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16. Abstract (Limit: 200 words)
This report describes work performed and results obtained for the technical and economic feasibility study of oil production by mining methods. The characteristics of oil fields which would make them amenable to mining techniques were identified. An inventory of known U.S. oil fields that offer this potential was collated. This was further divided into fields having potential for underground and surface mining systems development. Several candidate fields that fit particular underground and surface mining system types were then selected. Conceptual mining systems were designed for the selected fields. Five underground and four surface methods were chosen. Costs of oil production were estimated for these selections. The impact of oil mining on the environment was also considered.

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Petroleum geology	Circle Ridge	Sunnyside	
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Oil reservoirs	Yates	Santa Cruz	

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FOREWORD

This report was prepared by Golder Associates, Incorporated under USBM Contract Number JO275018. The contract was initiated under the Advancing Oil Shale Mining Technology Program with Mr. Richard Dick acting as the Technical Project Officer. Mrs. Darlene Wilson was the contract administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this contract during the period April 1, 1977 to July 31, 1978. This report was submitted by the authors in December 1978. This report contains no patentable information.

TABLE OF CONTENTS

		Page
REPORT DOCUMENTATION PAGE		1
FOREWORD		3
TABLE OF CONTENTS		5
LIST OF TABLES		11
LIST OF FIGURES		13
EXECUTIVE SUMMARY		17
1.0 INTRODUCTION		39
2.0 HISTORICAL REVIEW		47
2.1 PAST OPERATIONS		49
2.1.1	Pechelbronn	49
2.1.2	Wietze	50
2.1.3	Heide Meldorf	52
2.1.4	Franklin Oil	53
2.1.5	Higashiyama	53
2.2 EXISTING AND PLANNED OPERATIONS		55
2.2.1	Tar Sands	55
2.2.2	Yarega	56
2.2.3	Conoco	58
2.2.4	Getty Oil	58
REFERENCES		59
3.0 DISCUSSION OF THE RESOURCE AND SELECTION OF METHODS AND FIELDS FOR STUDY		61
3.1 POTENTIAL RESOURCES		63
3.1.1	Depleted Fields	63
3.1.2	Diatomites and Shales	67
3.1.3	Asphalt and Bitumen Deposits	70
3.1.4	Summary	71
3.2 SUMMARY OF TECHNICAL REASONS FOR INCOMPLETE CONVENTIONAL PRODUCTION		71
3.2.1	Variations in Permeability	72
3.2.2	Variations in Viscosity	73
3.2.3	Variations in Head Gradient	74
3.2.4	Summary	74
3.3 PRELIMINARY FIELD SELECTION CRITERIA		74

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Table of Contents continued

		Page
3.4	AVAILABLE DATA BASE	77
3.4.1	Mechanical Properties and Related Detailed Structural Geological Data	79
3.4.2	Hydrological Data	82
3.4.3	Geometry and Geology of Oil-Bearing Zones	82
3.5	CANDIDATE UNDERGROUND MINING SYSTEM	84
3.5.1	Extraction Methods	86
3.5.2	Fracturing and Drainage Methods	91
3.5.3	Drainage Methods	93
3.6	OPEN PIT MINING SYSTEMS	95
3.6.1	Overburden Removal	96
3.6.2	Ore Mining	100
3.6.3	Basis for Method and Field Selection	101
	REFERENCES	105
4.0	DISCUSSION OF PROCESSING AND ENVIRONMENTAL FACTORS	107
4.1	PROCESSING	109
4.1.1	Problem Definition and Background	109
4.1.2	Oil Recovery Methods	110
4.1.3	Description of the Various Recovery Methods	111
4.1.4	Necessity for Testing and Pilot Plant Operation	116
4.2	ENVIRONMENTAL FACTORS	117
4.2.1	Environmental Regulations	117
4.2.2	Impacts Associated with Mining and Waste Disposal	118
4.2.3	Impacts Associated with Processing	119
4.2.4	Impacts Associated with Community Support Facilities	119
5.0	UNDERGROUND MINING SYSTEMS	121
5.1	DIRECT STOPING METHODS	123
5.1.1	General Description	123
5.1.2	Geological Description	126
5.1.3	Mine Design and Scheduling	130

TABLE OF CONTENTS continued

		Page
DIRECT STOPING METHODS continued		
5.1.4	Processing	136
5.1.5	Safety	136
5.1.6	Environmental Factors	139
5.1.7	Technical Feasibility	139
5.2	BLOCK CAVING	140
5.2.1	General Description	140
5.2.2	Geological Description	143
5.2.3	Mine Design and Scheduling	146
5.2.4	Processing	149
5.2.5	Safety	149
5.2.6	Environmental	151
5.2.7	Technical Feasibility	152
5.3	SHATTER AND DRAIN METHOD	153
5.3.1	General Description	153
5.3.2	Geological Description	156
5.3.3	Mine Design and Scheduling	159
5.3.4	Processing	163
5.3.5	Safety	163
5.3.6	Environmental Factors	164
5.3.7	Technical Feasibility	164
5.4	DRAINAGE WITH STEAM	166
5.4.1	General Description	166
5.4.2	Geological Description	168
5.4.3	Mine Design and Scheduling	172
5.4.4	Processing	180
5.4.5	Safety	180
5.4.6	Environmental Factors	181
5.4.7	Technical Feasibility	181
5.5	GRAVITY DRAINAGE	182
5.5.1	General Description	182
5.5.2	Geological Description	183
5.5.3	Mine Design and Scheduling	188
5.5.4	Processing	194
5.5.5	Safety	194
5.5.6	Environmental Factors	194
5.5.7	Techical Feasibility	195
REFERENCES		196

TABLE OF CONTENTS continued

		Page
6.0	SURFACE MINING SYSTEMS	199
6.1	MODIFIED TERRACE PIT MINING	201
6.1.1	General Description	201
6.1.2	Geological Description	206
6.1.3	Mine Design and Scheduling	208
6.1.4	Processing	210
6.1.5	Safety	211
6.1.6	Environmental Considerations	211
6.1.7	Technical Feasibility	211
6.2	TERRACE MINING WITH BUCKET WHEEL EXCAVATORS	212
6.2.1	General Description	212
6.2.2	Geological Description	216
6.2.3	Development History	218
6.2.4	Mine Design	219
6.2.5	Processing	223
6.2.6	Safety	223
6.2.7	Environmental Considerations	223
6.2.8	Technical Feasibility	224
6.3	STRIP MINING	224
6.3.1	General Description	224
6.3.2	Geological Description	225
6.3.3	Reserves	230
6.3.4	Mine Design and Scheduling	230
6.3.5	Processing	231
6.3.6	Safety	233
6.3.7	Environmental Considerations	233
6.3.8	Technical Feasibility	233
6.4	OPEN PIT MINING	234
6.4.1	General Description	234
6.4.2	Geological Description	239
6.4.3	Mine Planning and Scheduling	241
6.4.4	Processing	242
6.4.5	Safety	243
6.4.6	Environmental Considerations	243
6.4.7	Technical Feasibility	243
	REFERENCES	244

TABLE OF CONTENTS continued

		Page
7.0	ECONOMIC EVALUATIONS	246
7.1	SYNTHESIS OF COSTS	248
7.1.1	Capital Costs	249
7.1.2	Operating Costs - Underground Mines	251
7.1.3	Operating Costs - Surface Mines	253
7.2	ESTIMATED COSTS	255
7.2.1	Direct Stoping Methods	255
7.2.2	Block Caving	258
7.2.3	Shatter and Drain Method	260
7.2.4	Drainage with Steam	263
7.2.5	Gravity Drainage Operation	266
7.2.6	Modified Terrace Pit Mining	269
7.2.7	Terrace Mining with Bucket Wheel Excavators	272
7.2.8	Strip Mining	276
7.2.9	Open Pit Mining	279
7.3	COST OF CONVENTIONAL OIL PRODUCTION	281
7.4	DISCUSSION OF ECONOMIC FEASIBILITY	287
	REFERENCES	294
8.0	DISCUSSION OF RESULTS	295
8.1	GENERAL CONCLUSIONS	297
8.2	RECOMMENDATIONS FOR FURTHER STUDIES	300
8.2.1	Factors Relevant to All Types of Operation	300
8.2.2	Factors Relevant to Potential Surface Mining Operations	303
8.2.3	Factors Relevant to Potential Underground Operations	305
	REFERENCES	307
	APPENDIX A	309

LIST OF TABLES

Table Number	
3-1	OIL LEFT IN PLACE AT END OF CONVENTIONAL PETROLEUM PRODUCTION AND PERCENT OF ORIGINAL RESOURCE THAT WILL REMAIN BY RESERVOIR LITHOLOGY
3-2	STATES AND OTHER API REPORTING UNITS LISTED IN ORDER OF THE PERCENTAGE OF OIL REMAINING IN RESERVOIRS AT THE END OF NORMAL PETROLEUM PRODUCTION
3-3	DISTRIBUTION OF ESTIMATED UNRECOVERABLE U.S. OIL RESOURCES ARRANGED BY GEOLOGIC AGE OF THE RESERVOIR ROCK
3-4	SHORTLIST OF CANDIDATE DEPOSITS
3-5	STANDARD OF AVAILABLE DATA
3-6	CANDIDATE FIELDS AND SELECTED MINING SYSTEM
5-1	CIRCLE RIDGE FIELD
5-2	CASMALIA FIELD
5-3	YATES FIELD
5-4	IRMA FIELD
5-5	COMPARISON OF REPORTED AND ASSUMED PARAMETERS FOR YAREGA AND IRMA FIELDS
5-6	WHEELER RIDGE FIELD
6-1	SUNNYSIDE FIELD
6-2	DETAILS OF PIT EXPANSIONS - SUNNYSIDE, UTAH
6-3	KERN RIVER FIELD
6-4	EDNA FIELD
6-5	SANTA CRUZ FIELD
7-1	CUT AND FILL AND RIB AND ROOM MINING CIRCLE RIDGE, WYOMING
7-2	BLOCK CAVING - CASMALIA, CALIFORNIA
7-3	SHATTER AND DRAIN - YATES, TEXAS

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LIST OF TABLES continued

7-4	UNDERGROUND STEAM STIMULATION - IRMA, ARKANSAS
7-5	DRILL AND DRAIN - WHEELER RIDGE, CALIFORNIA
7-6	MODIFIED TERRACE PIT - SUNNYSIDE, UTAH
7-7	TERRACE PIT - KERN RIVER, CALIFORNIA
7-8	STRIP MINING - SANTA CRUZ, CALIFORNIA
7-9	OPEN PIT - EDNA, CALIFORNIA
7-10	EXPLORATION, DEVELOPMENT AND LIFTING COSTS (1971-1975) - CONVENTIONAL PRODUCTION

LIST OF FIGURES

Figure Number	
3-1	DISTRIBUTION OF ESTIMATED OIL RESOURCE REMAINING AFTER FULL CONVENTIONAL PRODUCTIONS
4-1	SIMPLIFIED FLOW SHEETS FOR USBM AND GCOS OIL EXTRACTION SYSTEM
5-1	LOCATION MAP CIRCLE RIDGE OIL FIELD, WYOMING
5-2	PLAN AND GEOLOGIC SECTION CIRCLE RIDGE, WYOMING
5-3	ROOM AND RIB MINING - WITHOUT BACKFILL CIRCLE RIDGE - PHOSPHORIA
5-4	STOPING IN TENSLEEP SANDSTONES CIRCLE RIDGE MINE
5-5	LOCATION MAP CASMALIA OIL FIELD, CALIFORNIA
5-6	PLAN AND GEOLOGIC SECTION CASMALIA FIELD, CALIFORNIA
5-7	BLOCK CAVING CASMALIA FIELD, CALIFORNIA
5-8	LOCATION MAP YATES OIL FIELD, TEXAS
5-9	GEOLOGIC SECTION YATES, TEXAS
5-10	SHATTER AND DRAIN METHOD
5-11	LOCATION MAP IRMA OIL FIELD, ARKANSAS
5-12	PLAN AND GEOLOGIC SECTION IRMA OIL FIELD, ARKANSAS
5-13	DRAINAGE WITH STEAM STIMULATION IRMA FIELD

LIST OF FIGURES continued

5-14 DRAINAGE WITH STEAM STIMULATION
IRMA FIELD

5-15 LOCATION MAP
WHEELER RIDGE OIL FIELD, CALIFORNIA

5-16 PLAN AND GEOLOGIC SECTION
WHEELER RIDGE, CALIFORNIA

5-17 GRAVITY DRAINAGE
WHEELER RIDGE FIELD, CALIFORNIA

5-18 OIL PRODUCTION VS TIME IN SINGLE BOREHOLE
AT 50% RECOVERY

6-1 LOCATION MAP
SUNNYSIDE BITUMEN DEPOSIT, UTAH

6-2 AVERAGE OVERBURDEN THICKNESS AND GEOLOGICAL
SECTION - SUNNYSIDE, UTAH

6-3 MODIFIED TERRACE PIT - SUNNYSIDE, UTAH
PIT PLAN AND SECTION

6-4 TERRACE PIT - KERN RIVER, CALIFORNA
PIT PLAN AND MINING AND BACKFILLING SYSTEM

6-5 LOCATION MAP
KERN RIVER OIL FIELD, CALIFORNIA

6-6 PLAN AND GEOLOGIC SECTION
KERN RIVER OIL FIELD, CALIFORNIA

6-7 TERRACE PIT MINING SYSTEM
KERN RIVER, CALIFORNIA

6-8 STRIP MINING - SANTA CRUZ, CALIFORNIA
MINE PLAN

6-9 LOCATION MAP
SANTA CRUZ BITUMEN DEPOSIT, CALIFORNIA

6-10 PLAN AND GEOLOGIC SECTION
SANTA CRUZ BITUMEN DEPOSIT, CALIFORNIA

6-11 STRIP MINING - SANTA CRUZ, CALIFORNIA
MINING SYSTEM

LIST OF FIGURES continued

6-12 OPEN PIT - PLAN AND SECTION OF MINE
EDNA, CALIFORNIA

6-13 LOCATION MAP
EDNA BITUMEN DEPOSIT, CALIFORNIA

6-14 PLAN AND GEOLOGIC SECTION
EDNA, CALIFORNIA

7-1 EXPLORATION, DEVELOPMENT AND LIFTING COSTS
CONVENTIONAL PRODUCTION TECHNIQUES

7-2 POTENTIAL U.S. CRUDE OIL PRODUCTION RATE
FROM KNOWN FIELDS

7-3 EXPECTED COST RANGES - ALL SYSTEMS

7-4 SENSITIVITY OF DIRECT MINING METHODS
TO GRADE OF ORE (Bbl/Ton)

7-5 SENSITIVITY OF UNDERGROUND DRAINAGE METHODS
TO GRADE (Bbl/Ton) AND YIELD

A-1 EFFECT ON FLOW RATE, Q, DUE TO DECREASES IN HEAD
AT THE BOREHOLE, hw

A-2 RELATIONSHIP BETWEEN GRAVITY AND ABSOLUTE
VISCOSITY FOR VARYING TEMPERATURES

A-3 OIL PRODUCTION VS TIME FOR VARYING RECOVERIES

EXECUTIVE SUMMARY

It is a generally accepted and widely discussed fact that the world in general, and the United States in particular, are facing a shortage of energy at some time in the future. There is, however, no similar concurrence as to the actions which would prevent or overcome this expected shortage even though an immense variety of solutions has been put forward, ranging from the purely political to the outer fringes of sophisticated technology.

One fundamental resource which is often only cursorily discussed in this context is the immense known petroleum reserve lying within the United States. When this subject is discussed, it is usually in the context of the improvements in production or new discovery rate that could be expected to result from possible politico-economic actions that would raise the real price obtained for domestic crude. This interest in the potential for improved domestic production is undoubtedly justified, but very little attention is normally drawn to the fact that the majority of the oil that has been, or will be, discovered will remain in the ground due to the inherent limitations of production through surface wells. Among the possible ways of recovering a portion of this resource are several alternatives involving mining methods.

Mining techniques have been employed for oil production in several countries, over many centuries. In view of the success

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that was being achieved during the 1930's in Europe, a thorough review of those operations was conducted and resulted in the publication in 1932 of U.S. Bureau of Mines Bulletin 351. This document concluded that, under favorable conditions, additional oil might be profitably produced by mining methods. This present report results from a study whose prime purpose is to reassess the conclusions set out in Bulletin 351 in the light of any changes in technology or circumstances since its publication.

In the early stage of the study the characteristics of oil fields which could make them amenable to mining techniques were identified, together with the mining methods which seemed most likely to be successful. A choice was then made of the methods best suited for study and the specific fields on which they should be based. Mines were then designed for the selected fields and were subjected to evaluation of their technical and economic feasibility. By following, as far as possible, the discipline of working with specific methods designed for the geology of specific fields, an attempt was made to ensure that all of the major problems would be encountered and the methods with real potential would be identified.

The study was performed for the most part by members of the staff of Golder Associates whose background and experience is principally in conventional mining. This structure was deliberately retained to ensure that, to the greatest extent possible, the prospects were evaluated by normal mining standards. Invaluable assistance was given by outside consultants, however, particularly in the fields of petroleum geology and engineering.

HISTORY OF OIL MINING

Production of oil employing mining techniques has been carried out for centuries. The number of operations undertaken in modern times is, however, very small and it is almost always possible to identify some special circumstance which led to the project being undertaken. These have included:

- The need for strategic oil supplies during wartime, at almost any cost. This was the case in Germany and Japan during World War II.
- The need for domestic production in oil-poor nations during favorable economic times. The European operations during the 1920's and 1930's, when economies were depressed and labor was cheap, were examples of this.
- The particular circumstance of a directed economy, such as exists in the USSR.
- The requirement for special grades of oil, which stimulated an attempt at underground production in Pennsylvania.

In more recent times, marked increases in world oil prices, coupled with a perceived shortfall in domestic production in North America, have stimulated interest in oil mining from both governments and private industry. This has resulted in the current and planned operations in the Athabasca Tar Sands of Alberta, Canada, and to the announced interest of several companies in the United States in similar projects.

THE POTENTIAL RESOURCE

While it is common knowledge that the USA is a major oil producer and that not all oil contained in a reservoir will be recovered, very few members of the public are aware of the magnitude of the reserves involved. In fact, the best industry sources estimate that, in the producing or producible fields alone, a total of over 300 billion barrels of oil will remain in the ground on completion of production, some two-thirds of the original quantity.

Even such a large figure is in fact an underestimate of the oil in the ground which is the possible target for oil mining efforts. Numerous other hydrocarbon-impregnated rocks are known to exist which are not included in these figures since they have never been considered feasible for conventional production. Such deposits would typically include oils whose viscosity, or the nature of the host rock, inhibits flow to wells. Extreme examples of this are the diatomaceous deposits whose extent has never been demonstrated, or probably even seriously indicated, and the tar sands and asphaltic deposits lying near surface.

SELECTION OF METHODS AND FIELDS FOR STUDY

The total number of oil fields available for consideration in this study was too large, and the diversity of the levels of available data on their properties so wide that an arbitrary system of initial selection was essential. Using a simple set of mining-oriented criteria including depth below surface, field size and apparent grade, and oil-bearing zone thickness, an initial search was made using a computer data bank. Even this rather specific selection turned up no fewer than 10,000 fields. Many of these fields were, in fact, very minor reserves or were

in some other way easily disqualified and the list was reduced by inspection to a short list of some 50 fields.

At this stage, a more specific knowledge was needed of the mining systems to be evaluated and an inventory was made of potential methods, both underground and surface. Once again the list, including all significant variants, was long and it was reduced to a more manageable number by comparison with generally known oil field properties and by considering the normal economic performance of each method.

The methods which seemed most suitable were then matched against the short list of fields until a set of five underground and four surface options and fields was produced. This total number appeared manageable within the limitations of the project and the selection satisfied the vital criteria in that:

- It covered all of the major basic types of oil mining method.
- All of the methods offered the promise of being as economical as any other candidate in the same general category, thus giving the best chance of economic success.
- Each method was believed to be suited to at least one specific field on which its evaluation could be based.

LIMITATIONS IN DATA AVAILABILITY

Throughout the project, and particularly in the selection procedure and the assembly of mine geology, it became increasingly clear that the level of available data was going to be seriously inadequate. This was true in several areas of fundamental importance to mining engineers, particularly in the

areas of ore reserves estimation and rock quality determination. In both of these areas the requirements of mine design and evaluation are significantly different from those of the petroleum engineer. Even in fields where the most detailed work had been performed and records were freely available (and these are by no means typical circumstances), many poorly informed estimates, judgements and interpretations were necessary to produce the necessary geological basis for the mine designs.

For the purposes of a study of this nature which is essentially preliminary and general, these deficiencies, while disappointing, are not serious and are not believed to invalidate the conclusions that have been reached. They do, however, indicate areas where a substantial effort will be required to establish a sound mining geological understanding of oil field properties before widespread commercial operations can be expected.

PROCESSING

Any oil mining operation which involves the physical extraction of the reservoir rock from the ground will require a processing plant to separate the oil from the host rock and to upgrade it to a marketable quality. This portion of such a project would involve a major proportion of the capital expenditure and, at present, would be based on a level of proven technology which is no better, and in many cases substantially worse, than most features of the proposed mining systems.

Mined oil-bearing rock could be of a wide variety of types and characteristics, and the form of oil contained and the nature of its locking into the rock will directly influence the type of



processing required. The basic systems available, however, fall into these categories:

- Hot water filtration
- Solvent extraction
- Pyrolosis, or retorting and thermal distillation.

In addition, each specific plant will include, to varying degrees, crushing and grinding of the rock, stages to clean the oil product, (particularly of fine clay particles), and any necessary dilution or cracking to produce satisfactory refinery feedstock. Most development work on these processes has been directed at the recovery of heavy oils, resulting in the current operations in the Athabasca tar sands. Active research is also being undertaken by a number of companies into the appropriate processes for a variety of deposit types, including heavy oils in the United States and such potential materials as oil-bearing diatomaceous earths. There is, however, an immense need for further development and demonstration work before the feasibility of prospects requiring major processing can be definitely proven. This will require not only substantial programs of research, but also major and expensive pilot plant operations. It is appropriate to point out here that plant design and operation are at the mercy of the same detailed geological variability that influences the mines themselves. Abrupt variations in the physical properties and oil content of feed material can have a substantial impact on performance, and need to be avoided by feed blending wherever possible or, at the least, be reasonably predicted.

ENVIRONMENTAL FACTORS

The impact that oil mining operations will have on the environment vary widely, both with the different characteristics of the methods, and with the particular natures and sensitivities of specific sites. Some types of impact are to be anticipated from virtually all mines in any location, although in varying degrees of severity.

The mines themselves, with the exception of pure underground drainage methods, can involve major changes in topography, loss of vegetation, diversion, impoundment or pollution of surface and subsurface water flows, and possible problems with dust, noise, and odor. Disposal of solid waste products such as mined waste rock or de-oiled reservoir material, can also pose major difficulties and costs.

The social implications of introducing large scale industrial activity to essentially rural areas can also be immense. Direct work force increase for a major mine is potentially very large, bringing with it the need for service personnel and families, and causing in some cases a substantial population explosion. This in turn requires the provision of the full normal range of support facilities for a modern community, including such features as communications and power supply which themselves generate physical environmental perturbations. A particularly difficult feature of major local employment increases occurs when they are short-lived, and any mining operation with a limited life can generate as many problems in its termination as in the original start-up.

UNDERGROUND MINING OPERATIONS

Five such possible operations were designed and evaluated, two of them involving direct mining, two employing oil drainage, and the fifth using mining techniques to fracture the rock prior to drainage.

Room and Rib Stoping

A mine was designed for a portion of the Circle Ridge field in Wyoming, where two superimposed flat-lying oil-bearing formations are present which appear competent enough for safe operation. The upper one is a phosphatic dolomite with a mineable vertical thickness of some 50 feet. It will be mined by a heading and bench operation using continuous rib pillars to provide maximum positive control of ventilation airflow in the rooms.

The lower zone is a sandstone up to 100 feet thick. It would also be mined in a room and rib configuration. Mining would be from the footwall up, with the excavation being backfilled with de-oiled sand to provide a working platform and aid in mine stability.

One significant feature of both zones is their relatively low expected oil content at 0.18 bbl/ton. It appears likely that such generally lean grades can be expected in reservoirs which are competent enough to permit stoping. To feed a processing plant of large enough size to be economical, the overall mine production would be over 75,000 tons per day at these low grades.

To obtain the productivities that would be required for profitable operation the most mechanized and concentrated



production techniques would be essential and it is considered impossible to design and operate such a mine in such a way as to ensure safety. The underground mine will lie virtually completely within the reservoir zones, with all the attendant problems of potential water, oil and gas inflows. The risk of explosive gas concentrations would always be present and the possibility of spark generation in blasting and other mechanized operations is too real to be acceptable or avoidable at any reasonable level of cost.

The mine was, however, designed and evaluated on assumptions of safety so optimistic as to be nearly unrealistic in an attempt to establish the potential for an attractive operation, but even on that basis cannot be considered feasible.

Although this operation would be an underground mine generating minimal subsidence, the processing plant and surface waste disposal problem would be major and the level of employment created, with all the associated effects, would also be immense.

Block Caving

A wide range of oil fields could be expected to possess the free caving characteristics required for this system. The Casmalia field in California contains oil-bearing formations over a vertical thickness of many hundreds of feet and was selected as the basis for this evaluation.

The undercut and haulage drifts would be located in a relatively competent siltstone band, lying below the oil-bearing zone. The undercut itself would be formed by conventional fan drilling and blasting into the base of the oil-bearing zone. The planned production of ore is 32,000 tons per day.

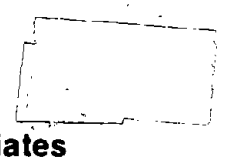
Environmentally this system could be extremely disruptive. The mine will induce massive subsidence over a wide area destroying for a long period, if not permanently, any potential for surface land use. The disruption of surface and subsurface water regimes could be even more serious. In addition, the full range of impacts associated with a major industrial plant and new levels of employment would be experienced.

The technical feasibility of this system is considered very doubtful from a safety point of view. As with the previous method, major routine drilling and blasting will be required to form the undercuts and this will be extremely difficult to perform both safely and economically. Gases must also be expected to be emitted throughout the rock loading and hauling system and it would be extremely difficult if not impossible to ensure safety without prejudicing productive efficiency. The specific Casmalia field also has substantial problems with overlying aquifers which would cause serious water inflow problems as the cave propagates.

Shatter and Drainage

This term describes a method in which a major mining effort is employed to systematically fragment a thick reservoir zone to improve recovery of trapped oil. The method of fragmentation evaluation was based on sublevel caving technology, with the minimum amount of rock, some 24,000 tons daily being drawn as mining proceeds to facilitate effective blasting.

This system would share with the two previously described, all the problems of safe operation within a reservoir. Even when the most optimistic assumptions are made as to the safety of



conventional drilling, blasting, ore handling and ancillary functions, the resultant system appears unattractive. There is therefore little ground for confidence in the possibility of economically working such deposits to standards of safety comparable to gassy coal mines.

This system also has additional technical problems in that a system for producing efficient fragmentation on a large scale without draw of a substantial portion of the rock has yet to be demonstrated in practice. There is also doubt that depleted reservoir rocks exist in significant quantities that would be likely to yield satisfactory flows of oil after such fracturing.

Drainage Methods

Two designs have been developed in which mine workings are employed to provide closely spaced drill stations above or below an oil reservoir. Based on the Irma Field, Arkansas, one of these designs involves drifts located in the reservoir cap rock and employs steam injection to lower the oil viscosity and provide drive. This is very similar to the operation currently underway in the Yarega field, USSR.

The Wheeler Ridge field, California, has an apparently suitable siltstone formation underlying the producing reservoir and as the second of these designs an evaluation was made of the use of this as the location for mine workings. Oil drainage in this case would be by gravity through holes drilled up from the mine.

Neither of these concepts offers particularly difficult mining problems provided that enough geological data can be gathered to enable ground conditions, including gas and oil

inflow potential, to be satisfactorily proved. The ease of doing this appears generically higher in the former case since reservoir cap rocks are by definition impermeable and, by implication, can be expected to be reasonably strong. No such general assumptions can be made about underlying rocks.

The technical feasibility of such methods depends almost entirely on their ability to yield a satisfactory proportion of the oil remaining in the reservoir. There is good reason to believe that a steam drive should prove effective, particularly at the close hole spacing envisaged, but no comparable basis exists for assessing the potential for pure gravity drainage. The close spacing of the holes, however, particularly in areas lying between the widely spaced conventional production wells, offers the potential for additional production.

Since the analytical and practical basis for estimating yield by the three drainage methods is inadequate, an initial assumption was made for planning purposes that they would eventually produce 50 percent of the oil in place at the start of the operation. This is a very optimistic target and the economic evaluation therefore also assessed the implications of lower recoveries and the need to employ steam in the gravity drainage system.

Surface Mining Operations

It became apparent early in the study that a large amount of residual oil lies at depths below surface which are within the range of well-proven surface mining techniques. Considerably more effort was therefore applied to this field of study than originally anticipated.

Four mines were designed and evaluated employing different equipment types and excavation principles. All of the systems are essentially normal in their mining aspects and are not expected to present any unusual problems. The processing technology is far less well established, however, and all of the proposed operations would have substantial environmental impacts.

A modified terrace pit has been designed for the Sunnyside deposit in Utah where up to 350 feet of bituminous sandstone lies under overburden ranging in thickness from 0 to 800 feet. A truck and shovel operation is planned with drilling and blasting being required in all material. An ore production rate of 100,000 tons per day is expected to yield bitumen at a rate of 51,300 bbls per day. Stripping ratios will average 2.55:1 and the operation will last for 28 years.

Terrace mining, employing a bucket wheel excavator, appears to be a suitable method for use in a deposit such as the Kern River field in California. In this field, oil-bearing sands and gravel some 700 feet thick lie under an average of 500 feet of overburden. All of the formations to be mined are poorly consolidated and should be easily handled by bucket wheel excavators feeding belt conveyor systems. Overburden will be dumped within the pit area. At an ore production rate of 130,000 tons per day, 50,000 bbls of oil will be produced daily. Stripping ratio will average 3.86:1 with an indicated mine life of 27 years.

Strip mining is a well established system for extensive deposits lying under shallow overburden cover and the Santa Cruz field in California appeared to be suitable for its evaluation. This deposit lies under an average overburden depth of 50 feet, which would be stripped with a dragline. The ore zone is a

bituminous sandstone averaging 15 feet in thickness and will be mined by truck and shovel methods after drilling and blasting. 4,200 tons of ore would be produced daily, giving an estimated 2,160 bbls of bitumen daily over a life of 12 years.

The final method considered was the traditional open pit configuration and this was considered suited to the Edna deposit in California. The sandstones in this deposit are impregnated with bitumen in an extremely variable way but large thicknesses are known to average over 10 percent bitumen. A pit has been designed to a depth of 350 feet at a stripping ratio of 1:1, with most of the waste occurring as barren or low grade zones included within the deposit. The mine would be a conventional truck and shovel operation producing 50,000 tons of ore daily for an output of 28,000 bbls/day of bitumen.

ECONOMIC EVALUATION

Each of the mining systems described was designed in enough detail to form the basis for the estimation of capital and operating costs.

Capital costs included expenditures for purchase of mine plant and equipment, preproduction mining work, exploration and design, and a processing plant where one is required. With the addition of anticipated capital replacement costs and a contingency allowance, these made up the estimated capital requirements. One major possible front-end cost for which no estimate was included was that of securing ownership of the deposit and/or unitizing a large enough area for efficient operation if that was necessary. There is no doubt that such costs could be very significant but there is no sound basis for making valid generalized estimates for the purpose of this study.

On the one hand, a candidate field might still be conventionally productive in whole or part, and fragmented in ownership. Such a case would require extremely large expenditures both in purchase price and legal costs. On the other hand, many potentially mineable fields are already in the hands of a single owner and would require no such expenditures.

Operating costs were assessed in a conventional manner, with labor and supplies costs being synthesized for each operation element. Included in this category was an estimate of expenditure for the disposal of mine wastes and also for the various actions required to mitigate all types of environmental impacts.

Recognition of the additional revenue required to service loan capital and provide a profit return to equity investors was a more complex problem. A thorough analysis of the DCF/ROI type would have required assumptions on product price and financing structure which could have obscured the true economic potential of the methods themselves. It was decided, therefore, to assess an arbitrary annual cost of 10 percent of the preproduction capital throughout the mine life to allow for these factors and this, together with the operating and amortized capital costs, comprises the total estimated product cost at the plant site.

The results achieved from the base cases studied varied widely, as would be expected, influenced both by the methods themselves and the characteristics of the individual deposits. The three underground methods which involved mining operations in the reservoir rock all showed costs in excess of $30 per bbl, with the direct stoping method at over $60 per bbl. These cases were all handicapped by low ore grades, but even when the results were adjusted to allow for a more favorable but still realistic grade, none appeared likely to fall below $30 per bbl.

The two underground drainage methods, on the other hand, gave better results, although the steam stimulation example was heavily handicapped by the low thickness of the particular oil-bearing zone evaluated. Both methods show potential for production at costs between $10 and $17 per bbl, provided that the projected oil yields can be attained. As would be expected, they are extremely sensitive to any factor which affects oil yield, including particularly the grade of the oil-bearing rock.

The four surface mining systems are projected to produce oil at costs ranging from $21, for modified terrace mining in hard rock, to $12 for a large terrace pit in poorly consolidated materials. These costs are particularly sensitive to ore grade, stripping ratio and ore hardness.

GENERAL CONCLUSIONS

The conclusions drawn in Bulletin 351 regarding underground oil mining operations have stood the test of time extremely well. Production of oil by drainage methods operated from underground workings still shows promise of improving recoveries at profitable cost levels. Direct extraction of oil-bearing rock by underground mining, however, still cannot be contemplated with any confidence, considering both their safety aspects and financial attractiveness.

Surface mining techniques offer low cost extraction of shallow lying fields. Provided that the problems of separation of the hydrocarbons from the host rock and the mitigation of the environmental impacts can be solved, these methods appear capable of making a rapid contribution to the nation's oil supply at prices which are not too far removed from present levels.

Several specific research projects have been identified which would materially advance the likelihood of such prospects being viewed favorably by mining investors. Perhaps the most basic need is in the area of estimation of mineable reserves. The true in-place quantity and distribution of hydrocarbons after conventional depletion has never been established in the detail necessary for mining purposes and similar lack exists in the level of knowledge of physical reservoir rock properties. It is considered essential that a detailed review is made of existing data for one or more typical fields and careful projections made of oil content and rock properties. These should then be checked by a limited program of sophisticated sampling and geotechnical core drilling in an attempt to establish methods for extracting the maximum benefit from existing data. Substantial economies could be achieved by combining the two investigations into a simple program.

The main additional outstanding research requirement affecting surface mining prospects is in the processing plant field and this technology is now being extensively developed by private industry. It seems possible in fact that in all respects enough data already exists for at least one surface mineable field to be subjected to prefeasibility analysis at this time to normal commercial standards. A successful project of that type would provide an invaluable boost to the prospects of oil mining and, at least, would serve to identify in more detail further areas of research.

With regard to the potential for successful underground operations, the key factor to be resolved is the prediction of yield. In-place drainage operations have relatively few problems of safety, environmental disruption etc., and offer the great

virtue of low capital cost. Their economic future, however, depends entirely on their ability to recover substantial proportions of residual oil. Reliable assessment of this potential will require a combination of the most careful and sophisticated reservoir engineering with a good knowledge of mining possibilities and will, undoubtedly require a pilot physical operation at an early stage.

In summary, therefore, the potential remains very real, as it was in 1932, for production of oil by mining methods to become a contributor to the national energy supply. It offers a possibility of recovery of some of the immense resource that lies beyond the reach of existing production technology and appears also to bring into consideration large volumes of hydrocarbons whose existence is either known or suspected but which have never been considered as a producible reserve. The potential seems too great not to be pursued further.

1.0 INTRODUCTION

This report is being produced at a time when public concern over the "energy problem" has become widespread and is the subject of extensive research and daily discussion. The search for solutions has encompassed ideas ranging fron conservation, through expanded use of coal and nuclear energy, to sources such as solar, wind, wave or geothermal, which have yet to be proven at all, at least on a significant commercial scale.

Appropriately enough, a good deal of attention has also been given to the potential for increased production from the domestic oil and gas industry. This debate has usually centered on the effects of tax and price structures and on the willingness of private industry to invest the extra capital resources stated to be necessary to boost domestic production. The arguments are usually couched in terms of the need for additional deep drilling equipment and cite as evidence the decline in recent years of domestic oil "finds." It would perhaps be only slightly inaccurate to characterize this as a plea for more available funds to permit industry to do essentially "more of the same."

Mining is recognized to be of major importance to the energy industry as the source of coal and uranium, but the role of innovative mining as an additional energy source is usually only discussed in the context of the putative oil shale industry, a large but so far economically unattractive resource, on which millions of dollars have been lavished.

One vast potential resource is excluded from most traditional lists of possible contributors to the closing of the energy gap. This is the staggering proportion of the nation's known liquid petroleum reserves which are not being, and presumably to a major degree never will be, recovered from their host rocks. This resource has certainly not escaped the notice of many companies and individuals engaged in the energy business but, with very few exceptions, nothing significant has been accomplished in realizing this potential not only in the United States, but in the entire world.

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In 1932 the U.S. Bureau of Mines published Bulletin 351 on the mining of petroleum by underground methods. After detailed investigations of contemporary European practice and consideration of the relevant circumstances in the United States, the author concluded "where conditions are favorable, mining methods in depleted oil fields may bring large financial returns and recover oil that might otherwise be lost."

Little has changed in the four decades that have passed since those words were written. Mining of oil is still not a contributor to the United States' energy supply and shows no sign of becoming so in a significant way. It is the purpose of this study to investigate that situation, survey the history of oil mining wherever possible, and to assess the future potential of the concept.

Two philosophical approaches were available to this problem, each with its advantages and limitations.

- The study could be addressed in general terms to the entire residual petroleum resource of the United States. In this case, any conclusions reached would presumably have well established relevance to the overall national potential for oil recovery by mining. On the other hand, such an approach would of necessity produce an extremely cursory evaluation of each individual potential area. Possibly more seriously, it would not satisfy the critical requirement that the more detailed problem areas which could hinder the realization of such technology should be encountered and resolved, or that at least the severity of such problem areas be properly assessed.

- Alternatively, the study could be confined to the evaluation of a set of specific fields. This approach would presumably permit the chosen potential operations to be evaluated to a higher standard of engineering, but would also run the risk of losing relevance to the overall national scene.

The methodology finally selected attempted to combine the better features of these extreme choices while avoiding their more serious weaknesses. In order to preserve a minimum level of engineering integrity in the evaluations, it was considered essential to work in terms of specific oil fields. Only in this way could any meaningful judgement be reached on many of the problems facing an oil mining operation. Having accepted this argument, the problem was one of ensuring the general significance of the results to be obtained. The selection of the fields for study therefore, became a vitally important activity and con-

siderable time was in fact spent on it in the early part of this study, as is described in Section 3 of this report. The fields had, of necessity, to be limited to a reasonable number, but the selection had to cover both the range of field types existing and the variety of potential mining systems deserving consideration.

The process was, perhaps inevitably, not as accurate in its results as could have been desired. This only became evident when the fields selected were subjected to the ultimate test of mine design, a process which revealed weaknesses both in the field selections and in the levels of available data.

The essential result of this study, however, is an assessment of the attractiveness of the techniques that were studied, rather than of the specific fields. It would have been too much to expect that such a brief search would identify an ideal field that is now ripe for mining. In fact, many of the fields used as geological models are still in profitable conventional production and will be for some years. It is therefore extremely unlikely that the owners will either switch to production by mining, however attractive it appears, or that such fields could be purchased by a potential mine operator at reasonable cost.

This report therefore draws conclusions on the merits of a broad selection of mining schemes, based on designs which were in turn based on specificly named oil fields. It also examines, as a final step, the potential for the existence in the United States in major quantity, of the geological circumstances that have been shown to be favorable.

Since this project concerns potential mining operations, it has been performed for the most part by personnel whose training and experience comes from the mining rather than the petroleum industry. Experienced petroleum geologists and engineers have made invaluable contributions to the study as external consultants but a conscious effort has been made throughout to ensure that the problem is looked at through "mining eyes." This approach has resulted in the use in this report of terminology and concepts which will appear foreign to oil men, such as the familiar mining term "grade" to indicate the valuable mineral content of a mass of rock.

Any report such as this is also directed at a variety of readers, many with advanced knowledge of much of the subject matter. Such readers will have to excuse the inclusion of some rather elementary and maybe grossly oversimplified treatment of complex technical areas whose inclusion is necessary to present an overall picture to an interested but less knowledgeable

person. Considerations of length have also necessitated the omission of much detail from descriptions of mining operations and other such technical areas.

Very nearly all work on this project was performed in the offices of Golder Associates in Kirkland (Seattle), Washington. The Project Director was Anthony Edey, assisted by Bruce Kennedy in the fields of open pit mining and costing, and Leigh Readdy, in charge of geology. Other staff members who made major contributions were Peter Bowen, Allen Graber and William Brown (mining), Gary Peniston, Marie Schauer and Rose Mary Silling (geology), and Jerry Rowe (fluid flow).

Valuable contributions were also made by external consultants in several areas. The assistance given by the following is gratefully acknowledged:

Petroleum Geology

P. F. Sollars - formerly private consultant, now with Aminoil USA, Inc., Houston, Texas.
C. Hoke - private consultant of Eldorado, Arkansas.

Petroleum Engineering

Tom Calhoun and Tom Brinkley of Calhoun Engineering, Inc., Dallas, Texas.

Processing

Earl Herkenhoff - formerly private consultant, now with Phillips Uranium Corp., Albuquerque, New Mexico.

Environmental Engineering

Errol Nelson - Wilsey & Ham, Tukwila, Washington.

Ventilation and Safety Engineering

Dr. Chris Hall - University of Idaho

Mining Engineering

John Cook and Terence Friese-Greene - RTZ Consultants Ltd., London, England

Collection of data on fields in California was made considerably easier by the cooperation extended by Fred Hallmark and Paul Land of the California Division of Oil and Gas in Bakersfield, California. Information on Utah fields was kindly

provided by Mr. Jock Campbell of the Utah Geological Survey. Valuable assistance in assessing the technology employed in the Yarega Oil Field, USSR, was received from the staff of The Resource Sciences Corporation, Tulsa, Oklahoma.

Finally, no document of this size is produced without great efforts on the part of secretarial, drafting and other support personnel, whose contribution is gratefully acknowledged.

The staff of the U.S. Bureau of Mines concerned with this project have been unfailingly helpful, and particular mention must be made in this report of the Technical Project Officer, Mr. Richard Dick, and the Contracts Specialist, Ms. Darlene Wilson.

Golder Associates

2.0 HISTORICAL REVIEW

The mining of rock outcrops for their oil content is recorded from antiquity, and was a feature of numerous local economies prior to the Industrial Revolution. The discovery of oil in circumstances where it was producible from wells in large quantity and at low cost, however, tended to overshadow such ventures and often destroy their economic reason for existence. Since that era, relatively few oil mining ventures have been undertaken and many, if not all, of those have had a special reason for their existence or have been essentially experimental in nature.

It is appropriate to consider this history briefly as a background to this report to establish the degree of success that has been achieved in the past, and to understand the reasons why such operations have not been more widespread.

2.1 PAST OPERATIONS

The best known historical operations are probably those conducted at Pechelbronn, France and Wietze, Germany in the first half of this century. These were comprehensively described in Bulletin 351.

2.1.1 Pechelbronn

Mining at Pechelbronn, in the Alsace district of France, was a low productivity operation of small capacity. Recovery by wells was limited due to the highly viscous nature of the oil, but it proved possible to recover additional oil by sinking pits into the oil-bearing sands from underground galleries. Oil mining was supplementary and actually concurrent with well pumping in the district.

Unique geological, political and economic conditions combined to make it economically feasible to mine oil at Pechelbronn. These factors included:

- Geological - The oil was contained in small lenses of fairly rich sands and sandstones with a high percentage of voids due to the coarse size of the sands.

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- Political - The wartime necessity for petroleum with little consideration of the cost of its production.

- Economic - The postwar depression in Europe with attendant availability of low-cost labor ($1.04 per shift of six hours in 1929).

The Pechelbronn field was a fault-type oil trap with oil situated in graben structures within the field. Lenticular units of sands and sandstone, 0.3 to 0.5 meter in thickness, contained the oil (Ref. 1). The beds dip at five to six degrees (Ref. 2). The oil is light, 31.1° API, but oil recovery by conventional pumping methods resulted in only limited recovery. According to de Chambrier (as quoted in Ref. 2), 16.7 percent of the oil in place had been recovered by pumping (Ref. 2), and drainage by mining recovered about one-third of the oil in place (Ref. 1). The original oil content of the reservoir rock was about 12 percent by weight (Ref. 2), with estimates varying from 0.75 to 0.58 bbl/T (Ref. 2).

The mining method which evolved at Pechelbronn consisted of driving galleries in the overlying marlstones and sinking pits into the oil-bearing zone. Oil would then gravitate to these pits and be lifted to a gathering line by positive displacement air pumps.

Prior to the war years production averaged 530,000 bbl per year of which 40 to 45 percent was mined oil. During the war years production averaged 442,000 bbl per year, of which 35 to 40 percent came from the mines. By the time of the German withdrawal in the fall of 1944, cumulative production totals at Pechelbronn were as follows (Ref. 1):

Wells	13,350,000 bbl
Mine	5,380,000 bbl
Total	18,730,000 bbl

2.1.2 Wietze

The Wietze field near Hanover, Germany had been producing by pumping methods since 1880, and was developed for oil mining in 1919. By 1929, nearly one-half of Germany's production of oil came from the Wietze-Steinforde field. Of this, about 57 percent came from mining and 43 percent came from wells (Ref. 2). In 1953, production from the mine was 12,300 bbl per month with 2,300 bbl per month coming from wells (Ref. 3).

Although Wietze was an important factor in the Germane nomy after World War I, and during World War II a mine of this size would have negligible impact on current U.S. requirements.

