995, the impact of the more rapid price increases seen in the higher price cases are evident as EOR production ranges from 1.3 million barrels a day to 1.7 million barrels a day. This range in 1995 is almost entirely due to the price response seen in gas flooding, essentially carbon dioxide flooding. The production rates for gas flooding in 1995 vary from .2 million barrels a day in the low price case to .5 million barrels a day in the highest price case analyzed.

In thermal production, most of the shallow, heavy oil resource base in California appears to be economically producible at the lower price path analyzed in the ARC which has a constant $15.00 per barrel world oil price (1978 dollars) through 1992 then increases to $16.50 per barrel in 1995. This category contributes between .9 and 1.1 million barrels a day during the 1985-1995 time frame. In thermal recovery, production from steam drive peaks around 1990 and then begins to decline reflecting limited resources for which this process is appropriate. This decline is partially offset as production from in situ processes continues to increase.

Chemical flooding techniques appear to hold very little promise in the period from 1985-1995, adding a maximum of 120,000 barrels per day in 1995.

Although thermal recovery techniques provide the bulk of production in the 1985 to 1995 period, they are projected to decline in importance over time, providing in the cases analyzed 52 to 57% of ultimate recovery (that is the total amount of production obtained from initiation to final abandonment.) Gas flooding will increase production over time to account for 37 to 41% of ultimate recovery and chemical flooding accounts for 6 to 7% of total projected ultimate recovery.

PROJECTIONS OF ENHANCED OIL RECOVERY: 1985-1995

INTRODUCTION

The purpose of this paper is to present supply estimates from enhanced oil recovery (EOR) techniques used for the analysis of domestic oil potential in the 1978 Energy Information Administration Annual Report to Congress.

Conventional techniques of crude oil production, essentially primary and secondary recovery, will produce only about 33 percent of the 450 billion barrels of original oil in place,

Table 1

Summary of 1977 EOR Production

Techniques	1977 Production (thousand barrels per day)		Active Projects	
Thermal Methods				
Steam Drive	150		43	
In Situ Combustion	10		16	
Steam Soak (gross production)	100		56	
		260		115
Gas Methods				
Carbon Dioxide Flooding	40		14	
Other	70		21	
		110		35
Chemical Methods				
Surfactant - Polymer	--		22	
Polymer Augmented Water-flooding	3		21	
Other	--		3	
		3		46
Total		373		196

Source: "Growth Marks Enhanced Oil Recovery", Oil and Gas Journal, March 27, 1978.

leaving approximately 300 billion barrels as the target for enhanced or tertiary recovery techniques. As of 1977, production from 196 projects using EOR techniques supplied 373,000 barrels per day (see Table 1) or 5 percent of total domestic production.

There are three principal categories of enhanced or tertiary techniques:

- o thermal processes where steam is used to decrease the viscosity of the oil and increase the mobility of the oil in the reservoirs. Techniques in this category include steam drive, steam soak (cyclic steam) and in situ combustion.

- o gas flooding processes in which gases are injected into the reservoir to either dissolve in the oil and increase its mobility or remain undissolved with the oil and act instead as a drive mechanism to move the oil. The most promising technique in this category over the long-term is carbon dioxide miscible flooding, even though immiscible gas flooding is currently contributing about 20% of EOR production.

- o chemical flooding in which materials such as detergents, caustics and polymers are injected to increase the mobility of the oil. These processes include surfactant/polymer flooding, polymer augmented waterflooding and alkaline flooding.

As Table 1 shows, the major portion of the activity and production is concentrated on the thermal processes. Steam drive and steam soak are the most advanced and widely used EOR processes. The other processes are still in the initial stages of development and have not as yet achieved widespread commercial application. (Appendix 3 provides more detailed information on the technical criteria governing application of the processes.)

The significance of the contribution of EOR to the domestic oil supply in the future is far from certain. While thermal processes (except in situ combustion) have been widely applied in California, the chemical and gas processes have not been proven economically. These projects require large front end investment and lengthy lead times. Costs for the projects are in many cases far greater than originally projected as inflation has pushed costs up particularly in the case of the carbon dioxide flooding.

Within the past year, however, there have been pricing regulation changes designed to provide incentives for EOR projects.

