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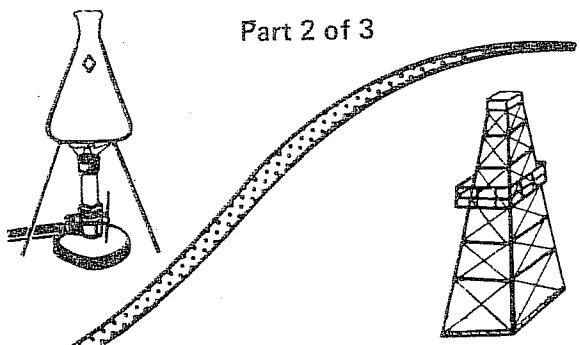
(Report of ERDA 77-20/2)

# RESEARCH & DEVELOPMENT IN ENHANCED OIL RECOVERY

## Final Report

### The Program

Part 2 of 3



MAY 1978

Prepared For
U.S. DEPARTMENT OF ENERGY
Assistant Secretary for Energy Technology
Office of Planning and Evaluation

Under Contract No. E(49-18) 2294

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# RESEARCH AND DEVELOPMENT IN ENHANCED OIL RECOVERY

Final Report
**The Program**
Part 2 of 3

May 1978

Prepared By
Lewin and Associates, Inc.

For
U.S. DEPARTMENT OF ENERGY
Assistant Secretary for Energy Technology
Office of Planning and Evaluation
Washington, D.C. 20545

Under Contract No. E(49-18) 2294

Note: This is a reprint of a document previously published by the Energy Research and Development Administration (ERDA) prior to the activation of the Department of Energy (DOE) by the Energy Reorganization Act. Therefore, wherever ERDA is mentioned, its functions have been transferred to DOE.

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# PREFACE

The objective of this work is to provide in-depth, quantitative analysis in support of strategic planning for ERDA's Enhanced Oil Recovery Program. The study directly addresses the questions of ERDA's role in RD&D in enhanced oil recovery (EOR) and the best composition and size of ERDA's EOR program.

The report is printed in three parts:

Part 1: Overview

Part 2: The Program

Part 3: The Methodology

The analysis contained in these volumes was the principal input to ERDA's "Management Plan for Enhanced Oil Recovery", which will be forthcoming shortly.

## ACKNOWLEDGEMENTS

The analyses reported in this volume were conducted by:

- Mr. Vello A. Kuuskraa, Project Director
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- Dr. Jerry P. Brashear, Project Manager
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Valuable assistance was also provided by numerous experts from universities, government agencies, and the petroleum industry. Their organizations are listed in Part 3 of this report. The principal authors thank all those who supported and assisted in shaping the assumptions and findings of this study. The authors, of course, retain responsibility for any errors in judgment or fact.

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# CHAPTER I

## INTRODUCTION TO PART 2

The final report, Research and Development in Enhanced Oil Recovery, consists of three parts. This volume -- Part 2 -- provides detailed analyses of the status of the technology and of the ERDA programs in each EOR technique. Part 1 provides an overview for advancing this technology. Part 3 addresses the major methodological issues in detail.

This Chapter provides a summary of the EOR technology and the analyzed ERDA R&D programs.

### Current Status of the Technology

Enhanced oil recovery is far from a proven technology. Years of testing have yielded only one process -- steam drive -- that approaches being a conventionally tested technique. Even with the experience of 187 projects and with over 130 thousand acres under current development summarized by technique and type in Exhibit I-1, enhanced oil recovery has advanced slowly. The current status of the technology can be summarized thus:

- EOR currently produces over 240,000 barrels per day (including hydrocarbon miscible but not cyclic steam projects).

EXHIBIT I-1

FIELD ACTIVITY IN ENHANCED OIL RECOVERY

| Technique | (Number of EOR Projects) Technical Pilots Total | Technical Pilots Current | Economic Pilots Total | Economic Pilots Current | Field Wide Development Total | Field Wide Development Current | Acreage Under Current Development |
|---|---|---|---|---|---|---|---|
| Steam Drive | 17 | 13 | 15 | 14 | 15 | 15 | 15,682 |
| In Situ Combustion | 17 | 9 | 7 | 6 | 19 | 10 | 4,548 |
| $CO_2$ Miscible and Non-Miscible | 5 | 4 | 6 | 6 | 2 | 2 | 38,618 |
| Surfactant/Polymer | 12 | 10 | 7 | 7 | 2 | 2 | 1,418 |
| Polymer Augmented Waterflooding | 3 | 0 | 14 | 9 | 14 | 11 | 14,624 |
| Caustic Augmented Waterflooding | 5 | 1 | 2 | 0 | 0 | 0 | 63 |
| Hydrocarbon Miscible | 9 | 7 | 6 | 5 | 10 | 8 | 56,782 |
| TOTALS | 68 | 44 | 57 | 47 | 62 | 48 | 131,735 |

*This is an update to the status report on EOR provided in The Potential and Economics of Enhanced Oil Recovery by Lewin & Associates, Inc., April, 1976. While this file may not contain some current EOR projects, it contains all that have been reported in the literature and several that are described only in company reports submitted directly to the study.

- Steam drive accounts for the largest portion of this production, 110,000 barrels per day, hydrocarbon miscible provides 70,000 barrels per day; carbon dioxide miscible contributes 40,000 barrels per day; in situ combustion, surfactant/polymer, and polymer caustic augmented waterflooding provide the remaining 20,000 barrels per day.

- Two important changes are underway that could significantly influence the amounts of enhanced oil being produced:

  -- First, several major operators indicate plans for converting their existing steam soak projects to steam drive. This alone could increase production by an additional 200,000 barrels per day should West Coast environmental problems be overcome and a market be established for heavy oil. (Should this occur, total EOR production would be on the order of 400-500 thousand barrels per day.)

  -- Second, due to the recent increases in natural gas prices, few major new efforts will rely on hydrocarbon miscible flooding. Several of the hydrocarbon miscible projects are converting (or already have converted) to other injection fluids, such as flue gas or carbon dioxide. In the future, carbon dioxide miscible flooding must fill the void created by the retrenchment of hydrocarbon miscible flooding.

- Substantial technical uncertainty besets the application of EOR:

  -- Unpredictable process performance in the reservoir.

  -- Unreliable data on reservoir characteristics, especially residual oil saturations and distributions.

  -- Uncertain costs of application.

- The uncertainties vary substantially by technique:

  -- Steam drive is approaching conventional application in the shallow, high saturation reservoirs in which it has typically been applied.

  -- In situ combustion, while having experienced substantial testing, remains unproven and difficult to predict.

  -- Carbon dioxide miscible flooding projects have not yet produced sufficient data to evaluate this technique's true potential. Some limits on its applicability have begun to appear.

  -- Chemical processes have not fared well in the transition from laboratory to field pilot operation. Surfactant, polymer and caustic applications are the least predictable and the farthest from conventional application.

- Major difficulties with many techniques have been encountered in extrapolating from laboratory results to field tests. Demonstrations of effectiveness in the lab have not been replicated in the field. This argues that substantial basic research, both in the lab and in the field, is required for the less proven techniques.

- Ongoing and planned research and development by industry is concentrating on improving the effectiveness of EOR techniques for the most favorable reservoirs which the specific operators control. Little attention is going toward solving the problems of less favorable reservoirs or toward finding generic solutions that would apply to large numbers of reservoirs. That is, future industry research and development will closely resemble current pilots in the field.

- Industry's expansion plans are limited. For the foreseeable future, industry will develop the most favorable reservoirs and will push a portion of the technology to conventional application. However, these developments will produce additional oil only slowly -- after industry's own research has made the techniques more predictable.

## The Base Case

Taking these factors into account an estimate was made of the Base Case -- the pace of technological development and the additions to recovery projected for industry with no ERDA programs.

Given the upper tier price and current taxes (referred to below as the Standard Economics Case), it is estimated that industry will ultimately recover approximately 11.9 billion barrels through enhanced oil recovery. Over half of this (6.2 billion barrels) will be from steam drive. Carbon dioxide miscible will contribute almost forty percent (4.7 billion barrels). Small additional amounts will be produced using in situ combustion (0.9 billion barrels) and polymer waterflooding (0.1 billion barrels). Under these economic conditions, no production from surfactant is expected. The majority of ongoing projects using this process are uneconomic, a fact recently confirmed by several operators of major surfactant projects.

Exhibit I-2 shows the production rates for the Base Case under Standard Economics conditions. In 1985, the production rate will be just under 600 thousand barrels per day. The production rate stays at this level through 1990, then declines slightly to 550 thousand barrels per day. Steam drive continues to produce at approximately its current rate throughout the period of interest, due primarily to the constraints imposed by environmental and market considerations in California. The rate for carbon dioxide miscible rises steadily until 1985, when it, too, becomes constrained, in this case by the limited supply of carbon dioxide. The rates for combustion and polymer rise until 1985, then stabilize as the number of candidate reservoirs becomes exhausted.

Exhibit I-3 shows the cumulative production for the Base Case. By 1995, given the current constraints on EOR production, less than one third of the ultimate recovery -- 3.7 billion barrels -- will have been produced.

EXHIBIT I-2

EXPECTED PRODUCTION RATES FOR THE INDUSTRY BASE CASE

(STANDARD ECONOMICS)

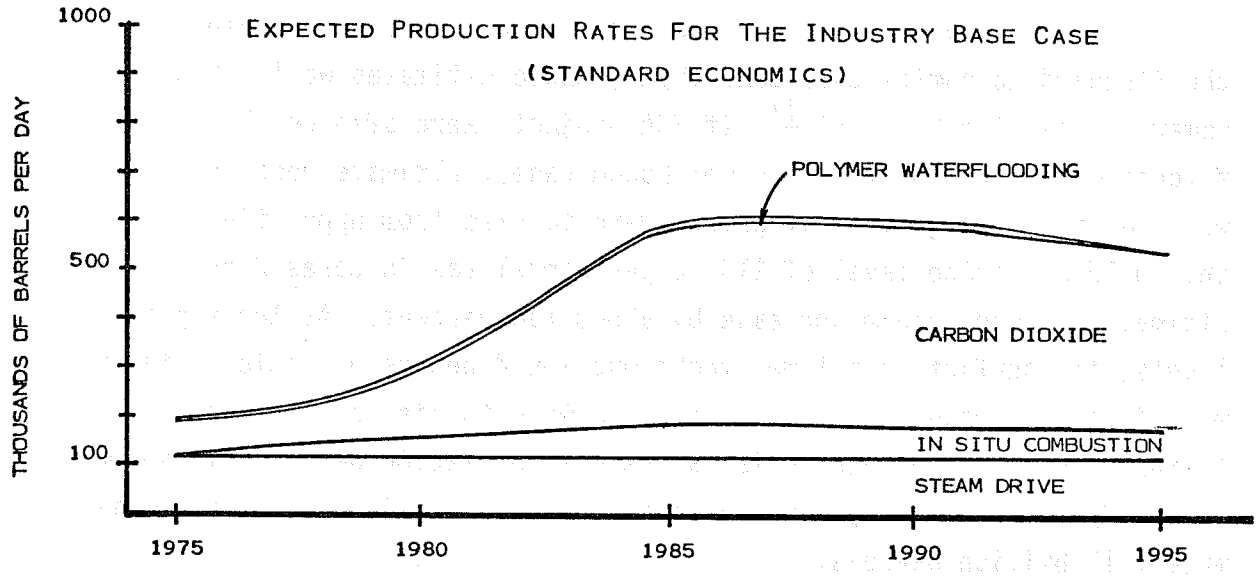
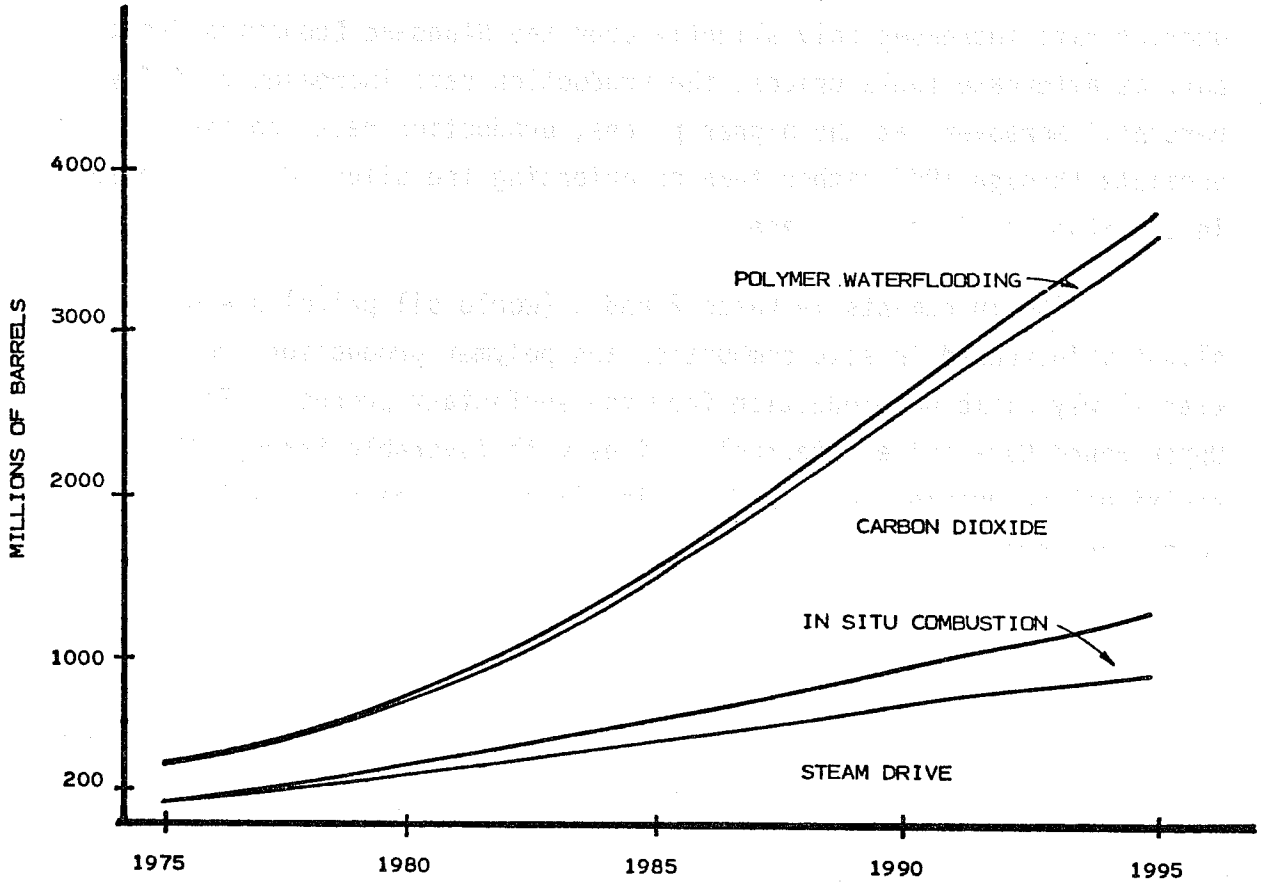



EXHIBIT I-3

EXPECTED CUMULATIVE PRODUCTION FROM THE INDUSTRY BASE CASE

(STANDARD ECONOMICS)



Should price/tax contingencies other than those assumed in the Standard Economics Case come about, these estimates would change somewhat (see Exhibit I-4).[1/] If EOR projects were afforded less favorable tax treatment (the Lower Bound Case), ultimate recovery would decrease slightly. If prices were to rise from upper tier to the world oil price level of $13.00 per barrel (as in Cases 2 and 4), ultimate recovery would increase by about ten percent. At these price levels, the surfactant/polymer technique would become economic in the more favorable reservoirs. If the price were to rise still further, to the price of alternate fuels, assumed to be $20.00 per barrel (shown in the Upper Bound Case), then ultimate recovery would rise to approximately 17 billion barrels.

More favorable tax/price conditions not only yield additional ultimate recovery, they accelerate the rate of production (see Exhibit I-5). At world oil prices and favorable taxes, the 1990 production rate increases only slightly over the Standard Economics Case; but, at alternate fuels prices, the production rate increases by fifty percent. Moreover, at the higher prices, production rates continue to escalate through 1995 rather than experiencing the slight decline noted in the Standard Economics Case.

The increments in Cases 2 and 4 (world oil price) are due to slightly increased in situ combustion and polymer production, coupled with slowly climbing production from the surfactant process. For the Upper Bound Case (alternate fuels prices with favorable taxes), the additional production results from significant increases from the surfactant process.

EXHIBIT I-4

SENSITIVITY OF INDUSTRY BASE CASE EXPECTED ULTIMATE RECOVERY TO PRICE/TAX CONTINGENCIES

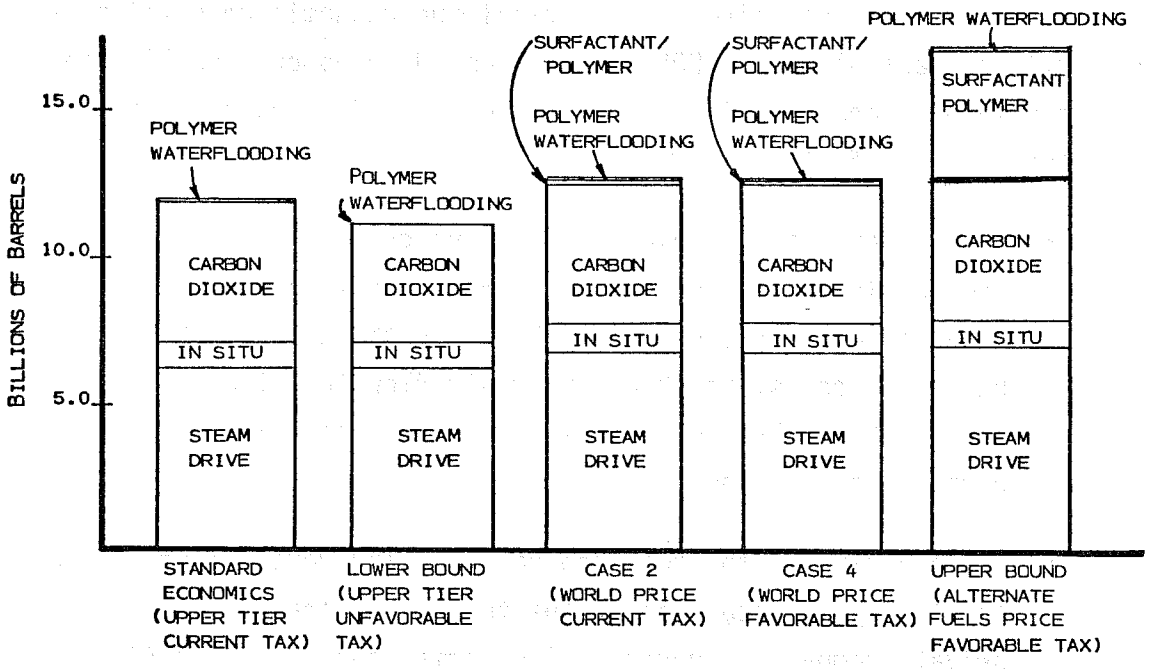
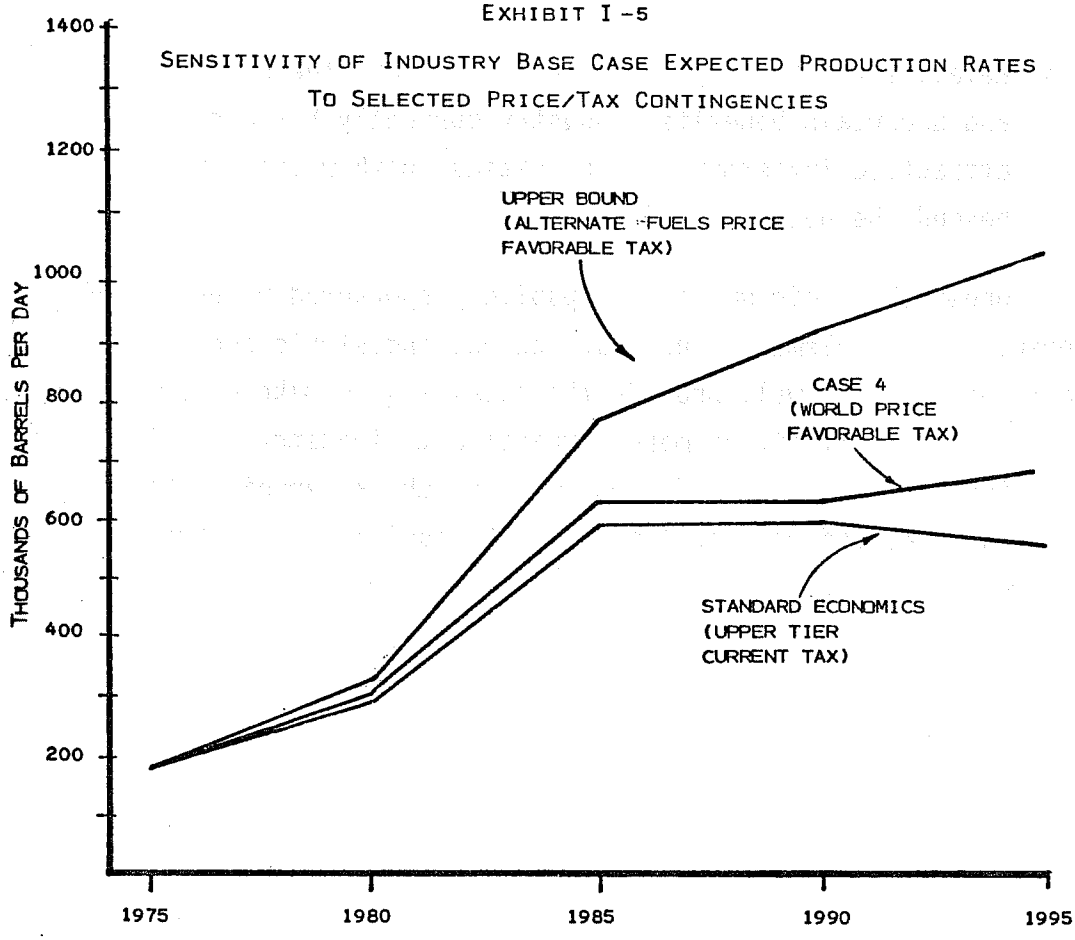



EXHIBIT I-5

SENSITIVITY OF INDUSTRY BASE CASE EXPECTED PRODUCTION RATES TO SELECTED PRICE/TAX CONTINGENCIES



## The ERDA Program

Given the extensive technological and economic uncertainties, industry's current plans for EOR research and development are limited, leaving numerous opportunities for expanded R&D. The opportunities arise from several factors:

- The research and development in enhanced oil recovery are costly. Moreover, many of the benefits of this research could not be internalized by the company that bears the costs; the benefits would flow to all operators with similar reservoirs, while the costs would be borne by only a few.

- The benefits of the required research and development are likely to occur far in the future, so that in a private company's present value terms, they are severely discounted.

- Relative to the large front end costs and the distant and uncertain benefits, industry currently has more attractive investment opportunities, both within and beyond the petroleum field.

Under these circumstances, publicly sponsored research and development that complements, not duplicates, industry's ongoing and planned research could well provide the catalysts to make otherwise unexploited EOR opportunities more attractive to industry. Public R&D can stimulate industry to develop more of the reservoirs that would otherwise be deferred or left fallow, resulting in either greater ultimate recovery, accelerated production, or -- most likely -- both.

The analytic approach used in identifying the most promising of these research opportunities consisted of: (a) examining the major reservoirs of the U.S. relative to their technical and economic potential for EOR application, (b) identifying the research and development achievements necessary to develop and produce these reservoirs, and (c) analyzing the breakthroughs and future applications likely to be achieved by Industry (these formed the Industry Base Case described above). This left a number of potential areas where ERDA's research and development might stimulate Industry activity.

Exhibit I-6 displays these target areas of opportunity (combinations of techniques with reservoir types) -- and R&D strategies (generic classes of research achievements) -- that resulted from this analysis. Entries in the table denote the relevant strategy that must be pursued for each specific target to be made attractive to industry. For each such intersection of a target with an R&D strategy, an ERDA program was defined. The entries on the Exhibit, e.g., SD-1, are the designations for the ERDA programs used in subsequent chapters.

For these programs, more detailed objectives and activities were developed, and the costs of these activities were estimated. Exhibit I-7 displays these program activities in physical units (person-years and field projects), over the next five years. Considerable emphasis is placed on verifying the resource base (through measurement, data base acquisition and analysis) and a laboratory based, fundamental research effort. These two activities are intended to reduce the major uncertainties that contribute to the current level of technological risks in EOR and to develop improved processes for the future. As the

EXHIBIT I-6 ANALYSIS OF R&D ACHIEVEMENTS REQUIRED TO STIMULATE PRODUCTION FROM EOR TARGETS

| STRATEGIES \ TARGETS | A. STEAM DRIVE | | | |
|---|---|---|---|---|
| | (1) SHALLOW/HEAVY OIL RESERVOIRS ≤ 2500', WITH UNSTIMULATED INFLUX | (2) OTHER HEAVY OIL RESERVOIRS > 2500', WITH UNSTIMULATED INFLUX | (3) LIGHT OIL RESERVOIRS THIN, LOW PERM. W/ LOW SOR | (4) HEAVY OIL RESERVOIRS W/ NO INFLUX (TAR SANDS) |
| I. DEVELOP AND IMPROVE EOR TECHNOLOGY: | | | | |
| A. IMPROVE RECOVERY EFFICIENCY | SD-1 | - | (SD-6) | - |
| B. EXTEND APPLICATION OF PROCESS | - | SD-5 | SD-6 W/SD-2 | SD-7 (QUALITATIVE) |
| C. IMPROVE MOBILITY CONTROL | (SD-1) | - | - | - |
| D. TEST SPACING/INJECTION PATTERNS | (SD-1) | - | - | - |
| E. EXAMINE IMPROVED PROCESS EFFICIENCIES | - | - | - | SD-7 (QUALITATIVE) |
| F. DEVELOP NEW PROCESSES | - | - | - | SD-7 (QUALITATIVE) |
| G. BRING TECH. TO CONVENT. APPLIC. | - | SD-5 | (SD-6) | - |
| II. OVERCOME NON-EOR PROCESS CONSTRAINTS: | | | | |
| A. OVERCOME EMISSION PROBLEMS | SD-3 | (SECONDARY EFFECT) | - | |
| B. EXAMINE ALTERN. USES AND/OR MKT. FOR WEST COAST OIL | SD-4 | (SECONDARY EFFECT) | - | |
| C. USE SUBSTITUTE (NON-PETRO) FUELS | SD-2 | (SECONDARY EFFECT) | (SPILLOVER BENEFITS) | |
| D. DEVELOP CHEAPER/ADEQUATE SUPPLY OF INJECTION MATERIALS | - | - | - | |
| E. ENSURE ADEQUATE CAPITAL/ ECONOMIC RETURN | - | - | - | |

EXHIBIT I-6 ANALYSIS OF R&D ACHIEVEMENTS REQUIRED
TO STIMULATE PRODUCTION FROM EOR TARGETS
(CONTINUED)

| STRATEGIES \ TARGETS | B. IN SITU COMBUSTION | C. $CO_2$ MISCIBLE | | | |
|---|---|---|---|---|---|
| | (1) HEAVY OIL RESERVOIRS | (1) S.W. & MONT. CARBONATES, W/HIGH SOR | (2) S.W. & MONT. CARBONATES, W/ WATERFLOOD SOR | (3) GULF COAST SANDSTONES W/WATERFLOOD SOR (HIGH & LOW DIP) | (4) CALIFORNIA APPALACHIAN AND OTHER SANDSTONES |
| I. DEVELOP AND IMPROVE EOR TECHNOLOGY: | | | | | |
| A. IMPROVE RECOVERY EFFICIENCY | | CD-1 | - | (CD-3) | - |
| B. EXTEND APPLICATION OF PROCESS | IC-1 | - | CD-2 | - | CD-4 |
| C. IMPROVE MOBILITY CONTROL | | (CD-1) | (CD-2) | - | - |
| D. TEST SPACING/INJECTION PATTERNS | | (CD-1) | (CD-2) | CD-3 | (CD-4) |
| E. EXAMINE IMPROVED PROCESS EFFICIENCIES | IC-2 | - | - | (CD-3) | - |
| F. DEVELOP NEW PROCESSES | | - | (CD-2) | - | (CD-4) |
| G. BRING TECH. TO CONVENT. APPLIC. | (IC-1) | (CD-1) | - | - | - |
| II. OVERCOME NON-EOR PROCESS CONSTRAINTS: | | | | | |
| A. OVERCOME EMISSION PROBLEMS | (SEC. EFFECTS FROM SD-2) | | | | |
| B. EXAMINE ALTERN. USES AND/OR MKT. FOR WEST COAST OIL | | | | | |
| C. USE SUBSTITUTE (NON-PETRO) FUELS | (SEC. EFFECTS FROM SD-2) | | | | |
| D. DEVELOP CHEAPER/ADEQUATE SUPPLY OF INJECTION MATERIALS | | CD-5 | (SECONDARY EFFECT) | | |
| E. ENSURE ADEQUATE CAPITAL/ ECONOMIC RETURN | | | | | |

EXHIBIT I-6 ANALYSIS OF R&D ACHIEVEMENTS REQUIRED TO STIMULATE PRODUCTION FROM EOR TARGETS (CONTINUED)

| STRATEGIES \ TARGETS | D. SURFACTANT/POLYMER | | | |
|---|---|---|---|---|
| | (1) SHALLOW/HOMOMOGENEOUS SANDSTONES OF THE ILLINOIS BASIN | (2) CALIFORNIA SANDSTONES | (3) GULF COAST SANDSTONES: SALINE; HIGH TEMP; HOMOGEN. | (4) OTHER SANDSTONES PARTICULARLY: MID-CONTINENT, ROCKY MT. & APPALACHIA |
| I. DEVELOP AND IMPROVE EOR TECHNOLOGY: | | | | |
| A. IMPROVE RECOVERY EFFICIENCY | SP-1 | SP-3 | SP-4 | SP-5 |
| B. EXTEND APPLICATION OF PROCESS | | ↓ | ↓ | ↓ |
| C. IMPROVE MOBILITY CONTROL | | | | |
| D. TEST SPACING/INJECTION PATTERNS | | | | |
| E. EXAMINE IMPROVED PROCESS EFFICIENCIES | | | | |
| F. DEVELOP NEW PROCESSES | | | | |
| G. BRING TECH. TO CONVENT. APPLIC. | SP-2 | – | – | – |
| II. OVERCOME NON-EOR PROCESS CONSTRAINTS: | | | | |
| A. OVERCOME EMISSION PROBLEMS | | | | |
| B. EXAMINE ALTERN. USES AND/OR MKT. FOR WEST COAST OIL | | | | |
| C. USE SUBSTITUTE (NON-PETRO) FUELS | | | | |
| D. DEVELOP CHEAPER/ADEQUATE SUPPLY OF INJECTION MATERIALS | SP-6 → | → | → | → |
| E. ENSURE ADEQUATE CAPITAL/ECONOMIC RETURN | | | | |

EXHIBIT I-6 ANALYSIS OF R&D ACHIEVEMENTS REQUIRED TO STIMULATE PRODUCTION FROM EOR TARGETS (CONTINUED)

| STRATEGIES \ TARGETS | E. POLYMER WATERFLOODING | F. SPECIAL TARGETS | | | |
|---|---|---|---|---|---|
| | (1) GENERAL RESERVOIRS | (1) VIRGIN RESVRS. (E.G., N. SLOPE; ELK HILLS) | (2) LOW RECOVERY RESERVOIRS (E.G., SPRAYBERRY TREND) | (3) TIME WINDOW RESERVOIRS (E.G., LA. OFFSHORE) | (4) EOR TARGET RESVRS. W/ SENSITIVE & QUESTIONABLE OIL SATURATION |
| I. DEVELOP AND IMPROVE EOR TECHNOLOGY: | | | | | |
| A. IMPROVE RECOVERY EFFICIENCY | (PW-1) | ST-1 | ST-2 | ST-3 (QUAL.) | |
| B. EXTEND APPLICATION OF PROCESS | PW-1 | - | - | (ST-3)(QUAL.) | |
| C. IMPROVE MOBILITY CONTROL | PW-1 | - | - | - | |
| D. TEST SPACING/INJECTION PATTERNS | | - | (ST-2) | (ST-3)(QUAL.) | ST-4* |
| E. EXAMINE IMPROVED PROCESS EFFICIENCIES | | (ST-1) | (ST-2) | - | |
| F. DEVELOP NEW PROCESSES | | (ST-1) | (ST-2) | - | |
| G. BRING TECH. TO CONVENT. APPLIC. | PW-2 | - | - | - | ST-4* |
| II. OVERCOME NON-EOR PROCESS CONSTRAINTS: | | | | | |
| A. OVERCOME EMISSION PROBLEMS | | | | | |
| B. EXAMINE ALTERN. AND/OR MARKET FOR WEST COAST OIL | | | | | |
| C. USE SUBSTITUTE (NON-PETRO) FUELS | | | | | |
| D. DEVELOP CHEAPER/ADEQUATE SUPPLY OF INJECTION MATERIALS | | | | | |
| E. ENSURE ADEQUATE CAPITAL/ ECONOMIC RETURN | | | | | (ST-4)* |

* PREREQUISITE OT ACHIEVING SUCCESS IN TARGETS A-3, C-2 THROUGH C-4, AND D-2 THROUGH D-4.

EXHIBIT I-6 ANALYSIS OF R&D ACHIEVEMENTS REQUIRED TO STIMULATE PRODUCTION FROM EOR TARGETS (CONTINUED)

| STRATEGIES \ TARGETS | E. POLYMER WATERFLOODING | F. SPECIAL TARGETS | | | |
|---|---|---|---|---|---|
| | (1) GENERAL RESERVOIRS | (1) VIRGIN RESVRS. (E.G., N. SLOPE; ELK HILLS) | (2) LOW RECOVERY RESERVOIRS (E.G., SPRAYBERRY TREND) | (3) TIME WINDOW RESERVOIRS (E.G., LA. OFFSHORE) | (4) EOR TARGET RESVRS. W/ SENSITIVE & QUESTIONABLE OIL SATURATION |
| I. DEVELOP AND IMPROVE EOR TECHNOLOGY: | | | | | |
| A. IMPROVE RECOVERY EFFICIENCY | (PW-1) | ST-1 | ST-2 | ST-3 (QUAL.) | |
| B. EXTEND APPLICATION OF PROCESS | PW-1 | - | - | (ST-3)(QUAL.) | |
| C. IMPROVE MOBILITY CONTROL | PW-1 | - | - | - | |
| D. TEST SPACING/INJECTION PATTERNS | | - | (ST-2) | (ST-3)(QUAL.) | ST-4* |
| E. EXAMINE IMPROVED PROCESS EFFICIENCIES | | (ST-1) | (ST-2) | - | |
| F. DEVELOP NEW PROCESSES | | (ST-1) | (ST-2) | - | |
| G. BRING TECH. TO CONVENT. APPLIC. | PW-2 | - | - | - | ST-4* |
| II. OVERCOME NON-EOR PROCESS CONSTRAINTS: | | | | | |
| A. OVERCOME EMISSION PROBLEMS | | | | | |
| B. EXAMINE ALTERN. AND/OR MARKET FOR WEST COAST OIL | | | | | |
| C. USE SUBSTITUTE (NON-PETRO) FUELS | | | | | |
| D. DEVELOP CHEAPER/ADEQUATE SUPPLY OF INJECTION MATERIALS | | | | | |
| E. ENSURE ADEQUATE CAPITAL/ ECONOMIC RETURN | | | | | (ST-4)* |

* PREREQUISITE OT ACHIEVING SUCCESS IN TARGETS A-3, C-2 THROUGH C-4, AND D-2 THROUGH D-4.

EXHIBIT I-7. ERDA PROGRAM ACTIVITIES IN PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | 8.3 | 3.3 | 1.7 | 1.7 | | 15.0 |
| B. RESERVOIR DATA BASE | 8.3 | 3.0 | 1.0 | | | 12.3 |
| C. RECOVERY MODELS | 11.3 | 13.5 | 11.5 | 10.5 | 3.5 | 50.3 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | 15.8 | 18.0 | 9.5 | 5.0 | 2.0 | 50.3 |
| E. PROCESS/FIELD TEST EVALUATION | 3.3 | 3.0 | 3.0 | 1.0 | 1.0 | 11.3 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 54.3 | 76.7 | 76.7 | 64.0 | 52.0 | 323.7 |
| B. FLOW STUDIES | 49.0 | 108.0 | 126.0 | 126.0 | 99.0 | 508.0 |
| C. FIELD LIAISON & ENG. STUDIES | 35.9 | 53.5 | 49.8 | 36.8 | 34.5 | 210.5 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | * | * | * | * | * | * |
| B. MINI-TESTS 1/ | 1.0 | 15.0 | 12.0 | 1.0 | | 29.0 |
| C. TECHNICAL PILOTS 1/ | 1.0 | 4.0 | | 1.0 | | 6.0 |
| D. ECONOMIC PILOTS 1/ | 8.0 | | 1.0 | 1.0 | | 10.0 |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | – | 1.5 | 2.5 | 0.5 | 4.5 | 9.0 |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ III B,C,D: FIGURES SHOWN ARE FOR PROJECTS STARTING IN EACH YEAR; MANY PROJECTS LAST MORE THAN A SINGLE YEAR. (SEE DETAILED CHARTS FOR INDIVIDUAL PROGRAMS.)

results of these measurements and basic research efforts become available, the emphasis shifts to mini-tests to confirm that extrapolation from laboratory conditions to the actual reservoir is viable. The results of such tests are then fed back into the analysis and laboratory efforts to validate or modify the basic models and process designs. Limited use is made of economic scale pilots except where the urgency of the reservoir conditions precludes the careful sequence of laboratory, mini-tests and technical pilots. The general principle applied in the analysis is that industry, given the appropriate support and economic situation, will conduct the economic pilots and commercial development.

In estimating the costs of individual programs, it was assumed that all person-year costs in activity Categories I, II and IV were fully borne by ERDA. In Category III, field-based research, tests, and demonstrations, a variable rate of cost-sharing between industry and ERDA was applied. ERDA would be responsible for all target identification activities, but the rate of sharing for mini-tests and pilots varied in proportion to the risks involved. In all cases, industry supplies, in kind, existing lease developments, equipment, etc., these in-kind costs have not been included in estimating the costs of field projects. Beyond these contributions, industry's share ranges from zero to fifty percent of incremental, out-of-pocket costs, with ERDA assuming the balance. For example, industry's share would be 25 percent for the pilots involved in improving recovery efficiency of steam drive in shallow reservoirs, but would be 50 percent for attaining acceptable oil/carbon dioxide ratios in high saturation carbonate reservoirs. Given the variable in-kind contributions, these assumptions are in accord with ERDA's guidelines for cost-sharing with industry.

Exhibit I-8 shows the costs of these programs in current (1976) dollars. The cost per year of the programs roughly doubles over the first three years, peaks in 1980, then declines. The total cost for the five-year period is about 260 million dollars, of which the ERDA portion is approximately 244 million dollars.

While it seems reasonable that a successful execution of these programs will stimulate industry to increase ultimate recovery and to recover the oil at a more rapid rate, there is considerable uncertainty as to the likelihood of achieving the R&D objectives. Thus, the estimates of potential recovery and production were reduced by using an expectation of success for each program. Appendix A to this chapter shows the expected production stimulated by each program.[1/]

Given upper tier prices and current tax provisions (the Standard Economics Case), the expected ultimate recovery attributable to stimulation by the ERDA programs is estimated at 14.3 billion barrels. Added to the anticipated recovery by industry alone, 11.9 billion barrels, expected ultimate recovery from EOR reaches 26.2 billion barrels. The ERDA programs combined with industry activity stimulate about a doubling of the industry-alone production in steam drive, carbon dioxide miscible, and polymer waterflooding. Surfactant/polymer flooding becomes feasible in the most favorable reservoirs, contributing one billion barrels to the total and a slight increase is realized from in situ, about 0.1 billion barrels. The special target reservoirs -- Spraberry Trend, Prudhoe Bay, Elk Hills, and offshore Louisiana -- together add about two billion barrels to expected ultimate recovery.

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1/ See Chapter II of Part 3 for a discussion of the approach used for deriving the individual values for expectations of success.

EXHIBIT I-8. ERDA PROGRAM COSTS -- FIVE YEARS
(THOUSANDS OF 1976 DOLLAR COSTS)

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | 500 | 200 | 100 | 100 | - | 900 |
| B. RESERVOIR DATA BASE | 495 | 180 | 60 | - | - | 735 |
| C. RECOVERY MODELS | 745 | 830 | 590 | 780 | 280 | 3225 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | 945 | 1080 | 570 | 300 | 120 | 3015 |
| E. PROCESS/FIELD TEST EVALUATION | 210 | 180 | 180 | 60 | 60 | 690 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 3260 | 4615 | 4600 | 3840 | 3120 | 19435 |
| B. FLOW STUDIES | 3180 | 6480 | 7560 | 7200 | 6060 | 30480 |
| C. FIELD LIAISON & ENG. STUDIES | 2337 | 3735 | 3350 | 2425 | 2250 | 14097 |
| D. LAB EQUIPMENT & FACILITIES | 4510 | 10000 | 6725 | 3950 | 2500 | 27685 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 7350 | 11350 | 7300 | 6800 | 2500 | 35300 |
| B. MINI-TESTS | 1500 | 5000 | 18250 | 22500 | 19250 | 66500 |
| C. TECHNICAL PILOTS | 1000 | 6000 | 6000 | 7500 | 7000 | 27500 |
| D. ECONOMIC PILOTS | 500 | 1500 | 7500 | 8500 | 11500 | 29500 |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | |
| B. SHARE INDUSTRY/ERDA DEVELOP. | - | 90 | 165 | 90 | 210 | 555 |
| TOTAL | 26532 | 51240 | 62950 | 64045 | 54850 | 259617 |
| ERDA SHARE | 24827 | 47365 | 58905 | 60295 | 52725 | 244117 |

Exhibit I-9 shows the expected production rate induced by the ERDA programs under the Standard Economics Case. Because these are increments to the Industry Base Case, they are shown as augmenting the production rates achieved without ERDA's stimulation. (Each line is added to the next lower line.) By 1985, total expected daily production reaches 1.7 million barrels per day. By 1990, it rises to nearly 2.6 million, and by 1995, the rate is 2.9 million barrels per day. Steam drive and carbon dioxide miscible contribute the majority of the production.

Exhibit I-10 shows the cumulative production in response to ERDA stimulation (again under the Standard Economics Case). Cumulative recovery by 1985 more than doubles over the Industry Base Case. By 1990, almost three times as much has been produced and by 1995 cumulative production reaches 13 billion barrels, nearly three and a half times as much as would have been obtained in the Industry Base Case alone. Even with this acceleration, nearly half of the total expected ultimate recovery remains, indicating substantial recovery for the twenty-first century.

Economic conditions different from upper tier prices at $11.63 per barrel and current tax provisions (as assumed in the Standard Economics Case) would significantly affect these outcomes. Exhibit I-11 displays the effects of the price/tax contingencies analyzed in this study on the total expected ultimate recovery. Contrasting the Standard Economics Case to the Lower Bound Case shows that ultimate recovery is reduced about eight percent, primarily by requiring the capitalization of injected materials. The effect is strongest, of course, for carbon

EXHIBIT I-9

# EXPECTED PRODUCTION RATES FOR TOTAL OF INDUSTRY BASE CASE AND ERDA PROGRAM STIMULATION

## (Standard Economics)

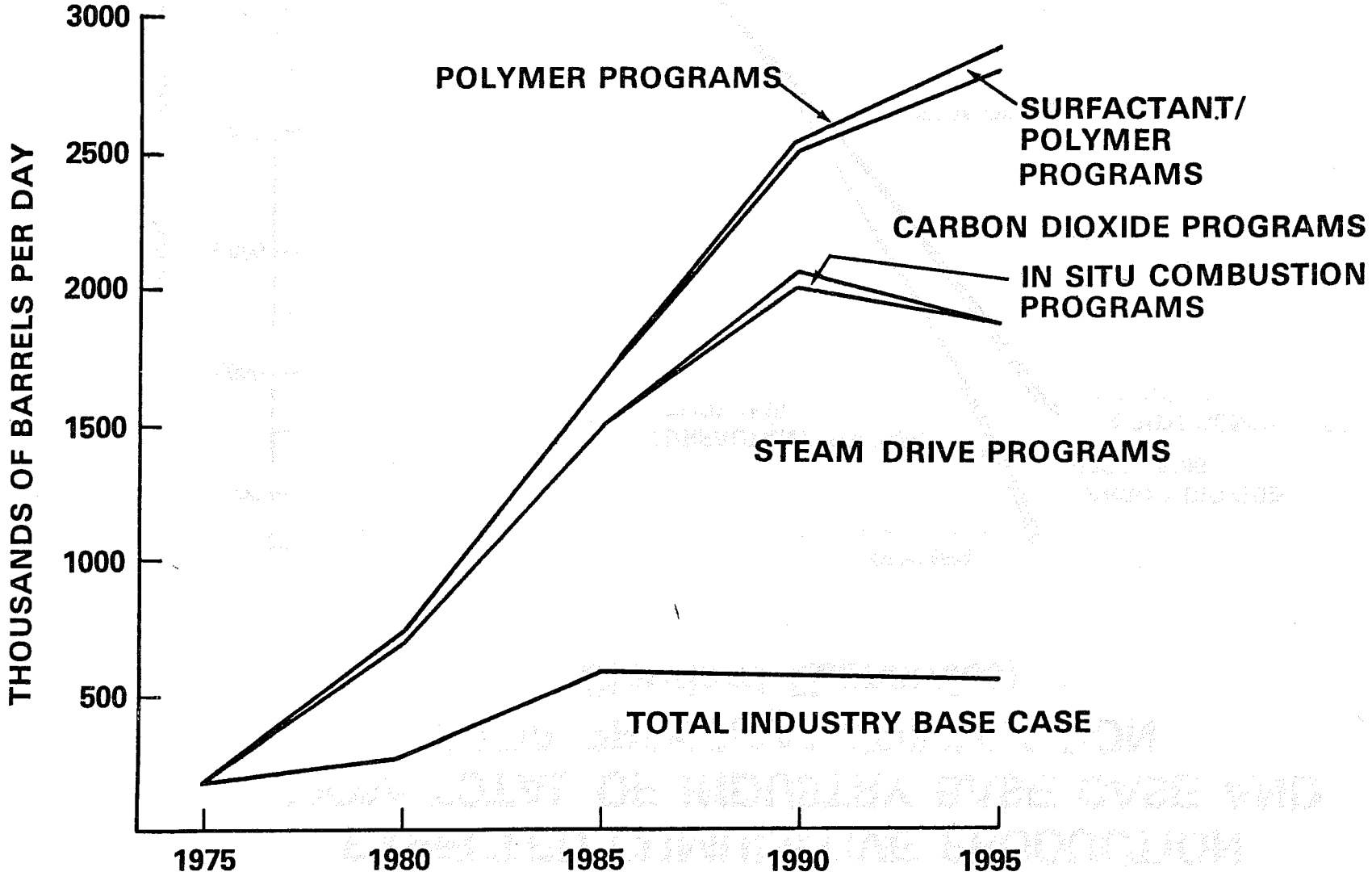


EXHIBIT I-10

# EXPECTED CUMULATIVE PRODUCTION FROM TOTAL OF INDUSTRY BASE CASE AND ERDA PROGRAM STIMULATION
## (Standard Economics)

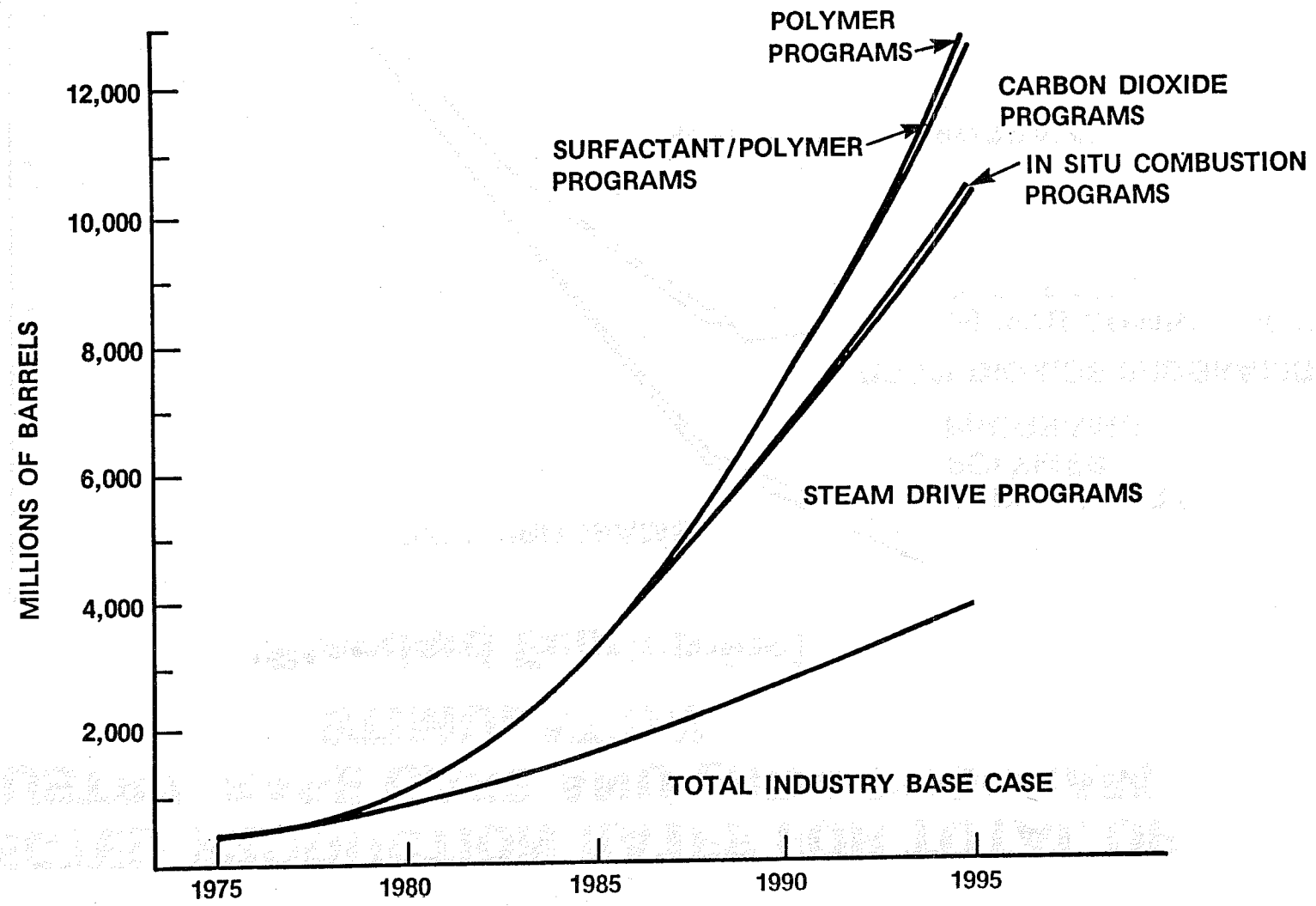
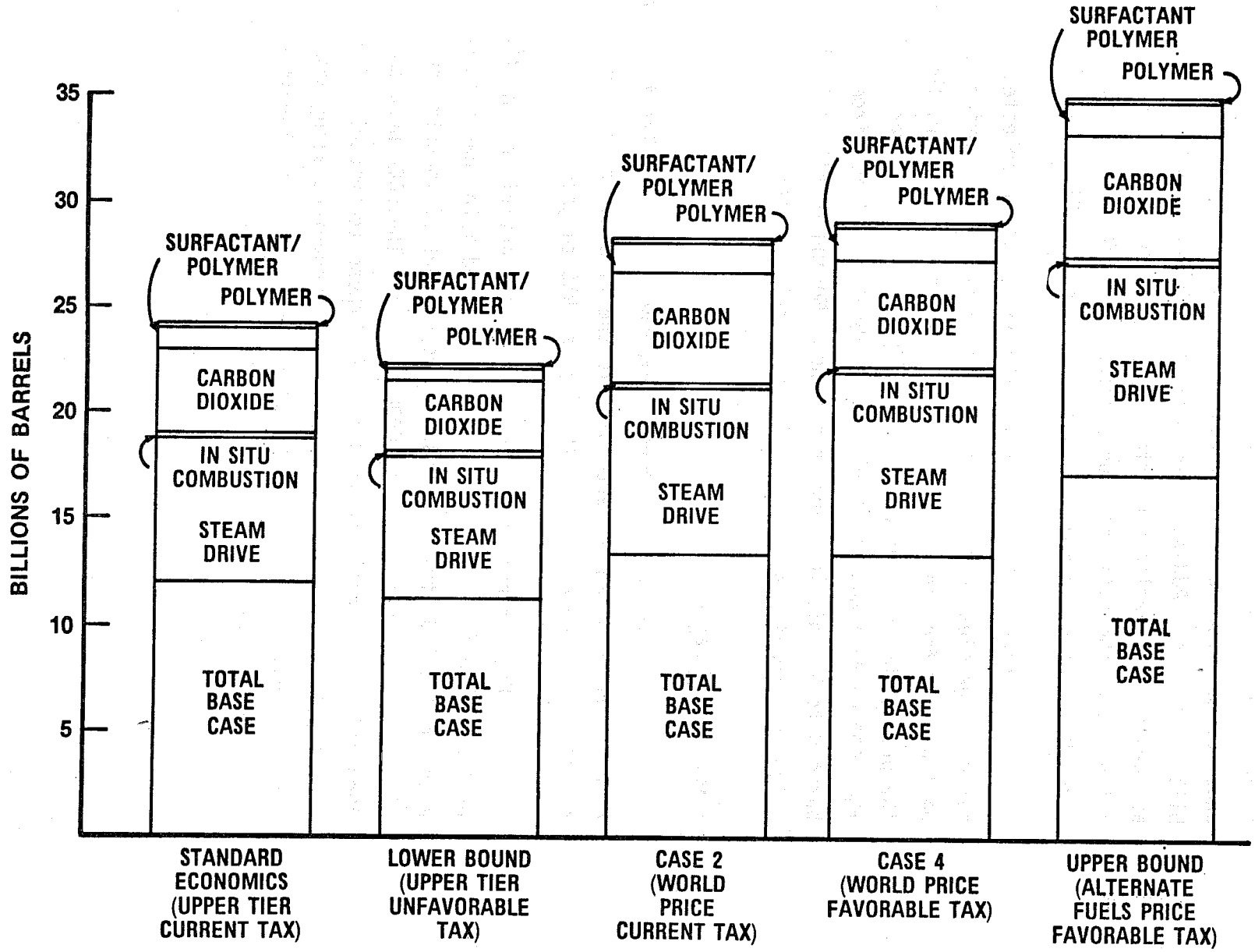


EXHIBIT I-11

# EXPECTED ULTIMATE RECOVERY UNDER PRICE/TAX CONTINGENCIES FOR TOTAL INDUSTRY BASE CASE AND ERDA PROGRAM STIMULATION



dioxide and surfactant processes. Raising prices from upper tier to world oil price levels of $13.00 per barrel, as in Case 2, increases expected ultimate recovery by nearly fifteen percent, from 26 to 30 billion barrels. Adding an improved investment tax credit, Case 4, appears to have negligible effect. Applying further increases in price, up to the alternate fuels price of $20.00 per barrel (the Upper Bound Case) increases ultimate recovery to 37 billion barrels.