The mining methods employed were highly labor intensive and certain geological and mineralogical features combined to allow extraction of oil from the reservoir rocks by drainage and hot water extraction.

The oil-bearing sands and sandstones occur on the flanks of salt domes. Bedding dips vary from 50 degrees (Ref. 2) to 6 degrees (Ref. 2). Four oil-bearing sands and sandstones are present varying in thickness from 11.5 to 51 feet (Ref. 2) and are separated by clay strata. The sands at Wietze were described as fairly coarse and uncemented except for the No. 4 bed which was fine grained.

In the Rhaetic sands, oil API was 28.0° to 26.7° whereas in the Wealden sands the oil has a density of 18.6 to 16.0° API. Oil content was about 0.6 bbl per ton (Ref. 1).

Two mining methods were employed at Wietze: the indirect or "Pechelbronn" method and the direct method. The direct method included hoisting oil sand to surface and washing the sand to release the oil. By 1953, the indirect method accounted for 72 percent, the direct method 26 percent, and horizontal wells contributed 2 percent of production. Cost per ton of oil for the direct method was twice that of the indirect method (Ref. 1). It is worth noting that this is the only known operation where significant production has been sustained from underground direct mining.

It was only possible to mine oil sand at Wietze by the direct method after the oil content had been reduced by other extraction methods, i.e., wells and seepage tunnels (Ref. 3). Therefore, oil won by direct mining came from lower grade sands. It was considered that only viscous oil would be amenable to direct mining techniques without having been previously depressurized and drained by wells and indirect mining.

Development for seepage-oil recovery was accomplished by driving drifts along the strike and connecting them at intervals with cross-cuts or raises. When the oil sand was unusually wet, it was necessary to use breast boards.

The other indirect mining method applied at Wietze was to drill drainage holes into the reservoir rock. This was particularly applicable in the hard Rhaetic sandstones which would have required drilling and shooting as an excavation method. The oil in the Rhaetic was light and would have posed a safety hazard had drilling and blasting taken place. A total of 37 two-inch drainage holes, each 164 to 574 feet in length, yielded 112,000 bbl of light oil. Total drilling was 10,220 feet of hole.



As of 1948, operations were being carried out at depths ranging from 410 feet to 1,067 feet below surface. Water inflows prevented minings continuing below these elevations. The water surrounding or bordering oil or gas is a pool. Edgewater usually encroaches on a field after much of the oil and gas has been recovered and the pressure has been greatly reduced (Ref. 4).

Processing of the oil sand mined by the direct method included leaching by hot water with soda salts and steam agitation (Ref. 2). After about two hours, a batch was drawn off, with the oil floating to the top and the sand being drawn off the bottom of the vessels (Ref. 1). A recovery of 90 percent of the oil present was claimed by Wietze management (Ref. 2).

Subsidence of the surface was a major problem at Wietze. Ground level in the mine area had subsided nearly 10 feet (Ref. 1) when operations were suspended.

Manpower productivity in 1929 was reported at 0.847 bbl/man shift for oil produced by the direct method and 1.869 bbl/man shift for the mine including indirect and direct methods. In seepage tunnels, the yield of oil was 18.5 bbl of oil per foot of tunnel (Ref. 3) up to 1952. Ultimate yield was estimated at 24.5 bbl per foot. Since 1871 production had totaled 17,000,000 bbl, of which 12,000,000 bbl came from wells and 5,000,000 bbl came from mining (Ref. 3).

As of 1953 a new mining method was being tested at Wietze which was a modification of the direct mining method previously employed. Oil sand was broken down from the face using pneumatic picks and was then flushed with cold (68°F) water under pressure. By using surfactant chemicals, it was possible to recovery 70 to 80 percent of the oil. Sand was then flushed into the mined-out area.

2.1.3 Heide Meldorf

Mention is made in Bulletin 351 (Ref. 2) of the oil saturated chalk deposits at Heide. At that time (1932) some exploration had been done underground but full-scale mining was awaiting some test work connected with the swelling nature of the ground.

During World War II it was decided by German naval officials to develop this deposit for exploitation. With a great deal of difficulty, a 230-foot shaft had been sunk and 2,600 feet of gallery had been driven. Ground conditions were extremely difficult and gas was encountered. In addition to the underground work, a distillation plant had neared completion by 1945.

As of 1945, RM 8,000,000 had been expended but no oil had been produced (Ref. 1).

2.1.4 Franklin Oil

During the latter part of World War II, a test was conducted in the Franklin field of Pennsylvania to determine if oil could be drained through horizontal radiating holes drilled in the reservoir rocks (Ref. 5). The oil was light (39° API) but had a viscosity of 220 SSU at 60°F. Several primary and secondary methods had been tried but failed to yield much oil. The oil apparently had good lubricating quantities and was badly needed for the war effort.

A 338-foot shaft was sunk into the reservoir rocks which had a net pay zone of 47 feet. Two holes were drilled into the formation in opposite directions and blasted to within 400 feet of the shaft. One hole was 2,334 feet in length and the other was 2,255 feet in length. Both holes were drilled 5 inches in diameter for the first 102 feet, then 3 inches in diameter to completion.

The blasted holes were subsequently cleaned out by drilling equipment but caved later. The holes produced substantial amounts of water but the test failed in its goal and was abandoned.

2.1.5 Higashiyama

The Higashiyama mine was a Japanese wartime operation in underground oil mining. Total production to 1942 was 156,710 bbl (Ref. 6). The mining scheme was basically the same as that at Pechelbronn, employing drainage galleries, except that the development work was actually done in the oil sands.

Prior to mining, the field had been partially depleted by wells. Edge water had apparently failed to keep up with depletion of the oil, thus providing an opportunity to recover the oil by mining with little interference from water.

The oil trap at Higashiyama was an anticlinal structure with dips of 15 to 20 degrees on the west flank and 20 to 30 degrees on the east flank. Minor faulting occurred in the oil sands on the west flank, but this had little effect on the overall structure. The oil sands consisted of five beds varying in thickness from 16 to 33 feet and were separated by sandy shale beds 6 to 16 feet in thickness. They are described as poorly cemented medium to fine-grained sands with many intercalated sandy shale streaks (Ref. 6).

Oil gravity was 25.7 to 26.6° API. Although the oil content in the field was extremely variable due to partial depletion by wells, it was estimated that the tenor of the oil sands was about 1,118 bbl/acre-foot (Ref. 6), about 0.4 bbl/ton (Ref. 7).

Water production from the mine was about six times the oil production, i.e., 25,000 gallons per day. Of this, about one-half was from surface and one-half from edge water.

Initially, access to the mine was through two vertical shafts 328 feet apart. After test work was performed from these shafts, two inclines were sunk, one incline was for haulage and downcast ventilation, and the other as an upcast air shaft.

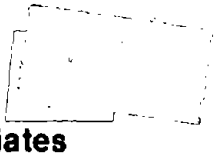
From the foot of the inclined shafts, galleries were driven on a plus 1.5° grade to facilitate oil flow. Drifts and cross-cuts were driven in such a way as to divide the mine into rectangular blocks 130 feet to 330 feet in length and 50 feet to 330 feet in width.

Drainage galleries had ditches in the middle for transport of oil and water. Pits were dug alternately left and right on 5-foot intervals. These pits were 2 feet x 2 feet x 2.5 feet in depth. In addition to the pits, drill holes were fanned out from the rib of the gallery. These holes were angled upward, and were 2.4 inches in diameter and 164 feet in length. In December 1946 there were 299 drainage pits and 102 boreholes in the mine. Oil was recovered from the pits and dumped into the ditch by hand-bailing with one-gallon dippers. Oil flowing from boreholes was collected in wooden tubs, gauged, then discharged into the ditches.

Oil and water flowed to a gathering sump at the shaft where they were separated. The water was lifted to surface by three centrifugal electric pumps in series and the oil was lifted in a 4-3/4 inch line by a single-stage reciprocating pump.

Total ventilation volume was 81,000 cfm. Most of the gas in the oil sands had been previously depleted by the wells.

Mine production had steadily increased from 1940 to 1946. Maximum production was in 1945 when 37,354 bbl were produced. In 1946, production declined to 33,960 bbl (Ref. 6). Average yield per foot of gallery was 4.7 bbl. In borehole drainage, the average decline in productivity was 10 percent per month. Manpower productivity was about 0.75 bbl per man-shift of eight hours. In over six years of operation, the Higashiyama mine lost money in five out of seven periods.



Although the mine was a failure as a financial enterprise, it did illustrate that it was possible to drain oil through underground galleries. During the period of operation, the Higashiyama provided 2-1/2 percent of the total Japanese production.

The main reasons for failure of the mine as a commercial enterprise were:

- Inadequate testing prior to mining.
- Poor recovery of oil.
- Low oil prices relative to labor and materials costs in postwar Japan.

2.2 EXISTING AND PLANNED OPERATIONS

2.2.1 Tar Sands

In the only major current free world demonstrations of oil mining, bituminous sands are being mined by open pit methods and processed to produce a synthetic crude oil. One operation is now on stream with one in construction and several more in the planning stage.

The tar sands of Athabasca consist of fluvial and deltaic sand deposits impregnated with bitumen (Ref. 8). Sand is primarily of rounded to subangular quartz grains (Ref. 9) closely sized and varying from coarse to fine. The grains are coated with water, which in turn is surrounded with bitumen which partially fills the voids between the wetted sand grains. Voids in the sand amount to about 35 percent, resulting in a mixture of about 83 percent sand and 17 percent water and bitumen by weight (Ref. 9). The bitumen content varies inversely with the percentage of fines.

The McMurray Formation, which contains about 90 percent of the heavy oils in northeast Alberta, lies on a Devonian limestone surface (Ref. 8). and is overlain by a varying thickness of glacial drift, sediments and muskeg (Ref. 9). The deposits are basically flat-lying, but the surface has been eroded to provide wide variances in overburden ratios.

High grade tar sand occurs in lenses surrounded by lower grade material that must be wasted. Bitumen grade varies from 0 to 17 percent by weight (Ref. 9) with an average plant feed grade of 12 percent bitumen. Cutoff grade at Great Canadian Oil Sands (GCOS) mine is approximately 8 percent depending on the strip ratio (Ref. 10).

Known reserves covered by less than 150 feet of overburden amount to 74 billion bbl of crude bitumen in place in the Athabasca deposit. Total reserves in Alberta to 2,500 feet of overburden depth amount to 895 billion bbl (Ref. 9).

At the GCOS operation the mining and stripping operation is broken down into three functions: muskeg stripping, overburden stripping and oil sand mining.

Oil sand mining at GCOS is done with two bucketwheel excavators with capacities of 10,000 TPH each. Average output per bucket wheel is 4,300 TPH. Mining is advanced on two benches by these machines. Product from the excavators is moved to the plant by high speed belts. As the oil sands are removed from the underlying limestone, tailings from the plant are brought into the worked-out area and the land is reclaimed.

Plant output is 55,000 bbl per day with a 90 percent recovery of bitumen. Plant feed is 140,000 tpd and overburden removal is 70,000 tpd.

The planned Syncrude Canada, Inc. operation is set for 125,000 bbl per day of crude oil. Syncrude plans to use large draglines to remove waste and mine oil sand. Waste material will be cast back into the mined-out pits by dragline. Planned excavation quantities are 45 million tons of overburden and 92 million tons of oil sand per year.

2.2.2 Yarega

The Soviet Union has been using an ingenious steam stimulation method for oil recovery at the Yarega field since 1968. Some of the features are:

- Recovery of high viscosity oil not recoverable by pumping.
- Competent overlying and reservoir rocks.
- Field lies at shallow depths.
- Viscosity is dramatically lowered with the application of steam.
- Steam is applied at unusually high intensity and low pressure when compared with steam stimulation from surface wells.

The final product from these mines is a crude oil which precludes waste disposal problems inherent in mining of oil sands for surface treatment. In addition, the mine plant is much smaller than a mine of similar daily oil production using direct mining techniques. This is due to the fact that the Yarega method is essentially an in situ process with only a

minor amount of development rock to be handled. Thermal efficiency will be higher for steam stimulation from underground than from the surface due to lower friction and heat losses in the conductor pipes. Drilling of steam and production wells will be mainly in the pay zone rather than in barren formations between surface and the pay zone.

Oil is trapped in an anticline in the Yarega field. Overlying rocks are argillites and tuffite diabase. An aquifer underlies the oil (Ref. 11). The reservoir rocks are highly fractured as a result of faulting.

The reservoir rocks are described as fine-to-medium grained quartz sandstone with conglomerate in some areas. Oil separation is 97 percent and oil content is 7 percent by weight (about 0.42 bbl/ton (Ref. 7). The unique feature of the Yarega oil is its high viscosity (15,000 to 20,000 cp) at 43°F reservoir temperature, which is reduced to 30 cp at 200°F. Porosity is 20 to 25 percent and permeability is 0.5 to 5 darcies with an average of 3.2 darcies. Oil is 17.5° API, and is characterized as resinous, sulfurous and nonparaffin.

Reservoir rocks have a total thickness of about 230 feet but net thickness of oil-bearing rock is 45 to 90 feet with an average of about 70 feet. Depth of the field is 590 to 606 feet.

Mine development methods are similar to those in use in conventional U.S. mines. Shafts provide access to the upper level workings and inclined winzes provide access to the oil production galleries in the bottom of the oil-bearing zone.

The upper level is 60 to 100 feet above the reservoir rock in tuffite diabase. Winzes are sunk at about 15 degrees to the bottom of the reservoir for development of the hexagonal production chambers. These hexagons are 80 feet in diameter and have a drainage area of about 4.5 acres.

In each gallery are about 250 production holes which are drilled to a length of 650 to 800 feet and which radiate from the gallery.

Steam injection wells are drilled downward from the upper level. Injection wells and production wells are drilled with a special rig capable of producing 24,000 to 30,000 feet per month with a two-man crew. The first 8 to 10 feet are drilled at 4-3/4 inch diameter, a 4-inch casing is set, and the remainder is drilled at 3-3/4 inch diameter. A blowout preventer may be installed after the collar pipe is set.

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To initiate production, steam is injected into the wells on the upper level, thus heating the oil to reduce the viscosity and to provide a pressure differential to move the oil to the production wells. Steam injection pressures are on the order of 75 to 120 psi and injection rates are several pounds to four or five tons per hour per well. Specific steam consumption is about three tons of steam per ton of oil. Cyclic steam injection is being used as a production technique. Hot water and surfactants are recycled into the reservoir.

At present, steam is produced by a central plant. Lightweight, portable boilers of 50 to 75 metric tons/hour capacity are planned for future operations (Ref. 12).

Anticipated production for three mines in the Yarega field is 6,700,000 bbl of oil per year. Labor productivity is claimed to be 24 bbl/man-shift. Development ratio is 85 bbl per foot of development and 6 bbl per foot of well drilled. The system uses about 21 kwh of electricity per bbl for oil recovery, compressed air and steam.

Costs have been reported of $5.29 per bbl (April 1976) with a capital expenditure of $8.8 million for a mine of 972,000 bbl per year capacity. Manpower requirements are 199 including surface and office workers. Some doubt exists, however, as to the basis for these figures and no verification has been possible.

2.2.3 Conoco

It was announced in Oil World of 8/22/77 that Conoco plans to drill five 2,000-foot horizontal holes into the Lakota formation to drain oil contained in the formation. The holes will be drilled from a chamber 180 feet underground (Ref. 13).

2.2.4 Getty Oil

In the June 1977 issue of Engineering and Mining Journal is a statement concerning Getty Oil Company's intention to pilot an operation to determine the commercial feasibility and environmental compatibility of an open pit mine in saturated diatomaceous earth.

An independent consultant has estimated oil-bearing diatomaceous sediments at 627 million tons with an average grade of over 28 gallons of crude per ton (Ref. 14).

CHAPTER 2
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3.0 DISCUSSION OF THE RESOURCE AND SELECTION OF METHODS AND FIELDS FOR STUDY

This chapter discusses the basic technical aspects of the resource, applicable elements of petroleum geology and reservoir production, the preliminary field selection criteria, the availability (or lack) of data, and potential mining methods. The gross distribution of the potential resource which is economically unexploitable by existing petroleum technology, but which in part may be amenable to production by mining methods, is discussed first. The following sections provide a brief summary of the factors that result in incomplete removal of the oil from reservoirs. The preliminary field selection criteria used to develop a list of candidate fields are documented, and a summary of the nature of the data base with respect to the type of data required for mining studies is presented. The last portion of this chapter introduces the candidate mining systems for surface and subsurface mining of oil and bitumen deposits.

3.1 POTENTIAL RESOURCES

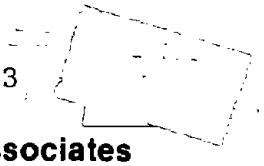
Prior to discussing the methods employed in this study to select representative oil fields for the application of oil mining, it is useful to comment on the character and distribution of potential resources considered to be available in the United States.

The possible target for oil mining operations is comprised of oil remaining in place in: 1) fields and pools that have reached economic depletion by current petroleum production methods and are not amenable to economic recovery by conventional petroleum industry techniques; 2) oil or bitumen saturated rocks that are not normally considered to constitute reservoirs, such as shales and diatomites; and 3) asphalt and bitumen impregnated rocks.

3.1.1 Depleted Fields

Estimates of the oil remaining in place after primary, secondary and nondestructive tertiary recovery vary. However, the evidence is that significantly more than one-half of the oil originally estimated to be in place, remains in the reservoir

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after all petroleum recovery techniques have been applied (Ref. 1). A comparison was made between the sum of the past production and the estimated remaining producible reserves in the U.S. oil fields and the American Petroleum Institute (API) estimate (1975) of total oil in place for the U.S. This comparison indicated that for the U.S. as a whole, 67 percent of the original oil content will remain in place at the end of the economic recovery process. The corresponding figure for the 100 largest oil fields was 63 percent remaining after full production. These figures are representative of oil fields that have been, or presently are, under production by conventional petroleum techniques, and do not include poorly known heavy crude reservoirs with limited production and reserves data, on tar sands, oil-impregnated diatomite deposits, etc.

The majority (85.7 percent) of the estimated economically ultimate unrecoverable resource of oil in the U.S. are contained in only eight states, each with a residual resource of more than 10 billion barrels (Ref. 2). These states, in order of decreasing estimated unrecoverable resource, are: Texas, California, Oklahoma, Louisiana, Alaska, New Mexico, Kansas and Wyoming. The distribution of the total U.S. oil resources currently projected to remain in the reservoirs after full conventional production is shown in Tables 3-1 and 3-2. The data is listed by state and production units within states, by order of decreasing resources remaining. These tables provide an indication of the relative total quantity of resource which will remain tabulated by state.

Review of the API (1977) estimates of oil originally in place and the ultimate recovery provides information on the character and location of the presently unrecoverable oil resource (Ref. 1). Based on a separation by trap type, 65.7 percent will remain in structural traps, while 72.10 percent will remain in stratigraphic traps. This indicates that certain oil pools associated with stratigraphic traps may, depending upon original oil concentration, be slightly more attractive candidates for oil mining ventures in terms of grade, although the difference is rather slight. Analysis of the resource data based on division of reservoir lithologies into sandstone, carbonate and other, shows that the resources anticipated to remain in the ground after production are respectively 66.32 percent, 71.67 percent and 81.22 percent of original content (Table 3-1). Therefore, reservoirs in "other" and carbonate lithologies appear to be potentially advantageous as to the proportion of the original resource remaining, as well as having features possibly more amenable to mining. However it should be acknowledged that the total resource in "other" reservoir rocks

TABLE 3-1

OIL LEFT IN PLACE AT END OF CONVENTIONAL PETROLEUM PRODUCTION AND PERCENT OF ORIGINAL RESOURCE THAT WILL REMAIN BY RESERVOIR LITHOLOGY
(Listed in decreasing order of unrecoverable resource by State and API (1977) reporting units within States)

		RESERVOIR LITHOLOGY					
		SANDSTONE		CARBONATE		OTHER	
LOCATION	RESOURCES REMAINING	RESOURCES REMAINING	% ORIGINAL RESOURCES REMAINING	RESOURCES REMAINING	% ORIGINAL RESOURCES REMAINING	RESOURCES REMAINING	% ORIGINAL RESOURCES REMAINING
Texas, Total	101.19	51.87	66.32	48.73	70.05	0.59	79.81
District 8	30.75	8.29	78.79	22.02	71.03	0.44	80.70
District 8-A	15.41	1.64	88.60	13.77	65.04	--	--
District 7-C	10.04	6.99	93.29	3.05	74.24	--	--
District 9	9.01	7.58	73.60	1.40	81.09	0.03	77.61
District 3	8.04	7.99	51.54	0.05	81.40	--	--
District 7-B	5.93	4.56	78.07	1.37	72.23	--	--
District 10	5.77	0.72	81.17	5.05	77.39	--	--
District 4	5.71	5.71	65.22	--	--	--	--
District 6	4.17	3.36	30.66	0.81	62.64	--	--
District 2	3.08	2.96	53.90	0.12	82.92	<0.01	71.79
District 1	2.39	1.28	78.70	0.99	66.65	0.12	79.34
District 5	0.89	0.79	46.08	0.10	64.51	--	--
California, Total	62.78	59.41	74.62	--	--	3.37	81.11
San Joaquin Basin	26.53	26.16	73.83	--	--	0.37	82.35
Los Angeles Basin	24.10	24.05	75.05	--	--	0.05	73.29
Coastal Region	12.15	9.20	75.78	--	--	2.95	81.35
Oklahoma	25.62	22.12	65.96	3.50	76.24	<0.01	82.31
Louisiana, Total	22.04	18.25	50.73	3.78	85.46	--	--
South	15.96	15.96	49.60	<0.01	60.00	--	--
North	6.08	2.30	60.32	3.78	85.46	--	--
Alaska	16.41	16.41	60.92	--	--	<0.01	70.89
New Mexico, Total	10.93	2.35	76.56	8.45	73.60	0.13	85.40
Southeast	10.18	1.77	75.62	8.41	73.61	--	--
Northwest	0.75	0.58	79.60	0.04	71.64	0.13	85.40
Kansas	10.55	2.75	64.96	7.79	68.69	<0.01	77.51
Wyoming	10.46	7.76	66.74	2.52	69.67	0.18	92.41
(Gulf of Mexico)*	7.79	7.79	53.74	--	--	--	--
Ohio	6.06	2.69	85.07	3.37	87.68	<0.01	89.99
Illinois	5.76	4.08	62.97	1.68	67.63	--	--
Pennsylvania	5.31	5.31	79.85	--	--	--	--
Montana	3.48	1.46	72.31	2.02	79.67	--	--
Mississippi	3.05	2.74	62.63	0.28	72.64	0.03	51.72
Utah	2.89	1.77	84.59	1.09	71.24	0.03	86.75
Arkansas	2.78	2.08	65.89	0.70	62.33	--	--
Colorado	2.74	2.53	65.11	0.09	77.73	0.12	83.74
West Virginia	2.08	2.07	79.19	0.01	87.17	<0.01	88.34
North Dakota	1.93	0.17	72.74	1.76	75.86	--	--
Michigan	1.79	0.01	70.63	1.79	68.09	--	--
Kentucky	1.43	0.79	66.94	0.64	69.24	--	--
Indiana	1.10	0.44	60.03	0.66	78.31	--	--
Nebraska	0.98	0.91	71.66	0.07	67.43	--	--
New York	0.88	0.88	78.83	--	--	--	--
Florida	0.58	--	--	0.58	56.41	--	--
Alabama	0.52	0.38	69.20	0.14	70.89	--	--
Miscellaneous**	0.10	0.01	80.72	0.01	80.08	0.08	78.38
South Dakota	0.03	<0.01	83.08	0.03	80.81	--	--
Tennessee	0.02	--	--	0.02	77.29	--	--
U.S. TOTAL	303.49	209.24	66.32	89.71	71.67	4.54	81.22

* Included with Texas and Louisiana
**Includes Arizona, Missouri, Nevada, Virginia and Washington

Resources Remaining are expressed in billions of barrels.

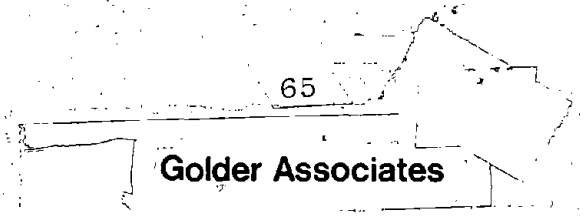


TABLE 3-2

STATES AND OTHER API REPORTING UNITS LISTED IN ORDER OF THE PERCENTAGE OF OIL REMAINING IN RESERVOIRS AT THE END OF NORMAL PETROLEUM PRODUCTION

State and Reporting Unit	Percent Remaining in Place at end of Conventional Petroleum Production: State	Other Reporting Unit	Magnitude of Resource In Billions of Barrels: State	Other Reporting Unit
Ohio	86.5%		6.06	
(Texas, Dist. 7-C)		86.5%		10.04
South Dakota	80.9		.03	
(New Mexico, Northwest)		80.1		.75
Pennsylvania	79.9		5.31	
West Virginia	79.2		2.08	
Utah	79.0		2.89	
Miscellaneous (includes Arizona, Missouri, Nevada, Virginia, Washington)	78.8		.10	
New York	78.8		.88	
(Texas, Dist. 10)		77.8		5.77
Tennessee	77.3		.02	
(California, Costal Region)		77.0		12.15
(Texas, Dist. 7-B)		76.6		5.93
Montana	76.3		3.48	
North Dakota	75.5		1.93	
(California, Los Angeles Basin)		75.1		24.10
California (overall)	74.9		62.78	
(Texas, Dist. 9)		74.7		9.01
New Mexico (overall)	74.3		10.93	
(California, San Joaquin Basin)		73.9		26.52
(New Mexico, Southeast)		73.9		10.18
(Louisiana, North)		73.8		6.08
(Texas, Dist. 1)		73.2		2.39
(Texas, Dist. 8)		73.1		30.75
Nebraska	71.3		.98	
Indiana	69.8		1.10	
Alabama	69.7		.52	
Michigan	68.1		1.79	
Kentucky	68.0		1.43	
Kansas	67.7		10.55	
Wyoming	67.7		10.46	
Oklahoma	67.2		25.62	
Texas (overall)	66.9		101.19	
(Texas, Dist. 8-A)		66.9		15.41
Colorado	66.1		2.74	
(Texas, Dist. 4)		65.2		5.71
Arkansas	65.0		2.78	
Illinois	64.3		5.76	
Mississippi	63.3		3.05	
Alaska	60.9		16.41	
Florida	56.4		.58	
(Texas, Dist. 2)		54.6		3.08
Louisiana (overall)	54.5		22.04	
(Texas, Dist. 3)		51.6		8.04
(Louisiana, South)		49.6		15.96
(Texas, Dist. 5)		47.6		.88
(Texas, Dist. 6)		34.0		4.17
U.S. (overall)	68.0 avg.			
		TOTAL	303.49	

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is only a fraction of that contained in sandstones and carbonates.

The total estimated unrecoverable resource, subdivided on the basis of geologic age of the reservoir rocks, (Ref. 1) is shown in Table 3-3 and is graphically presented on Figure 3-1. The data indicate that 52.71 percent of the resource will be contained in Paleozoic, 33.04 percent in Cenozoic, and 14.24 percent in Mesozoic age rocks. An insignificant amount with respect to the total resource (i.e., less than 1/1000th of 1 percent) will be contained in Precambrian age rocks. The distribution of the estimated oil originally in place is similar and is 49.73 percent, 34.27 percent and 15.99 percent, respectively. The difference is in part explained by a slight but significant average increase in the percentage of oil left behind in the older rocks as a result of reductions in size of pore space and permeability.

As a generalization, the older the reservoir and the greater its depth of burial the harder and more competent rock can be expected to be, and the higher the API gravity of the oil contained. Conversely, older rocks must be expected to be contained smaller pore spaces and less oil content per unit volume.

In summary, the oil fields in production or previously in production, contained an original total resource of 446.28 billion bbls of oil. After primary, secondary and tertiary methods have been applied, an estimated resource of 303.5 billion bbls of oil will remain in the ground (Ref. 1). Not included in these estimates, but potentially of large magnitude, are reservoirs which have never been placed into production normally due to high oil viscosity. An example of this would be the Paris Valley in California.

3.1.2 Diatomites and Shales

Discovery and/or recognition of oil saturated diatomite deposits within several oil fields of California within the past several years and previously recorded occurrences associated with asphalt deposits indicate that such deposits in tertiary basins may constitute a significant resource. This is particularly true in view of the high porosity but very low effective permeability of diatomite which results from the small individual pore size and associated capillary effects. Two fields where oil-impregnated diatomites occur are the McKittrick and Bellridge South fields of California. Oil concentrations of up to 1 bbl per ton are mentioned with regard to these deposits. The total extent of these deposits is apparently not as yet documented and little or no published data on these are available. It is known

TABLE 3-3

DISTRIBUTION OF ESTIMATED UNRECOVERABLE U.S. OIL RESOURCE
ARRANGED BY GEOLOGIC AGE OF THE RESERVOIR ROCK*

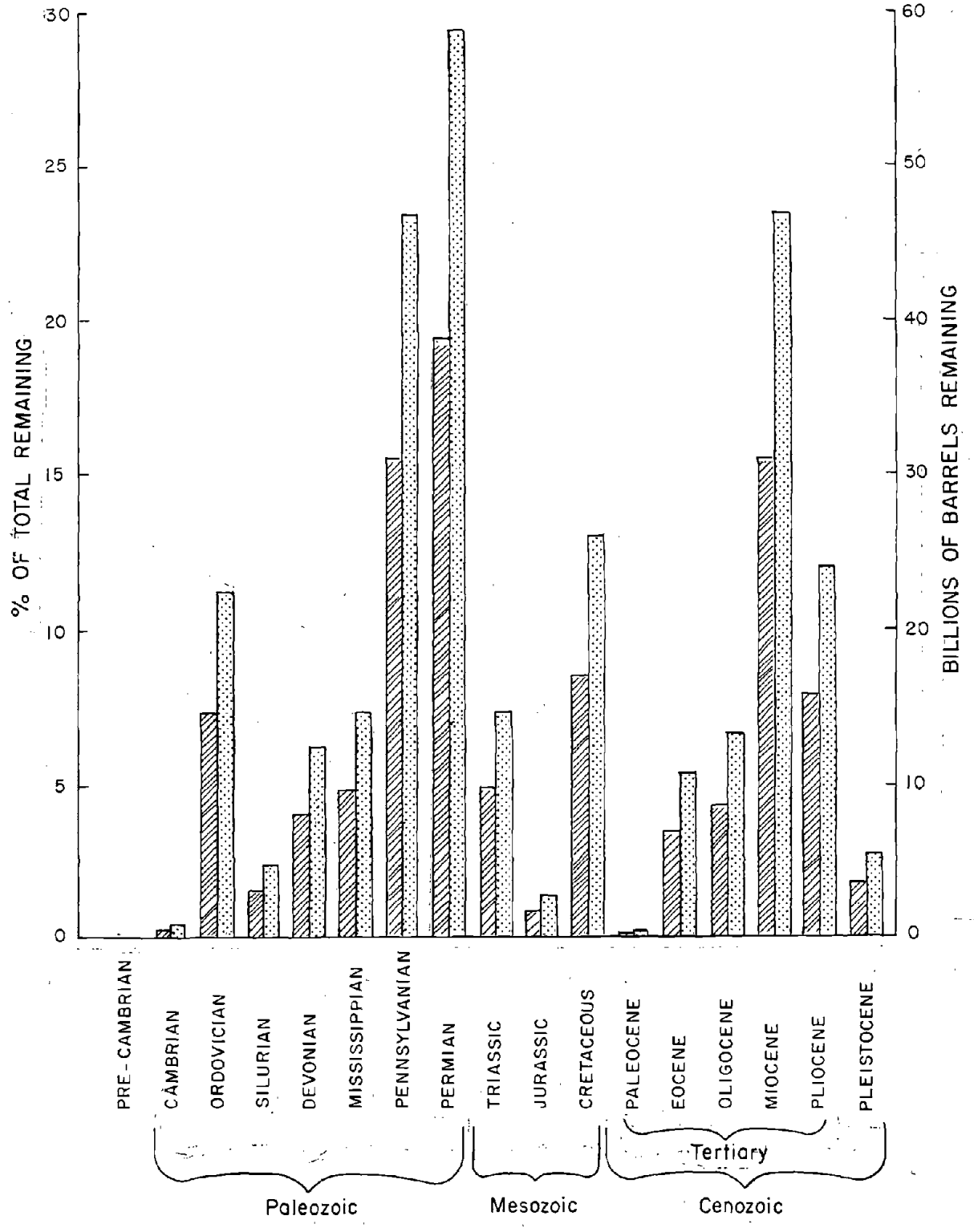
Age	Percent of Total Unrecoverable Resource			Billions of Barrels of Unrecoverable Resource		
CENOZOIC						
Quaternary:						
Pleistocene	1.75			5.32		
QUATERNARY TOTAL		1.75			5.32	
Tertiary:						
Pliocene	7.90			23.99		
Miocene	15.47			46.95		
Oligocene	4.36			13.24		
Eocene	3.50			10.61		
Paleocene	0.05			0.16		
TERTIARY TOTAL		31.28			94.95	
CENOZOIC TOTAL			33.03			100.28
MESOZOIC						
Cretaceous	8.55			25.96		
Jurassic	0.88			2.67		
Triassic	0.81			14.59		
MESOZOIC TOTAL			14.24			43.22
PALEOZOIC						
Permian	19.41			58.92		
Pennsylvanian	15.40			46.75		
Mississippian	4.86			14.74		
Devonian	4.03			12.24		
Silurian	1.52			4.62		
Ordovician	7.33			22.25		
Cambrian	0.16			0.47		
PALEOZOIC TOTAL			52.71			159.99
PRECAMBRIAN	<0.01			<0.01		
PRECAMBRIAN TOTAL			<0.01			<0.01
				TOTAL		303.49

*Economically unrecoverable by conventional petroleum techniques. Calculated from API (1977) data (3).

DISTRIBUTION OF ESTIMATED OIL RESOURCE REMAINING AFTER FULL CONVENTIONAL PRODUCTION

Figure 3-1

(Based on API data, 1977)



that one surface portion of the McKittrick deposit is being considered for mining. The Bellridge South occurrence has recently been fractured in a successful attempt to induce flow and is now in production (Ref. 3).

Little is known about the number of such deposits in California. However, the potential resource appears to be of a reasonable magnitude. It includes the Monterey shale, which in part is highly diatomaceous, which is very abundant in southern and central California in and adjacent to oil fields. The Monterey shale is an oil producer in some fields where it is highly fractured (Refs. 4, 5), and many exposures of this formation contain oil seeps, traces or shows. In addition, the Monterey shale has been considered by many geologists in California as being the most likely source rock for much of the oil found in California. This formation could contain a number of oil impregnated diatomaceous units that are not economically producible by conventional techniques and which could constitute a resource exploitable by mining methods.

3.1.3 Asphalt and Bitumen Deposits

Bituminous and asphalt deposits may form as the result of leakage to the surface or near-surface environment from deeper oil pools, by erosion processes bringing the oil pool into the near-surface environment, or by breaching of the oil-bearing zone to the atmosphere. Leakage from oil fields and pools at depth is evidenced by oil seeps, asphalt pools, breas, surface and near-surface tar sand deposits, asphalt impregnated rocks of all types, and dike or vein-like bodies of solid hydrocarbons. Such deposits have been used, and still are, albeit to a more limited extent, to indicate prospective areas for petroleum exploration. In the past, exploration in these areas has encountered asphalt and tar sands which may or may not have been recorded since these occurrences were at that time of no commercial value to the petroleum companies. Those deposits which were recorded are poorly defined in areal extent and have limited documenting information available. Even those deposits with abundant surface exposures are poorly documented as to bituminous content, tonnage and distribution with respect to depth.

According to Cupps, Land and Marchant (Ref. 6), partial resources estimates have been made for seven states and estimated resources of known deposits in California, Kentucky, New Mexico, Texas and Utah are approximately 29 billion barrels of bitumen. The potential for a substantially larger resource exists as poorly exposed or unexposed bituminous deposits. In those areas where there is abundant evidence for leakage of oil to the surface along faults or other crosscutting conduits, each permeable zone traversed by such pathways has the potential to

become oil or tar impregnated. This means that for each significant surface exposure of oil or tar there is the potential for one or more underlying deposits of heavy, viscous crude oil or asphalt impregnated rocks.

Examples of large and potentially large bituminous deposits are the Sunnyside and Edna deposits cited in this report. The bulk of the recognized bituminous resource is in the state of Utah with a total estimated resource of 28 billion barrels of bitumen (Ref. 6). The diatomites, mudstones and sands of the South and North Casmalia deposits which are reported to contain 1/2 bbl and 1 bbl per ton, respectively, with only gross speculations with regard to total resource in place with depth could also prove to be large deposits. Certainly at a minimum the larger known oil seeps and tar deposits in California, Texas, Kentucky, New Mexico and Utah should eventually be evaluated. One of these, the Uvalde district in Texas, does have reasonable reserve data with a reported estimated reserve of 347,650,000 tons (measured, indicated and inferred) and a content of 0.35 bbls of asphalt per ton, for a total estimated resource of 124.16 million bbls of bitumen (Ref. 4).

3.1.4 Summary

There is, therefore, no lack of potentially suitable shallow heavy oil fields, asphalt or tar deposits for evaluation as candidates for mining studies. There is, however, a general lack of data with respect to size, form, tonnage and grade for these deposits. The estimate of 29 billion bbls of identified recoverable bitumen cannot be significantly improved upon at the present time, and appears to have the potential of representing just the "tip of the iceberg" as the magnitude of the total resource is concerned. The deposits in near-surface tertiary sediments in California and the known giant deposits in Utah are of special interest and hold a significant promise of proving to represent a substantial resource amenable to extraction by surface mining methods. It is not difficult to envisage a total resource approaching 500 billion barrels remaining in the ground after present production technologies have been applied to their fullest extent.

3.2 SUMMARY OF TECHNICAL REASONS FOR INCOMPLETE CONVENTIONAL PRODUCTION

The primary reasons for lack of flow to a surface drilled well may be evaluated by examining the fundamental constitutive equations for flow through porous media. Fracture dominated flow is significantly less well understood, but it is potentially of

considerable interest in this study because of the high local permeability along fractures.

The flow law which Darcy formulated in the last century for porous media may be expressed as:

$$q = \frac{k}{\mu} (i)$$

where k is the resistance to flow factor commonly referred to as permeability
μ is the viscosity of the fluid
i is the head gradient, i.e., the difference in pressure in the direction of flow
q is the linear flow rate.

From this simple relationship it is clear that loss of the head gradient or extremely low permeabilities or high viscosities, either singly or in combination, can reduce the flow rate to a negligible amount.

It should be stated that the validation of Darcy's law for extremely low permeability materials is poorly established. For fracture flow the flow laws are still the subject of debate. The occurrence of turbulence (i.e., nonlaminar flow) is a function of the aperture width of a fracture, the roughness of the fracture and head gradient. Most proposed laws, validated by laboratory work, indicate that the flow rate is proportional to the cube of the aperture width (Ref. 7). Fractures as limited in width as 0.001 inch can have, within the fracture, permeabilities on the order of 50 darcies, which is very much higher than the permeability range normally encountered in porous media flow within a reservoir.

3.2.1 Variations in Permeability

Since the flow rate of oil in a reservoir is a function of a four phase medium (air, oil, gas and water), permeability must depend on the state and relative quantities of each phase. There are three definitions for permeability:

- Absolute permeability. This is the permeability of a porous media with only one fluid filling the pore spaces.

- Effective permeability. When more than one fluid is present in the rock, the permeability with respect to the flowing fluid is known as the effective permeability. For example, where both oil and water are present in the reservoir rock pore spaces and the oil is flowing, then the oil must squeeze through a pore space

that is reduced in cross-sectional area by the water wetting the grains bounding the pore space. The effective permeability for a given medium is related by a constant function to the degree of saturation.

- Relative Permeability. This is the ratio of the effective permeability of a phase (e.g., oil, gas, etc.) to the absolute permeability (i.e., at 100 percent saturation).

The relative permeability will thus vary from unity at 100 percent saturation for a particular phase to effectively zero when low percentage saturations of a particular fluid are reached.

3.2.2 Variations in Viscosity

Viscosity is a measure of the ability of a fluid to flow. The greater the viscosity of the fluid, the lower the rate of flow of a given volume through a given cross-sectional area. The viscosity of crude oil varies widely with the light, high API gravity oils having a low viscosity and flowing very readily while at the other end of the petroleum sequence are the semi-solid asphalts and bitumen deposits which have essentially no short time flow, although they do deform in a plastic manner. Viscosity varies with respect to the amount of gas dissolved in the oil, the temperature of the oil and its density, which in turn is related to the composition of the oil.

As viscosity increases, it becomes progressively more difficult for the oil to move through the reservoir. At some point the oil will cease altogether to move to a collection well under primary drive, until either the viscosity is decreased by the addition of heat or the field drive pressures are increased.

Since the normal history of petroleum reservoirs is to produce at least some of the gas with the oil, the oil left in place at the end of the primary recovery process, if a significant amount of gas was dissolved in the oil originally, will have a higher viscosity than that previously produced. The residual oil will also have a lower API gravity. In cases where the oil had lost much or all of its dissolved gases prior to discovery, the oil may be so viscous as to be marginal or uneconomic by conventional, including secondary, petroleum recovery techniques. In such instances a higher unit content of oil may be available for a potential mining project. Example fields include the Paris Valley field of California and other heavy oil pools that have a low cumulative production history.

3.2.3 Variations in Head Gradient

As conventional oil production proceeds the driving pressure gradient will reduce. The rate and form of the reduction in reservoir pressure will depend on whether there is solution gas or free gas cap drive and on the presence of an active water drive. This decay in natural drives is frequently compensated by various forms of artificially introduced drives until the cost of such measures finally becomes prohibitive.

3.2.4 Summary

The separation of wells and the resulting flow conditions set up in the reservoir rock, rate of production and reduction of head gradient, increase in viscosity and decrease in relation to effective permeability, can all contribute to the eventual decline, to uneconomic limits, of production from an oil reservoir by conventional petroleum techniques. The fundamental nature of the oil and the changes it undergoes as production continues, the large well spacings required by economic factors, and the problems of maintaining a satisfactory drive pressure all combine to ensure that substantial amounts of oil will remain in a reservoir at the conclusion of conventional production.

3.3 PRELIMINARY FIELD SELECTION CRITERIA

Since the number of oil fields existing in the United States is large, the first step in the study was a selection and evaluation procedure to narrow down the number of fields under consideration. This initial selection procedure involved two distinct steps:

- Ascertaining which important properties of the field, or pool, could be readily determined from existing published data
- Deciding which of these properties could be used as sorting criteria.

At this stage of the study there was such a wide variety of field characteristics, and the specific requirements of each potential mining system were so little known that only the most general selection criteria were used. This selection was also complicated by the dissimilarities between the basic information requirements of the petroleum and mining industries. The data required from an exploration program for oil and gas is markedly different from that traditionally produced by a search for solid minerals. These differences are perhaps best summarized in two categories:

- In conventional mining, the valuable mineral is fixed in the host rock although its distribution in that rock may be highly variable. In mining projects it is therefore essential to delineate the mineralized zone and to map the distribution of the valuable mineral in terms of grade, such as "percent" or "pounds per ton." In other words, the location or distribution of the valuable mineral must be reliably estimated since it will remain fixed in place until it is removed by mining. By contrast, in a petroleum field the requirement is much more to determine the general gross valuable reserve in an area and to assess its ability to "travel," or flow, to production wells.

- The design and economics of a mine, particularly an underground operation, depend very directly on the physical properties of the rock formations. In particular, the strength of the rock mass is critical to the mining engineer and this may be true of the overlying and underlying formations as well as the "ore" zone or reservoir itself. Such properties tend to be, at best, of only indirect interest, however, to a petroleum geologist or engineer.

Examination of the data available for U.S. oil fields soon revealed that the types of information necessary to evaluate oil fields from a mining standpoint are not easily retrievable and would have to be deduced or assumed for specific fields at a later stage in the study. Consequently, the initial selection of oil fields to be considered was made on broader grounds using readily available properties whose economic significance in a mining operation could be clearly seen. These initial criteria were:

- Depth Below Surface. Petroleum deposits in the U.S. range in depth from tens of feet, as in parts of California and Pennsylvania, to pools lying well in excess of 15,000 feet deep. Clearly for open pit extraction, the mining costs will be very directly related to depth, and particularly to the thickness of overburden. Consequently, an arbitrary figure of 500 feet was chosen as one cutoff depth and it was assumed that mining of any fields above this depth would be by open pit methods.

  At depths greater than this, it was considered that surface mining costs would rise markedly, and that underground extraction would progressively become more economically attractive. Consequently, an interim depth

category, 500 to 1,000 feet, was chosen as a zone where either open pit or underground mining was a possibility.

For underground mining, the range of feasible depth in general terms is far wider. Mining is being carried out for other minerals in various parts of the world at over 10,000 feet below surface, with the limits being set mainly by rock strength/stress relationships, rock temperatures and simple economics. It is the primary objective of this study, however, to determine the existence of some potentially mineable deposits rather than to attempt to identify all such deposits. Since deeper deposits are inherently more expensive to mine than shallower ones, it was decided to limit the study to fields lying at less than 3,000 feet below surface. This initial depth cut-off would then have been deepened if no suitable fields, or an inadequate selection, were obtained. It was expected in general that if the economics of potential operations at these moderate depths cannot be shown to be attractive, there is little chance of success at greater depths.

- Field Size. Any oil mining operation, with its attendant front-end costs, is going to require a substantial production rate and extended operating life, in order to be attractive. The decision was therefore made to arbitrarily limit the search to fields of substantial extent.

- Oil Content. Following the same principle, that the objective is to identify attractive deposits, the initial search was limited to fields containing a higher proportion of petroleum, i.e., "high grade ores." Initially a search range of 0.5 to 1.0 bbl/ton was used; however, this was later relaxed to 0.25 bbl/ton when it became evident that suitable higher grade fields were scarce. On the assumption that the attractive fields would already have been worked to some degree, the remaining oil content was taken as the indicator for this purpose.