As of September 1978, incremental production from certified enhanced oil recovery projects was permitted to receive the world price, and to date, five projects have been certified and permitted to price incremental production at world levels. In August 1979, regulations became effective which provide front end money to producers for development of certain types of EOR projects. Essentially, producers are permitted, for certain techniques, to sell crude oil currently produced by or for the producer at market prices using the difference to offset preproduction costs of EOR projects. In addition, the administration recently proposed that heavy crude oil, often produced using thermal recovery methods, be decontrolled and the profits not subject to the windfall profit tax. Thus, the regulatory climate for EOR has been changing over the past year and should have a significant impact on the number of projects being initiated.

SCOPE OF THE ANALYSIS

This paper discusses production potential for the years from 1985 to 1995 of enhanced oil recovery techniques and summarizes the analytical approach and assumptions used to estimate this production. Five world oil price scenarios used in the 1978 Energy Information Administration Annual Report to Congress (ARC) are analyzed. Estimates of capital investment for drilling requirements necessary to support the production are provided for the mid-supply, mid-price case. (See Chapter 1 of the 1978 ARC for a definition of the mid-term scenarios.)

In addition to the price level of crude oil, other critical assumptions are the technology development for each technique, environmental restrictions and material supply conditions. These assumptions are detailed in the following section. Appendix 1 describes the adjustments to the projections which were necessary for their inclusion in the 1978 ARC. A comparison of production levels seen in the 1977 and 1978 Annual Reports to Congress is included in Appendix 2.

Specifically, the following technologies are considered

- <u>thermal recovery</u>
  - steam drive in shallow, heavy oil reservoirs
  - in situ in reservoirs at depths of more than 500 feet and with a high residual oil concentration.

- <u>gas flooding</u>
  - carbon dioxide miscible injection in Southwest and Rocky Mountain carbonate reservoirs
  - immiscible gas flooding in projects already initiated
- <u>chemical flooding</u>
  - surfactant/polymer flooding in shallow and homogeneous reservoirs
  - polymer augmented waterflooding

Two techniques, steam soak and alkaline flooding, described in the introduction are omitted in this analysis. Steam soak is a recovery technique which has been widely used for a number of years. Projections of production from this technique are included with conventional recovery. Recovery using alkaline flooding has received little attention by the industry with only 3 projects currently being developed and no production. The information on this technique was not sufficient for analysis of its potential.

ANALYTICAL APPROACH

The supply productions presented in this paper were estimated using a model originally developed by Lewin and Associates for the Federal Energy Administration. The model is an engineering/economic simulation of the installation of EOR projects in a set of sample reservoirs. The model includes a recovery model for each technique which uses reservoir specific estimates of oil saturation, oil volume and primary and secondary recovery to develop enhanced oil recovery potential and an economics model which uses a discounted cash flow approach to determine the project's rate of return at a crude oil price or conversely, the price required to attain a specified rate of return. At an assumed crude oil price level, a project is initiated if it earns or exceeds a specified rate of return.

There are two important timing considerations contained in the model which have a major impact on the schedule of production over time.

- Limitations in manpower, equipment and capital argue that the industry will pursue a phased approach in developing their EOR prospects. The industry starts with those projects which have the highest rate of return, followed by the next best until the minimum economic return level is reached. For example, a project which earns only the minimum rate of return may not be started for over 10 years as the industry develops the better prospects. This accounts for the risk associated with these projects, in which higher return projects are begun when the technology is uncertain. As experience with the technology is gained through these projects, the technological and economic risk are reduced and industry will move to the projects earning a lower return.

- The development of a project from initiation to production is a lengthy process. For reservoirs in which no previous work has been done, there is a period in which the reservoir is evaluated, and technical and economic pilots undertaken before commercial production is initiated. The initial study phase varies by technique from seven to nine years.

Further information on the precise representation of these timing considerations will be available in the document "Enhanced Oil Recovery Model: Methodology Description."

The data base used in the simulation covers 385 fields (835 reservoirs) in 19 states and approximately 53% of original oil in place. Data generated by the model are expanded to state totals using extrapolation factors calculated on a state basis as the ratio of original oil in place contained in the sample data to the total original oil in place. The state data are then accumulated to national level total.

MAJOR ASSUMPTIONS

Level of Technology

Development of EOR technologies is dependent on the future economic potential perceived by the industry. Currently, EOR technology for other than steam drive and cyclic steam processes is not considered conventional by the investor. Over time, however, it is possible to reduce the risk as well as advance the efficiency of the technology. For this report, the approach was taken in which existing EOR technology was assumed to become widely accepted and applied and in most cases, a conventional (10%) real return on investment was assumed to be sufficient to attract investors. However the processes remain geologically limited in their application.