Exhibit I-12 shows the influence of three selected price/tax contingencies on the EOR production rate. Higher prices have negligible effect before 1980. After that time, however, the higher the price, the more rapid the rate of production. At world oil prices, the 1990 production rate increases by about one-third, from 2.6 million barrels to 3.4 million barrels per day. Moving to alternate fuels price will provide about 4.3 million barrels per day.

Structure of Part 2

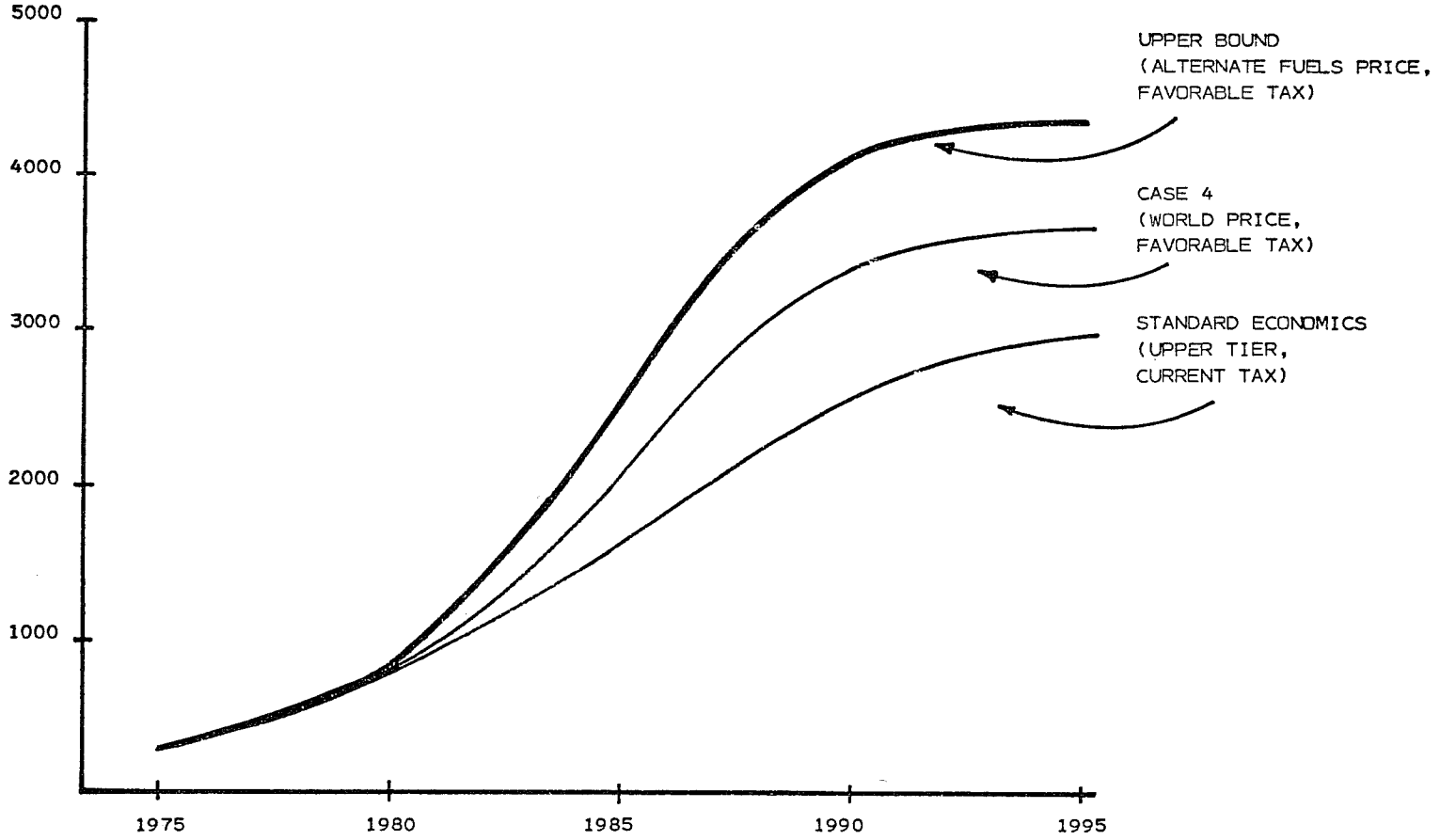
The remainder of Part 2 describes these results in greater detail. It is organized according to the five major techniques, with the final chapter devoted to the special R&D targets.

Each chapter discusses the current activities and the status of the technology. These are then translated into quantitative estimates of the Industry Base Case -- projections of industry production without the stimulation of an ERDA program. The ERDA programs are then defined and analyzed in detail for these techniques. Projections of potential and expected production are presented, along with cost-effectiveness indices for each program. Finally, the Industry Base Case and the production attributable to ERDA's stimulation are analyzed for their sensitivity to price/tax contingencies.

EXHIBIT I-12

EXPECTED PRODUCTION RATES UNDER SELECTED PRICE/TAX CONTINGENCIES

INDUSTRY BASE CASE AND ERDA PROGRAMS



# APPENDIX TO CHAPTER I

EXHIBIT I-13. EXPECTED PRODUCTION BENEFITS STIMULATED BY STEAM DRIVE PROGRAMS

| EXPECTED PRODUCTION BENEFITS \ TARGETS /PROGRAM | TARGET A-1 SHALLOW/HEAVY OIL RESRVS. ≤ 2500'; W/UNSTIMULATED INFLUX | | | | TARGET A-2 OTHER HEAVY OIL RESERVOIRS > 2500'; W/UNSTIMULATED INFLUX | TARGET A-3 LIGHT OIL RESRVS.; THIN, LOW PERM, W/ LOW SOR | TARGET A-4 HEAVY OIL RESRVS. W/ NO INFLUX (TAR SANDS) |
|---|---|---|---|---|---|---|---|
| | SD-1 | SD-2 1/ | SD-3 | SD-4 | SD-5 | SD-6 W/SD-2 | SD-7 |
| 1. EXPECTED ULTIMATE RECOVERY (IN MILLIONS OF BARRELS) | 2300 | 1000 | | | 1600 | 1800* | 0-600 |
| 2. EXPECTED ANNUAL PRODUCTION: (IN THOUSANDS OF BARRELS/DAY) IN: | | | | | | | |
| 1985 | 240 | 120 | 320 | | 120 | 90* | ** |
| 1990 | 320 | 140 | 380 | | 240 | 390* | ** |
| 1995 | 310 | 110 | 290 | | 230 | 380* | ** |
| 3. EXPECTED CUMULATIVE PRODUCTION (IN MILLIONS OF BARRELS) BY: | | | | | | | |
| 1985 | 400 | 190 | 660 | | 110 | 60* | ** |
| 1990 | 980 | 450 | 1400 | | 480 | 560* | ** |
| 1995 | 1510 | 680 | 1960 | | 960 | 1350* | ** |

* THESE FIELDS HAVE BEEN SELECTED FROM LIGHT OIL RESERVOIRS PREVIOUSLY SCREENED INTO SURFACTANT FLOODING, POLYMER AUGMENTED RECOVERY, OR NOT TECHNICALLY ELIGIBLE FOR ENHANCED OIL RECOVERY: THUS THE PRODUCTION BENEFITS MAY DOUBLE COUNT WITH SOME SURFACTANT AND POLYMER TARGETS DISPLAYED UNDER TARGETS D&E.

** INSUFFICIENT DATA FOR MAKING PRODUCTION ESTIMATES: FEA'S ENERGY OUTLOOK (1976) ESTIMATES EXPECTED ANNUAL PRODUCTION AT 24,000 BARRELS PER DAY IN 1985 AND 36,000 BARRELS PER DAY IN 1989; WE BELIEVE THESE ESTIMATES ARE TOO HIGH GIVEN THE POORLY UNDERSTOOD NATURE OF THE RESOURCE BASE AND THE CURRENT LACK OF AN ECONOMIC TECHNOLOGY FOR RECOVERYING THIS OIL.

1/ PRODUCTION BENEFITS OF SD-2 REPRESENT INCREMENTAL PETROLEUM, BUT NOT INCREMENTAL ENERGY. THE SUBSTITUTION OF LESS VALUABLE FUELS (E.G., COAL, REFINERY BOTTOMS) MAKES AVAILABLE THE CRUDE THAT WOULD HAVE BEEN BURNED IN GENERATING STEAM.

EXHIBIT I-13. EXPECTED PRODUCTION BENEFITS FROM CARBON DIOXIDE MISCIBLE AND IN SITU COMBUSTION PROGRAMS

(STANDARD ECONOMICS)

| TARGETS / PROGRAM — EXPECTED PRODUCTION BENEFITS | B. IN SITU COMBUSTION | C. $CO_2$ MISCIBLE | | | | |
|---|---|---|---|---|---|---|
| | (1) HEAVY OIL RESERVOIRS | (1) S.W. & MONT. CARBONATES, W/HIGH SOC | | (2) S.W. & MONT. CARBONATES, W/ WATERFLOOD SOC | (3) GULF COAST SANDSTONES W/WATERFLOOD SOC (HIGH & LOW DIP) | (4) CALIFORNIA APPALACHIAN AND OTHER SANDSTONES |
| | IC-1 & 2 | CD-1 | CD-5 | CD-2 | CD-3 | CD-4 |
| 1. EXPECTED ULTIMATE RECOVERY (IN MILLIONS OF BARRELS) | 100 | 3400 | – | 200* | 200 | 200 |
| 2. EXPECTED ANNUAL PRODUCTION (IN THOUSANDS OF BARRELS/DAY) IN: | | | | | | |
| 1985 | 40 | 140 | 10 | <10* | <10 | <10 |
| 1990 | 40 | 340 | 80 | <10* | <10 | 10 |
| 1995 | 30 | 670 | 160 | 40* | 30 | 30 |
| 3. EXPECTED CUMULATIVE PRODUCTION (IN MILLIONS OF BARRELS) BY: | | | | | | |
| 1985 | 70 | 160 | 10 | 10* | <10 | <10 |
| 1990 | 150 | 610 | 160 | 10* | 10 | 10 |
| 1995 | 200 | 1610 | 390 | 50* | 30 | 40 |

* AT UPPER TIER PRICES AND CONVENTIONAL (8% REAL) RATE OF RETURN: EXPECTED ULTIMATE RECOVERY WOULD BE 840 MILLION BARRELS; EXPECTED ANNUAL PRODUCTION IN 1985, 1990 AND 1995 WOULD BE 4,000 B/D, 9,000 B/D, AND 133,000 B/D RESPECTIVELY; EXPECTED CUMULATIVE PRODUCTION BY 1985, 1990, AND 1995 WOULD BE 10 MILLION BARRELS, 24 MILLION BARRELS AND 153 MILLION BARRELS RESPECTIVELY.

EXHIBIT I-13. EXPECTED PRODUCTION BENEFITS FROM SURFACTANT/POLYMER PROGRAMS

(STANDARD ECONOMIC)

| TARGETS/PROGRAM / EXPECTED PRODUCTION BENEFITS | D. SURFACTANT/POLYMER | | | | |
|---|---|---|---|---|---|
| | (1) SHALLOW/HOMOMOGENEOUS SANDSTONES OF THE ILLINOIS BASIN | | (2) CALIFORNIA SANDSTONES | (3) GULF COAST SANDSTONES: SALINE; HIGH TEMP; HOMOGEN. | (4) OTHER SANDSTONES PARTICULARLY: MID-CONTINENT, ROCKY MT. & APPALACHIA |
| | SP-1 & SP-2 | SP-6 | SP-3 | SP-4 | SP-5 |
| 1. EXPECTED ULTIMATE RECOVERY (IN MILLIONS OF BARRELS) | 400 | * | 600 | ** | *** |
| 2. EXPECTED ANNUAL PRODUCTION (IN THOUSANDS OF BARRELS/DAY) IN: | | | | | |
| 1985 | 0 | * | <10 | ** | *** |
| 1990 | 0 | * | 30 | ** | *** |
| 1995 | 10 | * | 80 | ** | *** |
| 3. EXPECTED CUMULATIVE PRODUCTION (IN MILLIONS OF BARRELS) BY: | | | | | |
| 1985 | <10 | * | <10 | ** | 10*** |
| 1990 | <10 | * | 20 | ** | 10*** |
| 1995 | <10 | * | 80 | ** | 10*** |

* BENEFITS OF LOWER COST SURFACTANTS ALREADY COUNTED IN SP-1 THROUGH SP-5

** UNECONOMIC AT THE TECHNOLOGICAL/ECONOMIC STANDARDS SET FOR THE TARGET, UPPER TIER PRICE AND HIGH RISK (20% REAL) RATE OF RETURN. AT UPPER TIER PRICES AND CONVENTIONAL (8%) REAL RATE OF RETURN: EXPECTED ULTIMATE RECOVERY WOULD BE 75 MILLION; EXPECTED ANNUAL PRODUCTION IN 1985, 1990, AND 1995 AND 1995 WOULD BE 0. 1000 B/D AND <1000 B/D RESPECTIVELY EXPECTED CUMULATIVE PRODUCTION IN 1985, 1990, AND 1995 WOULD BE 0, <1, AND 3 MILLION BARRELS RESPECTIVELY.

*** UNECONOMIC AT THE TECHNOLOGICAL/ECONOMIC STANDARDS SET FOR THE TARGET, UPPER TIER PRICE AND HIGH RISK (20% REAL) RATE OF RETURN. AT UPPER TIER PRICES AND CONVENTIONAL (8%) REAL RATE OF RETURN: EXPECTED ULTIMATE RECOVERY WOULD BE 684 MILLION BARRELS; EXPECTED ANNUAL PRODUCTION IN 1985, 1990, AND 1995 WOULD BE 0.0, AND 60,000 B/D, RESPECTIVELY: EXPCETED CUMULATIVE PRODUCTION IN 1985, 1990, AND 1995 WOULD BE 6 MILLION BARRELS, 9 MILLION BARRELS, AND 67 MILLION BARRELS, RESPECTIVELY.

EXHIBIT I-13. EXPECTED PRODUCTION BENEFITS FROM SPECIAL TARGETS PROGRAMS

(STANDARD ECONOMICS)

| TARGET/PROGRAM / EXPECTED PRODUCTION BENEFITS | E. IMPROVED WATERFLOODING | F. SPECIAL TARGETS | | | |
|---|---|---|---|---|---|
| | (1) GENERAL RESERVOIRS | (1) VIRGIN RESVRS. (E.G., N. SLOPE; ELK HILLS) | (2) LOW RECOVERY RESERVOIRS (E.G., SPRAYBERRY TREND) | (3) TIME WINDOW RESERVOIRS (E.G., LA. OFFSHORE) | (4) EOR TARGET RESVRS. W/ SENSITIVE & QUESTIONABLE OIL SATURATION |
| | IW 1 & 2 | ST-1 | ST-2 | ST-3 | ST-4 |
| 1. EXPECTED ULTIMATE RECOVERY (IN MILLIONS OF BARRELS) | 70 | PRUDHOE BAY: 1500-1900 ELK HILLS: 150-300 | 30-40 | 180-210 | THIS PROGRAM IS A PREREQUISITE TO TARGETS: A-3 C-2, C-3, C-4 D-2, D-3, D-4 |
| 2. EXPECTED ANNUAL PRODUCTION (IN THOUSANDS OF BARRELS/DAY) IN: | | | | | |
| 1985 | 20 | * | * | * | |
| 1990 | 10 | * | * | * | |
| 1995 | 0 | * | * | * | |
| 3. EXPECTED CUMULATIVE PRODUCTION (IN MILLIONS OF BARRELS) BY: | | | | | |
| 1985 | 50 | * | * | * | |
| 1990 | 70 | * | * | * | |
| 1995 | 70 | * | * | * | |

* REQUIRES FURTHER STUDY BEFORE RELIABLE ESTIMATES CAN BE MADE AS TO THE INCREMENTAL ANNUAL PRODUCTION DUE TO ERDA'S PROGRAM

# CHAPTER II

# STEAM DRIVE

## SECTION A: GENERAL DISCUSSION

### Description and Current Application of the Technology

Of all the EOR processes, steam drive comes closest to being considered a proven and widely used technique. Sufficient empirical information has been accumulated and disseminated in the engineering literature to allow steam drive to approach conventional usage.

The first modern attempt to use the steam drive technique occurred in Venezuela in the late fifties. The test was aborted when it was found by accident that the steam soak injecting steam into a well, then stopping and resuming production from the same well, was a more useful and profitable technique for accelerating oil production from heavy oil reservoirs. The steam soak (or cyclic steam), however, is generally limited in the amount of the reservoir the steam can contact and as a result recovery efficiency from the entire reservoir is limited.

Steam drive involves the injection of steam into a set of injection wells and the production of oil from another, offsetting pattern of producing wells, much as in waterflooding. The steam works by dehydrating and de-oiling the reservoir adjacent to the injection well, and driving the water and oil ahead to form an oil bank ahead

of the steamed out zone. The oil bank under ideal conditions is driven ahead, increasing in size, until it is produced at the offsetting production well. In actual operation, it is difficult to maintain the stability of the steam zone in back of the bank, and eventually steam breaks through into the producing well. Following steam breakthrough, oil production may be continued for some time by reducing injection rates and pressure, and the steam will now act to "drag" the heated oil into the producing wells.

Industry activity in using steam drive can be summarized in terms of past and current steam drive projects, as shown below in Exhibit II-1.

EXHIBIT II-1

Steam Drive Activity Summary

| | Technical Pilots | | Economic Pilots | | Fieldwide Development | |
|---|---|---|---|---|---|---|
| | Total | Current | Total | Current | Total | Current |
| Projects | 17 | 13 | 15 | 14 | 15 | 15 |
| Reservoirs | 13 | 9 | 12 | 8 | 11 | 11 |

In addition, current activity is characterized by the following facts:

- Currently, 15,682 acres are under development.
- The majority of projects and by far the majority of the acreage under steam drive are in California.

- Additional field activity occurs in Arkansas, Louisiana, Texas, and Wyoming, but is mostly early in development.
- In 1975 the use of steam drive provided over 100,000 barrels of oil per day, mostly in California.
- Current project activity is in relatively shallow reservoirs. No fieldwide development or economic pilot is deeper than 2300 feet. Only one technical pilot has gone as deep as 2500 feet.
- Steam drive projects tend to be in thicker pays bearing heavy viscous but flowing oils.

Even for such ideal reservoirs, the instability of the steam zone results in part of the formation being swept by hot water. This problem is compounded in that the current practice is to inject steam of less than 100% quality. Considerable problems exist in generating high quality steam with available brackish waters. As a result the injected steam segregates into hot water and live steam in the well bore and in the formation immediately at the start of the process, the water sweeping through the bottom part of the reservoir. The fraction so swept depends on reservoir and operating characteristics. The research problems associated with steam drive are further discussed below.

## Problems and Opportunities

The current technological status of and industry activity in steam drive is characterized by numerous constraints that impede its maximum utilization. Thus, even this relatively proven process presents numerous research opportunities:

1. The areal sweep of a steam drive in any single, relatively uniform sand is very high. This occurs despite the apparent poor mobility process. However, vertical sweep is affected by heterogeneities in the sand package, in fingering through depleted zones, and by the segregation of the vapor and steam condensate. Since the steam condensate is not as effective a displacement agent as the steam vapor (i.e., it does not reduce the residual saturation to as low a value), the overall reservoir recovery is limited. Displacement and sweep efficiency might be improved by introducing substances mixed with steam, alternating with steam, and/or following steam to reduce the residual saturation in those parts of the reservoir swept by steam condensate, or to isolate or plug thief zones and depleted zones.

2. Steam drive is an energy intensive scheme. In a typical steam drive project, nearly one-third of the produced crude is consumed in generating the required steam. Should one be able to substitute coal (or the less valuable refinery bottoms) for crude oil or fuel oil in generating steam, the domestic availability of crude oil or liquid fuels would be increased by the amount of such substitution. Such a substitution would: (a) extend economic limits of steam drive projects, and (b) increase the number of economically attractive candidate reservoirs. Therefore, recovery efficiency from already operating reservoirs and the number of economically feasible reservoirs would increase with a decrease in fuel costs.

3. Regulations in California now limit the amount of emissions that can be introduced into the air. The maintenance of clear air provisions limit these emissions to the total amount of emissions known

to exist in 1972. As a result, new steam drive operations cannot be implemented until others are suspended. Therefore, no expansion in the production of crude oil by steam drive can be anticipated until either a variance from maintenance of clean air regulations is obtained or lower emission methods for steam generation are devised and implemented. While no greater ultimate production would be expected from these estimates, the production rates could be substantially increased during the critical period 1985-1995.

4. Heavy crude oil production is geographically centered in the San Joaquin Valley (California), with substantial production also being achieved in the Los Angeles Basin fields. These crudes are transported to those refineries which have the capability of processing them and disposing of the additional quantities of pitch or coke that they yield. In late 1977, the West Coast anticipates the influx of North Slope oil. It will be a large source of crude of somewhat higher gravity than steam-produced crudes, but nevertheless, for refinery purposes, having some of the same characteristics. While it is not known at this time the exact competitive position of the heavy San Joaquin crude streams viz-a-viz the Prudhoe Bay crude, it seems likely that there will be an oversupply relative to available refinery capacity on the West Coast. Redistribution or alternate uses of the crude supply or expansion of capacity (and associated production distribution) should be envisioned. There is also evidence that the current "entitlements" program works to the disadvantage of heavy California crudes relative to imported, higher gravity crudes. Unless these problems are solved, it appears that the production of heavy oils using steam drive could be significantly limited.

It is distinctly possible that alternate uses of the heavy crude streams from California can be found. They can be topped on location and a more valuable distillate sent to the refinery, with the residues being used for boiler fuel or in combined power facilities where power and intermediates (such as hydrogen, carbon dioxide) are generated, in addition to steam for local use.

5. Depth poses a major limitation for steam drive. Fieldwide development and the economic pilots are all at less than 2300 feet, with the majority at less than 1500 feet. Only limited industry effort is being devoted to recovering oil at greater depths. In deep reservoirs, the radial heat losses from the injection string and difficulties in maintaining the mechanical integrity of the string itself have placed a depth limitation on the application of the steam drive process when other conditions would indicate its usefulness. The problem is compounded when the reservoir pressure and steam injection rates are such as to require the use of high pressure to inject the steam. Now, because so much of the heat of the steam is contained in the sensible heat of the liquid, steam bank development is retarded and much of the heat is produced in hot water reaching the producing wells. For the process to be efficient, heat recuperative techniques have to be applied. Possible solutions include combining displacement and sweep efficiencies; adding inert gases to reduce the partial pressure of the steam, thus reducing the temperature and consequent heat losses (but enabling the process to maintain a high total pressure upstream of the oil bank); and combining steam and air to supply heat by oxidation of the crude to supplement the latent heat of the injected steam.

6. Since steam will drive the contacted oil to a producer, and practically sweep clean a formation containing residual light oil (because of the additional effects of oil volatility), it is well to consider how this very effective displacement process can be extended to reservoirs other than the heavy oils of California. A substantial number of shallow, light oil reservoirs in Texas, Louisiana, and mid-continent have characteristics such as low residual oil saturations, thin pays, and/or low permeabilities that appear to make them economically unattractive for tertiary production. The chemical recovery processes that could be applied to these fields are unproven and even when proven would be costly. Under current economic limits imposed by an oil/steam ratio based on a fuel of comparable value to produced crude, steam drive is also economically unattractive. Without some form of improvement, these reservoirs would remain unproduced in the foreseeable future. However, process improvements such as the use of alternative fuels and additives to the steam could make such reservoirs highly attractive.

7. Steam drive or modifications of this process have, to date, been tried in only a limited way in accumulations of non-flowing heavy oils. Although non-flowing oils near the surface may be mineable, the deeper accumulations have so far eluded recovery. Even these, however, may be exploitable if they meet conditions by which the heat content of steam can be transferred to the oil. These conditions would include the presence of depleted gas zones, water zones, or fractures that would disseminate the heat. Fracturing along with steam drive might make these deposits accessible.

Future Directions of Industry Application -- The Base Case

Our discussions with industry practitioners, interviews with producers' management, and examination of the literature on steam drive support the conclusion that future industry activity will closely resemble that already underway. The environmental and market constraints, coupled with the present, relatively profitable operations, suggest that there is and will be only limited industry effort applied to the problems and opportunities described above. Based on examination of existing projects, this argues that industry's efforts will be strongly concentrated in relatively heavy (but flowing), shallow, oil reservoirs with high bulk oil saturations.

Taking into account the constraints on production due to refinery demand and environmental regulations and the types of reservoirs currently being tested and produced by industry, the Industry Base Case[1/] for steam drive is:

| | |
|---|---|
| Ultimate Recovery | 6.2 billion barrels |
| Production Rate In: | |
| 1985 | 110 thousand barrels per day |
| 1990 | 110 |
| 1995 | 110 |
| Cumulative Production By: | |
| 1985 | 540 million barrels |
| 1990 | 740 |
| 1995 | 940 |

1/ See Part 3, Chapter I, for a discussion of the methodology used for estimating the Base Case.

These estimates assume the Standard Economics price and tax contingency (i.e., upper tier price and current tax laws). The comparable effects of other price/tax contingencies are displayed in Exhibit II-2. Neither rising prices nor changes in taxes affect the production rate or cumulative production in the period of interest because of the non-EOR process constraints in California. Likewise, tax changes have no effect on ultimate recovery. Major increases in price and ultimate recovery, such as moving from the upper tier ($11.63/bbl) to alternate fuels levels ($20.00/bbl), adds 600 million barrels to ultimate recovery.

Overview of the Steam Drive Program

The generic problems and opportunities described above lead directly to the definitions of targets and research and development strategies for steam drive. These targets and strategies are as follows:

- Shallow, heavy oil reservoirs, less than about 2500 feet with unstimulated influx, and with oil gravities greater than about $11^{o}$ to $12^{o}$ API (and less than $25^{o}$ API).

  -- Apply and extend the current technology

  -- Improve recovery efficiency

  -- Use cheaper non-petroleum fuels (rather than crude oil and fuel oil) to generate steam

EXHIBIT II-2

INDUSTRY BASE CASE FOR STEAM DRIVE UNDER PRICE TAX CONTINGENCIES

| | STANDARD ECONOMICS (UPPER TIER W/ CURRENT TAX) | LOWER BOUND (UPPER TIER W/ UNFAV. TAX) | CASE 2 (WORLD PRICE W/ CURRENT TAX) | CASE 4 (WORLD PRICE W/ FAVORABLE TAX) | UPPER BOUND (ALTERNATE FUELS PRICE W/ FAVORABLE TAX) |
|---|---|---|---|---|---|
| ULTIMATE RECOVERY (BILLION BARRELS) | 6.2 | 6.2 | 6.6 | 6.6 | 6.8 |
| PRODUCTION RATE IN: (THOUSAND BARRELS PER DAY) | | | | | |
| 1985 | 110 | 110 | 110 | 110 | 110 |
| 1990 | 110 | 110 | 110 | 110 | 110 |
| 1995 | 110 | 110 | 110 | 110 | 110 |
| CUMULATIVE PRODUCTION BY: (MILLION BARRELS) | | | | | |
| 1985 | 540 | 540 | 540 | 540 | 540 |
| 1990 | 740 | 740 | 740 | 740 | 740 |
| 1995 | 940 | 940 | 940 | 940 | 940 |

-- Overcome emission problems or secure a variance on emissions

-- Examine alternative use of heavy crudes and/or markets for West Coast oil.

- Deeper, heavy reservoirs, deeper than 2500 feet, with unstimulated influx, and with oil gravities greater than about 12$^{o}$ API (and less than 25$^{o}$ API).

  -- Overcome heat loss problems in injection string, design reliable injection string, and develop efficient techniques for recuperating produced heat in deeper, heavy oil reservoirs.

- Light oil reservoirs (greater than 25$^{o}$ API), typically marked by thinner pays, lower permeability, and lower oil saturations than the first group of reservoirs listed above.

  -- Extend the application of the process to such reservoirs by using cheaper fuels for generating steam.

- Heavy oil reservoirs with no influx and with gravities between 8$^{o}$ API and 11$^{o}$ API.

  -- Extend the application of the process to non-flowing oils.

Research programs were defined and costed for each combination of strategies and targets. Exhibit II-3 shows the structure of the steam drive programs and the designations for the programs, which are described in Section B of this Chapter.

Exhibit II-4 summarizes these programs in physical units, either in person years or number of field projects. The steam drive programs grow from $4.7 mm in 1977 to a peak of $16.6 mm in 1979, then decline slightly. The total five-year cost is $61.2 mm, with ERDA's share being estimated at $57.6 mm.

Exhibit II-5 sets forth the costs of the steam drive programs, using constant, 1976 dollars.

The potential recovery and production attributable to the steam drive research programs (and calculated under the Standard Economics assumptions) is shown in Exhibit II-6.

The potential production multiplied by the expectation of success derives the expected recovery and production, as shown on Exhibit II-7.[2/]

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2/ The methodology used for calculating potential and expected recovery and production is described in Part 3, Chapters I and V.

EXHIBIT II-3 STRUCTURE OF THE STEAM DRIVE PROGRAMS

| STRATEGIES \ TARGETS | A. STEAM DRIVE | | | |
|---|---|---|---|---|
| | (1) SHALLOW/HEAVY OIL RESERVOIRS ≤ 2500', WITH UNSTIMULATED INFLUX | (2) OTHER HEAVY OIL RESERVOIRS > 2500', WITH UNSTIMULATED INFLUX | (3) LIGHT OIL RESERVOIRS THIN, LOW PERM. W/ LOW SOR | (4) HEAVY OIL RESERVOIRS W/ NO INFLUX (TAR SANDS) |
| I. DEVELOP AND IMPROVE EOR TECHNOLOGY: | | | | |
| A. IMPROVE RECOVERY EFFICIENCY | SD-1 | – | (SD-6) | – |
| B. EXTEND APPLICATION OF PROCESS | – | SD-5 | SD-6 W/SD-2 | SD-7 (QUALITATIVE) |
| C. IMPROVE MOBILITY CONTROL | (SD-1) | – | – | – |
| D. TEST SPACING/INJECTION PATTERNS | (SD-1) | – | – | – |
| E. EXAMINE IMPROVED PROCESS EFFICIENCIES | – | – | – | SD-7 (QUALITATIVE) |
| F. DEVELOP NEW PROCESSES | – | – | – | SD-7 (QUALITATIVE) |
| G. BRING TECH. TO CONVENT. APPLIC. | – | SD-5 | (SD-6) | – |
| II. OVERCOME NON-EOR PROCESS CONSTRAINTS: | | | | |
| A. OVERCOME EMISSION PROBLEMS | SD-3 | (SECONDARY EFFECT) | – | |
| B. EXAMINE ALTERN. USES AND/OR MKT. FOR WEST COAST OIL | SD-4 | (SECONDARY EFFECT) | – | |
| C. USE SUBSTITUTE (NON-PETRO) FUELS | SD-2 | (SECONDARY EFFECT) | (SPILLOVER BENEFITS) | |
| D. DEVELOP CHEAPER/ADEQUATE SUPPLY OF INJECTION MATERIALS | – | – | – | |
| E. ENSURE ADEQUATE CAPITAL/ ECONOMIC RETURN | – | – | – | |

EXHIBIT II-4. ALL STEAM DRIVE PROGRAMS -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | 2 | 1.0 | 1.0 | | | 4 |
| C. RECOVERY MODELS | 1 | 2.5 | 1.5 | 0.5 | 0.5 | 6 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | 6 | 6.5 | 4.5 | 2.0 | 2.0 | 21 |
| E. PROCESS/FIELD TEST EVALUATION | 1 | 1.0 | 1.0 | 1.0 | 1.0 | 5 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 5 | 10 | 11 | 13 | 11 | 50 |
| B. FLOW STUDIES | 17 | 30 | 29 | 30 | 28 | 134 |
| C. FIELD LIAISON & ENG. STUDIES | 9 | 22 | 18 | 6.5 | 6.5 | 62 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | * | * | * | * | * | * |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | 9 → | | | | | 9 |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS / B. SHARE INDUSTRY/ERDA DEVELOP. | | 0.5 | 0.5 | 0.5 | 0.5 | 2 |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

PGM: ALL CD

EXHIBIT IV-5. THE CARBON DIOXIDE PROGRAMS
IN 1976 DOLLARS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL 1/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | 60 | | | | | 60 |
| C. RECOVERY MODELS | 120 | 60 | | | | 180 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | 240 | 240 | 300 | 120 | | 900 |
| E. PROCESS/FIELD TEST EVALUATION | 60 | 60 | | | | 120 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 540 | 960 | 1020 | 900 | 840 | 4260 |
| B. FLOW STUDIES | 360 | 1620 | 2400 | 2400 | 2040 | 8820 |
| C. FIELD LIAISON & ENG. STUDIES | 177 | 295 | 390 | 390 | 315 | 1567 |
| D. LAB EQUIPMENT & FACILITIES | 1000 | 2750 | 1600 | 600 | 600 | 6550 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 3000 | 2250 | | | | 5250 |
| B. MINI-TESTS | | 1750 | 6500 | 9000 | 6250 | 23500 |
| C. TECHNICAL PILOTS | 1000 | 3000 | 2000 | 1500 | 3000 | 10500 |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. / B. SHARE INDUSTRY/ERDA DEVELOP. | | 60 | 60 | 60 | 60 | 240 |
| TOTAL | 6557 | 13045 | 14270 | 14970 | 13105 | 61947 |
| ERDA SHARE | 5557 | 10545 | 12020 | 13720 | 12980 | 54822 |

(ERDA SHARE BASED ON 50% CD-1 FIELD; 50% CD-3 FIELD FOR 1977, 78, 79)

1/ POST 1981 COMMITMENTS: $7,500,000 EACH IN 1982 AND 1983, TO PREVIOUSLY INITIATED FIELD OPERATIONS. IN ADDITION, AN AVERAGE COMMITMENT OF $3.7 MILLION PER YEAR IS ANTICIPATED FROM 1982 TO 1986.

EXHIBIT II-6. POTENTIAL PRODUCTION BENEFITS OF STEAM DRIVE PROGRAMS
(STANDARD ECONOMICS)

| TARGETS /PROGRAM — POTENTIAL PRODUCTION BENEFITS | TARGET A-1 | | | | TARGET A-2 | TARGET A-3 | TARGET A-4 |
|---|---|---|---|---|---|---|---|
| | SHALLOW/HEAVY OIL RESRVS. ≤ 2500'; W/UNSTIMULATED INFLUX | | | | OTHER HEAVY OIL RESERVOIRS > 2500'; W/UNSTIMULATED INFLUX | LIGHT OIL RESRVS.; THIN, LOW PERM, W/ LOW SOR | HEAVY OIL RESRVS. W/ NO INFLUX (TAR SANDS) |
| | SD-1 | SD-2 1/ | SD-3 | SD-4 | SD-5 | SD-6 W/SD-2 | SD-7 |
| 1. ULTIMATE RECOVERY (IN MILLIONS OF BARRELS) | 3100 | 3100 | | | 3600 | 3100* | 0-5000 |
| 2. ANNUAL PRODUCTION: (IN THOUSANDS OF BARRELS/ DAY) IN: | | | | | | | |
| 1985 | 310 | 380 | 380 | | 260 | 160* | ** |
| 1990 | 430 | 430 | 760 | | 540 | 690* | ** |
| 1995 | 410 | 340 | 580 | | 500 | 670* | ** |
| 3. CUMULATIVE PRODUCTION (IN MILLIONS OF BARRELS) BY: | | | | | | | |
| 1985 | 530 | 570 | 1310 | | 250 | 110* | ** |
| 1990 | 1300 | 1360 | 2790 | | 1080 | 980* | ** |
| 1995 | 2020 | 2040 | 3930 | | 2130 | 2360* | ** |

* THESE FIELDS HAVE BEEN SELECTED FROM LIGHT OIL RESERVOIRS PREVIOUSLY SCREENED INTO SURFACTANT FLOODING, POLYMER AUGMENTED RECOVERY, OR NOT TECHNICALLY ELIGIBLE FOR ENHANCED OIL RECOVERY: THUS THE PRODUCTION BENEFITS MAY DOUBLE COUNT WITH SOME SURFACTANT AND POLYMER TARGETS DISPLAYED UNDER TARGETS D&E.

** INSUFFICIENT DATA FOR MAKING PRODUCTION ESTIMATES: FEA'S ENERGY OUTLOOK (1976) ESTIMATES ANNUAL PRODUCTION AT 200,000 BARRELS PER DAY IN 1985 AND 300,000 BARRELS PER DAY IN 1989; WE BELIEVE THESE ARE TOO HIGH GIVEN THE POORLY UNDERSTOOD NATURE OF THE RESOURCE BASE AND THE CURRENT LACK OF AN ECONOMIC TECHNOLOGY FOR RECOVERYING THIS OIL.

1/ PRODUCTION BENEFITS OF SD-2 REPRESENT INCREMENTAL PETROLEUM, BUT NOT INCREMENTAL ENERGY. THE SUBSTITUTION OF LESS VALUABLE FUELS (E.G., COAL, REFINERY BOTTOMS) MAKES AVAILABLE THE CRUDE THAT WOULD HAVE BEEN BURNED IN GENERATING STEAM.

EXHIBIT II-7 - EXPECTED PRODUCTION BENEFITS FROM STEAM DRIVE PROGRAMS (STANDARD ECONOMICS)

| TARGET/PROGRAM — EXPECTED PRODUCTION BENEFITS | TARGET A-1 | | | | TARGET A-2 | TARGET A-3 | TARGET A-4 |
|---|---|---|---|---|---|---|---|
| | SHALLOW/HEAVY OIL RESRVS. ≤ 2500'; W/UNSTIMULATED INFLUX | | | | OTHER HEAVY OIL RESERVOIRS > 2500'; W/UNSTIMULATED INFLUX | LIGHT OIL RESRVS.; THIN, LOW PERM, W/ LOW SOR | HEAVY OIL RESRVS. W/ NO INFLUX (TAR SANDS) |
| | SD-1 | SD-2 1/ | SD-3 | SD-4 | SD-5 | SD-6 W/SD-2 | SD-7 |
| 1. EXPECTED ULTIMATE RECOVERY (IN MILLIONS OF BARRELS) | 2300 | 1000 | — | | 1600 | 1800* | 0-600 |
| 2. EXPECTED ANNUAL PRODUCTION (IN THOUSANDS OF BARRELS/DAY) IN: | | | | | | | |
| 1985 | 240 | 120 | 320 | | 120 | 90* | ** |
| 1990 | 320 | 140 | 380 | | 240 | 390* | ** |
| 1995 | 310 | 110 | 290 | | 230 | 380* | ** |
| 3. EXPECTED CUMULATIVE PRODUCTION (IN MILLIONS OF BARRELS) BY: | | | | | | | |
| 1985 | 400 | 190 | 660 | | 110 | 60* | ** |
| 1990 | 980 | 450 | 1400 | | 480 | 560* | ** |
| 1995 | 1510 | 680 | 1960 | | 960 | 1350* | ** |

* THESE FIELDS HAVE BEEN SELECTED FROM LIGHT OIL RESERVOIRS PREVIOUSLY SCREENED INTO SURFACTANT FLOODING, POLYMER AUGMENTED REOCVERY, OR NOT TECHNICALLY ELIGIBLE FOR ENHANCED OIL RECOVERY: THUS THE PRODUCTION BENEFITS MAY DOUBLE COUNT WITH SOME SURFACTANT AND POLYMER TARGETS DISPLAYED UNDER TARGETS D & E.

** INSUFFICIENT DATA FOR MAKING PRODUCTION ESTIMATES: FEA'S ENERGY OUTLOOK (1976) ESTIMATES EXPECTED ANNUAL PRODUCTION AT 24,000 BARRELS PER DAY IN 2985 AND 36,000 BARRELS PER DAY IN 1989; WE BELIEVE THESE ESTIMATES ARE TOO HIGH GIVEN THE POORLY UNDERSTOOD NATURE OF THE RESOURCE BASE AND THE CURRENT LACK OF AN ECONOMIC TECHNOLOGY FOR RECOVERYING THIS OIL.

1/ PRODUCTION BENEFITS OF SD-2 REPRESENT INCREMENTAL PETROLEUM, BUT NOT INCREMENTAL ENERGY. THE SUBSTITUTION OF LESS VALUABLE FUELS (E.G., COAL, REFINERY BOTTOMS) MAKES AVAILABLE THE CRUDE THAT WOULD HAVE BEEN BURNED IN GENERATING STEAM.

For the full set of steam drive programs, the total benefits are:

| | Potential Production | Expected Production | |
|---|---|---|---|
| Ultimate Recovery | 12.9-17.9 | 6.7-7.3 | billion barrels |
| Production Rate | | | |
| 1985 | 1750 | 890 | thousand barrels per day |
| 1990 | 2850 | 1470 | |
| 1995 | 2500 | 1320 | |
| Cumulative Production | | | |
| 1985 | 2770 | 1420 | million barrels |
| 1990 | 7510 | 3840 | |
| 1995 | 12480 | 6460 | |

To relate research costs to expected production, a series of cost-effectiveness indices were calculated for each program, as shown in Exhibit II-8. Under the Standard Economics contingency, all the steam drive programs were found to be highly cost-effective. On the basis of ultimate recovery, the programs for flowing oils range from 88 to 451 expected barrels per ERDA dollar (equivalent to an R&D investment of less than $0.01 per recovered barrel). In 1990 production rates, a dollar of ERDA funds yields between 4 and 138 additional barrels per year. The lack of data concerning non-flowing oils (tar sands) makes the calculation of its cost-effectiveness uncertain, but this program

EXHIBIT II-8. MEASURES OF EFFECTIVENESS OF STEAM DRIVE
(STANDARD ECONOMICS)

| MEASURES OF EFFECTIVENESS \ TARGET/PROGRAM | TARGET A-1 | | | | TARGET A-2 | TARGET A-3 | TARGET A-4 |
|---|---|---|---|---|---|---|---|
| | SHALLOW/HEAVY OIL RESRVS. ≤ 2500'; W/UNSTIMULATED INFLUX | | | | OTHER HEAVY OIL RESERVOIRS > 2500'; W/UNSTIMULATED INFLUX | LIGHT OIL RESRVS.; THIN, LOW PERM, W/ LOW SOR | HEAVY OIL RESRVS. W/ NO INFLUX (TAR SANDS) |
| | SD-1 | SD-2 1/ | SD-3 | SD-4 | SD-5 | SD-6 W/SD-2 | SD-7 |
| 1. EXPECTED ULTIMATE RECOVERY (IN MILLIONS OF BARRELS) | 88 | 206 | | | 561 | 125* | 0-44 |
| 2. EXPECTED ANNUAL PRODUCTION (IN THOUSANDS OF BARRELS/DAY) IN: | | | | | | | |
| 1985 | 3.3 | 9.1 | 117.0 | | 15.0 | 2.4* | ** |
| 1990 | 4.4 | 10.5 | 137.9 | | 30.7 | 10.1* | ** |
| 1995 | 4.3 | 8.4 | 106.4 | | 28.7 | 9.8* | ** |
| 3. EXPECTED CUMULATIVE PRODUCTION (IN MILLIONS OF BARRELS) BY: | | | | | | | |
| 1985 | 15 | 38 | 657 | | 39 | 5 * | ** |
| 1990 | 38 | 91 | 1400 | | 167 | 40 * | ** |
| 1995 | 58 | 136 | 1971 | | 332 | 95 * | ** |

* THESE FIELDS HAVE BEEN SELECTED FROM LIGHT OIL RESERVOIRS PREVIOUSLY SCREENED INTO SURFACTANT FLOODING, POLYMER AUGMENTED REOCVERY, OR NOT TECHNICALLY ELIGIBLE FOR ENHANCED OIL RECOVERY: THUS THE PRODUCTION BENEFITS MAY DOUBLE COUNT WITH SOME SURFACTANT AND POLYMER TARGETS DISPLAYED UNDER TARGETS D & E.