  Some fields were excluded on the rather arbitrary grounds that, although substantial in situ reserves had been indicated at one time, no significant production had been achieved over a protracted period and so the validity of the reserve was considered questionable.

- Thickness of Oil-bearing Zone. A substantial portion of the cost of any mining method is related to the plan area of the deposit to be mined rather than its volume,

and this consideration penalizes thin oil-bearing zones. A lower bound thickness was therefore assumed and was increased with increasing depth of the deposit to reflect the generally less favorable economics of deeper workings.

A search was made of the extensive information available from the computerized Petroleum Data Service of the University of Oklahoma at Norman. Considerable data is available for some fields including all the parameters requested in the search, including porosities, permeabilities, cumulative production, remaining reserves, average depth to top of reservoir, thickness, etc. However, on other fields minimal information is available and frequently would only include location, depth, thickness of pay zone and area. Consequently the initial search was made with the sorting order based on depth below surface and thickness of pay zone. The following ranges and units were used for the data search:

Depth below surface (ft)	Minimum thickness (ft)
0 - 500	No minimum
500 - 1,000	10
1,000 - 2,000	20
2,000 - 5,000	50

This search resulted in a candidate field list of approximately 10,000 oil fields. In addition to the computer search, a limited literature search centered around the USBM Ball Associates report (Ref. 4) and the more recent annotated bibliography of tar sands by the USGS (Ref. 5). These three primary data bases provided the basic candidate listing from which a representative selection of fields for study as possible underground and open pit mines was prepared. This list is shown in Table 3-4 and was used as the basis for consideration of the quality of available data and, after consideration of the potential mining methods, of the final selection of fields for study.

3.4 AVAILABLE DATA BASE

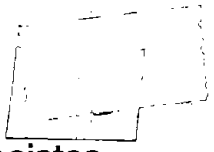
The information normally available on an oil field is, naturally concentrated on the properties of the reservoir rocks as they would affect conventional oil production. This production system is concerned with inducing flow of fluids through a porous medium when that medium is stressed by wells. A mining system, in contrast, involves the creation of excavations,

TABLE 3-4
SHORTLIST OF CANDIDATE DEPOSITS

0 to 500 feet		500 to 1,000 feet		1,000 to 3,000 feet	
State	Field Name	State	Field Name	State	Field Name(# of pools)
CA	McKittrick	CA	Kern River	CA	Kern River
		CA	Yorba Shallow Linda	CA	Coalinga West Side
CA	Eureka Canyon	CA	Tejon Hills'v'	CA	Belridge, So
		CA	Tejon Hills's'	CA	Lost Hills (2)
WY	Circle Ridge	CA	BArdsdale	CA	S. Belridge
		CA	Placerita	CA	San Ardo (2)
CA	Conejo	CA	Sisar-Silverthread	CA	Placeteria
		CA	Lockport	CA	Cymric (3)
LA	Bellvue	WY	Circle Ridge	CA	Lompoc
		WY	Dallas	CA	Midway Sunset (3)
TX	Slocum	WY	Lander	CA	Guadalupe
		KS	Allen	CA	Newport West (2)
TX	Nacogdaoches	WY	Tisdale, N	CA	Capitan
		CA	Pyramid Hills	CA	Los Angeles City
CA	Kreyenhagen	WY	Bison Basin	CA	Oakridge
		WY	Derby	AR	Irma
TX	Toburg	CA	Timbler Ranch	CA	Kern Bluff
		CA	Sargent	CA	McKittrick
		MO	Knoche	CA	Yorba Linda
		WY	Salt Creek	CA	Sisar-Silverthread
		WY	Simpson Ridge	CA	Antelope Hills (2)
		CA	Devils Den	CA	Wheeler Ridge
		CA	Comanche Pt.	CA	Wayside Canyon
		CA	Tip-Top	WY	Winkleman Dome (2)
		WY	Big Hollow	CA	Tapo Canyon
		CA	Cymric	WY	Hol Springs
		WY	Shannon	CA	Tapia Canyon
		CA	Newhall Group	CA	Huntington Beach
		CA	Terre Bella	CA	Mt. Poso
		TX	Moca	CA	Blackwells Corner
		TX	Comitas	AR	Railroad Gap
		TX	Los Olmos	CA	Railroad Gap
				AR	Willisville
				CA	Chico Martinez
				CA	Lynch Canyon
				CA	Alferitz
				CA	Casmalia
				CA	Tejon Grapevine

BITUMINOUS AND TAR SANDS

The Candidate list for this category was taken from the Ball Report "Surface and Shallow Oil-Impregnated Rocks and Shallow Oil Fields in the United States", U.S. Bureau of Mines Monograph 12, 1965. This report lists 546 tar sand deposits and 383 shallow oil fields in 27 states.



normally in the reservoir rock itself, as well as possibly in the formations under- and over-lying it. The data used for design must therefore, support estimates of the stability of such excavations and any problems in their creation, provide the basis for assessment of any effects they may have such as inducement of fluid inflows and, most importantly, give a reasonable basis for judgements of the valuable oil content of any rock removed for processing.

The type of information required for oil mining therefore includes:

- The mechanical properties of the reservoir rock mass, as well as, in many cases, the rock mass immediately below and the entire suite of rock masses overlying the potential production zone.

- Properties of fluid/gas flow of a reservoir at the time a mining based method of production is implemented.

- The geometry of the production zone is required to be defined in three dimensions. The presence of faults and associated disturbances of the rock mases will be required at a more detailed level than would be normally required for conventional oil production purposes. It is also essential to understand the distribution of the remaining oil within the reservoir.

Table 3-5 gives a subjective assessment of the quality of the data that is available in the relevent classifications.

3.4.1 Mechanical Properties and Related Detailed Structural Geological Data

Measured data on the strengths or competency of the rocks in and adjacent to the reservoir are not available and probably do not exist for most oil fields. The limited data regarding competency that is available is in the form of descriptive comments such as "soft," "fissile," etc. in subsurface descriptions, or "cliff forming," "poorly resistant to weathering," etc. for surface exposures. Some degree of speculative estimate (i.e., reasonable assumptions with low accuracy) as to the relative strength of reservoir rocks can be gained from the nature of the lithology, percentage of porosity, and permeability data. For first pass studies a limestone or dolomite with a low porosity and permeability may be assumed to be competent. In the case where such deposits have low porosity but high fluid production although measured core permeability is low, the presence of abundant fractures must be assumed--and rock mass competency must be seriously doubted. Again, as generalized assumption

TABLE 3-5

STANDARD OF AVAILABLE DATA

Oil Reservoir Parameters	Quality of Data
Original reserves	fair to good
Remaining reserve	poor to fair
Production in recent years	good
Cumulative production	good to fair
Thickness of pay zone(s)	good to fair
Average depth to top of pay zone(s)	moderately good to fair
Gravity (^{o}API)	fair
Temperature of oil reservoir	Poor (can be estimated reasonably)
Types of gases present	very poor
Gas/oil ratio	very poor
Gas pressure	very poor
Percent sulfur	fair to poor
Viscosity	poor to fair
Average of porosity of reservoir	good to fair
Average permeability of reservoir	poor to fair (?)
Percent bitumen or oil in rock	fair to very poor
Proved acreage	good
Total probable	fair to poor
Comments on secondary recovery	some information is available but nearly always very incomplete unless it is covered by a petroleum engineering report on the technique.
Oil/water ratio	fair to poor
Water quality in and adjacent to reservoir	poor to nonexistent
Barrels produced per year per acre-foot	fair (but is misleading in mining study since this does not represent in-place content)
Gross structural geology	good to fair

guides for limestones and sandstones, the older the rocks and the lower the porosity and permeability, the more likely they are to be reasonably competent. Conversely, sandstones and conglomerates with porosities of greater than 30 percent and high permeabilities should certainly be considered as probably having low strengths.

The data for estimating relative strengths of the non-oil producing rocks adjacent to petroleum reservoirs is just as limited as that for the producing reservoir rocks. In any case, strength of materials, degree, density and orientation of fracturing, and other specific data regarding the geotechnical characteristics of oil horizons are absent from the literature. There is some strength of materials data available for some of the very large tar sand and bituminous deposits of Utah (Refs. 6, 8, 9, 10, 11, 12); but similar data were not available for the other bitumen or asphalt deposits investigated. Rock competency has the least information available of any of the categories of information needed in the geological part of this study.

Essentially no information exists on the degree, orientation or density of fractures in the reservoir or surrounding rocks. The data on faulting in the reservoirs is developed from cross-sections of widely spaced drill holes and seismic data, and evidence of reservoir flow characteristics. These data are of necessity simplified and only the larger fault structures are presented.

The lack of detailed data on structure results from a combination of factors:

- Widely-spaced drill holes.
- Not all drill holes represent core drilling.
- Data on detailed structure are not required or logged by the petroleum companies.
- Seismic data available to the petroleum geologists is from widely spaced lines which may miss the actual fault structures.
- Representation of structural data in its simplest form and showing only major offsetting faults is generally adequate for petroleum industry purposes.
- Detailed information on structure where available would often not be published.

No measurements of groundwater pressure distribution or the in situ stress fields are available from the literature and such data probably do not exist. This information can be essential to determine the stability of major mine openings.

3.4.2 Hydrological Data

Data on the water content and flow conditions within and adjacent to the reservoir rocks are generally absent in the petroleum literature. However, the presence of an active water drive or details on the volume of water produced per bbl of oil provide some information on the water conditions in the reservoir itself. At times there is data on the quality or chemistry of this water. Infrequently the petroleum literature references overlying or underlying aquifers, or the depth to the water table.

Information on generally shallow-lying aquifers of potable water is contained in federal, state and county groundwater reports. However, these usually do not include much, if any, information on the saline aquifers frequently associated with petroleum deposits. Very shallow oil fields and asphalt or tar deposits are a possible exception to this case of lack of data.

As a general rule, a reasonable level of data on the porosity and permeability of the oil producing zone, or zones, and a history of production of the pool or field are available. Data that are not completely available include reservoir pressures and initial oil saturation. Data which would not be obtained from the available literature include:

- Variation in the degree of saturation of oil, gas and water throughout the reservoir.
- Variability in the relative permeabilities.
- Pressure distribution histories within the reservoir.
- Variation in viscosities of the in-place oil.

3.4.3 Geometry and Geology of Oil-Bearing Zones

The geologic structure of individual oil fields is fairly well documented and described and for those fields where the gross structure is not reported, this could usually readily be accomplished using available well log data. Most oil fields for which there is a published account present a structural contour map and cross-section of the field. The general areal form of the oil distribution is usually shown indicating known total area of oil production. This is essentially always a greater number of acres than the "proven" acreage. Data on major faults is usually provided on the sections and structural contour maps when these significantly displace the oil-bearing zone. Detailed sections and structural maps showing the types of minor faulting that could be of major importance to any mining plan, are not

available. The detailed distribution of the oil is also normally not available from the published literature.

The approximate structural form of the top and base of the oil-bearing subsurface formations is available. However, such information in the detail needed for evaluating a potential mining operation is not available in the published data and probably does not exist for any deposit. The published data on the base of the oil-bearing zones are generalized and frequently show the base of the "productive" oil zone as a planar surface resting on a water saturated zone. In actual fact the oil-water boundary is at best often progressive in character and the base of the zone containing substantial residual oil may well not be planar. Local changes in permeability, the rate of oil production, internal flow characteristics, etc., can be expected to develop an irregular base of the oil in detail, in particular with regard to any cutoff grade that may be selected.

Information on the gross lithology and age of the reservoir rock is generally readily available. In instances where there is no published field description but where production and other records are kept by the various state agencies, there is usually information on the age, the formation name and general rock type of the reservoir rock. Lithologic details within the reservoir are less available and in several instances during the present study the general information on the producing formation had to be obtained from the regional literature on stratigraphy.

As a general rule, detailed lithologic data on the overlying and the immediately underlying units is limited in nature or absent in the field descriptions. In these instances regional data were used. Information on the thickness of units within the field or pool is usually available but is often not precise.

For most fields where there is a published field or pool description, there is a good general discussion of the stratigraphic column. The column published in the field descriptions may not extend much below the lowest producing formation. Usually there are good published stratigraphic columns available in regional or basin studies. One problem with respect to stratigraphic nomenclature is that in some of the older field descriptions, local formation or member names were used. These are frequently at variance with the present day stratigraphic names or boundaries. Where the boundaries between the units have not shifted, this does not represent a problem but where there has been a reassignment of name and/or boundary, it is frequently difficult to equate the relationship of the old to new names using published oil field data alone, and may indeed be difficult using all available published data.

Asphalt deposits represent an even bleaker outlook for structural data and detail. Most of these have not been drilled at all, and those that have been drilled for data on the bitumen were drilled on wide spacings. Surface exposures have been mapped in a few instances. Subsurface form and structural configuration are projections and gross interpretations based on limited information. Only a few U.S. deposits have been studied in more than a limited amount of detail. All representations of structure of the fields used in the present study are from the published literature and are simplifications or caricatures of what must exist in nature. Rapid lateral and vertical variations influenced by primary and secondary structure are the general rule rather than the exception for the asphalt or tar deposits. The details of porosity changes and rapid horizontal variation in bitumen content have not been portrayed, or apparently considered, in previous studies of asphalt deposits. The apparent exceptions to this are the Uvalde district in Texas where some fairly closely-spaced drill data exists (Ref. 4), and the P.R. Springs deposit of Utah with widely spaced, but well documented drilling (Refs. 8, 9, 10, 11).

3.5 CANDIDATE UNDERGROUND MINING SYSTEMS

Theoretically, the mining engineer is faced with an immense array of potential mining methods from which to choose. In practice, however, the methods which would promise satisfactory results in any particular case are usually few, and in extremely adverse circumstances, may be none at all.

Granted a good knowledge of the relavent factors, mainly geological, it is usually relatively simple for an experienced engineer to reduce his options in a specific instance to a manageable number. In this study, however, the problem is complicated by the need to think in "generic" or "typical" terms.

This section of the report, therefore, attempts to catalogue all reasonably possible underground methods and to identify the natural circumstances under which they could be applicable. It has been assumed that the reader possesses a general working knowledge of the principles of mining systems and the descriptions have been kept extremely brief.

"Oil mining" is a term which proves on closer examination to be rather less specific than it at first appears. It has been interpreted, for this study, to include the use of any portion of the array of mining techniques, or their components, to bring about or enhance the production of oil.

The possible approaches fall into three categories:

- EXTRACTION METHODS, involving physical removal of reservoir material in part or in whole to a treatment plant where the oil would be separated from the host rock. These are also referred to as "direct" mining methods.

- DRAINAGE of oil from the reservoir rock by methods which are generally similar to conventional production techniques, including such stimulation methods as steam injection. Advantage would be taken, however, of access to the reservoir area through underground mine workings to produce a higher recovery than can be achieved through surface wells. The methods are often called "indirect."

- FRACTURING AND DRAINAGE systems would employ access to reservoirs underground to first fracture the reservoir rock, probably explosively, and then to recover oil by drainage methods.

Each of these groups of methods is discussed in this section, with particular attention being given to their applicability to varying geologic circumstances, such as rock conditions and the ability of the oil to flow. Three such factors were accepted as general field selection criteria.

Thickness - The vertical thickness of "ore" is clearly a key factor in the applicability of many of the possible techniques and is generally poorly known in comparison with conventional solid mineral deposits. Even where the original oil-saturated thickness is well documented, there may well be a much less reliable level of information on the thickness of residual oil.

Flow Characteristics - The phrase "flow characteristics" covers the range of oil and rock properties that determine the ability of the oil to flow into an excavation or drill hole. This ability will have a significant impact on method selection and performance. As was the case with thickness, this property is not available as a reliable number for each potential field. An estimate of the requirement has however been made for each method, once again in terms of "high" and "low" flow potential.

Rock Competency - This is also a composite characteristic which includes the effects of several individual physical properties such as compressive strength, jointing, etc. For the purposes of this study it is sufficient to form a general judgement of the potential rock behavior in tunnels

or larger underground excavations. Once again a "high" or "low" strength requirement has been accepted as a satisfactory means of determining field/system compatibility. Separate consideration has been given to the oil-bearing zone itself and to the formations that overlie and underlie it.

3.5.1 Extraction Methods

1. Cut and Fill

In a cut and fill operation the deposit is mined by blasting a series of horizontal slices, normally working from the bottom upwards. It is a basic feature of this method that men have to work continuously under the roof of the stope and it is therefore essential that the competency of the oil-bearing zone is high. Limited rock bolt support of this roof, which is also the stope face, can be tolerated but is not desirable.

Within the stope the men work on a floor composed of backfill. This fill would be supplied using de-oiled waste material from the treatment plant and delivered, probably hydraulically, to the stopes. Typically, a stope face would be drilled using stoping drilling jumbos and cleaned using diesel LHD machines. The oil-bearing rock would be dumped into stope passes leading to a haulageway where it would be loaded into trucks, trains, or conveyor belt for transport to the hoisting system.

Depending on the actual competency of the oil bearing zone, 60 to 90 percent extraction could be achieved with a series of primary stopes. Sixty percent primary extraction would be obtained using rib pillars large enough to permit later extraction by the same mining method. Ninety percent primary extraction would be obtained using post pillars and secondary extraction would not be attempted.

Preferably, this method should be used in a low potential oil flow situation. This is basically because in a high flow situation oil will exude into the stope from the rock roof and sidewalls, and from the broken muckpile. There would then have to be some control of this oil which would create a safety hazard and potentially be lost. In high permeability situations (above 500 millidarcies) a further hazard could be caused at the edges of the oil-bearing zone by water entering the stopes.

As the only development in this method is undertaken within the oil-bearing zone, it can be used regardless of the competency of the underlying rocks or, in fact, of the overlying formation provided a skin of competent ore is left to support the final stope hangingwall, if necessary. The most typically normal application of this method is in high value ores where lower production rates and higher costs are acceptable but high recovery is necessary. For oil mining, however, the ore value is low enough to preclude any but the most highly productive, low cost methods. The only form of cut-and-fill worth considering, therefore, is multi-lift room and pillar or rib and pillar mining using fill as a working platform.

2. Longwall

This method was used with some success many years ago in Germany to mine an oil sandstone, in addition to being a well established system for mining coal seams.

In this method, men have to work in very close proximity to the face and face instability could cause unacceptable roof conditions. Reasonably high competency is therefore required in the oil zone. The roof could be formed either by leaving some of the oil-bearing zone, as in coal practice, or by the overlying rocks if they are competent. Despite competent ground conditions heavy supports would be required along the face, and backstowing of de-oiled waste material from the surface treatment plant, would probably be necessary.

To have a productive mining system, the oil-bearing rock should be broken by mechanical means, i.e., shearers, trepanners, ploughs, etc. To allow the use of such machines, the rock should not be above 15,000 psi uniaxial compressive strength. This method would essentially be limited to use in thin oil-bearing zone situations.

Preferably this method should be used in a a low flow situation. In the high flow situation, oil would exude from the solid rock into the openings and from the fragmented rocks. This oil would be difficult to control and would create a fire hazard.

All operations would be carried out in the oilbearing zone and would be independent of the underlying rock

competency. Generally, however, face ground conditions would be easier if the underlying rocks are of high competency.

3. Room and Pillar

This is a highly productive method and is widely used in flat-lying, tabular deposits of many mineral types. It is essentially a partial extraction method with major recovery of pillars rarely attempted.

To achieve as high a percentage extraction as possible and to allow men to work in safety in the headings, a competent rock is required. The entries should be capable of standing open with little support.

This method is essentially for use in a thin oil-bearing zone situation. The maximum extraction height is directly dependent on rock properties but rarely exceeds 80 feet even in the strongest formations.

Preferably this method should be used in a low flow situation. In the high flow situation, oil exuding from the solid and fragmented rock would cause control problems and a fire hazard. All operations would be carried out in the oil-bearing zone and would be independent of the underlying rock competency. In the event of very weak underlying or overlying rock competency, a false floor or roof would need to be left.

4. Sublevel Open Stoping

In this method, ore is broken by blasting in large open stopes and is withdrawn from the bottom of each stope by front-end loaders.

While no men have to work in the actual stopes, relatively large openings have to stand open with virtually no support while the ore is extracted. Thus, high competency is essential. This can either be a partial extraction method with the open stopes left empty, or they can be filled after completion with waste de-oiled material and pillar extraction be attempted.

The ore would be broken in the stopes by drilling and blasting. Oil-bearing rock would be mucked from the

stopes using diesel LHD machines which would load into a truck or rail transport system situated at the base of the oil-bearing zone for removal of the material to the hoisting system.

This method is essentially suited to thick deposits.

While low flow characteristics are preferable, the method could be used in a high flow situation. However, oil exuding from the solid rock into extraction openings and from the fragmented rock would cause a control problem and fire hazard.

All development can be located in the oil-bearing zone and competency of the underlying rocks is therefore not essential. If they are competent, however, the haul-ageway could be sited there to achieve a better percentage extraction. If full extraction is to be achieved, the whole of the oil-bearing zone should be removed and the overlying rocks exposed. If these are weak, a roof barrier of stronger oil-bearing rock would have to be left.

5. Sublevel Caving

In this method the oil-bearing material would be broken and removed on sublevels while the overlying rock continuously caves in and fills the void that is created. It is a full extraction method and would cause major surface subsidence.

On the sublevels the oil-bearing rock would be broken using fan drilling jumbos, and the broken material would be mucked using diesel LHD machines. These would discharge into ore passes which would take the rock down to the haulage level where it would be loaded via chutes into trucks or trains for transport to the hoisting system.

This method is essentially suited to thick deposits. Low flow characteristics are preferable for this method, since high flow characteristics would result in oil exuding from the solid and fragmented rock, causing a control problem and potential hazard.

All development can be located within the oil-bearing zone so that the competency of the underlying rocks is not a constraint. Ideally, however, to improve the

percentage extraction, the haulage should be in the underlying rocks if these are competent.

6. Block Caving

In this system, a relatively thin horizontal slice is broken by blasting and drawn from the base of the ore zone. The main volume of the oil-bearing rock which has been undercut in this way is then allowed to break up using only natural forces. Because the bulk of the ore is required to break without mechanical aid and because men are not required to go into stopes, relatively incompetent rock is necessary.

The undercutting operation would probably be performed using long hole fan drilling and blasting from the drawpoints in the underlying rocks. This initially blasted material, followed by naturally broken material, would flow downwards into drawpoints. Here the material would be loaded by diesel LHD machines for transport to ore passes which would deliver the material via chutes to trucks or trains for transport to the hoisting system. A thick oil-bearing zone is a prerequisite for successful application of the method.

In this method no development is required in the oil-bearing zone so that oil exuding from the fragmented rock would be easy to control and thus would not constitute a hazard. In fact, in the high flow situation, a combination method of drainage and extraction could be used in which, after undercutting and the initiation of caving, oil would be allowed to drain. When significant flow ceases, drawing of the broken rock would commence.

While no men are required to work in the oil-bearing zone, the main extraction development will be in the underlying rocks. Thus, it is essential that these rocks are competent so that these tunnels can be excavated and maintained, with support if necessary.

7. Basis For Method Selection

No study of this type would be complete without including at least one of these direct methods, preferably having as good a chance of success as any of those listed. In practice it was considered that the study should include two systems.

In the appropriate conditions, block caving is by far the most economical of the methods available for mining massive deposits. It was therefore an essential candidate since if block caving could not be shown to be attractive, none of the other mass mining methods would be likely to merit further consideration. The Casmalia deposit in California appeared to possess a large enough thickness of weak oil-bearing rock for block caving. There also seemed to be underlying zones of sufficient competence to support extraction workings and it was therefore selected as the basis for a design of this method.

As a contrast, at least one "stable" mining method was required for study. Such a method would impose the requirement of operation within the reservoir rock and would also have the potential merit of inducing less environmental disturbance, particularly related to subsidence. Historically room and pillar mines have been the most productive and economical of such stable operations and this system was therefore selected for study.

The lack of recorded rock strength data made the search for a suitable field very difficult, particularly since a high grade of residual oil was desired. The Circle Ridge field in Wyoming offered the unusual feature of two flat-lying oil-bearing formations of interestingly different thicknesses and was therefore used on a basis for this design.

3.5.2 Fracturing and Drainage Methods

Such methods rely on a mining operation to fragment the oil-bearing zone so that the contained oil is able to drain more freely than is possible from the solid state. Apart from the natural drainage of the oil, stimulation techniques from above or below the oil-bearing zone could be applied. Only enough of the oil-bearing material would be removed from the mine to ensure that proper fragmentation could be achieved. Three possible such methods were identified.

1. Sublevel Shrinkage

   Drilling and blasting operations would be carried out in a similar way to sublevel caving. However, only sufficient broken material would be removed on each sublevel to enable blasting to continue. Because the method is only geared to breaking and not to full

extraction, the sublevel spacing would be considerably wider than with normal sublevel caving.

Because operations have to be carried out mainly from within the oil-bearing rock, its competency must be high, to ensure that the sublevels can be developed and maintained with little or no support. Drilling from these tunnels would be by fan drill jumbos, and the removal of broken material for swell relief purposes would be using LHD machines in a similar way to sublevel caving.

Development would be required underneath the broken rock zone, either in the underlying rocks or in the oil-bearing zone itself with boreholes connecting to the broken rock mass to enable oil to be drained out and stimulation techniques to be applied if necessary.

This method is essentially applicable to thick orebodies.

To give the best possibility of safety during fragmentation operations, the reservoir rock should preferably have low flow characteristics at that stage. The eventual success of the system, however, clearly depends on its ability to alter that to a high flow situation.

It is preferable that the underlying rocks are competent so that oil drainage development can be sited underneath the oil-bearing zone. However, such development within the oil-bearing zone is possible so the requirement is not critical. The strength of the overlying formations has no impact on this method.

2. Block Caving

This method is basically no different from the block caving extraction method except that draw of broken material would cease when the caving action has been propagated to the top of the oil-bearing zone.

An incompetent, thick oil-bearing rock would be required, and, as virtually no development would be in the oil-bearing zone, the flow characteristic would not be critical to safety. However, competent underlying rocks would be essential.

3. Remote Fracturing

Consideration was also given to inducing fracturing of the rock by drilling and blasting fans of holes from an underlying level. This would essentially be the addition of this fracturing operation to one of the drainage concepts described below.

In such a system, the competence of the reservoir rock would not be a major factor, provided that a zone could be found underlying the oil rich area in which to locate the development.

4. Basis for Method Selection

Of the possibilities listed above, sublevel fracturing was considered the most likely to induce consistent additional permeability throughout the reservoir zone of interest.

It was considered probable that the type of porosity and permeability typically found in carbonate reservoirs might be particularly amenable to this type of system. No ideal field could be identified within reasonable time, so the design was based on the Yates field in Texas, although there are many factors that would preclude its specific suitability for oil mining, not least its long conventionally productive future.

3.5.3 Drainage Methods

This group of methods is the furthest removed from a conventional mining approach but also, possibly, is the most promising of the underground options considered. All are variations of the same basic concept, which is that a network of underground tunnels is developed either in or adjacent to the oil-bearing zone. This tunnel system would provide the locations for drilling holes into the oil zone for production purposes and for stimulation if necessary. The availability of such holes at a greatly higher density than would be economically possible from surface has the potential to produce substantially enhanced recovery in fields of many types.

The systems identified under this heading are only basically different from a mining standpoint by the position in which the tunnel system is located with respect to the oil.

1. Single Level in Oil Zone

This system would correspond to that used in past European operations. It would be suited to a rela-

tively thin oil zone, all of which could be produced through holes of economical lengths, drilled from a single level.

It would require a reasonably competent oil-bearing rock to permit safe and economical development and operation of the system. This must also be coupled with a reasonably high flow potential. The properties of the formations overlying and underlying the oil zone are of no major significance in this system.

2. Multiple Levels in Oil Zone

In the case of an oil-bearing zone that is too thick to produce economically from a single level, multiple level operation would be employed. In all other respects, however, such a system would be similar to the previous one, and would require the same circumstances to be successful.

3. Remote Drainage

As an alternative to tunnelling within the oil-bearing rock itself, a suitable location could be selected in the rock formations either above or below. This arrangement would permit production from fields which might yield more readily but whose rock competence would make operations within the oil zone unacceptably hazardous or expensive.

The presence of a suitably competent, impermeable formation adjacent to the oil zone is the dominant criterion for this method. It could be either above or below but does not need to be both.

4. Basis for Method Selection

It was considered essential to include at least one of these concepts in the study. Examination of the available fields quickly showed the difficulty of identifying with enough confidence any field with the necessary high flow potential coupled with the rock strengths necessary for a safe and productive operation. It was therefore decided to concentrate the study on methods which would take advantage of relatively safe ground conditions in formations adjacent to the reservoir and a search was made for fields having such conditions either above or below.

The Irma field in Arkansas possesses a competent caprock and is adjacent to a field with current experience of steam stimulation. It was therefore used as a basis for studying drainage operation from overlying locations. The Wheeler Ridge field, in California, has, in contrast, a competent underlying formation which appears to be adjacent to a substantial amount of residual oil over an appreciable area. Gravity drainage from below the reservoir was therefore evaluated for this field.

3.6 OPEN PIT MINING SYSTEMS

The number of generic surface mining systems available for oil mining is limited, although the possible variations on them by using different combinations of equipment is quite extensive. This section of the report attempts to catalogue these possible surface mining systems and their variations and to identify the circumstances under which they could be applicable. All of them are extractive methods in which the oil-bearing rock is removed and processed elsewhere. Any drainage of oil into the pit would be additional recovery over and above that recovered in the main processing plant.

Potential surface mining systems can be divided into four categories.

- Strip mining involves the removal of the overburden by an excavating machine that directly transports the material across the excavation and then dumps it in the area from which the ore has been removed. Strip mining is suitable for tabular deposits that are either flat or have a very shallow dip, of less than 10 degrees. The maximum overburden depth should be about 150 feet, and the overall pit depth should not exceed approximately 200 feet. Depending upon the equipment used, reasonable highwall and dump stability are required, otherwise insufficient working room could result. If draglines are used, it is preferable that the overburden material be average to soft, though with good blasting, hard overburden can also be handled. If bucket wheel excavators with direct casting bridges are considered, the overburden must be unconsolidated. The limits of strip mine operations are usually determined more by the capacity of the equipment than by the economics of the deposit.

- Terrace mining involves the removal of the overburden by excavating machines and the transporting of the material around the pit on the level from which it is

excavated to be dumped back into the pit in the area from which the ore has been removed. Terrace mining requires a reasonably tabular deposit with a large areal extent. Other than these two factors, the system is fairly flexible. The excavating and transporting systems employed are very dependent upon the characteristics of the material being mined. The limits of terrace mining are generally set by the economic limiting stripping ratio.

- Combination of Terrace Mining and Strip Mining - In this method, the upper overburden material is removed by terrace mining and the last cut to the ore is made by strip mining. This system is able to achieve greater depths than normal terrace mining due to the relatively low cost of stripping the last 100 feet of overburden material. It is a flexible system since as the overburden increases in depth, the terrace mining system handles the extra material that the dragline cannot remove.

- The open pit method involves the removal of the waste material up grades by truck, conveyor, train, etc., for dumping outside the excavation limits. If the topography permits, level hauls to waste dumps can be achieved; however, usually an upgrade haul is encountered. The true open pit method has the greatest flexibility of all four systems, but also, in general, has the highest cost. In this case the limits of operation will be determined directly by the economic stripping ratio.

3.6.1 Overburden Removal

1. Strip Mining

Five different systems of strip mining were considered.

- Dragline - As with all strip mining systems, the dragline has a depth limitation. However, it can handle all forms of overburden whether they be hard, average or soft. The characteristic of the hangingwall of the ore itself do not affect the operation of the machine since it sits on the overburden material. Highwall and dump stability factors with dragline operation, however, are critical. If instability occurs in either the highwall or the dump, the low slope angles that will have to be adopted may make it impossible to reach the ore or to provide sufficient dump room. In addition, the area exposed for ore

mining may be too small to permit an efficient mining system. The method has, however, a high productivity since it is a direct casting system not requiring secondary haulage operations. The scale of operations can be variable and still operate economically.

- Stripping Shovel - Strip mining using a stripping shovel can handle all forms of overburden whether hard, average or soft, but this system is very dependent upon the equipment's ability to operate satisfactorily on the hangingwall material of the orebody. Shovels are less flexible than draglines and have fallen out of favor with operators for this reason (as evidenced by the fact that the last large stripping shovel went into operation in 1964). However, they do have application where the highwall is too unstable to operate a dragline on, but not sufficiently unstable to put the shovel at risk from failure of the highwall. Dump stability needs to be reasonable for the same reasons.

- Bucket Wheel Excavator (Direct Casting or in Combination with a Bridge Conveyor or Beltwagon). This system is primarily proven for use in unconsolidated overburdens, since to date there has been no really successful application of bucket wheel excavators in the excavation of blasted materials. The bucket wheel excavator requires that the hangingwall of the ore zone be reasonably competent since the machine stands at the toe of the overburden slope on the ore. The degree of dump stability is only a problem when using a bridge conveyor which travels on the dump itself. This can be overcome by having the main drive for the bridge conveyor operating on the footwall material or by using a belt wagon on the ore or the footwall. A further method of overcoming this problem is by having a long direct casting discharge boom. This system is generally applicable to medium or large operations only and can result in a low cost per ton in the correct ground conditions.

- Face Shovel and Bridge Conveyor - This system can be used in average and soft overburdens only and is very dependent upon the amount of material in the overburden too large for the conveyor to handle. The bucket wheel excavator with its much smaller bucket size per unit of output capacity cannot pass such oversize material to the conveyor but a face shovel, with its very large bucket, does not carry out any such selective sorting. Consequently, it would appear that even in well-blasted

overburden this system would be somewhat inflexible and inefficient. The system requires that the upper surface of the ore be reasonably competent to permit the machine to stand on it. Since the machine is operating at the toe of the highwall, reasonable highwall stability is also essential. As with the previous system, dump stability is only a problem if the bridge conveyor travels on the dump. This system can really only be considered in medium or large operations, primarily due to the cost of the bridge conveyor.

- Face Shovel-Crusher-Bridge Conveyor - This combination system can be used for hard, average or soft material, but does require that the hangingwall of the ore is reasonably competent to permit the equipment to operate. The highwall must be stable and the same factors apply regarding the dump stability as discussed in the previous paragraph. The method is only applicable to medium or large-scale operations, since the crusher-bridge conveyor complex is too expensive for small scale operation.

2. Terrace Mining

The terrace mining system requires reasonably tabular deposits of large extent and is limited by slope stability and the economic stripping ratio. Seven systems can be considered.

- Bucket Wheel Excavator and Terrace Conveyor - This system has really only demonstrated its practicality in unconsolidated overburdens, but is now being considered for average and hard overburdens using the latest heavy-duty BWE technology in combination with effective blasting of the material to provide good fragmentation. This system requires that the overburden and the ore be reasonably competent to support the machine and its ancillary equipment. It is applicable only to large and medium scale operations since it is a high initial capital cost system. However, its advantages increase with increasing scale of operation.

- Face Shovels and Trucks - This is an extremely flexible system that can be used in hard, average or soft overburden. It does require that the overburden and the ore be reasonably competent so that the equipment can work on the surface. It requires that both the highwall and the dump area have reasonable stability,



since it is essential to construct and maintain suitable haul roads which, in unstable conditions, can be expensive and depend upon the availability of suitable haul road construction material. This system is very applicable to small and medium scale operations and to a certain extent in large scale operations. In very hard blocky ground conditions, it has few competitors.

- Face Shovels and Conveyors - This system is of great value in situations where long hauls are involved and where haul roads would be expensive to install and maintain. However, these advantages can be negated by the necessity for frequent moves of the conveyor. It cannot be used in hard rock even after blasting due to the oversize material that could be fed to the conveyor. This problem also exists with average and soft rock although to a far lesser extent. The system is applicable where ground and dump conditions are unsuitable for the use of dump trucks. This method is primarily for use in medium or large-scale operations since conveyors are only competetive at high throughputs.

- Face Shovels Plus Crusher Plus Conveyor - This system is essentially the same as the previous one except that a crusher is introduced between the shovel and the conveyor. This permits it to be used in soft, average or hard material, since all the material is sized before transportation. The system is applicable to medium and large size operations only, as high throughput is required to keep unit costs reasonable.

- Scrapers - This system is only applicable where short hauls, bad operating conditions or small scale operations are under consideration. It is normally applicable only to soft unconsolidated overburdens, but could be used in average overburdens if this material is rippable.

- Rubber-Tired Loaders and Conveyors - This method is applicable to soft and average types of overburden and, as described in a number of the other systems above, is limited by the size of the overburden material which can be handled by the conveyor. This system requires that the hangingwall of the ore be competent to permit the machine to operate. The method is particularly applicable to medium and large-scale operations and in the correct application can provide a very high capacity at low cost.

- Rubber-Tired Loaders and Trucks - This system is applicable to soft and average overburdens and possibly hard overburdens if blasting is used. Reasonable highwall and dump stability is required for construction of haul roads and the hangingwall of the ore should be competent to permit the machines to operate upon it. The applicability of this method to medium and large-scale operations ensures greater flexibility but results in higher operating costs than alternatives utilizing conveyors.

3. Terrace/Strip Mining Combination

This system requires reasonably tabular deposits of a large area and is limited by the economic stripping ratio and wall stability. It is capable of going to greater depths than terrace mining, however, due to the cheaper bottom cut by strip mining. Any combination of the terrace mining and strip mining methods described above can be used.

4. Open Pit

Open pit mining will handle any configuration of orebody that can be mined from an economic and stability standpoint. There is little variation available on the shovel and truck system, except perhaps the shovel-truck in-pit crusher-conveyor system as employed at Twin Buttes in Arizona.

3.6.2 Ore Mining

Three systems of ore mining are available for consideration. These are:

1. Strip or Terrace/Strip Combination

This system has limited operating room and is somewhat inflexible. The inflexibility is reduced if a bridge conveyor system is used. The two best options in this case appear to be as follows:

- If a good footwall exists, shovels and trucks would be the best selection.
- If a poor footwall but good competent ore exists, a backhoe or dragline feeding trucks would be the best combination.

In both of the above case, poor highwall stability could result in very high costs for haul road construction and maintenance.

2. Terrace Mining

This system has much greater flexibility in stripping the overburden and therefore generally the ore mining is not quite so constrained as far as operating room is concerned. The options available for terrace ore mining are:

- If a good footwall exists, shovels and trucks.
- If a poor footwall but good competent ore exists, a backhoe or dragline feeding trucks could be used.
- If the ore is soft, a combination of a bucket wheel excavator and a conveyor could be used.
- If the ore is reasonably hard and thick, a shovel-crusher-conveyor system could be used.
- If thin ore or hard ore is encountered, the flexible system would be a shovel-truck-crusher-conveyor system.
- A Holland loader-bulldozer-conveyor system can be used in soft ore.

3. Open Pit

This system is limited to shovels and trucks, although in the correct situation an in-pit crushing system plus a conveyor may be applicable. In the ore mining operation, haulage is likely to be the major cost element. The selection of the haulage system will primarily be dependent upon the length and gradient of the haul profile and the ground conditions encountered in the haul profile.

3.6.3 Basis for Method and Field Selection

The surface mining methods described above are usually far lower in cost per ton of material extracted than any underground method. It was consequently decided to evaluate, if suitable fields could be found, each of the four generic surface mining systems.

1. Strip Mining

As described above, the strip mining system is suitable for shallow, less than 150 feet, flat-lying deposits

since the economic advantages of the system are limited by the capacity of the equipment to dig to depth. Because of the lack of detailed data on some of the close-to-surface heavy oil or bitumen deposits, not many candidates were immediately available. One field, however, had the ideal geometry for strip mining, namely the Santa Cruz field in California. This field is unfortunately small; however, the strip mining system is quite flexible with regard to size though obviously in a small field the economies of scale cannot be taken advantage of.

2. Terrace Mining

The terrace mining system is ideal for large flat-lying or gently dipping deposits where advantage can be taken of level hauls and dumping back into the mined areas is feasible. This system can be an extremely low cost producer, providing that the deposit is shallow. Costs increase rapidly with depth. An ideal candidate field which meets virtually all the criteria for a terrace pit is the Kern River field in California. This particular field is very large and lends itself to high tonnages and the mechanized approach of bucket wheel excavators.

3. Combination Terrace Pit and Open Pit Mining

One of the four generic systems described is the combination terrace/strip mine. No suitable candidates could be found for this system; however, a candidate was found for an alternative combination system. The alternative system is a combination terrace/open pit system, hereafter referred to as a modified terrace pit. In this system the first cut of the overburden, which does not lend itself to terrace mining due to depth and topography, is removed by an open pit mining system and the last cuts of overburden and ore are removed by terrace mining. An ideal candidate for this system is the bitumen deposit at Sunnyside, Utah. The same equipment, trucks and shovels, will be used for both the open pit and terrace pit portions of the operation.

4. Open Pit Mining

The fourth generic surface mining system is the traditional open pit mining system which has the greatest flexibility of all the systems. This system can be applied to any potential surface mining

operations. The candidate chosen for the open pit mining system is Edna, California. This orebody has a geometry similar to many metallic and non-metallic deposits and will necessitate mining to some depth below the topographic surface.

Summary of Candidate Fields and Selected Mining Systems

The candidate fields chosen for further study in this report and the mining system selected as being the best method for extracting the remaining oil from each field are summarized on Table 3-6.

TABLE 3-6

CANDIDATE FIELDS & SELECTED MINING SYSTEM

Candidate Field	Mining System	
UNDERGROUND	GENERAL TYPE	METHOD
Casmalia	Extraction	Block Caving
Circle Ridge	Extraction	Room & Pillar & Cut & Fill
Yates	Fracturing & Drainage	Sublevel Shrinkage
Irma	Drainage	Remote Drainage (above oil zone)
Wheeler Ridge	Drainage	Remote Drainage (below oil zone)

		EQUIPMENT TYPE	
SURFACE	GENERAL TYPE	OVERBURDEN REMOVAL	ORE MINING
Santa Cruz	Strip	Dragline	Loaders Trucks
Kern River	Terrace Pit	Bucketwheel Excavator Conveyors Stackers	Bucketwheel Excavator Conveyors Stackers
Sunnyside	Modified Terrace Pit	Shovel Truck	Shovel Truck Conveyor
Edna	Open Pit	Shovel Truck	Shovel Truck

CHAPTER 3
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4.0 DISCUSSION OF PROCESSING AND ENVIRONMENTAL FACTORS

4.1 PROCESSING

4.1.1 Problem Definition and Background

The processing of oil-bearing materials is probably the least understood area in oil mining technology since the only work in this area has been primarily at a laboratory scale or, where commercial operations exist, is tailored to a unique deposit such as the Athabasca tar sands.

The ultimate objective of any oil mining operation is to produce an oil-rich concentrate which can be marketed directly to a conventional oil refinery. The oil-rich concentrate in certain cases would be the product from underground "thermal" mining and may contain a high proportion of water, steam condensate, and entrained sand and silt. In other cases, it might be the product from a hot water (flotation) process or it might be mixtures of hydrocarbons distilled and condensed from some thermal or solvent extraction process. As is the case in hard rock mining for other minerals, each deposit will exhibit certain unique characteristics that may affect the extraction processes. In any of the proposed operations, the orebody will exhibit localized variations in porosity, grain size and silt content. These variations will affect the response of the material to subsequent oil recovery processes.

It is essential that the oil recovery method employed in an oil mining project be specially designed to handle the product from oil mining and to efficiently recover the oil as a marketable product at low cost.

Considerable background experience exists in oil recovery from tar sands, heavy oil sands and oil shales. The extraction of certain naturally occurring waxes in coals has provided some experience in hydrocarbon flotation and solvent extraction. However, due to the long prevailing low prices for crude oils and the abundant supply from oil wells, in the past there was little incentive to develop and apply oil recovery methods to heavy oil and tar sands.

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Probably the first investigators of oil recovery from oil sands were employees of the Pechelbronn oil mines in the Rhine Valley, where oil mining began around 1745 and was most active in 1918. However, due to the small extent of the deposit and the high costs of underground mining, only a small volume of oil-bearing sand was actually mined and brought to the surface for processing. The bulk of the oil was recovered by gravity drainage into mine openings, as discussed in Chapter 2.

The U. S. Bureau of Mines operated a pilot plant for heavy oil recovery from tar sands in 1948 and published their findings in RI 4871 and 4246. High recoveries were obtained with a simple hot water froth flotation scheme. Subsequently, much work has been done by the developers of the Athabasca tar sand deposits. Presently there is one project in commercial operation and a second will come into production shortly. Both projects are employing a hot water process.

4.1.2 Oil Recovery Methods

Broadly, there are three basic methods for recovering the oil or hydrocarbons from oil-bearing, naturally occurring materials such as tar sands, bituminous sands, heavy oil sands and related petroleum-bearing reservoir rocks. They are:

- Hot water flotation
- Solvent extraction
- Pyrolysis or retorting and thermal distillation.

The simplest and probably the cheapest method is hot water flotation, supplemented by the use of mechanical scrubbing or attrition devices, surface active chemical additives and hydrocarbon solvents for "thinners."

Solvent extraction processes can be highly efficient, but involve hazards from explosion and fire because the solvents usually are highly combustible. In addition, solvent loss through absorption in the solid mineral residues has resulted in high operating costs.

Pyrolysis or retorting-thermal distillation can efficiently recover the hydrocarbons and, in effect, partially accomplishes some oil refining steps by stage-removal and condensation of the more volatile constituents. The method also involves hazards similar to those encountered in solvent extraction, such as from explosion and fire. Other special problems include buildup of tars and cokes, dust entrainment in the gas streams, and, finally, disposal of the hot residues.

Although oil shales are completely different from the average conventional oil-bearing reservoir rocks, the recent intensive work on production of shale oil has resulted in the development of some highly efficient, low cost pyrolysis methods for extracting the kerogen values in the shale. It seems likely that some of those methods and the equipment by which they are carried out could have application to the recovery of oils from oil mining operations. Also, the development of high volume, low cost, pyrometallurgical processes for the production of oxide iron ore pellets in traveling grates, grate-kiln and shaft furnace equipment should offer some interesting potential process ideas for pyrolysis recovery of values from oil-bearing materials.