Price

Future prices of crude oil produced using EOR are assumed to follow the paths shown in Table 2 which approximate the delivered cost of foreign crude oil presented in the 1978 ARC. The EOR potential has been estimated under five alternative price trajectories from a 1978 landed cost of Arabian light marker crude of $15.00 per barrel. Table 2 labels the projection series as they were designated in the ARC.

Table 2

World Oil Price Assumptions
(Dollars per barrel)

Landed U.S. Price in 1978 Dollars	Year 1985	Year 1990	Year 1995	Year of Initial Real Price Increase
Projection Series				
A	15.00	16.00	19.50	1989
B, CHigh	21.00	23.50	31.50	1982
C	15.00	18.50	23.50	1986
D, CLow	15.00	15.00	16.50	1993
E	17.00	21.00	25.50	1983

Rate of Return

For conventional application of the techniques, the after tax real rate of return assumed was 10 percent. Although in-situ and polymer augmented water flooding are currently being applied, the performance of the techniques has not been as good as earlier anticipated. Consequently, for this analysis, a 20 percent real after tax rate of return for these two techniques was used. As noted in the Analytical Approach section, the model does not immediately start all projects with the targeted rate of return, but phases them in over time, starting with the project which would provide the highest return. For example, new projects which are assumed to become conventionally applied, are initiated in 1979 if they have a calculated real after tax rate of return of 30 percent or more; in 1985, with a return of 16 percent; and finally, in 1991, with a return of 10 percent.

Environmental Regulations

Environmental regulations are an important consideration in the projections of heavy crude oil production in California using steam drive. Much of the heavy oil reserves which are susceptible to the steam drive recovery technique are located in areas that are already in violation of or near the limits of federal and state air quality standards.

As of 1977, production of California crude oil using steam drive was 150,000 barrels per day. Additional production is principally limited by the cost of meeting air quality standards. One way of meeting the environmental regulations for control of sulfur dioxide emissions is the installation of stack scrubbers, another is the burning of cleaner fuels, such as distillate fuel oil or natural gas in place of the lease crude normally used.

In this analysis, it is assumed that with incremental crude oil from enhanced oil recovery projects receiving the world oil price and the increasing world oil prices analyzed, there is sufficient incentive for the producer to invest in emissions control technology to comply with air quality standards in bringing on additional production. (See Appendix A for discussion of per barrel costs for stack scrubbers.)

Carbon Dioxide Availability

Adequate supplies of CO_2 are assumed to be available from natural and manmade sources to meet the requirements for miscible and immiscible flooding. For this study, it was assumed that the most likely source of CO_2 would be from the naturally occuring deposits in the Four Corners area, and would occur in reservoirs of high purity CO_2. This CO_2 is assumed to be available to projects in the West Texas area at a cost of $.80 per MCF.

Additional pipeline capacity will be required to move the CO_2 from these areas to the reservoirs to be flooded. (Both Shell Oil and ARCO have indicated they are considering pipelines from Colorado and Northern New Mexico to the West Texas area.) Industry is assumed to construct pipeline capacity to move CO_2 from the Four Corners area to the West Texas area increasing capacity from the current 200 million cubic feet per day to 1 billion cubic feet per day by 1985. Beyond 1985, the higher price scenarios are assumed to provide the incentives for industry to increase pipeline capacity as needed to meet any higher demand levels for CO_2.

PROJECTION OF PRODUCTION RATES AND ULTIMATE RECOVERY

Table 3 summarizes the potential production rates for the six types of EOR processes discussed earlier, for the period 1985-1995, and ultimate recovery from EOR under the cases discussed above. The production rates are for incremental production or the additional production due to the application of EOR techniques.

As the table shows, there is essentially no variation in the supply possibilites in 1985 despite a price spread of $6 among the cases. This is due to two factors: first, most of the chemical and gas flooding projects require very long lead times, so the response to price changes is not seen until later years. Secondly, the analysis indicates that a large portion of the heavy oil reserves in California, recovered using thermal methods, are producible at a $15 per barrel world oil price which is attained in each projection series.

The analysis indicates that up to 17.7 billion barrels of the targeted 300 billion barrels may be recovered under these assumptions.