** INSUFFICIENT DATA FOR MAKING PRODUCTION ESTIMATES.

1/ PRODUCTION BENEFITS OF SD-2 REPRESENT INCREMENTAL PETROLEUM, BUT NOT INCREMENTAL ENERGY. THE SUBSTITUTION OF LESS VALUABLE FUELS (E.G., COAL, REFINERY BOTTOMS) MAKES AVAILABLE THE CRUDE THAT WOULD HAVE BEEN BURNED IN GENERATING STEAM.

could provide up to 44 barrels of expected ultimate recovery per ERDA R&D dollar.[3/]

Finally, steam drive programs were subjected to sensitivity analysis of five price/tax contingencies. Exhibit II-9 shows the effects of these contingencies on the expected production of the steam drive programs.

Tax and price (maintained in real terms relative to costs) appear to directly affect the expected ultimate recovery from the ERDA stimulated programs, although price has the stronger influence. Ultimate recovery would rise from 7.0 to 8.7 billion barrels. If the price changed from upper tier to world price, it could reach 9.2 billion barrels under a $20.00 per barrel alternate fuels price. Similarly, production in 1990 could range from 1,500 MB/D (under the Standard Economics Case) to nearly 2,000 MB/D (under world prices/more favorable taxes) and up to over 2300 MB/D given alternate fuels price. The production rate peaks around 1990, at the mid-point of the most critical period under all the price/tax contingencies. Cumulative production by 1995 could range from 6.4 to over 9 billion barrels, depending on price/tax contingencies.

---

3/ The activities conducted for one class of reservoir can have certain beneficial effects on other reservoir classes. For example, the use of cheaper fuels (Research Program SD-2) while analyzed for shallow, heavy oils, will directly benefit the production of light oils and will have secondary effects on deeper heavy oils. Similarly, the benefits of overcoming non-process constraints in California (allocated to shallow, heavy oils) will enable the deeper oils in that state to be developed. These secondary and spill-over benefits have not been quantified in the above measures of effectiveness.

EXHIBIT II-9

EFFECTS OF PRICE/TAX CONTINGENCIES ON EXPECTED PRODUCTION FROM STEAM DRIVE PROGRAMS

| | STANDARD ECONOMICS (UPPER TIER W/ CURRENT TAX) | LOWER BOUND (UPPER TIER W/ UNFAV. TAX) | CASE 2 (WORLD PRICE W/ CURRENT TAX) | CASE 4 (WORLD PRICE W/ FAVORABLE TAX) | UPPER BOUND (ALTERNATE FUELS PRICE W/ FAVORABLE TAX) |
|---|---|---|---|---|---|
| EXPECTED ULTIMATE RECOVERY (BILLION BARRELS) | 7.0 | 6.9 | 8.2 | 8.7 | 10.1 |
| EXPECTED PRODUCTION RATE IN: (THOUSAND BARRELS PER DAY) | | | | | |
| 1985 | 890 | 870 | 1180 | 1220 | 1450 |
| 1990 | 1470 | 1440 | 1860 | 1970 | 2300 |
| 1995 | 1320 | 1310 | 1400 | 1500 | 1570 |
| EXPECTED CUMULATIVE PRODUCTION BY: (MILLION BARRELS) | | | | | |
| 1985 | 1420 | 1410 | 1660 | 1680 | 1860 |
| 1990 | 3870 | 3780 | 4800 | 4980 | 5780 |
| 1995 | 6460 | 6320 | 7760 | 8220 | 9430 1/ |

1/ CUMULATIVE PRODUCTION WILL EXCEED EXPECTED ULTIMATE RECOVERY THROUGH THE YEAR 2000 AND THEN DECLINE TO THE EXPECTED ULTIMATE RECOVERY TOTAL. THIS ANOMALOUS EFFECT ARISES FROM THE ACCELERATION EFFECT DERIVED FROM RAISING CONSTRAINTS. THE ERDA PROGRAMS SP-3/SP-4 SERVE TO INCREASE THE PRODUCTION RATE BUT DO NOT ADD ULTIMATE RECOVERY DURING THE CRITICAL PERIOD.

SUMMARY: Combined Effects of Industry Activity and the Steam Drive Programs

The total potential of steam drive can be examined by combining the Industry Base Case with Industry's production stimulated by the ERDA programs. Under the Standard Economics condition, total expected ultimate recovery would be 12.9 to 13.5 billion barrels, depending on the feasibility of non-flowing oil reservoirs. Exhibits II-10 and II-11 show the expected production rates and cumulative production for all of steam drive. (In both Exhibits the contribution of each program is added to that of the next lower tier.) The combined production rate, in 1990, is expected to be nearly 1.6 million barrels per day. Moreover, steam drive is the one application proven to have the quickest response. For example, assuming a vigorous application of the research program, steam drive could provide over 7 billion barrels of oil between now and 1995.

A substantial portion of the production shown comes from the application of currently existing technology. The Industry Base Case is constrained to its flat level by the non-EOR processes factors of environmental regulations and market restrictions. Achieving breakthroughs that relax these constraints would permit industry to further apply the current, almost conventional technology in reservoirs where it is proved. The impact of this step can be seen by adding the quantities for the Base Case to those of SD-3 and SD-4 (the programs to deal with these constraints). Approximately 30 percent of the peak year (1990) production would come from current technology. This application also accounts for over a third of the cumulative production by 1995.

EXHIBIT II-10

EXPECTED STEAM DRIVE PRODUCTION RATES
(STANDARD ECONOMICS)

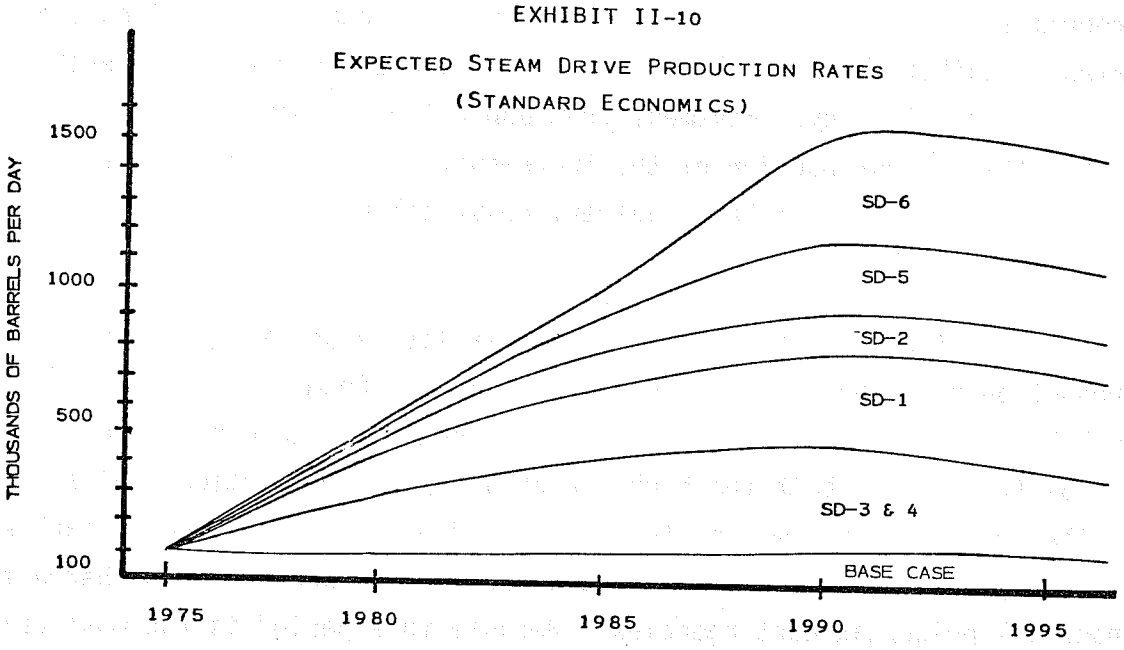
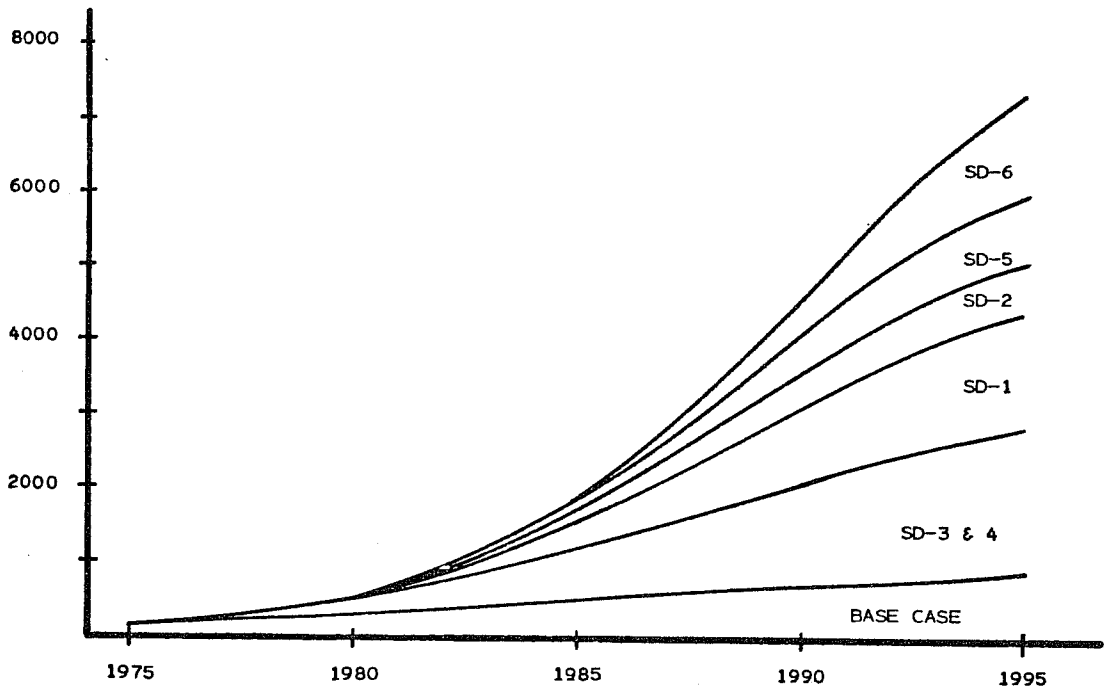



EXHIBIT II-11

EXPECTED STEAM DRIVE CUMULATIVE PRODUCTION
(STANDARD ECONOMICS)



The combined ultimate recovery of the Base Case and the ERDA program's stimulation responds only slightly to changes in prices and taxes. Exhibit II-12 displays expected ultimate recovery under each price/tax contingency. Movement from upper tier to world prices brings the largest portion of the increment, mostly through the enlargement of the benefits of SD-5, deeper, heavy oil reservoirs -- and SD-6 -- the poorer, light oil reservoirs.

Although ultimate recovery shows little sensitivity, the production rate shows more pronounced effects. From three cases shown in Exhibit II-13, movement of price from upper tier to world levels yields the bulk of both the higher peak and the acceleration, relative to the increment from moving to alternate fuels price. As noted earlier, the steam drive production rate peaks around 1990 and declines thereafter under all price/tax contingencies. Because this period is the most critical in terms of dependence on imports, however, steam drive is a most important technique from the national perspective.

EXHIBIT II-12

EXPECTED ULTIMATE RECOVERY UNDER

PRICE/TAX CONTINGENCIES FROM STEAM DRIVE PROGRAMS

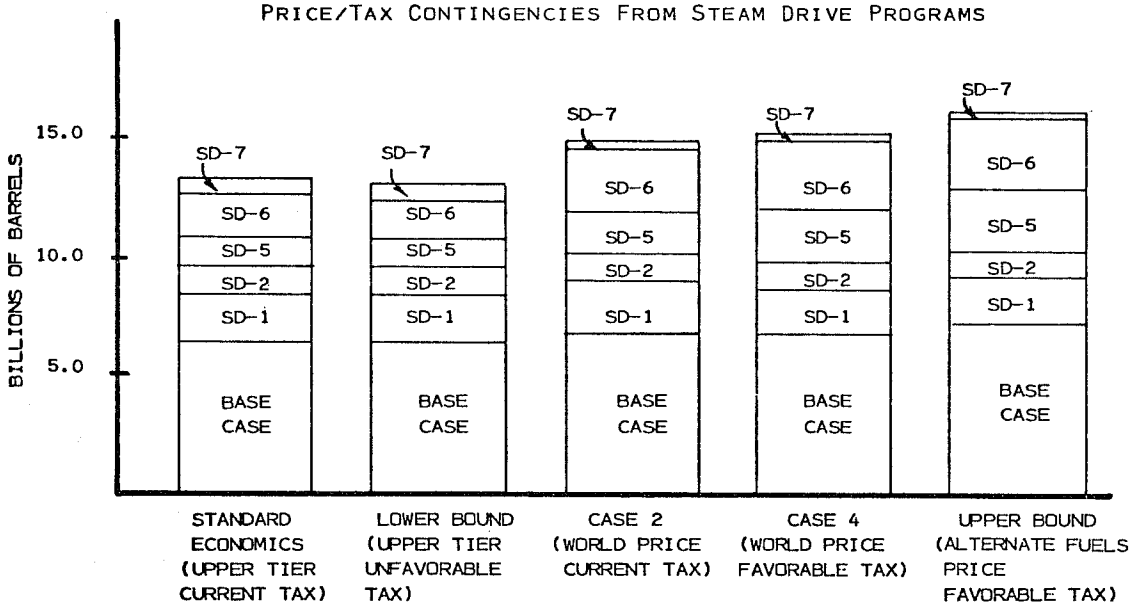
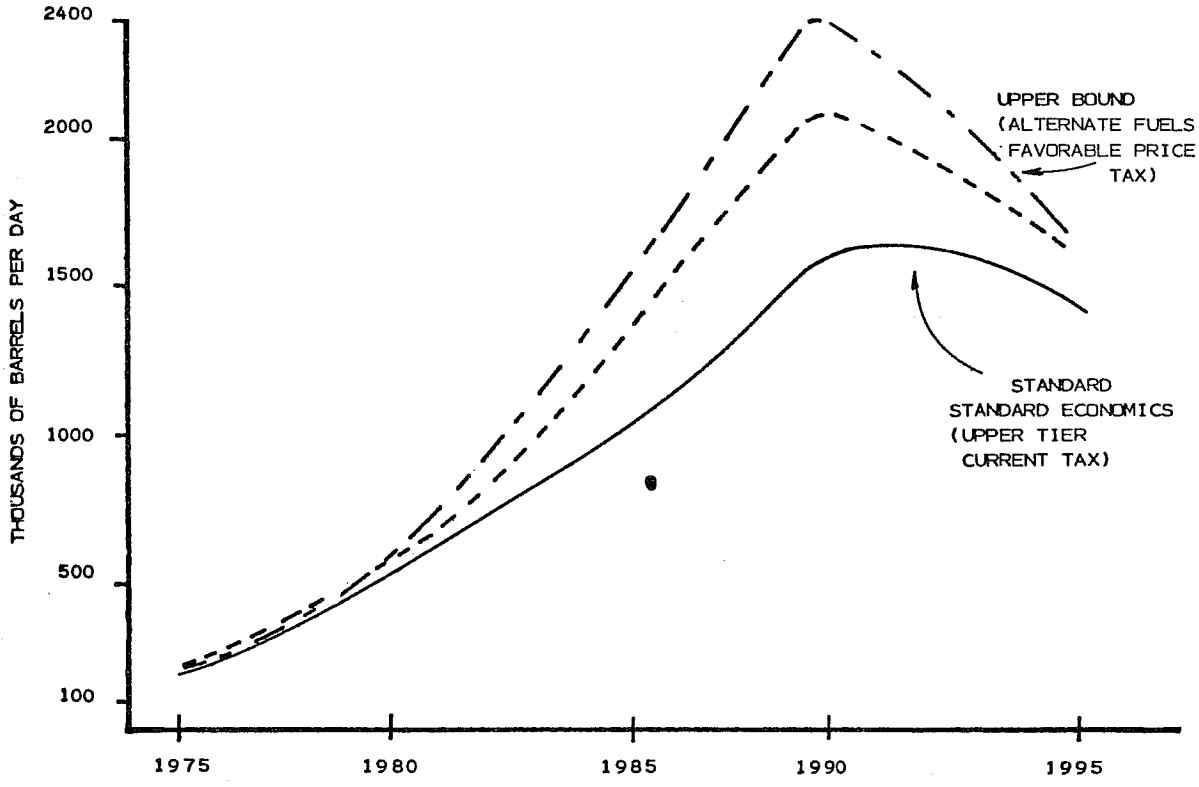



EXHIBIT II-13

EXPECTED STEAM DRIVE PRODUCTION RATES UNDER

SELECTED PRICE/TAX CONTINGENCIES

(COMBINED BASE CASE AND ERDA PROGRAMS)



## SECTION B: INDIVIDUAL STEAM DRIVE PROGRAMS

TARGET A-1: SHALLOW, HEAVY OIL RESERVOIRS; LESS THAN 2500', WITH SOME UNSTIMULATED INFLUX

R&D STRATEGY SD-1: IMPROVE RECOVERY EFFICIENCY

1. CENTRAL PROBLEM

While improving recovery efficiency is a research strategy that cuts across each of the steam drive targets, it has been highlighted for this particular target (group of reservoirs) because, once developed, it can be rapidly applied to the reservoirs already under full scale steam drive development.

The areal sweep of a steam drive in any single, relatively uniform sand is very high. This occurs despite the apparent poor mobility ratio of steam compared to oil because of the unique steam displacement process. However, vertical sweep is affected by heterogeneities in the sand package, in fingering through depleted zones, and by the segregation of the vapor and steam condensate. Since the steam condensate is not as effective a displacement agent as the steam vapor (i.e., it does not reduce the residual saturation to as low a value) the overall reservoir recovery is limited.

2. R&D GOALS

- To improve displacement efficiency by introducing substances mixed with steam, alternating with steam, and/or following steam to reduce the residual saturation in those parts of the reservoir swept by steam condensate. The substances to be tested include surfactants, solvents, soluble gases, pH controlling agents, and polymers.

- To investigate improvements in sweep efficiency by isolating or plugging thief zones and depleted zones by the application of well completion techniques or by injection reacting mixtures or foam-forming systems.

- The eventual R&D goal is to improve the overall recovery efficiency of steam drive by 50%.

3. R&D ACTIVITIES

The R&D activities would consist of a sequence of tasks as follows:

I. Building the Knowledge Base: starting in 1977

-- Evaluations of past and ongoing industry efforts.

-- Mathematical reservoir simulation.

II. Basic and Applied Research: starting in 1977

-- Physical chemistry bench experiments.

-- Flow tests in cores, sand packs, and scaled physical models.

III. Field Based Activities

-- Identify appropriate targets for the economic pilot starting in 1977.

-- Economic pilot tests in reservoirs currently being exploited by steam drive operations, starting in 1978.

IV. Transfer and Dissemination

PGM: SD-1

4. R&D ACTIVITIES --PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | | | | | | – |
| C. RECOVERY MODELS | | | | | | – |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | | | | | – |
| E. PROCESS/FIELD TEST EVALUATION | 1 | 1 | 1 | 1 | 1 | 5 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 4 | 7 | 7 | 7 | 7 | 32 |
| B. FLOW STUDIES | 10 | 20 | 20 | 20 | 20 | 90 |
| C. FIELD LIAISON & ENG. STUDIES | 1 | 2.5 | 2.5 | 2.5 | 2.5 | 11 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | 8 → | | | | | 8 1/ |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): 2/ | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ FIELD OPERATIONS WILL BE SUPERIMPORSED ON ONGOING, COMMERCIAL OPERATIONS.

2/ INCLUDED IN ABOVE FIGURES.

PGM: SD-1

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL 1/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | - |
| B. RESERVOIR DATA BASE | | | | | | - |
| C. RECOVERY MODELS | | | | | | - |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | | | | | - |
| E. PROCESS/FIELD TEST EVALUATION | 60 | 60 | 60 | 60 | 60 | 300 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 240 | 420 | 420 | 420 | 420 | 1920 |
| B. FLOW STUDIES | 600 | 1200 | 1200 | 1200 | 1200 | 5400 |
| C. FIELD LIAISON & ENG. STUDIES | 60 | 150 | 150 | 150 | 150 | 660 |
| D. LAB EQUIPMENT & FACILITIES | 650 | 2000 | 1500 | 500 | 300 | 4950 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | - |
| B. MINI-TESTS | | | | | | - |
| C. TECHNICAL PILOTS | | | | | | - |
| D. ECONOMIC PILOTS | 500 | 1500 | 2500 | 5000 | 5000 | 14500 2/ |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 3/ |
| TOTAL | 2110 | 5330 | 5830 | 7330 | 7130 | 27730 |
| ERDA SHARE | 1985 | 4955 | 5205 | 6080 | 5880 | 24105 |

1/ POST 1981 COMMITMENTS: AN AVERAGE OF $2,000,000 PER YEAR FOR 5 YEARS, 1982-1986

2/ FIELD OPERATIONS WILL BE SUPERIMPOSED ON ONGOING, COMMERCIAL OPERATIONS

3/ INCLUDED IN ABOVE COSTS

PGM: SD-1

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 23103 | 28973 |
| ERDA'S SHARE | 20184 | 26053 |

7. EXPECTATION OF SUCCESS: 75%

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 3,100 | 2,300 | 88 |
| DAILY PRODUCTION IN: | | | |
| 1985 | 315 | 236 | 3.3 |
| 1990 | 426 | 319 | 4.4 |
| 1995 | 414 | 310 | 4.3 |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 532 | 399 | 15 |
| 1990 | 1302 | 977 | 38 |
| 1995 | 2017 | 1513 | 58 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

TARGET A-1 (Continued)

R&D STRATEGY SD-2: USE CHEAPER NON-PETROLEUM FUELS (RATHER THAN CRUDE OIL AND FUEL OIL) TO GENERATE STEAM

1. CENTRAL PROBLEM

Steam drive is an energy intensive scheme. (In a typical steam drive project, nearly one-third of the produced crude is consumed in generating the required steam.) Should one be able to substitute coal (or the less valuable refinery bottoms) for crude oil or fuel oil in generating steam, the domestic availability of crude oil or liquid fuels would be increased by the amount of such substitution.

A second problem facing the application of steam drive is that the economic limit for injecting steam is reached when the oil/steam ratio falls to such a value that operating costs are equal to the value of the produced crude. Operating costs are dominated by fuel costs for generating steam. It follows that cheaper fuels result in (a) the extension of the economic limit and (b) increasing the number of economically attractive candidate reservoirs. Therefore, both recovery efficiency from an already operating reservoir and the number of economically feasible reservoirs will increase with a decrease in fuel costs.

This strategy when realized: (a) will have immediate application to the Target A-1 reservoirs (those already being produced and similar to those in production); (b) will be vital to the successful development of Target A-3, Steam Drive in Light Oil Reservoirs; and (c) will have secondary benefits in Target A-2, the deeper heavy oil reservoirs.

## 2. R&D GOALS

- To demonstrate that steam generators using cheaper fuels, particularly coal, are feasible for oil field service. The overall goal is the design and ultimate development of steam generators that use coal as fuel and are economically and environmentally preferable to the use of oil- and gas-fired generators. Feasibility studies on the transportation and storage of coal to oil field locations will be required as an integral part of the study. The environmental influence of such proposed operations will need to be carefully spelled out so that an appropriate socio-economic assessment of the use of coal for such purposes can be made.

- The first order R&D goal is to make available, for other domestic usage, the crude oil/fuel oil now used for generating steam. Complementary goals will be to: (a) realize sufficiently low steam costs to make economic the currently economically unfavorable Target A-3 light oil reservoirs; and (b) extend the economic limit of already being produced Target A-1, shallow, heavy oil reservoirs.

## 3. R&D ACTIVITIES

The R&D activities would consist of a sequence of tasks as follows:

I. Building the Knowledge Base: starting in 1977

-- Studying economic feasibility of coal shipments and storage on-site.

-- Environmental studies of coal usage on-site.

II. Basic and Applied Research: starting in 1977

-- Design work on coal fired steam generators.

-- Tests of alternate size models for economic scale.

-- Examination into alternate means for transporting the generators among sites.

III. Field Based Activities

-- Prototype construction of boilers to verify laboratory results, starting in 1979.

-- Economic pilots in conjunction with field based activities being considered for Programs SD-1 and SD-6, starting in 1979.

PGM: SD-2

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | - |
| B. RESERVOIR DATA BASE | | | | | | - |
| C. RECOVERY MODELS | | | | | | - |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | 2 | 2 | 2 | 1 | 1 | 8 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | - |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | - |
| B. FLOW STUDIES | | | | | | - |
| C. FIELD LIAISON & ENG. STUDIES | 2 | 12 | 6 | | | 20 |
| D. LAB EQUIPMENT & FACILITIES * | | | | | | - |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | 1 → | → | → | 1 1/ |
| B. MINI-TESTS | | | | | | - |
| C. TECHNICAL PILOTS | | | | | | - |
| D. ECONOMIC PILOTS | | | | | | 2/ |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 3/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ PROTOTYPES

2/ FIELD OPERATIONS TO BE CONDUCTED WITH RUD PROGRAMS SD-1 AND SD-6.

3/ INCLUDED IN THE ABOVE FIGURES.

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

PGM: SD-2

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL 1/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | - |
| B. RESERVOIR DATA BASE | | | | | | - |
| C. RECOVERY MODELS | | | | | | - |
| D. ECONOMIC & OTHER FEASIB. STUDIES | 120 | 120 | 120 | 60 | 60 | 480 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | - |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | - |
| B. FLOW STUDIES | | | | | | - |
| C. FIELD LIAISON & ENG. STUDIES | 200 | 1080 | 500 | | | 1780 |
| D. LAB EQUIPMENT & FACILITIES | | | | | | - |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | 250 | 2000 | 500 | 2750 |
| B. MINI-TESTS | | | | | | - |
| C. TECHNICAL PILOTS | | | | | | - |
| D. ECONOMIC PILOTS | | | | | | 2/ |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 3/ |
| TOTAL | 320 | 1200 | 870 | 2060 | 560 | 5010 |
| ERDA SHARE | 320 | 1200 | 870 | 2060 | 560 | 5010 |

1/ POST 1981 COMMITMENTS: $250,000 PER YEAR FROM 1982 TO 1986.

2/ FIELD OPERATIONS TO BE CONDUCTED WITH R&D PROGRAMS SD-1 AND SD-6.

3/ INCLUDED IN ABOVE COSTS.

PGM: SD-2

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 4224 | 4958 |
| ERDA'S SHARE | DO | DO |

7. EXPECTATION OF SUCCESS: 33%

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 3100 | 1023 | 206 |
| DAILY PRODUCTION IN: | | | |
| 1985 | 375 | 124 | 9.1 |
| 1990 | 434 | 143 | 10.5 |
| 1995 | 344 | 114 | 8.4 |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 570 | 190 | 38 |
| 1990 | 1360 | 450 | 91 |
| 1995 | 2050 | 685 | 136 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

TARGET A-1 (Continued)

R&D STRATEGY SD-3: OVERCOME EMISSION PROBLEMS AND/OR SECURE VARIANCE ON EMISSIONS

1. CENTRAL PROBLEM

Regulations now limit the amount of emissions that can be introduced into the air. The maintenance of clean air provisions limit these emissions to the total amount of emissions known to exist in 1972. As a result, new thermal operations cannot be implemented until others are suspended. Therefore, no expansion in the production of crude oil by thermal operations can be anticipated until some variance from maintenance of clean air regulations is obtained or less polluting methods of steam generation are devised. However, any suspension of regulations on, for example, carbon dioxide emissions, would have to be won by limiting the simultaneous emission of some of the more detrimental products such as sulphurous oxides and nitrogen oxides.

2. R&D GOALS

- To develop steam generators and/or ancillary techniques for controlling emissions of steam generators, and/or systems of fuel utilization which reduce the levels of proscribed combustion products to acceptable levels.

- The eventual R&D goal is to remove the current production ceiling on Target A-1 reservoirs; secondary benefits would be realized as Target A-2 reservoirs are brought under development.

3. R&D ACTIVITIES

The R&D activities would consist of a sequence of tasks as follows:

I. Building the Knowledge Base: starting in 1977

-- Conduct cost/benefit studies in socio-economic terms of the effects of allowing greater flexibility in the application of emission standards.

-- Examine the effect of ancillary techniques for controlling emissions on the economic threshold of steam drive.

II. Basic and Applied Research: starting in 1977

-- Study means of controlling levels of proscribed combustion effluents from field steam generators.

-- Study effect of using alternate fuels on such levels.

-- Study effect of using integrated field usage of produced crude, viz., topping and use of heavy ends in combined power cycles for generation of steam and other products, see Target A-1, Strategy SD-4.

III. Field-Based Activities

-- Test findings using field based activities in program SD-1 and SD-6.

PGM: SD-3

4. R&D ACIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | | | | | | – |
| C. RECOVERY MODELS | | | | | | – |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | 1 | 1 | | | | 2 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | – |
| B. FLOW STUDIES | | | | | | – |
| C. FIELD LIAISON & ENG. STUDIES | 1 | 1 | 1 | | | 3 |
| D. LAB EQUIPMENT & FACILITIES * | | | | | | – |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | – |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | 1/ |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ FIELD OPERATIONS TO BE CONDUCTED WITH R&D PORGRAMS SD-1 AND SD-6.

2/ INDLUDED IN ABOVE FIGURES.

5. COSTS OF R&D ACTIVIES (THOUSANDS OF 1976 DOLLARS): PGM: SD-3

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | - |
| B. RESERVOIR DATA BASE | | | | | | - |
| C. RECOVERY MODELS | | | | | | - |
| D. ECONOMIC & OTHER FEASIB. STUDIES | 60 | 60 | | | | 120 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | - |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | - |
| B. FLOW STUDIES | | | | | | - |
| C. FIELD LIAISON & ENG. STUDIES | 60 | 60 | 60 | | | 180 |
| D. LAB EQUIPMENT & FACILITIES | | | | | | - |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | - |
| B. MINI-TESTS | | | | | | - |
| C. TECHNICAL PILOTS | | | | | | - |
| D. ECONOMIC PILOTS 1/ | | | | | | 1/ |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |
| TOTAL | 120 | 120 | 60 | | | 300 |
| ERDA SHARE | 120 | 120 | 60 | | | 300 |

1/ FIELD OPERATIONS TO BE CONDUCTED WITH R&D PROGRAMS SD-1 AND SD-6.

2/ INCLUDED IN ABOVE COSTS.

NOTE: Please see R&D strategy SD-4 for the discussion of items:

6. Present Value of Costs.
7. Expectation of Success.
8. Outcome of the R&D Program.

TARGET A-1 (Continued)

## R&D STRATEGY SD-4: EXAMINE ALTERNATE USE OF HEAVY CRUDES AND/OR MARKETS FOR WEST COAST OIL

### 1. CENTRAL PROBLEM

Heavy crude oil production is geographically centered in the San Joaquin Valley (California) with some lesser production being achieved in the Los Angeles Basin fields. These crudes are transported to those refineries which have the capability of processing them and disposing of the additional quantities of pitch or coke that they yield. In late 1977 the West Coast anticipates the influx of North Slope oil. It will be another large source of crude of somewhat higher gravity than steam-produced crudes, but nevertheless for refinery purposes having some of the same characteristics. While it is not known at this time the exact competitive position of the heavy San Joaquin crude stream viz-a-viz the Prudhoe Bay crude, it seems likely that there will be an oversupply available on the West Coast and redistribution or alternate uses of the crude supply should be envisioned. Unless this problem is solved, it appears that the production of heavy oils using steam drive could be significantly curtailed.

### 2. R&D GOALS

- To study alternate economic uses for the San Joaquin Valley heavy crude stream, to maximize its value as a refinery intake stream, a source of local fuel and power, and/or as feed stock for petrochemicals.

- The eventual R&D goal is to remove the current production ceiling on Target A-1 reservoirs, thus this strategy is complementary to strategy SD-3 (overcoming emission problems); secondary benefits would be realized as Target A-2 reservoirs are brought on stream.

3. R&D ACTIVITIES

The R&D activities would consist of a sequence of tasks as follows:

I. Building the Knowledge Base: starting in 1977

-- Study the feasibility of using the total crude stream for large scale generation of electric power for California and neighboring states.

-- Study the feasibility of using the total crude stream, or the pitch or residue from topping operations in combined power cycle plants for generation of power, process steam, carbon dioxide if needed for enhanced recovery operations, and hydrogen (for further petrochemical processing or a world scale ammonia plant).

II. Basic and Applied Research: starting in 1977

-- Study the feasibility of central collection and processing of the heavy crude stream to a pitch or coke for use in steam generators and a distillate of considerably higher value as a refinery intake stream.

-- Study alternative approaches of boiler design for using such pitch or coke for central steam generation facilities.

PGM: SD-4

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | - |
| B. RESERVOIR DATA BASE | | | | | | - |
| C. RECOVERY MODELS | | | | | | - |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | 2 | 2 | | | | 4 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | - |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | - |
| B. FLOW STUDIES | | | | | | - |
| C. FIELD LIAISON & ENG. STUDIES | 1 | 3 | 5 | | | 9 |
| D. LAB EQUIPMENT & FACILITIES * | | | | | | - |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | - |
| B. MINI-TESTS | | | | | | - |
| C. TECHNICAL PILOTS | | | | | | - |
| D. ECONOMIC PILOTS | | | | | | 1/ |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ FIELD OPERATIONS TO BE CONDUCTED WITH R&D PROGRAMS SD-1 AND SD-6.

2/ INCLUDED IN ABOVE FIGURES.

PGM: SD-4

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | - |
| B. RESERVOIR DATA BASE | | | | | | - |
| C. RECOVERY MODELS | | | | | | - |
| D. ECONOMIC & OTHER FEASIB. STUDIES | 120 | 120 | | | | 240 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | - |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | - |
| B. FLOW STUDIES | | | | | | - |
| C. FIELD LIAISON & ENG. STUDIES | 60 | 180 | 300 | | | 540 |
| D. LAB EQUIPMENT & FACILITIES | | | | | | - |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | - |
| B. MINI-TESTS | | | | | | - |
| C. TECHNICAL PILOTS | | | | | | - |
| D. ECONOMIC PILOTS 1/ | | | | | | 1/ |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY 2/ | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |
| TOTAL | 180 | 300 | 300 | | | 780 |
| ERDA SHARE | 180 | 300 | 300 | | | 780 |

1/ FIELD OPERATIONS TO BE CONDUCTED WITH R&D PROGRAMS SD-1 AND SD-6.

2/ INCLUDED IN ABOVE COSTS.

PGM: SD-3/4

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|---|
| ALL ERDA | SD-3 | 283 | 283 |
| | SD-4 | 715 | 715 |
| | TOTAL | 998 | 998 |

7. EXPECTATION OF SUCCESS: 50% (SD-3 AND 4 COMBINED)

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | N/A | N/A | N/A |
| DAILY PRODUCTION IN: | | | |
| 1985 | 640 | 320 | 117.0 |
| 1990 | 755 | 377 | 137.9 |
| 1995 | 583 | 291 | 106.4 |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 1313 | 656 | 657 |
| 1990 | 2794 | 1397 | 1400 |
| 1995 | 3916 | 1963 | 1967 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

TARGET A-2: HEAVY OIL RESERVOIRS, GREATER THAN 2500', PRESSURE ABOVE 1000 PSI, SOME UNSTIMULATED INFLUX

R&D STRATEGY SD-5: OVERCOME HEAT LOSS PROBLEMS IN INJECTION STRING, DESIGN RELIABLE INJECTION STRING, AND DEVELOP EFFICIENT TECHNIQUES FOR RECUPERATING PRODUCED HEAT

1. CENTRAL PROBLEM

Depth poses a major limitation for steam drive. Field wide development and the economic pilots are all at less than 2,300 feet, with the majority at less than 1,500 feet, and only limited industry effort is being devoted to recovering oil at greater depths. For example, only one of the eleven reported technical pilots is as deep as 2,500 feet and none are reported (as currently being attempted) below that depth.

In deep reservoirs, the radial heat losses from the injection string and difficulties in maintaining the mechanical integrity of the string itself have placed a depth limitation on the application of the steam drive process when other conditions would indicate its usefulness. The problem is compounded when the reservoir pressure and steam injection rates are such as to require the use of a high pressure to inject the steam. Now, because so much of the heat of the steam is contained in the sensible heat of the liquid, steam bank development is retarded and much of the heat is produced in hot water reaching the producing wells. For the process to be efficient, heat recuperative techniques have to be applied.

2. R&D GOALS

- To develop economic well completion techniques that permit successful injection of steam at depths greater than 2500'.
- To determine if reduction in the partial pressure of steam (by using steam/gas mixtures) will lower oil/steam ratios (increase thermal efficiency) without sacrificing overall volumetric recovery of crude.
- To determine if heat recuperative systems can be economically applied.
- To construct reservoir recovery and cost models for reliably predicting anticipated results in this class of reservoir.
- The eventual R&D goal is to first bring on the heavy oil reservoirs between 2500 and 5000 feet of depth and second to make the steam drive a conventionally applied technique at these depths.

3. R&D ACTIVITIES

The R&D activities would consist of a sequence of tasks as follows:

I. Building the Knowledge Base: starting in 1977

-- Mathematical reservoir simulation studies of steam drive operations at partial pressures of steam less than unity.

-- Extrapolation of studies under Target A-1 (SD-1).

II. Basic and Applied Research: starting in 1978

-- Design studies of injection strings.

-- Design studies of heat recuperative systems.

-- Scaled physical model studies.

III. Field Based Activities

-- Field injectivity operations using single well tests in 1979.

IV. Transfer and Dissemination

PGM: SD-5

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | | | | | | – |
| C. RECOVERY MODELS | | 0.5 | 0.5 | 0.5 | 0.5 | 2 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | 0.5 | 0.5 | | | 2 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | 1/ |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | – |
| B. FLOW STUDIES | | | | | | – |
| C. FIELD LIAISON & ENG. STUDIES | 2 | 1.5 | 1.5 | 2.0 | 2.0 | 9 |
| D. LAB EQUIPMENT & FACILITIES * | | * | * | * | | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | 1.0 | 1.0 | | 2 2/ |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS / B. SHARE INDUSTRY/ERDA DEVELOP. | | 0.5 | 0.5 | 0.5 | 0.5 | 2 |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ USES THE RESULTS OF SD-1.

2/ SINGLE WELL TESTS

PGM: SD-5

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | | | | | | – |
| C. RECOVERY MODELS | | 30 | 30 | 30 | 30 | 120 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | 60 | 30 | 30 | | | 120 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | 1/ |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | – |
| B. FLOW STUDIES | | | | | | – |
| C. FIELD LIAISON & ENG. STUDIES | 120 | 90 | 90 | 120 | 120 | 540 |
| D. LAB EQUIPMENT & FACILITIES | | 500 | 500 | 500 | | 1500 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | 500 | 500 | | 1000 |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. / B. SHARE INDUSTRY/ERDA DEVELOP. | | 30 | 30 | 30 | 30 | 120 |
| TOTAL | 180 | 680 | 1180 | 1180 | 180 | 3400 |
| ERDA SHARE | 180 | 680 | 1180 | 1180 | 180 | 3400 |

1/ USES THE RESULTS OF SD-1.

PGM: SD-5

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 2890 | 2890 |
| ERDA'S SHARE | DO | DO |

7. EXPECTATION OF SUCCESS:

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 3600 | 1620 | 561 |
| DAILY PRODUCTION IN: | | | |
| 1985 | 265 | 119 | 15.0 |
| 1990 | 541 | 243 | 30.7 |
| 1995 | 505 | 117 | 28.7 |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 250 | 110 | 39 |
| 1990 | 1080 | 480 | 167 |
| 1995 | 2130 | 960 | 332 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

## TARGET A-3: LIGHT OIL RESERVOIRS, THIN, LOW PERMEABILITY, LOW RESIDUAL OIL SATURATION RESERVOIRS

### R&D STRATEGY SD-6 with SD-2: EXTEND APPLICABILITY OF PROCESS BY USING CHEAPER FUELS FOR GENERATING STEAM

#### 1. CENTRAL PROBLEM

A substantial number of shallow, light oil reservoirs in Texas, Louisiana and mid-continent have characteristics such as low residual oil saturations, thin pays and/or low permeabilities that make them economically unattractive for tertiary production. The chemical recovery processes that could be applied to these fields are unproven and even when proven would be high cost. Under current economic limits imposed by an oil/steam ratio based on a fuel of comparable value to produced crude, steam drive is also economically unattractive. Without some form of improvement these reservoirs would remain unproduced in the foreseeable future.

#### 2. R&D GOALS

- Using a relatively cheaper fuel than the crude oil, such as has already been described under Target A-1 (SD-2), show that economic production of crude oil from such reservoirs is possible using steam drive techniques. Essential to this first goal will be the design and ultimate development of steam generators that use coal as fuel and are economically operable in the oil field environment.

- Establish the technical basis of such operations and show that calculated results are confirmed or improved upon in practice.

- This goal would be reached in two stages. The first stage would involve technical and economic demonstrations of the feasibility of using a lower cost steam drive process in these reservoirs. The second stage would be designed to bring the application of steam drive in these reservoirs to a conventional application.

3. R&D ACTIVITIES

The R&D activities would consist of a sequence of tasks as follows:

I. Building the Knowledge Base: starting in 1977

-- Physical model studies on steam displacement in light oil reservoirs.

-- Mathematical reservoir simulation studies.

-- Extrapolation of results of studies under Target A-1 (SD-1).

II. Basic and Applied Research: starting in 1977

-- Design and development work on coal fired steam generators and economic feasibility studies of coal usage (see Target A-1, SD-1).

III. Field Based Activities

-- Technical field studies of well completions, steam injectivity, and profile control in such reservoirs, starting in 1978.

-- Large economic pilots, starting in 1979.

IV. Transfer and Dissemination

PGM: SD-6

4. R&D ACTIVITIES -- PHYSICAL UNITS:

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | 2/ |
| B. RESERVOIR DATA BASE | 1 | | | | | 1 |
| C. RECOVERY MODELS | | 1 | | | | 1 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | | 1 | | | 1 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | 3/ |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | 1 | 2 | 2 | 1 | 6 |
| B. FLOW STUDIES | 5 | 5 | 4 | 5 | 4 | 23 |
| C. FIELD LIAISON & ENG. STUDIES | 1 | 1 | 1 | 1 | 1 | 5 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | * | * | | | | * |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | 1 → | → | → | 1 4/ |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 5/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 5/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.
1/ USED WITH SD-2
2/ RELIES ON RESIDUAL MEASUREMENT PROGRAM ST-4
3/ USES RESULTS OF SD-1
4/ LARGE ECONOMIC PILOT
5/ INCLUDED IN ABOVE FIGURES

PGM: SD-6 1/

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL 2/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | 3/ |
| B. RESERVOIR DATA BASE | 60 | | | | | 60 |
| C. RECOVERY MODELS | | 60 | | | | 60 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | | 60 | | | 60 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | 4/ |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | 60 | 120 | 120 | 60 | 360 |
| B. FLOW STUDIES | 300 | 300 | 240 | 300 | 240 | 1380 |
| C. FIELD LIAISON & ENG. STUDIES | 60 | 60 | 60 | 60 | 60 | 300 5/ |
| D. LAB EQUIPMENT & FACILITIES | 400 | 1000 | 500 | 300 | 250 | 2450 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 350 | 1000 | | | | 1350 |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | 5000 | 2000 | 2000 | 9000 5/ |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 6/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 6/ |
| TOTAL | 1170 | 2480 | 5980 | 2780 | 2610 | 15020 |
| ERDA SHARE | 1170 | 2480 | 5980 | 2780 | 2610 | 15020 |

1/ USED WITH SD-2

2/ POST 1981 COMMITMENTS: $500,000 PER YEAR FROM 1982 TO 1986

3/ RELIES ON RESIDUAL MEASUREMENT PROGRAM ST-4

4/ USES RESULTS OF SD-1

5/ REQUIRES POST 1981 FUNDING COMMITMENTS

6/ INCLUDED IN ABOVE COSTS

PGM: SD-6

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|---|
| TOTAL COSTS ERDA'S SHARE | ALL ERDA | 12718 | 14186 |

7. EXPECTATION OF SUCCESS: 57%

8. OUTCOMES OF THE R&D PROGRAM: (SEE NOTE ON NEXT PAGE)

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 3100 | 1767 | 125 |
| DAILY PRODUCTION IN: | | | |
| 1985 | 163 | 93 | 2.4 |
| 1990 | 687 | 392 | 10.1 |
| 1995 | 669 | 381 | 9.8 |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 110 | 60 | 5 |
| 1990 | 980 | 560 | 40 |
| 1995 | 2360 | 1350 | 95 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

Note on Production Benefits of SD-6 with SD-2:

The reservoirs in this target are light oil reservoirs previously screened into one of three categories.

- Surfactant/polymer
- Polymer waterflooding
- EOR not applicable

While some reservoirs in the first two categories may be counted twice the bulk of the reservoirs in the first two categories proved uneconomic in their original EOR technique. Thus most of these reservoirs would be rejected based on the economic screen making the double counting minimal.

## TARGET A-4: HEAVY OIL RESERVOIRS WITH NO INFLUX ($8^o$ - $11^o$ API)

## R&D STRATEGY SD-7: EXTEND APPLICABILITY OF STEAM DRIVE PROCESS

### 1. CENTRAL PROBLEM

A wide range of opinion exists as to the actual resource and reserve base of oils that are too viscous to flow without artificial stimulation -- the estimates range from 5 to over 50 billion barrels. A recent National Academy of Sciences estimate placed the potential at 29 billion barrels.

There are two distinct categories of such accumulations: one is a near-surface accumulation that may be mined and processed to separate the hydrocarbon material from the mineral matrix; the second is enough for the application of in situ processing but the reservoir energy is insufficient to establish any sustained influx by stimulation of the producing wells. Without the energy required to sustain influx, piston-type drive processes cannot succeed. Without the possibility of depleting the reservoir by stimulation, fluid injection is impossible unless the reservoir contains high saturation gas or water zones that can serve to disseminate heat between wells, or fractures can be induced which will serve to communicate heat throughout the formation.

### 2. R&D GOALS

- The first and foremost goal of any program aimed at this target must be to establish that a real target exists. None of the existing studies on the occurrence of such accumulations have been sufficiently critical nor aware

of the problems to reach a valid assessment of the resource and that part of it which could conceivably be a target for recovery schemes.

- A second goal is to determine if the targets do have depleted zones, gas zones or water zones, or can be successfully (horizontally) fractured to permit injectivity of steam, including studies on the technical feasibility of exploitation by such techniques.

- A third goal is to examine those accumulations near the surface, which preclude in situ exploitation for the technical and economic feasibility of mining and surface separation of the resource.

- The eventual R&D goal for this target is the accumulation of sufficient knowledge to make judicious longer term decisions for recovering this resource.

3. R&D ACTIVITIES

The R&D activity would consist of a sequence of tasks as follows:

I. Building the Knowledge Base: starting in 1977

-- Define the resource and fraction amenable to recovery.

-- Define communicating channels, zones, etc. in any indicated amenable accumulations.

-- Examine economic feasibility of exploitation by mining or developing communication channels.

II. Basic and Applied Research: starting in 1978

-- Examine feasibility of mining and surface processing schemes of any indicated amenable accumulations.

-- Examine feasibility of developing communicating channels by depletion, or fracturing.

-- Conduct scaled physical model studies/mathematical reservoir simulation studies of process.

III. Field Based Activities

-- Conduct technical pilots of developing communication channels, starting in 1978.

-- Technical pilots of mining operations, should the resource prove to be economically recoverable, would begin after 1981.

PGM: SD-7

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | (SEE ACTIVITY III.A) | | | | – |
| B. RESERVOIR DATA BASE | 1 | 1 | 1 | | | 3 |
| C. RECOVERY MODELS | 1 | 1 | 1 | | | 3 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | 1 | 1 | 1 | 1 | 4 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 1 | 2 | 2 | 4 | 3 | 12 |
| B. FLOW STUDIES | 2 | 5 | 5 | 5 | 3 | 21 |
| C. FIELD LIAISON & ENG. STUDIES | 1 | 1 | 1 | 1 | 1 | 5 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | 1/ | | | 1/ |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ 15 CORE HOLES AND 3 TESTS OF MINING DEPOSITS. (III-A)

2/ INCLUDED IN ABOVE FIGURES.