Although current literature contains very little information on the development of heavy oil recovery processes, there is active study and research going on in the laboratories of certain major oil companies who control, or are interested in, heavy oil deposits. Also, the Department of Energy, Division of Oil, Gas and Shale Technology, headquartered in Bartlesville, Oklahoma has begun to fund programs to evaluate and core drill the shallow heavy oil resources of southeastern Kansas, western Missouri and northeastern Oklahoma. This work should eventually lead to investigations of methods for the extraction of the heavy oils from deposits in those states by methods other than "in-situ," and thereby stimulate and revive government research work on oil recovery processes.

4.1.3 Description of the Various Recovery Methods

1. Water-Flotation Process

The hot water-flotation process now in use at the Great Canadian Oil Sands operation on the Athabasca tar sands has proven to be positive, efficient and low cost. As mentioned earlier, the same basic process was piloted by the U. S. Bureau of Mines in 1948. The process utilizes equipment of more or less conventional design and commercial availability.

The objective of the process is to decrease the viscosity of the bitumen or tar with hot water, and remove it from the sand grains by means of mild attrition scrubbing (aided by sodium hydroxide) and by utilizing the natural froth flotation amenability of oil-sand-and-water mixtures.

For ease of reference, a simplified extraction plant flowsheet for the GCOS operation and the flowsheet of

the U. S. Bureau of Mines pilot plant work on the Edna bituminous sandstone are shown in Figure 4-1. Recoveries of from 90 to 95 percent of the bitumen are reported. Because practically no crushing and grinding are required, which steps are usually the highest cost in metallic ore processing, the operating costs are low. The heating of the pulp is probably the most expensive step in the process.

Where bitumen and clean sand are the major constituents of a low-clay tar sand feed to the process, excellent separations are made. However, when there is a high clay and silt content in the feed, appreciable amounts of the oil become trapped in a middling product and fail to separate into the froth layer. In the GCOS process this problem is addressed by the separate treatment of the middlings in a scavenger circuit followed by a froth settling step. In addition, a final bitumen cleanup step is applied by thinning the product with naphtha and centrifuging out the majority of silt, water and fine sand. The naphtha-bitumen mixture is sent to a naphtha recovery section of the refinery where the naphtha is recovered for recycling prior to coking of the bitumen.

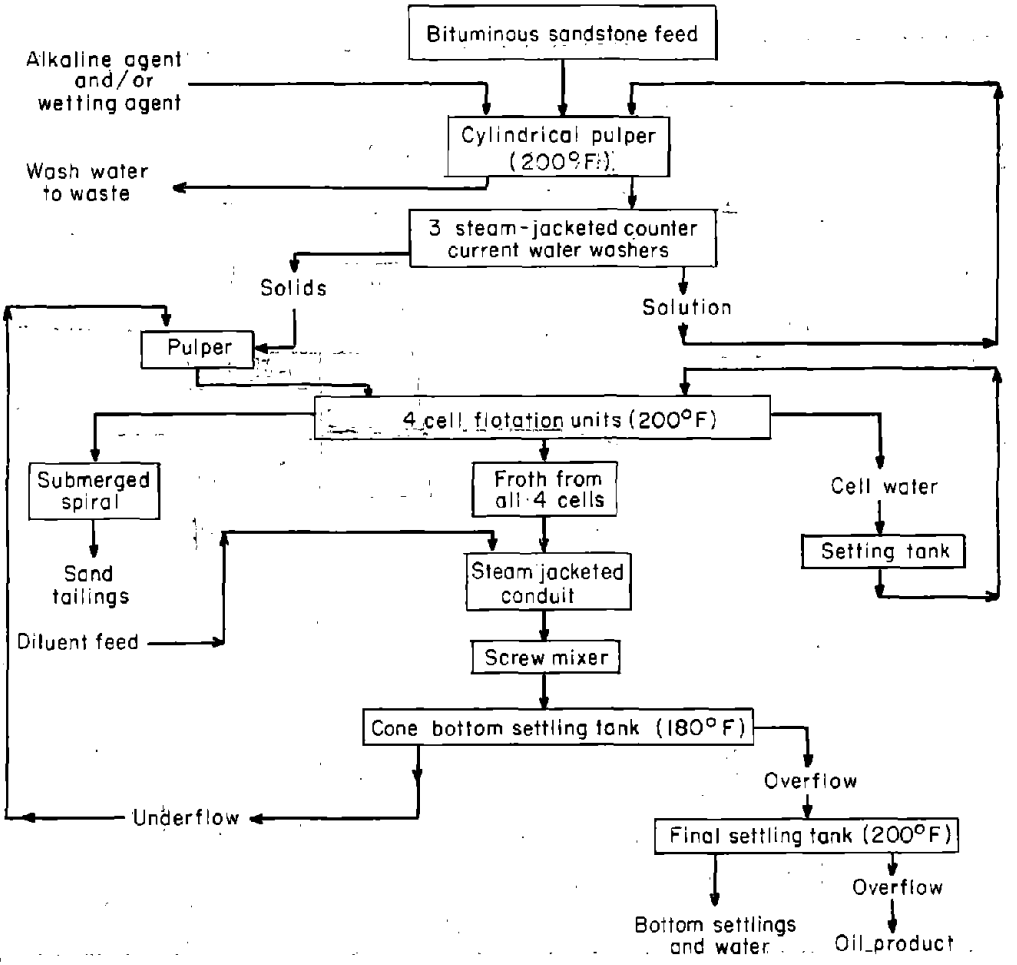
Most silt and slimes which are dispersed into the ore pulp during processing remain with the sand tailings and because of the dispersed pulp condition (resulting from the use of sodium hydroxide) create difficulties in clarifying the tailings waters in tailings basins. However, parallel problems often occur in the treatment of phosphate rock, taconites and porphyry copper ores, and schemes such as accelerated settlement, flocculation, etc., have been developed to cope with the problem. Silt contamination in the final bitumen product is a more serious problem and must be strictly controlled.

In comparison with solvent extraction and pyrolysis or retorting processes, the tailings from hot water flotation processes are more readily disposable in impoundment dams and the coarse fractions can be isolated for backfilling of the mine if desired. Problems associated with disposal of dry, dusty and/or hot residues from oil extraction are thereby avoided.

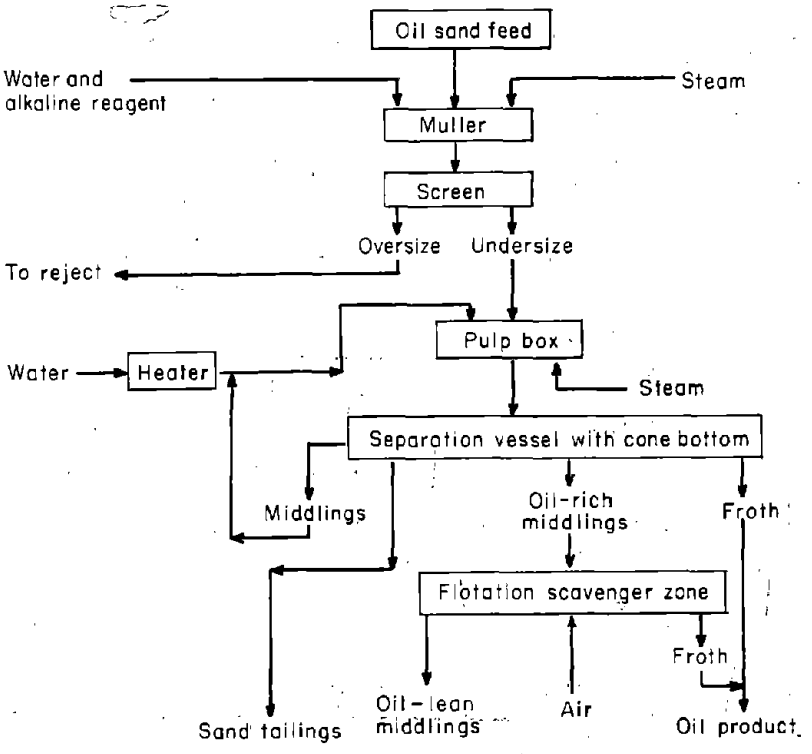
Most investigators agree that the high recoveries obtained with the hot water flotation process on the Athabasca tar sands are due to a special natural condition wherein the sand grains are water-wetted rather

SIMPLIFIED FLOW SHEETS FOR USBM AND GCOS OIL EXTRACTION SYSTEMS

Figure 4-1



USBM HOT WATER EXTRACTION PROCESS



GREAT CANADIAN OIL SANDS HOT WATER PROCESS

than oil-wetted. This may not be the case with many other tar sands and oil sands, and hence will affect oil recovery by this process. However, application of more intensive mechanical agitation via scrubbers and attritioning machines should improve removal of the oil from surfaces of the sand. If there is a high silt content in the feed, the more intense mechanical scrubbing will aggravate problems associated with silt dispersion in the ore pulps and subsequent contamination of the oil product.

Due to the extremely fine particle size of the diatoms which make up diatomaceous earths, it is highly unlikely that a hot water process can be employed to recover oils from such materials.

2. Solvent Extraction Processes

If an oil-bearing sand, shale, limestone or diatomaceous earth is leached with a suitable low viscosity hydrocarbon solvent, the oil can be dissolved in the leaching agent and thus be extracted and washed from the solid material. Subsequently, the oil must be separated from the solvent so that the solvent can be recycled to the leaching stage.

At first glance such processes appear simple, positive and low cost. However, there are serious problems associated with the volatility of the solvent and solvent-oil mixtures, and loss of solvent due to absorption in the solid residues. Hazards from explosion and fire are extreme and maintenance of vapor seals throughout the processing steps pose formidable problems to the designer and operator. The literature contains relatively little information on pilot plants or actual operation of solvent extraction plants for oil recovery. Some plants have been built for extraction of special waxes from certain coals using hydrocarbon solvents, and one was known to have been destroyed by fire not long after setup.

Because the leaching step must be carried out on relatively dry material, residue disposal may have to contend with dusts and residual absorbed solvent vapors which will present environmental problems. There are several alternates for the actual leaching step but the washing or rinsing cycle must be followed by vacuum filtering in order to achieve low solvent losses. Filtering costs generally are high both in capital and operation.

As is the case with retorting or thermal distillation, recovery of oil by solvent extraction overlaps the refining of oil because separation of the solvent and oil necessarily must be accomplished by distillation. The capital costs therefore would probably exceed those for a simple oil recovery process plant which yields a crude oil suitable for marketing to a conventional oil refinery, since a partially refined oil would be the end product.

3. Pyrolysis or Retorting and Thermal Distillation

The application of simple heating can achieve partial oil recovery from high-viscosity crudes contained in sands and related reservoir rocks, and this principle is utilized in the "in situ" steaming of oil reservoirs. However, much of the oil remains on the material and recoveries therefore are low. If the degree of heat application is sufficiently high, virtually all the oil can be removed, some by distillation and some by combustion. Here, as in solvent extraction processes, the oil recoveries by pyrolysis or retorting overlap the field of oil refining because the distillation products must be condensed from gas streams at various temperature ranges.

Large amounts of money have been spent in recent years to develop methods for retorting the kerogens from oil shales and several ingenious processes, plus the related specially designed equipment to carry them out, have been operated in large-scale pilot plants. However, there are significant differences between oil shales and tar sands or oil sands, both in physical properties and in the character of the contained hydrocarbons. Most of the oil shale retort feeds are far coarser than any oil sand and if an oil shale retort were fed with oil sands, there is a good possibility that it would not function. However, briquetted or agglomerated oil sands might be handled.

Among the better known retorting and distillation methods for hydrocarbon recovery are the TOSCO and Paraho processes for oil shales and the Lurgi processes for coal, shales and tar sands. The Lurgi Ruhrgas (LR) process for producing synthetic crude oil from fine-grained coal has been in commercial operation and many variations have been tested on tar sands.

All pyrolysis processes suffer from the disadvantage of heat requirement to remove moisture from the incoming feed. Diatomaceous earths, for example, may contain from 20 to 30 percent moisture as well as a high oil content. Recovery of heat from and the disposal of the residues of the final coking step in pyrolysis is also a problem.

Some interesting results are reported recently with processes which incorporate a single, circular traveling grate for the sequential drying, distillation and coking steps. Tar sands probably will require briquetting or agglomeration akin to pelletizing before they can be handled on traveling grates. Among the advantages offered by circular traveling grates are high capacity, positive gas seals, sintering of the depleted residues and positive mechanical control of material flow through the process. Most of these features have been proven by many years of operating experience in the pelletizing plants of the taconite iron ore industry.

4.1.4 Necessity for Testing and Pilot Plant Operation

In common with all mining ventures which treat the run-of-mine material in a processing plant, it is necessary to design the plant to handle the variations which may occur in the plant feed. Usually this calls for close coordination between the geological, mine engineering and metallurgical departments that are responsible for the overall project development.

For any oil mining project the same requirement exists. It is essential to conduct test work on samples which will represent as closely as possible the type of material that will be delivered to the processing plant bins by the mining operation. Fresh core from drill holes, or fresh bulk samples from test pits and tunnels, must be supplied to the laboratory or pilot plant.

The percent moisture in the mined material is highly important where pyrolysis methods are employed because of the high energy requirement to evaporate such water. The aging of hydrocarbon-bearing material is also important because oxidation may affect behavior in processing. It is also important during sampling and testing to evaluate the effect of high proportions of normally minor amounts of deleterious material such as silts, shale layers, clays and erratic rock masses.

No orebody is completely homogeneous and this is especially true in the case of reservoir rocks which may vary widely vertically and horizontally in physical characteristics as well as in oil and water contents.

The best assurance for a successful oil mining-processing venture is to base it on a pilot mining and processing operation. In order to avoid risky extrapolations from very small scale tests, a pilot plant operation having a capacity of about 3,000 tons of oil-bearing feed per day should be installed. The costs for such a pilot mine and processing plant will be substantial but well justified when it is considered that a commercial mining venture probably would not be smaller than 30,000 tons per day and most likely would be constructed in stages aimed at an ultimate capacity of 100,000 tons per day and costing around $500,000,000. The incentives and rewards for a correct plant design are therefore extremely high.

Of equal importance is the need to supply substantial quantities of the oil products from the plant to potential buyers or refiners and thereby determine the market value of the product.

4.2 ENVIRONMENTAL FACTORS

The environmental impacts of the proposed oil mining operations are obviously site specific and will vary depending upon the mining method proposed and the specific geographical location. The detailed quantification of the possible environmental impacts at each of the operations is premature until a more detailed study of the individual sites could be conducted. However, it is possible to qualitatively assess the types of impact that might occur and their potential significance.

The environmental impacts that will be general to all of the potential operations are examined in this section, and more site specific impacts are discussed in the relevant operation sections. The four areas that must be considered in general for all the operations are: 1) the compliance of the operation to environmental regulations; 2) the environmental impacts associated with mining the material and the dumping of waste; 3) the environmental impacts associated with processing the ore; and 4) the environmental impacts associated with the community support facilities.

4.2.1 Environmental Regulations

There are numerous federal, state and local laws and regulations governing the extraction and processing of minerals.

These laws and regulations vary widely in the amount of regulation imposed and the number of permits required for the operation to proceed and to continue operating. Presently these regulatory procedures are in a state of flux with many regulations being modified and many added.

Federal requirements include compliance with laws regarding surface mining, water pollution, air pollution, employee safety (MSHA and OSHA), toxic substances control, endangered species and general environmental impacts. Many of these laws necessitate the obtaining of permits prior to proceeding with work. Most of the states have similar laws which require permits. Local requirements usually encompass health and safety, and zoning on land use control.

In general, it does not seem likely that oil mining operations will have excessive or absolutely unique problems in complying with the great majority of these requirements.

4.2.2 Impacts Associated with Mining and Waste Disposal

The proposed mining methods for the oil mining operation are both surface and underground mining techniques. The potential environmental impacts will obviously vary with the type of mining system used.

Surface mining will require the removal and disposal of substantial quantities of overburden. The actual removal of the overburden and oil-bearing material will create substantial quantities of dust during drilling and blasting, where applicable, and in loading and hauling. Water courses that cross the areas to be mined will probably require diversion or, in the worst case, impoundment. Vegetation will be removed and consequently the erosion potential could be increased. In certain cases, the groundwater regime will be altered.

Since the surface mines are open to the air, the risk of explosion due to flammable gases is reduced when compared to underground mining. The use of backfill dumping in the pit with the consequent deposition of tailings on top of the overburden may increase the potential for leaching of chemicals. These chemicals could come from the extraction process or from the natural leaching of minerals. The revegetation of reclaimed areas may be necessary. The operation of equipment will create noise which will impact on the surrounding countryside.

Underground mining will result in less surface air pollution than open pit mines since the majority of the dust and gases will be entrained by the ventilation system, whose discharge can be controlled. The risk of exposure to explosive or

toxic gases is higher to underground miners than in the open pit mines. With certain mining systems, the potential subsidence of the natural ground surface could occur. In the worst case this subsidence could be equal in displacement to the mined out thickness of the orebody. In most cases mine water inflow will have to be pumped out of the mine and will require treatment before disposal or reinjection back into the ground. Some of the proposed operations will be backfilled, which will increase the potential for chemical leaching into the groundwater regime. Equipment noise impacts will be great in localized areas of the mine.

4.2.3 Impacts Associated with Processing

The majority of the extraction processes suggested utilize dry crushing followed by wet grinding and extraction of the oil by hot water, steam, flotation or solvent extraction. There will be dust generated during the crushing operation which will cause a localized impact; however, dust control equipment will prevent any excessive general impact. The water used in the grinding and extraction circuits will be recycled to absolutely minimize losses to the environment and makeup water will be added as necessary. The need for a large water supply in water short areas may impact the local groundwater table.

During the dewatering, desludging, and oil/gas separation operations substantial amounts of odor could be produced. Hydrogen sulfide is the principal contaminant, with other organic sulfides and mercaptans present in smaller amounts. These odors can be detected by humans at very low concentrations (parts per billion) and consequently very small quantities can produce an adverse impact. Odor treatment will be necessary in most cases, especially in those fields close to population centers. There will be some evaporation of volatile hydrocarbons during both the mining and the processing operations.

In addition, the process plants may have to comply with the new Source Performance Standards and Prevention of Significant Deterioration Standards under the 1977 Federal Clean Air Act. Emissions of pollutants into Class I (pristine) areas may necessitate the use of the best available air pollution control technology in the process plant regardless of its location.

4.2.4 Impacts Associated with Community Support Facilities

Indirectly associated with the mining operations will be the facilities required to accommodate the employees and their families. For each person employed at the mine there are others that are subsequently employed to provide the various services including grocery stores, clothing stores, cars, real estate and

the myriad of other services necessary for a complete community. In addition, public services such as police and fire protection, schools, road construction, parks, etc., and utilities such as sewer, water, electricity, and telephone must be provided for the community. For each person employed in a basic industry, it is estimated that two additional jobs are created to provide these services. With the addition of families, an average of seven persons are added to an area with the addition of each job in a basic industry. Obviously, in some instances massive infrastructure will already exist in the area and consequently the impact from an oil mining operation in that area would be small.

Also related to the community structure is the possibility that a project in a remote location has for creating a boom-bust cycle. If the mining activity proposed is the sole or major contributor to the area's economy then there can be a potentially severe long-term impact when mining is complete. In the more remote locations, an entire community may have to be quickly built with all the related support services and utilities creating a boom economy. When the mining is completed then the community is left without a principal source of employment, the services required are reduced, and the population declines drastically. Of course, if the project is close to an existing population center which is dependent on other industries, this boom-bust effect is minimal.

The specific impact of each project on its surrounding area will be discussed in more detail in Chapters 5 and 6. Population estimates for the surrounding communities are 1975 revisions derived by the U.S. Census Bureau.

5.0 UNDERGROUND MINING SYSTEMS

This chapter contains brief descriptions of each of the five underground operations designed in the course of the study, together with comments on their technical feasibility, safety, and other significant features.

Throughout the design of all of these examples problems were encountered, with varying degrees of severity, as to the basic practicality of the schemes. This was particularly so where mining would actually take place in reservoir rock. Difficulties were also encountered with either a lack of geological data or an emerging geological picture which diverged from the properties favorable to the system being evaluated. It was considered essential, however, that all of the potential methods were carried right through to economic evaluation, even if that required that some far-reaching assumptions were made as to their safety during the design stage. Only in this way could the concept be given any ranking at all, and a determination made as to whether there appeared to be a large enough potential profit margin to allow major extra costs to be incurred in offsetting the problems.

5.1 DIRECT STOPING METHODS

5.1.1 General Description

One of the main direct mining systems which was considered to deserve evaluation in this study was extraction of oil-bearing rock by room-and-pillar or open stoping methods. The Circle Ridge field, in Fremont County, Wyoming appeared to offer suitable conditions in two separate zones for such mining. Key properties of the Cricle Ridge field are summarized in Table 5-1. This was particularly so as the field contains two relatively flat-lying oil-bearing formations, of differing thickness, both in reasonably competent rock.

The Circle Ridge Oil Field is located in T.6-7N., R.2-3W., W.R.M., Fremont County, Wyoming. The field lies approximately 28 miles east of the town of Dubois and 50 miles northwest of Lander, Wyoming, in the northwestern portion of the Wind River Basin (Figure 5-1). Circle Ridge is one of approximately 60 oil and gas fields in the basin. This field produces oil from

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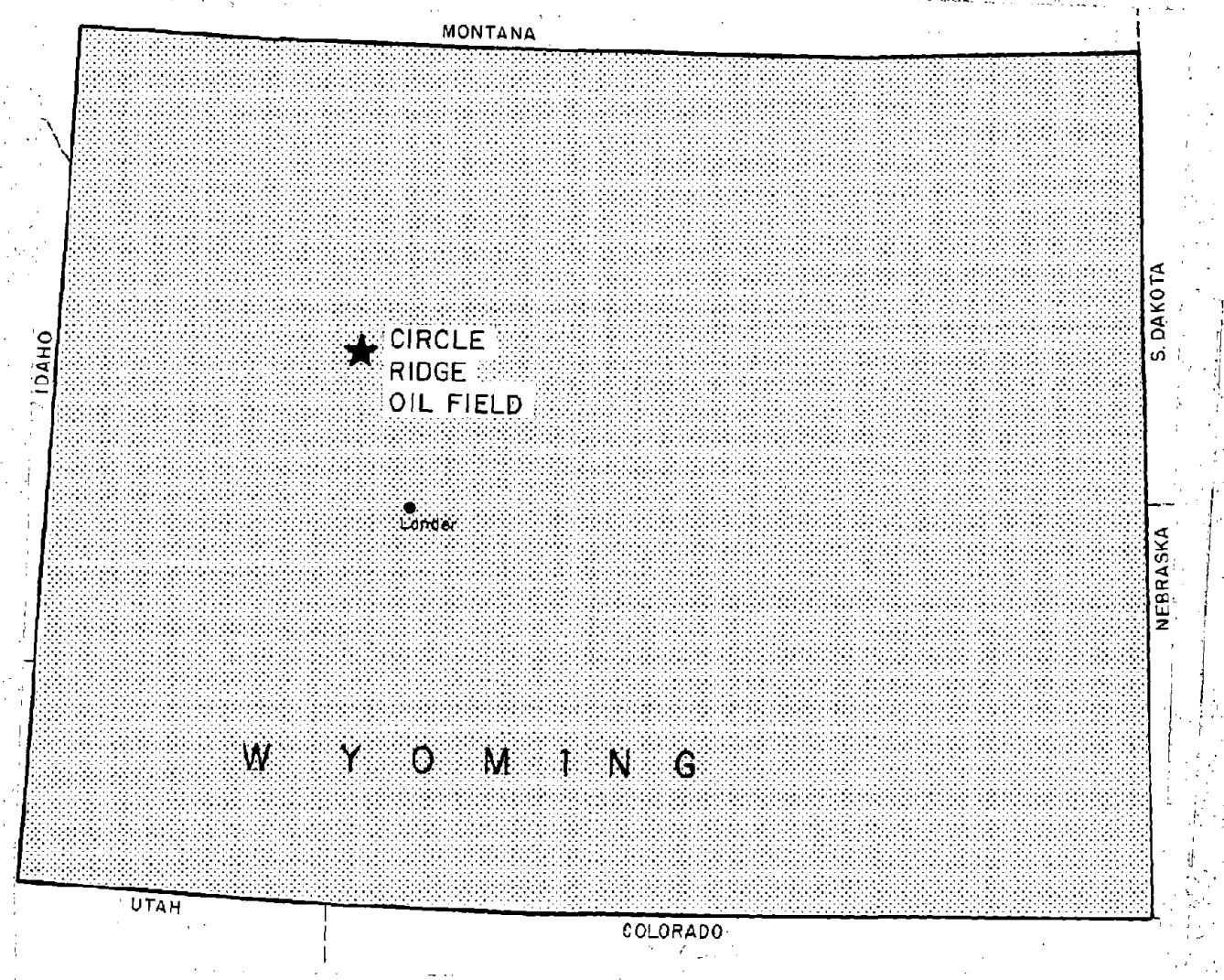
TABLE 5-1

CIRCLE RIDGE FIELD

	Phosphoria	Tensleep
Permeability (millidarcies)	Not available	65
Porosity (%)	16	14
Oil Gravity	23°-24°	23°-24°
In-Place Grade (bbl/T)	0.19	0.18
Depth to Top of Oil (feet)		
Minimum	185	730
Ave.	850	900-1200
Thickness of Oil Zone (feet)	110	110
Dip of Oil Zone	Approx. 35°	Approx. 35°
Overlying Rock		
Type	Shale, Limestone, Sandstone	Limestone, Dolomite, Shale, Sandstone
FM Name	Chugwater Gr.	Phosphoria
Age	Triassic	Permian
Underlying Rock		
Type	Sandstone	Limey Dolomite, Sandstone, Siltstone
FM Name	Tensleep	Amsden
Age	Pennsylvanian	Pennsylvanian
Oil-Bearing Rock		
Type	Dolomite	Sandstone
FM Name	Phosphoria (Embar)	Tensleep
Age	Permian	Pennsylvanian

LOCATION MAP
CIRCLE RIDGE OIL FIELD, WYOMING

Figure 5-1



five pools contained in four formations: the Phosphoria (Embar), Tensleep, Amsden and Madison, all of Paleozoic age. Only two of the four producing formations, the Phosphoria (Permian) and the Tensleep (Pennsylvanian), have been considered as candidates for mining in the present study.

5.1.2 Geological Description

The structural trap for the pools within this field is a thrust-faulted, northwest-trending anticline (Figure 5-2). The northeastern flank of the anticline dips between 12 degrees and 35 degrees to the northeast. The western portion is a partially overturned to near-vertical faulted segment (Ref. 1).

At the surface the crestal portion of the Phosphoria formation has been thrust over the overturned Chugwater formation (Triassic). Approximately 800 feet of fault-related closure has been formed in the Phosphoria, and similar fault related closure exists in the Tensleep (Ref. 1).

The stratigraphic succession in the non-overturned portions of the field is: Chugwater formation (Triassic), Phosphoria-Embar-or-Park City formation (Permian), Tensleep sandstone (Pennsylvanian), Amsden formation (Pennsylvanian), Madison limestone (Mississippian), Darby formation (Devonian), and the Bighorn dolomite (Ordorician).

1. Overlying Formations

   Sediments of the Triassic Chugwater group overlie the Phosphoria. The Chugwater is composed of the basal Red Peak shale, the Alcova limestone, and possibly some of the overlying members including the Crow Mountain sandstone and the Popo Agie member. The Phosphoria is the overlying formation with respect to the pool in the Tensleep sandstone.

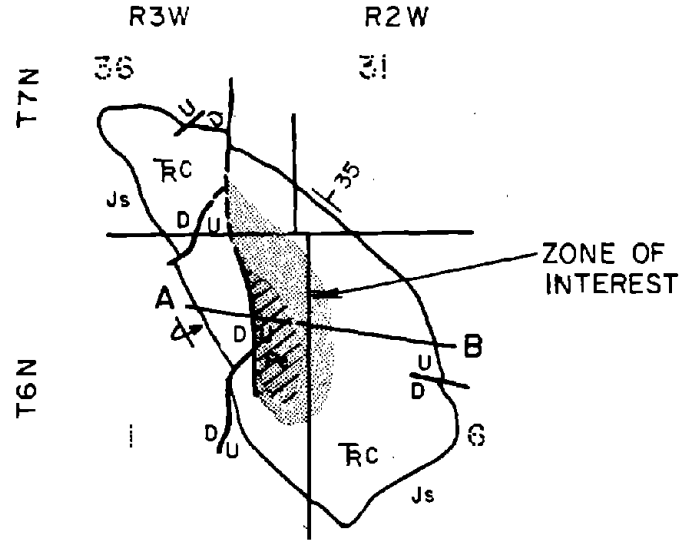
2. Oil-Bearing Zones

   The two oil bearing formations of interest to this present study are the Phosphoria and the Tensleep Sandstone. These two formations represent markedly different lithologies and physical characteristics but appear to contain very similar if not identical oil, even though there is a very slight decrease in reported API gravity with depth.

   In the area considered for mining there is no evidence, in the published data, for significant faulting or offset of the formations to be mined. This is, of

PLAN AND GEOLOGIC SECTION
CIRCLE RIDGE, WYOMING

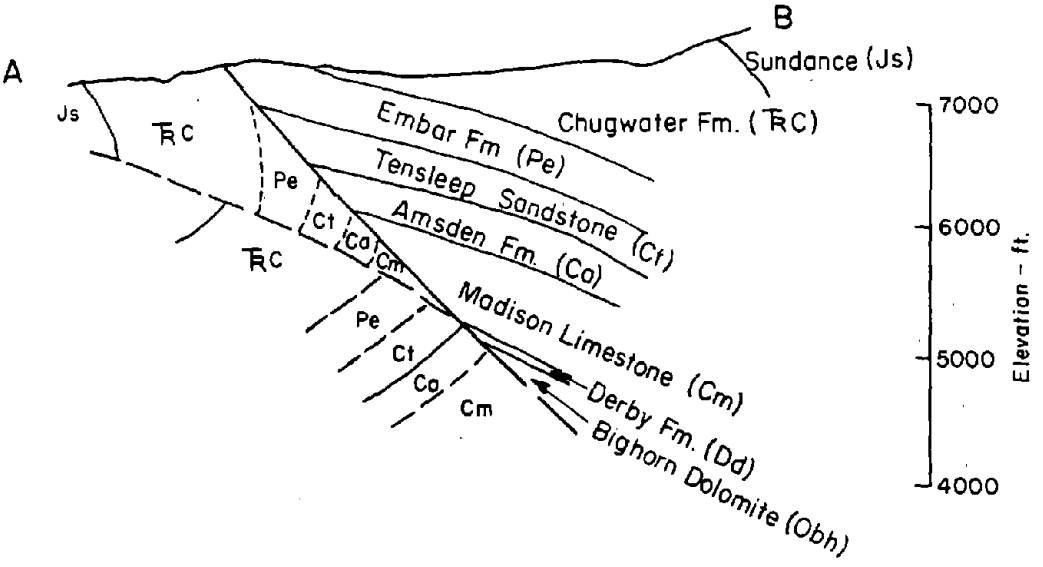
Figure 5-2



Redrawn from: Olsen, W.G., (1951)

PLAN

0 — Scale in Miles



0 — 1 mile

Horizontal Scale

SECTION

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course, extremely important to the successful application of the mining methods selected.

There is no reported gas production from any of the five pools in the Circle Ridge oil field. There is also no mention of the presence of gas in the published data, and gas analysis for H S and isotopic sulfur, are published for many fields in the basin (Ref. 2), were conspicuously absent. These facts and the low production rates, related to viscosity of the oil, lead us to assume that there is very little if any gas present within the two reservoirs being considered as candidates for mining.

The Phosphoria - The name "Phosphoria" is used in this report although this formation has been variously referred to as the Embar formation or more recently the Park City formation. The Phosphoria is composed of approximately 240 to 250 feet of interbedded limestone, dolomitic limestone or dolomite, shale, very fine-grained sandstone, and a few thin beds of chert and phosphatic oolite. Portions of the remainder of the formation are slightly phosphatic. The reservoir is within the dolomite (Ref. 3).

The depth to the top of the producing interval varies. The shallowest depth to the producing zone reported in the literature is 185 feet (Ref. 4). The published figures for the average depth of the oil pool vary from 800 (Ref. 2) to 950 (Ref. 5) feet and is probably close to 850 feet. The average thickness of the oil producing interval is 110 feet (Ref. 4) but the effective pay is reported to be only 40 feet thick (Ref. 6). Average porosity of the formation is 16 percent (Ref. 4). No published data was found on the permeability of this producing zone; however, the average horizontal permeability from a single core analysis from this field is 12 millidarcies (Ref. 7).

Examination of a single core analysis report (Ref. 7) indicates a water saturation of the pore spaces in the Phosphoria ranging from 4 percent to 34 percent. The average pore water saturation from this core analysis is 17 percent.



The Tensleep Sandstone - This formation is approximately 270 to 280 feet thick in the Circle Ridge field. It is a cross-bedded to massive, fine- to medium-grained sandstone with thin, irregular beds or lenses of chert and thin beds of hard limestone and dolomite. The formation is relatively massive in character and forms cliffs and dip slopes in the region. However, it is also reported (Ref. 8) to be "rather friable and porous, but locally it is hard and quartzitic." Inspection of caliper logs from several drill holes in this field indicate a very uniform character (Ref. 9).

The depth to the top of the producing interval varies with the shallowest published figure given as 730 feet (Ref. 4). The average depth to this pool is in the range of 900 feet (Ref. 2) to 1,200 feet (Ref. 5, 6). Average thickness of the pool is 110 feet. Average porosity of the formation is 14 percent. Average permeability is 65 millidarcies (Ref. 4). It should be anticipated that portions of this reservoir may have reasonably abundant jointing or fractures and thus may have a very high permeability along the fractures.

Evaluation of core analysis data for a single hole in this deposit (Ref. 7) shows that water saturation in the Tensleep varies from two percent to 48 percent of the pore space. The average water saturation for this hole is 15 percent.

3. Underlying Formations

The Phosphoria formation is underlain by the Tensleep, briefly described in the preceeding section. The Tensleep sandstone is underlain by the Amsden formation, which is composed of about 240 feet of sandstones, siltstone and limey dolomite. The upper half (120 feet) of the Amsden formation is composed of partly limey dolomite with minor amounts of siltstone which is in turn underlain by 20 feet of red siltstone (Ref. 5, 8).

4. The Resource

The two pools that are included in this study contain essentially identical oil. The API gravity of the oil is 23 degrees to 24 degrees, and the sulfur content is 2.6 to 2.7 percent (Ref. 2). Production from the

Phosphoria (Embars Pool) is approximately 10 bbls of oil per day per well. This is undoubtedly the result of a combination of very low permeability and the viscosity of the oil. The wells in the Tensleep sand reservoir produce approximately 15 to 19 bbls of oil per day per well.

Cumulative oil production as of 1974 was 5,744,699 bbls for the Phosphoria and 10,210,861 bbls for the Tensleep. The available data (1957) on developed acreage for these two pools is 640 acres for the Phosphoria and 760 acres for the Tensleep. Within the past two to three years Continental Petroleum, the operator of the field, has done a considerable amount of drilling and additional development in this field.

Examination of the results of a single core analysis from this field showed that the oil saturation in the Phosphoria varies from 20 percent to 80 percent and averages 64 percent. Corresponding oil saturation figures for the Tensleep ranged from 36 percent to 93 percent and averaged 66 percent (Ref. 7).

The estimated total oil remaining in place, as opposed to estimated produceable reserves, is approximately 16.7 million bbls for the Phosphoria and 44.1 million bbls for the Tensleep pool. Total estimated present resource in the two pools considered as candidates for the mining systems is of the order of 60.8 million bbls of 23 degrees to 24 degrees gravity oil. The estimated grade of the oil-impregnated rock in these two zones is 0.19 bbls per ton in the Phosphoria and 0.18 bbls per ton in the Tensleep Sand.

5.1.3 Mine Design and Scheduling

The Circle Ridge field offers the opportunity to evaluate the type of non-caving direct mining system expected to prove most favorable, large scale room and pillar mining. The two oil bearing formations considered have significantly different thicknesses and are therefore suited to different variants of the system. In the thinner Phosphoria, a simple room and pillar system appears workable but the thickness of more than 100 feet in the Tensleep Sandstone would require multiple-pass mining, with placement of fill to provide a working platform. The access to both formations to be mined will be through a common set of vertical shafts located on the boundary of the field.

In order to ensure that the processing plant will be of economical size, an ore production rate was chosen that would

produce 14,000 bbl/day. At the anticipated ore grade, this would require a daily ore production of over 76,000 tons.

1. Operations in Phosphoria Formation

Major access to the stopes will be through a series of four main drifts driven down-dip from the shaft area in a central pillar at 12 percent grade (Figure 5-3). From this main entry system, strike drifts will be developed to the extremities of the deposit at 1,300 feet intervals, for access to the stoping panels.

The stoping method chosen is a room and rib system, with the 50 feet estimated ore thickness being mined by heading and bench methods. The room and rib configuration was preferred over the more traditional checkerboard room and pillar design due to the greater ease of positive control of ventilation airflow. Room width is 30 feet, separated by continuous pillars 20 feet in thickness. Available information on the rock strengths to be expected indicated that this configuration should be stable with only routine rockbolting in the headings.

Stope panels are separated by 60-feet thick dip pillars which each contain access to the upper heading, or level. On alternate pillars connections are made to haulageways at the lower level.

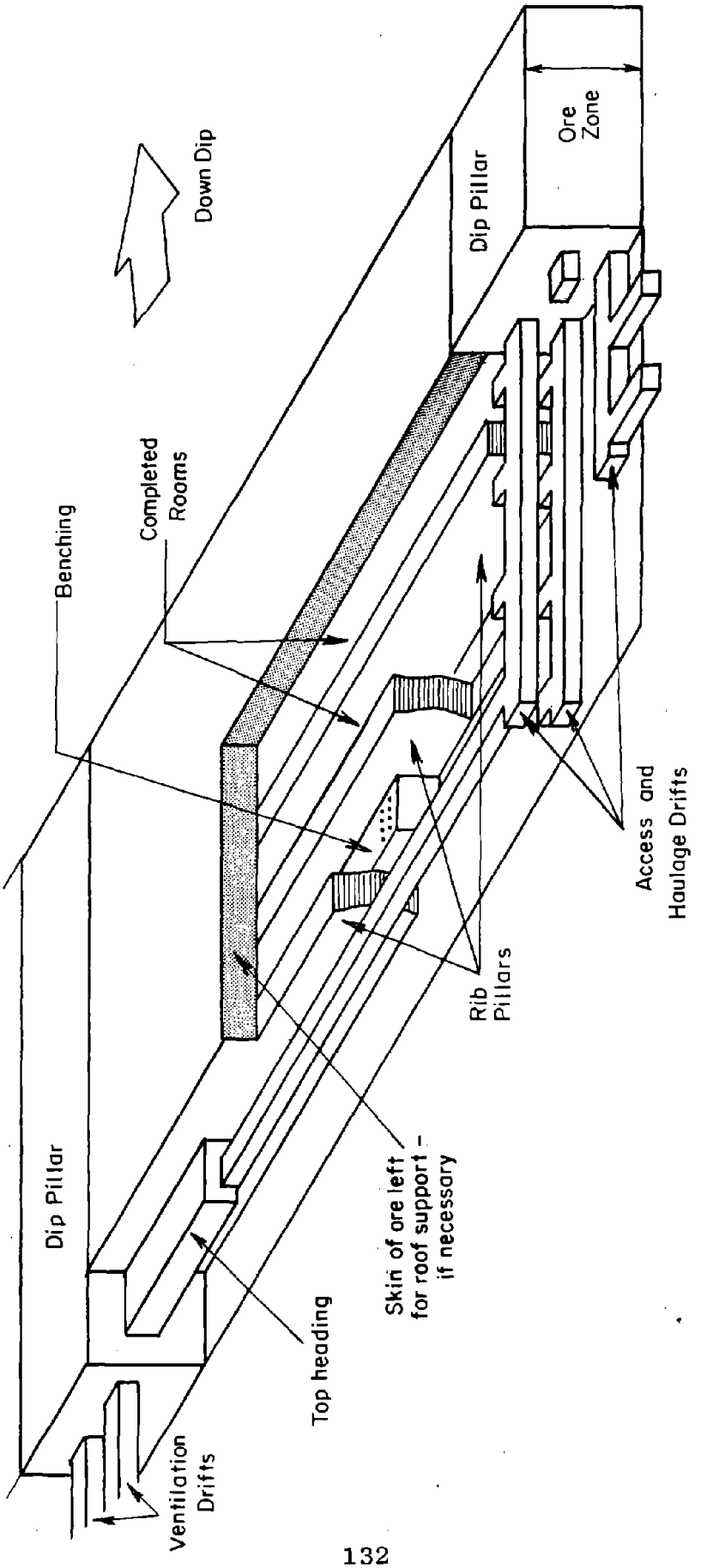
In order to ensure the fastest possible establishment of through ventilation in the stope rooms, the initial headings will be driven through at a reduced size of 10 feet by 10 feet, and slabbed to full width later. This system will adversely impact the economics of the operation but is considered essential for safety purposes.

Heading development and slabbing will be performed by standard three-boom jumbo drill rigs. Rotary drills will be employed for the three-inch diameter benching holes. All blasting is assumed to be with ANFO.

Broken rock will be mucked and hauled from the rooms by 8 cubic yard front-end loaders, loading into 28-ton capacity trucks for the haul to the shaft area. Rock from the upper, heading level will be dumped down raises located in the dip pillars and loaded into the trucks through portable chutes.

ROOM AND RIB MINING - WITHOUT BACKFILL
CIRCLE RIDGE - PHOSPHORIA

Figure 5-3



The total recoverable tonnage estimated from the Phosphoria is 52.2 million tons. Production is expected to build up more rapidly than in the underlying Tensleep and will rise to a maximum of nearly 41,000 tons per day. This rate will only be sustained briefly, however, and will soon reduce to less than 10,000 tons per day, with production being complete in year 10.

At all times production from the Phosphoria will precede that from the underlying Tensleep to avoid additional ground control problems.

2. Operations in Tensleep Formation

The general layout of operations in the Tensleep sandstones is very similar to that described for the Phosphoria, with a main dip pillar carrying the major entries and a series of strike haulage and access ways (see Figure 5-4). Stope development and extraction are, however, substantially different due to the estimated 110 feet vertical thickness of the ore zone. Stope configuration is again essentially room and rib, with 40 feet wide rooms. The separating pillars are of 10 feet nominal thickness and are designed mainly to restrain the sandfill that will be placed as mining progresses. The ultimate overburden load will be carried jointly by the pillars and the fill.

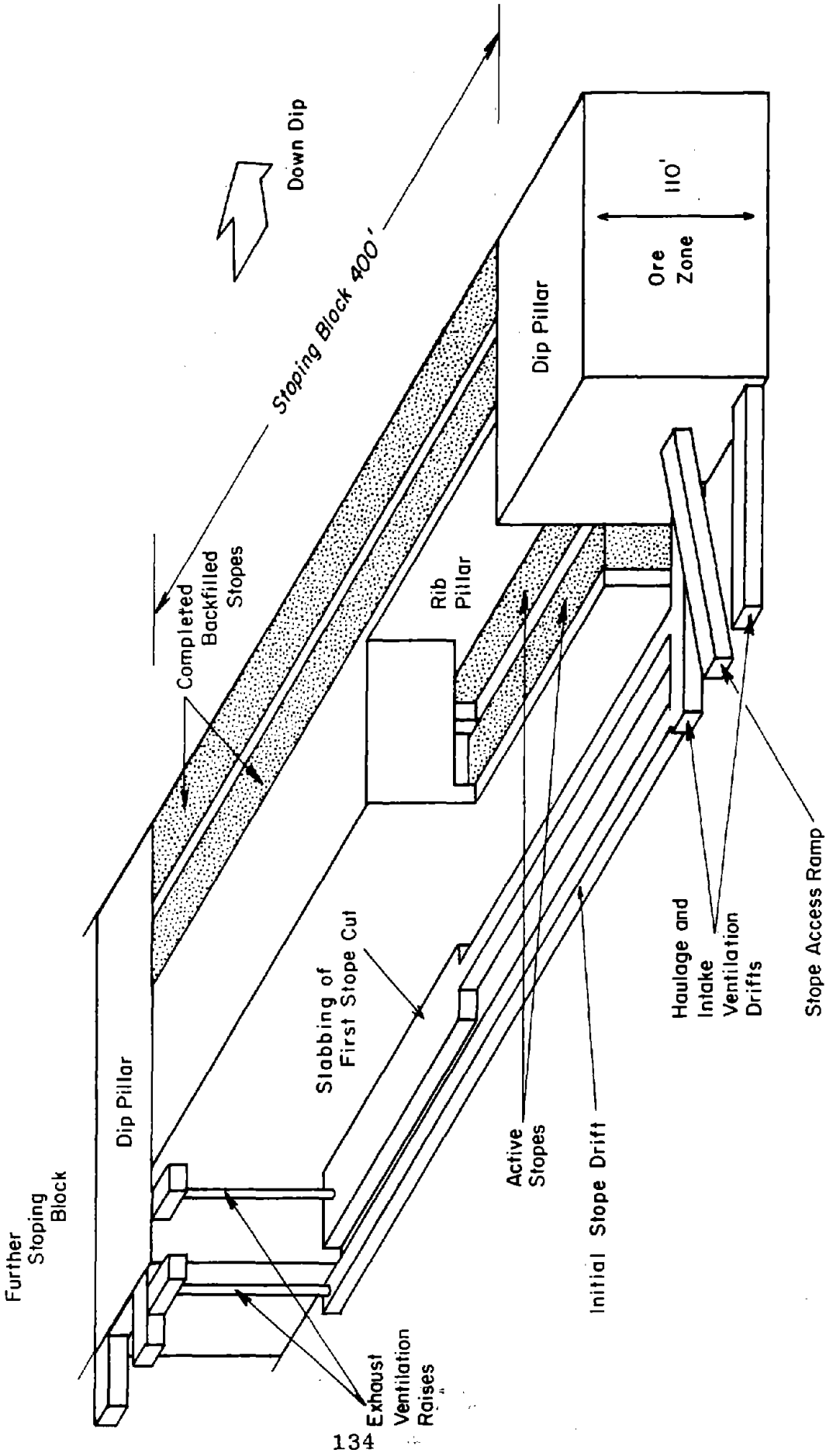
All stope tonnage will be broken by three-boom jumbo rigs drilling horizontal holes. This system will ensure the provision of the best available roof conditions in the stopes and maintains the minimum cross-section area, which will aid ventilation sweep. It is, however, less productive than up-hole drilling.