Table 3

EOR Supply Possibilities by Technique
by Series, 1985-1995

Series/Technique		1977 b/	Production (Thousand Barrels Per Day) 1985	1990	1995	Ultimate Recovery (Billion Barrels)
A						
World Oil Price			15.00	16.00	19.50	
Total EOR	a/	243	900	1360	1350	13.9
Thermal Recovery		130	750	1110	1000	7.7
Gas Flooding		110	140	180	250	5.4
Chemical Flooding		3	10	70	100	.8
B, CHigh						
World Oil Price			21.00	23.50	31.50	
Total EOR	a/	243	910	1410	1680	17.7
Thermal Recovery		130	760	1140	1040	9.8
Gas Flooding		110	140	200	520	6.8
Chemical Flooding		3	10	70	120	1.1
C						
World Oil Price			15.00	18.50	23.50	
Total EOR	a/	243	900	1390	1430	14.9
Thermal Recovery		130	750	1130	1010	7.8
Gas Flooding		110	140	190	320	6.1
Chemical Flooding		3	10	70	100	1.0
D, CLow						
World Oil Price			15.00	15.00	16.50	
Total EOR	a/	243	900	1320	1290	13.5
Thermal Recovery		130	750	1110	990	7.7
Gas Flooding		110	140	140	200	5.0
Chemical Flooding		3	10	70	100	.8
E						
World Oil Price			17.00	21.00	25.50	
Total EOR	a/	243	900	1400	1510	14.9
Thermal Recovery		130	750	1140	1030	7.8
Gas Flooding		110	140	190	380	6.1
Chemical Flooding		3	10	70	100	1.0

Table 3 Continued

a/ This category includes net steam drive production

b/ The 373,000 barrels per day total for 1977 production shown in Table 1 has been adjusted as follows: Approximately 100,000 barrels per day of production from steam soak methods has been deducted from the thermal recovery category. As discussed in the Scope of the Analysis section, this was eliminated from our analysis. Secondly the steam drive projections in this analysis are net of lease fuel use, while the projections in Table 1 are gross production. Thus, 30,000 barrels per day were deducted from the steam drive category. This is summarized below:

Total EOR Production from Table 1	373,000 barrels
Less Steam Soak Production	100,000
Less Crude Oil Used as Fuel for Steam Generation	30,000
Total EOR Production from Table 3	243,000

Thermal Recovery

As seen in Table 3, the significant advances in production over the 1985-1995 period come from the thermal recovery processes.

Substantial reserves are producible using steam drive at world oil prices. However, the bulk of current production is in California from fields where environmental regulations on emissions and marketing problems are limiting production using steam drive to 150,000 barrels per day gross production (120,000 barrels per day net of fuel use). Steam drive at the current level of technology is applied principally to heavy oil reservoirs with a gravity range of 10^{o} to 25^{o} API. This type of oil production has been earmarked for special production incentives in the President's Import Reduction Program. Essentially, production of heavy oil in specified gravity ranges will be allowed to receive the market level price and will be exempt from the windfall profits tax. This program recognizes the environmental problem facing the production and states that the Department of Energy will take steps to ensure that natural gas is available for steam generation.

The projections shown in Table 3 are for net production from steam drive recovery techniques. If the operator were to substitute natural gas for lease crude in the generation of steam, approximately 25 percent additional oil, would become available. However, while the total crude oil production would increase, there would be no net energy increase.

Thermal recovery techniques are projected to provide the larger portion of EOR production from 1985 to 1995. Over the long run, they are estimated to provide about half of ultimate recovery. Steam drive production peaks around 1990 and then starts to decline. This decline is offset by in-situ production which increases throughout the period. Of the total thermal potential, in situ production, although contributing as much as 190,000 barrels per day in 1995, is assumed to remain a high risk technology. Producers have begun to close down combustion projects in favor of the more efficient steam drive projects, and the number of combustion projects has declined from 38 in 1970 to 16 in 1977. As a result, estimates of its potential do not change significantly across cases. The principal response to the assumed price changes then is in the estimates of steam drive potential. However, this response is limited by the resource base which is economic in this range of prices.

Miscible and Immiscible Gas Flooding.

The recovery process which is likely to provide the greatest potential recovery in this category is the carbon dioxide miscible process. Most of the recent developments have been in carbon dioxide miscible processes and the analyses centers on that technique. This process is currently being tested in several pilot field tests. Although, preliminary indications are that the process has significant potential, large uncertainty surrounds any projection using the technique since the operating efficiency and economics of the process have not yet been firmly established. The availability of sufficient supplies of CO_2 may also be a potential problem.

It is this area of EOR that shows the most responsiveness to price in the 1985-1995 time frame in percentage terms based on a variation in prices of $16.50 to $31.50 per barrel. By 1995, the production possibilities range from 200-520,000 barrels per day. Production from other gas flooding techniques is assumed to be constant at current levels, 70,000 barrels per day, from 1985-1995 in all cases. Ultimate recovery from these techniques provides 37 to 41 percent of the total in this analysis.