PGM: SD-7

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL 1/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | (SEE ACTIVITY III.A) | | | | |
| B. RESERVOIR DATA BASE | 60 | 60 | 60 | | | 180 |
| C. RECOVERY MODELS | 60 | 60 | 60 | | | 180 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | 60 | 60 | 60 | 60 | 240 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | - |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 60 | 120 | 120 | 240 | 180 | 720 |
| B. FLOW STUDIES | 120 | 300 | 300 | 300 | 240 | 1260 |
| C. FIELD LIAISON & ENG. STUDIES | 75 | 75 | 75 | 75 | 75 | 375 |
| D. LAB EQUIPMENT & FACILITIES | 250 | 500 | 250 | 250 | 250 | 1500 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | 1500 | 1500 | 1500 | | 4500 |
| B. MINI-TESTS | | | | - | | - |
| C. TECHNICAL PILOTS | | | | | | 1/ |
| D. ECONOMIC PILOTS | | | | | | - |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | - | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |
| TOTAL | 625 | 2675 | 2425 | 2425 | 805 | 8955 |
| ERDA SHARE | 625 | 2675 | 2425 | 2425 | 805 | 8955 |

1/ POST 1981 COMMITMENTS: $10 MILLION FOR TECHNICAL PILOT IF FEASIBILITY IS ESTABLISHED.

2/ INCLUDED IN ABOVE COSTS.

PGM: SD-7

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|---|
| TOTAL COSTS ERDA'S SHARE | ALL ERDA | 7698 | 13567 |

7. EXPECTATION OF SUCCESS: 12%

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 0-5000 | | 0-44 |
| DAILY PRODUCTION IN: | | | |
| 1985 | | | |
| 1990 4/ | | | |
| 1995 | | | |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | | | |
| 1990 4/ | | | |
| 1995 | | | |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

4/ INUSFFICIENT DATA FOR MAKING PRODUCTION ESTIMATES: FEA'S ENERGY OUTLOOK (1976) ESTIMATES ANNUAL PRODUCTION AT 200,000 BARRELS PER DAY IN 1985 AND 300,000 BARRELS PER DAY IN 1989: WE BELIEVE THESE ESIMTATES ARE TOO HIGH GIVEN THE POORLY UNDERSTOOD NATURE OF THE RESOURCE BASE AND THE CURRENT LACK OF AN ECONOMIC TECHNOLOGY FOR RECOVERING THIS OIL.

# CHAPTER III

## IN SITU COMBUSTION

### Description and Current Application of the Technology

An alternative to steam drive for introducing heat and pressure into a reservoir is the use of in situ combustion, or "fire flooding". Spontaneous combustion was accidentally triggered during the air injection pressure maintenance efforts of the early 1900s and the initial patent was issued to F.A. Howard (Standard Development Company) in 1923. However, even after this considerable passage of time, the process is still considered risky and only partly proven.

The basic process consists of the injection of air into the reservoir to burn some of the oil-in-place. By controlling the air injection, the amount of oil burned (and therefore heat generated) is kept within desired limits. The hot combustion gases thus generated flow toward production wells, pushing or carrying the oil as they pass. In some cases, cyclic steam injection may be used in conjunction with projects of this type to increase oil recovery rates.

Typically, air is injected into the reservoir to create a gas saturation high enough to allow the large air flows necessary to sustain combustion. When the air flow is large enough, spontaneous combustion may take place, otherwise, a downhole heater may be used in the injection well to initiate the combustion. The temperature of the combustion is maintained at about $900^{o}$ F. and the burning oil front proceeds slowly through the reservoir. Higher rates of air injection tend to burn excessive amounts of the oil in the reservoirs and may cause the burning front to override the oil.

Although the temperature can be controlled by changing the air injection rate, a more recently developed method accomplishes this by forward combustion and water. This method cools the combustion zone by vaporizing the water and the resulting hot vapor helps to move the heat through the reservoir ahead of the combustion front. While this process is still economically unproven, it appears promising as reported in a series of small pilots and in one large (930 acre) field test at the Sloss Field, in Nebraska.

Industry activity using in situ combustion is described in the summary of past and current projects, shown in Exhibit III-1, below:

EXHIBIT III-I

In situ Combustion Activity Summary

| | Technical Pilots | | Economic Pilots | | Fieldwide Development | |
|---|---|---|---|---|---|---|
| | Total | Current | Total | Current | Total | Current |
| Projects | 17 | 9 | 7 | 6 | 19 | 10 |
| Reservoirs | 16 | 8 | 7 | 6 | 18 | 9 |

In situ combustion activity is further characterized by the following:

- 4,548 acres are under current development; this is down sharply from only a few years ago

- In response to a variety of problems, the newer projects tend to be smaller technical pilots rather than the larger economic tests or fieldwide efforts

- In situ combustion tends to be used in deeper, thinner pay zone and lower residual oil saturation on fields than steam drive

- Current R&D appears to be taking in situ combustion to greater depths. Whereas only one fieldwide project is deeper than 5,000 feet, all the technical pilots are at or below this depth. One economic pilot at 11,800 feet, is reported as profitable and promising.

Although numerous in situ combustion pilots have been conducted in the United States, the early efforts have provided generally discouraging results. Based on this and the substitution of steam drive in many of the shallower, heavy oil reservoirs of California, field application and research in in situ combustion has declined. Some of the operating problems are described in the next section.

Problems and Opportunities

While several firms, including some independent operators, have developed considerable expertise in applying combustion and remain bullish on its prospects, the majority of operators have encountered substantial problems. These problems have led to a decrease in overall activity.

One of the attractions of combustion is that it can rely on a "free good", the previously unrecovered oil in the reservoir, to provide the major source of fuel. Compensating for the "free fuel", however, is the fact that air must be compressed and delivered to the formation

and that burning the oil in the reservoir reduces the amount available for recovery. The fuel required for compressing the air together with the purchase and maintenance costs of the compressor are high enough that the overall costs for delivering air to the reservoir can be substantial. Relative to energy-intensive steam drive, the costs for in situ combustion are lower only when the formation is less than 30 to 50 feet in thickness. For thicker reservoirs, the heat losses during a steam drive are low enough to enable the heat to be delivered at a lower cost.

Other problems have also arisen in the application of the in situ combustion process that have detracted from its wide spread application in thin reservoirs. These include: the relatively low sweep of the fire front because of the instability of the frontal advance (compared to the relatively high stability of the steam front); the high incidence of corrosion and burnouts at producing wells; and the problems in producing wells at high gas-oil ratios, because combustion gases must be produced in amounts approximately equal to the amount for the injected air.

Finally, because many combustion opportunities are in California, the constraints due to environmental restrictions and market opportunities that limit steam drive also contrain combustion applications.

Currently available literature is not adequate to establish which of these problems -- or others -- accounts for the discouraging results to date. It is important to determine if the problems are at all subject to economic correction. Considerable investigative research seems justified because of the distinct value of developing a process which is capable of economically recovering oil from reservoirs that are too thin or too deep for steam drive.

Future Directions of Industry Application--The Base Case

Discussions with industry experts and an examination of the literature on in situ combustion support the conclusion that research and field application of in situ combustion are at a crossroad. The standard procedures [1/] for computing the Base Case (described in Chapter I of Part 3) were used, with one modification. Because ERDA is currently funding about 20 percent of the on-going R&D in combustion, 20 percent of the production from the Base Case reservoirs is attributed to ERDA. Under Standard Economics, the resulting Base Case for combustion is as follows:

| | |
|---|---|
| Ultimate Recovery | 900 million barrels |
| Production Rate in: | |
| 1985 | 60 thousand barrels per day |
| 1990 | 70 |
| 1995 | 40 |
| Cumulative Production by: | |
| 1985 | 140 million barrels |
| 1990 | 250 |
| 1995 | 380 |

As can be seen, the production rate peaks in 1990, when the earlier candidate reservoirs begin to decline and are not replaced by other reservoirs.

Exhibit III-2 shows the sensitivity of these Base Case estimates tax contingencies analyzed in the study. Given the limited opportunities assumed available for in situ combustion, changes in prices have only a small effect and changes in taxes have no measurable effect.

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[1/] Including the constraints on California heavy crude production.

Ultimate recovery increases from 900 to 1,100 million barrels, as the price goes from upper tier ($11.63) to the alternate fuels level ($20.00) and the production rate increases by about 20,000 barrels per day.

The In Situ Combustion Programs

Two in situ combustion programs are analyzed. The first program (referred to as IC-1, below) examines improved process efficiencies. The second program (IC-2), should the first program show the process to be capable of improvement, tests the process in the field.

Because these programs are so highly interactive, they are discussed together in the following section. Overcoming California environmental and market constraints would be dependent on the effectiveness of the SD-2 research program in steam drive.

EXHIBIT III-2

PRICE/TAX CONTINGENCIES FOR IN SITU COMBUSTION BASE CASE

| | STANDARD ECONOMICS (UPPER TIER W/ CURRENT TAX) | LOWER BOUND (UPPER TIER W/ UNFAV. TAX) | CASE 2 (WORLD PRICE W/ CURRENT TAX) | CASE 4 (WORLD PRICE W/ FAVORABLE TAX) | UPPER BOUND (ALTERNATE FUELS PRICE W/ FAVOR. TAX) |
|---|---|---|---|---|---|
| ULTIMATE RECOVERY (BILLION BBL.) | 0.9 | 0.9 | 1.0 | 1.0 | 1.1 |
| PRODUCTION RATE IN: (THOUSAND B/D) | | | | | |
| 1985 | 60 | 60 | 70 | 70 | 90 |
| 1990 | 70 | 70 | 70 | 70 | 90 |
| 1995 | 40 | 40 | 60 | 60 | 60 |
| CUMULATIVE PRODUCTION BY: (MILLION BBL.) | | | | | |
| 1985 | 140 | 140 | 140 | 140 | 150 |
| 1990 | 250 | 250 | 270 | 270 | 310 |
| 1995 | 380 | 380 | 400 | 400 | 470 |

## TARGET B-1: PRODUCTION OF HEAVY CRUDES BY THE USE OF IN SITU COMBUSTION

### R&D STRATEGY IC-1 AND IC-2: DETERMINE APPLICABILITY OF THE IN SITU COMBUSTION PROCESS

#### 1. CENTRAL PROBLEM

The original promise of in situ combustion as a scheme for increasing the recovery of heavy oils has not been realized. Of the numerous attempts to implement the process, few have survived as commercial ventures. Most new ventures have been concentrated in shallow sands in Northern Louisiana because of environmental and market constraints in California. The problems that have been encountered fall into three categories: poor fuel/oil ratios, poor reservoir sweep, and difficulty in maintaining the integrity of producing wells. The last problem is associated with high temperatures, corrosive gas production, and high sand velocities resulting from the high gas-oil ratios of unconsolidated sands that are characteristic of many of the reservoirs in which combustion operations have been attempted.

The published literature is not sufficiently complete to permit an assessment to be made of the cause of the major problems. Consequently, neither the technical viability of the process nor its competitive position relative to steam operations can be evaluated.

#### 2. R&D GOALS

- To determine whether the poor results of many past in situ combustion operations can be attributed to a dominant factor, viz., difficulty of maintaining operations at a reasonable cost, or due to inefficient reservoir performance.

- To evaluate the potential for overcoming the negative effects of such factors by engineering study and laboratory model experiments.

- To demonstrate the feasibility of improved operations in a field application.

- The eventual R&D goal, should the problems be overcome, would be to make the process conventionally applicable with recoveries and costs comparable to those being experienced in the shallower sandstones of Texas and Northern Louisiana.

3. R&D ACTIVITIES

I. Building a Knowledge Base

-- A detailed and systematic assessment of all the available data on in situ combustion would be first priority for any future activity for in situ combustion.

-- A second supporting effort would be focused on constructing improved recovery models and on verifying the economic feasibility of the process.

II. Basic and Applied Research

-- If the studies above prove there is merit in such an approach, laboratory and engineering design studies would be initiated to elaborate on those parameters that need further demonstration and improvement to make in situ combustion technologically viable.

III. Field Operations

-- A small mini-test would be conducted if positive information is developed by the preceding activities; it would start in 1979.

-- Should the mini-test prove successful, an economic pilot would be started in 1980.

IV. Transfer and Dissemination

4. R&D ACTIVITIES — PHYSICAL UNITS PGM: IC-I&2

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | | | | | | – |
| C. RECOVERY MODELS | | | | | | – |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | | | | | – |
| E. PROCESS/FIELD TEST EVALUATION | 1 | | | | | 1 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS) | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | 1 | | | | 1 |
| B. FLOW STUDIES | | 2 | 8 | 8 | 8 | 26 |
| C. FIELD LIAISON & ENG. STUDIES | | | 0.2 | 0.7 | 0.1 | 1 |
| D. LAB EQUIPMENT & FACILITIES | | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (NUMBER) | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | – |
| B. MINI-TESTS | | | 1 | | | 1 |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | 1 | | 1 |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON YEARS) | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | 1 | 1 |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ CORE HOLES.

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL 1/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | | | | | | – |
| C. RECOVERY MODELS | | | | | | – |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | | | | | – |
| E. PROCESS/FIELD TEST EVALUATION | 75 | | | | | 75 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | 75 | | | | 75 |
| B. FLOW STUDIES | | 120 | 480 | 480 | 480 | 1560 |
| C. FIELD LIAISON & ENG. STUDIES | | | 25 | 75 | 15 | 115 |
| D. LAB EQUIPMENT & FACILITIES | | 100 | 750 | 500 | 500 | 1850 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | 250 | | | 250 |
| B. MINI-TESTS | | | | | | |
| C. TECHNICAL PILOTS | | | | | | |
| D. ECONOMIC PILOTS | | | | 1500 | 4500 | 6000 |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | – | 60 | 60 |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | |
| TOTAL | 75 | 295 | 1505 | 2555 | 5555 | 9985 |
| ERDA SHARE | 75 | 295 | 1505 | 2555 | 5555 | 9985 |

1/ POST 1981 COMMITMENTS: $2,000,000 IN EACH YEAR, 1982 AND 1983.

PGM: IC-1&2

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 7750 | 10371 |
| ERDA'S SHARE | DO | DO |

7. EXPECTATION OF SUCCESS: 30%

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 400 | 120 | 12 |
| DAILY PRODUCTION IN: | | | |
| 1985 | 120 | 40 | 1.3 |
| 1990 | 120 | 40 | 1.4 |
| 1995 | 90 | 30 | 1.0 |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 220 | 70 | 6 |
| 1990 | 500 | 150 | 14 |
| 1995 | 660 | 200 | 19 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

Item 8, on the preceding page, shows that production for the ERDA stimulated combustion projects peaks in 1990 as the opportunities for this technique become exhausted.

Also notable in Item 8 are the cost-effectiveness measures. While these are not as high as for some other programs, they are substantial. Twelve barrels of ultimate recovery per dollar of ERDA expenditure are anticipated, equivalent to about eight cents per barrel of ERDA R&D stimulated production. Because this production peaks during the critical period, the majority of this oil is recovered when the need is greatest.

The apparently anomaly of cumulative production in excess of ultimate recovery arises from the convention used in this study to allocate benefits between ERDA and industry when non-EOR process constraints are present. Lifting of these constraints leads to an acceleration of production, allocated to ERDA stimulation for the period 1985-1995. However, since industry would have eventually produced the oil without ERDA stimulation, it retains the allocation of ultimate recovery. When the production figures for the Base Case are combined with those from the ERDA programs, the apparent anomaly is reconciled.

The effects of the price/tax contingencies analyzed in this study are displayed in Exhibit III-3. Tax effects on combustion projects appear to be negligible. Only at the extreme, as represented by alternate fuels price of $20.00 per barrel, does price have effect on production -- and this only a slight acceleration of production rates and cumulative recovery.

EXHIBIT III-3

PRICE/TAX CONTINGENCIES FOR THE IN SITU COMBUSTION PROGRAMS

| | STANDARD ECONOMICS (UPPER TIER W/ CURRENT TAX) | LOWER BOUND (UPPER TIER W/ UNFAV. TAX) | CASE 2 (WORLD PRICE W/ CURRENT TAX) | CASE 4 (WORLD PRICE W/ FAVORABLE TAX) | UPPER BOUND (ALTERNATE FUELS PRICE W/ FAVOR. TAX) |
|---|---|---|---|---|---|
| ULTIMATE RECOVERY (BILLION BBL.) | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| PRODUCTION RATE IN: (THOUSAND B/D) | | | | | |
| 1985 | 40 | 40 | 40 | 40 | 40 |
| 1990 | 40 | 40 | 40 | 40 | 40 |
| 1995 | 30 | 30 | 20 | 20 | 20 |
| CUMULATIVE PRODUCTION BY: (MILLION BBL.) | | | | | |
| 1985 | 70 | 70 | 70 | 70 | 90 |
| 1990 | 150 | 150 | 150 | 150 | 180 |
| 1995 | 200 | 200 | 200 | 200 | 220 |

SUMMARY: Combined Effects of Industry Activity and the ERDA R&D Program for In situ Combustion

The production stimulated by the ERDA programs is expected to add about 100 million barrels to ultimate recovery and to accelerate the rate of production over the comparable figures for the Industry Base Case, under Standard Economics. Exhibits III-4 and III-5 show the expected production rate and cumulative production for the combined Industry Base Case and ERDA R&D programs under the Standard Economics case. Peak expected production rates, at slightly over 100 MB/D, occurs in 1990 -- the middle of the period of the critical shortage and cumulative production by 1995 is expected to be nearly 500 million barrels.

These projections have assumed the conditions of the Standard Economics Case. The effects of price/tax contingencies are shown in Exhibit III-6 for ultimate recovery and in Exhibit III-7 for the production rates.

As noted earlier, changes in taxes have no effect on in situ combustion. In terms of ultimate recovery, raising price from upper tier to world levels increases the size of the Base Case, but does not effect the ERDA-stimulated portion. Further increasing price -- up to the alternate fuel level of $20.00 per barrel -- increases the size of the Industry Base Case and the ERDA increment. Note that in situ combustion is a technique for which raising prices represents an alternative to public R&D. That is, combustion at alternate fuels price -- without an ERDA program -- yields as much ultimate recovery as the upper tier price with an ERDA program.

EXHIBIT III-4

EXPECTED IN SITU COMBUSTION PRODUCTION RATES
(STANDARD ECONOMICS)

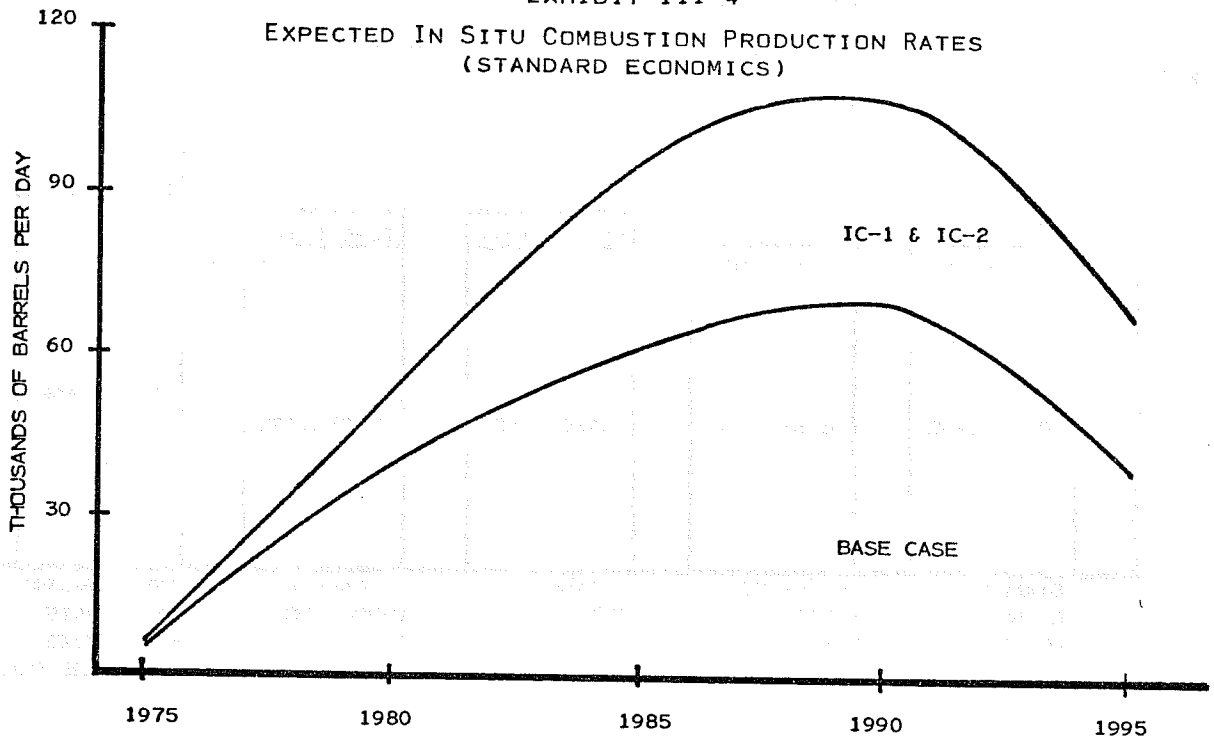



EXHIBIT III-5

EXPECTED IN SITU COMBUSTION CUMULATIVE PRODUCTION
(STANDARD ECONOMICS)

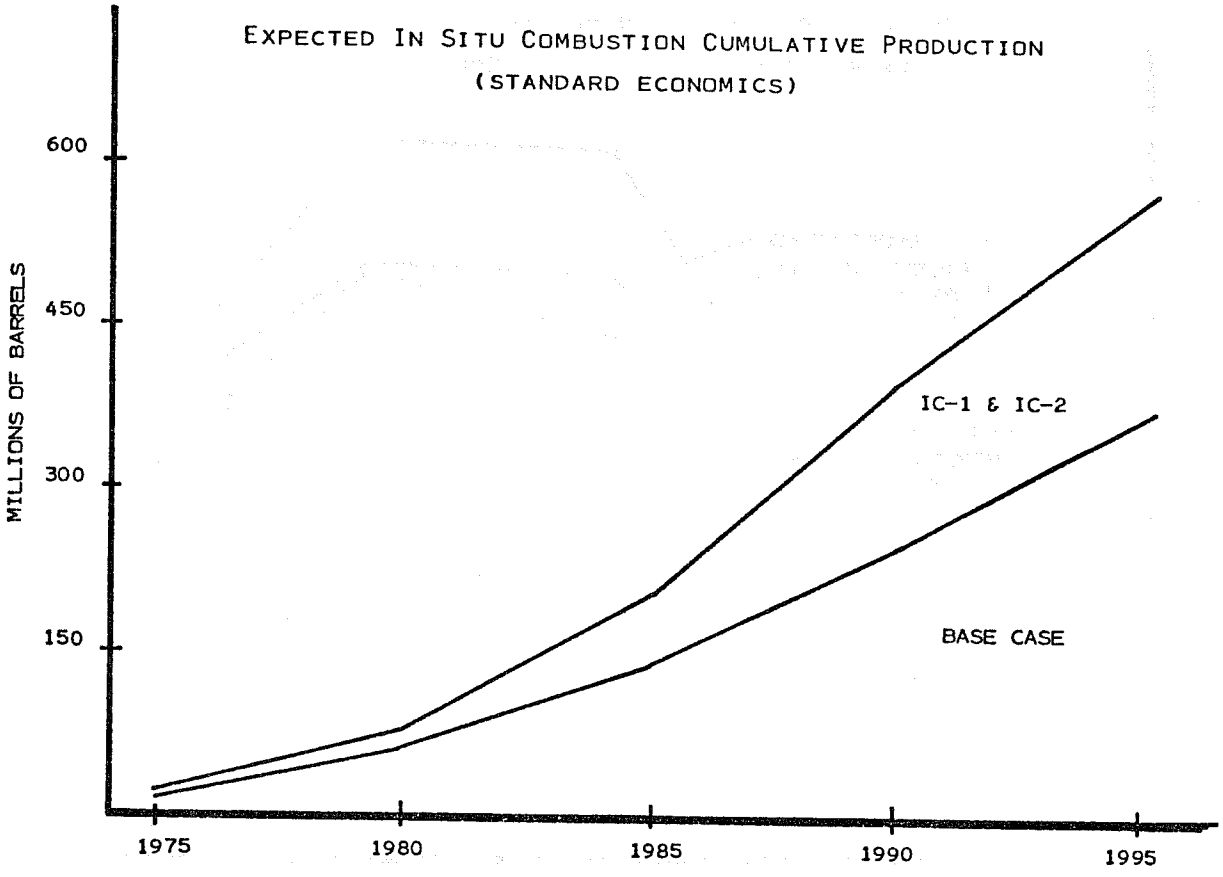


EXHIBIT III-6

EXPECTED ULTIMATE RECOVERY OF IN SITU COMBUSTION UNDER PRICE/TAX CONTINGENCIES

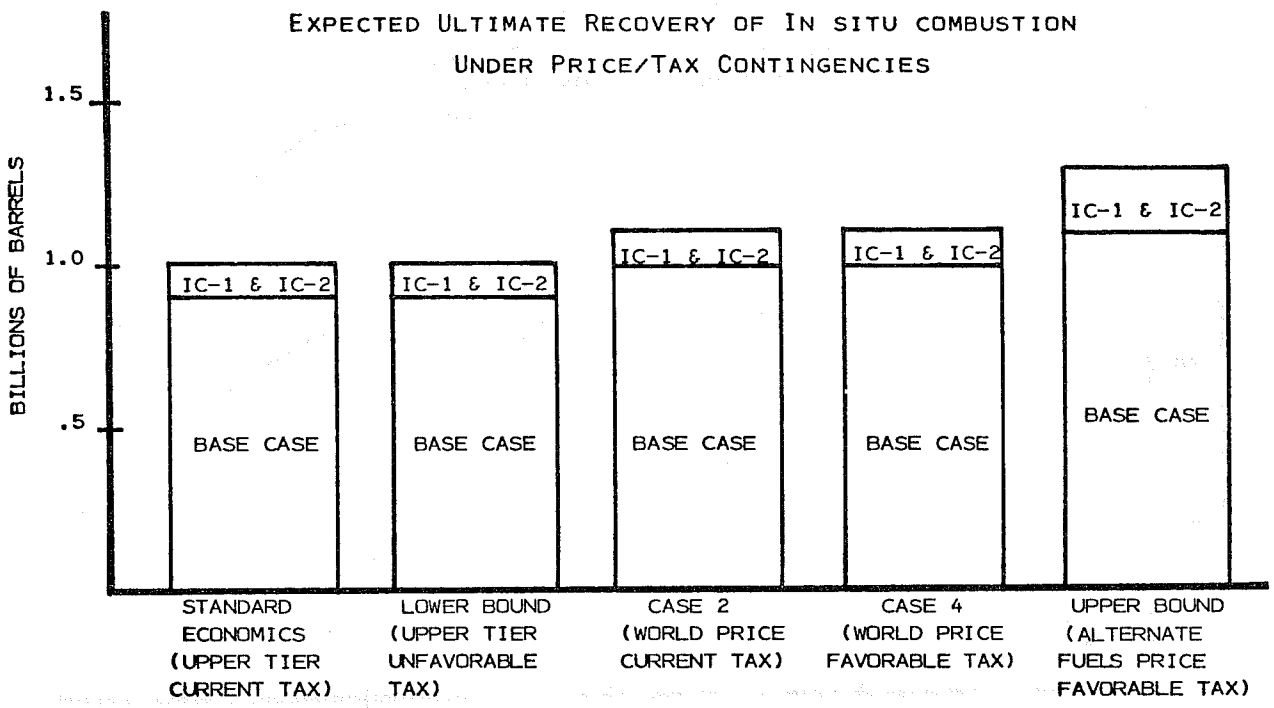
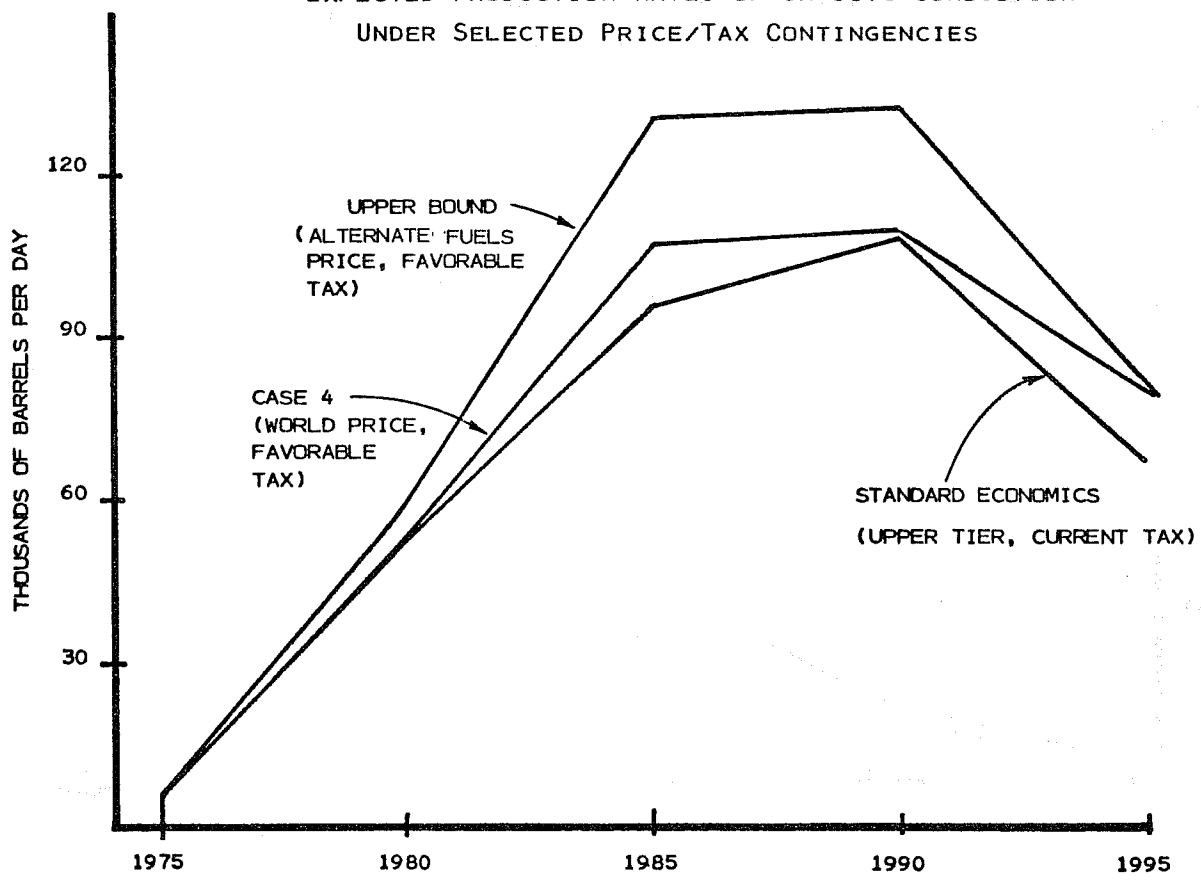



EXHIBIT III-7

EXPECTED PRODUCTION RATES OF IN SITU COMBUSTION UNDER SELECTED PRICE/TAX CONTINGENCIES



Increasing price also increases the rate of production. At world prices, combustion production reaches and maintains its peak five years earlier than at upper tier prices. The alternate fuels price yields a higher rate and more rapid production. Under all price/tax contingencies, the production rate drops off after 1990 as the candidate reservoirs begin to decline and no new ones are added.

# CHAPTER IV

# CARBON DIOXIDE MISCIBLE FLOODING

## SECTION A: GENERAL DISCUSSION

### Description and Current Application of the Technology

Miscible recovery processes, theoretically, hold the promise of meeting the ultimate objective of enhanced oil recovery -- production of 100 percent of the oil-in-place. For such a process to work, the injection fluid must be completely miscible with the reservoir crude oil and the injected material must invade all regions of the reservoir.

The carbon dioxide flood is one of several embodiments of the miscible drive process that have been proposed. As distinguished from non-miscible drives in which the displacing phase acts primarily as the transmitter of the pressure gradients required to displace the crude, a miscible drive affects the volumetric relations between the residual oil and water as well as supplying the required pressure gradients.

In a miscible flood, the injected material dissolves in or is dissolved by the residual oil which it contacts, resulting in an increase in volume of the oil phase. The volume of the oil phase increases until it reaches a pore saturation level where it is mobile. (In tertiary application, it follows that the interstitial water must be displaced ahead of the miscible fluid; otherwise a volume increase

in the oil phase would be impossible.) The mobile oil phase, moving through the reservoir, encounters additional quantities of residual oil which are assimilated into the growing oil bank. If injection of the miscible fluid continues, the oil will be completely swept out of all portions of the reservoir contacted by the fluid. In the end, the reservoir will be filled with the solution of the miscible agent and crude oil and an irreducible water saturation.

Available solvents, or miscible fluids, however, are too expensive to be used in this manner. It is necessary to use only a slug of solvent, which in turn is displaced by water. This slug of solvent must be large enough that it is not reduced in saturation to a residual level by the displacing water before the oil bank is produced. If the solvent slug is not of sufficient size, then the advancing water will be able to penetrate the oil bank and an immiscible displacement process will then prevail.

In its current application, because the solvents have a much lower viscosity than the crude, the solvent will finger its way through the oil bank and even ahead of it. The solvent then acts only as an extractant for the residual oil in the paths that are adjacent to the one being followed by the highly mobile solvent. Heterogeneities in the formation accentuate this fingering process. To the extent that fingering occurs, recovery efficiency is reduced, and an economically profitable operation becomes difficult to achieve.

Several miscible agents have been applied, notably alcohols, hydrocarbon gases, and carbon dioxide. While alcohols are miscible with the reservoir oil, their general use is limited by substantial

technical problems and their high costs. Recent rises in value of hydrocarbon gases have made this process uneconomic also.

Thus, only carbon dioxide appears to be an economically viable solvent. Engineering experience with the earlier miscible processes, especially hydrocarbon miscible, however, provides some insights into the carbon dioxide process.

Carbon dioxide dissolves in most crudes, and at increasing pressures the solubility increases. For some crudes, it has been reported that at high enough pressures carbon dioxide and the crude become miscible. However, carbon dioxide, in the super critical condition it must be in to be miscible, is very mobile. Its viscosity is of the order of one tenth that of most low viscosity crude oils. Thus, the problem of fingering is still present. As a result, its successful application has so far been limited to situations where fingering can be reduced by gravity stabilization (dipping reservoirs), or where it is so cheap that it can be "wasted" in circulation through the reservoir.

Reduction in mobility of the carbon dioxide has been attempted by alternating the injection of carbon dioxide with water, relying on the Jamin forces to increase the resistance to flow. Although such a procedure will slow down the flow of the carbon dioxide, it detracts from the efficiency of the process by decreasing the saturation of the oil/solvent bank.

Industry field activity in carbon dioxide and hydrocarbon miscible projects is summarized in Exhibit IV-1 below:

EXHIBIT IV-1

Miscible Displacement Activity Summary

| | Technical Pilots | | Economic Pilots | | Fieldwide Development | |
|---|---|---|---|---|---|---|
| | Total | Current | Total | Current | Total | Current |
| **Carbon Dioxide** | | | | | | |
| Projects | 5 | 4 | 6 | 6 | 2 | 2 |
| Reservoirs | 5 | 4 | 6 | 6 | 2 | 2 |
| **Miscible Hydrcarbon** | | | | | | |
| Projects | 9 | 7 | 6 | 5 | 10 | 8 |
| Reservoirs | 9 | 7 | 6 | 5 | 10 | 8 |

In addition, current activity in using the miscible processes is characterized by the following:

- Currently 38,618 acres are under carbon dioxide flooding with an additional 56,782 acres under hydrocarbon miscible flooding.

- The large-scale, 29,000 acre, secondary base application of carbon dioxide in the SACROC unit of the Kelly-Snyder field (in West Texas) promises to add several hundred million barrels of additional recovery.

- In Crossett, another West Texas field, secondary application of carbon dioxide flooding is projected to more than double the amount of oil recovered through previous primary and secondary operations.

- Few, if any, additional hydrocarbon miscible projects are anticipated due to increased gas prices; many hydrocarbon projects are being evaluated for conversion to carbon dioxide or flue gas where available.

- Field experience has only recently begun to accumulate with carbon dioxide miscible flooding. All the projects reported have been begun since 1972, thus only limited empirical data is currently available.

- Whether the carbon dioxide achieves and maintains miscibility in the current pilots is subject to discussion and at least two of the twelve are clearly immiscible floods.

- The majority of current tests are in reservoirs with high oil saturations -- ten of the twelve had greater than 50 percent oil saturation at project initiation.

- Whereas these tests have shown the effectiveness of the process when used in secondary model (before waterflooding), the use of carbon dioxide miscible in tertiary mode (after waterflooding) is more problematic. In another portion of SACROC and at Little Creek, tertiary carbon dioxide floods developed the desired bank and oil was produced, but the amount of carbon dioxide required was uneconomically excessive.

- As recently reported in the trade literature, AMOCO is actively field testing this technique and, if proven successful, estimates that they could add 1.5 to 2 billion barrels of reserves from their holdings in West Texas alone.

Problems and Opportunities

Although the small number and still incomplete nature of projects using carbon dioxide miscible flooding limit the amount of empirical data available, the results to date have been sufficient to identify several major problems and opportunities with the technique:

1. The first problem concerns the threshold level of oil saturation. Efficiency of the process appears to be reduced when applied to reservoirs with lower saturation, as after waterflooding. Achieving miscibility and maintaining the required bank are impeded by the fingering induced through the watered out channels. Experience in SACROC has been that the same process applied before and after waterflooding had markedly different results -- success in the former and failure in the latter. Since many carbon dioxide candidates, indeed most in some

regions (e.g., West Texas) have been or are being actively waterflooded, high oil saturations will be the exception and not the rule. A possible technique for overcoming this defect is to initially reinject a significant slug of produced crude ahead of the carbon dioxide. This is almost prohibitively expensive on a reservoir basis. However, if the problem is approached from a province-wide viewpoint it may be feasible. If use of a slug of produced crude is staggered and initial well spacing is reduced by infilling, it might be possible to build up a viable province-wide operation. In terms of future production and recovery gains, such a scheme might more than offset the initial production declines due to reinjection.

For those candidate reservoirs that have not been watered out, the alternative is to bypass the waterflood, using carbon dioxide miscible in the secondary mode. To exploit this opportunity, however, requires an acceleration of carbon dioxide application as increasing numbers of candidate reservoirs are reaching waterflood residual oil saturations.

2. The second problem concerns the uncertainty in the actual level and distribution of the residual oil. The one direct and consistent way to evaluate this quantity of residual is to subtract the sum of production and reserves (which together equal the ultimate recovery from the reservoir) from that quantity of oil which was reported to be in place upon discovery of the reservoir. Although this is a consistent and straightforward approach, the result is subject to possibly substantial error. This error arises from either an initial error in

estimating the original oil-in-place in the reservoir and/or the non-uniformity with which the reservoir is depleted by conventional technology. Seventy-five percent of the oil that has been discovered was found prior to 1950 when the techniques for evaluation and measurement were not as accurate as they have become, due to subsequent technological development. Thus the possibility exists for errors in the original oil-in-place and oil saturation. Depletion in many cases is suspected of being non-uniform and therefore some of the total residual oil will not be accessible to the injection fluid. It may well be that the estimated amount of residual oil, derived by the material balance method described above, provides an optimistic estimate of the oil that is the target for recovery. This cloud of uncertainty has discouraged wide-scale application of the carbon dioxide miscible process.

Given the sensitivity of project success to variations in oil saturation, and the uncertainty as to the amount and distribution of the residual oil, engineering a successful project becomes a highly speculative matter. In such cases many operators will table this option in favor of the more predictable waterflood, thus tending to slow the number of carbon dioxide applications and practically ensuring a reduction in incremental recovery efficiency, when attempted later at a lower saturation.

3. A third problem common to all miscible flooding is mobility control. Even where the displacing phase is absolutely miscible with the crude under all conceivable in situ conditions, an unfavorable mobility ratio leads to fingering and thus low recovery efficiency. Since the viscosity of super-critical carbon dioxide is of the order of 0.2 cp., the viscosity ratio will clearly be unfavorable even with the highest

gravity crudes. In order to secure a favorable mobility ratio, the relative permeability of carbon dioxide would have to be lowered to a value which is a fraction of the relative permeability to the oil ahead of the carbon dioxide front. Many research avenues for examining mobility control of carbon dioxide remain uninvestigated, including the effects of temperature and fluid composition, use of foams, PH control in sandstone reservoirs, and selective perforations to minimize carbon dioxide channeling.

4. It now is apparent that carbon dioxide is not always miscible on first contact with crudes contained in reservoirs for which the process superficially appears applicable. Although miscibility developed on multiple contact will eventually result in some downstream displacement, the overall recovery will have been penalized by this delay in reaching miscibility. Recent publications have also indicated miscibility may not be achieved even on multiple contact and that the phase relationships are very complex. If miscibility is not achieved, then the best performance that can be envisioned is that of an immiscible gas displacement resulting from increased pressure, reduced viscosity and increased bulk volume.

Short core tests may fail completely in assessing the potential of carbon dioxide flooding. The true conditions existing around an injection well may not be recreated with any faithfulness by waterflooding a short core. This is important, since the initial oil bank build-up engendered by carbon dioxide flooding may well be dependent upon the exact conditions existing around such injectors. Moreover, the complex equilibria between carbon dioxide and crude oil are definitely a function of pressure, temperature and fluid-fluid contact sequences. The appropriate range of conditions which would exist in a reservoir operation may not be easily replicated in short core tests.

5. Widespread application of carbon dioxide miscible flooding is constrained by the limited availability of nearby, naturally occurring carbon dioxide. While substantial quantities of naturally occurring carbon dioxide are often found associated with natural gas, it has historically been considered a waste product and released into the air (except for the small amount captured for industrial use, e.g., for making dry ice). Several major natural sources of carbon dioxide have been recently identified, but these are located considerable distances from the most favorable areas for application. The economics of carbon dioxide development are dependent on economies of scale and constant, predictable levels of use. The scarcity and cost of carbon dioxide may be alleviated somewhat, since it can be produced with the recovered oil and reused. This recycling of the carbon dioxide, however, requires purification, pressurization, and reinjection. These are costly and capital intensive processes that require further economic evaluation.

6. Carbon dioxide is a by-product of numerous manufacturing processes used in ammonia, gasoline, and chemical plants. It may be possible to extract carbon dioxide from manufacturing operations or from stack gases more inexpensively than obtaining it from natural sources requiring considerable transportation. For example, combined power cycle plants, using residual fuels (and in some cases ash-bearing solids such as coal and lignite) can be designed to optimize the production of carbon dioxide, power, and hydrogen (which may be used for additional power generation or ammonia manufacture). Recovery from stack gases has not yet been sufficiently studied to make an economic evaluation. One of the significant items not yet specified is the exact degree of purity required for carbon dioxide in various reservoirs. This is crucial in that the cost of purifying the carbon dioxide is exponentially related to the level of purity required.

Future Directions of Industry Application -- The Base Case

Discussions with researchers, interviews with production managers, and examination of the literature on carbon dioxide miscible flooding lead to the assumption that the more favorable reservoirs -- those with high oil saturations, still under primary development or in the very early stages of waterflooding, will be developed by industry. Reservoirs where there are economic pilot activity currently underway will be developed first. These will be followed by reservoirs similar to those currently under development, in the order of their profitability.

Because of limited supplies of carbon dioxide, production will be constrained at about 400 thousand barrels per day. Industry will probably acquire the required amount of carbon dioxide without public assistance up to this level.

Industry research and development during this period will be directed primarily toward improving the predictability and recovery performance of the process as applied to the most favorable reservoirs. While these efforts will add to ultimate recovery, the limited availability of carbon dioxide will push any incremental recovery to beyond 1995. Should oil prices increase dramatically in the near term, industry will begin to apply the process in additional reservoirs, thus gaining credit for increases in ultimate recovery; but, because of limitations on carbon dioxide supply, this will provide no additional production during the critical period.

Using these assumptions, the detailed procedures for computing the Base Case (described in Chapter I of Part 3) were applied, with one exception. It was assumed that an alternate fuel price of $20.00 per barrel would escalate the level of industry R&D and would result in a reallocation of production benefits from ERDA to industry, thus increasing the Industry Base Case under the Upper Bound price/tax contingency.

The Industry Base Case for carbon dioxide miscible, under Standard Economics conditions, was estimated as follows:

| | | |
|---|---|---|
| Ultimate Recovery | 4.7 | billion barrels |
| Production Rate | | |
| 1985 | 400 | |
| 1990 | 400 | Thousand barrels per day |
| 1995 | 400 | |
| Cumulative Production | | |
| 1985 | 880 | |
| 1990 | 1610 | Million barrels |
| 1995 | 2340 | |

Under other possible price/tax contingencies (see Exhibit IV-2), ultimate recovery varies, but production rates stay the same due to limitations on carbon dioxide availability. Comparing the first two columns shows the effect of less favorable taxes. The fairly sizeable difference is attributable principally to the requirement, in the Lower Boundary case, that the injected carbon dioxide be capitalized. Reading across, a small increase in ultimate recovery results from a price increase from upper tier to world levels. A much greater rise in ultimate recovery is noted as the price increases to the alternate fuels price. A substantial portion of this jump is attributable to increased industry R&D stimulated by the higher price.

Price changes also affect cumulative production, but only slightly. This is because the higher prices bring on the projects faster, so the constrained maximum production is reached sooner, increasing the cumulative recovery for the dates shown.

EXHIBIT IV-2

INDUSTRY BASE CASE FOR CARBON DIOXIDE MISCIBLE
UNDER THE PRICE/TAX CONTINGENCIES

| | STANDARD ECONOMICS (UPPER TIER W/ CURRENT TAX) | LOWER BOUND (UPPER TIER W/ UNFAV. TAX) | CASE 2 (WORLD PRICE W/ CURRENT TAX) | CASE 4 (WORLD PRICE W/ FAVORABLE TAX) | UPPER BOUND (ALTERNATE FUELS PRICE W/ FAVORABLE TAX) |
|---|---|---|---|---|---|
| ULTIMATE RECOVERY (BILLION BARRELS) | 4.7 | 4.1 | 4.8 | 4.8 | 5.9 |
| PRODUCTION RATE IN: (THOUSAND BARRELS PER DAY) | | | | | |
| 1985 | 400 | 400 | 400 | 400 | 400 |
| 1990 | 400 | 400 | 400 | 400 | 400 |
| 1995 | 400 | 400 | 400 | 400 | 400 |
| CUMULATIVE PRODUCTION BY: (MILLION BARRELS) | | | | | |
| 1985 | 880 | 870 | 890 | 890 | 890 |
| 1990 | 1610 | 1610 | 1620 | 1620 | 1620 |
| 1995 | 2340 | 2340 | 2350 | 2350 | 2350 |

## Overview of the Carbon Dioxide Programs

Because industry will concentrate on the more favorable reservoirs and because of the constraint on carbon dioxide, numerous targets and strategies remain unexploited except for possibly publicly sponsored research and development. From the Base Case and the problems and opportunities described above, the following targets and strategies have been defined:

- Carbonate reservoirs in the Southwest (West Texas and Southeastern New Mexico) and Montana with high oil saturations (current saturations of 50% or greater)

  -- And with high anticipated residual oil saturations (average residual saturations of 45% or greater)

  - Apply and extend the technology as currently defined
  - Improve recovery efficiency
  - Develop adequate and cheaper supplies of carbon dioxide

  -- And with low anticipated residual oil saturations (average residual saturations of less than 45%)

  - Accelerate the application of the process prior to the waterflood residual being reached, and achieve improved efficiency using acceptable oil/carbon dioxide ratios

- Carbonate reservoirs in the Southwest and Montana with current oil saturations already reduced by waterflooding to 45% or less.

  -- Extend the application of the process to reservoirs with low current oil saturations.

- Gulf Coast (East Texas and Southern Louisiana) sandstone reservoirs with a significant dip, having low saturations, due to efficient waterfloods.

  -- Make the process economic in these high dip reservoirs by gravity-stabilizing the carbon dioxide drive.

- Other sandstone reservoirs, especially in California and Appalachia.

  -- Extend the application of the process to these tight sandstone reservoirs with varying degrees of depletion.

Programs of activities were defined that would carry out each of the strategies for the relevant targets. Exhibit IV-3 shows the carbon dioxide miscible programs (by the designations used below) and the targets and generic strategies to which they relate. Exhibit IV-4 summarizes these programs in physical units (person-years and projects) and Exhibit IV-5 shows their costs in current (1976) dollars. As can be seen, the program costs double after the first year, then increase slowly to a maximum of just under fourteen million dollars in 1980, after which they decline slowly. The total five-year ERDA cost is approximately $55 million; the total cost of the carbon dioxide programs, including industry's share, is about $62 million.