Stope lifts will be filled promptly with hydraulically placed de-oiled sand. In all but the final lift, filling will be stopped some three feet short of the roof to maintain ventilation flow. The final lift will be filled completely.

Access and intake ventilation to each stope will be from the ramp system located in alternate dip pillars, supplemented if necessary by a steel-lined raise carried up through the fill. A bored or drop-raised ventilation raise at the opposite end of each stope provides a positive return to the main exhaust system.

STOPING IN TENSLEEP SANDSTONES
CIRCLE RIDGE MINE

Figure 5-4



Mucking in the stope will be by 8 cubic yard front-end loaders. In the first lift, these will load directly into trucks for haulage to the shaft. Subsequent lifts will be dumped down steel muckways carried through the fill and discharging through portable chutes into the trucks.

The total recoverable tonnage estimated from the Tensleep formation is 139.7 million tons. Production will build up steadily throughout the projected 11-year life to replace the declining output from the Phosphoria horizon.

3. Ventilation

All the main shafts downcast air, which is distributed to stoping areas through the main haulage and access ways. After passing through a stope, the air is not re-used but is passed directly to the exhaust shafts located on the orebody perimeter.

The air quantity required within each horizon varies as the balance of development and production activity alters. The total requirement, however, never falls below 3 million cfm, requiring a system pressure of 16 inch swg.

4. Mine Plant

Rock hoisting will be through three 22-feet diameter circular concrete lined shafts, one 1,200 feet and the other two 1,400 feet in depth. Each shaft will be equipped with two koepe type friction hoists, handling 40 ton bottom-dump skips running on rope guides. All rock will be loaded from a single level in each shaft, set far enough below the Tensleep formation to permit reasonable storage capacity. Each shaft is rated at 30,000 tons per day.

The service shaft will also be 22 feet in diameter. It will have a twin-decked main cage large enough to carry most subassemblies for mobile units directly on the decks, with larger units being slung below the cage or lowered with the cage removed, as weight considerations dictate.

The main shaft area underground on each production level will contain the usual service facilities for a

major mechanized mine, including workshop, fuel storage, sanitation, lunchrooms, etc.

Compressed air requirements will be relatively small, since all major drilling will be by electric hydraulic units. Minor amounts will, however, be needed for tools, occasional pneumatic drills etc, and will be supplied by mobile compressors located adjacent to operating areas.

5.1.4 Processing

The feed to the Circle Ridge processing plant will be a medium-hard rock requiring both crushing and grinding. Since two different formations are being mined, blending will be required to provide as constant a feed as is possible.

The actual method of oil extraction can only be definitely determined through bench scale and pilot plant testing. It is believed, however, that either a hotwater or solvent extraction process could be used with some form of mechanical scrubbing. Considerable cleaning of the oil-rich product will probably be necessary to remove the fines generated in the crushing and grinding steps of the process. Some thinning of the final product will probably also be required utilizing a low viscosity dilutive such as naphtha. Final removal of suspended insoluble material can be accomplished by centrifuging or similar method.

The Circle Ridge processing plant would handle 17.4 million tons of ore per year producing 3,150,000 barrels of oil per year.

5.1.5 Safety

This is the only system of those studied which inherently places all the mine production workings actually in the oil reservoir rock. It therefore offers the highest possible exposure to any hazards that may be caused by the presence of petroleum gases and liquids in mine workings.

The main safety implications of this arrangement can be classified under three headings:

- Ground stability
- Explosive or noxious gases
- Oil seepage

1. Ground Stability

The most severe of the criteria used in selecting this field for application of this system was the competence of the reservoir rock. Both of the formations at Circle Ridge appear to be of a quality that should induce no more stability problems than are normal in an operation of this type. Room and pillar mining, or the rib and room variants employed here, require that the roof rock be capable of standing at reasonable spans and that the pillars remain essentially intact. Reliable prediction of these characteristics typically relies very heavily on knowledge of geological structure, particularly in applications such as this where the depths below surface are moderate and stress levels should not be excessive.

The data available are inadequate to form any reliable judgements on this for the specific formations considered. It is a reasonable assumption at this stage, though, that any problems should not be beyond the normal range expected in underground mining and should be controllable by standard support systems. It is less certain, however, that suitable conditions will be found in a large enough number of oil fields for this. It is also important to realize that the cost of proving that conditions are satisfactory by core drilling from the surface could be very substantial in a marginal case.

2. Explosive/Noxious Gases

This is undoubtedly the most severe of the hazards. Even though it is an essential prerequisite of this system that the reservoir gas pressure has previously been relieved by well production, the probability is still extremely high that gas emissions will be present. At worst these could consist of releases of pockets of high pressure gas not previously tapped by the wells; at best they would represent a continuing release of volatiles from the oil contained in the rock as mining proceeds.

Sophisticated estimation of the quantities that could be expected were warranted neither by the level of data available nor by the depth of this study. All the experience available from tunnelling through depleted reservoirs, however, indicates that the problem would be serious and that the potential will

continually exist for the creation of an explosive atmosphere.

This conclusion, if accepted, would totally dominate the selection of mining techniques and equipment, including particularly the blasting method and materials. The cost implications of such measures would be severe and it was therefore decided, as a first approximation, to base the operation on the extreme assumption that the situation could be satisfactorily controlled by diluting ventilation. If this proved attractive economically, the more expensiv options for more severe situations could then be evaluated As will be seen later in this report, however, this did not prove to be the situation and the conclusion has to be drawn that such an operation can only be contemplated if significant gas problems can be proved to be absent.

3. Oil Seepage

The severity of problems which may be caused by seepage of oil from reservoir rocks is subject to the same uncertainties as gas emission, but appears likely to be substantially less based on the available data for the Circle Ridge reservoirs. The oil content is low and is of high viscosity; these are, of course, the very conditions that limited original well production. A conservative approach has therefore been taken by assuming that the dangers from this source would be limited to minor seepages leading to potential problems in maintaining traction of mobile units.

If the problem proves to be substantially worse than this in practice, consideration could be given to the use of initial development headings for deliberate pre-drainage and recovery of oil. The analysis in this study has, however, assumed no such problems or offsetting benefits.

The general conclusion on the safety of this proposed operation must be that it cannot be shown to be satisfactory. In view of the general economic unfavorability of the project, even under the optimistic assumptions made, further in-depth study of these problem areas is not warranted at this stage.

5.1.6 Environmental Factors

Mining will be done underground using a rib and room technique in the Phosphoria formation and a cut and fill operation in the Tensleep sandstones. Impacts associated with extraction are principally odor and noise. Processing will be done with a hot water-caustic soda solution. A substantial proportion of the spoil will be backfilled into the stopes but major disposal operations will still take place on surface.

The site is located over 60 miles from Riverton (population 9,000) in Fremont County (population 31,500). There are a number of smaller towns closer but they have very small populations (less than 1,000 in each).

Impacts associated with support facilities will be severe. The project will have a direct employment of 3,000 people. This is expected to generate an additional 6,000 jobs and attract a total of 21,000 people to the area. This will require the construction of an entire new community with all its associated impacts.

The life of the project is expected to be only 10 to 11 years. This will magnify the boom-bust cycle since a large community may have to be abandoned if other sources of employment are not found, and this may further inflate the total investment requirements necessary for the project. Homeowners may end up taking a severe loss on their homes at the end of the useful life of the project. Otherwise, the short project life will create a town constructed with inexpensive, small houses or mobile homes.

5.1.7 Technical Feasibility

Throughout the design of this operation, a consciously optimistic policy was adopted. There were so many obstacles to the generation of a believable design that there was a constant temptation to abandon the entire concept. Such a decision would not, however, have enabled the full range of possibilities and difficulties to be thought through, or have permitted the formation of any sort of economic judgement on the proposed methods.

The design presented here is therefore full of assumptions that problems will either not exist or that they will be economically soluble. In this section of the report, however, such assumptions have to be subjected to a sceptical assessment of practical feasibility and, regrettably, on several counts the test is failed.

The most serious problems arise from the emission of gases into the mine air stream, as discussed in the earlier section on Safety. Even with assured airflow through all working areas at good velocity and without re-use of air, there can be no real assurance that toxic or explosive mixtures will not occur, if only locally. Similarly, there can be very little real likelihood of completely preventing spark generation, if an efficient, productive operation is to be maintained in a siliceous formation such as the Tensleep Sandstone. In this respect, it is worth noting that even in civil engineering tunnelling projects such as Sylmar, Los Angeles, explosions have not been successfully prevented.

If the prospect were a bright one economically, or even marginally so, it would be necessary to pursue the potential for improving on its safety through gas drainage, reduced scale operation with enhanced ventilation, remote operation, etc. As will be seen later, however, this is not the situation and the type of operation described has regretfully to be termed unfeasible.

5.2 BLOCK CAVING

5.2.1 General Description

Block caving is, in the correct circumstances, the most economical and simplest of mining systems. It was therefore, considered essential to evaluate its potential as a method of extracting poorly consolidated oil reservoir rocks. The Casmalia oil field chosen as the basis for this design was selected due to the expected presence of large vertical thickness of weak, oil-bearing rock underlain by a formation competent and thick enough to accommodate the mine extraction working.

The field is located one and one-half miles northeast of the village of Casmalia, in the northwest-trending Casmalia Hills in Santa Barbara County, California (Ref. 10) (Figure 5-5). It occupies 3,000 proven acres (Ref. 11) in Sections 13, 14, 24 and 25, Township 9 North, Range 35 West, and Sections 17-21 and 28-30, Township 9 North, Range 34 West, San Bernardino Base Meridian (Ref. 12). The oil field lies eight miles southwest of the city of Santa Maria. The Southern Pacific Railroad and secondary roads cross through the field (Ref. 13). Key properties of Casmalia oilfield are summarized in Table 5-2.

The topography is characterized by rounded hills and rather deep V-shaped ravines with an average elevation of approximately 500 feet. Fairly heavy stands of oak cover the northern slopes

LOCATION MAP
CASMALIA OIL FIELD, CALIFORNIA

Figure 5-5

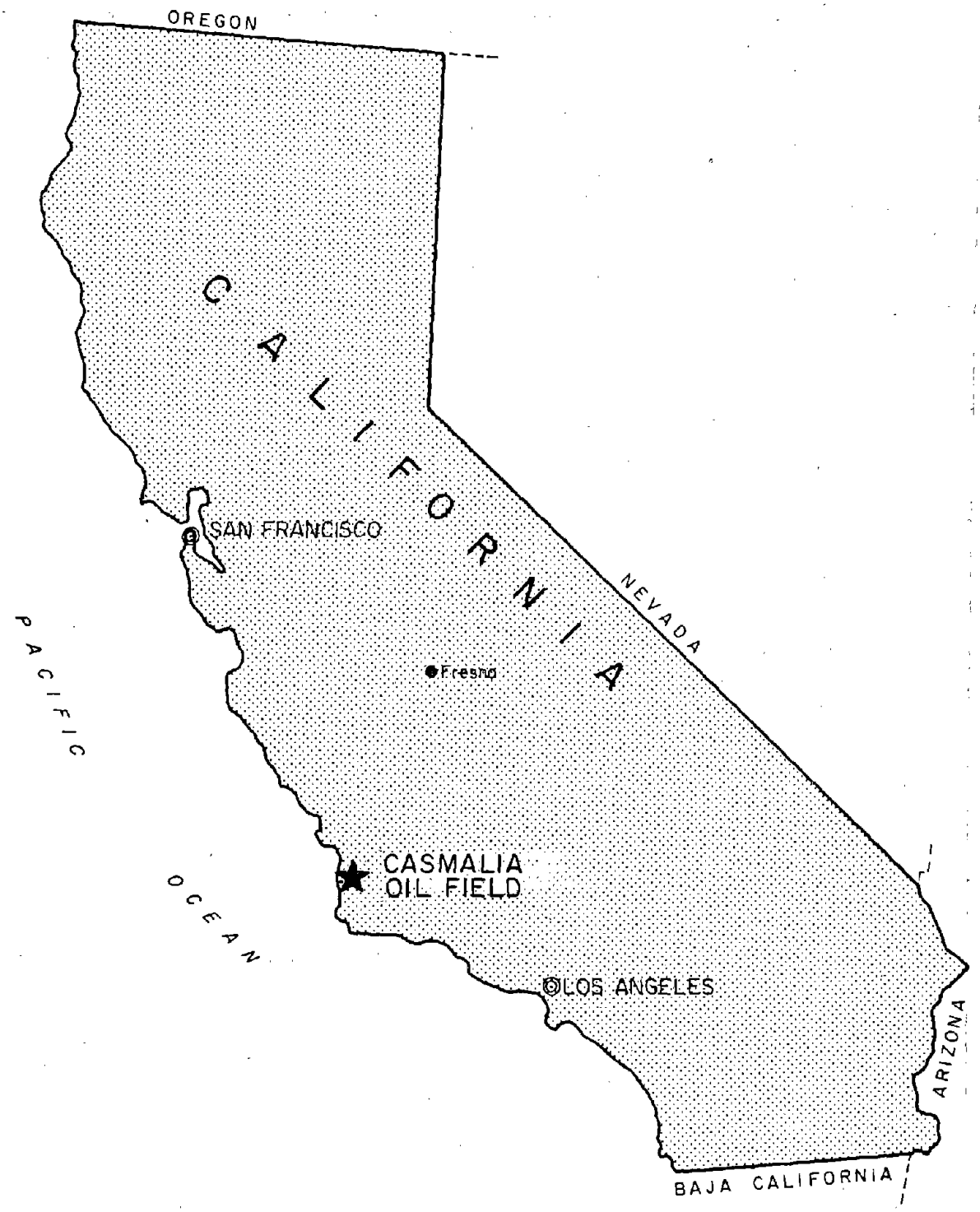


TABLE 5-2

CASMALIA FIELD

Permeability	>10
Porosity (%)	31
Oil Gravity	10° API
In-Place Grade (bbl/T)	0.38
Depth to Top of Oil (feet)	
Maximum	2000
Ave.	1000
Thickness of Oil Zone (feet)	75-700 (main horizon 200)
Dip of Oil Zone	Varies
Overlying Rock	
Type	Diatomaceous Mudstones, Claystones, and Shale
FM Name	Sisquoc FM, and Upper Member of Monterey FM
Age	Miocene
Underlying Rock	
Type	Siltstone, Mudstone, Sandstone, and Shale
FM Name	Point Sal FM, and Lower Member of Monterey FM.
Age	Miocene
Oil-Bearing Rock	
Type	Cherty Shale Member
FM Name	Monterey FM, (Middle Member)
Age	Miocene

of the hills; sage and other brush cover the southern slopes, and the hilltops are generally open and covered with grass (Ref. 14). The climate is coastal (the Pacific Ocean is five miles to the west) (Ref. 10), with mild winters and moderately warm summers. The average annual rainfall is approximately 20 inches.

5.2.2 Geological Description

The oil accumulation occurs along the easterly plunge of the Casmalia Anticline, a faulted asymmetrical fold striking northeast-southwest, and tending to be overturned towards the north (Ref. 15). (See Figure 5-6).

1. Overlying Formations

The oil-producing horizon of interest, the Miocene Monterey shale, is overlain by the diatomaceous mudstones and claystones of the Sisquoc formation, also Miocene in age. The upper member of the Sisquoc is a diatomaceous mudstone of 700 to 1,500 feet in thickness. The lower member is the Todos Santos, a claystone or clayey mudstone with a thickness varying from 750 to 1,750 feet containing thin interbeds of porcelaneous shale and some silty sandstone, which increase in abundance towards the base of the member. The Todos Santos is described as grading down into the upper Monterey through a transition zone of alternating claystone and porcelaneous shales. A cross-section produced by the California Division of Oil and Gas, however, shows the contact to be unconformable within the Casmalia Field (Ref. 11).

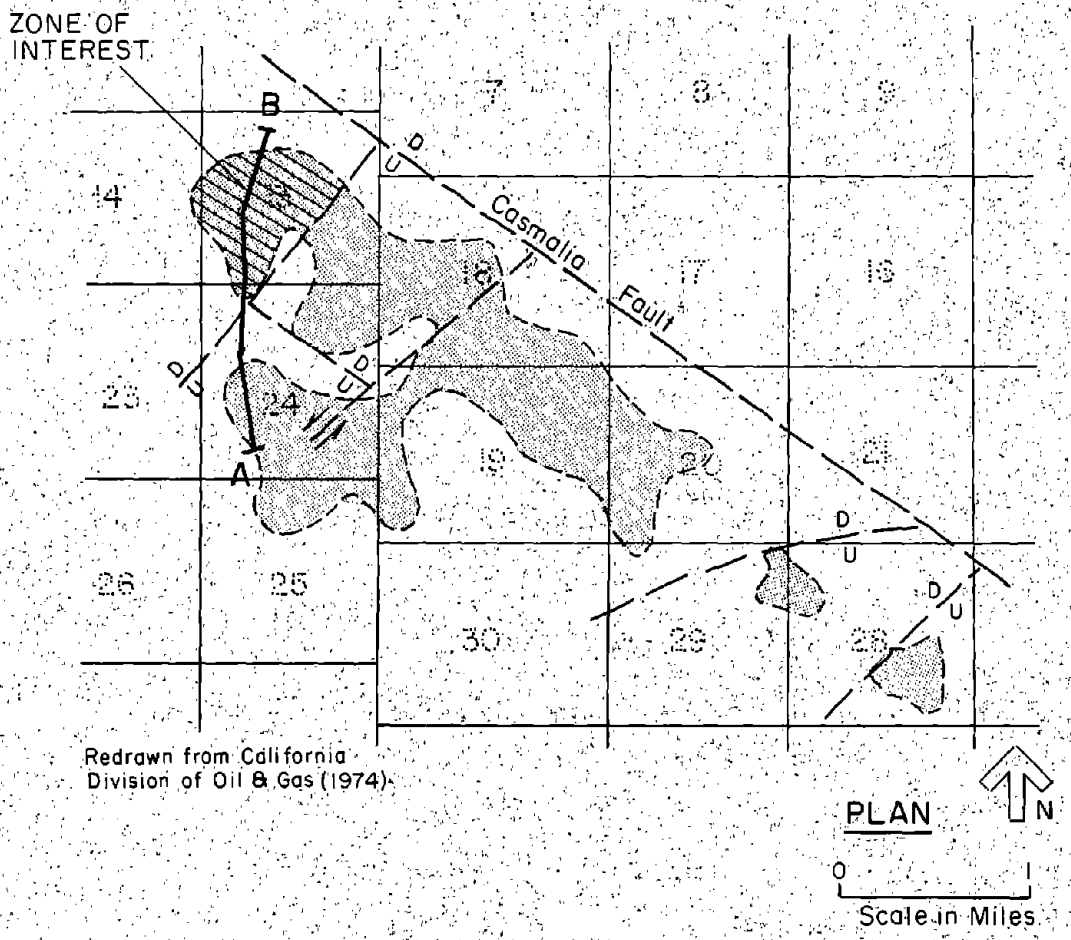
Over the proposed mine area, the average thickness of overburden is some 1,000 feet. It is almost a certainty that several aquifers exist between Todos Santos claystone and the surface. Data on early drilling practice (1918) in this field indicates that the surface water zone extended to 396 feet but that the interval from 396 feet and 1,873 feet was relatively dry, (Ref. 16).

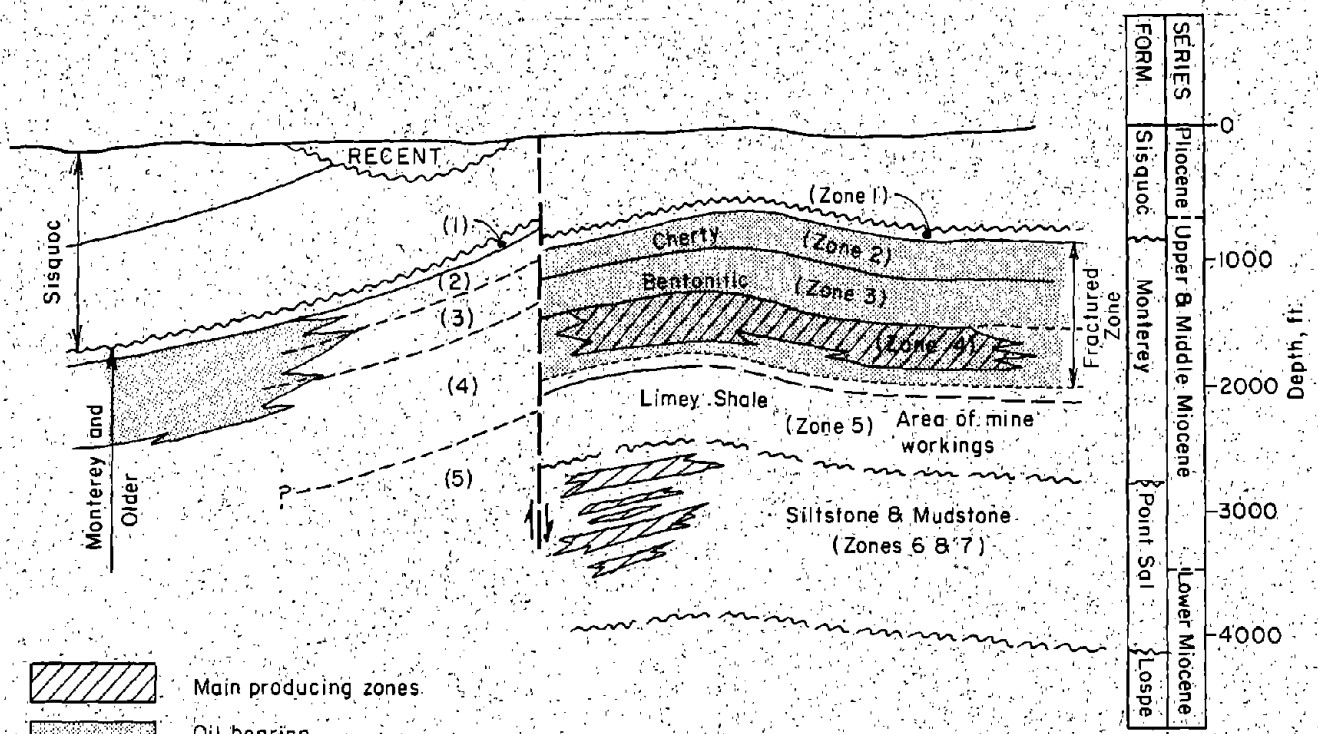
2. The Oil-Bearing Zone

The oil producing zone of interest is the cherty shale middle member of the Miocene Monterey formation. This formation contains two other members, an upper member of 600 to 1,000 feet of platey porcelaneous shale, and a lower member of 200 to 900 feet of phosphatic to somewhat porcelaneous shale (Ref. 10).

PLAN AND GEOLOGIC SECTION
CASMALIA, CALIFORNIA

Figure 5-6





The middle member is on the order of 200 feet thick, consisting of thinly bedded or laminated chert and cherty shale, with some porcenaleous shale and limestone (Ref. 10). Taff (1934) describes the shales as "crushed and sheared" (Ref. 15).

The thickness of the pay zone in this field varies from 75 to 700 feet, with the main producing horizon described as a "cherty shale" with a thickness of 200 feet (Ref. 10) occurring as the middle member of the Monterey formation, which is 1,275 feet thick. The average depth to the top of the Monterey is 700 feet (Ref. 11). The average permeability is in excess of 10 darcies (Ref. 17), and the porosity is 31 percent (Ref. 4). Due to the broken nature of the rock, oil and water cannot be separated, and in the wells near the top of the structure the oil may be displaced by hot water "after a short period of pumping" (Ref. 15). The gravity of the oil varies from 8 degrees to 23 degrees API, with an average gravity of 10 degrees (Ref. 4).

A considerable amount of water is currently being produced with the heavy oil. In 1976 water constituted 94 percent of the total fluids being produced from the field. Water and oil are produced from the highly fractured portions of the Monterey formation, (Ref. 17).

The abundant leakage potential of the oil producing along numerous faults and the highly fractured shales is evidenced by abundant tar sands and bituminous impregnations in the overlying rocks (Refs. 14, 15, 17, 18). This reduced the original gas content in the Monterey formation and production has further reduced this. Gas pressure within the reservoir is assumed to be less than 500 psi. The gas to oil ratio for the 1976 production was 846 cubic feet of gas per bbl of oil and this was accompanied by 16 bbls of water (Ref. 19).

The upper two members of the Monterey formation are highly fractured porcelaneous to cherty shale (Refs. 10, 15, 16, 17, 18). The underlying shale member (Zone 5) has some oil production and is a less fractured limey shale (Refs. 10, 11, 15). The zone beneath the Monterey is the Point Sal formation which is predominantly composed of unfractured siltstone, mudstone and local fine-grained sandstone. Some of the oil-bearing Monterey formation contains very



viscous, low API gravity oil which is not produceable. The highly fractured oil-impregnated zones in the Monterey should be readily amenable to caving (Refs. 15, 17, 18).

The area of proven acreage is 2,090 acres (Ref. 11). The estimated oil in place is 100,000,000 bbls, with the estimated grade of oil in place being 0.38 bbls/ton.

3. Underlying Formations

In the Casmalia field, the Monterey is underlain by the Point Sal formation, a Miocene series of marine siltstones and mudstones, with some thin interbeds of medium-grained sandstone, varying in thickness from 150 to 1,500 feet (Ref. 10).

5.2.3 Mine Design and Scheduling

The reservoir rocks are expected to cave readily when undercut and the mine will be of very simple design. All drifts will be located in the relatively competent lower Monterey, with the undercut fans penetrating to the base of the oil-bearing middle member of the Monterey formation.

1. Development

The typical mine layout is shown in Figure 5-7. Undercut drifts are driven on 70-foot centers immediately below the base of the oil-bearing zone. Parallel to them and 20 feet lower are the loading drifts with finger raises on both sides at 35-foot centers collared from the back of stub drawpoint crosscuts.

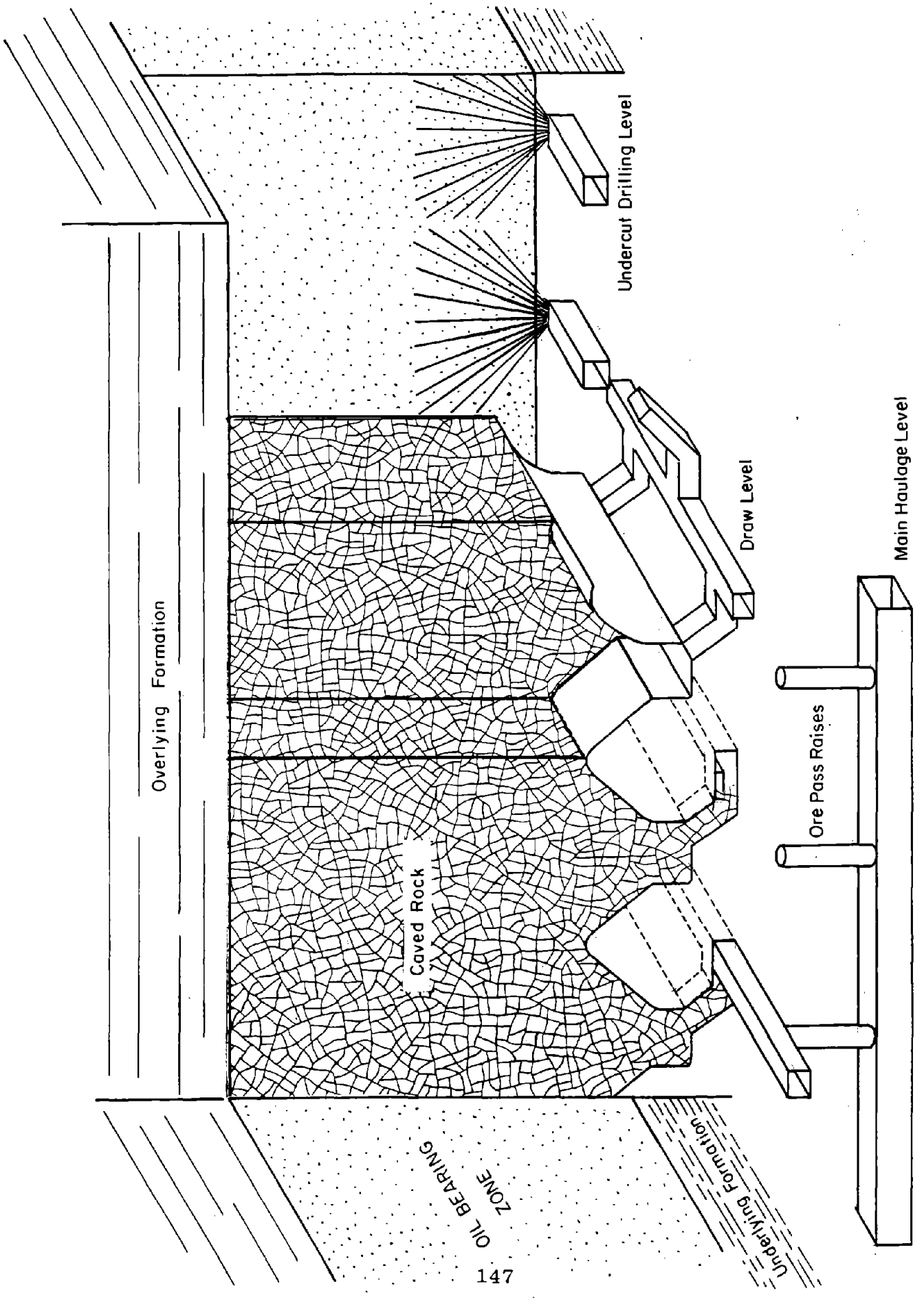
The main haulage is located at least 50 feet below the loading drifts with a conventional rail haulage system loading out of chutes.

All development will be advanced using conventional drill-blast methods, mucked by rubber-tired loaders. It has been assumed that all drifts will require substantial rock bolt and mesh support during development and that 12-inch monolithic unreinforced concrete will be required in the production drifts and drawpoints.

All levels will be connected by an access ramp system during the development stage to allow for efficient

BLOCK CAVING
CASMALIA OIL FIELD, CALIFORNIA

Figure 5-7



equipment access and supervision. The total development required to bring the mine to full production will be 48,600 feet. An annual total of 16,200 feet will be needed thereafter to maintain block availability for production.

2. Production

Undercutting will be by conventional fan drilling using a trackless twin-boom jumbo drilling a maximum hole length of 57 feet. Blasting will be with ANFO.

Caved ground will be loaded out with rubber-tired loaders. Considerable difficulty was experienced in making this choice of loading system from a safety point of view, as is discussed later.

The main haulage system will consist of 20- to 25-ton electric trolley locomotives pulling fifteen 15-ton cars on a loop system. Unit productivity is estimated at 1,350 ton-miles per shift with an average round trip haul of 19,000 feet.

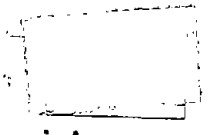
In order to produce rock containing 10,000 bbl/day of oil, some 32,000 tons per day of diluted rock must be produced. Assuming a caving rate of 0.83 feet per day this will require an area of 525,000 square feet under draw at any one time. Each block of 250 feet by 350 feet will have a producing life of 1,080 days and yield a total of 5,625,000 tons, assuming a recovery of 69 percent and 20 percent dilution.

Some 800,000 feet of undercut drilling will be needed to establish the full production rate, with a subsequent yearly requirement of 266,600 feet.

The mine will have a productive life of 20 years, with development and undercut activity continuing into the 18th year.

3. Mine Plant

Main access to the mine will be through a pair of 22-foot diameter concrete-lined shafts. One of these will serve as a rock shaft, equipped with 30-ton skips running on rope guides. A friction hoist is preferred for this application.



The service shaft will contain a double-deck cage running on fixed guides with a counterweight as well as pipes, cables, and manway compartments.

A 22-foot diameter exhaust ventilation shaft will be located remote from the main shafts and will be equipped to accept an emergency hoist and capsule for rescue purposes if required.

The normal infrastructure of a mechanized mine will be provided in the main shaft area, including workshops, fuel storage, electrical distribution, etc.

4. Ventilation

During development operations, ventilation would be provided to headings through an auxiliary overlap system employing 36-inch ducting delivering 35,000 cfm to each active heading. Through ventilation will be established at the earliest possible stage and this will be particularly important in the loading drifts during production. Total air quantity is estimated at 1.5 million cfm.

5.2.4 Processing

The processing method for the Casmalia ore will be similar or identical to that proposed for Circle Ridge. The plant will handle 10,936,800 tons of ore per year and will produce 3,150,000 barrels per year.

5.2.5 Safety

There are three areas in this operation which could be considered potentially unusually hazardous.

- Undercut drilling and blasting
- Rock stability
- Ventilation.

1. Undercutting

This operation requires the efficient breaking and draw of the base of the reservoir rock. In the same operation the cones or troughs which will subsequently be used for draw will be formed. Since the underlying rock, in which the mine workings are to be situated, is expected to be reasonably competent, drilling and blasting will be required and this will have to be an efficient routine operation to break the required tons

per day of undercut. It is therefore assumed that drilling and explosive fracturing are possible. The risks of drilling into pressurized gas pockets, flowing oil, or pressure water cannot be excluded, however. Even if the mine is designed on the basis of good quality geological data and interpretation, the likelihood of local irregularity in the physical position and contents of the base of the reservoir zone is substantial. There must therefore be considered to be a major risk of uncontrolled gas emission or blast-induced explosion.

2. Rock Stability

The entire concept of the operation depends on finding a valuable reservoir underlain by a formation comtent enough to sustain mine openings.

The available information on the horizons selected in the Casmalia field indicates that there should be no serious problems if the support methods specified are employed.

3. Ventilation

As in all the underground oil mining systems discussed, this is an area of real and major concern. The problem centers most seriously around the release of volatiles from the caved rock, primarily in the draw points, but also throughout the ore handling system. The ventilation system proposed will provide positive feed of fresh air through each extraction drift, returning directly to the exhaust system. This should take care of regular gas emissions by dilution but there is always a risk of sudden gas release, possibly due to a "run" of ground in a drawpoint, and the possibility must exist of generation of explosive mixtures in such events. Perhaps the most difficult and potentially dangerous places to ventilate are the undercut drifts during the blasting process. This is not an unusual situation in a favorable block caving environment and the assumption has been made that heavy support will be needed in production openings. In general, this risk is considered to be no worse than normal and certainly less than the severity of other categories of risk. At that time there is no possibility of maintaining through ventilation and the freshly fragmented rock is, presumably, most likely to release gases.

The ore handling system, if designed for the efficient operation of all components, will contain substantial ore storage pockets. These could well provide the potential for build-up of explosive and noxious gas concentrations which would be difficult, if not impossible, to control, even by the most careful ventilation provisions.

The conclusion seems unavoidable that security of personnel from gas-related hazards cannot be guaranteed to satisfactory standards even by the best practical ventilation system. In addition, in an operation of the size proposed, some local failures of ventilation are to be expected, due either to equipment failure or human error. We consider that this situation, coupled with the other risks associated with geological uncertainties and irregularities, make the proposed operation, based on present data, unacceptably hazardous on a full-scale commercial basis.

5.2.6 Environmental

Mining will be done underground using block caving methods. Apart from the usual occupational environmental factors in a mining operation, such a system induces major subsidence of the ground surface. This would result in large areas becoming unusable unless the depression, probably hundreds of feet deep, is filled with plant waste. Such filling would have to be very carefully performed to avoid the generation of hazards to underground personnel. Subsidence of the type envisaged would also have a major potential impact on regional surface and groundwater regimes. Environmental impacts associated with processing are principally odor, dust, and noise, as described in Chapter 4. Spoil will be disposed above ground and revegetation will be necessary.

Impacts will occur principally from the increase in support services. The Casmalia site is located about three miles west of Orcutt in Santa Barbara County. The nearest large town is Santa Maria, about 10 miles northwest, with a 1975 population estimated at 33,600. Santa Barbara County has a total population of about 280,000. The project would add about 1,300 employees. This would create an additional 2,600 jobs and a total population of about 9,100 would be affected. The reasonably large population base in the area will provide a large number of the basic employees and related service jobs. There will be a moderate need to increase the services available and facilities in the vicinity of the project. The 20-year life of the project will add to the economy but will not cause extensive dislocations in the area when the project terminates. If both the Casmalia project and Edna project are implemented simultaneously, there will be some overlapping impacts in the support sector.

5.2.7 Technical Feasibility

Block caving is a well established and highly successful method of mining, with particular application to weak, poorly consolidated formations or those which have been substantially weakened by alteration or fracturing. There is little doubt, therefore, that a large proportion of oilfields, if not all, are fundamentally "caveable." There are, however, several severe and possibly fatal problems in introducing this system into an oil field.

As discussed previously, mine ventilation is a major problem area and, even when a comprehensive and expensive system has been provided, the certainty of safe operation must be rated as low. The loading system specified for the Casmalia field was chosen largely for its minimizing of spark production, compared, for example, to slusher operation, but could still hardly be considered spark-proof. In particular, the handling and breaking of oversize boulders in drawpoints could pose severe difficulties. From an explosion/fire point of view, therefore, the system has to be considered unsatisfactory unless an essentially inert, oil bearing formation can be identified.

The specific Casmalia field has given little cause for optimism as to the suitability of block caving from several other points of view. As a full caving operation such a mine will induce major subsidence, propagating through all formations from the base of the cave zone to surface. Any aquifer comparing in this area will therefore drain freely into the mine, if it has not been effectively pre-drained. The Casmalia field is overlain by several waterbearing sequences which would add prohibitive cost to the operation. Even where there is no overlying water, moreover, there is a basic probability that the reservoir rock itself will contain substantial water, particularly at the lower end, and that such water would be attracted to the caved zone.

This leads to the conclusion that the method is also only likely to find application in a field which is essentially hydrologically inactive. There may well be a substantial number of such fields, but these restrictions are expected to preclude the acceptance of block caving as a likely major feature of the oil production scene.

5.3 SHATTER AND DRAIN METHOD

5.3.1 General Description

As a compromise between the methods based on direct mining of the oil-bearing rocks and underground drainage methods, the possibility was investigated of performing an in situ fracturing operation, using mining techniques, and thus inducing additional drainage.

This method and the two that follow it in this Chapter share the feature that most or all of the oil production is by drainage through drill holes or underground excavations. The prediction of yield in such an operation is a new technical province and this study has not attempted to generate a methodology for its solution, much less validate it in practice. Such an undertaking will require the collection of sophisticated additional reservoir data, extensive modeling studies and, ultimately, proof in pilot operation.

It was, however, necessary to provide some consistent basis for this study and this was done by assuming that each of the three drainage operations would eventually recover 50 percent of the oil remaining in the reservoir prior to mining. Such a value is very high indeed in relation to the results achieved conventionally in oil field production and may indeed prove to be totally unrealistic. This possibility is recognized in the economic evaluation discussed in Chapter 7 and sensitivity studies were performed to test the effect of oil yields as low as 10 percent of the residual reserve.

It was initially considered that a carbonate reservoir might prove amenable to this type of system, and the method was designed around the geology of the Yates field in Pecos County, Texas. Key properties of the Yates field are summarized in Table 5-3. Since this particular field is currently, and will remain for many years, a prolific producer, there is no implication that it is recommended as a potential target for such operations for many years to come.

The Yates oilfield is located in the northwestern part of the Edwards Plateau in the southern end of the Central Basin (Ref. 20), southwest of the Pecos River (Ref. 21) in northeastern Pecos County, Texas (Figure 5-8). The current proven area is 26,000 acres in Sections 22 to 24, 27 and 28, Block 194 (G.C. and S.F. Railroad Co.) (Ref. 21). The principal towns are Rankin, 30 miles to the south, and McCamey. Good, graded dirt roads connect the field with these supply points. Secondary roads also lead from the field to connect with the Old Spanish Trail Highway to the southwest. The Kansas City, Mexico and

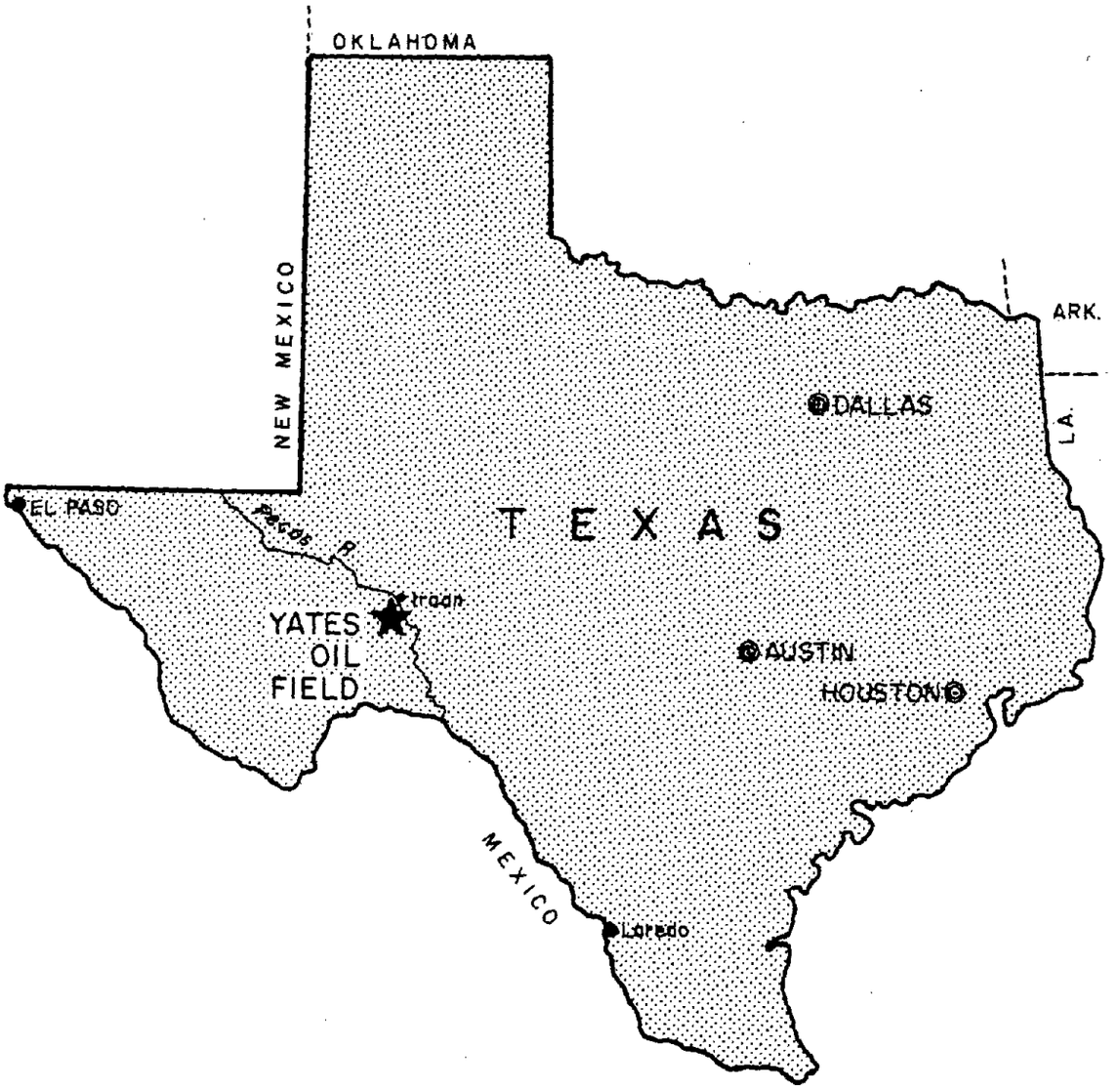
TABLE 5-3

YATES FIELD

Permeability	Wide variability		
Porosity (%)	31		
Oil Gravity	20°-30° API		
In-Place Grade (bbl/T)	Not applicable		
Depth to Top of Oil (feet)			
Ave.	1500		
Thickness of Oil Zone	to 500 feet? Av. 220		
Dip of Oil Zone	Varies (Elliptical Anticline)		
Overlying Rock			
Type	Anhydrite Series		
FM Name	Seven Rivers and Upper Part of Queen		
Age	Permian		
Underlying Rock			
Type	Dolomite(?)		
FM Name	San Andres(?)		
Age	Permian		
Oil-Bearing Rock			
Type	Basal Sands of Anhydrite	Dolomite Limestone	Dolomite Limestone
FM Name	Queen	Grayberg	San Andres
Age	Permian	Permian	Permian

LOCATION MAP
YATES OIL FIELD, TEXAS

Figure 5-8



Orient Railway runs through Rankin. The field is four miles wide and eight miles long (Ref. 22).

The topography is rugged. Small, intermittent tributaries to Pecos River have cut deep, steep-sided canyons into the relatively flat-lying, resistant limestones of the Edwards Plateau, forming flat-topped mesas. The topographic relief varies from a minimum elevation of approximately 2,150 feet in the Pecos River bed to a maximum of approximately 3,000 feet on the higher parts of the mesas. The topography of the northern and eastern parts of the field is that of a gently sloping alluvial plain which extends from the base of the mesas to the Pecos River. The average annual rainfall in the area is about 20 inches.

5.3.2 Geological Description

The Yates field is a cross-folded domal anticline. The oil is trapped in the highly permeable carbonate reservoir by an overlying, thick, impervious anhydrite sequence (See Figure 5-9).

1. Overlying Formations

   The main oil producing zone is overlain by a series of Cretaceous limestones and sandstones, Triassic sands and clays and Permian sands, shales and anhydrites. Of particular importance to this present study are the Permian sediments which immediately cap the oil-producing zone. These sediments represent a "red-bed" including evaporite series. The anhydrites at the base of this section are the Seven Rivers formation and the upper part of the Queen formation. Together these two anhydrite formations aggregate from 400 to 550 feet of stratigraphic section.