Chemical Flooding.

There are two chemical methods analyzed in the report: these are surfactant polymer and polymer augmented waterflooding. The industry has been active in testing these techniques with the number of projects increasing from 19 in 1970, to 27 in 1975 and finally 43 projects in 1977. Activity in this area is slowing as operators reportedly plan 5 new projects in the 1977 survey taken by the Oil and Gas Journal versus 11 planned projects in the 1975 survey. Very little production is expected from these techniques in 1985, but a steady increase through 1995 is seen, so that ultimate recovery using these techniques amounts to 6 to 7% of the total.

Investment and Drilling Activity

Table 4

Investment and Drilling Requirements for Enhanced Oil Recovery-Series "C"

	1979-1985	1985-1990	1990-1995
Drilling Requirements (Thousand Feet)	62,095	39,966	35,761
Capital Investment for Drilling and Equipping Wells (Million 1978 Dollars)	5,995	5,126	4,799

A large portion of the drilling activity to support the production rates seen in the Series C is concentrated in the years from 1979-1985, and tapers off in the following periods. The footage in the early period is principally shallow wells for heavy oil in California. The shift over time from thermal projects to CO_2 projects causes a large decrease in drilling footage but a less than proportional decrease in capital investment because of the deeper and therefore more expensive drilling for CO_2 recovery methods.

Because of this pattern, capital expenditures for drilling and equipping wells during the period decline steadily. The outlay for drilling and equipping wells for EOR is still small in relation to total industry expenditure for exploration and development, amounting to 6% of the total projected for the period from 1979 to 1990.

Appendix 1: Mid-Term Energy Forecasting System (MEFS) Implementation

For the analysis of petroleum supply and demand in the 1978 ARC, the estimates of EOR potential were input into the Mid-Term Energy Forecasting System (MEFS) along with estimates of all other domestic sources of energy supply. Some adjustments were necessary to the EOR data to ensure consistency with the data input for other supply sources and to permit the analysis of different options available to producers to deal with the environmental regulations on emissions from steam generation. These adjustments are described below.

- The data were regionalized into National Petroleum Council (NPC) regions. (See Figure A-1). The following data show the percent of production potential allocated to each region.

Technique	NPC Region
Steam Drive	2 (100%)
In-Situ Combustion	2 (40%)
	6 (60%)
Gas Flooding	5 (100%)
Chemical Flooding	8,9,10 (100%)