EXHIBIT IV-3 STRUCTURE OF CARBON DIOXIDE MISCIBLE PROGRAMS

| STRATEGIES \ TARGETS | $CO_2$ MISCIBLE | | | |
|---|---|---|---|---|
| | (1) S.W. & MONT. CARBONATES, W/HIGH SOR | (2) S.W. & MONT. CARBONATES, W/ WATERFLOOD SOR | (3) GULF COAST SANDSTONES W/WATERFLOOD SOR (HIGH & LOW DIP) | (4) CALIFORNIA APPALACHIAN AND OTHER SANDSTONES |
| I. DEVELOP AND IMPROVE EOR TECHNOLOGY: | | | | |
| A. IMPROVE RECOVERY EFFICIENCY | CD-1 | - | (CD-3) | - |
| B. EXTEND APPLICATION OF PROCESS | - | CD-2 | - | CD-4 |
| C. IMPROVE MOBILITY CONTROL | (CD-1) | (CD-2) | - | - |
| D. TEST SPACING/INJECTION PATTERNS | (CD-1) | (CD-2) | CD-3 | (CD-4) |
| E. EXAMINE IMPROVED PROCESS EFFICIENCIES | - | - | (CD-3) | - |
| F. DEVELOP NEW PROCESSES | - | (CD-2) | - | (CD-4) |
| G. BRING TECH. TO CONVENT. APPLIC. | (CD-1) | - | - | - |
| II. OVERCOME NON-EOR PROCESS CONSTRAINTS: | | | | |
| A. OVERCOME EMISSION PROBLEMS | | | | |
| B. EXAMINE ALTERN. USES AND/OR MKT. FOR WEST COAST OIL | | | | |
| C. USE SUBSTITUTE (NON-PETRO) FUELS | | | | |
| D. DEVELOP CHEAPER/ADEQUATE SUPPLY OF INJECTION MATERIALS | CD-5 | (SECONDARY EFFECT) | | |
| E. ENSURE ADEQUATE CAPITAL/ ECONOMIC RETURN | | | | |

EXHIBIT IV-4. THE CARBON DIOXIDE PROGRAMS
IN PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | 1 | | | | | 1 |
| C. RECOVERY MODELS | 2 | 1 | | | | 3 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | 4 | 4 | 5 | 2 | | 15 |
| E. PROCESS/FIELD TEST EVALUATION | 1 | 1 | | | | 2 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 9 | 16 | 17 | 15 | 14 | 71 |
| B. FLOW STUDIES | 6 | 27 | 40 | 40 | 34 | 147 |
| C. FIELD LIAISON & ENG. STUDIES | 2.8 | 3.9 | 5.2 | 5.2 | 4.2 | 21.3 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | * | * | | | | * |
| B. MINI-TESTS | | 1 | 4 | 5 | 3 | 13 |
| C. TECHNICAL PILOTS | 2 → | | | | | 2 |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS<br>B. SHARE INDUSTRY/ERDA DEVELOP. | } | 1 | 1 | 1 | 1 | 4 |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

EXHIBIT IV-5. THE CARBON DIOXIDE PROGRAMS
IN 1976 DOLLARS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL 1/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | 60 | | | | | 60 |
| C. RECOVERY MODELS | 120 | 60 | | | | 180 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | 240 | 240 | 300 | 120 | | 900 |
| E. PROCESS/FIELD TEST EVALUATION | 60 | 60 | | | | 120 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 540 | 960 | 1020 | 900 | 840 | 4260 |
| B. FLOW STUDIES | 360 | 1620 | 2400 | 2400 | 2040 | 8820 |
| C. FIELD LIAISON & ENG. STUDIES | 177 | 295 | 390 | 390 | 315 | 1567 |
| D. LAB EQUIPMENT & FACILITIES | 1000 | 2750 | 1600 | 600 | 600 | 6550 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 3000 | 2250 | | | | 5250 |
| B. MINI-TESTS | | 1750 | 6500 | 9000 | 6250 | 23500 |
| C. TECHNICAL PILOTS | 1000 | 3000 | 2000 | 1500 | 3000 | 10500 |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. / B. SHARE INDUSTRY/ERDA DEVELOP. | | 60 | 60 | 60 | 60 | 240 |
| TOTAL | 6557 | 13045 | 14270 | 14970 | 13105 | 61947 |
| ERDA SHARE | 5557 | 10545 | 12020 | 13720 | 12980 | 54822 |

(ERDAHSHARE BASED ON 50% CD-1 FIELD; 50% CD-3 FIELD FOR 1977, 78, 79)

1/ POST 1981 COMMITMENTS: $7,500,000 EACH IN 1982 AND 1983, TO PREVIOUSLY INITIATED FIELD OPERATIONS. IN ADDITION, AN AVERAGE COMMITMENT OF $3.7 MILLION PER YEAR IS ANTICIPATED FROM 1982 TO 1986.

The potential and expected production from investing in research in carbon dioxide programs was estimated as described in Chapters I and V of Part 3. Exhibits IV-6 and IV-7 summarize these projections under the Standard Economics contingency. For the full set of carbon dioxide programs, the combination of ERDA R&D and industry activity production benefits are:

| | Potential Production | Expected Production | |
|---|---|---|---|
| Ultimate Recovery | 7.5 | 4.0 | billion barrels |
| Production Rate | | | |
| 1985 | 270 | 150 | thousand barrels per per day |
| 1990 | 700 | 430 | |
| 1995 | 1540 | 930 | |
| Cumulative Production | | | |
| 1985 | 310 | 180 | Million barrels |
| 1990 | 1290 | 800 | |
| 1995 | 3510 | 2120 | |

To relate costs to the expected production benefits, measures of effectiveness were calculated by dividing the expected production by the present value of the ERDA program budget. Exhibit IV-8 shows these cost-effectiveness measures for the carbon dioxide programs. These programs were found to be highly cost-effective in terms of ultimate recovery. Here the indices range from eight to two hundred and forty-nine expected barrels per dollar of ERDA expenditure. This is equivalent to investing from less than one to twelve cents per barrel to assure substantial amounts of additional domestic production.

EXHIBIT IV-6 POTENTIAL PRODUCTION BENEFITS OF CARBON DIOXIDE MISCIBLE PROGRAMS

(STANDARD ECONOMICS)

| POTENTIAL PRODUCTION BENEFITS / TARGETS / PROGRAM | C. $CO_2$ MISCIBLE | | | | |
|---|---|---|---|---|---|
| | (1) S.W. & MONT. CARBONATES, W/HIGH SOC | | (2) S.W. & MONT. CARBONATES, W/ WATERFLOOD SOC. | (3) GULF COAST SANDSTONES W/WATERFLOOD SOC (HIGH & LOW DIP) | (4) CALIFORNIA APPALACHIAN AND OTHER SANDSTONES |
| | CD-1 | CD-5 | CD-2 | CD-3 | CD-4 |
| 1. ULTIMATE RECOVERY (IN MILLIONS OF BARRELS) | 6000 | – | 600* | 300 | 600 |
| 2. ANNUAL PRODUCTION: (IN THOUSANDS OF BARRELS/ DAY) IN: | | | | | |
| 1985 | 240 | 10 | 10* | <10 | 10 |
| 1990 | 590 | 80 | 10* | <10 | 20 |
| 1995 | 1180 | 160 | 90* | 30 | 80 |
| 3. CUMULATIVE PRODUCTION (IN MILLIONS OF BARRELS) BY: | | | | | |
| 1985 | 280 | 0 | 20* | 10 | <10 |
| 1990 | 1060 | 160 | 30* | 10 | 30 |
| 1995 | 2830 | 390 | 130* | 40 | 120 |

* AT UPPER TIER PRICES AND CONVENTIONAL (8% REAL) RATE OF RETURN: ULTIMATE RECOVERY WOULD BE 2100 MILLION BARRELS; ANNUAL PRODUCTION IN 1985, 1990 AND 1995 WOULD BE 11,000 B/D, 22,000 B/D AND 332,000 B/D RESPECTIVELY; CUMULATIVE PRODUCTION BY 1985, 1990 AND 1995 WOULD BE 25 MILLION BARRELS, 60 MILLION BARRELS, AND 383 MILLION BARRELS RESPECTIVELY.

EXHIBIT IV-7. EXPECTED PRODUCTION BENEFITS FROM CARBON DIOXIDE MISCIBLE PROGRAMS

(STANDARD ECONOMICS)

| EXPECTED PRODUCTION BENEFITS / TARGETS / PROGRAM | C. $CO_2$ MISCIBLE | | | | |
|---|---|---|---|---|---|
| | (1) S.W. & MONT. CARBONATES, W/HIGH SOC | | (2) S.W. & MONT. CARBONATES, W/ WATERFLOOD SOC. | (3) GULF COAST SANDSTONES W/WATERFLOOD SOC (HIGH & LOW DIP) | (4) CALIFORNIA APPALACHIAN AND OTHER SANDSTONES |
| | CD-1 | CD-5 | CD-2 | CD-3 | CD-4 |
| 1. EXPECTED ULTIMATE RECOVERY (IN MILLIONS OF BARRELS) | 3400 | - | 200* | 200 | 200 |
| 2. EXPECTED ANNUAL PRODUCTION (IN THOUSANDS OF BARRELS/DAY) IN: | | | | | |
| 1985 | 140 | 10 | <10* | <10 | <10 |
| 1990 | 340 | 80 | <10* | <10 | 10 |
| 1995 | 670 | 160 | 40* | 30 | 30 |
| 3. EXPECTED CUMULATIVE PRODUCTION (IN MILLIONS OF BARRELS) BY: | | | | | |
| 1985 | 160 | 10 | 10* | <10 | <10 |
| 1990 | 610 | 160 | 10* | 10 | 10 |
| 1995 | 1610 | 390 | 50* | 30 | 40 |

* AT UPPER TIER PRICES AND CONVENTIONAL (8% REAL) RATE OF RETURN: EXPECTED ULTIMATE REOCVERY WOULD BE 840 MILLION BARRELS; EXPECTED ANNUAL PRODUCTION IN 1985, 1990 AND 1995 WOULD BE 4,000 B/D. 9,000 B/D AND 133,000 B/D RESPECTIVELY; EXCECPTED CUMULATIVE PRODUCTION BY 1985, 1990, AND 1995 WOUDL BE 10 MILLION BARRELS. 24 MILLION BARRELS AND 153 MILLION BARRELS RESPECTIVELY.

EXHIBIT IV-8. MEASURES OF EFFECTIVENESS FOR CARBON DIOXIDE MISCIBLE PROGRAMS (STANDARD ECONOMICS)

| TARGET/PROGRAM / MEASURES OF EFFECTIVENESS | CARBON DIOXIDE | | | | |
|---|---|---|---|---|---|
| | (1) S.W. & MONT. CARBONATES, W/HIGH SOC | | (2) S.W. & MONT. CARBONATES, W/ WATERFLOOD SOC | (3) GULF COAST SANDSTONES W/WATERFLOOD SOC (HIGH & LOW DIP) | (4) CALIFORNIA, APPALACHIAN AND OTHER SANDSTONES |
| | CD-1 | CD-5 | CD-2 | CD-3 | CD-4 |
| 1. ULTIMATE RECOVERY/ COST RATIO (EXPECTED ULTIMATE BARRELS/NPV TOTAL ERDA) | 249 | – | 8* | 18 | 16 |
| 2. ANNUAL PRODUCTION/COST RATIO IN: (EXPECTED ANNUAL BARRELS/NPV TOTAL ERDA) | | | | | |
| 1985 | 3.6 | 4.8 | <0.1* | <0.1 | 0.1 |
| 1990 | 9.0 | 40.7 | <0.1* | 0.1 | 0.2 |
| 1995 | 17.9 | 78.9 | 0.5* | 0.8 | 0.8 |
| 3. TOTAL ERDA | | | | | |
| 1985 | 12 | 5 | <1* | <1 | <1 |
| 1990 | 44 | 215 | <1* | 1 | 1 |
| 1995 | 118 | 510 | 2* | 3 | 3 |

* AT UPPER TIER PRICES AND CONVENTIONAL (8% REAL) RATE OF RETURN, ULTIMATE RECOVERY RATIO WOULD BE 29; ANNUAL PRODUCTION RATIOS IN 1985, 1990, AND 1995 WOULD BE <0.1, 0.1, AND 1.7 RESPECTIVELY; CUMULATIVE RPODUCTION RATIOS IN 1985, 1990, AND 1995 WOULD BE <1, 1, AND 5 RESPECTIVELY.

The R&D programs designed to improve recovery efficiency and to develop adequate supplies of carbon dioxide (CD-1 and CD-5) also have highly favorable cost-effectiveness indices on production rates and cumulative production research. Because of the lengthy lead-times, the Southwest, Gulf Coast and Other Sandstone targets (CD-2, CD-3, and CD-4) show less favorable production rate and cumulative production indices, the lowest being for the Southwest and Montana carbonates that have already been waterflooded. However, using ultimate recovery even these programs are cost-effective -- requiring about six cents per barrel for R&D. Moreover, as the footnote in the exhibit indicates, these ratios would improve substantially if the process were to become less risky -- down to the level of conventional processes. Similarly, improved predictability would improve the performance of the other programs. To be conservative, we have assumed that this development will not take place. Several industry analysts, however, have argued that this is not out of reach, given proper research and development.

The activities conducted for one class of reservoirs can have beneficial effects in other reservoirs. In the case of carbon dioxide, the benefits ascribed to developing adequate quantities of carbon dioxide were only attributed to the reservoirs with higher oil saturations in the Southwest and Montana. While secondary effects of achieving this objective aid in production from other reservoirs, these secondary benefits have not been included in the cost-effectiveness index.

The contingencies presented by changing prices and taxes from the Standard Economics Case have substantial effects on the expected production from the carbon dioxide programs (see Exhibit IV-9). Comparing the Standard Economics and the Lower Bound Cases shows the effect of making taxes favorable. The pronounced effect -- the loss of 700 million barrels -- is due to the change from expensing to capitalizing the injected carbon dioxide. Comparing the Standard

EXHIBIT IV-9

EFFECTS OF PRICE/TAX CONTINGENCIES ON
EXPECTED PRODUCTION FROM CARBON DIOXIDE PROGRAMS

| | STANDARD ECONOMICS (UPPER TIER W/ CURRENT TAX) | LOWER BOUND (UPPER TIER W/ UNFAV. TAX) | CASE 2 (WORLD PRICE W/ CURRENT TAX) | CASE 4 (WORLD PRICE W/ FAVORABLE TAX) | UPPER BOUND (ALTERNATE FUELS PRICE W/ FAVORABLE TAX) |
|---|---|---|---|---|---|
| ULTIMATE RECOVERY (BILLION BARRELS) | 4.0 | 3.3 | 5.1 | 5.3 | 5.9 |
| PRODUCTION RATE IN: (THOUSAND BARRELS PER DAY) | | | | | |
| 1985 | 150 | 140 | 210 | 210 | 230 |
| 1990 | 430 | 370 | 600 | 600 | 690 |
| 1995 | 930 | 630 | 1150 | 1180 | 1490 |
| CUMULATIVE PRODUCTION BY: (MILLION BARRELS) | | | | | |
| 1985 | 180 | 180 | 240 | 240 | 260 |
| 1990 | 800 | 730 | 1080 | 1080 | 1080 |
| 1995 | 2120 | 1670 | 2780 | 2830 | 330 |

Economics Case with Case 2 shows the effect of raising the price from the upper tier ($11.63 per barrel) to the world oil price ($13.00 per barrel): an additional 1.1 billion barrels is recovered ultimately with the production coming on stream substantially sooner. More favorable tax treatment (Case 4) has only marginal effect at world oil prices. Further, raising the price to the alternate fuels level of the Upper Bound Case ($20.00 per barrel) yields greater ultimate recovery, but only slight improvements in the production rate before 1995.

SUMMARY: Combined Effects of Industry Activity and Carbon Dioxide Miscible Programs

Combining the production stimulated by the ERDA R&D program with industry's activity shows that substantial quantities of oil may be recoverable by using carbon dioxide miscible flooding. Under the Standard Economics Case, the total ultimate recovery from carbon dioxide miscible would be 8.7 billion barrels. Exhibits IV-10 and IV-11 show the expected production of all of carbon dioxide applications. (In both figures, the curves are each added to the next lower). The Industry Base Case rises until it meets the constraint on carbon dioxide availability -- at 400 MB/D. The curve for CD-5 represents the relaxation of this constraint, raising production to 480 MB/D in 1990. This amount is available using current technology in the highly favorable reservoirs. The contribution of CD-1 begins to be felt as early as 1980, but significant escalation of production rate occurs after 1985. By 1990, CD-1 has brought the expected production to 820 MB/D. As noted earlier, the other carbon dioxide programs have later impacts -- contributing substantially to ultimate recovery only after 1995.

EXHIBIT IV-10

EXPECTED CARBON DIOXIDE PRODUCTION RATES

(STANDARD ECONOMICS)

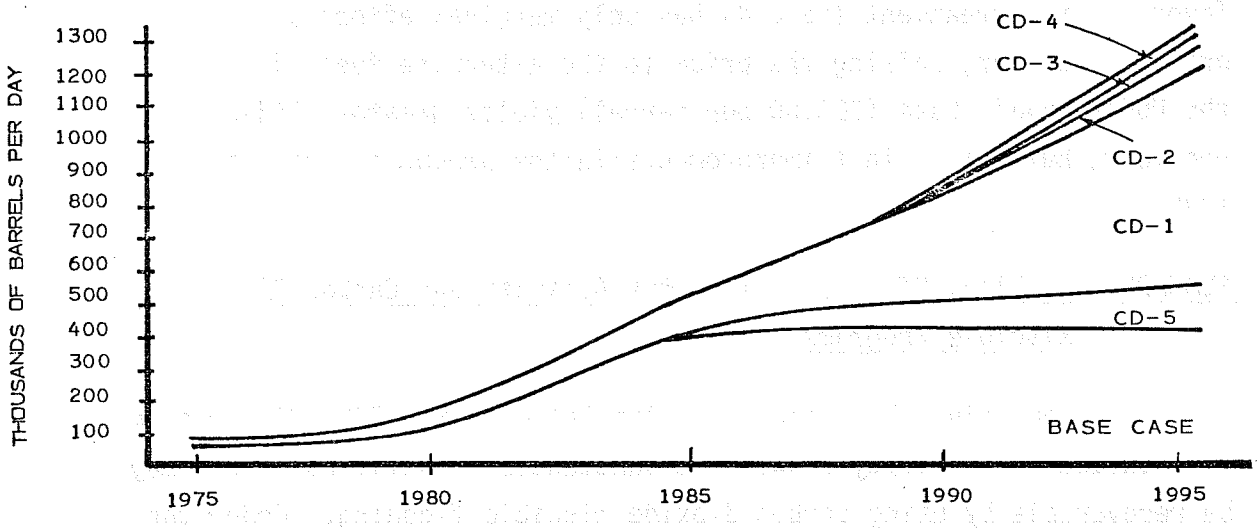
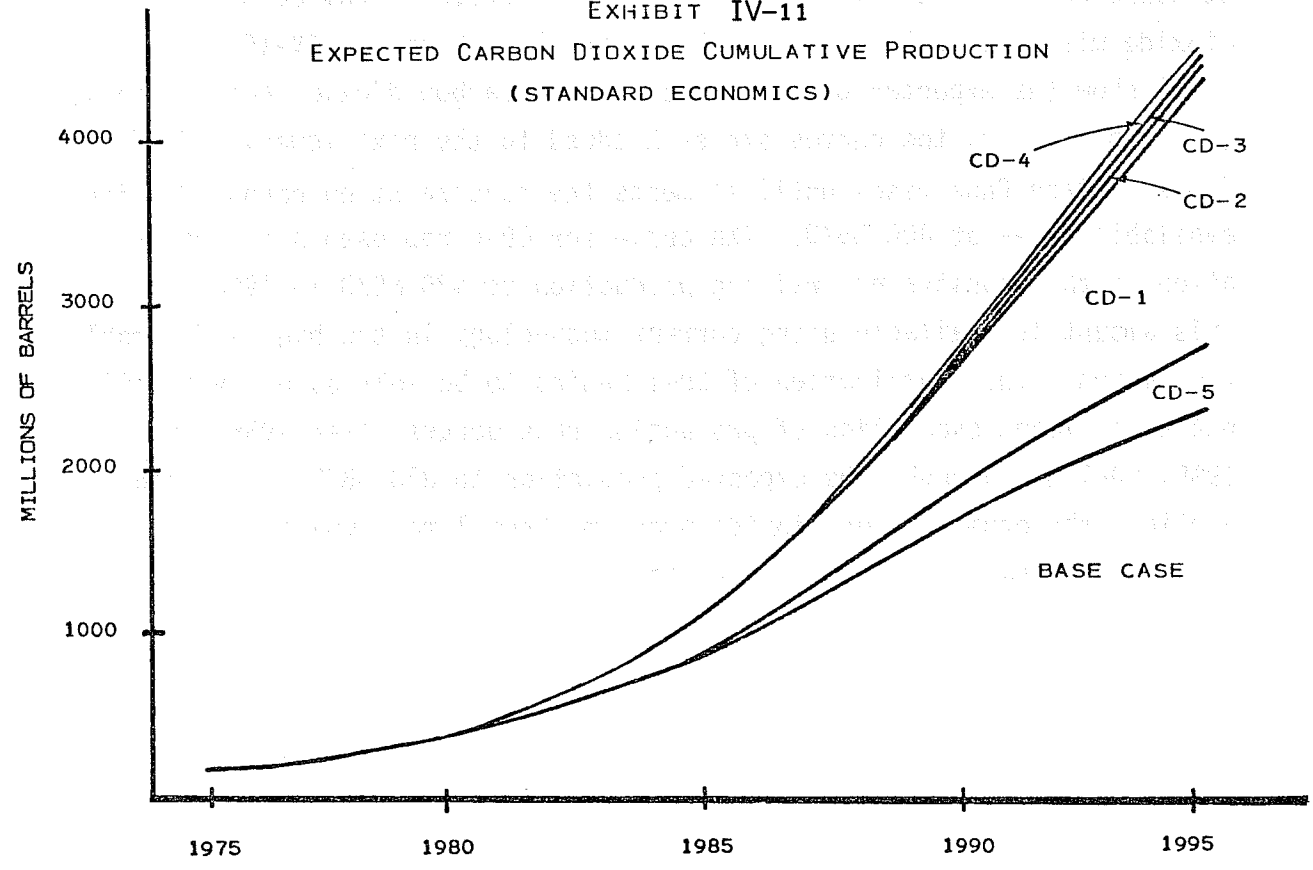



EXHIBIT IV-11

EXPECTED CARBON DIOXIDE CUMULATIVE PRODUCTION

(STANDARD ECONOMICS)



The total carbon dioxide production (from the Industry Base Case and the ERDA program) was seen to be sensitive to price/tax contingencies. Exhibit IV-12 displays expected ultimate recovery under each of the contingencies analyzed. Exhibit IV-13 shows the effects of the most salient price/tax contingencies on production rates.

As can be seen in Exhibit IV-12 (comparing the first two bars), removal of the opportunity to expense the injected carbon dioxide results in a substantial reduction in ultimate recovery, as the Industry Base Case shrinks and only one ERDA program stimulates additional production. With prices rising to the world oil price (Case 2 and 4), oil recovery from the Industry Base Case and that stimulated by ERDA's programs increase. Comparing these two cases shows the small effect that moderate (3%) increases in the investment tax credit have on ultimate recovery. Further increases in price -- up to alternate fuels level -- expand the ultimate recovery of the Industry Base Case and of ERDA's program. The relatively smaller contribution of CD-1 is due to the allocation of some of this benefit to industry R&D, i.e., it is incorporated into the Base Case at this price level. (Note that the reason CD-5 does not appear in this figure is because its contribution is acceleration of production by relaxing the limitations posed by lack of carbon dioxide supply. Thus, it does not add to ultimate recovery -- the Industry Base Case contains that recovery but this would be produced at a slow rate and thus at a later date.)

As seen in the lower figure, the acceleration of the overall production rate due to improved economics is almost unnoticeable before 1985, but begins to have significant effect after 1990. This acceleration effect is most pronounced under the alternate fuels price.

EXHIBIT IV-12

EXPECTED ULTIMATE RECOVERY UNDER PRICE/TAX CONTINGENCIES FROM CARBON DIOXIDE PROGRAMS

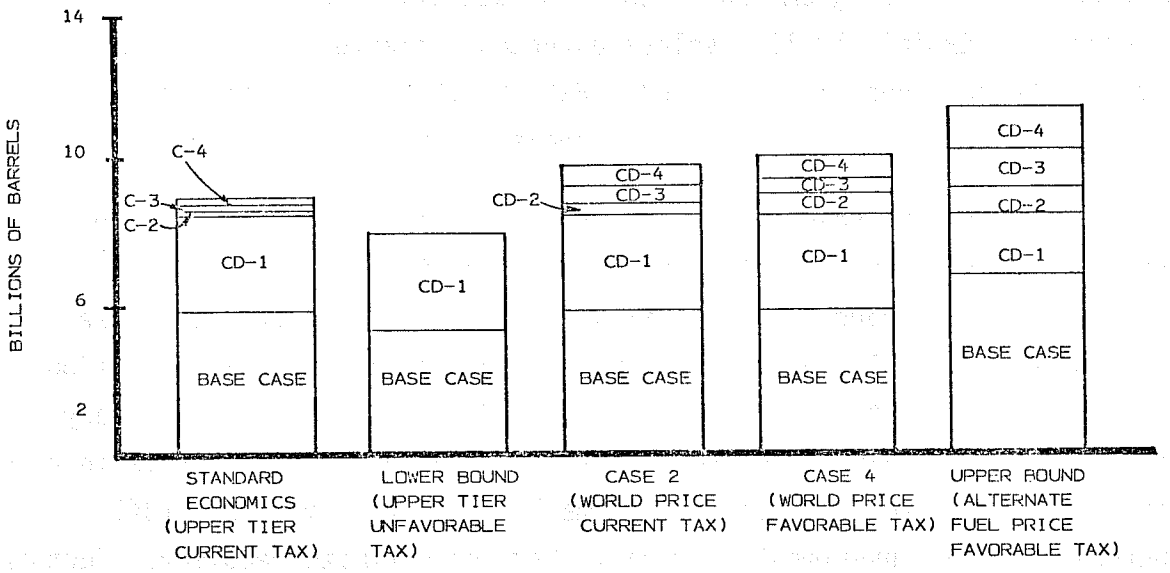
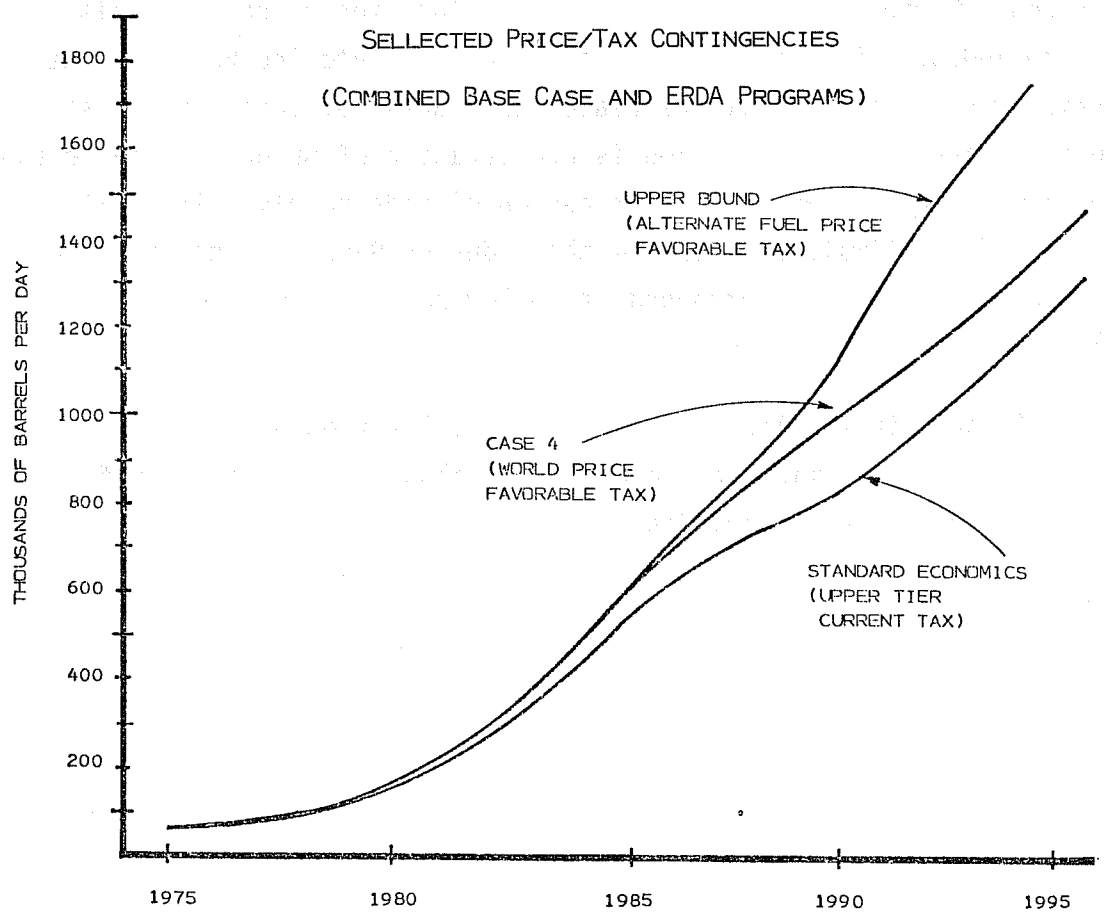



EXHIBIT IV-13

EXPECTED CARBON DIOXIDE PRODUCTION RATES UNDER SELLECTED PRICE/TAX CONTINGENCIES (COMBINED BASE CASE AND ERDA PROGRAMS)



## SECTION B: INDIVIDUAL CARBON DIOXIDE MISCIBLE PROJECTS

## TARGET C-1: CARBON DIOXIDE MISCIBLE DISPLACEMENT IN CARBONATE RESERVOIRS HAVING A HIGH (45% or greater) RESIDUAL OIL SATURATION

## R&D STRATEGY CD-1: SECURE ADEQUATE RECOVERY OF CRUDE AT ACCEPTABLE OIL/$CO_2$ RATIOS

### 1. CENTRAL PROBLEM

To achieve effective miscible displacement of crude oil, the carbon dioxide must be miscible relatively soon after injection into the reservoir. Moreover, its mobility must be as close to that or even less than that of the crude oil bank being formed ahead of the carbon dioxide.

Carbon dioxide is a very low viscosity fluid under the super-critical conditions at which it is used to achieve miscibility. Therefore, a bank of high oil saturation (and high mobility) and the absence of any watered-out channels available for by-passing will promote effective displacement of the crude by carbon dioxide. The 45% saturation is presumed to be a cut-off for classifying reservoirs into this category.*

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*The cut-off of 45% is a presumed one, and of course cannot be expected to represent a sharp and absolute demarcation between reservoirs that will respond well and those that will not respond to carbon dioxide. The value of 45% is derived from reconstructing the saturations which existed in the SACROC reservoir prior to initiating the carbon dioxide floods. In the SACROC unit, a carbon dioxide flood was initiated in the area of the reservoir early in the life of a waterflood, and a pilot was also initiated in the area that was completely watered out. Using the operator's published data on the performance of the reservoir and anticipated performance to continued conventional operations, calculations were made which indicate the oil saturation in the area that was not reduced to a water flood residual saturation was at 0.60 oil saturation, and the residual saturation in the watered out area was 0.43. (These saturations are average values and do not take into account areal sweep effects. The calculations leading to such representation of saturations give boundary values, viz., the actual values in the two areas of the reservoir are probably somewhat lower and higher, respectively.) Based on this calculation, a conclusion would be that if the reservoir saturation in such a carbonate is 43% or less, a carbon dioxide flood would not be applicable at this time, and a minimum saturation somewhere between 43 and 60% would be required for successful application.

The problem is that currently operators, except in special cases, tend to wait until the end of the waterflood before initiating or even considering the injection of carbon dioxide. Should the oil saturations in these reservoirs be driven below 45%, the technical and economic application of carbon dioxide in a tertiary mode could be severely impaired.

Second, mobility control is a major problem in miscible flooding. Even where the displacing phase is absolutely miscible with the crude under all conceivable in situ conditions, an unfavorable mobility ratio will lead to fingering and low recovery efficiency. Since the viscosity of super-critical $CO_2$ is of the order of 0.2 cp., the viscosity ratio will clearly be unfavorable even with the highest gravity crudes. In order to secure a favorable mobility ratio, the relative permeability of $CO_2$ would have to be lowered to a value which is a fraction of the relative permeability to the oil ahead of the $CO_2$ front.

2. R&D GOALS

- To establish (a) the range of physical conditions under which carbon dioxide is miscible with the crude oils of these target reservoirs; (b) the nature of additives that might promote miscibility; and (c) where miscibility is not achieved on first contact, the point in the reservoir at which miscibility can be expected to be achieved.

- To establish the cut-off oil saturation at which the performance of carbon dioxide floods degenerates rapidly, as a function of reservoir lithology and other reservoir parameters.

- To determine the possibility of affecting the mobility ratio without vitiating miscibility by additions or alternation of injection materials with the carbon dioxide.

- To determine the possibility of overcoming the innate heterogeneities of the formation by well completions, well locations, and flooding patterns, or other operating practices.

- The eventual R&D goals are twofold:

  a) to accelerate the application of $CO_2$ prior to a reservoir reaching the critical oil saturation level and;

  b) to improve the sweep efficiency of the process by 50% over that currently attributed to carbon dioxide flooding.

3. R&D ACTIVITIES

I. Building the Knowledge Base; starting in 1977

-- Determine current levels of oil saturation.

-- Examine and evaluate ongoing industry applications of carbon dioxide.

-- Construct recovery models with sweeps and displacement parameters dependent on reservoir characteristics.

II. Basic and Applied Research: starting in 1977

-- Phase relations studies of crude oil/carbon dioxide/additive systems under the range of physical conditions and contact anticipated in the reservoir.

-- Long core/sandpack studies to determine extension of phase relations studies to dynamic flow system.

-- In-depth lithological studies of porous media in target reservoirs to assess conditions imposed by heterogeneity of carbonate rocks.

-- Displacement studies in carbonate cores, slabs, and in large, scaled physical models if the latter are feasible.

-- Study of additives that may improve recovery performance: effective range of use of alternating slugs of water, use of foaming agents, emulsifiers, polymeric additives, graded (viscosity) slugs of carbon dioxide and crude, and pre-injection of crude.

III. Field Based Activities

-- Mini-tests in selected reservoirs, starting in 1977.

PGM: CD-1

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | - |
| B. RESERVOIR DATA BASE | | | | | | - |
| C. RECOVERY MODELS | | | | | | - |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | | | | | - |
| E. PROCESS/FIELD TEST EVALUATION | 1 | 1 | | | | 2 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 3 | 6 | 5 | 3 | 3 | 20 |
| B. FLOW STUDIES | 4 | 16 | 20 | 12 | 10 | 62 |
| C. FIELD LIAISON & ENG. STUDIES | 1 | 2 | 2 | 2 | 1 | 8 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 6 1/ → | | | | | 6 1/ |
| B. MINI-TESTS | | 3 → | → | → | → | 3 |
| C. TECHNICAL PILOTS | | | | | | - |
| D. ECONOMIC PILOTS | | | | | | - |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS / B. SHARE INDUSTRY/ERDA DEVELOP. | | 1 | 1 | 1 | 1 | 4 |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ CORE - HOLES

PGM: CD-1

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | | | | | | – |
| C. RECOVERY MODELS | | | | | | – |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | | | | | – |
| E. PROCESS/FIELD TEST EVALUATION | 60 | 60 | | | | 120 1/ |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 180 | 360 | 300 | 180 | 180 | 1200 1/ |
| B. FLOW STUDIES | 240 | 960 | 1200 | 720 | 600 | 3720 1/ |
| C. FIELD LIAISON & ENG. STUDIES | 60 | 150 | 150 | 150 | 75 | 585 |
| D. LAB EQUIPMENT & FACILITIES | 750 | 2000 | 750 | 250 | 250 | 4000 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 1000 | 250 | | | | 1250 |
| B. MINI-TESTS | | 1750 | 2500 | 2500 | 250 | 7000 |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. / B. SHARE INDUSTRY/ERDA DEVELOP. | | 60 | 60 | 60 | 60 | 240 |
| TOTAL | 2290 | 5590 | 4960 | 3860 | 1415 | 18115 |
| ERDA SHARE | 1790 | 4590 | 3710 | 2610 | 1290 | 13990 |

1/ POST 1981 COMMITMENT: AN ESTIMATED EXPENDITURE OF $500,000 PER YEAR, 1982-1986 INCLUSIVE

PGM: CD-1

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 15823 | 17290 |
| ERDA'S SHARE | 12141 | 13708 |

7. EXPECTATION OF SUCCESS: 57%

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 6000 | 3420 | 249 |
| DAILY PRODUCTION IN | | | |
| 1985 | 239 | 136 | 3.6 |
| 1990 | 594 | 339 | 9.0 |
| 1995 | 1182 | 674 | 17.9 |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 282 | 161 | 12 |
| 1990 | 1064 | 607 | 44 |
| 1995 | 2830 | 1614 | 118 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

TARGET C-1 (Continued)

R&D STRATEGY CD-5: DEVELOP ADEQUATE/CHEAPER SUPPLIES OF CARBON DIOXIDE

1. CENTRAL PROBLEM

Widespread use of carbon dioxide miscible displacement schemes will be dependent upon the availability of cheap and adequate sources of carbon dioxide. There is, as of today, no firm understanding as to the adequacy of natural or manufactured supplies of carbon dioxide in the Southwest and Montana regions to serve the potential targets for this scheme. The assumption is presently made that there is currently an adequate economic supply of carbon dioxide available for production of 400,000 B/D of crude oil and that industry exploration/R&D efforts will secure sufficient new supplies of carbon dioxide to achieve their base case production targets.

2. R&D GOALS

- To establish the range of available natural and manufactured supplies of carbon dioxide at various price levels delivered to locations in the Southwest and Montana.
- The eventual R&D goal is to overcome any ceilings on production imposed by inadequate supplies of carbon dioxide.

3. R&D ACTIVITIES

I. Building the Knowledge Base

-- Study and survey available documentation on natural sources of carbon dioxide.

-- Conduct studies and surveys on available supply of by-product carbon dioxide, individual engineering/economic feasibility studies for recovering it.

II. Basic and Applied Research

-- Conduct engineering/economic feasibility studies of specialty manufacturing schemes for producing carbon dioxide.

-- Conduct engineering/economic studies of transportation and recycling of carbon dioxide.

PGM: CD-5

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | | | | | | – |
| C. RECOVERY MODELS | | | | | | – |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | 4 | 4 | 4 | 2 | | 14 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | – |
| B. FLOW STUDIES | | | | | | – |
| C. FIELD LIAISON & ENG. STUDIES | | | | | | – |
| D. LAB EQUIPMENT & FACILITIES * | | | | | | – |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | – |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 1/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 1/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ INCLUDED IN ABOVE FIGURES

PGM: CD-5

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | | | | | | – |
| C. RECOVERY MODELS | | | | | | – |
| D. ECONOMIC & OTHER FEASIB. STUDIES | 240 | 240 | 240 | 120 | | 840 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | – |
| B. FLOW STUDIES | | | | | | – |
| C. FIELD LIAISON & ENG. STUDIES | | | | | | – |
| D. LAB EQUIPMENT & FACILITIES | | | | | | – |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | – |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 1/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 1/ |
| TOTAL | 240 | 240 | 240 | 120 | | 840 |
| ERDA SHARE | 240 | 240 | 240 | 120 | | 840 |

1/ INCLUDED IN ABOVE COSTS

PGM: CD-5

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|---|
| TOTAL COSTS | ALL ERDA | 763 | 763 |
| ERDA'S SHARE | | | |

7. EXPECTATION OF SUCCESS: N/A

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | - | - | - |
| DAILY PRODUCTION IN | | | |
| 1985 | 10 | 10 | 4.8 |
| 1990 | 85 | 85 | 40.7 |
| 1995 | 165 | 165 | 78.9 |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 4 | 4 | 5 |
| 1990 | 164 | 164 | 215 |
| 1995 | 389 | 389 | 510 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

## TARGET C-2: CARBON DIOXIDE MISCIBLE DISPLACEMENT IN THE SOUTHWEST AND MONTANA CARBONATE RESERVOIRS HAVING A SATURATION LESS THAN 45%

## R&D STRATEGY CD-2: EXTEND APPLICABILITY OF PROCESS TO RESERVOIRS WITH LOW OIL SATURATION

### 1. CENTRAL PROBLEM

It is apparent from the results that have appeared of technical and economic $CO_2$ floods that the efficiency of the flood, both in terms of recovery of crude and the oil/$CO_2$ ratio, decreases with saturation of oil in the reservoir. (See discussion of Target C-1 for strategies designed to define the critical saturation range at which flooding efficiency begins to degenerate rapidly.)

The problems stemming from low oil saturation in these reservoirs are compounded by the adverse mobility ratio of the displacing fluid and the crude oil causing overriding and fingering of the carbon dioxide through the crude oil. Further, it now appears that carbon dioxide is not always miscible on first contact with the crudes, a problem that appears to be magnified in instances of low oil saturation.

### 2. R&D GOALS

- To determine the possibility of conducting a successful carbon dioxide flood at low residual oil saturation given that conditions for miscibility can be attained. (Target C-1, strategy CD-1.)

- The eventual R&D goal would be to achieve a level of recovery in these reservoirs comparable to those being projected under current technology for the favorable reservoirs.

3. R&D ACTIVITIES

I. Building the Knowledge Base: starting in 1977

-- Determine current levels of oil saturation.

-- Construct recovery models with sweep and displacement parameters dependent on reservoir characteristics.

-- Examine the economic feasibility of applying the process, observing particularly those problems posed by the low oil saturations.

-- Examine and evaluate ongoing industry applications of carbon dioxide on Target C-1 reservoirs.

II. Basic and Applied Research: starting in 1977

-- Phase relations studies of crude oil/carbon dioxide/additive systems under the range of physical conditions and contact anticipated in the reservoir.

-- Long core/sandpack studies to determine extension of phase relations studies to dynamic flow system.

-- In-depth lithological studies of porous media in target reservoirs to assess conditions imposed by heterogeneity of carbonate rocks.

-- Displacement studies in carbonate cores, slabs, and in large, scaled physical models if the latter are feasible.

-- Study of additives that may improve recovery performance: effective range of use of alternating slugs of water, use of foaming agents, emulsifiers, polymeric additives, graded (viscosity) slugs of carbon dioxide and crude, and pre-injection of crude.

-- Emphasis on studies which will lead to early build-up of an oil bank, other than by $CO_2$ injection, which subsequently can be driven through the formation by the $CO_2$ industry concentrated surfactant systems, microemulsions, oil slugs, and steam slugs.

III. Field Based Activities

-- Pre-evaluation of amenable reservoirs, starting in 1977.

-- Mini-tests in selected reservoirs, starting in 1978.

-- Technical pilots, starting in 1981

PGM: CD-2

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | 1/ |
| B. RESERVOIR DATA BASE | 1 | | | | | 1 |
| C. RECOVERY MODELS | | 1 | | | | 1 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | | 1 | | | 1 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 3 | 5 | 7 | 10 | 10 | 35 |
| B. FLOW STUDIES | | 6 | 12 | 14 | 14 | 46 |
| C. FIELD LIAISON & ENG. STUDIES | 1 | 1 | 2 | 2 | 2 | 8 |
| D. LAB EQUIPMENT & FACILITIES * | | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 5 2/ | 5 2/ | | | | 10 2/ |
| B. MINI-TESTS | | | 6 → | → | → | 6 |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 3/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ RELIES ON RESIDUAL MEASUREMENTS PROGRAM, ST-4.

2/ CORE HOLES

3/ INCLUDED IN ABOVE FIGURES

PGM: CD-2

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL 1/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | 2/ |
| B. RESERVOIR DATA BASE | 60 | | | | | 60 |
| C. RECOVERY MODELS | | 60 | | | | 60 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | | 60 | | | 60 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 180 | 300 | 420 | 600 | 600 | 2100 1/ |
| B. FLOW STUDIES | | 360 | 720 | 840 | 840 | 2760 1/ |
| C. FIELD LIAISON & ENG. STUDIES | 60 | 75 | 150 | 150 | 150 | 585 1/ |
| D. LAB EQUIPMENT & FACILITIES | | 500 | 750 | 250 | 250 | 1750 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 1000 | 1000 | | | | 2000 |
| B. MINI-TESTS | | | 2500 | 4000 | 5000 | 11500 |
| C. TECHNICAL PILOTS | | | | | | |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | – | | 3/ |
| TOTAL | 1300 | 2295 | 4600 | 5840 | 6840 | 20875 |
| ERDA SHARE | 1300 | 2295 | 4600 | 5840 | 6840 | 20875 |

1/ POST 1981 COMMITMENTS: $5,000,000 IN 1981 AND $2,500,000 IN 1983 RESPECTIVELY, FOR FIELD WORK. IN ADDITION, AN AVERAGE COMMITMENT OF $2,500,000 PER YEAR FROM 1982 TO 1986.

2/ RELIES ON RESIDUAL MEASUREMENTS PROGRAM, PROGRAM ST-4

3/ INCLUDED IN ABOVE COSTS

PGM: CD-2

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|---|
| TOTAL COSTS | ALL ERDA | 17032 | 29348 |
| ERDA'S SHARE | | | |

7. EXPECTATION OF SUCCESS: 40%

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 600 | 240 | 8 |
| DAILY PRODUCTION IN: | | | |
| 1985 | 6 | 2 | * |
| 1990 | 6 | 2 | * |
| 1995 | 95 | 38 | 0.5 |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 20 | 8 | ** |
| 1990 | 33 | 13 | ** |
| 1995 | 126 | 50 | 2 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

* LESS THAN 0.1

** LESS THAN 1

Note on Production Benefits and Cost-Effectiveness Indices of Program CD-2

The production benefits shown assume upper-tier prices and high risk (20% real) rate of return requirement. The assumption that the risk premium will not be reduced through the program is highly sensitive. Should $CO_2$ miscible become a conventional technology (i.e., require an 8% real rate of return), the impact would be as shown below:

| | HIGH RISK (NOTED ABOVE) | CONVENTIONAL RISK |
|---|---|---|
| POTENTIAL PRODUCTION BENEFITS: | | |
| ULTIMATE RECOVERY (MMB) | 600 | 2100 |
| DAILY PRODUCTION MB/D) IN: | | |
| 1985 | 6 | 11 |
| 1990 | 6 | 22 |
| 1995 | 95 | 332 |
| CUMULATIVE PRODUCTION (MMB) BY: | | |
| 1985 | 20 | 25 |
| 1990 | 33 | 60 |
| 1995 | 126 | 383 |
| COST/EFFECTIVENESS INDICES: | | |
| ULTIMATE RECOVERY/ COST | 8 | 29 |
| ANNUAL PRODUCTION/ COST | | |
| 1985 | * | * |
| 1990 | * | 0.1 |
| 1995 | 0.5 | 1.7 |
| CUMULATIVE PRODUCTION/ COST | | |
| 1985 | ** | ** |
| 1990 | ** | 1 |
| 1995 | 2 | 5 |

* LESS THAN 0.1
** LESS THAN 1

The sensitivity of these results to the risk premium assumption should be borne in mind in evaluating Program CD-2. It is not currently possible to assign a probability to making $CO_2$ conventional for these targets. The substantial program described above sets the stage for subsequent efforts after 1981 designed to make this program a conventional recovery technology.

## TARGET C-3: CARBON DIOXIDE MISCIBLE DISPLACEMENT IN GULF COAST SANDSTONES

## R&D STRATEGY CD-3: EXTEND APPLICABILITY OF PROCESS

### 1. CENTRAL PROBLEM

There are two distinct types of reservoirs for which $CO_2$ is to be considered in this region: one type of reservoir is a dipping reservoir in which a $CO_2$ flood can be gravity stabilized, and the second type is the more typical flat sand which has been driven to a low residual saturation by a water drive. Applications to the latter will encounter much the same problems as those detailed under Target C-2. Differences will occur due to the uniformity of the sands, higher attainable velocities, and possible differences in the phase relations between the carbon dioxide and crudes, and under the pressure and temperature conditions of the Gulf Coast.

The sands in which gravity stabilized floods can be developed will be effective if the carbon dioxide can be secured cheaply enough or if it can be displaced with air so that the carbon dioxide can be re-used in another operation. Recovery of the carbon dioxide is required if cheap material cannot be secured because the reservoir must be filled with the reagent at the conclusion of the operation. (Displacement by water is obviously impossible if the gravity stabilization is to be maintained.)

### 2, R&D GOALS

- For the low saturation reservoirs, determine the possibility of conducting a successful carbon dioxide flood at low residual oil saturation given that conditions for miscibility can be attained.

- The eventual R&D goal for the flat sand reservoirs will be the same as for Target C-2, strategy CD-2.

- For the dipping reservoirs, establish the potential of the effects of combining miscibility and gravity drainage on conducting a successful carbon dioxide flood.

- The eventual R&D goal for the dipping sandstone reservoirs would be to achieve a total sweep efficiency of approximately 60%.

3. R&D ACTIVITIES

I. Building the Knowledge Base: starting in 1977

-- Determine current levels of oil saturation.

-- Construct recovery models with sweep and displacement parameters dependent on reservoir characteristics.

-- Examine the economic feasibility of using carbon dioxide with attention to the differences due to reservoir lithology, reservoir conditions, and the nature of the crude oil.

-- Examine and evaluate ongoing industry applications of carbon dioxide under Target C-1 reservoirs.

II. Basic and Applied Research: starting in 1977

-- Phase relations studies of crude oil/carbon dioxide/additive systems under the range of physical conditions and contact anticipated in the reservoir.

-- Long core/sandpack studies to determine extension of phase relations studies to dynamic flow system.

-- In-depth lithological studies of porous media in target reservoirs to assess conditions imposed by heterogeneity of carbonate rocks.

-- Displacement studies in carbonate cores, slabs, and in large scaled physical models if the latter are feasible.