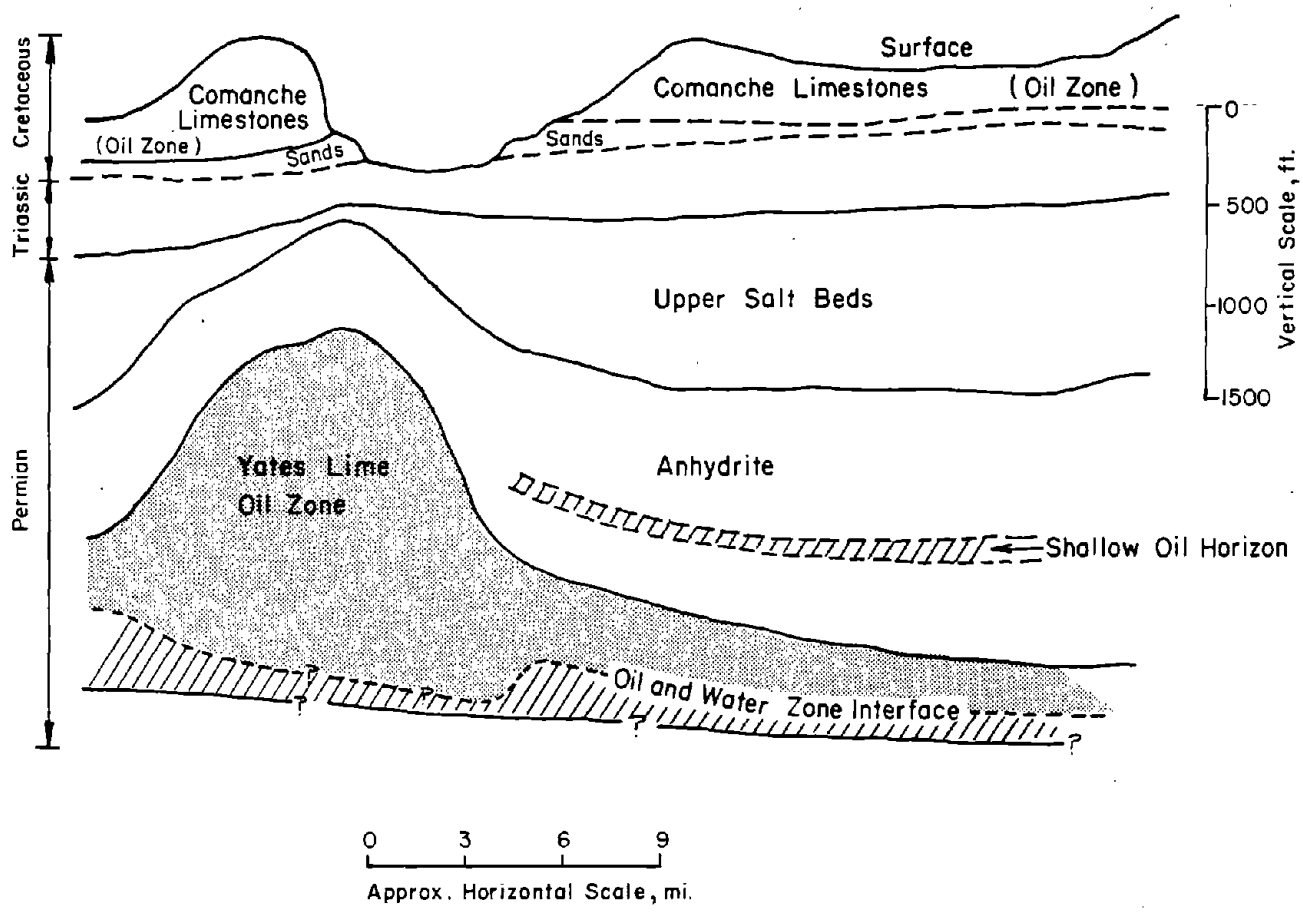
2. The Oil-Bearing Zone

   Oil is produced from the Permian carbonate rocks of the Queen, Grayburg and San Andres formations. The productive interval starts with the sands in the Queen formation at the base of the anhydrite and is on the order of 500 feet thick.

   The producing member within the Queen formation is the "River Bed Sand." This is comprised of the basal sands of the anhydrite series, which range from zero to 120 feet in thickness. This formation also contains dolomitic sands which are locally productive (Ref. 20).

GEOLOGIC SECTION
YATES, TEXAS

Figure 5-9



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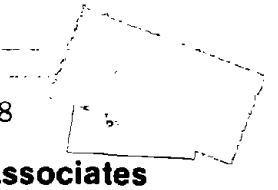
The Grayburg formation is the main producing formation of the Yates reservoir (Ref. 21). It varies from 85 to 145 feet in thickness. This formation is a dolomitic limestone containing some fine-grained sandstones. The upper 30 feet is very sandy, characteristically browned with oil, and is referred to as the "Brown Lime" (Refs. 21, 22).

Porosity of the limestone is variable and is related to irregular vuggy solution cavities as large as 1/10 inch in diameter, and in some places 1/2 inch or more in length. In some cases the cavities form layers parallel to the bedding which may contain dolomite crystals. There are minute interstitial voids in the granular phases which also constitute porosity. The porosity is highly variable but averages 31 percent (Ref. 4). The permeability ranges widely, from a fraction of a millidarcy to values in excess of 100 darcies (Ref. 23). In spite of the large volume of secondary, solutional, pore spaces and a moderate amount of pin hole porosity between carbonate grains, the evidence indicates that the carbonate reservoir rocks are hard and competent. The growth of dolomite crystals within some of the solutional cavities (Ref. 20) indicates that some cementation by dolomite probably has occurred. One photograph of core from the Grayburg producing zone (Ref. 20) shows a very vuggy but competent and solid sample.

The San Andres formation is a non-sandy dolomitic limestone underlying the Grayburg formation which corresponds to the "pure lime" of the early field descriptions. It is a gray to brown dolomite, usually with a layer of bentonite (Ref. 22).

A field rule established early in the history of the field limited drilling depth to 225 feet into the "big lime," and resulted in little knowledge of this formation beyond that depth. Oil production extends to the total depth tested and the base of the oil zone remains to be defined. An increase in water content with depth in the San Andres formation probably indicates a gradual transition to an underlying water zone.

Estimated oil originally in place varies from 3.7 to 4.3 billion barrels. Cumulative production to January 1, 1976 is 620 million barrels. Estimated recoverable reserves are greater than one billion barrels. The



oil has a gravity of 20 to 30 degrees API, and contains 1.5 percent sulfur (Refs. 21, 23). There is both an active gas cap and a water drive. The reservoir pressure has dropped from approximately 700 psi (1929) to 410 psi (1976) (Ref. 23).

3. Underlying Rocks

Because of the field rule limiting drilling depth to 225 feet in the San Andres, the base of the oil-bearing zone is not clearly defined although it is expected to have a thickness of up to 500 feet. Deep tests in this part of the Permian basin indicate that on the order of 2,000 feet of limestone will be encountered in the field. Thus, it is assumed that the underlying rock is the San Andres dolomite, or a similar carbonate formation (Refs. 20, 23).

5.3.3 Mine Design and Scheduling

The proposed system utilizes conventional drilling and blasting techniques to rubblize the reservoir rock with the intention of inducing improved oil recovery. In order to produce any substantial sustained effect, it is necessary to do more than merely fracture the rock; open fractures must be induced and this will involve some block rotation. It is considered unlikely that such a result will be attainable without the removal of a proportion of the broken rock to permit a degree of expansion during blasting.

The proposed design to achieve this is based on the sublevel caving system of mining and is similar to systems that have been proposed for preparation of oil shales for in-situ retorting.

1. Development

The oil bearing zone of interest is some 250 feet in thickness. A haulage and drainage level will be mined at the base of the zone with two fragmentation and draw levels at 30 and 140 feet respectively above. The haulage level is at a depth of 1,650 feet below surface.

All openings will be advanced using conventional drilling and blasting techniques. Blast holes on the blasting levels will be drilled with a trackless two-boom jumbo capable of drilling a ten-foot round. It is expected that the ground will be soft and rather nonabrasive. It will be necessary to use a rail

mounted jumbo in the haulageway drifts. It has been assumed that a mix of 50 percent ANFO and 50 percent dynamite or slurry will be used to accommodate wet holes, lifters and burn holes.

Rounds will be mucked out with a five cubic-yard front-end loader which will tram the broken rock to orepasses. Each sublevel crew will consist of three men; two men on the jumbo and one man on the loader handling several headings.

Ventilation will be handled by push/pull fans with the exhaust fans discharging the air to the crosscut nearest the heading being advanced. Ventilation requirements will be 1.5 million cfm. This should be adequate to dilute any methane present, dilute diesel exhaust gases and to carry away dust and powder smoke. In addition to ventilation, pipe, air and water lines will be installed as needed for development. The main haulage drifts will be equipped with electric lights. For the purpos of costing it has been assumed that drifts will be adequately supported with roofbolts and mesh.

2. Rock Fracturing

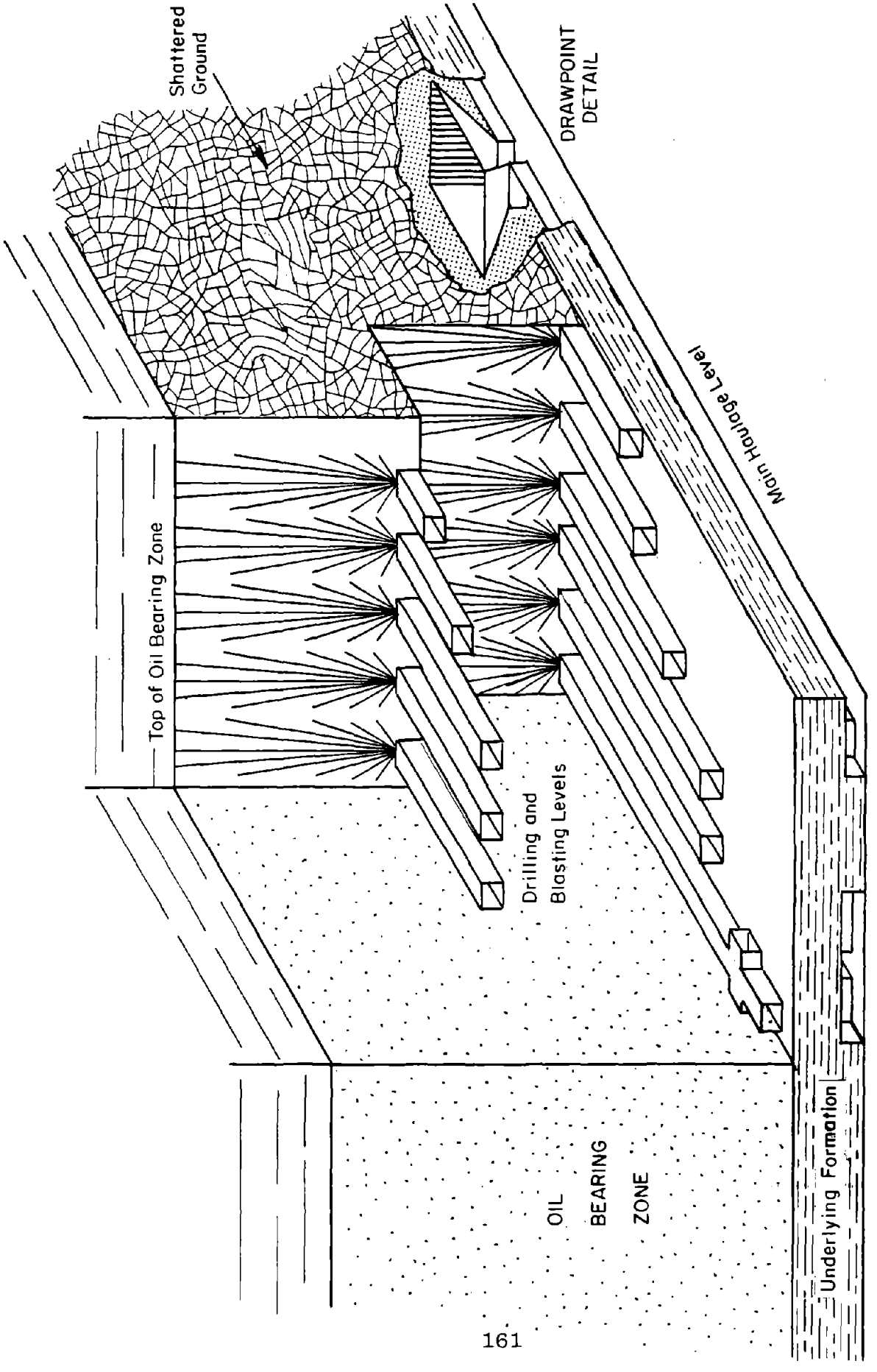
Blastholes will be drilled from the two sublevels in the general patterns shown in Figure 5-10. Drilling these holes will be done with a two-boom rubber-tire mounted fan drill. Maximum hole length will be 100 feet. Burden on the rings will be eight feet. Explosives will consist of ANFO detonated with a suitable primer. Broken rock from the stopes will be mucked by overshot loader into trains in the loading drifts. It will be necessary to load out a minimum of 20 percent of the volume of solid rock to allow for swell. This will be done from drawpoints on the haulage level directly into trains. Supplementary loading, if necessary to ensure blasting efficiency, will be done by loading on the sublevels.

The active drainage area will be 3,230,000 square feet which will include 216 drilling drifts. In addition to the drilling drifts, it will be necessary to have at least 27 development places under development at any one time.

Fresh air will be downcast in the production and service shafts, will travel into the production area through the haulage drifts, and will travel up to the

SHATTER AND DRAIN METHOD

Figure 5-10



30-feet and 140-feet sublevels through the vent raises. Return air will be picked up at the face in a rigid duct and will be directed through a brattice to the next drilling drift that is inactive, from where it will be passed to the exhaust shafts through a separate network of ventilation drifts and raises.

The haulage system on the main level will consist of trains made up of 15 ten-ton cars being pulled by 15-ton trolley locomotives. Each train will produce about 600 tons per shift. Train productivity is estimated at 1,150 ton-miles per train shift. Daily production will be 24,400 tons, requiring 14 trains operating on each shift.

3. Mine Plant

The shafts and hoisting systems have been sized to accommodate hoisting of 24,400 tons per day on a 250-day per year basis although shaft diameters will be dictated by ventilation requirements rather than by the equipment in use in the shaft. A friction hoist is favored for hoisting from 1,500 feet at the rate of 1,250 tons per hour. A conventional double-drum hoist with cage and counterweight would be suitable for use in the service shaft. The ventilation shaft will be unequipped but will be available for use as an escape shaft with an escape hoist and torpedo capsule.

The surface plant will consist of engine house, dry, shops, office, storage buildings and magazines. The shafts will be 30 feet in diameter, circular in cross-section and concrete-lined. The rock shaft will be equipped with rope guides. The service shaft will be equipped with conventional guides and butons, and will contain a double deck cage, ladder and pipe compartments and a counterweight compartment.

The main level drifts will connect from the production shaft to the loading drifts through twin main haulages. Ventilation drifts to the bottom of the vent shaft will be 15 by 15 feet in cross section.

Compressed air requirements will be quite high due to the nature of the operation. It is estimated that at least 30,000 cfm of compressed air will be needed.

4. Oil Production

After the blasting process has passed each set of drawpoints, the drawpoints will be bulkheaded and equipped with pipes for the collection of oil. As areas are worked out, they will be sealed from the rest of the mine area to prevent oil and gasses from leaking into active areas of the mine.

It is anticipated that oil will be pumped to the surface using beam pumps installed in wells bored for this purpose. This will keep oil lines out of the shaft and will reduce the amount of pipeline required for oil transport underground.

As previously mentioned, there is no simple and reliable method for predicting total yield in such an operation. The evaluations that were performed were therefore based on an assumed recovery of 50 percent, with lesser values being assessed by sensitivity calculations. Drainage is estimated to produce 1,750,000 bbls per year, with an additional 878,000 bbls per year coming from surface treatment of drawn rock.

5.3.4 Processing

The main processing plant feed will be that portion of the reservoir rock which is drawn to aid the blasting process, and will be a hard competent rock with the oil primarily contained in the solution cavities within the rock. Either a hot water or solvent extraction process will be used. The plant will also perform any necessary separation, cleaning and upgrading of the oil produced by drainage from underground. It will process 6,100,000 tons of ore per year and is expected to produce 2,620,000 barrels of oil per year.

5.3.5 Safety

This potential system shares the inherent risks discussed in the preceding sections associated with blasting operations in reservoir rocks, seepage of oil into active workings and discharge of noxious or explosive gases into working areas. They will not be discussed further here except to point out that there are features of the fragmentation system that will make explosion prevention and safe ventilation very difficult to attain.

The blasting will be on a large scale, if reasonable efficiency is to be attained. It will also be into a rock mass

with substantial void space, say 20 percent, and good permeability. In addition, and most significantly, the mine ventilation system will certainly have resulted in injection of some air to the cave adjacent to the blasting face, with the potential creation of an explosive mixture over a large volume. This danger appears real enough, and its elimination by safe blasting procedures, either impractical or expensive enough that we judge it to be an unacceptable risk.

The ventilation system on the sublevels is quite complex and consists largely of "dead-end" drifts, posing a major problem. If gas release from the rock is a real factor, as seems inevitable, the degree of dilution needed and the inability to employ series ventilation of headings will result in enormous air quantities and costs.

5.3.6 Environmental Factors

Mining will be conducted underground by blasting and draining. Processing will be with a hot water caustic soda wash. There will be some odor and noise associated with the processing as described in Chapter 4. Spoil will be disposed of above ground with revegetation necessary.

There will be a substantial impact of the facility on support services. The Yates field is about five miles from Iraan (population 800) in Pecos County (population 13,000). The nearest city is Fort Stockton (population 8,400) about 70 miles away.

Mining employment will be about 1,500 persons. This will create approximately 3,000 jobs in the support sector and increase the population in the area by about 10,500 people. There are no existing facilities in the area that can accommodate this influx of people. An entire community will have to be constructed to provide the necessary housing and services required to support the mining activity. Upon termination of the mining, after about 22 years, if sufficient other employment activity is not found a severe decline in the population will be experienced. This boom-bust cycle can only be broken with sufficient employment opportunities to keep the local economy at a steady level.

5.3.7 Technical Feasibility

The basic objective of this system, enhanced recovery by the use of mining-enhanced permeability, still appears to have important potential. It must said, however, that the design produced and evaluated here does not contain the answers to all the questions it poses. Three of these unresolved areas are vital.

1. Safety

The safety implications were discussed above and can not be satisfactorily dealt with at reasonable cost, based on present knowledge. We are sceptical that it will prove possible to conduct mining operations on a major production scale and to economic levels of performance, from within an oil reservoir.

2. Fragmentation Efficiency

The main foundation of the operation is the ability to produce effective permeability in the reservoir rock. To achieve this, a portion of the rock has to be removed and the resultant void distributed as evenly as possible throughout the remainder.

The selected approach to this task permits the development of a continuous, efficient production operation but has several unproven elements of major importance. The major elements concern fragmentation efficiency and rock mobility.

The efficiency of any oil recovery system after fragmentation will be dependent on the size range that can be attained with large boulders and fines having adverse effects. Under any circumstances this would be a difficult standard to achieve in a blasting operation. It will be made even more difficult, however, by the need to reduce to a minimum, for economic reasons, the proportion of the rock that is drawn as "swell." This will ensure that all blasting is performed under "choked" conditions and make it very difficult for rock to move downwards toward the draw points.

The problem areas can only be resolved by practical experimentation which would only be justified if the economic prospects for the system appear bright.

3. Potential for Oil Yield

Even if the above problem areas can be satisfactorily resolved, there remain serious doubts as to whether the process would produce substantially induced oil recovery. The severity of the other technical and economic difficulties facing such a system discouraged

further pursuit within the limited resources of this study, but the subject may well deserve additional consideration in the future.

In particular, the concept appears well suited to production from types of reservoirs having locally high but discontinuous porosity and permeability. Such types of trap could well yield a high proportion of their content if connected to the flow system and oil trapped in this way appears more likely to be recoverable than that remaining in intergranular pores. It is also, of course, ironically true that the existence of such trapped oil would be very hard to prove.

5.4 DRAINAGE WITH STEAM

5.4.1 General Description

One of the most promising practical demonstrations of oil production using mining techniques has been the underground steam injection project at Yarega in the USSR. Results from pilot operations appear encouraging enough to warrant expanded exploitation in that field and the technique was considered to deserve evaluation in this study. It has been applied to a hypothetical field with properties based on the Irma field in Nevada County, Arkansas (Table 5-4). The main reasons for selecting this field were:

- Low recovery of oil by pumping from surface wells due to the high viscosity of the oil.
- Overlying rocks are relatively strong; reservoir rocks are weak and the underlying rocks are below the water table.
- The field is fairly shallow.
- The field has a reasonably good reserve of oil that cannot be recovered by conventional methods (41.5 million barrels).
- The field has a relatively high permeability.

The specific Irma field is not ideal in all respects. Some of its negative features are:

- It is too small to write off a large mine plant.
- The oil-bearing zone is quite thin, resulting in high unit costs for development (average 20 feet thick for Irma versus 70 feet for the Yarega field).
- The amount of oil per acre foot is rather low--1,200 barrels per acre foot for Irma versus 1,656 barrels per acre foot at Yarega (Ref. 24).

TABLE 5-4

IRMA FIELD

Permeability (millidarcies)	1500
Porosity (%)	35
Oil Gravity	14° API
In-Place Grade (bbl/T)	0.38
Depth to Top of Oil (feet)	
Ave.	1150
Thickness of Oil Zone (feet)	20-27
Dip of Oil Zone	Flat to 5°
Overlying Rock	
Type	Marl, Shale, Sandstone
FM Name	Arkadelphia
Age	Upper Cretaceous
Underlying Rock	
Type	Chalk and Marl
FM Name	Saratoga
Age	Upper Cretaceous
Oil-Bearing Rock	
Type	Calcareous Sand, Arenaceous Limestone, Shales
FM Name	Nacatoch
Age	Upper Cretaceous

The field was, however, the most suitable that could be identified within the time available. It was accepted as the basis for design and evaluation in this study in spite of the drawbacks listed above and particular care was taken, through sensitivity studies, to ensure that the eventual evaluation reflected the potential of the method rather than the specific field.

The Irma Oil Field is located three miles southeast of the town of Irma in south-central Nevada County, Arkansas (see Figure 5-11) (Ref. 24). It occupies portions of Sections 1-3 and 9-16, Township 14 South, Range 21 West, Sections 5-8, 17 and 18, Township 14 South, Range 20 West, and Sections 31 and 32, Township 13 South, Range 20 West (Ref. 25). The town of Reader is 20 miles to the northwest and the town of Waldo, on the Cotton Belt Railroad, is 13 miles south. The field is served by a branch of the Missouri Pacific Railroad. The field is four miles long and an average of 1/2 mile wide. The topography of the area is hilly, with northeast-trending hills. The average elevation of the hilltops is 375 feet and of the valleys is 275 feet. There are many small streams, with two major northward-flowing ones (Ref. 24). The average annual rainfall is about 50 inches.

5.4.2 Geological Description

Faulting associated with graben development has produced closure in the Nacatoch sand along the crestal portion of a faulted monocline. The closure may exceed 70 feet, but at most only 50 feet of this has proven productive (Figure 5-12) (Refs. 24, 25).

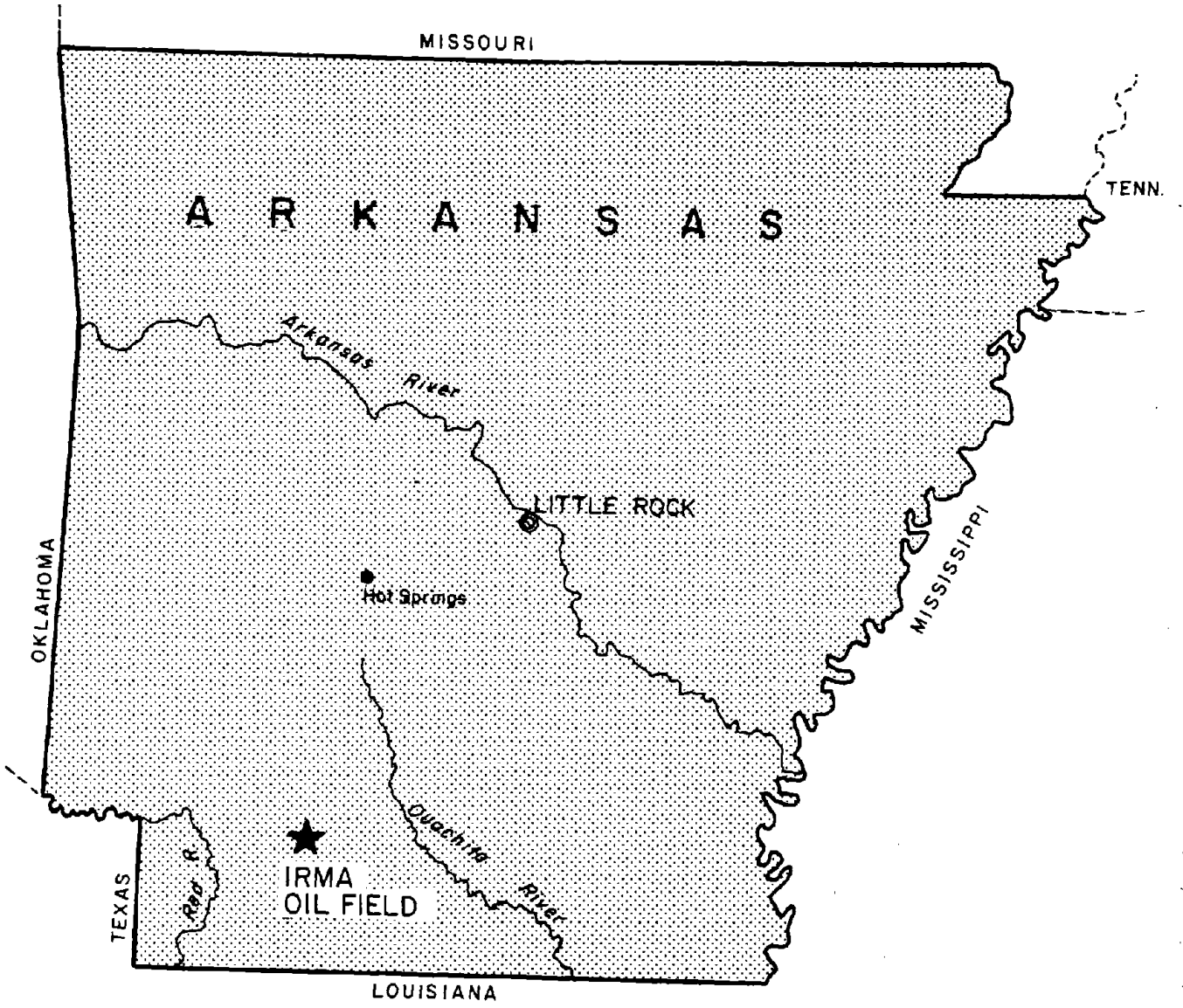
1. Overlying Formations

   The oil-producing zone is immediately overlain by the upper Cretaceous Arkadelphia formation, comprised of 75 to 100 feet of marl, gray shale and sandstone. Available information indicates that these strata are competent and continuous enough for mine development to be performed reasonably safely and economically. The Arkadelphia formation is separated from the overlying Eocene Midway formation by an unconformity (Ref. 24).

   The Arkadelphia formation and the underlying oil-bearing Nacatoch sand are cut by faults associated with a 2-1/2 mile wide graben. One of these faults produced the closure that allowed the pool to develop in the Nacatoch beneath the relatively impermeable

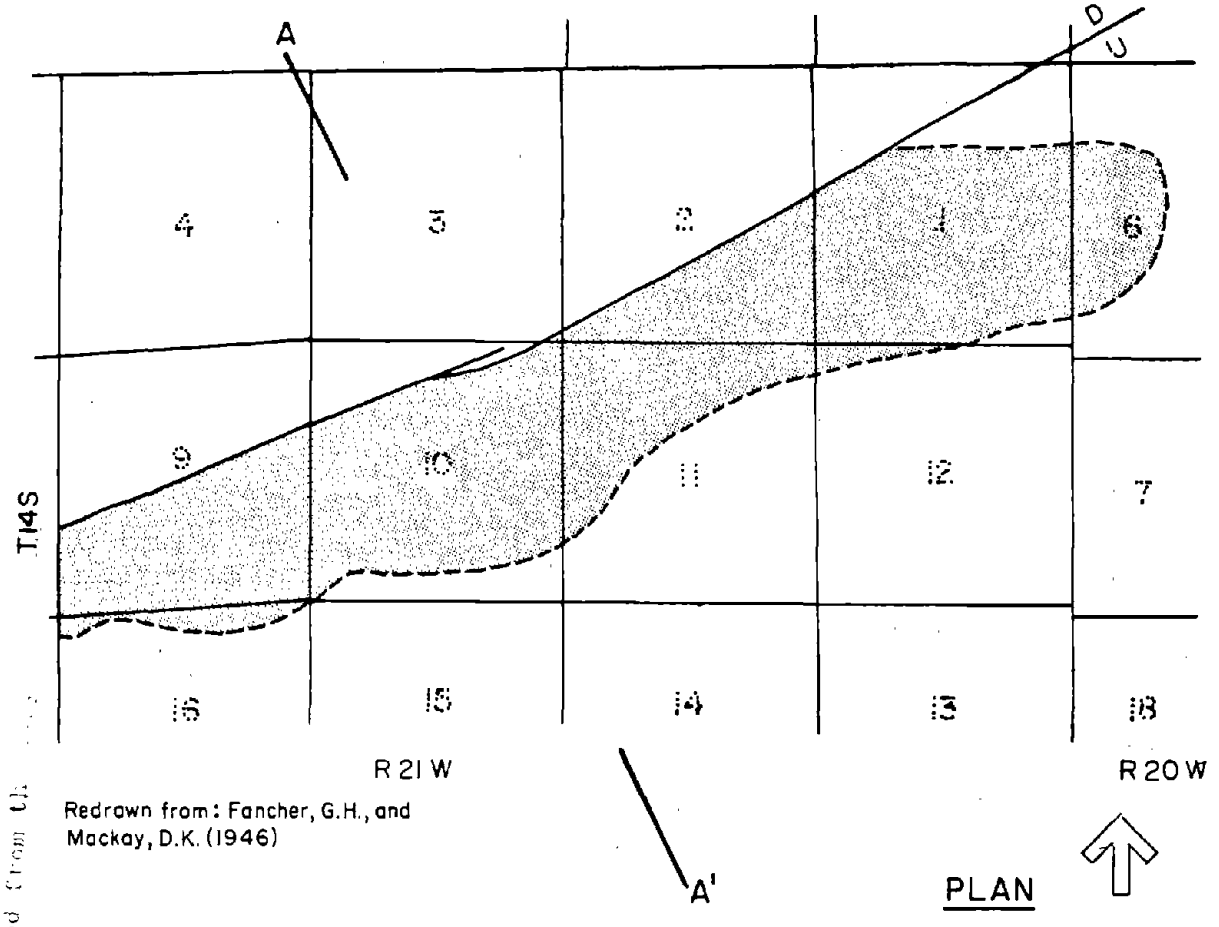
LOCATION MAP
IRMA OIL FIELD, ARKANSAS

Figure 5-11

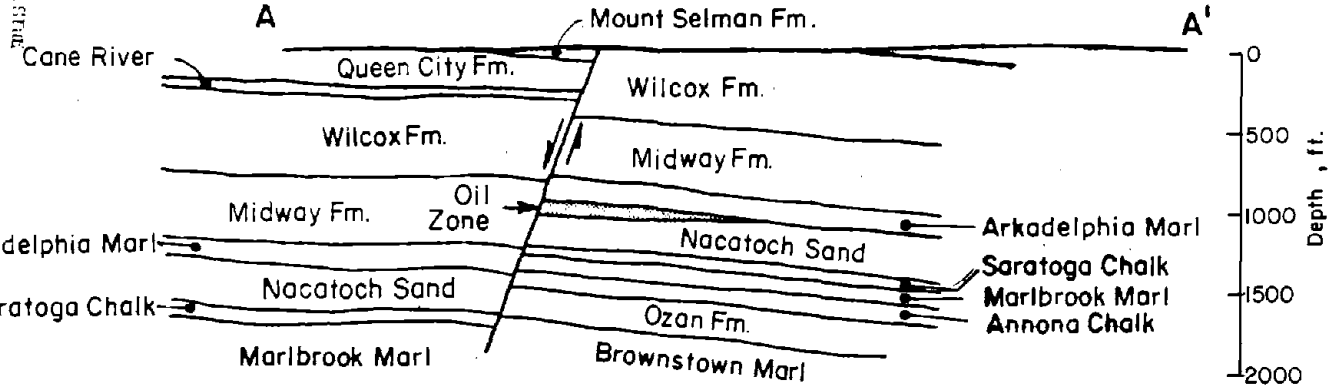


PLAN AND GEOLOGIC SECTION
IRMA OIL FIELD, ARKANSAS

Figure 5-12



Redrawn from: Fancher, G.H., and Mackay, D.K. (1946)



Modified from: Teas, L.P. (1929)

SECTION

0 1 mile

Horizontal Scale

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marl. There is no other published evidence of faulting in the immediate area of the oil field. The structural contours indicate a conformable boundary between the Arkadelphia and Nacatoch dipping gently, approximately five degrees to the southeast.

2. The Oil-Bearing Zone

The producing zone is in the uppermost portion of the Upper Cretaceous Nacatoch sand. This formation is composed primarily of calcareous sands and arenaceous limestones with interbedded shales. The top of the Nacatoch sand lies at an average depth of 1,150 feet beneath the surface (Ref. 4).

Although this formation is 300 feet thick, the oil-producing zone is confined to the upper 50 feet. The producing zone ranges in thickness from 15 to 50 feet but averages 20 to 27 feet. The Nacatoch sand has an average porosity of 35 percent and permeabilities ranging from 500 to 2,500 millidarcies, with an average of approximately 1,500 millidarcies (Ref. 4). Water saturation within the oil-producing interval is 35 to 45 percent (Ref. 25).

There is an active, albeit ineffective, natural water drive and the Nacatoch sand below the producing horizon is water saturated. There is no active gas cap and only a very small amount of gas is present with only about 10 cubic feet of gas produced per barrel of oil in 1946. The gas content was steadily decreasing during that year (Ref. 25).

The area of proven acreage is 2,166 acres (Ref. 4). Estimates of oil originally in place vary and a figure of 51,500,000 barrels was used for this study (Ref. 4). The oil has a gravity of 14 degrees API (Ref. 25) and contains 2.7 percent sulfur. Viscosity of the oil is 1,270 centipoises at 100°F (Ref. 25). The estimated grade of the oil-bearing rock is 0.38 bbls/ton.

The cumulative field production to the end of 1976 was 10,592,601 bbls with production during 1976 only 60,806 bbls (Ref. 2).

3. Underlying Formations

The Nacatoch sand is immediately underlain by the upper Cretaceous Saratoga formation, comprised of up



to 75 feet of hard, white and gray highly fossiliferous chalk and marl (Ref. 24).

5.4.3 Mine Design and Scheduling

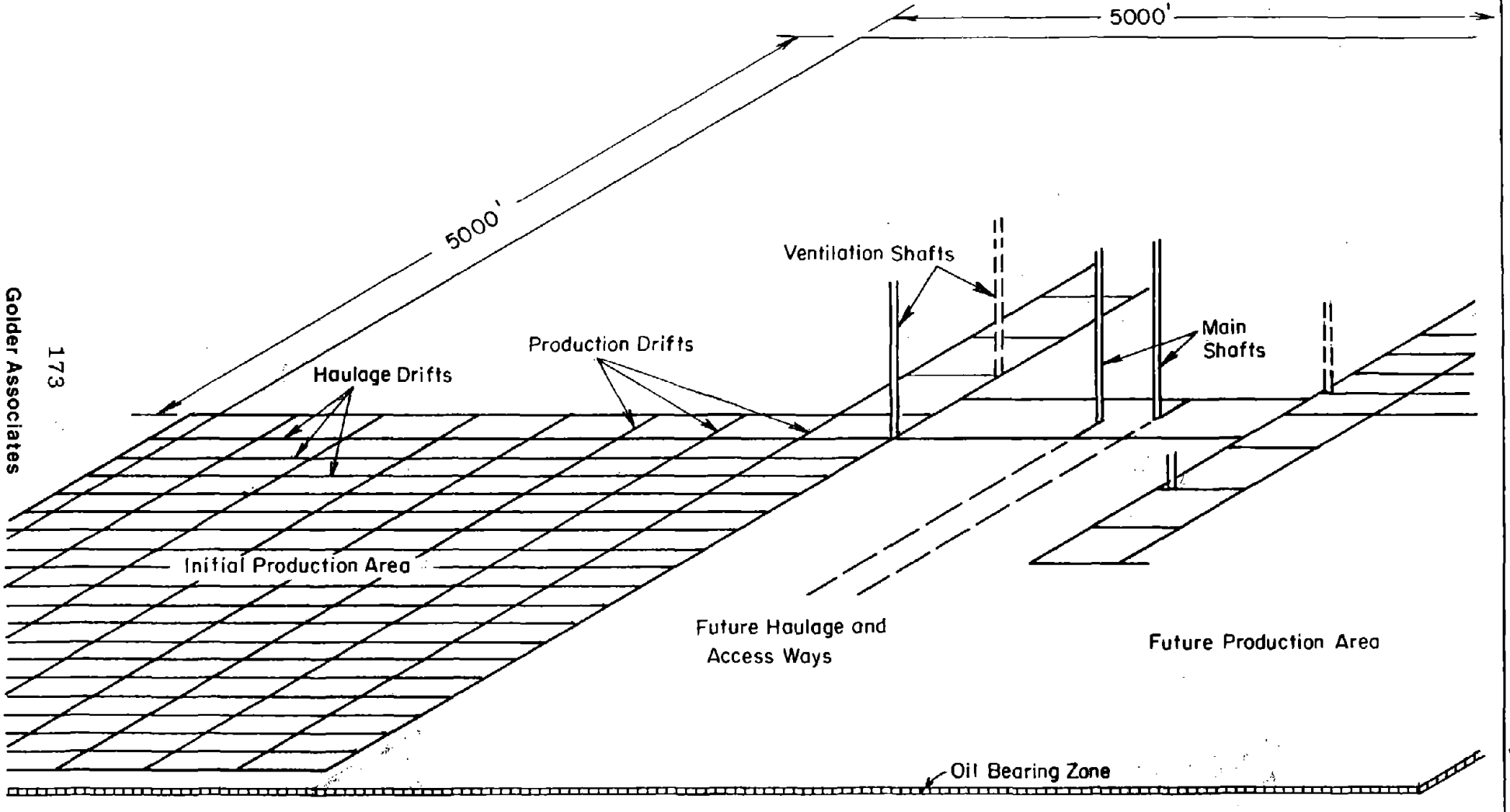
The proposed plan involves the driving of a network of galleries in the marlstone caprock overlying the oil-bearing zone. From these galleries wells would be drilled into the reservoir for steam injection and production purposes.

1. Development

Haulage drifts, access drifts, and production lines will be driven in the marlstones overlying the reservoir, using a continuous miner of the Alpine or Dosco type. The typical drift layout is shown in Figures 5-13 and 5-14. Access and production drifts will be 10 feet wide by 15 feet in height to accommodate drilling machines for the production and steam wells. It is expected that an average advance rate of eight feet per shift can be attained with a three-man crew. Broken rock from the miner will be dumped on the floor of the drift to the rear of the miner, and trammed by front-end loader to a muck bay near the main haulageway. One loader will be able to handle the cuttings produced by each miner with haulage drifts spaced on 625-foot centers.

Other utility lines will consist of a six-inch compressed air line and a two-inch water line in the haulage drifts. Production drifts will have four-inch compressed air lines and one-inch water lines. Haulage drifts will be equipped with electric lights. There is not enough specific data available on the physical characteristics of the ground to properly assess the ground support requirements for the drifts, but for the purpose of costing it has been assumed that the ground would be adequately supported with roof bolts on five-foot centers and mesh to the springline of the drifts.

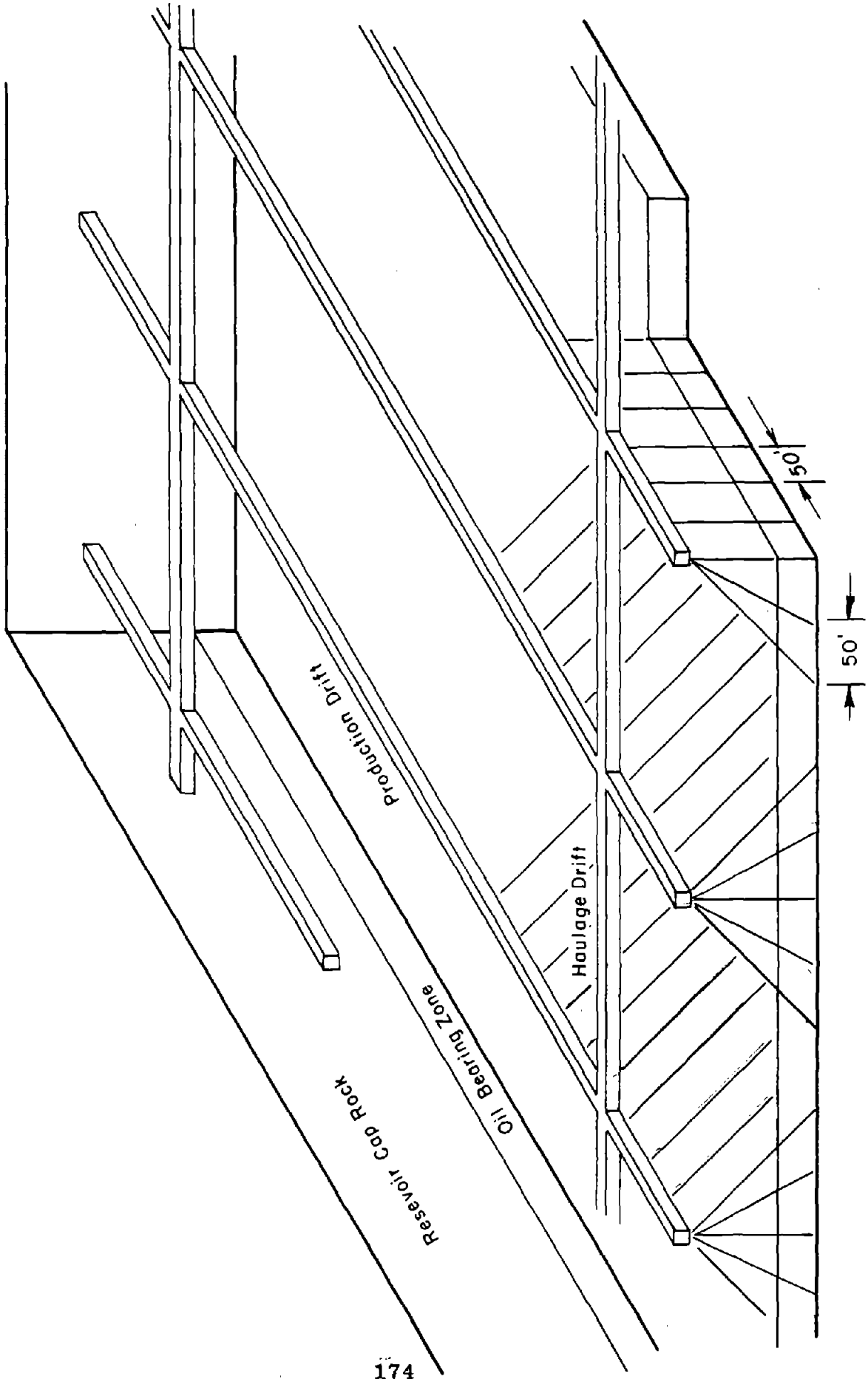
Due to the relatively minor amount of development muck produced by this extraction method, estimated at 2,200 tons per day, a simple rail haulage system will be able to handle the muck produced. Train productivity will be about 500 ton-miles per train shift using a 10-car train on a 6,500 foot haul. Two trains will be required.



GENERAL MINE ARRANGEMENT

DRAINAGE WITH STEAM STIMULATION
IRMA FIELD

Figure 5-14



2. Mine Plant

The rock hoisting shaft will be 12 feet in diameter, circular, and concrete-lined. The total depth of the shaft will be about 1,130 feet with the main level at 1,050 feet below surface. A storage pocket will be located below the floor elevation of the main level feeding to the skip loaders. It will also be necessary to provide spill pockets in the tailshaft. The rock hoist will be a conventional double drum unit with skips of six-ton capacity being hoisted in balance.

The service shaft will also be 12 feet in diameter, circular in cross-section, concrete-lined. The total depth of this shaft will be about 1,110 feet with the main level at depth 1,050 feet. The service hoist will be a conventional double drum hoist operating a cage and a counterweight. Equipment in both shafts will be kept as simple as possible to minimize friction losses in the downcast ventilation air. The service shaft will be equipped with conventional guides and buntons, and the rock shaft will be fitted with rope guides.

Surface buildings will include engine house, dry, shop, office, magazines, and warehousing. Compressed air for drilling, roof bolting, operation of skip loading gates, and other auxiliary functions will require 1,500 to 2,000 cfm, which will be supplied by stationary compressor on surface.

Mine water will flow to sumps located near the shaft complex for collection and settling of solids. Water will be lifted to the surface in one lift from the main level. It is anticipated that the mine will have an inflow of 1,000 gpm, requiring a column line of eight-inch diameter. All pumping systems will be duplicated underground and emergency power will be available on surface to run the pumps.

3. Ventilation

Boreholes to serve as upcast ventilation shafts will be located in the near corner in each quadrangle of the mine. These shafts will be 12 feet in diameter and about 1,050 feet in length. If ground conditions permit, the holes will be down-drilled and up-reamed to finished size with cuttings being brought out from underground. In case of bad ground, it may be



necessary to blind-bore the holes from surface and line them before removing the drilling fluids. In either case, the holes will be lined with steel liners grouted in place.