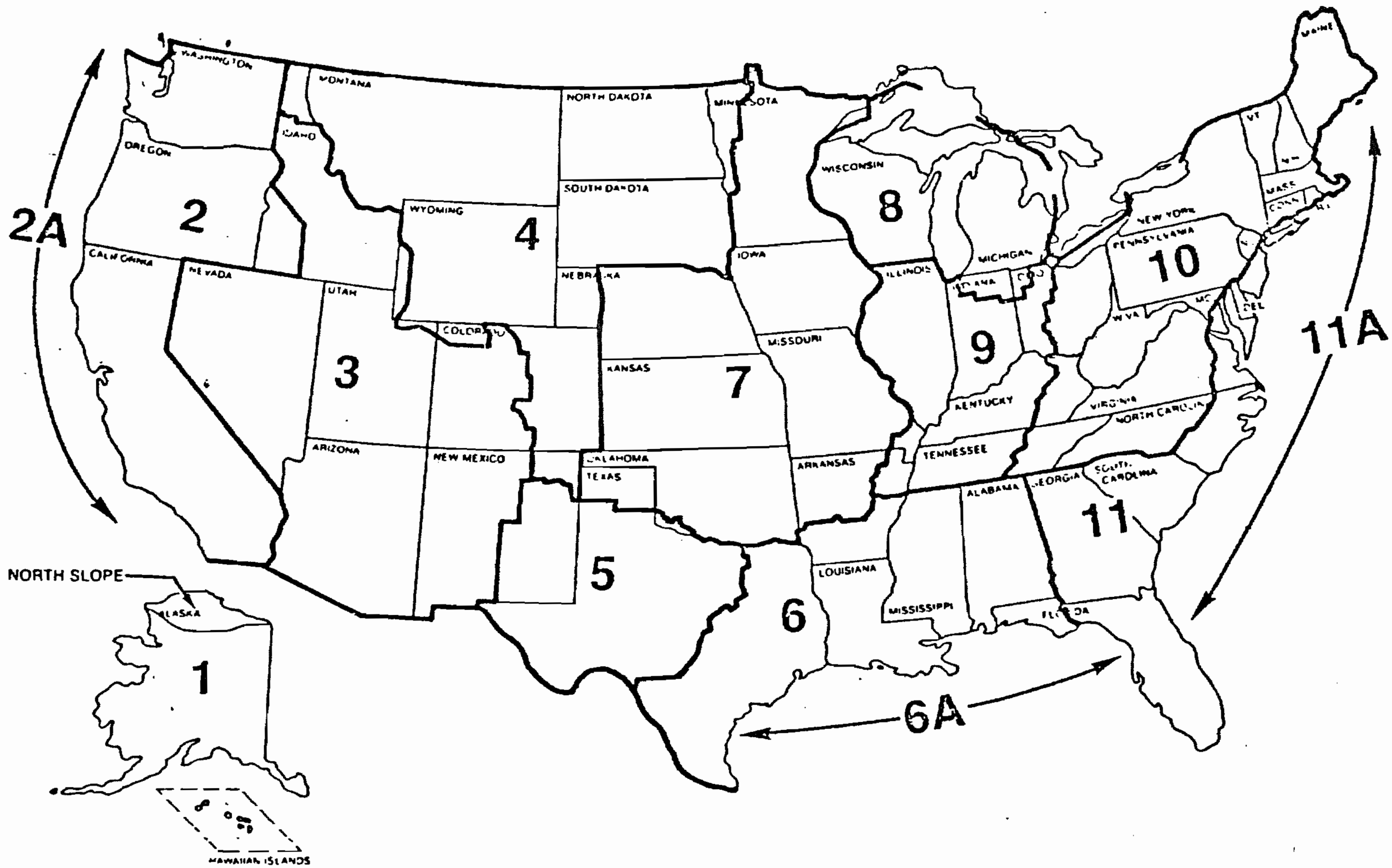
- The production data for the steam drive recovery technique was adjusted from net production i.e., net of fuel use for steam generation to gross production. In general, approximately one out of every 3 or 4 barrels of oil produced is burned for steam generation. For this analysis, net production was increased by 25% to provide estimates of gross production. This adjustment was made to permit the selection of fuel used on site for steam generation to be determined in MEFS based on the relative economics of alternative fuels. The minimum acceptable prices shown for the steam drive production do not include the cost of fuel for steam generation.

The operator was permitted to burn lease crude with no additional cost to maintain current levels of production. For any production above that level, the operator was required either to install stack scrubbing devices or burn alternative fuels, such as distillate fuel oil or natural gas for steam generation.

Fuel costs for production using lease crude was estimated as equal to the world oil price level and an additional charge of $2.25 per barrel of oil produced was added for the cost of emissions control. This was based on the cost of installing stack scrubbers on a 50 million BTU per hour steam generator. Because of the uncertainty of the assumptions, the calculated cost of $1.50 per barrel of oil produced was increased by $.75. Any use of natural gas was incrementally priced.

- The third adjustment to the production data was to correct a double-counting problem between the conventional oil supply projections and the enhanced oil recovery projections.

  Currently estimates of lower-48 onshore production are derived using a decline curve analysis, based on year-end estimates of proven reserves from the American Petroleum Institute publication entitled "Reserves of Crude Oil, Natural Gas Liquids, and Natural Gas in the United States and Canada as of December 31, 1977." See Table A-1. Approximately, 1.5 billion barrels of EOR reserves are included in the proved reserves listed. Thus the mid-term oil and gas supply model which projects conventional lower-48 onshore production and the enhanced oil recovery model were each showing production from these reserves.



Regional Boundaries: Region 1—Alaska and Hawaii, except North Slope; Region 2—Pacific Coast States; Region 2A—Pacific Ocean, except Alaska; Region 3—Western Rocky Mountains; Region 4—Eastern Rocky Mountains; Region 5—West Texas and Eastern New Mexico; Region 6—Western Gulf Basin; Region 6A—Gulf of Mexico, Region 7—Midcontinent; Region 8—Michigan Basin; Region 9—Eastern Interior; Region 10—Appalachians, Region 11— Atlantic Coast; Region 11A—Atlantic Ocean.

Source: NPC, *Future Petroleum Provinces of the United States* (July 1970)—with slight modification.

Figure 1 Petroleum Provinces of the United States.