-- Study of additives that may improve recovery performance: effective range of use of alternating slugs of water, use of foaming agents, emulsifiers, polymeric additives, graded (viscosity) slugs of carbon dioxide and crude, and pre-injection of crude.

III. Field Based Activities

-- For the dipping reservoirs, search for a suitable dipping reservoir comprised of a sufficiently small fault block in which a technical pilot can be operated, starting in 1977.

-- Coordinate with the field work on Targets C-1, C-2, and C-4 for making performance projections on the flat, sandstone reservoirs.

-- Mini-test in 1980 in a flat reservoir.

-- Conduct technical pilots, in non-dipping sandstone reservoirs, should successful results be realized in the above field work, starting in 1980.

PGM: CD-3

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | 1/ |
| B. RESERVOIR DATA BASE | | | | | | – |
| C. RECOVERY MODELS | 1 | | | | | 1 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | | | | | – |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 1 | 2 | 2 | | | 5 |
| B. FLOW STUDIES | | 2 | 2 | 6 | 2 | 12 |
| C. FIELD LIAISON & ENG. STUDIES | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 3 |
| D. LAB EQUIPMENT & FACILITIES | | | | | | – |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | – |
| B. MINI-TESTS | | | | 1 → | → | 1 |
| C. TECHNICAL PILOTS | 1 → | → | → | → | → | 1 |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | 2/ |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ RELIES ON RESIDUAL MEASUREMENTS PROGRAM, ST-4

2/ INCLUDED IN ABOVE FIGURES

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL 1/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | - | 2/ |
| B. RESERVOIR DATA BASE | | | | | | - |
| C. RECOVERY MODELS | 60 | | | | | 60 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | | | | | - |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | - |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 60 | 120 | 120 | | | 300 |
| B. FLOW STUDIES | | 120 | 120 | 360 | 120 | 720 |
| C. FIELD LIAISON & ENG. STUDIES | 45 | 45 | 45 | 45 | 45 | 225 |
| D. LAB EQUIPMENT & FACILITIES | | | | | | - |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | - |
| B. MINI-TESTS | | | | 1000 | 1000 | 2000 |
| C. TECHNICAL PILOTS | 1000 | 3000 | 2000 | 1000 | 2000 | 9000 |
| D. ECONOMIC PILOTS | | | | | | - |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 3/ |
| TOTAL | 1165 | 3285 | 2285 | 2405 | 3165 | 12305 |
| ERDA SHARE | 665 | 1785 | 1285 | 2405 | 3165 | 9305 |

1/ POST 1981 COMMITMENTS $1,000,000 IN 1982 AND $3,000,000 IN 1983 RESPECTIVELY FOR FIELD WORK. IN ADDITION, AN AVERAGE COMMITMENT OF $2,000,000 PER YEAR FROM 1982 TO 1986.

2/ RELIES ON RESIDUAL MEASUREMENTS PROGRAM, PROGRAM ST-4

3/ INCLUDED IN ABOVE COSTS

PGM: CD-3

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 10,401 | 13,660 |
| ERDA'S SHARE | 7,655 | 10,914 |

7. EXPECTATION OF SUCCESS: 75% (ASSUMING DIPPING RESERVOIRS; 25% FOR RESERVOIRS THAT DO NOT DIP. ALL THAT WERE ECONOMIC IN THIS TARGET WERE DRIPPING RESERVOIRS.)

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 300 | 200 | 18 |
| DAILY PRODUCTION IN | | | |
| 1985 | 1 | 1 | * |
| 1990 | 4 | 3 | 0.1 |
| 1995 | 34 | 25 | 0.8 |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 5 | 4 | * |
| 1990 | 11 | 8 | 1 |
| 1995 | 43 | 32 | 3 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

* LESS THAN 0.1

## TARGET C-4: CARBON DIOXIDE MISCIBLE FLOODING IN SANDSTONES OTHER THAN THOSE ALONG THE GULF COAST

## R&D STRATEGY CD-4: EXTEND APPLICABILITY OF PROCESS OF CARBON DIOXIDE FLOODING

### 1. CENTRAL PROBLEM

A substantial number of sandstone reservoirs in California, Appalachia and other areas appear to be amenable only to carbon dioxide recovery. However, little is known of the conditions required for miscibility, injectivity of carbon dioxide, and total availability of carbon dioxide at these locations. Considerable basic study and information seems essential before one can knowledgeably discuss the potential of the carbon dioxide process in such reservoirs.

### 2. R&D GOALS

- To determine the technical feasibility of extending carbon dioxide to first the California and Appalachia sandstones and then to the other sandstone reservoirs.
- To establish the availability of carbon dioxide at affordable prices at such locations.

### 3. R&D ACTIVITIES

I. Building the Knowledge Base: starting in 1977

-- Assimilation of results of activities under Target C-1.

-- Establishing the residual oil saturations.

-- Building a detailed data base on these reservoirs.

-- Constructing reliable recovery models of the process as applied to this category of reservoirs.

-- Studying the economic feasibility of applying the process and obtaining supplies of carbon dioxide.

II. Basic and Applied Research: starting in 1977

-- Phase relations studies of crude oil/carbon dioxide/additive systems under the range of physical conditions and contact anticipated in the reservoir.

-- In-depth lithological studies of porous media in target reservoirs to assess conditions imposed by heterogeneity of rock and distribution of residual oil.

-- Displacement studies in long cores, and in large, scaled physical model studies if the latter are feasible.

III. Field Based Activities

-- Coordinate with the field pilots under Targets C-1, C-2 and C-3, utilizing the already ongoing pilots in the Appalachia region and introducing an additional mini-test/technical pilot in the California region.

-- Mini-tests (or technical pilots) in selected reservoirs.

PGM: CD-4

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | 1/ |
| B. RESERVOIR DATA BASE | | | | | | – |
| C. RECOVERY MODELS | 1 | | | | | 1 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | | | | | – |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 2 | 3 | 3 | 2 | 1 | 11 |
| B. FLOW STUDIES | 2 | 3 | 6 | 8 | 8 | 27 |
| C. FIELD LIAISON & ENG. STUDIES | 0.2 | 0.3 | 0.6 | 0.6 | 0.6 | 2.3 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 5 2/ | 5 2/ | | | | 10 2/ |
| B. MINI-TESTS | | | 3 → | → | | 3 |
| C. TECHNICAL PILOTS | | | | 1 → | → | 1 |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 3/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ RELIES ON RESIDUAL MEASUREMENT PROGRAM ST-4

2/ CORE-HOLES

3/ INCLUDED IN ABOVE FIGURES.

PGM: CD-4

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL 1/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | 2/ |
| B. RESERVOIR DATA BASE | | | | | | - |
| C. RECOVERY MODELS | 60 | | | | | 60 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | | | | | - |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | - |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 120 | 180 | 180 | 120 | 60 | 660 |
| B. FLOW STUDIES | 120 | 180 | 360 | 480 | 480 | 1620 |
| C. FIELD LIAISON & ENG. STUDIES | 12 | 25 | 45 | 45 | 45 | 172 |
| D. LAB EQUIPMENT & FACILITIES | 250 | 250 | 100 | 100 | 100 | 800 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 1000 | 1000 | | | | 2000 |
| B. MINI-TESTS | | | 1500 | 1500 | | 3000 |
| C. TECHNICAL PILOTS | | | | 500 | 1000 | 1500 |
| D. ECONOMIC PILOTS | | | | | | - |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 3/ |
| TOTAL | 1562 | 1635 | 2185 | 2745 | 1685 | 9812 |
| ERDA SHARE | 1562 | 1635 | 2185 | 2745 | 1685 | 9812 |

1/ POST 1981 COMMITMENT: $1,500,000 IN 1982 AND $2,000,000 IN 1983 RESPECTIVELY FOR FIELD WORK. IN ADDITION, AN AVERAGE COMMITMENT OF $500,000 PER YEAR FROM 1982 TO 1986.

2/ RELIES ON RESIDUAL MEASUREMENTS PROGRAM ST-4

3/ COSTS INCLUDED ABOVE.

PGM: CD-4

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|---|
| TOTAL COSTS | ALL ERDA | 8367 | 12114 |
| ERDA'S SHARE | | | |

7. EXPECTATION OF SUCCESS: 32%

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 600 | 192 | 16 |
| DAILY PRODUCTION IN | | | |
| 1985 | 6 | 2 | 0.1 |
| 1990 | 20 | 6 | 0.2 |
| 1995 | 83 | 27 | 0.8 |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 4 | 1 | * |
| 1990 | 32 | 10 | 1 |
| 1995 | 121 | 39 | 2 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

# CHAPTER V

## SURFACTANT/POLYMER FLOODING

### SECTION A: GENERAL DISCUSSION

#### Description and Current Application of the Technology

The use of surfactants to displace crude oil is the most recent and least proven of the enhanced recovery processes. Oil displacement by a surfactant slug or micellar solution, while not truly miscible,[1/] is at such low interfacial tensions that miscibility is approached. Under these conditions virtually all of the oil could be displaced. Therefore, displacement efficiency and the maximum potentially obtainable recovery are nearly the same as for the miscible slug processes (see Chapter IV of this Part). Although theoretic possibilities and initial laboratory results were highly promising, field experience to date has been largely disappointing.

The surfactants used in this process are generally mixtures of petroleum sulfonates and other chemicals (alcohols and cosurfactants) in aqueous solutions or in microemulsion dispersed in oil (the micellar formulation). A variation is the in situ formation of similar substances that results from the injection of caustic into reservoirs with oil of certain specific compositions. The displacing agent is driven through the reservoir by water. Polymer solutions are frequently injected after the surfactants to improve mobility control. The specific surfactant system must be engineered to the particulars of given reservoir and fluid characteristics.

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1/ Some researchers argue that surfactants are truly miscible in certain crude oils.

Substantial quantities of oil are trapped in the porous rock medium of the reservoir by capillary action. Capillary trapping is the resistance of a non-wetting fluid (oil) to flow through a microscopic pore or constriction which is wetted by a second fluid (water). One way these forces can be overcome is through establishing an enormous pressure gradient, to push the oil. The magnitude of this gradient, however, is impracticably large, given the limitations of the reservoir structure and lithology. The original concept for using surfactants was as an alternative to such pressures -- to overcome the capillary forces by reducing the interfacial tension between the two fluids.

Tremendous decreases in interfacial tension, however, are required at ordinary pressure gradients to release or prevent the trapping of residual oil by capillary action. Values of $10^{-4}$ dynes per centimeter, compared to the ordinary level of 30 dynes per centimeter between oil and water, are required to effect any significant reduction in the amount of oil held by capillary action. Early attempts to achieve these low values encountered problems with adsorption of the surfactants so that after a short travel through the reservoir, the surfactants were depleted from solution. Further recovery of oil following such a depletion could only be attributable to a relatively dilute emulsion of the oil.

More recent activity in this field has involved the preparation of rather highly concentrated slugs of surfactants[2/] for injection into reservoirs. The surfactant slugs are nearly miscible with the oil

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2/ Some operators are also testing low-concentration slugs.

and displace the oil over a significant length of the reservoir -- just as in the case of the injection of simpler, miscible fluids (see the discussion of Carbon Dioxide Flooding). Adsorption is reduced by the formulation of the slug or merely reduced to negligible importance by using slugs of high concentration. Mobility of the surfactant slug is controlled either by the addition of water-soluble polymers or by slug formulation which results in a viscosity-building process when the slug contacts reservoir fluids.

Ultimately, the surfactant slug is displaced by a less mobile (more viscous) solution of polymer thickened water. Under laboratory conditions, the chemical flood has been shown to be effective using a wide variety of surfactant/polymer formulations. Thus, it would appear that the ideal, highly effective, mobility controlled displacement process is available through the use of surfactants and polymers, and that this process has applicability to large numbers of reservoirs in diverse geological provinces.

Field results, however, have shown much poorer performance than would have been anticipated based on the laboratory studies. This has been so prevalent that it may be concluded that the actual reservoir and its configuration of oil and water has not been modeled well in the laboratory, or that the process is vitiated by factors which have not been taken into account in assessing the results of laboratory studies.

It is probable that both of these shortcomings exist in laboratory studies. Degradation of the polymer and surfactant effectiveness can be traced to salinity, temperature, and adsorption effects

which just cannot be reproduced in the short systems used in laboratory studies. Of even greater suspected effect is the inability of the surfactant/polymer systems to initiate the build-up of an oil bank which is vital to the propagation of an effective process through the formation. The distribution of residual oil and water around an injection well after the injection of large quantities of water under high pressure gradients may also not be reproducible in the laboratory. As a result, in the laboratory the build-up of the oil bank occurs much more readily. Without the initiation of the oil bank, the process will behave more like the unstable injection of a surfactant solution alone, where the oil is produced by entrainment (emulsification) in the flowing surfactant stream. Indeed, many results of field pilots have suggested this to be the prevailing production mechanism.

The formulation which has been claimed to come close to economic application involves the use of the surfactant dispersed and/or dissolved in an oil slug. The comparative effectiveness of this system may be indeed related to the presence of the oil in initiating the formation of an oil bank in the reservoir. Regardless of the exact cause, it would appear that near term implementation of this chemical flood process will be limited to the use of this and related systems in shallow reservoirs with closely spaced well patterns.

Field testing of surfactant processes to date is summarized in Exhibit V-1, below:

EXHIBIT V-1

SURFACTANT/POLYMER AND CAUSTIC FLOODING ACTIVITY SUMMARY

| Surfactant/ Polymer | Technical Pilots | | Economic Pilots | | Fieldwide Development | |
|---|---|---|---|---|---|---|
| | Total | Current | Total | Current | Total | Current |
| Projects | 12 | 10 | 7 | 7 | 2 | 2 |
| Reservoirs | 11 | 10 | 6 | 6 | 1 | 1 |
| Caustic Floods | | | | | | |
| Projects | 5 | 1 | 2 | 0 | 0 | 0 |
| Reservoirs | 5 | 1 | 2 | 0 | 0 | 0 |

In addition, surfactant/polymer and caustic flooding activity can be characterized by the following:

- Currently, 1,418 acres are under surfactant development; caustic is being applied to 63 acres.
- The amount of testing has accelerated from five projects in 1970 to 19 currently active.

- Most of the projects that have been tried are quite small, the majority being less than ten acres.

- Except for Texaco's two small pilots in carbonates, all of the ongoing and planned efforts are in sandstone reservoirs.

- The majority of the field efforts have been in relatively shallow sands; all economic pilots and field-wide developments are at less than 3000 feet; only two technical pilots are deeper than 5000 feet.

- The mid-continent (e.g., Illinois, Oklahoma, Wyoming, etc.) appear to offer the most immediate and most favorable targets for surfactant/polymer recovery; 14 of the 19 current surfactant pilots are located in this section of the country.

- Marathon, one of surfactant's strongest advocates, has recently announced that, at current $11.63 "upper tier" prices, their Robinson tests -- in a shallow, homogeneous, nearly ideal reservoir -- are not economic. World oil prices of $13.00 plus improved taxes would be required to ensure the economic viability for continuing their planned expansion in the Robinson field. They have, however, been successful in recovering a considerable portion of the remaining oil-in-place.

That surfactant processes have been used to date primarily in the most favorable reservoirs -- and have been economically unsuccessful -- is indicative of the number of difficult problems remaining to be overcome before surfactant/polymer floods will significantly add to the nation's oil supply. Some of these problems are highlighted in the next section.

Problems and Opportunities

Theoretically, if an aqueous system is introduced into a reservoir which provides a low interfacial tension against the crude ($10^{-4}$ dynes/cm) and mobility less than that of the resulting oil bank, and the surfactant (low tension) system is in turn displaced with a still less mobile interfacially inactive phase, then an almost perfect recovery will be achieved.

This theory has been amply demonstrated in the laboratory, but has been seldom replicated in the field. Numerous problems beset the translation of lab results to recovery in the field, including:

1. The hiatus between laboratory tests and field results suggests that a major gap in understanding persists as a constraint on application. Little is known concretely about the actual behavior of the complex surfactant systems under reservoir conditions. Theories abound but progress towards understanding the causes of the field failures has been difficult because of the proprietary nature of a number of the systems that have been used and because, in general, the field experiments have been relatively heavily weighted towards demonstrating recovery rather than seeking to validate extrapolation of laboratory performance.

The additional expense of measurement through core holes, mini-tests, tracers, etc., has been larger than most project operators have been willing to bear. Even measurement of exact reservoir conditions into which surfactants have been injected has been inadequate to replicate these conditions in laboratories. Some of the conditions, e.g., the distances the slug must travel, cannot be replicated in the laboratory. Thus, an important opportunity for improving surfactant performance lies in learning more about how it behaves in the field. More thorough measurement of existing projects, mini-tests in a variety of reservoirs, and more sophisticated laboratory designs will all aid in overcoming the basic knowledge gap. As this understanding accumulates, improved surfactant systems can be engineered. More than any other EOR process, basic research on the performance of surfactant systems flowing through porous mediums is required for these systems.

2. Several reservoir conditions present major hazards to the application of surfactants. High temperatures (resulting from the depth of reservoirs), high salinity, and the presence of heavy metal ions cause the surfactants to degrade. Low permeability can reduce the velocity of the slug to the point where the necessary oil bank fails to form. Clays in the reservoir may adsorb the surfactant. Each of these problems reduces the number of reservoirs amenable to surfactants or reduces the effectiveness of the surfactant performance. Each represents an area where special engineering may be able to achieve the breakthroughs needed to make the process viable. For example, salinity and ion exchange problems may be overcome by pre-flushing the reservoir with low salinity water with an effective ion balance.

3. As with carbon dioxide, mobility control remains a problem. Additional development of appropriate polymers (or other substances) is required before fingering and overriding of the surfactant slug and its oil bank can be avoided.

One school of thought advances that initiation of the surfactant/polymer process early in a reservoir's life could circumvent adverse mobility ratios caused by low oil saturations. Currently, however, operators are opting to test the surfactant systems only in reservoirs that have been well-defined (and thus depleted) by waterflooding. Work on earlier initiation of the process could yield valuable results.

4. The success of the surfactant process is highly sensitive to variations in residual oil saturation and location. As discussed in the preceding chapter, these factors have not been adequately defined for many reservoirs, particularly the older ones for which EOR might be considered in the near term. Errors in initial estimation of oil-in-place, uncertainty as to the uniformity of the previous depletion, and unknown geology of the formations can lead to highly divergent estimates of saturations and distributions. Because these factors are so critical to performance and profitability, most operators will hesitate to apply surfactant processes. Substantial measurement of reservoir and fluid conditions will need to be conducted before rapid application of this process will take place in the field.

5. The chemicals that comprise the surfactant system are costly. Currently, estimates of the costs of these surfactants on a mass-produced basis vary by almost 100 percent. Surfactant costs are critical

in the economics of the process because this chemical is the principal component in the injection slug. Uncertainty as to the costs of surfactants and other chemicals could cause some operators to delay implementing surfactant processes, even when proved.

Future Directions of Industry Application -- The Base Case

The disappointing history of surfactant pilots, coupled with the current views of practitioners, suggests little or no new significant field activity in surfactants. Expansion of existing projects is unlikely unless economic conditions change. Limited laboratory work will continue, but at the rate consistent with current prices and taxes, this research will have little effect during the period of interest. (Industry practitioners suggest that improved price/tax conditions could accelerate the rate of R&D.)

These qualitative conclusions were borne out in the quantitative estimate of the Base Case.[2/] Where the Base Case calculations were made under the Standard Economics Case, no current surfactant candidates were found to meet the respective economic hurdle rates. Because this substantiated very recent reports from the field, it was not surprising. It was concluded that, under upper tier prices and current tax policies, industry would not pursue surfactant other than in the laboratory.

Increasing prices to the world price level, however, made a few, highly favorable candidate reservoirs marginally economic (see Exhibit V-2). These shallow, homogeneous reservoirs in the mid-continent

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2/ The assumptions and methods used in estimating the Base Case are described in Chapters I and V of Part 3.

EXHIBIT V-2

INDUSTRY BASE CASE FOR SURFACTANT/POLYMER UNDER PRICE/TAX CONTINGENCIES

| | STANDARD ECONOMICS (UPPER TIER W/ CURRENT TAX) | LOWER BOUND (UPPER TIER W/ UNFAV. TAX) | CASE 2 (WORLD PRICE W/ CURRENT TAX) | CASE 4 (WORLD PRICE W/ FAVORABLE TAX) | UPPER BOUND (ALTERNATE FUELS PRICE W/ FAVORABLE TAX) |
|---|---|---|---|---|---|
| ULTIMATE RECOVERY (BILLION BARRELS) | 0 | 0 | .6 | .6 | 3.0 |
| PRODUCTION RATE IN: (THOUSAND BARRELS PER DAY) | | | | | |
| 1985 | 0 | 0 | 0 | 0 | 110 |
| 1990 | 0 | 0 | 1 | 2 | 300 |
| 1995 | 0 | 0 | 55 | 110 | 480 |
| CUMULATIVE PRODUCTION BY: (MILLION BARRELS) | | | | | |
| 1985 | 0 | 0 | 5 | 5 | 150 |
| 1990 | 0 | 0 | 6 | 7 | 620 |
| 1995 | 0 | 0 | 26 | 70 | 1370 |

(where much of the current testing is being conducted), yield a small but not insignificant amount of production. This production, however, is quite late, most of it occurring after the period of concern. Note that, once the price is adequate to initiate production, tax changes have the effect of somewhat accelerating production. In this case, the tax change was relatively slight (a 3 percent increase in the investment tax credit -- equivalent to about 20 to 30 cents per barrel), but these reservoirs are so close to the margin that even this small change can have substantial effect.

Further increases in price, up to the alternate fuels level of $20.00 per barrel, is projected to result in a substantial increase in industry R&D,[3/] resulting in a number of additional reservoirs being developed. At this price, surfactant can make a major contribution to the overall supply.

Overview of the Surfactant/Polymer Programs

Overcoming the classes of problems described above, particularly for the most favorable reservoir application, defines the potential targets and strategies for an ERDA program in surfactant/polymer flooding. These are:

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3/ This additional production, attributed to industry, was computed based on an assumption of substantial R&D by industry. It represents the achievement of several major breakthroughs that industry is not currently contemplating. To this extent, it is something of a speculation that industry would respond to higher prices by increasing surfactant research. The substantially higher production attributed to industry is due to an allocation of these benefits from ERDA to industry. One-half of the production attributable to the research was assigned to ERDA; the other half to industry. This somewhat artificial allocation was necessary because the alternate fuels price so far exceeds the price industry currently assumes that industry's current R&D plans cannot be extrapolated with accuracy for this contingency. Because the reservoir base is relatively firm, the estimate of total recovery is relatively firm, but the allocation of the benefits between ERDA and industry may be imprecise.

- Basic surfactant: Build basic understanding that will improve recovery efficiency for target reservoirs throughout the U.S. through the development of surfactant systems which maintain their effectiveness in the sub-surface environment. Develop cheaper and adequate supplies or surfactants.

- Shallow, homogeneous sandstone reservoirs (e.g., Illinois basin).

  -- Assume adequate recovery efficiency and make the process conventional in shallow Illinois sandstones where economic pilots have indicated proximate success.

- California sandstone reservoirs.

  -- Extend the application of the process to California sandstone reservoirs, which generally are laden with clays (high adsorptive and cation exchange values).

- Gulf Coast (East Texas and Southern Louisiana) sandstones marked by high salinity, high temperature, but with potential for high fluid flow velocity and relatively high homogeneity.

  -- Improve recovery efficiency and extend the application of the process to Gulf Coast sandstone reservoirs.

- Other sandstones, including the Mid-Continent, Rocky Mountains, and Appalachian regions.

-- Examine the application of the surfactant recovery system in these sandstone reservoirs, which will range in clay content and permeability variance.

Programs of activities were defined to carry out these strategies and the costs of these programs were estimated. Exhibit V-3 relates the programs, targets and strategies and shows the program designations used below.[4/] Exhibits V-4 and V-5 summarize these programs in physical units and constant (1976) dollars, respectively. Both non-field and field research are required, with the field work consisting of core holes and mini-tests. The program costs build to a peak in 1979, then stabilize for an extended period. No cost-sharing is anticipated because of the nature of the research programs and industry's flagging interest in surfactants. The five-year total budget is slightly over fifty million dollars.

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4/ The Basic Surfactant Program, designated SP in Section B, is not shown because it affects all targets together.

EXHIBIT V-3. STRUCTURE OF THE SURFACTANT/POLYMER PROGRAMS

| STRATEGIES \ TARGETS | D. SURFACTANT/POLYMER | | | |
|---|---|---|---|---|
| | (1) SHALLOW/HOMOMOGENEOUS SANDSTONES OF THE ILLINOIS BASIN | (2) CALIFORNIA SANDSTONES | (3) GULF COAST SANDSTONES: SALINE; HIGH TEMP; HOMOGEN. | (4) OTHER SANDSTONES PARTICULARLY: MID-CONTINENT, ROCKY MT. & APPALACHIA |
| I. DEVELOP AND IMPROVE EOR TECHNOLOGY: | | | | |
| A. IMPROVE RECOVERY EFFICIENCY | SP-1 | SP-3 | SP-4 | SP-5 |
| B. EXTEND APPLICATION OF PROCESS | | ↓ | ↓ | ↓ |
| C. IMPROVE MOBILITY CONTROL | | | | |
| D. TEST SPACING/INJECTION PATTERNS | | | | |
| E. EXAMINE IMPROVED PROCESS EFFICIENCIES | | | | |
| F. DEVELOP NEW PROCESSES | | | | |
| G. BRING TECH. TO CONVENT. APPLIC. | SP-2 | – | – | – |
| II. OVERCOME NON-EOR PROCESS CONSTRAINTS: | | | | |
| A. OVERCOME EMISSION PROBLEMS | | | | |
| B. EXAMINE ALTERN. USES AND/OR MKT. FOR WEST COAST OIL | | | | |
| C. USE SUBSTITUTE (NON-PETRO) FUELS | | | | |
| D. DEVELOP CHEAPER/ADEQUATE SUPPLY OF INJECTION MATERIALS | SP-6 → | → | → | → |
| E. ENSURE ADEQUATE CAPITAL/ECONOMIC RETURN | | | | |

EXHIBIT V-4. ALL SURFACTANT POLYMER PROGRAMS -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | 1.25 | | | | | 1.25 |
| C. RECOVERY MODELS | 1.25 | | | | | 1.25 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | 3.25 | 3 | | | | 6.25 |
| E. PROCESS/FIELD TEST EVALUATION | .25 | | | | | .25 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 17 | 20 | 19 | 16 | 16 | 88 |
| B. FLOW STUDIES | 14 | 19 | 17 | 18 | 13 | 81 |
| C. FIELD LIAISON & ENG. STUDIES | 3.77 | 3.77 | 3.15 | 4.15 | 4.15 | 19 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 22 1/ | → | → | | | 22 1/ |
| B. MINI-TESTS | 1 | 12 | → | → | → | 13 |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): 2/ | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS / B. SHARE INDUSTRY/ERDA DEVELOP. | | | 1 | | | 1 |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ CORE HOLES

2/ INCLUDED IN ABOVE FIGURES EXCEPT AS NOTED

EXHIBIT V-5. ALL SURFACTANT/POLYMER PROGRAMS

(IN THOUSANDS OF 1976 DOLLARS COSTS)

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE<br>C. RECOVERY MODELS<br>D. ECONOMIC & OTHER FEASIB. STUDIES<br>E. PROCESS/FIELD TEST EVALUATION | 360 | 180 | | | | 540 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 1020 | 1120 | 1140 | 960 | 960 | 5280 |
| B. FLOW STUDIES | 900 | 1140 | 1020 | 900 | 900 | 4860 |
| C. FIELD LIAISON & ENG. STUDIES | 275 | 275 | 225 | 300 | 300 | 1375 |
| D. LAB EQUIPMENT & FACILITIES | 1210 | 600 | 375 | 300 | 300 | 2785 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 1000 | 2500 | 1000 | | | 4500 |
| B. MINI-TESTS | 1500 | 2250 | 8750 | 9500 | 9000 | 31000 |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS.<br>B. SHARE INDUSTRY/ERDA DEVELOP. | | | 75 | | | 75 |
| TOTAL | 6265 | 8145 | 12585 | 11960 | 11460 | 50415 |
| ERDA SHARE | 6265 | 8145 | 12585 | 11960 | 11460 | 50415 |

POST 1981 COMMITMENTS: COMPLETION OF THE FIELD WORK COMPONENT WILL REQUIRE $3.5 MILLION IN 1982 AND 2 MILLION IN 1983 TO COMPLETE THE RESERVOIR IDENTIFICATION AND MINI-TESTS STAGE; $1.2 MILLION PER YEAR FOR 1982 THROUGH 1986 WILL BE NEEDED FOR PERSONNEL AND LAB WORK. (THE ASSUMPTION IS THAT THE MINI-TESTS WILL ALSO SUBSTITUTE FOR THE TECHNICAL PILOTS AND THAT INDUSTRY WILL CONDUCT THE ECONOMIC PILOTS REQUIRED TO BRING THIS PROCESS TO COMMERCIAL APPLICATION.)

The potential production stimulated by ERDA's surfactant research programs (calculated under Standard Economics assumptions) is shown in Exhibit V-6. Multiplying the potential production by the expectation of success yields the expected production shown in Exhibit V-7. [5/] For the full surfactant research program, the following results are predicted.

| | Potential Production | Expected Production | |
|---|---|---|---|
| Ultimate Recovery | 2300 | 1000 | million barrels |
| Production Rate | | | |
| 1985 | 10 | 0 | thousand barrels per day |
| 1990 | 70 | 30 | |
| 1995 | 230 | 90 | |
| Cumulative Production | | | |
| 1985 | 30 | 10 | million barrels |
| 1990 | 80 | 30 | |
| 1995 | 240 | 90 | |

These numbers indicate that, while substantial ultimate recovery can be stimulated by ERDA research, this production will come relatively late in the period of interest. The preponderance of surfactant production will occur after the year 2000.

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5/ The procedures for estimating potential and expected production are described in Part 3, Chapters I, II, and V.

EXHIBIT V-6. POTENTIAL PRODUCTION BENEFITS OF SURFACTANT/POLYMER PROGRAMS
(STANDARD ECONOMICS)

| TARGETS/PROGRAM / POTENTIAL PRODUCTION BENEFITS | D. SURFACTANT/POLYMER | | | | |
|---|---|---|---|---|---|
| | (1) SHALLOW/HOMOMOGENEOUS SANDSTONES OF THE ILLINOIS BASIN | | (2) CALIFORNIA SANDSTONES | (3) GULF COAST SANDSTONES: SALINE; HIGH TEMP; HOMOGEN. | (4) OTHER SANDSTONES PARTICULARLY: MID-CONTINENT, ROCKY MT. & APPALACHIA |
| | SP-1 & SP-2 | SP-6 | SP-3 | SP-4 | SP-5 |
| 1. ULTIMATE RECOVERY (IN MILLIONS OF BARRELS | 600 | * | 1700 | ** | *** |
| 2. ANNUAL PRODUCTION (IN THOUSANDS OF BARRELS/DAY) IN: | | * | | | *** |
| 1985 | 0 | * | 10 | ** | 10*** |
| 1990 | 0 | * | 70 | ** | 0*** |
| 1995 | 10 | * | 220 | ** | 0*** |
| 3. CUMULATIVE PRODUCTION (IN MILLIONS OF BARRELS) BY: | | | | | |
| 1985 | 10 | * | 10 | ** | 20*** |
| 1990 | 10 | * | 50 | ** | 20*** |
| 1995 | 10 | * | 210 | ** | 20*** |

* BENEFITS OF LOWER COST SURFACTANTS ALREADY COUNTED IN SP-1 THROUGH SP-5

** UNECONOMIC AT THE TECHNOLOGICAL/ECONOMIC STANDARDS SET FOR THE TARGET, UPPER TIER PRICE AND HIGH RISK (20% REAL) RATE OF RETURN. AT UPPER TIER PRICES AND CONVENTIONAL (8%) REAL RATE OF RETURN: ULTIMATE RECOVERY WOULD BE 178 MILLION: ANNUAL PRODUCTION IN 1985, 1990 AND 1990 WOULD BE 0, 2,000 B/D AND 1,000 B/D RESPECTIVELY, AND CUMULATIVE PRODUCTION IN 1985, 1990, 1995 WOULD BE 0, 1, AND 8 MILLION BARRELS RESPECTIVELY.

*** UNECONOMIC AT THE TECHNOLOGICAL/ECONOMIC STANDARDS SET FOR THE TARGET, UPPER TIER PRICE AND HIGH RISK (20% REAL) RATE OF RETURN. AT UPPER TIER PRICES AND CONVENTIONAL (8% REAL) RATE OF RETURN: ULTIMATE RECOVERY WOULD BE 1800 MILLION BARRELS: ANNUAL PRODUCTION IN 1985, 1990 AND 1995 WOULD BE 0, 0 AND 160,000 B/D RESPECTIVELY; CUMULATIVE PRODUCTION BY 1985, 1990 AND 1995 WOULD BE 17 MILLION BARRELS, 23 MILLION BARRELS, AND 176 MILLION BARRELS RESPECTIVELY.

EXHIBIT V-7. EXPECTED PRODUCTION FROM SURFACTANT/POLYMER PROGRAMS

(STANDARD ECONOMICS)

| EXPECTED PRODUCTION BENEFITS / TARGET / PROGRAM | D. SURFACTANT/POLYMER | | | | | |
|---|---|---|---|---|---|---|
| | (1) SHALLOW/HOMOMOGENEOUS SANDSTONES OF THE ILLINOIS BASIN | | (2) CALIFORNIA SANDSTONES | (3) GULF COAST SANDSTONES: SALINE; HIGH TEMP; HOMOGEN. | (4) OTHER SANDSTONES PARTICULARLY: MID-CONTINENT, ROCKY MT. & APPALACHIA | |
| | SP-1 & SP-2 | SP-6 | SP-3 | SP-4 | SP-5 | TOTALS |
| 1. EXPECTED ULTIMATE RECOVERY (IN MILLIONS OF BARRELS) | 400 | * | 600 | ** | *** | 1000 |
| 2. EXPECTED ANNUAL PRODUCTION (IN THOUSANDS OF BARRELS/DAY) IN: | | | | | | |
| 1985 | 0 | * | <20 | ** | *** | 0 |
| 1990 | 0 | * | 30 | ** | *** | 30 |
| 1995 | 10 | * | 80 | ** | *** | 90 |
| 3. EXPECTED CUMULATIVE PRODUCTION (IN MILLIONS OF BARRELS) BY: | | | | | | |
| 1985 | <10 | * | <10 | ** | 10*** | 0 |
| 1990 | <10 | * | 20 | ** | 10*** | 20 |
| 1995 | <10 | * | 80 | ** | 10*** | 80 |

* BENEFITS OF LOWER COST SURFACTANTS ALREADY COUNTED IN SP-1 THROUGH SP-5

** UNECONOMIC AT THE TECHNOLOGICAL/ECONOMIC STANDARDS SET FOR THE TARGET, UPPER TIER PRICE AND HIGH RISK (20% REAL) RATE OF RETURN. AT UPPER TIER PRICES AND CONVENTIONAL (8%) REAL RATE OF RETURN: EXPECTED ULTIMATE RECOVERY WOULD BE 75 MILLION; EXPECTED ANNUAL PRODUCTION IN 1985, 1990, AND 1995 AND 1995 WOULD BE 0. 1000 B/D AND <1000 B/D RESPECTIVELY EXPECTED CUMULATIVE PRODUCTION IN 1985, 1990, AND 1995 WOULD BE 0, <1, AND 3 MILLION BARRELS RESPECTIVELY.

*** UNECONOMIC AT THE TECHNOLOGICAL/ECONOMIC STANDARDS SET FOR THE TARGET, UPPER TIER PRICE AND HIGH RISK (20% REAL) RATE OF RETURN. AT UPPER TIER PRICES AND CONVENTIONAL (8%) REAL RATE OF RETURN: EXPECTED ULTIMATE RECOVERY WOULD BE 684 MILLION BARRELS; EXPECTED ANNUAL PRODUCTION IN 1985, 1990, AND 1995 WOULD BE 0.0, AND 60,000 B/D, RESPECTIVELY: CUMULATIVE PRODUCTION IN 1985, 1990, AND 1995 WOULD BE 6 MILLION BARRELS, 9 MILLION BARRELS, AND 67 MILLION BARRELS, RESPECTIVELY.

The last two exhibits also illustrate that, under Standard Economics, two of the surfactant targets will not become economic even with the ERDA research program. These programs do, however, yield positive economic results under different price/tax contingencies, as discussed in Section B of this chapter.

To relate ERDA's costs to the production benefits stimulated by ERDA's programs, cost-effectiveness measures were calculated for each program by dividing the expected production by the present value of ERDA's total expenditure. These indices are displayed in Exhibit V-8. Because of the previously noted lack of economic results for two surfactant/polymer programs, no cost-effectiveness indices are shown. As shown in the footnote, reduction in risk to conventional levels would make these marginally attractive. Moreover, alternative price/tax contingencies also make them more attractive. SP-5 produces substantial benefits at the world price level and SP-4 brings additional reservoirs under development at the alternate fuels price.[6/]

The two surfactant/polymer programs that show positive results under the Standard Economics contingency are highly productive in terms of ultimate recovery. Between one and two cents per barrel is the predicted cost of the research and development programs for the Illinois and California sandstones. Because their production is later, however, the indices for production rate and cumulative production are less favorable than the indices for programs in some of the other techniques.

It should be noted that all the program benefits shown presuppose successful completion of a basic research program (referred to as SP in Section B, below) that is not specific to any particular

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6/ These effects are discussed in Section B for the individual program.

EXHIBIT V-8. MEASURES OF EFFECTIVENESS OF SURFACTANT/POLYMER PROGRAMS

(STANDARD ECONOMICS)

| TARGET/PROGRAM / MEASURES OF EFFECTIVENESS | D. SURFACTANT/POLYMER | | | | |
|---|---|---|---|---|---|
| | (1) SHALLOW/HOMOMOGENEOUS SANDSTONES OF THE ILLINOIS BASIN | | (2) CALIFORNIA SANDSTONES | (3) GULF COAST SANDSTONES; SALINE; HIGH TEMP; HOMOGEN. | (4) OTHER SANDSTONES PARTICULARLY; MID-CONTINENT, ROCKY MT. & APPALACHIA |
| | SP-1 & SP-2 | SP-6 | SP-3 | SP-4 | SP-5 |
| 1. ULTIMATE RECOVERY/ COST RATIO (EXPECTED ULTIMATE BARRELS/NPV TOTAL ERDA) | 94 | * | 59 | ** | *** |
| 2. ANNUAL PRODUCTION/COST RATIO IN: (EXPECTED ANNUAL BARRELS/NPV TOTAL ERDA) | | | | | |
| 1985 | 0 | * | 0.1 | ** | *** |
| 1990 | 0 | * | 0.9 | ** | *** |
| 1995 | 0.5 | * | 2.7 | ** | *** |
| 3. CUMMULATIVE PRODUCTION/COST RATIO BY: (EXPECTED CUMULATIVE BARRELS/NPV TOTAL ERDA | | | | | |
| 1985 | 1 | * | <1 | ** | *** |
| 1990 | 1 | * | 2 | ** | *** |
| 1995 | 1 | * | 7 | ** | *** |

*

** UNECONOMIC AT THE TECHNOLOGICAL/ECONOMIC STANDARDS SET FOR THE TARGET, UPPER TIER PRICE AND HIGH RISK (20% REAL) RATE OF RETURN. AT UPPER TIER PRICES AND CONVENTIONAL (8%) REAL RATE OF RETURN: ULTIMATE RECOVERY RATIO WOULD BE 5: ANNUAL PRODUCTION RATIOS IN 1985, 1990 AND 1995 WOULD BE 0, <0.1, AND <0.1 RESPECTIVELY: CUMULATIVE PRODUCTION RATIOS IN 1985, 1990, 1995 WOULD BE 0, <1, AND <1 RESPECTIVELY.

UNECONOMIC AT THE TECHNOLOGICAL/ECONOMIC STANDARDS SET FOR THE TARGET, UPPER TIER PRICE AND HIGH RISK (20% REAL) RATE OF RETURN. AT UPPER TIER PRICES AND CONVENTIONAL (8% REAL) RATE OF RETURN: ULTIMATE RECOVERY RATIO WOULD BE 55: ANNUAL PRODUCTION RATIOS IN 1985, 1990 AND 1995 WOULD BE 0, 0 AND 1.8 RESPECTIVELY: CUMULATIVE PRODUCTION RATIOS IN 1985, 1990 AND 1995 WOULD BE <1, 1 AND 5 RESPECTIVELY.

reservoir targets. The costs of this program were spread evenly across the four targets shown. Had they been allocated only to the programs that resulted in economic production under Standard Economics, the indices would be reduced slightly, but not substantially. On the basis of ultimate recovery, the research costs would still be on the order of four to eight cents per barrel for these two programs.

The surfactant/polymer programs were analyzed for their sensitivities to five different price/tax contingencies. Exhibit V-9 shows the effects of these contingencies on the expected production of the surfactant/polymer programs. The Lower Bound and the Standard Economics case differ principally in that the former assumes capitalized injection materials, whereas the latter assumes expensed injection materials. This change in tax provisions has a clearly detrimental effect, dropping ultimate production by sixty percent and practically eliminating production in the period of interest. Raising prices from upper tier to world level adds substantially to surfactant production. These effects would be even more marked except that some of the production at world prices was attributed to industry in the Base Case. A three percent increase in the investment tax credit (Case 4 compared to Case 2) yields additional ultimate recovery, but has little impact on the production rate. Finally, raising the price to the alternate fuels level accelerates production dramatically in the early years, but does not add to the ERDA-stimulated ultimate recovery. Again, however, this is explained by a large allocation to an accelerated industry research and development effort, discussed earlier.

EXHIBIT V-9

EFFECTS OF PRICE/TAX CONTINGENCIES ON EXPECTED PRODUCTION FROM SURFACTANT/POLYMER PROGRAMS

| | STANDARD ECONOMICS (UPPER TIER W/ CURRENT TAX) | LOWER BOUND (UPPER TIER W/ UNFAV. TAX) | CASE 2 (WORLD PRICE W/ CURRENT TAX) | CASE 4 (WORLD PRICE W/ FAVORABLE TAX) | UPPER BOUND (ALTERNATE FUELS PRICE W/ FAVORABLE TAX) |
|---|---|---|---|---|---|
| EXPECTED ULTIMATE RECOVERY (BILLION BARRELS) | 1.0 | 0.4 | 1.4 | 1.6 | 1.6 |
| EXPECTED PRODUCTION RATE IN: (THOUSAND BARRELS PER DAY) | | | | | |
| 1985 | 2 | 0 | 10 | 10 | 110 |
| 1990 | 30 | 0 | 190 | 190 | 190 |
| 1995 | 90 | 10 | 240 | 240 | 210 |
| EXPECTED CUMULATIVE PRODUCTION BY: (MILLION BARRELS) | | | | | |
| 1985 | 10 | <10 | <10 | <10 | 150 |
| 1990 | 30 | 10 | 250 | 250 | 480 |
| 1995 | 90 | 10 | 600 | 610 | 810 |

SUMMARY: Combined Effects of Industry Activity and the Surfactant/ Polymer Programs

Under the Standard Economics condition, no production was attributable to industry without ERDA research and development. Industry is expected to respond to ERDA's programs, however, as shown in Exhibits V-10 and V-11. (In both figures, the curves are added.) Under these economic conditions, all the production is attributable to ERDA's stimulation, so no Base Case appears. Ultimate recovery from surfactants then, would be about one billion barrels, with the production rate only beginning to climb by 1985. Ten years later, however, total surfactant production reaches 90 thousand barrels per day. By 1995, over 90 million barrels will have been produced by this process.

At higher prices, it is anticipated that industry will begin to take a substantial interest in surfactant/polymer research and thus bring on a portion of the surfactant/polymer potential. Exhibit V-12 shows expected ultimate recovery by the surfactant/polymer process under five of the price/tax contingencies analyzed. At upper tier prices, only ERDA-stimulated production is present, but at world prices, industry R&D has begun to contribute. The allocation rules employed in the analysis essentially assigned the benefits of SP-1 and SP-2 to industry. At these prices, ERDA'a program SP-5 (reservoirs in Appalachia, mid-continent etc.) makes a major contribution. At alternate fuels price, the Industry Base Case grows to five times its size as at world prices. In addition, ERDA's efforts in the Gulf Coast (SP-4) begin to contribute. Thus, ultimate recovery by surfactant/ polymer is highly sensitive to both price and tax contingencies.