During the early development stages it will be necessary to downcast the service shaft and upcast the rock shaft. After the development drifts reach the borehole locations and the ventilation boreholes are equipped for upcasting, both shafts will be utilized for downcasting fresh air. Each borehole will be equipped with a main exhaust fan which will be offset from the line of the borehole as in coal mining practice. It will also be necessary to equip each borehole with an auxiliary fan powered with an internal combustion driven motor. In addition to the ventilation function of the boreholes, they will serve as escapeways in case of emergency underground using a portable hoist with a torpedo. The main fans should be equipped to be reversed in case of fire or gas problems in the mine.

The maximum amount of air required will be 800,000 cfm, with each of the two production exhaust fans handling 225,000 cfm and the development fan exhausting 350,000 cfm.

Ventilation in the headings will be accomplished by push/pull fans from the last crosscut with the exhaust air being discharged into the drift next to the one being driven. It is expected that two drifts will be advanced together at all times with connecting crosscuts on 250-foot centers. Brattices will be constructed in all of the crosscuts except the one nearest the face. Air volume to the development headings will be 30,000 cfm in order to dilute any gas emissions and to dilute any dust produced by the miner. A minimum air velocity of 30 feet per minute will be maintained in all active production drifts.

4. Oil Production

Production and steam wells will be drilled into the oil-bearing zone from the floor of the production drifts. After collaring, a packer and gate valve will be set into the hole, which will then be completed by drilling through the packer. It will be necessary to case the hole from the collar to the bottom to prevent caving during production and steaming operations. The lower part of the casing in the oil-bearing zone will

be perforated to allow outflow of steam from the steam wells and inflow of fluids from the production wells.

It is anticipated that production and steam wells will be four to six inches in diameter and will be drilled to a maximum length of 150 feet. Spacing at hole bottom will be approximately 50 feet.

Steam will be generated by portable electric boilers located near the steam drive area. These boilers will be supplied with treated water from a treatment plant located on the surface, with distribution lines branching to the steam drive areas underground. Steam will be distributed to the steam wells through insulated pipes to prevent heat loss to the mine atmosphere.

Production wells will either be operated by steam displacement, positive displacement by compressed air, hot water displacement, or by vacuum created by a steam ejector. It has been assumed that gas pressure in the reservoir will be so low that gas drive will provide no significant lift in the production wells. Some lift of the oil is, however, expected to be provided by water drive. As an alternative to steam, it may be possible to inject hot compressed air into the wells. This air would contact the connate water in the oil sands and flash it to steam. The advantages of this system would be to utilize the heat of compression of the air and to reduce the amount of water mixed with the oil. In order to best utilize the heat of air compression, it would be necessary to install small, electrically driven compressors near to the steam drive area. Electric heat exchangers could also be used to increase the air temperature before it is injected into the well.

Steam injection will serve several functions. It will:

- Lower the viscosity of the oil by heating
- Drive the oil toward the production wells
- Provide some lift in the production wells.

Successful steam drives have been performed in the same pay zone in the Smackover Field of Arkansas (Ref. 25). The well density provided by underground drilling of wells on 50-foot centers should increase both the total percent yield and the rate of yield in comparison with steaming operations from surface in which one well may cover several acres. Production

parameters have been projected for the Irma field from data on the Yarega operation (Refs. 4, 24, 26) and the Smackover data (Ref. 25). These parameters are shown in Table 5-5.

In order to produce at the rate of 5,000 barrels per day, it will be necessary to have an area of about 386 acres under steam at any one time, assuming an oil-bearing zone that is 20 feet thick. At Yarega, the yield is 16 barrels per day per acre (Ref. 24) and in the Nacatoch Sandstone of the Smackover field, production in a 10-acre test peaked about nine months after steaming began and returned to a level between 50 and 100 percent of primary about two years after steaming began (Ref. 25).

Well products will be transported in sealed gathering lines, to a central sump where settling of sand and water will occur and the gas will rise to the top of the mixture for separate transport to surface. The hot water fraction could be reinjected to the reservoir to lift the oil. Crude oil will be lifted to surface with conventional beam pumps located in each quadrangle of the mine. Sand that gathers in the sump will be drawn off at intervals for hoisting to surface.

Energy for the production of steam will be a major item of cost. It is proposed to transmit this energy underground in the form of electricity for the following reasons:

- Lower power loss between the source and the point of use
- Elimination of long steam lines in haulageways, thus lessening the chance of accidental rupture of the steam lines underground
- Less heating of the mine atmosphere by radiation from the steam lines.

A daily mine production of 5,000 barrels has been selected for the purposes of costing the project. Based on the indicated reserves remaining in the Irma field, the mine will have a productive life of less than 12 years with one year of preproduction development. It is anticipated that steaming operations will take place on a 350-day-per-year basis, 24 hours per day. Development will be scheduled on the basis of 250 days per year, three shifts per day. Oil production

TABLE 5-5

COMPARISON OF REPORTED AND ASSUMED PARAMETERS FOR YAREGA AND IRMA FIELDS

Reservoir Properties	Yarega Field	Irma Field
Depth	590 to 660 ft.	1150 ft.
Net Thickness	45 to 90 ft.	20 ft.
Average Permeability	3.2 darcies	1.8 darcies
Porosity	0.20 to 0.25	0.35
Oil Saturation	0.97	0.80
Reserves Index	1656 BOIP/A. ft.	1200 BOIP/A. ft.
Original GOR	240 cu. ft./bbl	100-200 cu. ft./bbl
Fluid Properties		
Gravity	17.4 ^{o}API	14 ^{o}API
Production Parameters		
Well depth	600-800 ft.	110-150 ft.
Well diameter, uncased	3-3/4"	4-6"
Reservoir area/injection well	2150-3225 sq. ft.	1960 sq. ft.
Specific steam consumption	3 tons/ton	3 tons/ton*
Bbl/day/acre	16	13
Percent yield	up to 60%	50%
Bbl produced/ft. of drift	85**	47
Bbl produced/ft. of hole	6**	5

*Based on information published in "Journal of Petroleum Technology," August 1973 and August 1975.

**Mine #1, Area T-2

will be 1,750,000 barrels per year. Annual development footage requirements during production will be 55,160 feet of drifts. It will also be necessary to drill 717,000 feet of production and steam wells per year.

5.4.4 Processing

The oil produced from the steam stimulation method selected for the Irma field will require minimal processing prior to shipment. The proposed plant for Irma will primarily consist of oil/water and oil/gas separation units. Dependent upon the amount of fine clay or silt that is present in the oil, a process such as centrifuging may be required to remove the suspended material before final shipping of the product.

5.4.5 Safety

This system is inherently the safest of the underground options considered for three reasons:

- The mine-oil interface is controlled by seals on drill holes, piping of products, etc.
- The mine workings are designed to be totally contained in reservoir cap rock. By definition this is of extremely low permeability and, by implication, is also more competent than can be assumed of any other zone
- The nature of the operation requires mine openings of only a relatively modest size.

There are, however, still risks associated with such a venture which are not normal to underground mining and which can only be satisfactorily resolved in the detailed geology and engineering stages.

Even though reservoir cap rock appears, as a generalization, to be a favorable location for mine development, the potential still exists for gas pockets, gas permeability, or erratic stratigraphic boundaries causing connection to reservoir formations, zones of weak ground and so on. In order to raise the available data to a level suitable for detailed mine design and definitive feasibility determination, substantial additional drilling will be required in all candidate fields of which we are aware. It is reasonable to assume, however, that once drilling is performed to normal mining evaluation density and standards, an operation could be designed and implemented without accepting levels of risk to personnel which would not normally be tolerated.

5.4.6 Environmental Factors

Oil mining at Irma will be underground using steam injection. Principal mining impacts will be those associated with normal underground activity as delineated in Chapter 3. Mining transport and processing will create some odor and dust. The small amount of spoil produced will be disposed of above ground with revegetation necessary.

Impacts related to community support facilities will be substantial. The majority of towns in the vicinity of the project (Rosston, Willisville), have less than 200 population each. Waldo, 13 miles south, has a population of 1,750 and Hope, about 20 miles west, has a population of about 9,000. Nevada County has a total population of about 10,500.

The project will increase employment by about 600 people. This provides employment for a total of 1,800 people (600 in the mine plus 1,200 support employees). Total population increase is estimated at about 4,200 persons. This would increase the population of Nevada County by 40 percent, creating a substantial demand for housing services and employees that cannot be entirely handled by the local economy.

When coupled with the 12-year life of the project there is a moderate boom-bust cycle that will be created. A rapid influx of new people would provide about a decade of prosperity, followed by a rapid decline in population and high local unemployment when the project is terminated.

5.4.7 Technical Feasibility

The basic practicality of this operation is probably the highest of any of the underground operations evaluated in this study. The mining operation itself is relatively simple and is to be conducted at modest depths below surface.

The shafts will probably be sunk through unfavorable formations, poorly consolidated materials with considerable water problems. Such circumstances are often encountered, however, in the upper portions of mine shafts and can normally be overcome through the use of grouting and freezing. The horizontal development consists of modest, normal sized tunnels which should pose no unusual difficulties in drifting, support or long-term maintenance.

The only substantial question hanging over these aspects of the scheme concern the level of geological certainty that can be generated from available data to permit design of a safe mining operation. It is necessary to be able to establish with good

confidence that the strata selected will exhibit the required competence and impermeability with good continuity. At this time this appears to be a reasonable expectation.

The drilling of the holes, with adequate safeguards against gas blowouts, steam and oil leaks, etc., is not an established underground technology. All elements of such a system are in common use on surface, however, and there should be no severe problems in developing a rig which is compact and mobile enough for use in a mine.

The certainty of obtaining a satisfactory additional yield of oil from this method is difficult to determine at this time. The availability of lines of holes at the close spacings anticipated creates a very different order of possibility in steam drive efficiency. In particular, the opportunity to employ an essentially linear rather than radial drive could be extremely beneficial. The generation of reliable predictions of this type, however, will require substantially more specific theoretical work than was possible in this study and will then need validation by field trials. It is our conclusion at this time, however, that the prospects are bright for obtaining good results.

5.5 GRAVITY DRAINAGE

5.5.1 General Description

The simplest of all possible systems for underground recovery of oil is the drainage method and it was considered essential to include an example of the technique in this study. If successful in achieving a substantial recovery of the in-situ oil, such a system would represent an optimally simple and effective technique. It thus in a real sense represents the "lower bound" case of all those studied and is therefore of great significance in evaluating the future of oil mining. The Wheeler Ridge Field, in Kern County, California, was selected for this purpose, mainly based on the following factors:

- The field has relatively high permeability.
- The oil-bearing sands are thin enough to be reached by simple drilling with moderate sized equipment from underground openings.
- The competency of the oil-bearing sands is low and would be very unlikely to permit mining operations within them at reasonable cost.
- The competence of the underlying beds would permit establishment and maintenance of production openings at reasonable cost.

The Wheeler Ridge Oil Field is located 25 miles south of the city of Bakersfield, in the south-central San Joaquin Valley, in Kern County, California (Ref. 27) (see Figure 5-15). It occupies 620 proven acres (Ref. 4) in Sections 20 and 27-29, Township 11 North, Range 20 West (Ref. 27). The oilfield is one mile long and 1/2 mile wide (Ref. 15), and lies just south of the California Aqueduct. Federal and state highways lie to the east and north, and secondary roads serve the area itself (Ref. 28). Wheeler Ridge is a northwest-trending (Ref. 29) foothill of the San Emigdio Mountains (Ref. 15). The elevation of the area ranges from 1,000 to 1,900 feet. The climate is arid to semi-arid, with an average annual rainfall of about 15 inches. Parameters of the oildfield are summarized in Table 5-6.

5.5.2 Geological Description

The Wheeler Ridge oil field is an assymmetrical anticline thrust faulted over an elongate dome (Ref. 11). There are numerous oil producing zones and areas that comprise this field, with the Coal Oil Canyon Zone of the "Central Area" being the subject of this study (See Figure 5-16).

1. Overlying Formations

   The oil-producing horizon of interest is overlain by a series of Pliocene to Recent sediments. These are, from the surface down, Recent alluvium, the Pleistocene Tulare formation and the Pliocene San Joaquin-Etchegoin formation. The Tulare formation is composed of hard sandstone and zones of yellow and blue clays. The San Joaquin-Etchegoin formation is composed of green and gray sands, sandy clays and clays with some zones of gravel. Of these overlying formations, only the Etchegoin is of marine origin and is separated from the producing Coal Oil Canyon zone of the Santa Margarita formation by an unconformity.

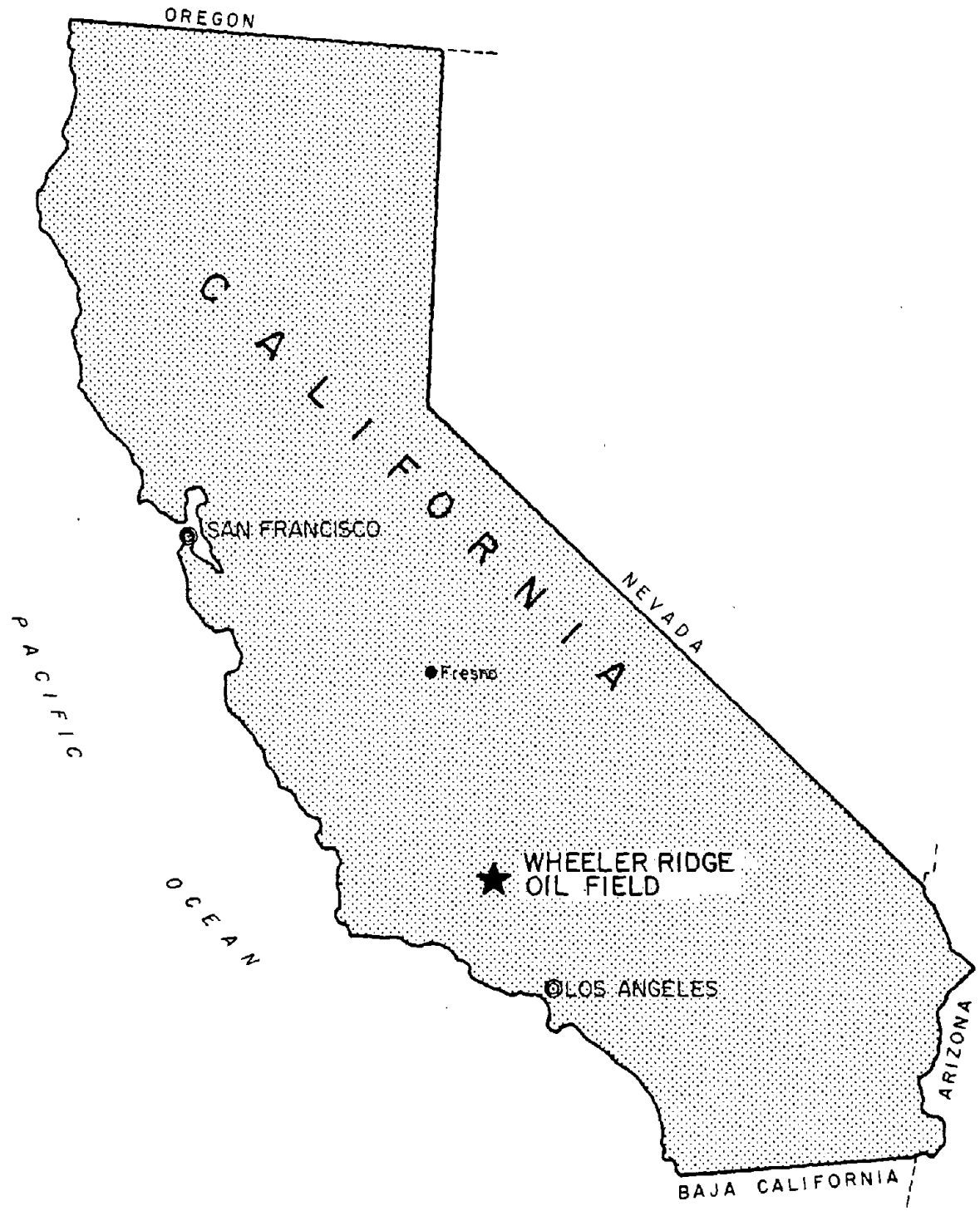
2. The Oil-Bearing Zone

   As mentioned in a preceding paragraph, there are a number of oil-producing zones and pools in the Wheeler Ridge field. For the purposes of this study only the Coal Oil Canyon zone of the upper Miocene Santa Margarita formation will be discussed.

   The Santa Margarita sandstone is comprised of 170 feet of fine-grained, well-sorted, gray, friable sandstone interbedded with greenish-gray siltstone and is of marine origin. The top of the target horizon is 1,000

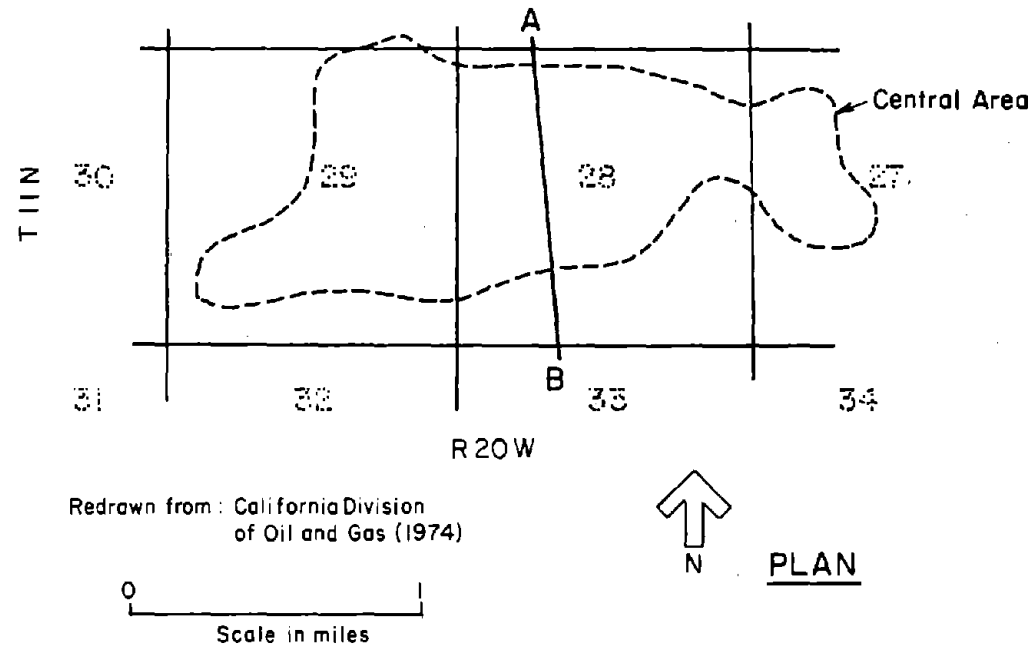
LOCATION MAP
WHEELER RIDGE OIL FIELD, CALIFORNIA

Figure 5-15



PLAN AND GEOLOGIC SECTION
WHEELER RIDGE, CALIFORNIA

Figure 5-16



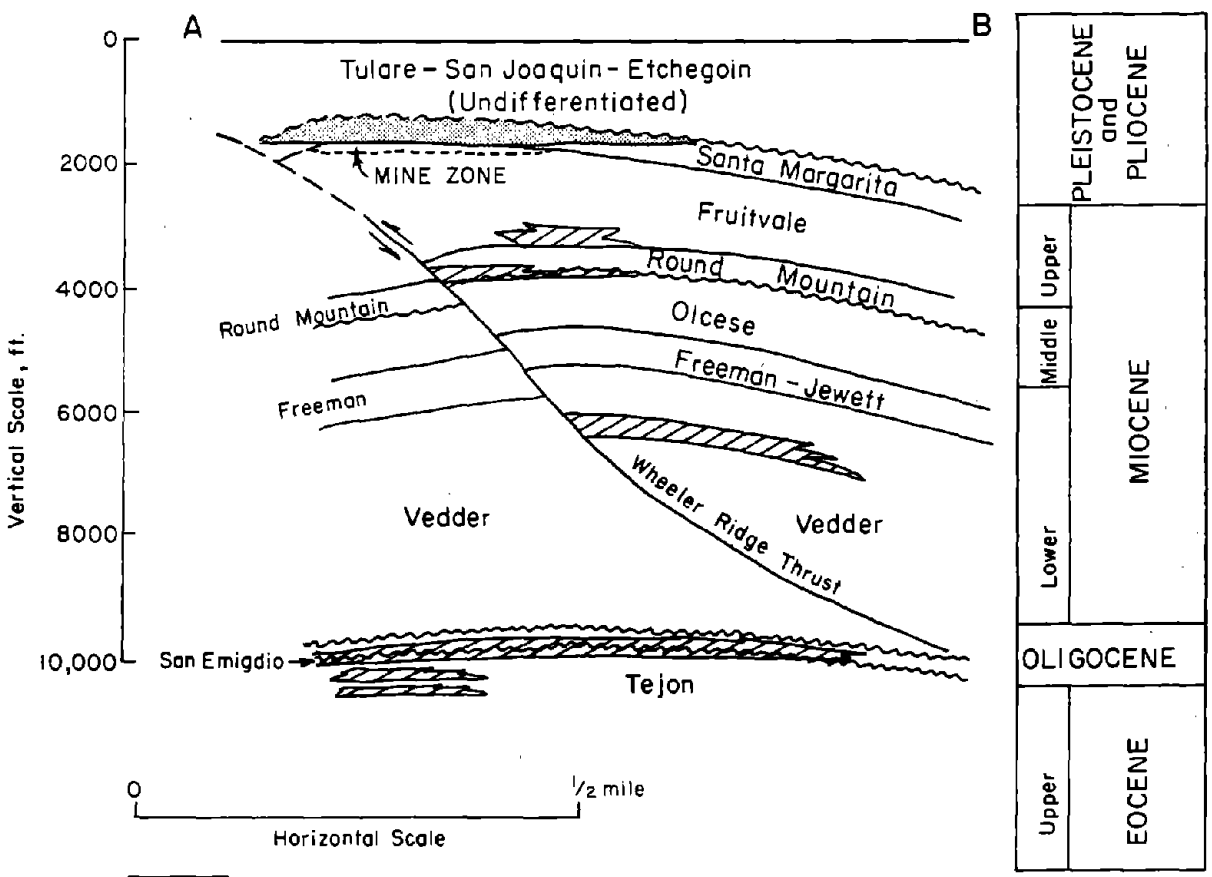


TABLE 5-6
WHEELER RIDGE FIELD

Permeability (millidarcies)	Approx. 800
Porosity (%)	Approx. 32
Oil Gravity	22° API
In-Place Grade (bbl/T)	0.28
Depth to Top of Oil (feet)	
Minimum	1000
Maximum	1310
Thickness of Oil Zone (feet)	170
Dip of Oil Zone	Asymmetrical Anticline--Dips Vary
Overlying Rock	
Type	Sand, Sandy Clay, Clay, Sandstone, Alluvium
FM Name	San Joaquin-Etchegoin, Tulare
Age	Pliocene to Recent
Underlying Rock	
Type	Siltstone with interbedded Sandstone
FM Name	Fruitville
Age	Upper Miocene
Oil-Bearing Rock	
Type	Sandstone interbedded with Silstone
FM Name	Santa Margarita (Coal Oil Canyon Zone)
Age	Upper Miocene

to 1,310 feet below the surface (Refs. 4, 11). The average thickness of the pay zone is 170 feet.

The total proven acreage as of 1974 was 620 acres (Ref. 4). The estimated oil remaining in place is 93,000,000 barrels. Present oil content of the producing zone is estimated to be 0.28 bbls per ton of 22° API gravity heavy crude oil (Ref. 4). Production history from this field shows a steady decline in the average daily production from the wells in this pool. The initial production from wells in Coal Oil Canyon pool ranged from 11 bbls per day up to 165 bbls per day (Ref. 27). In 1951 the average production per well was approximately 68 bbls per day (Ref. 27). Even after initiation of a water flood in 1962 and depressurization with gas during the period 1960-1969, the average daily well production in 1972 was only slightly over 23 bbls (Ref. 11) and this had declined to just under 9 bbls by 1976 (Ref. 19). During the same interval of time the production of water to oil continued to increase, particularly after initiation of the water flood program (Refs. 11, 25).

There was no recorded gas production from this pool until after the injection of 27,337,000 Mcf of gas during a nine-year pressure maintenance program in the 1960's (Ref. 11). The heavy crude oil is assumed to have had a very low gas to oil ratio. The gas to oil ratio in 1976 was only 139 cubic feet of gas per barrel of oil.

There is no published data on the porosity and permeability of this producing zone. However, the data available indicate that the porosity is 32 percent and that the permeability is 800 millidarcies. The low production rates and anticipated low recovery of the contained oil is more than likely the direct result of the viscosity of the heavy crude oil. Close spaced drainage holes drilled from underground locations in similar fields, preferably prior to water or steam flooding, may offer a significant advantage with respect to the percent of the total resource produced.

3. Underlying Formations

Immediately underlying the Santa Margarita formation is the upper Miocene Fruitvale formation. This formation is comprised of brown to brownish-gray siltstone with interbeds of very fine- to coarse-grained sandstone. Indications are that these formations are

relatively competent and contain impermeable bands which could be suitable for mine development.

5.5.3 Mine Design and Scheduling

The method evaluated here is the simplest, and perhaps therefore the most optimistic, possible. A network of tunnels is mined in a relatively competent formation lying just below the oil-bearing zone. A dense pattern of holes is drilled up into the reservoir and oil recovered by simple gravity drainage.

1. Development

Mine development is carried out on a single elevation located in a siltstone formation situated some 50 feet below the reservoir zone. A double entry layout will be used to ensure good ventilation distribution. A pattern of drilling drifts will be mined, as shown in Figure 5-17.

Haulage, ventilation and accessways will be driven using a continuous miner of the Alpine or Dosco type. All drifts will be 15 feet wide by 10 feet high to accommodate the equipment chosen and to allow for acceptable air flow velocities. Heading crews will consist of three men, one miner-operator, one LHD operator, and one helper.

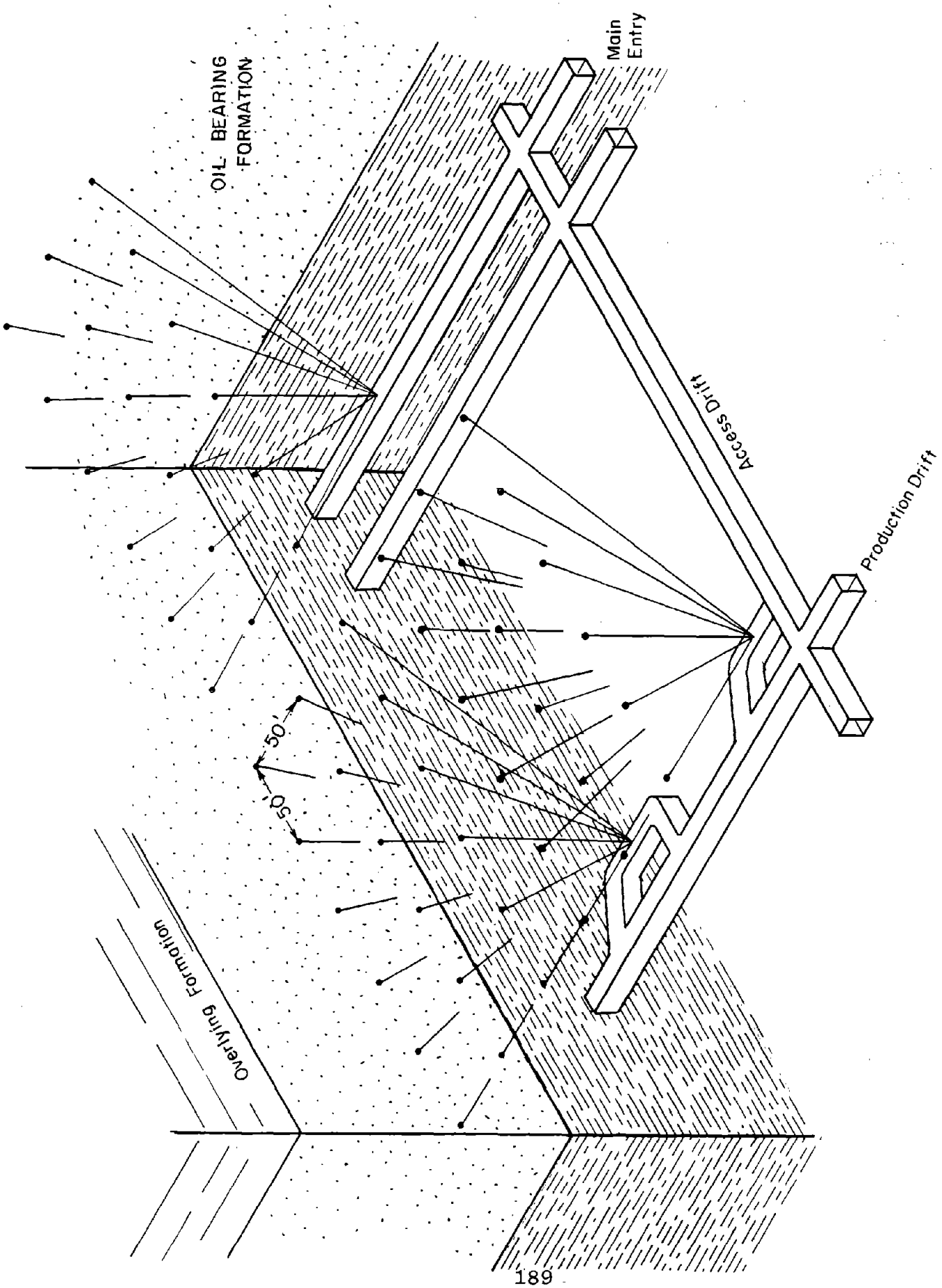
A minimum production rate of eight feet per shift has been used as the basis for determining equipment requirements. At the estimated requirement of 14 feet per shift, two continuous miners will be necessary.

Broken rock created by the miner will be dumped to the rear by the miner's conveyor for the LHD to collect and tram to the hoisting shaft. Although LHD's are normally limited to a maximum working range of about a thousand feet, the low tonnage requirement and relatively concentrated mining area has extended that distance in this instance.

An equipment usage tabulation was prepared for the 19-year expected life, showing that even under the most demanding conditions two LHD machines could handle the muck flow expected. Consideration was also given to LHD-truck haulage, but higher estimated costs, both capital and operating, made it unattractive in this low tonnage application.

GRAVITY DRAINAGE METHOD
WHEELER RIDGE FIELD, CALIFORNIA

Figure 5-17



Based on the limited data available, the rock in the working horizon has been assumed to have a strength of about 5,000 psi without serious jointing or faulting. By driving with a continuous miner, and bolting immediately, care will be taken to preserve the support characteristics of the rock mass. Six-foot bolts will be placed on five-foot centers where local conditions require, and along main haulageways the additional precaution of installing wire mesh will be employed.

Once the desired level or production is attained, annual development requirements will be 10,750 feet, or approximately 14 feet per shift. In excess of 150,000 feet of drilling will be necessary on a yearly basis. Hoisting requirements will be minimal at about 420 tons per day.

2. Mine Plant

Access to the mine will be through a simple service and rock hoisting shaft, handling downcast air, and a single exhaust ventilation shaft.

The service/hoisting shaft will be 18 feet diameter, circular concrete-lined and equipped with steel sets. The rock hoisting duty is very light, some 420 tons per day, and will be handled with a single skip and counterweight. A single-decked cage with counterweight will be used for transport of men and materials and the shaft will also contain the usual manway and service lines.

The ventilation shaft will be 12 feet in diameter and would be lined but not otherwise equipped. It will, however, be able to accept an emergency capsule for evacuation purposes if required.

3. Production System

The basic mine pattern will be typical double-entry system, on 1,050-foot by 750-foot pattern, within which a single entry system will be placed on 350-foot centers. Drill stations will be located at 150-foot intervals along those drifts.

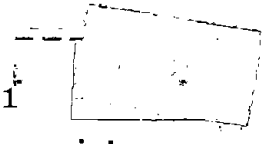
Three fans of drainage holes will be drilled from each chamber and will bottom 25 feet below the top of the oil-bearing horizon. Each fan will contain nine holes, giving a hole distribution of 50-foot centers

at the ends. A maximum hole length of 250 feet will be used, which will be easily attained in four-inch size by the machines chosen.

Since the production holes will be drilled from chambers off the side of drifts, the drills will not impede traffic in the accessways and, by the utilization of brattices, a positive flow of air will be maintained to sweep each drilling area. A stuffing box and valve will be emplaced at the hole collar, allowing control of gas or liquid emissions during and after completion of the drill hole. This will reduce the danger of a buildup of volatiles in mine airways. It is expected that perforated casing will have to be set in the holes, but this is only an assumption until detailed drilling can be performed to define ground conditions. Such casing will definitely be required if the lower part of the reservoir is water-bearing.

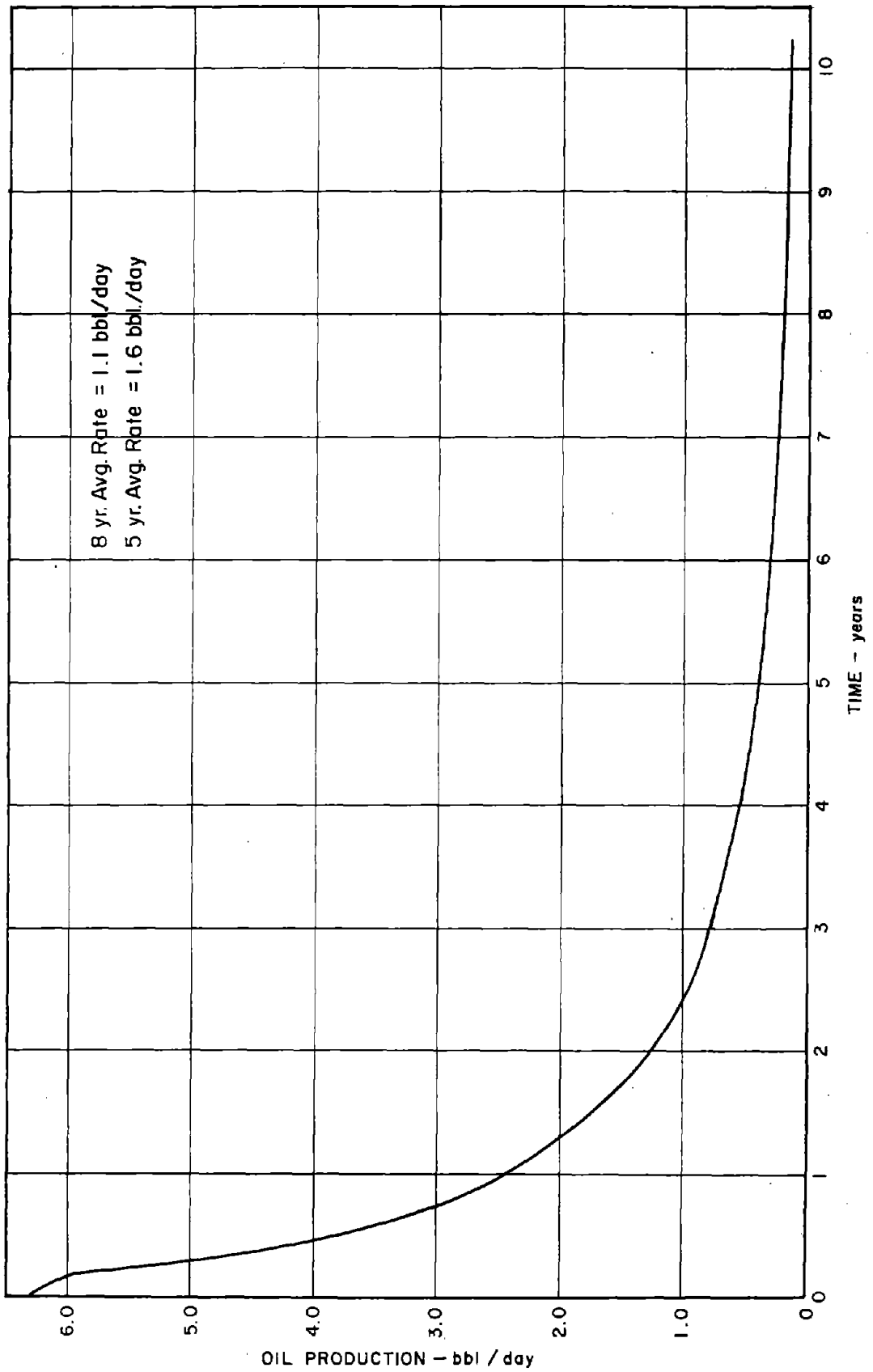
As previously discussed, no practically proven method is available for predicting the level of oil recovery that might be expected from such a system. As a basis for this study, therefore, the assumption was made that the reservoir can be expected to yield a total of up to 50 percent of the reserve remaining at the start of this operation. A yield against time curve was drawn up (Figure 5-18) showing a variable rate of flow, tailing off to minor amounts. The basis for the analysis which produced these results are shown in Appendix A. Using a 0.5 barrels per day cutoff, which is expected to be reached after five years of flow, and integrating the area under the curve and dividing by time, an average rate of flow of 1.6 barrels per day per hole is projected. This would result in an approximate recovery of 50 percent of the oil remaining at the start of the operation. The cutoff yield rate of 0.5 barrels per day was arbitrarily chosen and would have to be established for each actual operation.

The water-oil-gas outflow from the drill holes will be encased from the hole collar and flow or be pumped to a central sump near the shaft in gathering lines. Differential settling of sludge, solids, water and gases would take place to some extent in this sump. Taps at several elevations would permit a semi-separation at this point. The gas and oil-water mixture would be piped to the surface in separate pipes located for safety in a borehole rather than in either of the shafts. Additional separation facilities



OIL PRODUCTION VS TIME IN SINGLE BOREHOLE
AT 50% RECOVERY

Figure 5-18



and sumps will be located on surface to upgrade the product to pipeline quality.

Production at the rate of 6,600 barrels per day would give a reserve life exceeding 20 years, allowing adequate time for depreciating the capital investment required. Drainage operations will be conducted on a 350-day basis, and mine development on a 250-day work year, three shifts per day. At 6,600 barrels per day, oil production will be 2.31 million barrels per year.

4. Ventilation

At any one time, some 250 acres of the mine is expected to be in production. If a minimum velocity of 30 feet per minute is to be maintained in all active roadways, a total of 300,000 cfm will be required to maintain safe conditions in the production area. This figure includes a generous allowance for recirculation but does assume that some production areas could be ventilated in series. Return air from the active blocks will also be used to sweep abandoned areas that are not sealed off to ensure that they remain clear of gas concentrations.

Development by the continuous miners will require 90,000 cfm, but the development air requirement will, in fact, be determined by the diesel equipment at 110,000 cfm. The total development air necessary, including an allowance for leakage, has been estimated at 150,000 cfm. The main fans, located at the top of the upcast shaft, will therefore be specified to handle 450,000 cfm at 11 inches SWG.

Ventilation practice in the twin headings will be similar to that employed in conventional coal mining practice, with crosscuts between the headings at prescribed distances. When a heading advances from the fresh-air base, ventilation initially will be by a secondary fan and fan bagging. If this proves insufficient and not positive enough to cope with encountered conditions, a piped exhaust system will be employed, in addition to the fan and fan bagging. This system will also be employed in the case of the single entry drifts. Air availability and the flexibility of the system will be such as to permit far higher than average flows to be concentrated in single headings or working areas if necessary.

5.5.4 Processing

The processing plant at Wheeler Ridge will only be required to carry out the same function as the plant prepared for Irma, namely oil/water separation and the removal of any suspended solids.

5.5.5 Safety

This system offers the same benefit as the previous one in that the mine workings are only connected to the reservoir through drillholes. In this respect it too may be described as basically safe.

The inherent risk is, however, greatly increased by locating the mine in the underlying strata rather than in reservoir cap rock. There is no proper fundamental assumption that underlying formations are either impermeable or competent, and indeed, as a general rule the opposite would be more true: formations underlying valuable oil-bearing areas would tend to be poorly consolidated sandstones saturated with water under pressure.

The evidence appears to indicate, however, that enough satisfactory instances could exist of suitable underlying rock conditions for the concept to be valuable. It will, however, be necessary to establish during drilling, to the same high standard as previously indicated, that the favorable circumstances necessary for safe mine development and operation exist continuously and reliably. If this situation can be successfully demonstrated to be the case, there is no reason why this should not be a safe, routine type of operation.

5.5.6 Environmental Factors

Mining will be underground using gravity flow excavation. There will be no impacts from processing other than desludging and dewatering activities. Mined rock will be disposed of above ground with revegetation necessary, but the quantity concerned is minimal compared to the other operations.

Support facilities requirements include an employment of 300 people and a total maximum population affected of about 2,100 persons. The site is located about 13 miles south of Greenfield (population 3,000) and 20 miles south of Bakersfield (population 77,000) in Kern County (population 350,000).

It is expected that the majority of employees can be found in the Bakersfield area. This will minimize the impact on population and the increase in support functions. The project

life of 20 years will have minor influence on the long-term economy of the area.

5.5.7 Technical Feasibility

To a substantial degree, the comments made on the mining aspects of the Irma operation are also applicable here. None of the activities involved are unusual in a mining operation and the size of all mine openings will be modest enough to make serious problems unlikely in normal circumstances.

The main question, however, is once again that of geological certainty. The comments made with respect to the previous system also apply here, but with the added complication that no natural assumption can be made as to the competence or impermeability of underlying strata. Indeed, if one seeks a general statement as to the properties of rock immediately underlying a petroleum reservoir, it would be that it is frequently a depleted reservoir material containing residual oil fractions, minor gas and completely saturated with drive water. This type of situation is clearly not the environment for which this system is suited. The necessary favorable circumstances will have to be carefully identified and proven to a good standard by surface drilling.

The oil yield to be expected in total from this operation is, at this stage, more of an assumption than an estimate. As noted before, there is little or no relevant empirical experience of the behavior of such systems available to serve as the basis for analytical determination of yield. Raising of such judgements to a standard suited to support a commercial venture will require substantial research and, almost certainly, pilot operation(s). The system designed here has not included the use of steam to assist in production, although that could very well be necessary. It would, however, be a very simple feature to add, employing the same approach as in the preceeding system, and has been considered as an alternative in the economic evaluations.

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6.0 SURFACE MINING SYSTEMS

This chapter contains brief descriptions of the four surface mining operations designed as part of this study. Included are discussions of the location, geology, mining method, processing, environmental factors and the technical feasibility of each proposed method. Surface mining systems have proved, over many years, to be the cheapest mineral extraction methods available and is usually far cheaper than any underground mining system. The four surface methods considered are modified terrace pit mining, terrace mining, strip mining and the traditional open pit method.

6.1 MODIFIED TERRACE PIT MINING

6.1.1 General Description

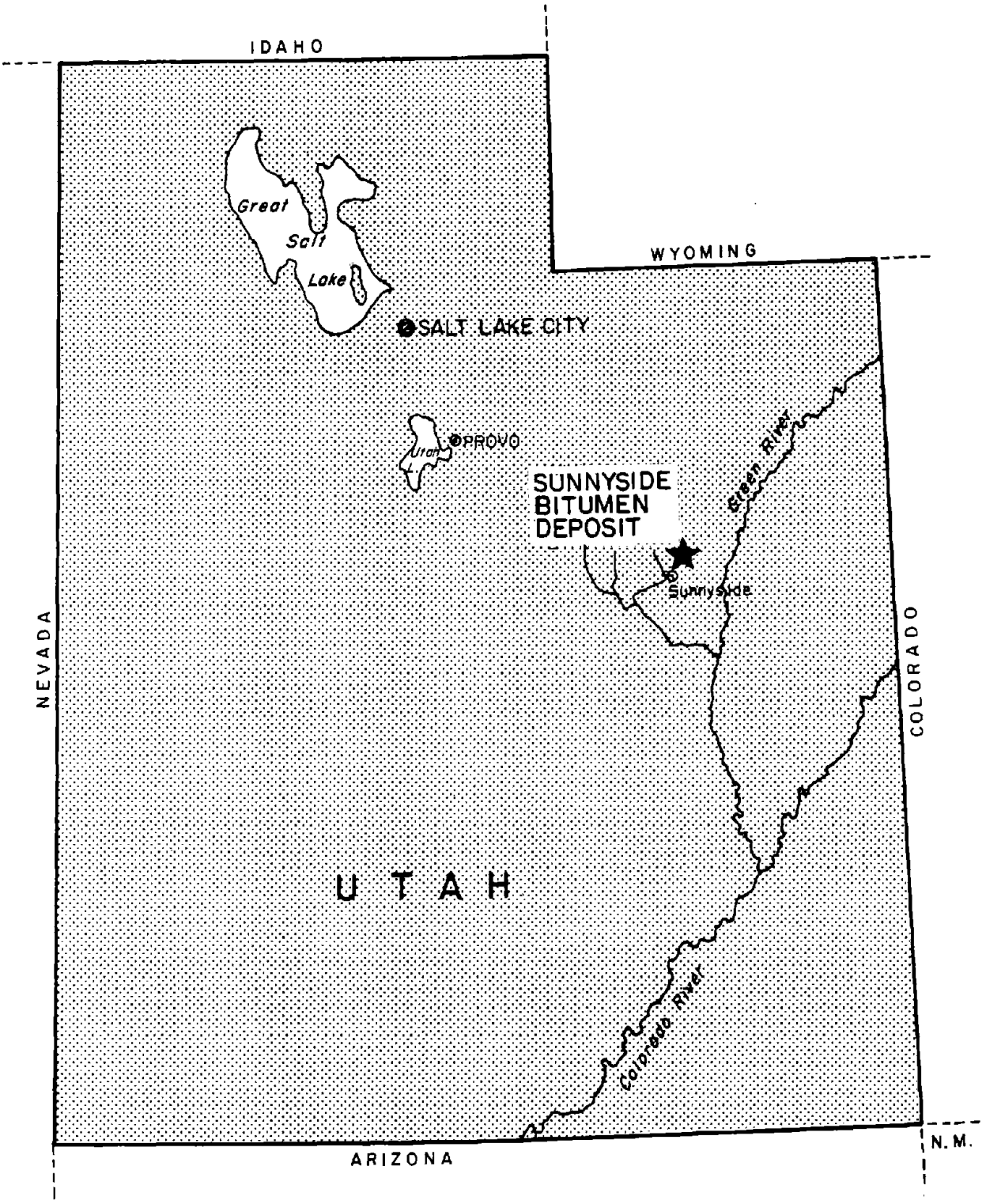
The modified terrace pit mining system utilizes a combination of the terrace pit level haul system and the normal open pit system in which the waste is hauled up ramps out of the pit. This waste is then dumped into a previously mined out portion of the pit. The maximum use is made in this method of the terrace pit hauling system because of its inherent cost advantages.