Table A-1
EOR Proved Reserves Included in Mid-Term
Oil and Gas Model

	NPC Region	
	2	5
Proved Reserves (billion barrels)	1.3	.2
Production Rates (thousands barrels per Day		
1985	155	27
1990	90	14
1995	55	5

The projected production rates from these reserves were derived using decline rates from the Mid-Term Oil and Gas Supply Model for the region. For NPC2, the decline rate was 9.9%; for NPC5, the rate was 13%.

These production rates were then subtracted from the estimates of EOR supply.

- Minimum acceptable prices were established for each of the quantities. For steam drive, in particular, additional model runs were made to establish quantities which would be supplied at prices lower than the world oil price. This was necessary for an analysis of the crude oil glut on the West Coast. The transportation differential between the world oil price and domestically produced oil was also taken into account in establishing minimum acceptable prices.

Figure 1 Petroleum Provinces of the United States.

Appendix 2: Comparison of Projections With Earlier Studies

In the 1977 Energy Information Administrator's Annual Report to Congress, estimates of production from enhanced oil recovery or tertiary production were reported. The estimates presented in this year's annual report differ significantly from last year's projections. Table A-3 provides a comparision of the projections seen in these two reports.

Table A-3

Comparison of EOR Production Projections
(Million Barrels Per Day)

	1977 ARC Series C	1978 ARC Series C
1985	.5	.8
1990	.7	1.5

The principal differences between the two projections are the following:

1. The 1977 projections assumed the production of heavy crude oil in California was constrained by environmental regulations and limited to 110,000 barrels per day.

   In the 1978 projections, costs for overcoming the environmental regulations were incorporated. Essentially it was assumed that operators could increase production by installing stack scrubbers on steam generation units or by burning fuels other than lease crude, such as natural gas or distillate, at an appropriate cost. In fact, the option of burning alternative fuels under the relative cost assumptions would be economically attractive to the industry and an increase of about 25 percent above the net production levels using steam drive is made available in this analysis for the years 1985, 1990 and 1995.

2. Prospects for the other techniques are lower than the earlier study because field tests are indicating that the processes, other than steam drive, are

not as efficient as earlier anticipated and more costly than expected. However, the increasing prices seen by the industry in the 1978 study partly offset this decline.

Appendix 3: Screening Criteria for Application of the EOR Techniques

In assigning techniques to reservoirs, an initial screening was done using four basic criteria to eliminate those reservoirs with low EOR potenital. Reservoirs with the following characteristics were excluded from further consideration.

-- active natural water drive

-- major primary or secondary gas cap

-- API gravity less than 10^{o}

-- residual oil saturation less than 20%

For all reservoirs except those in which steam drive processes were applicable, reservoirs known to have extensive fracturing were eliminated. These reservoirs have a tendency to channel the injected materials away from the oil-bearing portion of the reservoir, reducing the amount of oil recovered.

The following table provides a summary of minimum technical requirements for application of each technique in a reservoir.

Table 1: Criteria for the Application of Selected Enhanced Oil Recovery Methods

Screening Parameters	Steam Drive	In Situ Combustion	CO2 Miscible	Surfactant/ Polymer	Polymer Waterflood
Viscosity - CP at Reservoir Condition	NC	NC	< 15	< 20	< 200
Gravity - Degree API	> 10	10 - 45	> 25	NC	NC
Fraction of Oil Remaining In Area to be Flooded (Before EOR) - % PV	> 40	> 40	> 20	> 25	> 30
Oil Concentration - B/AF	> 500	> 400	NC	NC	NC
Porosity X Oil Saturation	> .065	> .050	NC	NC	NC
Depth - Feet	< 5000	> 500	> 3000	10-8500	10-8500
Temperature - Degree F	NC	NC	NC	< 200	< 200
Original Bottom Hole Pressure - PSI	NC	NC	> 1500	NC	NC
Net Pay Thickness - Feet	> 20	> 10	NC	NC	NC
Permeability - MD	NC	NC	NC	> 20	> 20
Transmissibility (Perm. * Thick / Visc)	> 100	> 20	NC	NC	NC
Salinity - PPM	NC	NC	NC	< 150000	NC
Hardness - PPM Calcium Magnesium	NC	NC	NC	< 1000	NC
Fractures	NC	None to Low	None to Low	None to Low	NC
Lithology	Sandstone Only	Sandstone Only	NC	Sandstone Only	Sandstone Only

NC = Not critical.

Steam Drive

For this analyses, only the application of this technique to shallow, heavy oil reservoirs was investigated. The gravity range permitted was between 10^{o} and 25^{o} API.