EXHIBIT V-10

EXPECTED SURFACTANT/POLYMER PRODUCTION RATES
(STANDARD ECONOMICS)

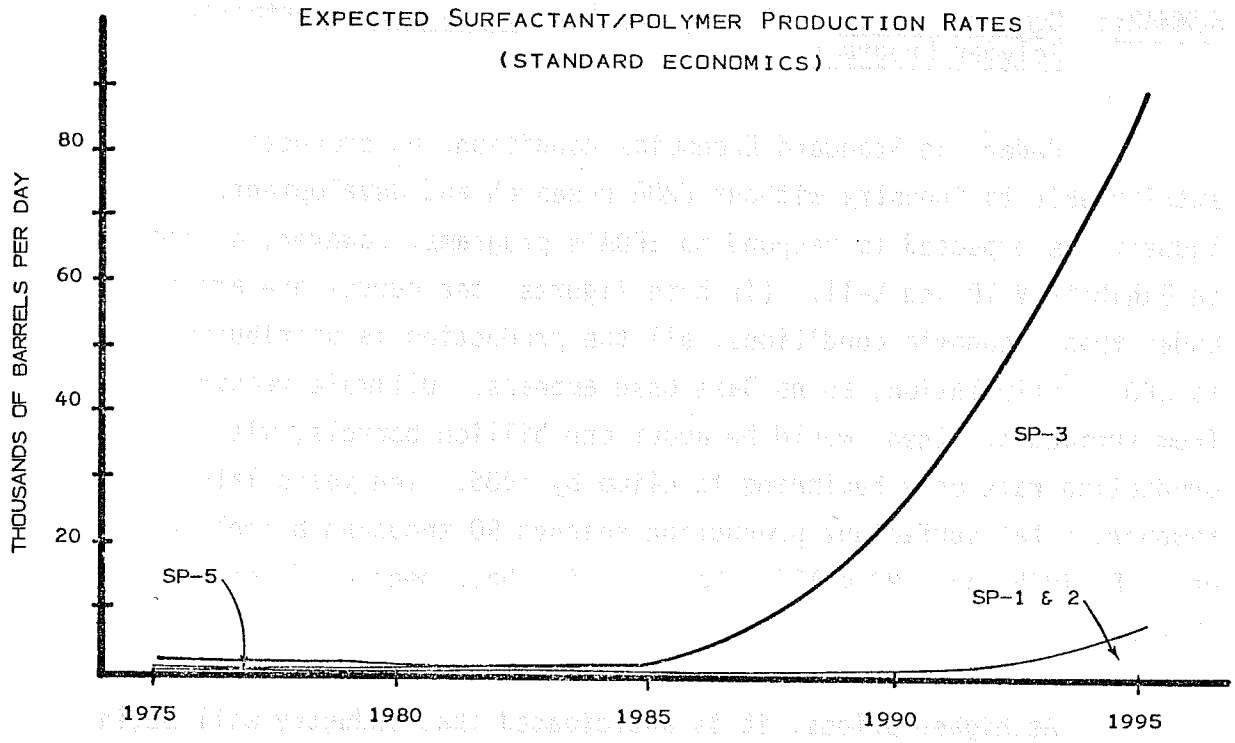



EXHIBIT V-11

EXPECTED SURFACTANT/POLYMER CUMULATIVE PRODUCTION
(STANDARD ECONOMICS)

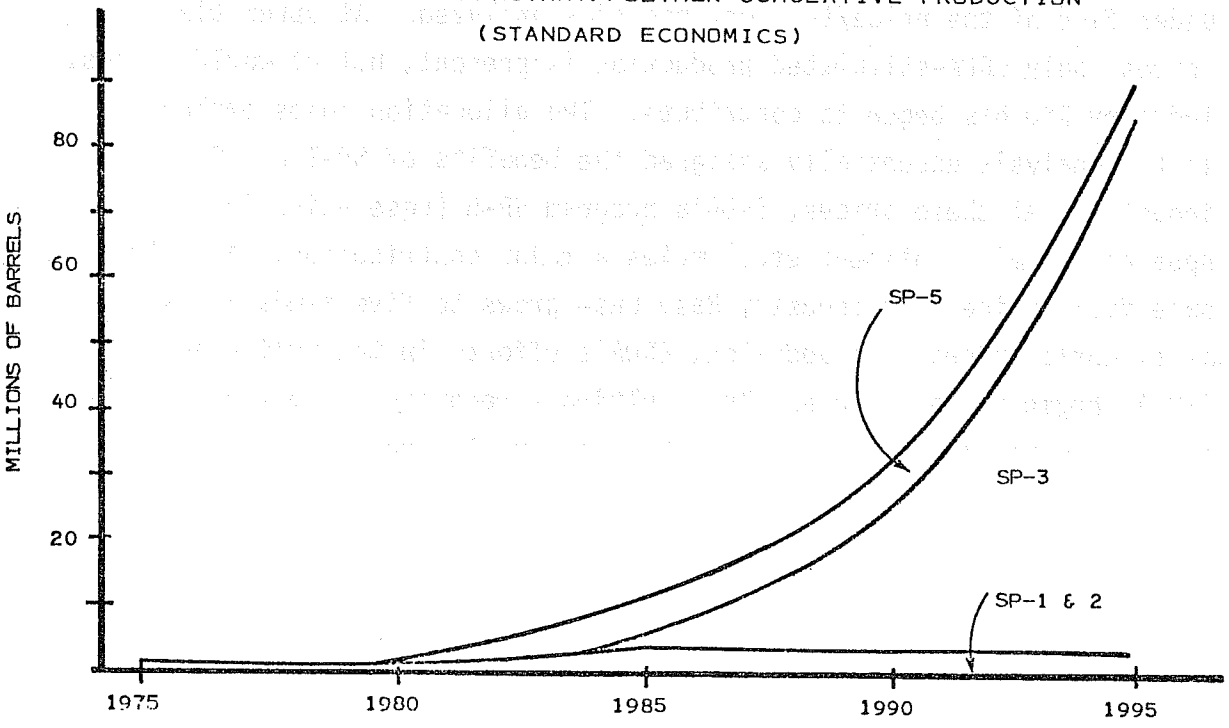


EXHIBIT V-12

EXPECTED ULTIMATE RECOVERY UNDER PRICE/TAX CONTINGENCIES FROM SURFACTANT/POLYMER PROGRAMS

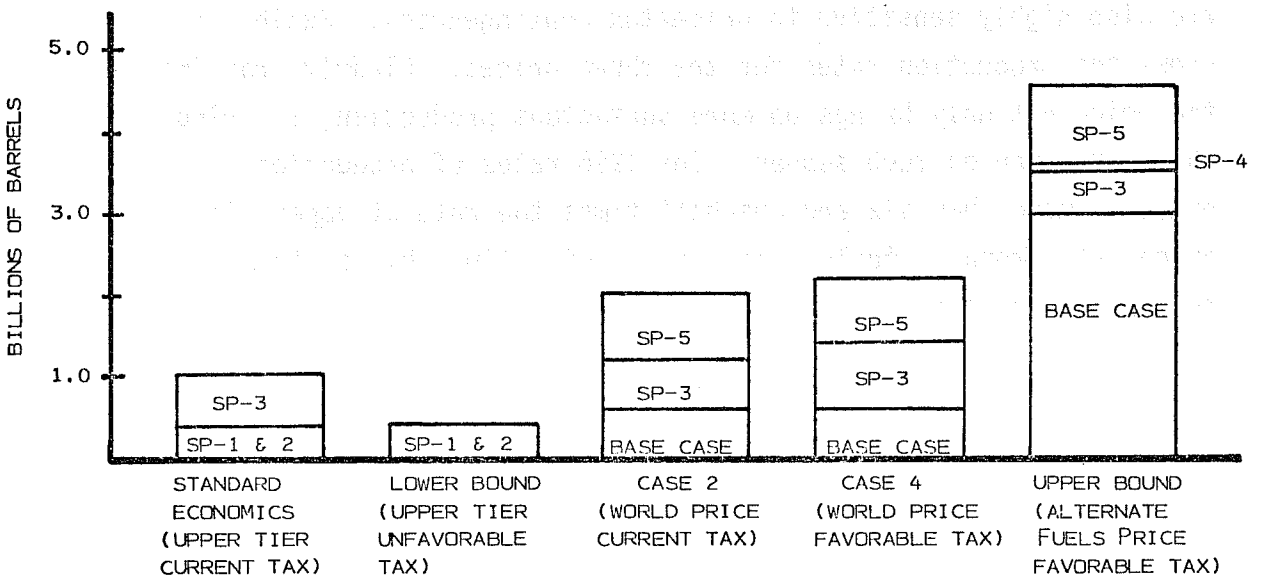
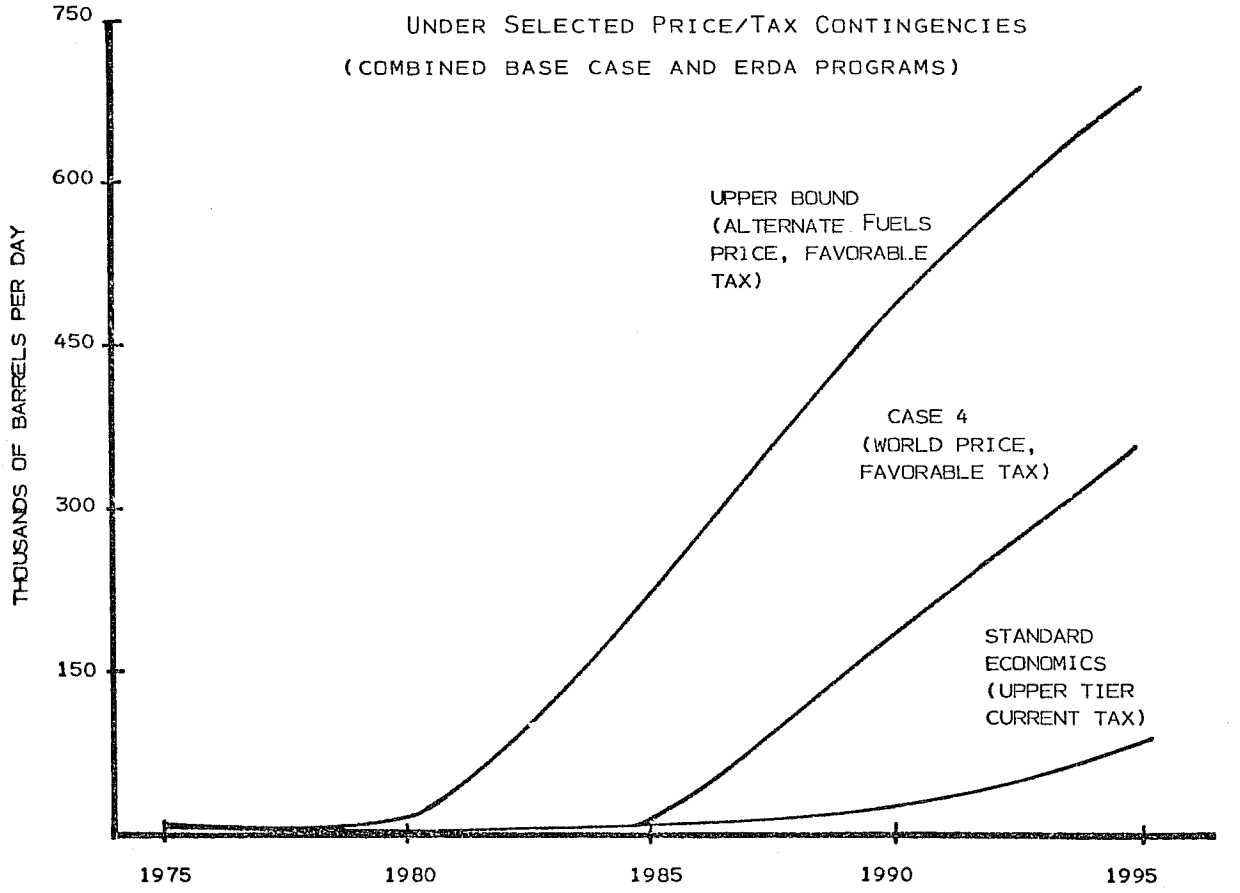



EXHIBIT V-13

EXPECTED SURFACTANT/POLYMER PRODUCTION RATES UNDER UNDER SELECTED PRICE/TAX CONTINGENCIES (COMBINED BASE CASE AND ERDA PROGRAMS)



The rate of production (and hence cumulative production) are also highly sensitive to price/tax contingencies. Exhibit V-13 shows the production rates for the three prices. Clearly, raising the price not only brings on more surfactant production, it brings the production on much sooner. The 1995 rates of production at world price is more than six and one-half times the rate at upper tier price; at alternate fuels price, it is nine times higher than at the upper tier price.

## SECTION B: INDIVIDUAL SURFACTANT/POLYMER PROGRAMS

TARGET D: ALL SURFACTANT RESERVOIRS

R&D STRATEGY SP: BASIC SURFACTANT: IMPROVE RECOVERY EFFICIENCY FOR TARGET RESERVOIRS THROUGHOUT U.S. BY USE OF SURFACTANT SYSTEMS

Because of the still evolving nature of the surfactant/polymer oil recovery technology the R&D targets and strategies will be presented somewhat differently than the other sections. Two challenges face the researchers in the surfactant technologies: (a) basic, across target problems of making the process work under less than ideal conditions; and (b) having achieved success with the basic technology, adapting and proving the technology under a variety of distinct reservoir conditions. Thus, the central problems and R&D goals will first be presented for an overall program (SP) in surfactant technology with individual R&D strategies being discussed on a geographical basis (under R&D strategies SP1 - SP6).

1. CENTRAL PROBLEM

Flooding oil reservoirs with surfactant systems has been looked upon as one of the most promising recovery schemes. A perfectly formulated system will in effect be "miscible" and sufficiently viscous to achieve both high displacement and high sweep efficiencies.

The weight of experience to date has been negative. With one exception, all attempts to reduce the recovery scheme to practice have failed.

Progress towards understanding the causes of the failures has been difficult because of the proprietary nature of a number of the systems that have been used and because, in general, the field experiments have been relatively heavily weighted towards demonstrating recovery rather than seeking to validate extrapolation of performance.

There are, of course, valid reasons for such weighting given the great cost of the operations. Nevertheless, based on the reported results in comparison with those emanating from the R&D bench scale tests, it is obvious that a hiatus exists between the lab and the field.

Theoretically, if an aqueous system is introduced into a reservoir which provides a low interfacial tension against the crude ($10^{-4}$ dynes/cm.) and mobility less than that of the resulting oil bank, and the surfactant (low tension) system is in turn displaced with a still less mobile interfacially inactive phase, then an almost perfect recovery will be achieved.

The problem seems to be attaining in the field the behavior secured in the laboratory, and possibly, in addition, determining the exact conditions prevailing in the sub-surface so that appropriate experiments may be performed in the laboratory.

Clear progress in this program is a necessary condition for meeting the objectives of the other surfactant programs, although preliminary steps may be taken concurrently with the others. Because this program is a prerequisite to all the others, it would be misleading to present its costs, benefits, or probability of success separately from the programs in which the results of this effort are applied. These costs and benefits, then, have been allocated to the other surfactant programs.

2. R&D GOALS

- To develop surfactant systems which are sufficiently viable under reservoir conditions to achieve the high ultimate recovery promised by theoretical studies.

- To develop surfactants which will give the greatest cost-benefit results in reducing interfacial tension

in the reservoir environment (viz. saline environment, temperature, velocity, activity of mineral surfaces, crude oil chemistry, and lithology).

- While substantial polymer development will be pursued under Target E, other development is required for this target to secure compatible operations of both surfactant and polymer in reservoir operations.

- The eventual R&D goal is to develop surfactant flooding systems that will economically recover the residual oil in reservoirs following waterflooding.

3. R&D ACTIVITIES

I. Building the Knowledge Base: starting in 1977

-- Accumulation and evaluation of the prolific literature on surfactant flooding, and attempt to secure industry information on field test operations.

II. Basic and Applied Research: starting in 1979

-- Physical chemistry bench studies on surfactant/polymer and surfactant-forming (e.g., NaOH) systems.

-- Core studies, long cores and slabs. Scaled physical models to be investigated but probably not applicable.

-- Polymer development and formulation (costed and described under Target E).

-- Surfactant development and formulation.

III. Field Based Activities:

-- See individual program SP1-SP5.

NOTE: Probability of success, costs of the program, and production benefits are incorporated into programs SP-1 - SP5. In addition to the costs shown in these programs, approximately two-thirds of the non-field based costs of the polymer programs, IW-1 and IW-2, (totaling $4,357,000 for the five-year period and $9,357,000 overall) are required for success in the surfactant programs. If the polymer programs are not included in the overall plan, these costs must be added to the surfactant programs.

TARGET D-1: SHALLOW, HOMOGENEOUS SANDSTONES IN ILLINOIS

R&D STRATEGY SP-1 AND SP-2: IMPROVE RECOVERY EFFICIENCY AND MAKE THE PROCESS CONVENTIONAL

1. CENTRAL PROBLEM:

It is in these sands that technological success has been reported using a proprietary formulation of the surfactant/polymer system. Because of this past experience and the relatively low cost of drilling and operations in these shallow sands, they are an ideal setting for operating a series of mini-tests using different formulations of the surfactant/polymer systems. Such tests permit comparisons of chemical stability, displacement efficiency, injectivity, and overall performance of alternative systems.

2. R&D GOALS:

- Obtain basic data for examining process performance, recovery, economic feasibility, and process efficiencies.
- Demonstrate the commercial applicablility of the surfactant/polymer in the shallow homogeneous Illinois Basin sandstones.

3. R&D ACTIVITIES:

I&II. Building the Knowledge Base and Conducting Basic and Applied Research:

(to be accomplished under the Basic Surfactant Program - SP)

III. Field Based Activities:

-- Mini tests of preferred systems in order to diagnose seeming divergences in laboratory and field behavior, starting in 1977.

PGM: SP-1 & 2

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | – |
| B. RESERVOIR DATA BASE | | | | | | |
| C. RECOVERY MODELS | 1 | | | | | 1 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | | | | | |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | – |
| B. FLOW STUDIES | 2 | 2 | | | | 4 |
| C. FIELD LIAISON & ENG. STUDIES | 1 | 1 | | | | 2 |
| D. LAB EQUIPMENT & FACILITIES * | * | | | | | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | – |
| B. MINI-TESTS | 1 | 1 | 1 | | | 3 |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | 1 | | | 1 |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

PGM: SP-1 & 2

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | – | | | | | – |
| B. RESERVOIR DATA BASE | | | | | | |
| C. RECOVERY MODELS | | | | | | |
| D. ECONOMIC & OTHER FEASIB. STUDIES | 60 | | | | | 60 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | – |
| B. FLOW STUDIES | 120 | 120 | | | | 240 |
| C. FIELD LIAISON & ENG. STUDIES | 75 | 75 | | | | 150 |
| D. LAB EQUIPMENT & FACILITIES | 60 | | | | | 60 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | – |
| B. MINI-TESTS | 1500 | 1500 | 1500 | | | 4500 |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | 75 | | | 75 |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | |
| TOTAL | 1815 | 1695 | 1575 | – | – | 5085 |
| ERDA SHARE | 1815 | 1695 | 1575 | – | – | 5085 |

PGM: SP - 1&2

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|---|
| TOTAL COSTS ERDA'S SHARE | ALL ERDA | 4807* | 4807* |

7. EXPECTATION OF SUCCESS: 75%

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 600 | 450 | 94 |
| DAILY PRODUCTION IN: | | | |
| 1985 | 0 | 0 | 0 |
| 1990 | 0 | 0 | 0 |
| 1995 | 10 | 7 | 0.5 |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 5 | 4 | 1 |
| 1990 | 6 | 4 | 1 |
| 1995 | 6 | 4 | 1 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

* INCLUDES 25% OF ERDA NPV FOR SP-6

## TARGET D: ALL SURFACTANT RESERVOIRS

## R&D STRATEGY SP-6: DEVELOPMENT OF CHEAPER AND ADEQUATE SUPPLIES OF SURFACTANTS

### 1. CENTRAL PROBLEM

Estimates of the costs of surfactants on a mass-produced basis range from 20 to 37 cents per pound. Surfactant costs are critical in the economics of the process because these chemicals are the principal components in the injection stage. Uncertainty as to the costs of surfactants and other chemicals could cause some operators to hesitate in implementing surfactant processes even if proved in programs SP-1 through SP-5. This program is to reduce this uncertainty. Because its benefits are shared across the targets, the costs, benefits, and probability of success have been incorporated in the respective calculations of the programs.

### 2. R&D GOALS

- To develop precise estimates of the costs of mass-produced chemicals (batch and continuous process) under various demand conditions.
- To determine whether there is a need for cost-reduction engineering studies in surfactant components.

3. R&D ACTIVITIES:

I. Building the Knowledge Base

-- Economic/engineering studies of the costs of manufacturing critical chemicals and their sensitivity to demand.

-- Studies of the feasibility of cost reduction through plant engineering on improved distribution.

II. Basic and Applied Research

-- Any further work relies on the results of those listed above.

PGM: SP-6

4. R&D ACTIVITIES -- PHYSICAL UNITS

| | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | - |
| B. RESERVOIR DATA BASE | | | | | | - |
| C. RECOVERY MODELS | | | | | | - |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | 2 | 3 | | | | 5 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | - |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | - |
| B. FLOW STUDIES | | | | | | - |
| C. FIELD LIAISON & ENG. STUDIES | | | | | | - |
| D. LAB EQUIPMENT & FACILITIES | | | | | | - |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | - |
| B. MINI-TESTS | | | | | | - |
| C. TECHNICAL PILOTS | | | | | | - |
| D. ECONOMIC PILOTS | | | | | | - |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 1/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 1/ |

1/ INCLUDED IN ABOVE FIGURES

PGM: SP-6

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | - |
| B. RESERVOIR DATA BASE | | | | | | - |
| C. RECOVERY MODELS | | | | | | - |
| D. ECONOMIC & OTHER FEASIB. STUDIES | 120 | 180 | | | | 300 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | - |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | - |
| B. FLOW STUDIES | | | | | | - |
| C. FIELD LIAISON & ENG. STUDIES | | | | | | - |
| D. LAB EQUIPMENT & FACILITIES | | | | | | - |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | | | | | - |
| B. MINI-TESTS | | | | | | - |
| C. TECHNICAL PILOTS | | | | - | | - |
| D. ECONOMIC PILOTS | | | | | | - |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 1/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | - | | |
| TOTAL | 120 | 180 | - | - | - | 300 |
| ERDA SHARE | 120 | 180 | - | - | - | 300 |

1/ COSTS INCLUDED ABOVE

PGM: SP-6

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | (APPORTIONED AMONG TARGETS D-1 THROUGH D-4) | |
| ERDA'S SHARE | | |

7. EXPECTATION OF SUCCESS: (INCORPORATED INTO PROBABILITIES OF PROGRAMS SP-1 THROUGH SP-5)

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | | | |
| DAILY PRODUCTION IN: | | | |
| 1985 | | | |
| 1990 | | | |
| 1995 | | | |
| CUMULATIVE PRODUCTION BY: | (BENEFITS OF LOWER COST SURFACTANTS ALREADY COUNTED IN SP-1 THROUGH SP-5) | | |
| 1985 | | | |
| 1990 | | | |
| 1995 | | | |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

## TARGET D-2: CALIFORNIA SANDSTONES

## R&D STRATEGY SP-3: EXTEND APPLICATION OF PROCESS

### 1. CENTRAL PROBLEM

In addition to the general problems of applying surfactants under reservoir conditions, California sandstones present the problem that they are high in clay content. The clays lead to high rates of absorption of the surfactants, ion exchange, and reduced permeability due to clay swelling. These special problems must be overcome to realize the potential of California surfactant reservoirs.

Included in this program, however, is the assesment of the potential of processes in which the surfactant is formed in situ. Most California crudes, having a naphthenic base, show some reactivity towards caustic solutions. The reaction results in the formation of a sodium naphthenate which is very interfacially active under certain conditions and shows promise of increasing recovery efficiency.

### 2. R&D GOALS:

- Study the application of caustic injection combined with other additives in the displacing phase.
- Determine the preferred surfactant/polymer system for the California reservoirs.
- Test the preferred system to the point of technical feasibility.

### 3. R&D ACTIVITIES:

I&II. (to be accomplished under Basic Surfactant Program, SP)

III. Field Based Activities:

-- Testing and measurements to identify favorable pilot test candidates, starting in 1977

-- Mini tests in the high potential reservoirs, starting in 1978

PGM: SP-3

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES 1/ | 1/ | | | | | 1/ |
| B. RESERVOIR DATA BASE | | | | | | |
| C. RECOVERY MODELS | 1 | | | | | 1 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | | | | | |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 3 | 5.5 | 6 | 4 | 4 | 22.5 |
| B. FLOW STUDIES | 2 | 6 | 6 | 6 | 2 | 22 |
| C. FIELD LIAISON & ENG. STUDIES | 1 | 1 | 1 | 1 | 1 | 5 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 10 2/ | | | | | 10 2/ |
| B. MINI-TESTS | | | | | | 4 |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 3/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.
1/ RELIES ON RESIDUAL MEASUREMENTS PROGRAM ST-4
2/ CORE HOLES
3/ INCLUDED IN ABOVE FIGURES.

PGM: SP-3

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL 1/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | 2/ | | | | | 2/ |
| B. RESERVOIR DATA BASE | | | | | | |
| C. RECOVERY MODELS | | | | | | |
| D. ECONOMIC & OTHER FEASIB. STUDIES | 60 | | | | | 60 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 180 | 330 | 360 | 240 | 240 | 1350 1/ |
| B. FLOW STUDIES | 180 | 360 | 360 | 180 | 240 | 1320 1/ |
| C. FIELD LIAISON & ENG. STUDIES | 75 | 75 | 75 | 75 | 75 | 375 1/ |
| D. LAB EQUIPMENT & FACILITIES | 250 | 400 | 125 | 100 | 100 | 975 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 500 | 1000 | 500 | | | 2000 |
| B. MINI-TESTS | | 250 | 1250 | 3000 | 2500 | 7000 1/ |
| C. TECHNICAL PILOTS | | | | – | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | – | | 3/ |
| TOTAL | 1245 | 2415 | 2670 | 3595 | 3155 | 13080 |
| ERDA SHARE | 1245 | 2415 | 2670 | 3595 | 3155 | 13080 |

1/POST 1981 COMMITMENTS: $2,500,000 IN 1982, $5000.000 IN 1983, FOR FIELDWORK; IN ADDITION, AN AVERAGE OF $600,000 PER YEAR 1982-1986 FOR PERSONNEL AND LAB WORK.

2/ RELIES ON RESIDUAL MEASUREMENT PROGRAM ST-4

3/ COSTS INCLUDED ABOVE

PGM: SP-3

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 11015* | 11015* |
| ERDA'S SHARE | | |

7. EXPECTATION OF SUCCESS: 38%

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 1700 | 646 | 59 |
| DAILY PRODUCTION IN: | | | |
| 1985 | 5 | 2 | 0.1 |
| 1990 | 69 | 26 | 0.9 |
| 1995 | 216 | 82 | 2.7 |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 4 | 2 | ** |
| 1990 | 52 | 20 | 2 |
| 1995 | 213 | 81 | 7 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

* INCLUDES 25% OF ERDA NPV FOR SP-6

** LESS THAN 1

NOTE: Production Benefits and Cost-Effectiveness Indices of Program SP-3

The production benefits shown assume upper tier prices and high risk (20% real) rate of return requirement. The assumption that the risk premium will not be reduced through the program is relatively sensitive. Should surfactant/polymer become a conventional technology in California (i.e., carry an 8% real rate of return), the impact would be as below:

| | HIGH RISK (NOTED ABOVE) | CONVENTIONAL RISK |
|---|---|---|
| POTENTIAL PRODUCTION BENEFITS: | | |
| ULTIMATE RECOVERY (MMB) | 1700 | 2500 |
| DAILY PRODUCTION MB/D) IN: | | |
| 1985 | 5 | 55 |
| 1990 | 69 | 127 |
| 1995 | 216 | 487 |
| CUMULATIVE PRODUCTION (MMB) BY: | | |
| 1985 | 4 | 29 |
| 1990 | 52 | 144 |
| 1995 | 213 | 852 |
| COST-EFFECTIVENESS INDICES | | |
| ULTIMATE RECOVERY/ COST | 59 | 86 |
| ANNUAL PRODUCTION/ COST | | |
| 1985 | 0.1 | 0.7 |
| 1990 | 0.9 | 1.6 |
| 1995 | 2.7 | 6.1 |
| CUMULATIVE PRODUCTION/ COST | | |
| 1985 | ** | 1 |
| 1990 | 2 | 5 |
| 1995 | 7 | 29 |

** LESS THAN 1

The sensitivity of these results to the risk premium assumption should be borne in mind in evaluating Program SP-3. It is not currently possible to assign a probability to making surfactant/polymer conventional for these targets. The substantial program described above sets the stage for subsequent efforts after 1981 designed to make this program a conventional recovery technology.

## TARGET D-3: GULF COAST RESERVOIRS

### R&D STRATEGY SP-4: EXTEND APPLICATION OF PROCESS

1. CENTRAL PROBLEM:

Sandstones of the Gulf Coast are ideal candidates for the surfactant/polymer process because of their general uniformity and high permeability. These two characteristics, combined, enable high velocities to be achieved and fingering to be minimized, greatly contributing to the success of the process. On the other hand, the generally higher temperatures of the Gulf Coast sands and the higher operating costs, both due to greater depths, may offset these advantages. Certain specially formulated surfactants and polymers may have to be developed for these higher temperature reservoirs.

Salinity of these reservoirs will also be greater than that of many other oil provinces, but this to some extent depends on whether the sand was displaced by a natural water drive or was subjected to a water flood using water with high salinity. Although salinity is a recognized problem in maintiaining the activity of surfactants, the problems may be minimized by the prior history of flooding in the reservoir. Moreover, pre-flushes of various sorts can be used to reduce the reservoir salinity in many reservoirs.

2. R&D GOALS:

- Develop surfactant/polymer systems that will stand up to the higher salinity, and higher temperature conditions faced in Gulf Coast Sandstones.

- Verify the technical feasibility of improving recovery efficiency in watered out Gulf Coast sandstones.

3. R&D ACTIVITIES:

I. Building the Knowledge Base

(Rely on activities under Basic Surfactant Program SP)

II. Basic and Applied Research

-- Augment the activities under Basic Surfactant with special research and development focused on the development of surfactant systems that can cope with higher salinities and higher temperatures.

III. Field Based Activities

-- Identify suitable reservoir targets, starting in 1978

-- Mini tests, starting in 1979

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | 1/ |
| B. RESERVOIR DATA BASE | | | | | | |
| C. RECOVERY MODELS | 1 | | | | | 1 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | | | | | |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 7 | 8 | 6.5 | 5.5 | 5.5 | 32.5 |
| B. FLOW STUDIES | 5 | 6 | 5 | 5 | 4 | 25 |
| C. FIELD LIAISON & ENG. STUDIES | 0.77 | 0.77 | 1.15 | 1.15 | 1.15 | 5 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | 2 2/ | | | | 2 2/ |
| B. MINI-TESTS | | | 2 → | → | → | 2 |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 3/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.
1/ RELIES ON RESIDUAL MEASUREMENTS PROGRAM, ST-4
2/ CORE HOLES
3/ INCLUDED IN ABOVE FIGURES

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL 1/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | 2/ |
| B. RESERVOIR DATA BASE | | | | | | |
| C. RECOVERY MODELS | 60 | | | | | 60 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | | | | | |
| E. PROCESS/FIELD TEST EVALUATION | – | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 420 | 480 | 390 | 330 | 330 | 1950 1/ |
| B. FLOW STUDIES | 300 | 360 | 300 | 300 | 240 | 1500 1/ |
| C. FIELD LIAISON & ENG. STUDIES | 50 | 50 | 75 | 75 | 75 | 325 1/ |
| D. LAB EQUIPMENT & FACILITIES | 450 | 100 | 125 | 100 | 100 | 875 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | 500 | | | | 500 |
| B. MINI-TESTS | | | 4000 | 4000 | 4000 | 12000 |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 3/ |
| TOTAL | 1280 | 1490 | 4890 | 4805 | 4745 | 17210 |
| ERDA SHARE | 1280 | 1490 | 4890 | 4805 | 4745 | 17210 |

1/ POST 1981 COMMITMENTS: $4,000,000 IN 1982 PLUS AN AVERAGE OF $500,000 PER YEAR 1982-1986 FOR PERSONNEL AND LAB WORK.

2/ RELIES ON RESIDUAL MEASUREMENT PROGRAM ST-4

3/ COST INCLUDED ABOVE

PGM: SP-4

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|---|
| TOTAL COSTS ERDA'S SHARE | ALL ERDA | 14226* | 14226* |

7. EXPECTATION OF SUCCESS: 42%

8. OUTCOMES OF THE R&D PROGRAM: **

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 0 | | |
| DAILY PRODUCTION IN: | | | |
| 1985 | 0 | | |
| 1990 | 0 | | |
| 1995 | 0 | | |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 0 | | |
| 1990 | 0 | | |
| 1995 | 0 | | |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

* INCLUDES 25% OF ERDA NPV FOR SP-6

** SEE NOTE ON NEXT PAGE

NOTE: Production Benefits and Cost-Effectiveness Indices of Program SP-4

The production benefits shown in item 8 in the foregoing assume the Standard Economics conditions. This means that these benefits are computed using upper tier prices (with current tax policies). As shown below, the production benefits and cost-effectiveness indices are sensitive to large changes in price.

Comparing the Case 2 column to the Standard Economics, High Risk column shows the effect of raising the price from upper tier to world levels. Moderate price increases have no effect. As the last column shows, however, if prices should rise to the alternate fuels price level, this program would stimulate substantial production.

SP-4

| | STANDARD ECONOMICS | CASE 2 | UPPER BOUND |
|---|---|---|---|
| POTENTIAL PRODUCTION BENEFITS: | | | |
| ULTIMATE RECOVERY (MMB) | 0 | 0 | 200 |
| DAILY PRODUCTION MB/D) IN: | | | |
| 1985 | 0 | 0 | 0 |
| 1990 | 0 | 0 | 2 |
| 1995 | 0 | 0 | 1 |
| CUMULATIVE PRODUCTION (MMB) BY: | | | |
| 1985 | 0 | 0 | 0 |
| 1990 | 0 | 0 | 1 |
| 1995 | 0 | 0 | 7 |
| COST-EFFECTIVENESS INDICES: | | | |
| ULTIMATE RECOVERY/ COST | – | – | 6 |
| ANNUAL PRODUCTION/ COST | | | |
| 1985 | – | – | 0 |
| 1990 | – | – | * |
| 1995 | – | – | * |
| CUMULATIVE PRODUCTION/ COST | | | |
| 1985 | – | – | 0 |
| 1990 | – | – | ** |
| 1995 | – | – | ** |

* LESS THAN 0.1
** LESS THAN 1

## TARGET D-4: OTHER SANDSTONE RESERVOIRS

### R&D STRATEGY SP-5: EXTEND THE APPLICATION OF THE PROCESS

1. CENTRAL PROBLEMS:

All other sandstone reservoirs, not included in the above targets, will be included in this target: the reservoirs will range from Appalachia to the Rockies to the Mid-Continent and South Texas. The reservoir conditions will vary and will correspond to some of the conditions described for Targets SP-1 to SP-4 above, although in most cases, incremental R&D will be required for each.

2. R&D GOALS

- Determine the technical validity of the surfactant system under a variety of reservoir conditions.

3. R&D ACTIVITIES:

I&II. (Draw on the Bank being performed under Basic Surfactant, SP)

III. Field Based Activity

-- Identify and delineate target reservoirs starting in 1977.

-- Conduct mini-tests starting in 1978

PGM: SP-5

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | 1/ | | | | | 1/ |
| B. RESERVOIR DATA BASE | | | | | | |
| C. RECOVERY MODELS | 1 | | | | | 1 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | | | | | |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | - |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 7 | 6.5 | 6.5 | 6.5 | 6.5 | 33 |
| B. FLOW STUDIES | 5 | 5 | 6 | 7 | 7 | 30 |
| C. FIELD LIAISON & ENG. STUDIES | 1 | 1 | 1 | 2 | 2 | 7 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 10 2/ → | → | → | | | 10 2/ |
| B. MINI-TESTS | | 4. → | → | → | → | 4 |
| C. TECHNICAL PILOTS | | | | | | - |
| D. ECONOMIC PILOTS | | | | | | - |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 3/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.
1/ RELIES ON RESIDUAL MEASUREMENT PROGRAM, ST-4
2/ CORE HOLES
3/ INCLUDED IN ABOVE FIGURES

PGM: SP-5

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. 1/ TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | 2/ | | | | | 2/ |
| B. RESERVOIR DATA BASE | | | | | | |
| C. RECOVERY MODELS | 60 | | | | | 60 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | | | | | |
| E. PROCESS/FIELD TEST EVALUATION | – | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 420 | 390 | 390 | 390 | 390 | 1980 |
| B. FLOW STUDIES | 300 | 300 | 360 | 420 | 420 | 1800 |
| C. FIELD LIAISON & ENG. STUDIES | 75 | 75 | 75 | 150 | 150 | 525 |
| D. LAB EQUIPMENT & FACILITIES | 450 | 100 | 125 | 100 | 100 | 875 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 500 | 1000 | 500 | | | 2000 |
| B. MINI-TESTS | | 500 | 2000 | 2500 | 2500 | 7500 1/ |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 3/ |
| TOTAL | 1805 | 2365 | 3450 | 3560 | 3560 | 14740 |
| ERDA SHARE | 1805 | 2365 | 3450 | 3560 | 3560 | 14740 |

1/ POST 1981 COMMITMENTS: $2,500,000 IN 1982 FOR FIELDWORK PLUS AN AVERAGE OF $700,000 PER YEAR 2982-1986 FOR PERSONNEL AND LAB WORK.

2/ RELIES ON RESIDUAL MEASUREMENT PROGRAM ST-4

3/ COSTS INCLUDED ABOVE

PGM: SP-5

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 12467* | 12467* |
| ERDA'S SHARE | DO | DO |

7. EXPECTATION OF SUCCESS: 38%

8. OUTCOMES OF THE R&D PROGRAM: ****

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | ** | ** | - |
| DAILY PRODUCTION IN: | | | |
| 1985 | 1 | *** | - |
| 1990 | 0 | 0 | - |
| 1995 | 0 | 0 | - |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 17 | 6 | ** |
| 1990 | 17 | 6 | ** |
| 1995 | 17 | 6 | ** |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

* INCLUDED 25% OF ERDA NPV FOR SP-6

** LESS THAN 1

*** LESS THAN 0.1

**** SEE NOTE ON NEXT PAGE

NOTE: Production Benefits and Cost-Effectiveness Indices of Program SP-5

The production benefits and cost-effectiveness indices shown in Item 8 in the foregoing assume the Standard Economics conditions and that the technology remains highly risky. This means that these benefits were computed at upper tier prices (with current taxes) and 20 percent real rate of return requirement. As shown below, the benefit estimates are highly sensitive to both price and risk assumptions. Contrasting of the second and third columns to the first shows that either reduced risk (dropping the real rate of return requirement from 20 to 8 percent) or a price rise to world levels (without a reduction in risk) would add considerably to estimated ultimate recovery and production. The price rise would result in somewhat more and earlier production. Further increases in price or reduction in risk at the higher price would contribute additional production. Substantially higher prices would also stimulate additional research and development by industry.

This analysis clearly indicates that numerous candidate reservoirs in Appalachia, the Mid-Continent, the Rockies, and South Texas are very close to being economic. Either risk-reducing technological breakthroughs or a rise in price could bring them into production. It should be understood, however, that the more limited technological achievements of ERDA's program have been assumed into the price-sensitivity calculation. That is, the production that is related to a rise in price is available only if the ERDA research and development are carried out.

| | STANDARD ECONOMICS (UPPER TIER PRICE, CURRENT TAX) | | CASE 2 |
|---|---|---|---|
| | HIGH RISK | CONVENTIONAL RISK | HIGH RISK |
| POTENTIAL PRODUCTION BENEFITS: | | | |
| ULTIMATE RECOVERY (MMB) | ** | 1800 | 2100 |
| DAILY PRODUCTION MB/D) IN: | | | |
| 1985 | 1 | 0 | 17 |
| 1990 | 0 | 0 | 418 |
| 1995 | 0 | 159 | 405 |
| CUMULATIVE PRODUCTION (MMB) BY: | | | |
| 1985 | 17 | 17 | 4 |
| 1990 | 17 | 23 | 588 |
| 1995 | 17 | 176 | 1367 |
| COST-EFFECTIVENESS INDICES: | | | |
| ULTIMATE RECOVERY/ COST | ** | 55 | 64 |
| ANNUAL PRODUCTION/ COST | | | |
| 1985 | * | 0 | 0.2 |
| 1990 | 0 | 0 | 4.7 |
| 1995 | 0 | 1.8 | 4.5 |
| CUMULATIVE PRODUCTION/ COST | | | |
| 1985 | ** | ** | ** |
| 1990 | ** | 1 | 18 |
| 1995 | ** | 5 | 42 |

* LESS THAN 0.1
** LESS THAN 1

# CHAPTER VI

## POLYMER AUGMENTED WATERFLOODING

### Description and Current Application of the Technology

The sweep efficiency of any fluid drive can be increased if the mobility of the displacing fluid is lower than that of the crude being displaced. This fact can be demonstrated by relatively simple analysis using well-established fractional flow relationships. More sophisticated proof can be secured with mathematical reservoir simulation techniques. In this sense, efficiency refers to the amount of water required to drive the oil saturation down to its "absolute" residual value. Moreover, in a real reservoir the sweep, even with a favorable mobility ratio, is affected by the heterogeneity of the formation. As a result of perturbations in fluid flow and a range of permeabilities in parallel paths, sweep efficiency is lowered. This is accentuated when the mobility ratio is unfavorable (where the mobility of the displacing fluid is less than that of the crude) and significant areas of the reservoir are bypassed.

Early attempts to increase the viscosity of the injected water used natural gums which were subject to rapid hydrolytic and bacterical decomposition. About ten years ago, the hydrolyzed polyacrylamides were introduced as stable, water soluble polymers for increasing the viscosity of water. Somewhat more recently, polysaccharides have also been offered on the market. Both additives exhibit the desired properties in the laboratory -- they "thicken" the water so less bypassing and fingering occur.

Numerous pilot and field scale development operations have been carried out with polymers. The results to date have been either inconclusive or negative. Since the theoretical basis for expecting improved sweep (horizontally and vertically) is so firm and the ability of the polymers to raise and maintain the higher viscosity in laboratory operations is so well defined, it is necessary to determine why the results of theoretical and model studies cannot be extrapolated to the field. Two serious questions must be addressed: is the sweep of reservoirs with slightly unfavorable mobility ratios as poor as predicted by theoretical and model analyses? Does the polymer's effectiveness survive the many months and years of contact in the sub-surface with reservoir rock, fluids, and reservoir ambience? The experimental work in the field conducted to date has not examined these questions. Rather, it has been primarily concerned with a production response.

The level and types of industry field activity to date are summarized in Exhibit VI-1, below:

EXHIBIT VI-1

Polymer Waterflood Activity Summary

| | Technical Pilots | | Economic Pilots | | Fieldwide Development | |
|---|---|---|---|---|---|---|
| | Total | Current | Total | Current | Total | Current |
| Projects | 3 | 0 | 14 | 9 | 14 | 11 |
| Reservoirs | 3 | 0 | 14 | 9 | 13 | 10 |

Polymer flooding activity is further characterized by the following:

- Currently, 14,624 acres are under development.
- The general reduction in the number of tests is largely attributable to negative results.
- Substantial amounts of this field testing is relatively recent, much in the last two years.
- ERDA is supporting two of the newer projects, in the Stanley Stringer (Oklahoma) and Coalinga (California) fields.

Because of the initially uninspiring results, and because many polymer candidates are also amenable to more efficient enhanced recovery processes, the target for polymer is relatively small. Polymer problems, however, must also be overcome to allow the surfactant/polymer systems to operate effectively. These problems are the subject of the next section.

## Problems and Opportunities

Although the process is conceptually simple and well understood in terms of the laws of fluid behavior and in laboratory results, it is not well understood under reservoir conditions. The leading hypothesis for explaining the discouraging results to date is that the polymers degrade in the reservoir.

It is known that both polyacrylamides and polysaccharides have defects which limit their use under various reservoir conditions. No systematic field efforts have shown the exact limits of their applicability. The research and development efforts that have been conducted so far have been more concerned with recovery than with the type of measurement needed to define these limits or to make them less constraining.

Since polymer projects have been generally conducted as part of conventional waterflooding (with some exceptions, such as Getty's projects in the Robinson Sand in Illinois), determining the incremental production over anticipated waterflood recovery is difficult. Compounding the problem is the fact that incremental recovery attributable to polymer recovery is generally small, on the order of 10 to 20% over anticipated waterflood recovery and on the order of three percent of the original oil. Several operators have come to express serious doubt that polymers increase total recovery at all.

When applied after a waterflood, incremental production is quite low, and often uneconomic. Moreover, many candidate reservoirs for tertiary application of polymer floods are also amenable to other, more efficient enhanced recovery techniques. Thus, by and large, only those reservoirs regarded as marginal for other EOR processes are considered for polymers.

Substantial opportunities exist, however, for using alternative formulations of polymers or polymers in different forms (e.g., foams) to increase effectiveness. Further, polymers may be useful in correcting certain reservoir deficiencies so that production rates

increase over waterflood rates, even if there is no incremental ultimate recovery attributable to the polymers. Finally, improvements in polymers will translate directly into increased efficiency of the surfactant processes, in which the polymers are critical to protecting the oil-displacing slug.

## Future Directions of Industry Application -- The Base Case

Discussions with engineers and managers in operating companies and examination of the recent literature on polymer flooding suggests that industry plans to proceed only in the most favorable reservoirs and -- in them -- very cautiously. Many look to ERDA for further development of the technique. Thus, the standard procedures for estimating the Base Case[1/] were modified for polymer flooding. Because ERDA-supported projects are so much in the forefront of the development of this technique, fifty percent of production by polymer flooding from reservoirs where there is current, economic activity and from reservoirs very similar to the ones under development, has been attributed to ERDA's stimulation. The balance of this production was estimated to be produced by industry without ERDA's assistance. Under Standard Economics conditions, the resulting Base Case for polymer is as follows:

| | |
|---|---|
| Ultimate Recovery | 80 million barrels |
| Production Rate in: | |
| 1985 | 14 thousand barrels per day |
| 1990 | 8 |
| 1995 | 0 |
| Cumulative Production by: | |
| 1985 | 46 million barrels |
| 1990 | 71 |
| 1995 | 77 |

1/ See Chapter I of Part 3.

Although the estimated ultimate recovery is relatively small, production comes on rather early -- over half has been produced by 1985. The decline toward the end of the period is due to the number of candidate reservoirs being exhausted.

Exhibit VI-2 shows the sensitivity of the Polymer Base Case estimates to changes in prices and taxes. The tax changes analyzed have only negligible impact. Price changes up to the world level bring on only slightly more oil. At alternate fuels price, substantially more oil is produced. The rate of production in each case peaks in 1985.

EXHIBIT VI-2

INDUSTRY BASE CASE FOR POLYMER UNDER PRICE/TAX CONTINGENCIES

| | STANDARD ECONOMICS (UPPER TIER W/ CURRENT TAX) | LOWER BOUND (UPPER TIER W/ UNFAV. TAX) | CASE 2 (WORLD PRICE W/ CURRENT TAX) | CASE 4 (WORLD PRICE W/ FAVORABLE TAX) | UPPER BOUND (ALTERNATE FUELS PRICE W/ FAVORABLE TAX) |
|---|---|---|---|---|---|
| ULTIMATE RECOVERY (BILLION BARRELS) | 0.1 | * | 0.1 | 0.1 | 0.2 |
| PRODUCTION RATE IN: (THOUSAND BARRELS PER DAY) | | | | | |
| 1985 | 14 | 13 | 23 | 23 | 42 |
| 1990 | 8 | 6 | 13 | 13 | 13 |
| 1995 | 0 | 0 | 0 | 0 | 0 |
| CUMULATIVE PRODUCTION BY: (MILLION BARRELS) | | | | | |
| 1985 | 50 | 40 | 80 | 80 | 130 |
| 1990 | 70 | 60 | 110 | 110 | 180 |
| 1995 | 80 | 70 | 120 | 120 | 190 |

* <.1

## The Polymer Waterflood Programs

Two polymer programs have been designed. The first (PW-1) is to develop means for improving the recovery efficiency of the process. The second (PW-2), assuming success of the first, is to reduce the risks of polymer flooding to the level of conventional application. Because the two are so closely intertwined, they are discussed together below, in the standard program description format.

## TARGET E-1: POLYMER WATERFLOODING

## R&D STRATEGY PW-1 AND PW-2: IMPROVE RECOVERY EFFICIENCY AND MAKE POLYMER FLOODING A CONVENTIONAL TECHNOLOGY

### 1. CENTRAL PROBLEM

Theoretically, polymer augmentation of a water flood alters the mobility ratio so as to substantially improve the efficiency of the flood. This is due both to reducing the mobility of the water, relative to the crude, and to dampening the perturbations caused by heterogeneities in the rock matrix. Field trials using polymer augmented waterfloods have failed to yield encouraging results. Because the fluid flow relationships are well understood and have been frequently demonstrated under laboratory conditions, the results in the field must be attributed to failures of the polymers themselves. Thus, work is needed to understand the in situ performance of the polymers and to formulate more stable and effective polymers for field use.

### 2. R&D GOALS

- To improve recovery efficiency from reservoirs in which flooding with available water is at an unfavorable mobility ratio, by using more viscous aqueous displacing phases.

- To develop required expertise to use polymers in real reservoirs effectively and economically.

- To conduct basic studies on the development and manufacture of polymers.

- The eventual R&D goal is to improve overall sweep efficiency of the immiscible, displacing aqueous phase. (The production benefits estimated below apply only to the reservoirs flooded by polymer waterflooding, and do not include the collateral benefits from improved polymers attributed to the surfactant/polymer process. Thus, the polymer production benefits are understated because this program benefits both processes. This understatement was necessary to avoid double counting of benefits. Should the surfactant process fail or be slow to materialize, additional recovery and production could be obtained from the polymer programs since the reservoirs assigned to surfactants would then be developed for polymer augmented waterflooding.)

3. R&D ACTIVITIES

I. Building a Knowledge Base

-- Evaluation of past efforts at using polymers.

-- Confirmation of theoretical conclusions on effectiveness of mobility control.

-- Structuring of specific data base to show applicability of process in reservoirs with poor mobility ratio.

II. Basic and Applied Research

-- Evaluation of currently available polymers.

-- Development of new polymers and improvements in molecular structure or conditions of commercially available polymers.

-- Study of foams and foam forming systems to provide effective viscosity control of displacing aqueous phase.

-- Analyses of polymer-manufacturing process for possible cost reductions on economies of scale.

-- Flow tests in cores and scaled, physical models including continued simulation studies, starting in 1978.

III. Field Based Activities

-- Injectivity tests and mini-tests to validate performance of polymers, starting in 1978.

IV. Transfer and Dissemination

PGM: PW-1 & PW-2

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | 1/ | | | | | 1/ |
| B. RESERVOIR DATA BASE | 1 | | | | | 1 |
| C. RECOVERY MODELS | 1 | | | | | 1 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | 1 | | | | 1 |
| E. PROCESS/FIELD TEST EVALUATION | | | 1 | | | 1 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 9.3 | 15.7 | 15.7 | 6 | 5 | 51 |
| B. FLOW STUDIES | 4 | 8 | 8 | 8 | 8 | 36 |
| C. FIELD LIAISON & ENG. STUDIES | 2 | 2 | 3 | 3 | 3 | 13 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | 2 2/ | 2 2/ | | | 4 2/ |
| B. MINI-TESTS | | 3 → | → | → | → | 3 |
| C. TECHNICAL PILOTS | | | | | | - |
| D. ECONOMIC PILOTS | | | | | | - |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | 1 | 1 |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ RELIES ON RESIDUAL MEASUREMENT PROGRAM, ST-4.

2/ SINGLE-WELL TESTS.

PGM: ST-1A (ELK HILLS)

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | 1/ |
| B. RESERVOIR DATA BASE | 30 | | | | | 30 |
| C. RECOVERY MODELS | 60 | | | | | 60 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | 60 | | | | 60 |
| E. PROCESS/FIELD TEST EVALUATION | | 30 | | | | 30 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 360 | 360 | 360 | 360 | 240 | 1680 |
| B. FLOW STUDIES | 240 | 360 | 360 | 360 | 240 | 1560 |
| C. FIELD LIAISON & ENG. STUDIES | 60 | 180 | 270 | 270 | 270 | 1050 |
| D. LAB EQUIPMENT & FACILITIES | 250 | 500 | 250 | 250 | 100 | 1350 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 1000 | | | | | 1000 |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | 2000 | 3000 | 3000 | 2000 | 10000 |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |
| TOTAL | 2000 | 3490 | 4240 | 4240 | 2850 | 16820 |
| ERDA SHARE | 2000 | 3490 | 4240 | 4240 | 2850 | 16820 |

1/ RELIES ON RESIDUAL MEASUREMENT PROGRAM – PROGRAM ST-4

2/ COSTS INCLUDED ABOVE

PGM: PW-1 & PW-2

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 18961 | 21896 |
| ERDA'S SHARE | DO | DO |

7. EXPECTATION OF SUCCESS: 50% (FOR FIELD APPLICATION OF POLYMERS ONLY NOT INCLUDING APPLICATIONS WITH SURFACTANTS.)

8. OUTCOMES OF THE R&D PROGRAM: 4/

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 140 | 70 | 3 |
| DAILY PRODUCTION IN: | | | |
| 1985 | 31 | 16 | 0.3 |
| 1990 | 9 | 5 | 0.1 |
| 1995 | 0 | 0 | – |
| CUMULATIVE PRODUCTION BY: | | | |
| 1985 | 99 | 50 | 2 |
| 1990 | 133 | 67 | 3 |
| 1995 | 140 | 70 | 3 |

NOTES:

1/ UNITS: ULTIMATE RECOVERY — MILLIONS OF BARRELS; DAILY PRODUCTION — THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION — MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION — EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

4/ POLYMER PRODUCTION BENEFITS ONLY, I.E., NOT INCLUDING SURFACTANT BENEFITS; SEE NOTE ON NEXT PAGE.

NOTE: Cost-Effectiveness Indices of Programs PW-1 and PW-2

The indices shown are computed on the basis of the full costs of the polymer program. If the portion of these costs that aid the surfactant program are stripped out, this could reduce the costs to $18,115,000 total NPV ERDA. The impact on the benefit/cost indices is shown below:

| COST-EFFECTIVENESS INDICES: | FULL COST | PW ONLY |
|---|---|---|
| ULTIMATE RECOVERY/ COST | 3 | 4 |
| ANNUAL PRODUCTION/ COST | | |
| 1985 | 0.3 | 0.3 |
| 1990 | 0.1 | 0.1 |
| 1995 | – | – |
| CUMULATIVE PRODUCTION/ COST | | |
| 1985 | 2 | 3 |
| 1990 | 3 | 4 |
| 1995 | 3 | 4 |

Thus, the impact on benefit/cost indices of the joint portion of the costs is negligible.

From item 8 in the foregoing, it can be seen that, like the Industry Base Case, the ERDA-stimulated polymer projects show peak production around 1985, with a decline after that as the candidate reservoirs are exhausted. As the cost-effectiveness indices show, three barrels of production -- all within the period of interest -- are available for each dollar of ERDA expenditure. This is the equivalent of about 33 cents per barrel for research and development costs.

The effects of the price/tax contingencies on production are shown in Exhibit VI-3. Contrasting the Standard Economics condition with the Lower Bound case shows that requiring that the injected polymers be capitalized suppresses the rate of production, but the effect is slight. Increasing the price to the world levels presents the apparent anomaly of reduced production rates and cumulative production. The explanation for this is that a higher price will enable industry to develop the now marginal reservoirs without ERDA stimulation, thereby reducing the number of reservoirs in which ERDA's impact is felt. This, then, is one limited case in which price increase can substitute for some research and development. Increasing price to the alternate fuel price adds no more recovery, but accelerates the production rate.

EXHIBIT VI-3

EFFECTS OF PRICE/TAX CONTINGENCIES OF EXPECTED PRODUCTION FROM POLYMER PROGRAMS

| | Standard Economics (Upper Tier w/ Current Tax) | Lower Bound (Upper Tier w/ Unfav. Tax) | Case 2 (World Price w/ Current Tax) | Case 4 (World Price w/ Favorable Tax) | Upper Bound (Alternate Fuels Price w/ Favorable Tax) |
|---|---|---|---|---|---|
| Expected Ultimate Recovery (Billion Barrels) | .1 | .1 | .1 | .1 | .1 |
| Expected Production Rate In: (Thousand Barrels Per Day) | | | | | |
| 1985 | 16 | 12 | 12 | 12 | 21 |
| 1990 | 5 | 6 | 7 | 7 | 7 |
| 1995 | – | – | – | – | – |
| Expected Cumulative Production By: (Million Barrels) | | | | | |
| 1985 | 50 | 30 | 35 | 38 | 68 |
| 1990 | 67 | 47 | 57 | 57 | 91 |
| 1995 | 70 | 51 | 62 | 62 | 95 |

SUMMARY: Combined Effects of Industry Activity and the Polymer Waterflood Programs

The production stimulated by the ERDA program is expected to add 70 million barrels ultimate recovery to the 100 million barrels to be produced in the Industry Base Case under Standard Economic conditions. The ERDA program, however, would accelerate production for each case. Exhibits VI-4 and VI-5 display the expected production and cumulative production for the Base Case and that stimulated by ERDA programs. Peak production from polymer floods occur about 1985 -- relatively early in the period of interest. Cumulative production is expected to be nearly 150 million barrels by 1995. By that time, production by polymer flooding is exhausted.

These projections have assumed the conditions of the Standard Economics Case. Just as each of the elements of total polymer production were seen to be influenced somewhat by price/tax contingencies, their combination is also affected, as shown in Exhibit VI-6 for ultimate recovery and in Exhibit VI-7 for production rates.

As noted earlier, improvement in taxes has negligible effect on production by polymer waterflooding; but, the requirement that the injected polymer be capitalized would supress the amount of production that is economic. In terms of ultimate recovery, raising price from upper tier to world levels somewhat increases the size of the Base Case, but as price increases to the alternate fuels level, the size of both the Base Case and the ERDA increment increase. (Note that polymer waterflooding is a technique for which raising prices represents an alternative to public R&D. That is, polymer at alternate fuels price -- without an ERDA program -- yields about as much ultimate recovery as the upper tier price with an ERDA program.)

EXHIBIT VI-4

EXPECTED POLYMER WATERFLOODING PRODUCTION RATES

(STANDARD ECONOMICS)

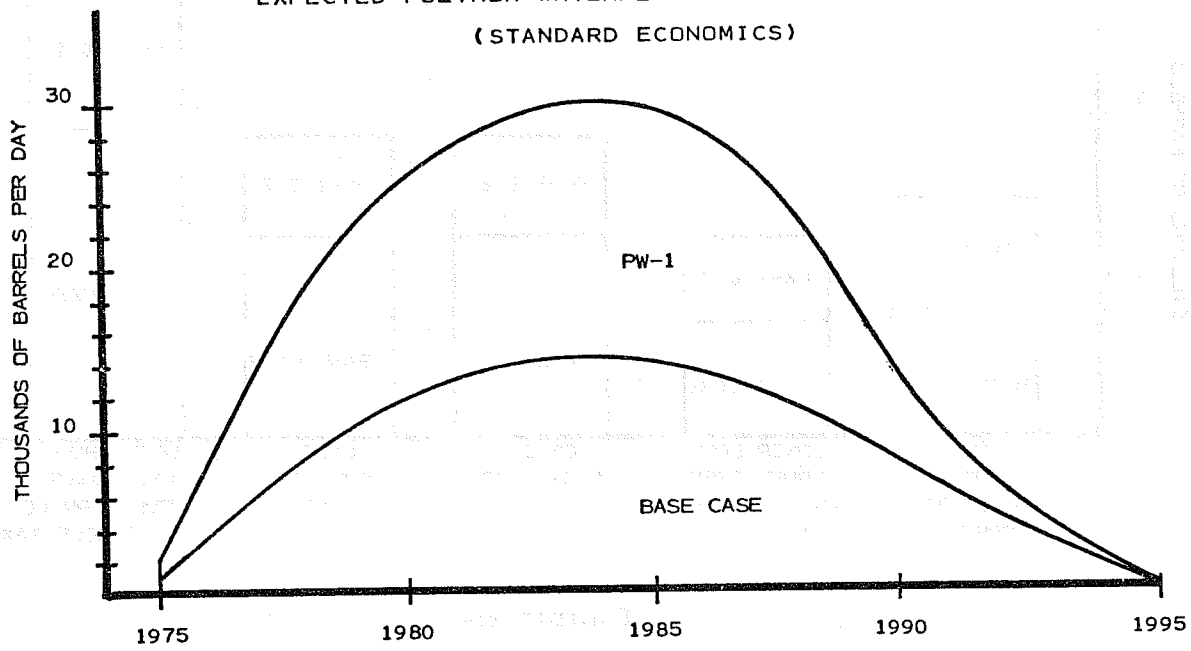



EXHIBIT VI-5

EXPECTED POLYMER WATERFLOODING CUMULATIVE PRODUCTION

(STANDARD ECONOMICS)

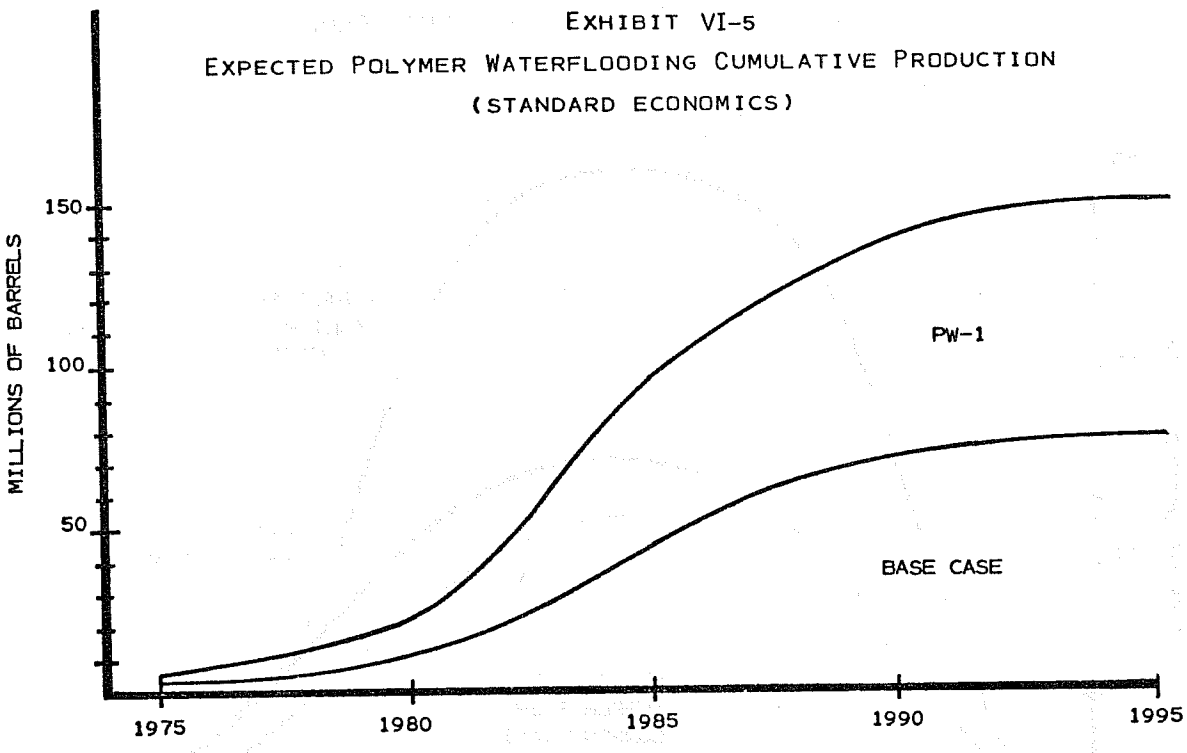


EXHIBIT VI-6

EXPECTED ULTIMATE RECOVERY UNDER PRICE/TAX CONTINGENCIES FROM POLYMER WATERFLOODING PROGRAMS

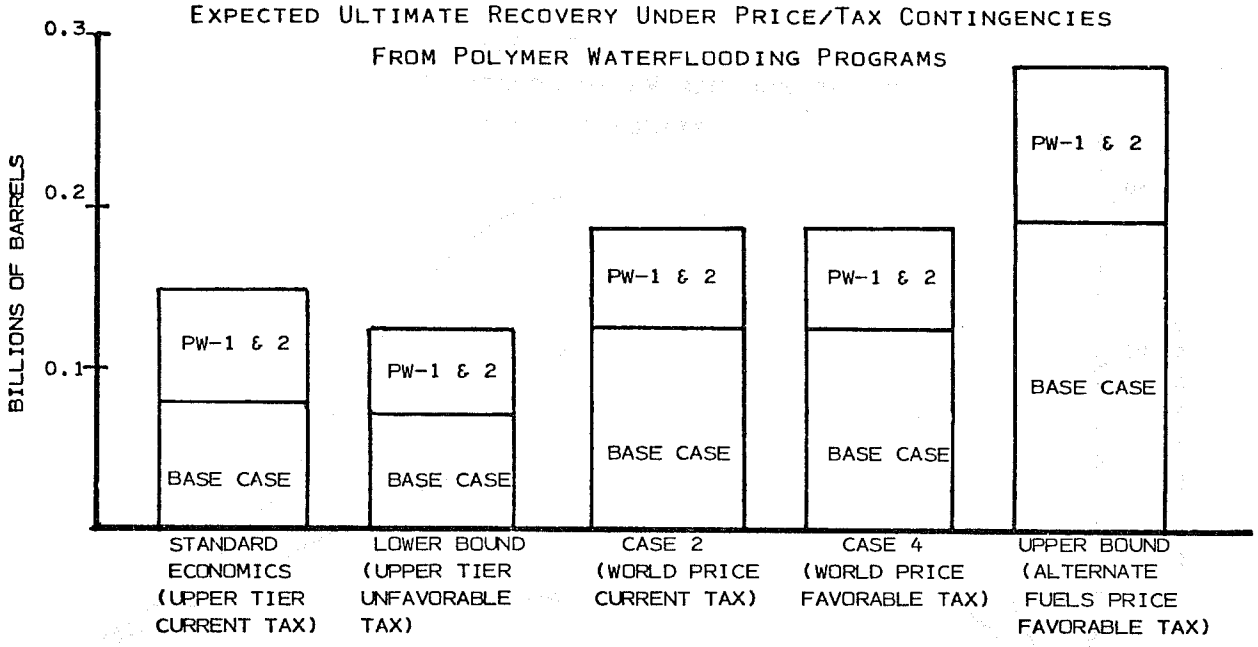
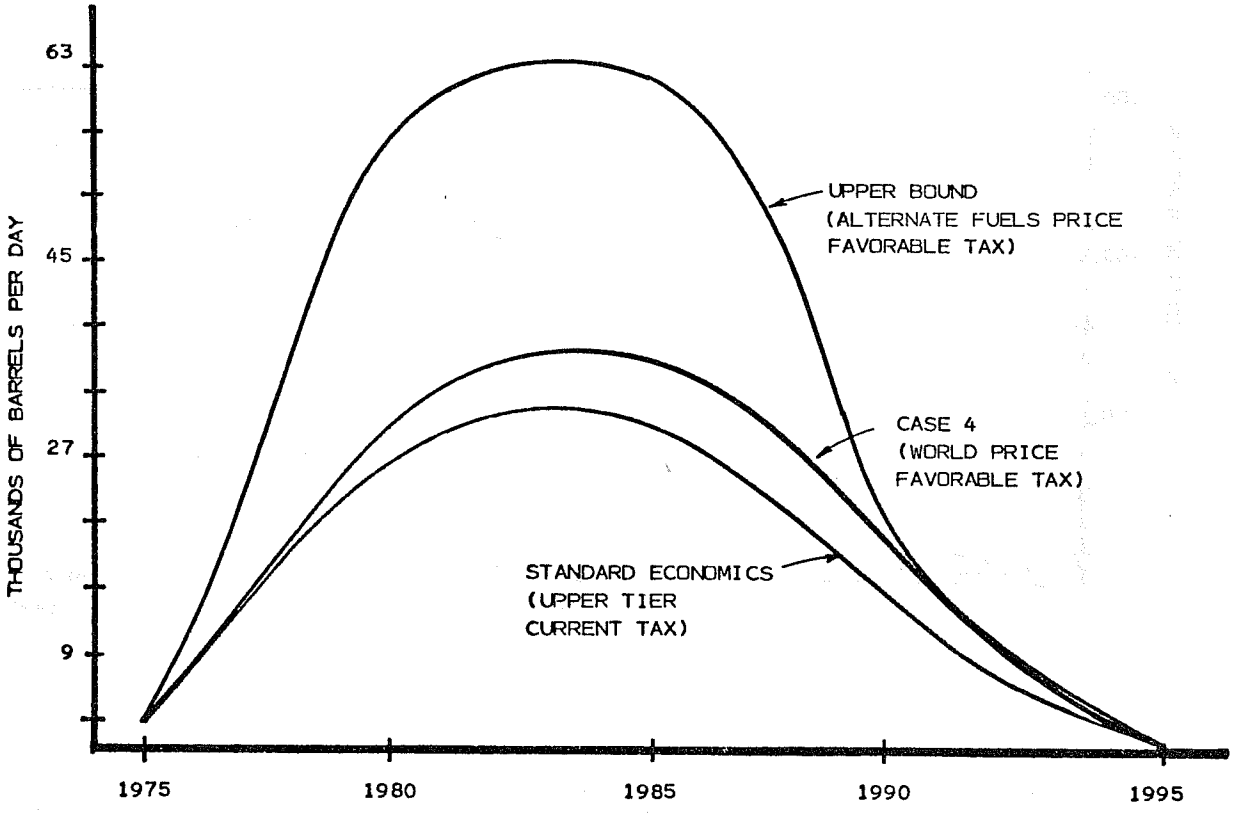



EXHIBIT VI-7

EXPECTED POLYMER WATERFLOODING PRODUCTION RATES UNDER SELECTED PRICE/TAX CONTINGENCIES (COMBINED BASE CASE AND ERDA PROGRAMS)



Examination of the production rates for the three cases shown reveals that increasing price also increases the rate of production. At world prices, production comes on sooner and peaks higher than at upper tier prices. Alternate fuels price, of course, yields both a higher rate and more rapid production. Under all price/tax contingencies, the production rate drops off after 1985 as the candidate reservoirs begin to decline and no new ones are added.

# CHAPTER VII

## SPECIAL TARGETS

### Introduction

In addition to the targets discussed in the five preceding chapters, four additional areas of inquiry offer fruitful opportunities for an ERDA involvement. These are areas in which industry currently does not plan activity but which, with preliminary research and development by ERDA, could become attractive to industry. The reasons that industry is not actively pursuing these areas vary, and are best understood in the context of each program.

Three of these special targets are classes of reservoirs in which no EOR is currently anticipated. Because they hold considerable resource potential, intensive study to determine the feasibility of EOR application could be rewarded by substantial incremental production. These reservoir classes are:

1. Giant, virgin and partially depleted reservoirs. It has been argued in the preceding chapters that EOR processes are most effective when applied at higher oil saturations. Application of suitable EOR techniques early in the life of a reservoir could substantially increase total production at a lower overall cost. Prudhoe Bay and Elk Hills are two such reservoirs. New discoveries will add to this category. The operators in these fields are unlikely to consider EOR at the current time because primary production by itself is

quite profitable and the operators seek to recover the substantial outlays they have already made without the burden of additional investment. Intensive study by ERDA could lead to a reassessment of the optimal development pattern of these reservoirs either by the operators or by the jurisdictions in which they lie.

2. Low recovery reservoirs. Some huge reservoirs in the U.S. have had relatively low rates of recovery under conventional operations, on the order of five to ten percent of the original oil. Severe problems owing to reservoir characteristics have limited production.

Because of the very poor response of these reservoirs to conventional attempts to increase recovery, and the fact that they will probably yield only to a massive and novel research approach, it is highly unlikely that any single operator would make the necessary investment in development activity. The chances for success are indeed small, but the more eclectic and imaginative the program that is brought to bear on the problem, the more likely the problem could be solved. The Spraberry Trend in Texas is one such reservoir. Because its remaining oil is on the order of seven billion barrels, even a small improvement could add several hundred million barrels in ultimate recovery.

3. "Time window" reservoirs. Many U.S. reservoirs are nearing their economic limits, even under stripper production. Once abandoned, they would have to be reopened to permit EOR development. Except for very deep reservoirs, this represents relatively little problem on land. Wells in these older reservoirs would require redrilling or costly workovers whenever EOR is begun. Offshore operations, however, present quite

a different situation. Especially in the Gulf of Mexico, natural water drives cause these reservoirs to deplete rapidly. High operating costs cause the economic limits to be reached much earlier than for comparable onshore operations. Once abandoned, the costs of redeveloping these reservoirs would be prohibitively high, in that platforms are generally removed and wells are not just capped, as they are onshore, but are filled with concrete to protect against environmental hazards. Many operations in the Gulf are currently approaching abandonment. Thus, if any EOR technique is to be tried, the necessary R&D must begin immediately. Operators are deterred from engaging in this R&D because, to each individually, it would be quite costly and, even if appropriate schemes were developed the problems of transporting and storing injection materials would remain. ERDA could initiate the necessary recovery process R&D on a regional basis, which would make the results available to all the operators. Moreover, with ERDA's assistance, a regional system for transportation and storage could also be devised.

4. Other Targets. The fourth area for ERDA involvement cuts across nearly all potential EOR reservoirs. As pointed out in earlier chapters, recovery is highly sensitive to the amount and distribution of the residual oil. Uncertainty about this key parameter currently deters EOR development in many reservoirs, especially for carbon dioxide, surfactant, and polymer candidates. The interviews with operators brought out: (a) that no consensus exists as to the oil saturations in many of the largest reservoirs, and (b) that actual measurement of residual saturation would accelerate EOR applications. Thus, ERDA's role in this case is to take the measurements, so that the pace of EOR applications by industry will increase. This activity is a prerequisite to achieving the benefits of the carbon dioxide and surfactant targets, and of the light oil steam targets.

Because these four areas are so diverse, they are discussed individually below, in the standard program format.

## SPECIAL TARGET F-1: GIANT, VIRGIN AND PARTIALLY DEPLETED RESERVOIRS

### R&D STRATEGY ST-1: ASSESS VALUE OF EARLY VS. STEP-WISE IMPLEMENTATION OF ENHANCED RECOVERY PROCESSES

1. CENTRAL PROBLEM

As noted and discussed further under Target F-4, the efficiency of most proposed tertiary schemes increases with an increase in the oil saturation at the time of inception of the process. From this observation it may be surmised that implementation of a suitable tertiary scheme of recovery in a near virgin, or only partially depleted reservoir, should result in an overall recovery that is higher than could be achieved by step-wise implementation of a primary, secondary, and tertiary recovery. Two giant reservoirs in the United States which could be examined in this light are Prudhoe Bay and Elk Hills.

Since the characteristics of the two fields in question may not be generally known, the following information has been assembled:

A. Prudhoe Bay. Available public reports indicate the main Prudhoe Bay accumulation contains a significant gas cap which overlaps about 1/3 to 1/2 of the oil column. A water leg on the south flank may or may not be a sufficiently strong aquifer to equal the anticipated high withdrawal rate. If not, it would have to be supplemented by water injection. In either case, a recovery efficiency of 40 to 45% is anticipated if water encroachment does keep up with withdrawals. (Considering the apparent heterogeneity

of the sands, this may be an optimistic estimate.) If water is to be injected then consideration can be given to early inclusion of surfactants and/or polymers that will reduce the residual saturation and increase recovery. Not only will the surfactant/polymer system be acting on a higher oil saturation, but the cost of combined pressure maintenance/secondary/tertiary would be consolidated to a major extent. An alternative approach would be to inject carbon dioxide/methane/propane mixtures, as a supplement to displacement by water contact. The density of the carbon dioxide rich fluid could be adjusted to a value between that of the crude and the national gas. The drainage residual would be expected to be 5%, and thus a significant increase in recovery would accrue. While the Bureau of Mines has indicated that Alaskan natural gas is rich with carbon dioxide, it is not known whether sufficient quantities of carbon dioxide would be available or could be economically generated on-site. (The foregoing suggestions are not offered as definitive proposals, but only to note that possibilities exist for securing increased recovery from the field.) A 10% increase in absolute recovery efficiency would amount to over 2 billion barrels of crude oil.

B. Elk Hills. The Elk Hills field includes the upper Etchegoin Sand which is reported to have produced about 20% of the original viscous (35 cps.) oil-in-place and the lower Stevens Zone that contains 31 pools from which only a small fraction of the original oil has been withdrawn. For both reservoirs it is optimistically anticipated that a recovery efficiency of 40% or more will be secured by primary recovery and water flooding. The Etchegoin Sand

is deeper than most steam drive prospects, but considering the size of the reservoir, intensive study should be given to a technique which would be able to recover more than water flooding from such a viscous oil reservoir. For the Stevens Zone, depending upon a structural configuration of the many small traps, ultimate recovery systems superior to mere waterflooding, e.g., carbon dioxide or surfactant, may be able to increase the anticipated recovery efficiency. A 10% increase in absolute recovery efficiency in each of the two reservoirs would amount to nearly 300 million barrels of crude oil.

## 2. R&D GOALS

- To ascertain the value of early implementation of the ultimate recovery scheme versus the traditional step-wise implementation of primary, secondary, and tertiary operations.

- To improve the ultimate recovery from the Prudhoe Bay and Elk Hills fields by developing and initiating an early application of an advanced improved recovery technique.

- The eventual R&D goal is to improve the absolute recovery in the Prudhoe Bay reservoirs by 10% and in the Elk Hills reservoirs by 20%.

## 3. R&D ACTIVITIES

I. Extending the Knowledge Base

- -- Comprehensive reservoir study of both fields
- -- Technical and economic evaluations of the efficiency of currently contemplated recovery processes.
- -- Development of new recovery models
- -- Economic feasibility studies of ultimate recovery processes.

II. Basic and Applied Research

- -- Crude oil and mineral studies and physical chemistry bench scale studies
- -- Laboratory, scaled model, and simulation studies of feasible recovery processes.

III. Field Based Activities

- -- Two technical pilot tests in the Elk Hills Field, starting in the Etchegoin Sand in 1978 and the Stevens Zone in 1979.

PGM: ST-1A (ELK HILLS)

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | 1/ |
| B. RESERVOIR DATA BASE | 0.5 | | | | | 0.5 |
| C. RECOVERY MODELS | 1 | | | | | 1 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | 1 | | | | 1 |
| E. PROCESS/FIELD TEST EVALUATION | | 0.5 | | | | 0.5 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 6 | 6 | 6 | 6 | 4 | 28 |
| B. FLOW STUDIES | 4 | 6 | 6 | 6 | 4 | 26 |
| C. FIELD LIAISON & ENG. STUDIES | 1 | 3 | 4.5 | 4.5 | 4.5 | 17.5 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | * | | | | | * |
| B. MINI-TESTS | | | | | | - |
| C. TECHNICAL PILOTS | | 2 → | | | | 2 |
| D. ECONOMIC PILOTS | | | | | | - |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ RELIES ON RESIDUAL MEASUREMENT PROGRAM, ST-4.

2/ INCLUDED IN ABOVE FIGURES.

PGM: ST-1A (ELK HILLS)

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | 1/ |
| B. RESERVOIR DATA BASE | 30 | | | | | 30 |
| C. RECOVERY MODELS | 60 | | | | | 60 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | 60 | | | | 60 |
| E. PROCESS/FIELD TEST EVALUATION | | 30 | | | | 30 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 360 | 360 | 360 | 360 | 240 | 1680 |
| B. FLOW STUDIES | 240 | 360 | 360 | 360 | 240 | 1560 |
| C. FIELD LIAISON & ENG. STUDIES | 60 | 180 | 270 | 270 | 270 | 1050 |
| D. LAB EQUIPMENT & FACILITIES | 250 | 500 | 250 | 250 | 100 | 1350 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 1000 | | | | | 1000 |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | 2000 | 3000 | 3000 | 2000 | 10000 |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |
| TOTAL | 2000 | 3490 | 4240 | 4240 | 2850 | 16820 |
| ERDA SHARE | 2000 | 3490 | 4240 | 4240 | 2850 | 16820 |

1/ RELIES ON RESIDUAL MEASUREMENT PROGRAM – PROGRAM ST-4

2/ COSTS INCLUDED ABOVE

PGM: ST-1A (ELK HILLS)

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 14327 | 15688 |
| ERDA'S SHARE | DO | DO |

7. EXPECTATION OF SUCCESS: 75%

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 200-400 | 150-300 | 10-19 |
| DAILY PRODUCTION IN: | | | |
| 1985 | | | |
| 1990 | | | |
| 1995 | | | |
| CUMULATIVE PRODUCTION BY: | (REQUIRES FURTHER STUDY BEFORE RELIABLE ESTIMATES OF INCREMENTAL EOR PRODUCTION CAN BE MADE.) | | |
| 1985 | | | |
| 1990 | | | |
| 1995 | | | |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | 1/ |
| B. RESERVOIR DATA BASE | 0.5 | | | | | 0.5 |
| C. RECOVERY MODELS | 1 | | | | | 1 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | 1 | | | | 1 |
| E. PROCESS/FIELD TEST EVALUATION | | 0.5 | | | | 0.5 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 6 | 6 | 6 | 6 | | 24 |
| B. FLOW STUDIES | 4 | 10 | 12 | 10 | | 36 |
| C. FIELD LIAISON & ENG. STUDIES | 3.5 | 10 | 11 | 8 | 8 | 40.5 |
| D. LAB EQUIPMENT & FACILITIES * | * | * | * | * | | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | | RELIES ON FIELD OPERATOR | | | | |
| B. MINI-TESTS | | | | | | |
| C. TECHNICAL PILOTS | | | | | | |
| D. ECONOMIC PILOTS | | | | | | |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ RELIES ON RESIDUAL MEASUREMENT PROGRAM ST-4.

2/ INCLUDED IN ABOVE FIGURES.

PGM: ST-1B (PRUDHOE BAY)

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | 1/ |
| B. RESERVOIR DATA BASE | 30 | | | | | 30 |
| C. RECOVERY MODELS | 60 | | | | | 60 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | 60 | | | | 60 |
| E. PROCESS/FIELD TEST EVALUATION | | 30 | | | | 30 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 360 | 360 | 360 | 360 | | 1440 |
| B. FLOW STUDIES | 240 | 600 | 720 | 600 | | 2160 |
| C. FIELD LIAISON & ENG. STUDIES | 210 | 610 | 700 | 480 | 480 | 2480 |
| D. LAB EQUIPMENT & FACILITIES | 250 | 1000 | 250 | 250 | | 1750 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | RELIES ON FIELD OPERATOR | | | | | |
| B. MINI-TESTS | | | | | | |
| C. TECHNICAL PILOTS | | | | | | |
| D. ECONOMIC PILOTS | | | | | | |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |
| TOTAL | 1150 | 2660 | 2030 | 1690 | 480 | 8010 |
| ERDA SHARE | 1150 | 2660 | 2030 | 1690 | 480 | 8010 |

1/ RELIES ON RESIDUAL MEASUREMENT PROGRAM

2/ COSTS INCLUDED ABOVE

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 7048 | 7048 |
| ERDA'S SHARE | DO | DO |

7. EXPECTATION OF SUCCESS: 75%

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 2000-2500 | 1500-1875 | 213-266 |
| DAILY PRODUCTION IN: | | | |
| 1985 | | | |
| 1990 | | | |
| 1995 | | | |
| CUMULATIVE PRODUCTION BY: | (REQUIRES FURTHER STUDY BEFORE RELIABLE ESTIMATES OF INCREMENTAL EOR PRODUCTION CAN BE MADE.) | | |
| 1985 | | | |
| 1990 | | | |
| 1995 | | | |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

## SPECIAL TARGET F-2: LOW RECOVERY RESERVOIRS (SPRABERRY TREND)

## R&D STRATEGY ST-2: SEEK NOVEL SYSTEM FOR INCREASING RECOVERY EFFICIENCY

### 1. CENTRAL PROBLEM

The principal reservoir in the Spraberry Trend has been identified as the matrix siltstone with a porosity of some 8% and a permeability of less than one millidarcy (an average of 0.5 md. is reported). The low permeability is apparently due to argillaceous material in the pores of the rock, and productivity appears to be related to the intensity of local (natural) fracturing. Over the last three decades, repeated fracturing. acidization, and the introduction of waterflooding in selected locations have been unable to raise the forecasted recovery efficiency above 5 to 6%.

Yet, since the Spraberry Trend reservoirs are reported to have contained 7.7 billion barrels of original oil in place, it is a massive resource where even a small boost in the recovery efficiency could add several hundred million barrels of reserves.

### 2. R&D GOALS

- To confirm the values of original oil-in-place, and that a residual oil accumulation of some 7 billion barrels currently exists.
- To seek out any recovery technique that might achieve an increase in absolute recovery of 5% or more.

## 3. R&D ACTIVITIES

### I. Building the Knowledge Base

-- Bring together all the information available on the geology and lithology of the Trend.

-- Study the performance of the water floods and stimulation techniques that have been used to date.

-- Increase the data base as necessary by field observations, simulation studies, and possibly additional core holes to confirm the state of depletion in active producing areas.

### II. Basic and Applied Research

-- Investigate the stimulation schemes that have been used, and the possibility of using novel techniques: nuclear fracturing has not been attempted in these sands although the thickness is sufficient to contain such detonations (matrix flow is apparently sufficient to sustain production where fractures exist).

-- Investigate new production schemes including a reinvestigation of water imbibition and soaking by other reagents. Since the argillaceous content of the siltstone is presumed to be responsible for the low permeability, soaking by reagents specifically designed to reduce such impairment and the use of carbon dioxide flooding and cyclic application in producing wells should be investigated.

III. Field Based Activities

-- Field definition studies starting in 1977.

-- Pilot technical operations of stimulation or flooding schemes shown to be favorable from the Basic and Applied Research activities above, starting in 1978.

IV. Dissemination of Information

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | 1/ |
| B. RESERVOIR DATA BASE | 1 | 1 | | | | 2 |
| C. RECOVERY MODELS | | 1 | | | | 1 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | 1 | | | 1 | | 2 |
| E. PROCESS/FIELD TEST EVALUATION | | | 1 | | | 1 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 2 | 2 | 2 | 2 | 2 | 10 |
| B. FLOW STUDIES | | 6 | 6 | 6 | 4 | 22 |
| C. FIELD LIAISON & ENG. STUDIES | 2 | 2 | 3 | 3 | 4 | 14 |
| D. LAB EQUIPMENT & FACILITIES | | * | * | * | * | * |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | * | | | | | * |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | 2 → | → | → | → | 2 |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |

* ACTIVITY INVOLVES COSTS HAVING NO CONSISTENT PHYSICAL UNIT OF MEASURE.

1/ RELIES ON RESIDUAL MEASUREMENT PROGRAM, ST-4.

2/ INCLUDED IN ABOVE FIGURES.

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL * 1/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | 2/ |
| B. RESERVOIR DATA BASE | 60 | 60 | | | | 120 |
| C. RECOVERY MODELS | | 60 | | | | 60 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | 60 | | | 60 | | 120 |
| E. PROCESS/FIELD TEST EVALUATION | | | 60 | | | 60 |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | 120 | 120 | 120 | 120 | 120 | 600 |
| B. FLOW STUDIES | | 360 | 360 | 360 | 240 | 1320 |
| C. FIELD LIAISON & ENG. STUDIES | 120 | 120 | 180 | 180 | 240 | 840 |
| D. LAB EQUIPMENT & FACILITIES | | 300 | 250 | 250 | 100 | 900 |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 500 | | | | | 500 |
| B. MINI-TESTS | | | | | | - |
| C. TECHNICAL PILOTS | | 1000 | 1000 | 3000 | 2000 | 7000 |
| D. ECONOMIC PILOTS | | | | | | - |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | - | | 3/ |
| TOTAL | 860 | 2020 | 1970 | 3970 | 2700 | 11520 |
| ERDA SHARE | 860 | 2020 | 1970 | 3970 | 2700 | 11520 |

1/ POST 1981 COMMITMENT $2,000,000 IN 1982
2/ RELIES ON RESIDUAL MEASUREMENT PROGRAM ST-4
3/ COSTS INCLUDED ABOVE

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 9555 | 10917 |
| ERDA'S SHARE | DO | DO |

7. EXPECTATION OF SUCCESS: 10%

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 300-400 | 30-40 | 3-4 |
| DAILY PRODUCTION IN: | | | |
| 1985 | | | |
| 1990 | | | |
| 1995 | | | |
| CUMULATIVE PRODUCTION BY: | (REQUIRES FURTHER STUDY BEFORE RELIABLE ESTIMATES OF INCREMENTAL EOR PRODUCTION CAN BE MADE.) | | |
| 1985 | | | |
| 1990 | | | |
| 1995 | | | |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

SPECIAL TARGET F-3: TIME WINDOW RESERVOIRS (GULF COAST OFFSHORE EARLY ABANDONMENT)

R&D STRATEGY ST-3: TO ASCERTAIN IF SIGNIFICANT OFFSHORE ABANDONMENTS WILL OCCUR WITHIN A FIVE YEAR PERIOD, ASCERTAIN PREFERRED RECOVERY SCHEMES, AND ACCELERATE APPROPRIATE TARGET ACTIVITY, ACCORDINGLY

1. CENTRAL PROBLEM

Because of the high operating costs and environmental problems of operating offshore, the economic limit of individual wells (and platforms) may be reached earlier than corresponding wells onshore. Also, because of the nature of the reservoirs, oil production drops in a precipitous fashion from many locations following the breakthrough of water. Once offshore wells are abandoned, the cost of reactivating a platform is so excessive that it could not be contemplated for a subsequently developed enhanced recovery process.

It is not clear at this time what the appropriate schemes are for enhancing recovery in these reservoirs under the Gulf. Because of the relatively high recovery that has been experienced, it is necessary, more so than in other producing provinces, to reach a high degree of understanding of where the residual oil is in these reservoirs and what are the factors that limit recovery. It may well be asked if success in restricting influx of water into the well bore would not only eliminate operating problems but permit still higher recovery without any tertiary scheme being called for. An inquiry must also be made as to whether vertical conformance is the weak link in achieving higher recovery efficiency. If so, then more sophisticated recompletion and interval-exclusion techniques could well be the route to enhanced recovery. If horizontal or areal conformance prove to be a limiting factor on

recovery then an inquiry must be made as to the value (cost benefit) of infill drilling. These matters require answers in the case of the South Louisiana reservoirs because of the superficially very high recoveries that are reported for these reservoirs.

Should it prove to be the microscopic displacement that is the limiting factor, then a tertiary scheme, in the sense usually used, will be required. At this time it would have to be said that carbon dioxide flooding or surfactant flooding are the only two schemes that have promise.

2. R&D GOALS

- To assess the anticipated rate of abandonment of offshore wells in the coming two five-year periods using the best estimates of production rates and prices available.
- To ascertain the most technically and economically feasible recovery process for this group of reservoirs.

3. R&D ACTIVITIES

I. Extend the Knowledge Base

-- Conduct economic studies of offshore operations.

-- Assess rate of offshore abandonment.

II. Basic and Applied Research

-- Test suitable recovery processes.

III. Field Based Activities

-- Reservoir definition.

-- (If the magnitude of abandonments is significant, accelerate the introduction of enhanced recovery operations.)

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 1/ | 1980 1/ | 1981 1/ | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | | | | | | 2/ |
| B. RESERVOIR DATA BASE | 1 | 1 | | | | 2 |
| C. RECOVERY MODELS | 1 | 1 | | | | 2 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | 1.5 | 1.5 | | | | 3 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | – |
| B. FLOW STUDIES | | | | | | – |
| C. FIELD LIAISON & ENG. STUDIES | 3.5 | 3.5 | | | | 7 |
| D. LAB EQUIPMENT & FACILITIES * | | | | | | – |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 4 | 4 | | | | 8 3/ |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): 4/ | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 4/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 4/ |

1/ POST 1978 : DEPENDENT ON FINDINGS FROM ACTIVITIES CONDUCTED IN 1977 AND 1978.
2/ RELIES ON RESIDUAL MEASUREMENT PROGRAM ST-4.
3/ CORE HOLES.
4/ INCLUDED IN ABOVE FIGURES.

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 1/ | 1980 1/ | 1981 1/ | 5-YR TOTAL 1/ |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | | | | | | 2/ |
| B. RESERVOIR DATA BASE | 60 | 60 | | | | 120 |
| C. RECOVERY MODELS | 60 | 60 | | | | 120 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | 90 | 90 | | | | 180 |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | - |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | - |
| B. FLOW STUDIES | | | | | | - |
| C. FIELD LIAISON & ENG. STUDIES | 210 | 210 | | | | 420 |
| D. LAB EQUIPMENT & FACILITIES | | | | | | - |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 1000 | 1000 | | | | 2000 |
| B. MINI-TESTS | | | | | | - |
| C. TECHNICAL PILOTS | | | | | | - |
| D. ECONOMIC PILOTS | | | | | | - |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 3/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 3/ |
| TOTAL | 1420 | 1420 | | | | 2840 |
| ERDA SHARE | 1420 | 1420 | | | | 2840 |

1/ POST 1978: DEPENDENT ON FINDINGS FROM ACTIVITIES CONDUCTED IN 1977 AND 1978

2/ RELIES ON RESIDUAL MEASUREMENT PROGRAM - PROGRAM ST-4

3/ COSTS INCLUDED ABOVE

PGM: ST-3

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 2735 | 2735 |
| ERDA'S SHARE | DO | DO |

7. EXPECTATION OF SUCCESS: 30%

8. OUTCOMES OF THE R&D PROGRAM:

| | POTENTIAL PRODUCTION 1/ | EXPECTED PRODUCTION 2/ | COST-EFFECTIVENESS INDEX 3/ |
|---|---|---|---|
| ULTIMATE RECOVERY | 600-700 | 180-210 | 66-77 |
| DAILY PRODUCTION IN : | | | |
| 1985 | | | |
| 1990 | | | |
| 1995 | | | |
| CUMULATIVE PRODUCTION BY: | (REQUIRES FURTHER STUDY BEFORE RELIABLE ESTIMATES OF INCREMENTAL EOR PRODUCTION CAN BE MADE.) | | |
| 1985 | | | |
| 1990 | | | |
| 1995 | | | |

NOTES:

1/ UNITS: ULTIMATE RECOVERY -- MILLIONS OF BARRELS; DAILY PRODUCTION -- THOUSANDS OF BARRELS PER DAY; CUMULATIVE PRODUCTION -- MILLIONS OF BARRELS

2/ EXPECTATION OF SUCCESS TIMES VALUES IN POTENTIAL PRODUCTION COLUMN

3/ UNITS: ULTIMATE RECOVERY AND CUMULATIVE PRODUCTION -- EXPECTED BARRELS PER PRESENT VALUE DOLLAR OF ERDA'S COST; FIGURES IN DAILY PRODUCTION ROWS ANNUALIZED, THEREFORE UNITS ARE EXPECTED BARRELS PER YEAR PER PRESENT VALUE DOLLAR OF ERDA'S COST

## SPECIAL TARGET F-4: ALL POTENTIAL EOR RESERVOIRS

## R&D STRATEGY ST-4: MEASUREMENT AND DEFINITION OF RESIDUAL OIL SATURATION AND ITS DISTRIBUTION

### 1. CENTRAL PROBLEM

The exact amount of the residual oil saturation and its distribution determine the accessibility of the residual oil to injected fluids. This has been recognized as a significant factor in determining the potential and the economic success of any proposed enhanced oil recovery scheme.

Moreover, this study, and others, have argued that the residual saturation may also be a critical parameter in determining the technological success of such processes. It appears that this might be a general observation for all the proposed processes except, perhaps, steam drive.

Because of the problems involved in averaging reservoir parameters which are measured at isolated locations of drilled wells, and the fact that parameter measuring techniques have shown much improvement in recent years, older measurements and estimates of the original oil-in-place are now being seriously questioned. Estimates of residual saturation that rely on estimates of original oil and of reservoir parameters that were measured by older techniques are proving inadequate for the more advanced, reservoir sensitive tertiary recovery operations.

### 2. R&D GOALS

- To establish the true potential for enhanced recovery operations by accurate determinations or calculations of the residual oil in major target reservoirs.

- The eventual R&D goal would be to ensure that future research expenditures are judiciously made on the proper target, and that the industry has sufficient confidence in the levels and distributions of the residual oil to assume the commercial application of technically proven processes, such as are being contemplated for Targets A-2, A-4, B-1, C-2, C-3, C-4 and D-2, D-3 and D-4.

3. R&D ACTIVITIES

- Plan and implement a regional program of residual saturation measurement using field operators in the major reservoirs.

- Test reservoir simulation techniques to determine their usefulness in supplementing and in part substituting for field determination of residual saturation.

- Seek correlations between newly measured and/or calculated values of residual determinations with those resulting from volumetric and material balances using prior estimates/reservoir parameters.

4. R&D ACTIVITIES -- PHYSICAL UNITS

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YEAR TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG/ECON. UNCERTAINTY (PERSON-YEARS): | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEASUREMENT TECHNIQUES | 8.3 | 3.3 | 1.7 | 1.7 | | 15 |
| B. RESERVOIR DATA BASE | | | | | | – |
| C. RECOVERY MODELS | 3 | 7 | 7 | 10 | 3 | 30 |
| D. ECONOMIC & OTHER FEASIBILITY STUDIES | | | | | | – |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | – |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES (PERSON YEARS): | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | – |
| B. FLOW STUDIES | | | | | | – |
| C. FIELD LIAISON & ENG. STUDIES | 8.3 | 3.3 | 1.7 | 1.7 | | 15 |
| D. LAB EQUIPMENT & FACILITIES | | | | | | – |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS (PROJECTS): | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 1/ | 1/ | 1/ | 1/ | 1/ | 1/ |
| B. MINI-TESTS | | | | | | – |
| C. TECHNICAL PILOTS | | | | | | – |
| D. ECONOMIC PILOTS | | | | | | – |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY (PERSON-YEARS): | | | | | | |
| A. PROVIDE TECHN. TO INDEPENDENTS | | | | | | 2/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 2/ |

1/ NUMBER OF CORE HOLES, ETC., TO BE DETERMINED AFTER FIRST YEAR.

2/ INCLUDED IN ABOVE FIGURES.

PGM: ST-4

5. COSTS OF R&D ACTIVITIES (THOUSANDS OF 1976 DOLLARS):

| ACTIVITY | 1977 | 1978 | 1979 | 1980 | 1981 | 5-YR. TOTAL |
|---|---|---|---|---|---|---|
| I. VERIFY RESOURCE BASE AND REDUCE ENG./ECON. UNCERTAINTY | | | | | | |
| A. RESIDUAL OIL MEASUREMENT & IMPROVED MEAS. TECHNIQUES | 500 | 200 | 100 | 100 | | 900 |
| B. RESERVOIR DATA BASE | | | | | | - |
| C. RECOVERY MODELS | 250 | 500 | 500 | 750 | 250 | 2250 |
| D. ECONOMIC & OTHER FEASIB. STUDIES | | | | | | - |
| E. PROCESS/FIELD TEST EVALUATION | | | | | | - |
| II. CONDUCT NON-FIELD BASED RESEARCH AND RELATED ACTIVITIES | | | | | | |
| A. RECOVERY PROCESS BENCH STUDIES AND THEORY | | | | | | - |
| B. FLOW STUDIES | | | | | | - |
| C. FIELD LIAISON & ENG. STUDIES | 500 | 200 | 100 | 100 | | 900 |
| D. LAB EQUIPMENT & FACILITIES | | | | | | - |
| III. CONDUCT FIELD BASED RESEARCH, TESTS AND DEMONSTRATIONS | | | | | | |
| A. TARGET IDENTIFICATION/FIELD SUPPORT/MATERIALS | 500 | 2100 | 2800 | 2800 | 2000 | 10200 |
| B. MINI-TESTS | | | | | | - |
| C. TECHNICAL PILOTS | | | | | | - |
| D. ECONOMIC PILOTS | | | | | | - |
| IV. TRANSFER & SUSTAIN EOR TECHNOLOGY THROUGHOUT INDUSTRY | | | | | | |
| A. PROVIDE TECHNOLOGY TO INDEPENDTS. | | | | | | 1/ |
| B. SHARE INDUSTRY/ERDA DEVELOP. | | | | | | 1/ |
| TOTAL | 1750 | 3000 | 3500 | 3750 | 2250 | 14250 |
| ERDA SHARE | 1170 | 2000 | 2330 | 2500 | 1500 | 9500 |

1/ COSTS INCLUDED ABOVE

6. PRESENT VALUE OF COSTS (THOUSANDS OF 1976 DOLLARS):

| | 5-YEAR COST | TOTAL PROGRAM |
|---|---|---|
| TOTAL COSTS | 12159 | 12159 |
| ERDA'S SHARE | 8107 | 8107 |

7. EXPECTATION OF SUCCESS: N/A

8. OUTCOMES OF THE R&D PROGRAM: PROGRAM ST-4 IS A NECESSARY PRE-REQUISITE TO ACHIEVING THE BENEFITS OF TARGETS:

- A-2, A-4
- B-1
- C-2, C-3, AND C-4
- D-2, D-3, AND D-4

(THE COST EFFECTIVENESS INDEX IS NOT APPLICABLE)

9. SPECIAL NOTE - COST SHARING: THE MEASUREMENT AND DEFINITION OF RESIDUAL OIL SATURATION AND ITS DISTRIBUTION CALLS FOR ERDA AND INDUSTRY TO EQUALLY SHARE THE COST OF THE FIELD-BASE MEASUREMENT ACTIVITIES, SHOWN IN ITEM 4-III AND 5-III ON THE PREVIOUS PAGES. IT IS ASSUMED THAT ERDA WOULD BEAR THE FULL COST OF THE NON-FIELD BASED R&D ACTIVITIES. THIS COST SHARING IS REFLECTED IN THE PROGRAM COSTS SHOWN IN ITEM 6 ABOVE.

Price/Tax Sensitivities for Special Target Reservoirs

Due to the limited data available on the reservoirs included as special targets, detailed examination of the effects on production of changes in prices and taxes was infeasible. It was felt, however, that substantial price increases (up to the alternate fuel price) could provide greater flexibility to the range of possible novel solutions and would increase the expectation that the potential ultimate recovery would be actualized. For Spraberry Trend this resulted in making an upward adjustment in the expectation of success from 12 to 18 percent; and for the offshore reservoirs, an upward adjustment from 30 to 40 percent. No adjustment was necessary for Elk Hills and Prudhoe Bay because the expectation for these was already high.

Using the mid-points of the estimated ranges, these adjustments had the effect of increasing the expected recovery from Spraberry Trend by 35 million barrels and that from the Gulf offshore by 65 million barrels.