The critical screening parameters for the recovery models used for this technique are summarized below. A reservoir depth of 5000 feet or less was critical to prevent execessive heat losses and pressure problems which tend to increase with depth. Reservoir net pay of greater than 20 feet was required to prevent heat losses to non-oil-bearing formations from becoming excessive. Residual oil greater than 500 barrels/acre foot was the minimum considered to be economic. Finally, transmissability greater than 100 was required. Transmissibility is a measure of the rate at which the oil moves through the reservoir. Factors less than 100 millidarcy feet/ centipoise, slow the rate of production and reduce the chance of an economic project.

In Situ Combustion

For application of the in situ combustion process, five critical screening criteria had to be meet. The minimum reservoir depth was 500 feet, the miminum necessary to provide sufficient overburden to control the process. The maximum permissable gravity was 45^{o} API. This gravity constraint is determined by the capability of a particular reservoir rock/crude oil combination to deposit enough coke to sustain combustion. Other critical factors were reservoir transmissability of 20 millidarcy feet/centipoise, net pay thickness greater than 10 feet and residual oil greater than 400 barrels per acre foot.

Carbon Dioxide Miscible Flooding

There were three principal factors considered for the application of this technique. A gravity of 25° API or greater was required to obtain a good sweep efficiency. Oil viscosity of less than 15 centipoises was used as a screen based on current field tests. Finally, reservoir depth of 3,000 feet or more was necessary to obtain the 1500 psi reservoir bottom hole pressure required for miscible displacement.

Surfactant/Polymer Flooding

The surfactant/polymer flooding process is currently applicable to sandstone reservoirs only. Surfactants and polymers are available which tolerate temperatures up to 170°F. It was assumed that additional testing will develop systems which can tolerate temperatures up to 200°F. Oil viscosity must be less than 20 centipoises to allow an effective sweep. A critical variable in the process is the composition of the formation water. It was assumed that the salinity tolerance of the process would be about 150,000 parts per million or less and the process would be compatible with water hardness of 1,000 parts per million or less.

Polymer - Augmented Water flooding

This technique involves the use of chemicals to increase the visosity of the water thereby improving the efficiency of the waterflood. Polymer flooding is not a potential process for all reservoirs which can be waterflooded. Geologic constraints, properties of the reservoir rock and oil, and stage of the waterflood are all critical. For this study, a permeability of 20 millidarcies or more was required. The use of polymers is currently limited by temperature. Consequently, the reservoirs were screened for temperatures of 200 ^{o}F or less. Finally, crude oil viscosity of less than 200 centipoises was required.

Table A-2
Supply Possibility Data Incorporated in MEFS

Technique	NPC Region	1985 Minimum Acceptable Price (1978 dollars)	1985 Cumulative Quantity Supplied	1990 Minimum Acceptable Price (1978 dollars)	1990 Cumulative Quantity Supplied	1995 Minimum Acceptable Price (1978 dollars)	1995 Cumulative Quantity Supplied
Steam Drive d/ (Gross Production)							
Series C,CLow a/	2	5.60	40	5.60	100	5.60	140
		7.20	464	7.20	719	7.20	614
		8.40	673	8.40	1100	8.40	930
		12.00	690	12.00	1116	12.00	930
				14.40	1140	14.40	971
Series CHigh b/	2	5.60	40	5.60	100	5.60	140
		7.20	464	7.20	719	7.20	614
		8.40	673	8.40	1100	8.40	932
		12.00	690	12.00	1116	12.00	932
		14.40	704	14.40	1156	14.40	998
						25.20	1005
In-Situ Combustion							
All Series c/	2	10.50	32	10.50	56	10.50	76
All Series c/	6	10.50	48	10.50	84	10.50	114
Gas Flooding							
All Series c/	5	13.50	110	14.50	130	16.00	200
				15.50	160	19.00	240
				18.00	170	23.00	320
				23.00	190	25.00	370
						31.00	490
Chemical Flooding							
All Series c/	8/9/10	14.00	10	15.00	70	16.50	100

a/ Series A and B - these supply quantities were used but the minimum acceptable price (MAP) was decreased by 10% to take into account the cost variations assumed for these scenarios. For Series E, the MAP was increased by 10%.

b/ For Series B, the supply data for the CHigh case was used with the minimum acceptable price increased by 10%.

c/ For Series A and D, the minimum acceptable price was decreased by 10% and for Series B and E, it was increased by 20%.

d/ Costs of fuel for steam generation are not included in the minimum acceptable prices listed here for steam drive.