The geometry of the Sunnyside bituminous sandstone deposit, located seven miles northeast of the coal mining town of Sunnyside, Carbon County, northeastern Utah, makes it an ideal candidate for this system (See Figures 6-1, 6-2 and 6-3 and Table 6-1). Figure 6-3 best illustrates this favorable geometry. The waste from the first (or most northernly) expansion would be placed in a canyon outside the pit limits, as indicated on the Figure 6-3 plan. When this expansion is finished, the waste from the remaining three expansions may be backfilled into the void left when the previous expansion has been depleted. Ramps (not detailed on Figure 6-3) left in the highwall on the east side of the pit would be used to truck waste from the working excavation in the expansion being mined to the dump being filled in the previous expansion. The system is called a "modified" terrace pit because the surface and orebody geometry of Sunnyside will require some haulage upgrade in order to return the pit to the approximate original surface and, more importantly to build large enough dumps to handle all of the

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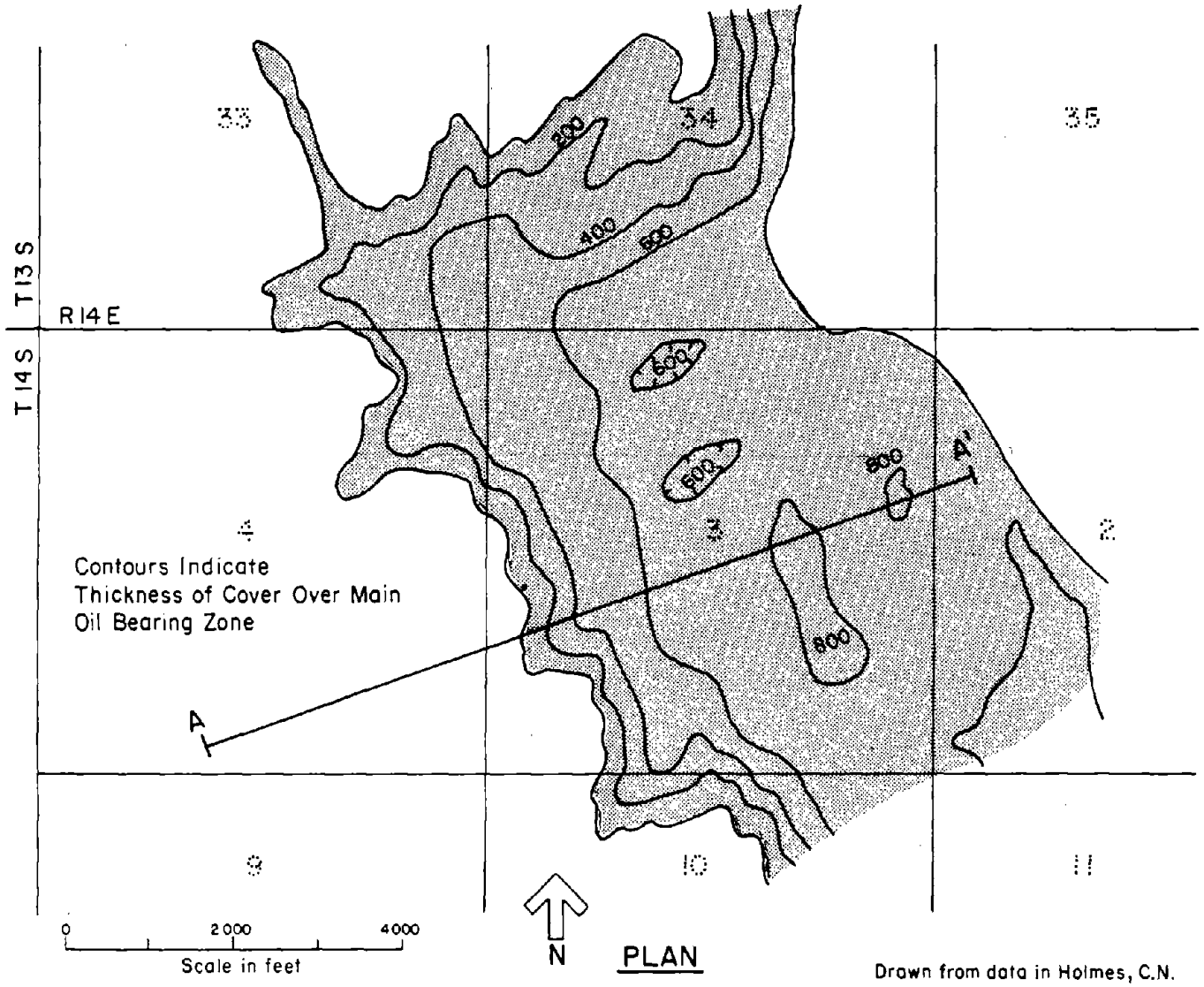
LOCATION MAP
SUNNYSIDE BITUMEN DEPOSIT, UTAH

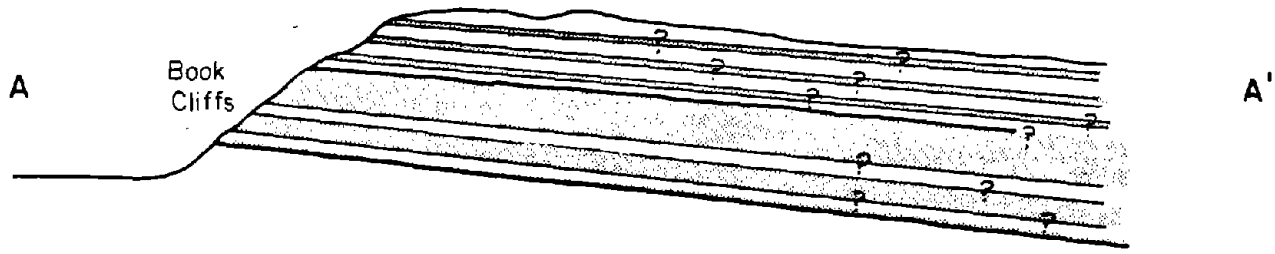
Figure 6-1



AVERAGE OVERBURDEN THICKNESS AND GEOLOGICAL SECTION – SUNNYSIDE, UTAH

Figure 6-2





Top of Main Zone

Base of Main Zone

Bituminous Zone

Assumed Uniform Dip 7°

SECTION

MODIFIED TERRACE PIT – SUNNYSIDE, UTAH
PIT PLAN AND SECTION

Figure 6-3

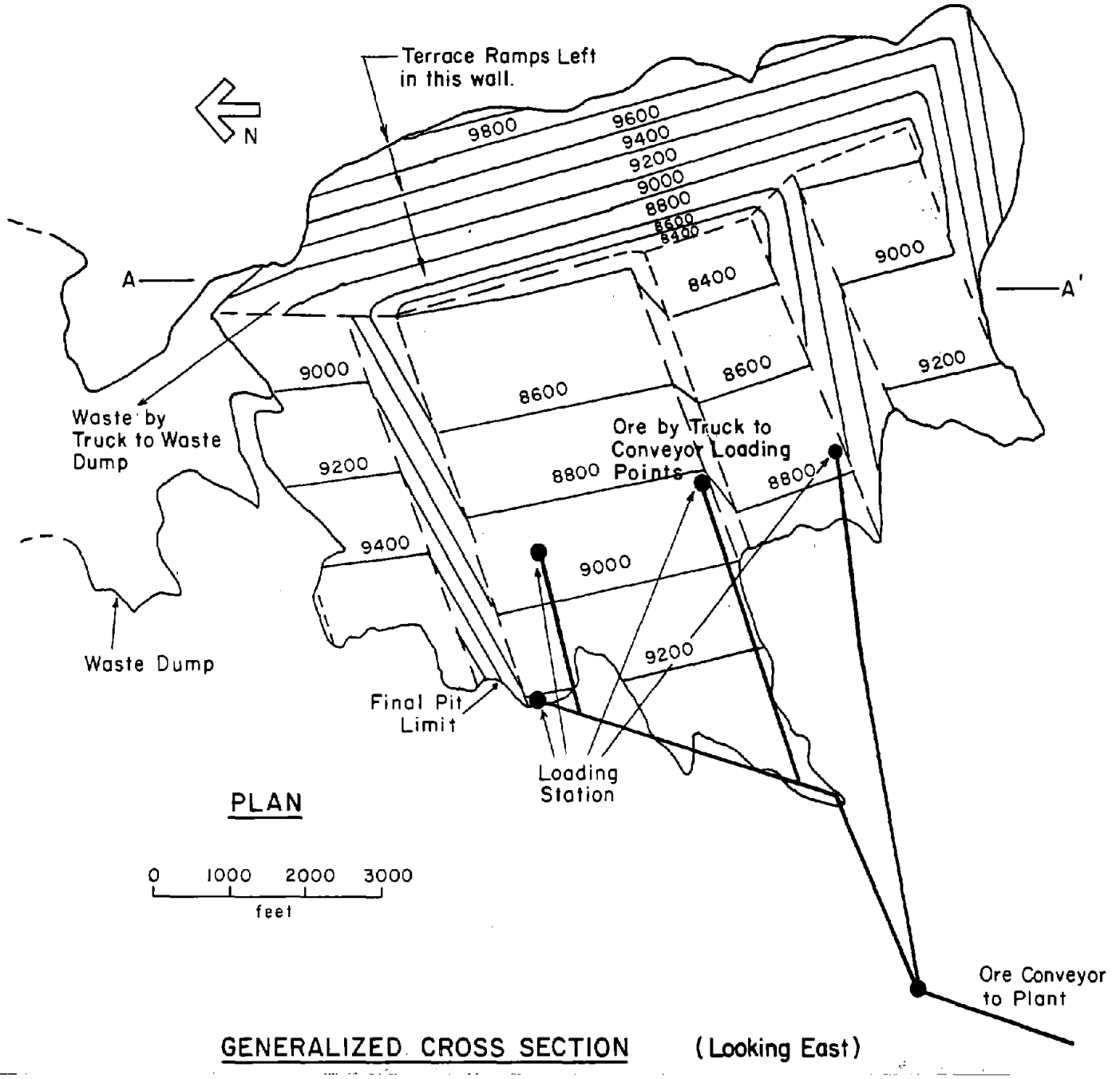


TABLE 6-1
SUNNYSIDE FIELD

Permeability (millidarcies)	730
Porosity (%)	21
Oil Gravity	Not available-asphalt
In-Place Grade (bbl/T)	0.57
Depth to Top of Oil (feet)	
Minimum	0
Maximum	800
Thickness of Oil Zone (feet)	10 to 350
Dip of Oil Zone	3° to 10° NE
Overlying Rock	
Type	Sandstone and Shale
FM Name	Green River
Age	Eocene
Underlying Rock	
Type	Interbedded Sandstone, Shale, Mudstone, and Limestone
FM Name	Wasatch
Age	Lower Eocene
Oil-Bearing Rock	
Type	Bituminous Sandstone interbedded with Shale, Mudstone, and Limestone
FM Name	Wasatch
Age	Lower Eocene

waste. The ore would be crushed in the pit and conveyed to a processing plant located in a flat area in a canyon below the ridge.

The deposit outcrops in Townships 13 and 14 South, Ranges 13 and 14 East (Salt Lake Meridian). These outcrops extend about 9 miles along the Book Cliffs, a southwest-facing, steep, rugged escarpment on the southwest margin of the Uinta Basin, and occur at elevations between 9,000 and 10,000 feet, near the top of the Cliffs. To the southwest is a wide belt of mountainous terrain, while north and northeast of the crest of the escarpment is the broad, somewhat dissected plateau of the Uinta Basin. The elevation of the area ranges from 5,000 feet at the base of the escarpment to more than 10,000 feet on the plateau. There are many small springs in the area and some of these form very small perennial streams which, for the most part, are intermittent. All of these streams are part of the drainage basin of the Green River. The climate of the area is arid to semi-arid, with an average annual rainfall of 15 inches (Ref. 1).

6.1.2 Geological Description

The rocks in the Sunnyside area form a continuous depositional sequence made up chiefly of nonmarine sandstone and shale of Eocene age. This sequence is divided, on the basis of lithology and mode of deposition, into two units, the Wasatch and Green River formations. The lower part of the sequence, which is chiefly fluviatile, is assigned to the Wasatch formation, and the upper part, chiefly lacustrine, is assigned to the Green River formation. The transition between the two formations is gradational throughout an interval of several hundred feet (Ref. 2).

The Wasatch formation, of lower Eocene age, contains the bulk of the bituminous sandstone deposits, and makes up most of the steep face of the Book Cliffs (Figure 6-2). This formation is 3,750 feet thick and consists predominantly of sandstone interbedded with shale, mudstone and thin beds of hard limestone. The sandstone beds, whether bituminous or not, are fine- to medium-grained, and are thin to massively bedded and have a tendency to be lenticular. The bituminous sandstone deposits occur in beds ranging from 10 feet to 350 feet in thickness in the upper 1,000 feet of the Wasatch formation. Generally the bituminous sandstone is quite hard and requires drilling and blasting in existing quarry operations (Ref. 1). Its porosity averages about 21 percent by volume and the permeability is approximately 730 millidarcies (Ref. 3).

Little or no water is present in the interstitial space, and on the average 45 percent of the pore volume is filled by bitumen.

1. Structure

The structure is essentially homoclinal with the units dipping 3 degrees to 10 degrees northeast into the Uinta Basin. The formations are broken by several vertical faults with displacements ranging from 1 to about 150 feet. Locally systems of vertical joints may be observed, as in the sandstone promontories in the amphitheatre at the head of Water Canyon. No reversals of dip are present (Ref. 1).

2. Development History

The deposits have been quarried, for asphalt, at various times since 1892. Between 1927 and 1948 operations were more or less continuous but only intermittent mining has taken place since 1948. An estimated 750,000 tons of asphaltic sandstone, averaging about 10 percent bitumen by weight, has been mined and shipped as paving material. The material is crushed and used for surfacing without further treatment.

No large-scale systematic attempts have been made to extract the bitumen from the bituminous sandstone beds near Sunnyside, although the U.S. Bureau of Mines have made extractive tests with good results. Experimental work has been carried out by the U.S. Bureau of Mines and several independent companies on similar deposits at the Asphalt Ridge, Utah deposit and at deposits in California. The possibility for workable and economically feasible extraction processes definitely exists (Ref. 1).

3. Reserves

The reserves of bituminous sandstone in the potential mine area total some 1,600 million cubic yards, of which 900 million cubic yards are either measured or indicated by geologic evidence, and 700 million cubic yards are inferred. Information on the grade of the deposits is very scarce. However, work done by the Oil and Gas Laboratory of the U.S. Geological Survey on 27 grab samples showed that the grades at Sunnyside could range from a few percent to over thirteen percent bitumen. At least half of the samples were in excess of 9 percent contained bitumen. For the

purposes of this study, it has been assumed that at least half of the reserve quoted above contains 10 percent by weight, or 0.57 barrels per ton, of bitumen. Therefore the geologic reserve upon which the mine plan was based was considered to be 800,000,000 cubic yards (1,416,000,000 tons) at 0.57 barrels per ton.

6.1.3 Mine Design and Scheduling

Since the Sunnyside deposits are fairly shallow, the depth of overburden to the main bitumen zone varying from 0 to 800 feet, see Figure 6-2, a modified terrace pit mining method was selected. The overburden and pay zone are too deep for dragline operation, and the rock is too hard for bucket wheel excavators. Consequently, a truck and shovel system was selected with drilling and blasting. The proposed open pit will be a modified terrace pit developed in four expansions; hence maximizing the use of level hauls (Figure 6-3). The waste from the first expansion will be dumped close to, but outside the pit, and the remainder of the waste from Expansions II, III, and IV will be backfilled within the pit.

The location for the open pit mine was chosen to permit earliest exposure of the ore with minimal prestripping. The mine was designed with 1.4:1 overall slopes and in four pit expansions to a final pit limit. The total rock tonnages in the four pit expansions were determined for each terrace level, and totaled for each pit expansion. The quantity of bituminous rock at each contour level in each pit expansion was determined through the use of vertical sections constructed across the bituminous sandstone deposits. Assuming that 50 percent of the bituminous rock has an average grade of 10 percent bitumen by weight and will therefore be mined as ore, the tonnages of mineable bituminous rock, and the tonnages of waste for each contour level were calculated. The stripping ratios of waste to ore were calculated for each pit expansion.

An ore production rate of 100,000 tons per day was selected for the base case assuming that the mine would operate 3 shifts per day, 7 days per week, for 330 days a year. The operation would consequently produce 33,000,000 tons of ore per year and 84,150,000 tons of waste at a stripping ratio of 2.55:1 with a mine life of 28 years. The tonnages of waste, and ore, stripping ratios and life of each of the pit expansions are shown in Table 6-1. Based upon these figures a mining schedule was developed.

TABLE 6-2
DETAILS OF PIT EXPANSIONS - SUNNYSIDE, UTAH

	Pit Expansion			
	I	II	III	IV
Total Tonnage In Expansion	1,165,000,000	1,064,000,000	689,000,000	353,000,000
Total Tonnage Of Bituminous Rock	648,445,000	604,290,000	413,930,000	175,151,250
Tonnage Of Bituminous Rock With 10% by Weight Bitumen	324,222,500	302,145,000	206,965,000	87,575,625
Tonnage of Waste	840,777,500	761,855,000	482,035,000	265,424,375
Stripping Ratio	2.6:1	2.59:1	2.33:1	3.01:1
Life - Days	3,242	3,021	2,070	876
- Years	10	9	6	3

The Sunnyside pit will be mined by the standard drill-blast-shovel loading-truck haulage open pit method. The modified terrace pit approach will permit much larger working areas for the shovels than in a normal open pit and will maximize the use of level hauls. The mine has been designed with 50-foot high benches. It is estimated that eight rotary blasthole drills of the Bucyrus Erie 61-R class will be required to maintain adequate blasted rock ahead of the shovels. Loading would be by ten 21 cubic-yard capacity electric power shovels of the P&H 2300 type loading into 170-ton capacity diesel-electric drive rear-dump haulage trucks. The truck fleet will contain some 90 units. Ancillary mining equipment will include 12 large bulldozers, 5 large front-end loaders, 10 motor graders and 11 rubber-tired bulldozers.

A location for a waste dump was selected and a dump was designed. The potential volume of this dump was determined and the tonnage capacity calculated, which proved to be in excess of one billion tons. The waste will be hauled out from the waste benches to this dump (Figure 6-3).

An overland belt conveyor will be required to transport ore from the mine to the oil separation plant. The route for this overland belt was selected such that the maximum slope of the belt would be no more than 17 degrees. The main overland belt that is common to all four pit expansions is 1.9 miles long. The belt from the common point to pit Expansion I is 1.3 miles long, to pit Expansion II is 0.4 mile long, to pit Expansion III is 0.8 mile long, and to pit Expansion IV (final) is 1.3 miles long. The layout for the ore conveyor is shown in Figure 6-3.

6.1.4 Processing

Oil plant feed, delivered by the overland belt, must be stockpiled in an area with capacity sufficient to supply feed continuously to the separation plant. The stockpile should preferably provide blending capabilities and should be accessible to mechanical reclaiming equipment in case the material tends to bridge over in the reclaiming feeder hoppers.

Processing must provide for control over the top size of material to be treated and hammer mills or toothed roll crushers probably will suffice. The sized feed can then be delivered to the 3 or 4 required production lines or modules in the plant. The first step of this process would be a major grinding section to reduce the material to a suitable size for further processing.

A hot water process is believed to be adequate for oil recovery. Variations in length of time during the pulping-scrubbing steps, pulp temperature and use of chemical additives such as caustic soda, sodium silicate and other wetting agent-dispersants must be determined through pilot plant tests prior to design of the production plant.

The degree of cleaning of the oil-rich froth product from the rougher section of the plant will depend on the silt, clay or shale content of the plant feed. Possibly the viscosity of the final oil-rich product from the separation plant must be lowered by dilution with a low viscosity solvent such as naphtha (which subsequently is recovered by distillation from the plant product (Ref. 4)), after which the suspended insoluble matter can be removed by centrifuging or additional flotation steps. Recirculation of certain middling products may be required to improve oil recoveries and quality of final product.

The proposed processing plant would operate 3 shifts per day, 7 days a week, for 330 days a year, handling 100,000 tons per day or ore. A plant recovery rate of 90 percent has been assumed which will result in the production of 9,000 tons or 51,300 barrels per day of bitumen. This would give an annual

production of 16,929,000 barrels, for a total of 474,012,000 barrels of oil over the 28-year mine life. Tailings will be produced from the oil separation plant at the rate of 91,000 tons per day for a total of 840,840,000 tons over the 28-year mine life.

A tailings dam location was selected and a two-layer dump designed with a 5:1 slope on the face, capable of holding the tailings produced during the entire life of the project.

6.1.5 Safety

No unusual safety problems or hazards are anticipated, other than those normally encountered in open pit coal mines. Gases are not expected to be a problem.

6.1.6 Environmental Considerations

There will be some odor, dust and noise impacts associated with the mining and processing, and waste dumps will probably need to be topsoiled and revegetated.

Impacts on the support facilities could be severe. Sunnyside (population 500) is about five miles from the site in Carbon County (population 18,000). The nearest city is Price (population 7,400) located 25 miles west of the site.

The Sunnyside mine is expected to provide employment for 2,500 persons. This will create an additional 5,000 support jobs and increase the population in the area by almost 17,500 persons. An entire new community with all its related impacts must be constructed. The 28-year projected life span is sufficiently long to be able to anticipate the growth necessary and provide a life span long enough to utilize the support facilities. There will be a decline in employment on the completion of mining activity unless sufficient substitute employment possibilities are found.

6.1.7 Technical Feasibility

The proposed open pit mining method suggested for the Sunnyside, Utah deposit is completely feasible from a technical standpoint. The open pit method is a well-known and extensively practiced mining method, and the types of equipment used throughout the mining operation are standard items available from known manufacturers. The daily tonnage of material to be moved is large, but open pits exist elsewhere in the United States which move larger tonnages with the same type of equipment.

The Sunnyside open pit utilizes a modified terrace pit method, whereby hauling of waste and ore is kept as far as possible on the level. This is possible at Sunnyside because of the existing topography and the potential location of the waste dumps. This modified terrace pit approach makes the mining operation a great deal simpler than the normal type open pit where spiral ramps are required for lifting the waste material the dump sites and the ore to the processing plant.

The use of overland conveyors to the processing plant is a commonly used system throughout the world, and the technology has been in existence for many years.

The processing plant design for the Sunnyside material is, as with all processing plants mentioned in this report, one of the major areas of uncertainty. The Sunnyside ore is hard material and would necessitate crushing and grinding prior to liberation of the heavy oils. Since no major pilot plants have been operated or tested with this material, the technical feasibility of the processing method cannot at this time be assessed.

6.2 TERRACE MINING WITH BUCKET WHEEL EXCAVATORS

6.2.1 General Description

The terrace mining system is well suited to very large deposits which can be mined with level hauls for the overburden transportation and which, by their geometry, permit dumping of the overburden material back into the pit. The Kern River Oil Field in California is an ideal candidate for this method. This geometry is best illustrated in the section shown on Figure 6-4. The waste material contained in the excavations noted as A, B and C would be cut and loaded by bucket wheeled excavators onto belt conveyors. The conveyors would then transport the waste on to terraces around the pit to the dump. The oil-bearing ore would be transported to a processing plant, the oil removed, and the sand tailings returned to the pit and dumped as indicated Key properties of the Kern River Field are summarized in Table 6-3.

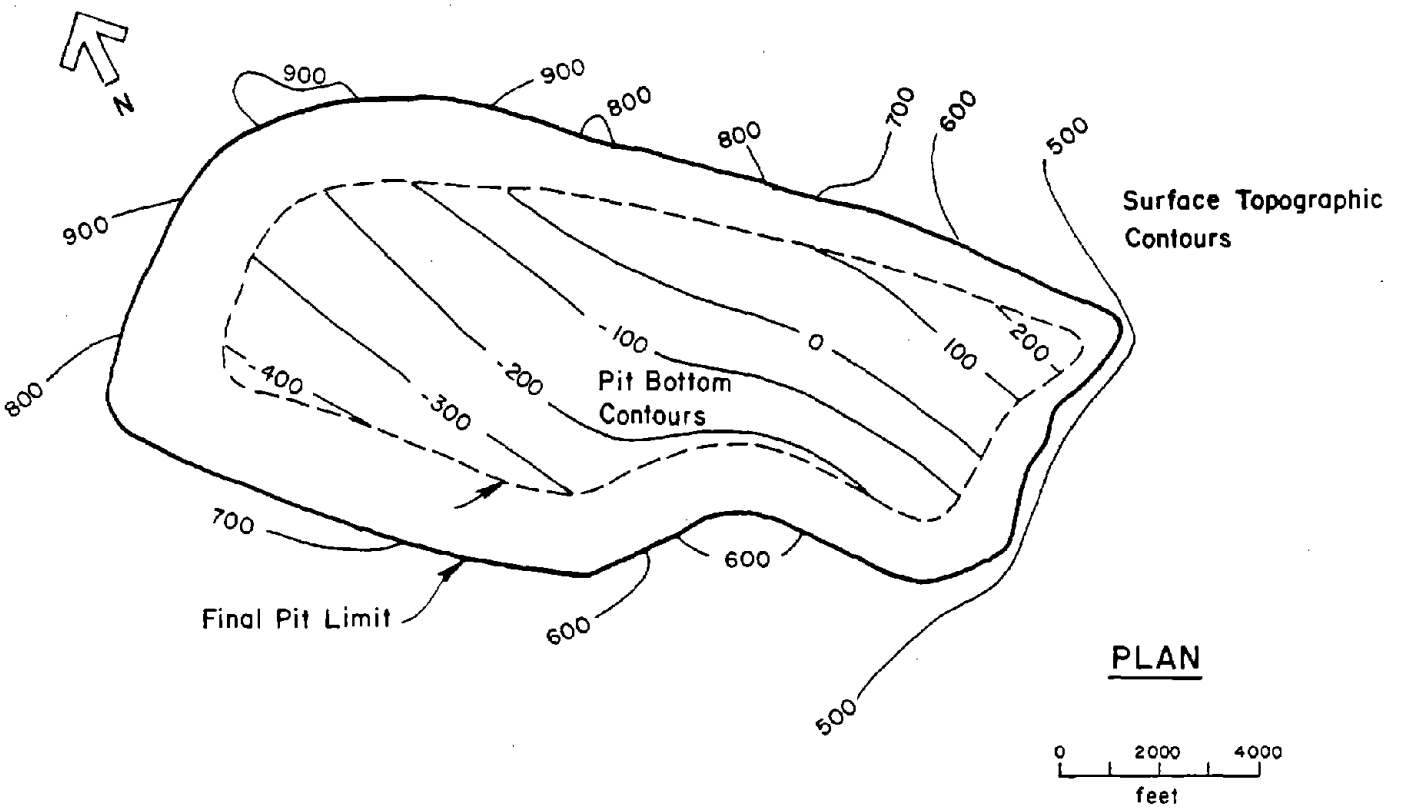
The Kern River Oil Field is located on the east side of the San Joaquin Valley, 5 miles north of Bakersfield, Kern County, California along the north side of the Kern River (Figure 6-5). The field consists of 9,385 proved acres or 14 square miles lying within Townships 28 and 29 south, Ranges 27 and 28 east (Mount Diablo Base and Meridian). The topography of the area consists of low rolling hills which are essentially barren of vegetation (Ref. 5). The climate of the area is arid to semi-arid, with an average rainfall of less than 10 inches.

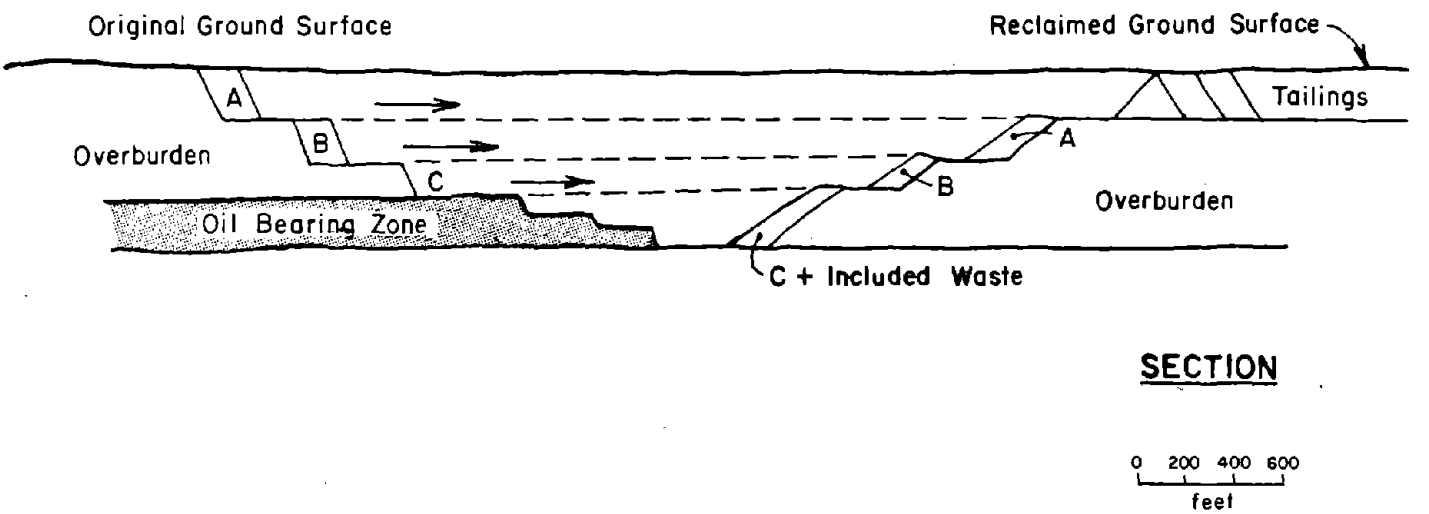
TABLE 6-3

KERN RIVER FIELD

Permeability	Variable (very high)
Porosity (%)	34
Oil Gravity	12° to 13° API
In-Place Grade (bbl/T)	0.62
Depth to Top of Oil (feetO	
Minimum	43
Maximum	900
Ave.	500
Thickness of Oil Zone (feet)	700
Dip of Oil Zone	2° to 4° SW
Overlying Rock	
Type	Gravel, Sand, and Silt
FM Name	---
Age	Upper Pliocene and Pleistocene
Underlying Rock	
Type	Sands
FM Name	Santa Margarita
Age	Miocene
Oil-Bearing Rock	
Type	Lenticular Sands and Clays
FM Name	Kern River
Age	Pliocene

TERRACE PIT - KERN RIVER, CALIFORNIA
PIT PLAN AND MINING AND BACKFILLING SYSTEM Figure 6-4





LOCATION MAP
KERN RIVER OIL FIELD, CALIFORNIA

Figure 6-5



6.2.2 Geological Description

The oil-bearing zone is the Pliocene Kern River Formation, consisting of interbedded and lenticular sands, gravels and clays as shown in Figure 6-6. The producing horizon is a zone of lenticular sands and clays (Ref. 6) having an average thickness of 700 feet (Ref. 7). The top of the zone of oil-bearing sands and gravels has an estimated average depth of 500 feet. The formation is overlain by upper Pliocene and Pleistocene gravel, sand and silt (Ref. 6), and underlain by the coarse-grained grey and blue sands of the Miocene Santa Margarita formation (Refs. 1, 7). A total of 3,000 feet of sands and diatomaceous and foraminiferous shales, including the Santa Margarita, lie below the Kern River formation and appear to be the source of the Kern River oil (Ref. 6). The oil-saturated material is dark brown to black and soft. The porosity of the oil-bearing zones is approximately 34 percent and the permeability is very high, although it is highly variable. The Kern River oil field has a water drive and consequently water inflow into the pit may be a problem. Very small quantities of gas accompanied the oil in 1934 (Ref. 4), and gas production in 1972 averages only 0.15 cubic feet per barrel of oil produced (Ref. 7). The overburden material is a reworked continental sediment, probably Upper Pliocene and recent alluvial gravels, sands, and silts up to 800 feet thick (Figure 6-6).

1. Structure

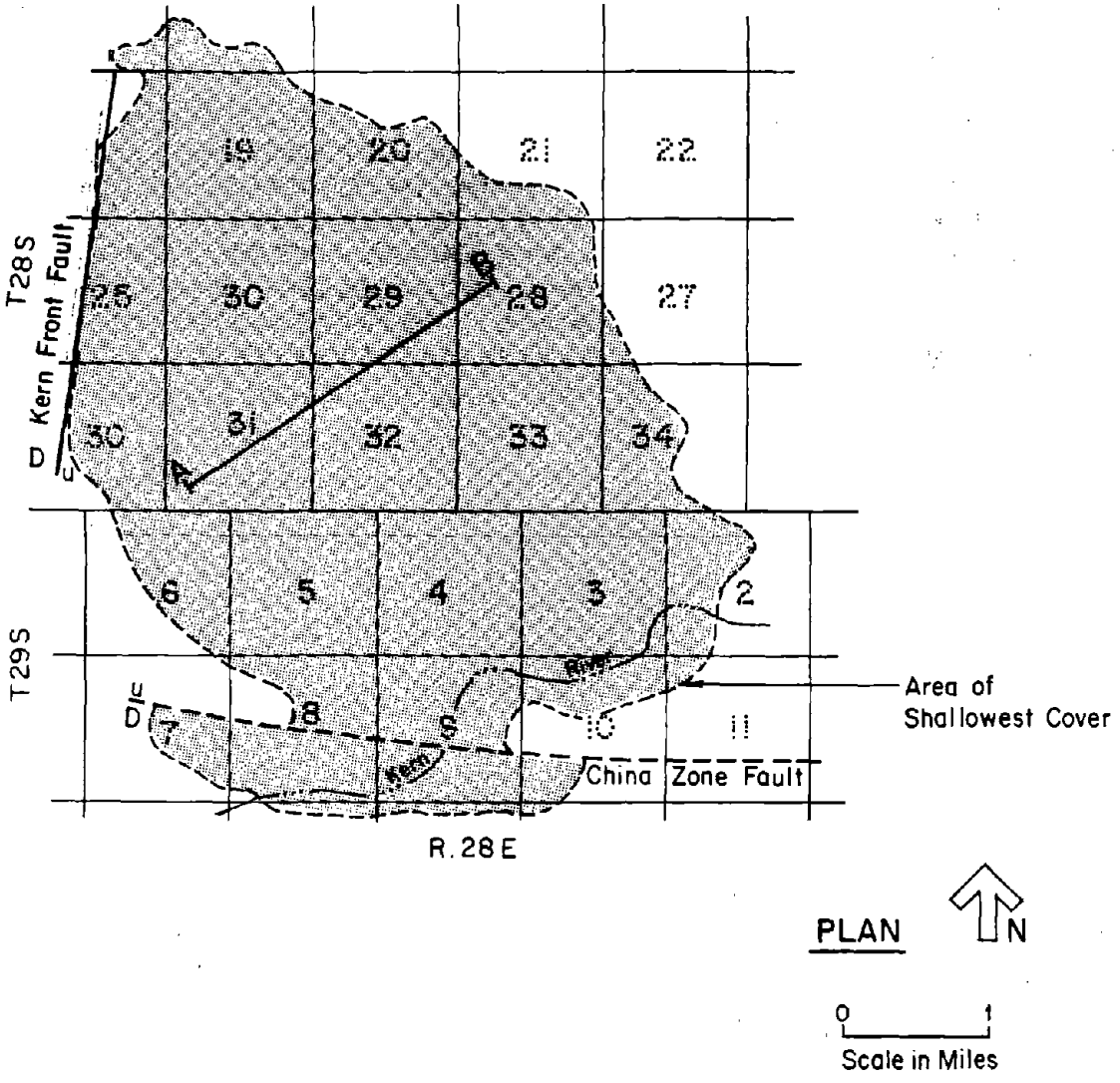
The area is structurally a faulted homocline, gently dipping at 2 degrees to 4 degrees to the southwest (Refs. 1, 4). The oil producing sands appear to pinch out updip (Ref. 5).

The the oil has migrated into the Kern River formation along faults or by seepage from the underlying Santa Margarita formation. The level of the oil-bearing zones in the formation is related to permeability boundaries and represent former water drive levels.

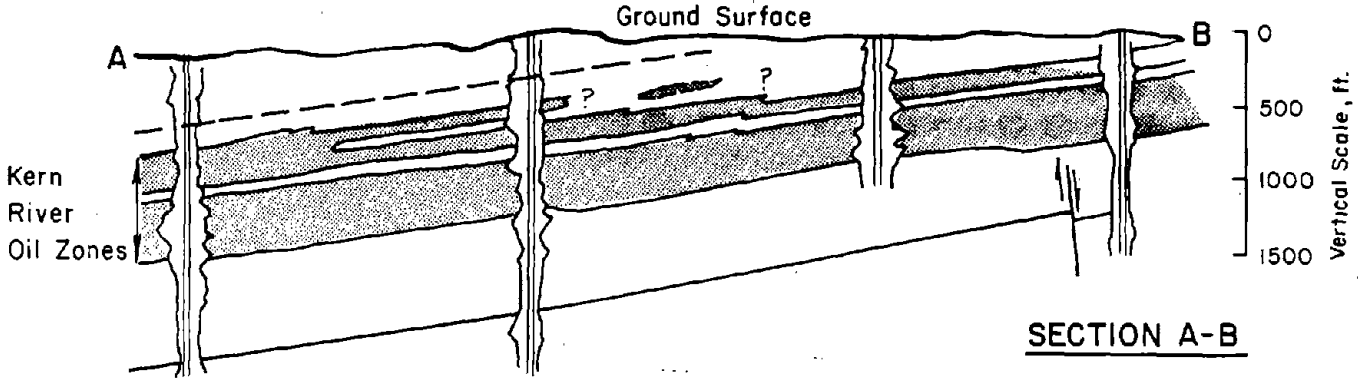
Two main faults exist within the Kern River formation namely the Kern Front fault and the China Zone Fault. The Kern Front Fault strikes N10°E, in the northwest portion of the field and is the seal separating the Kern River field from the Kern Front field. The China zone fault is in the southern part of the field and strikes N88°W.

PLAN AND GEOLOGIC SECTION
KERN RIVER OIL FIELD, CALIFORNIA

Figure 6-6



Redrawn from: California Division of Oil and Gas (1974)



6.2.3 Development History

The Kern River oil field was discovered in 1899, by a hand-augered well at a total depth of 43 feet. The field reached a peak production of almost 17,000,000 barrels of oil per year by 1904, thus attaining, at the time, the reputation as one of the principal oil fields of the state of California (Ref. 1). Since that time, production from the Kern River field has depended greatly on economic conditions relating to the demand for heavy crude oil. It was not until the 1950's that the demand for heavy oils stabilized at an increased level. These conditions provided the economic incentive for experimenting with new recovery methods at this field (Ref. 2). The Kern River field is currently under steam flood.

Cumulative oil production to 1976 was 689.7 million barrels. The annual oil production in 1976 was 30.7 million barrels from an average number of 5,018 producing wells. The average oil production per well per producing day was 18.1 barrels in 1976. Cumulative gas production to 1976 was 2,600,000 thousand cubic feet. No gas was produced in 1976 (Ref. 3).

A topographic map of the Kern River area was overlaid on the isopach map of the oil bearing zone to ascertain the geometry and volume of both the oil-bearing zone and the overburden. Numerous "grades" have been quoted for the original "in situ" Kern River oil field; however, the estimates prepared by the California Division of Oil and Gas indicate that in areas of high oil saturation the oil comprises 65 percent and the water 35 percent of the available pore space. The average porosity of the horizon is estimated at 34 percent, which yields an oil "grade" of 1,700 barrels per acre-foot or 26 gallons per ton and a total original reserve for the oil field of 1.38 million acre-feet, equivalent to 2,400 million barrels at 1,700 barrels per acre-foot prior to exploitation.

In order to arrive at a more realistic and current grade for the Kern River Field, the possible oil in place that would exist in 1980 was calculated. Since total oil production from the Kern River field to the end of 1976 was 690 million barrels and current production is running at 30 million barrels per year, it was estimated that by 1980 the total oil extracted will be on the order of 800 million barrels. This would leave 1,600 million barrels of the original reserve in place. The average "grade" will then have reduced from the original 26 gallons per ton (in, say, 1900) to 17.3 gallons per ton or approximately 6.2 percent oil by weight. Average oil recovery of the original reserve by 1980 will be about 33 percent.

There is insufficient published data to be able to assess the lateral continuity of the oil saturated horizons within the oil-bearing zone. This is an important consideration in any mining venture and would have to be studied carefully in any future feasibility study. However, for this study, with such a large resource, it is assumed that economics will dictate that ore grades should be maintained at the expense of some loss of "ore" rather than vice versa. In addition, it is assumed that "ore" losses from the main horizon due to this strategy are compensated for by additional "ore" from horizons which are known to exist above the main oil-bearing zone. On this basis, it is assumed that a mining operation at Kern River would manage to maintain a mill feed grade of 17.3 gallons per ton.

6.2.4 Mine Design

For mine design purposes the following base assumptions were made:

- That due to the size of the reserve the operation should be on a large scale - greater than 100,000 tons per day of ore.
- That a terrace pit mining system should be used for efficiency and low cost.
- That for environmental and reclamation purposes overburden should be disposed of into mined-out areas as soon as possible.
- That for lowest cost and large volumes, a bucket wheel excavator-conveyor system should be used for overburden removal/transport/dumping.
- That bucket wheel excavators should also be used for ore mining to give a combination of high output and good selectivity in relatively thin horizons.

An initial evaluation of possible mining costs showed that the break-even stripping ratio could be as high as 17:1. Because of the uncertainty regarding grade distribution in the orebody, a break-even stripping ratio of 10:1 has been used for this study. The break-even stripping ratio is an economic factor which sets the maximum stripping ratio above which the operation would lose money. Owing to the unconsolidated nature of the material and the known high groundwater, it has been assumed that final pit slopes will stand at 29 degrees.

For a production of 50,000 barrels per day, operating 360 days per year, 47 million tons of ore would have to be mined each year. This is approximately 130,000 tons of ore per day.

Generally, the maximum overburden thickness in the designed pit at Kern River is 600 feet, consequently, a three bucket wheel excavator system has been selected with each bucket wheel handling up to 200 feet. The 200 foot high cut would be mined with a 120 foot face, a 40 foot step height and a 40-foot trough cut (Figure 6-7). In the initial mining area in the southeast corner, the overburden is relatively thin, less than 480 feet, and therefore there is probably no need for the trough cut and possibly not even the step cut. This will reduce the necessary operating room and hence, allow steeper effective working pit slope angle.

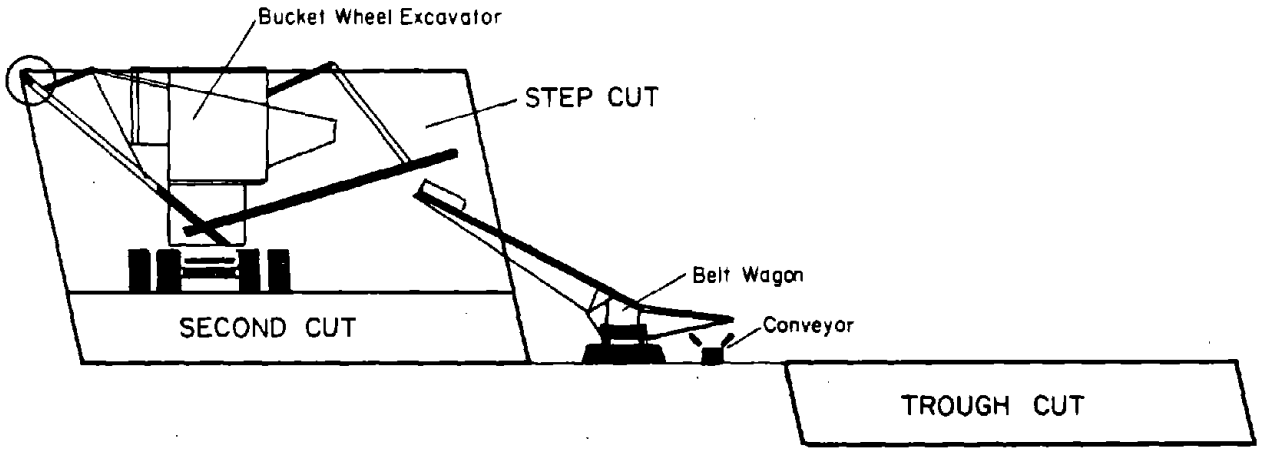
The three bucket wheel excavators used for overburden stripping would each have an effective output of 6,000 bank cubic yards per hour and would feed onto beltwagons which would transfer the overburden to main trunk conveyors on each bench. The main trunk conveyor system will transport the overburden around the pit to a stacker on each bench elevation, which will dump the material back into the worked out area of the operation (Figure 6-4).

The method of ore mining is similar to the overburden operating concept described above and permits the system to handle ore and contained waste. Each bucket wheel system in ore would handle up to 100 feet of orebody thickness. Since the dip of the oil-bearing zone is approximately 4 degrees and the dip of the surface topography is generally less, it is probably advantageous to operate the bucket wheel systems parallel to the dip of the oil-bearing zone. This avoids benches daylighting or, conversely, face heights getting excessive, and the bucket wheel excavator/conveyor system can be operated very satisfactorily at shallow angles. The three bucket wheel excavators for ore mining would each be capable of producing 3,500 bank cubic yards per hour. The excavators would feed onto belt wagons and hence onto the bench conveyors.

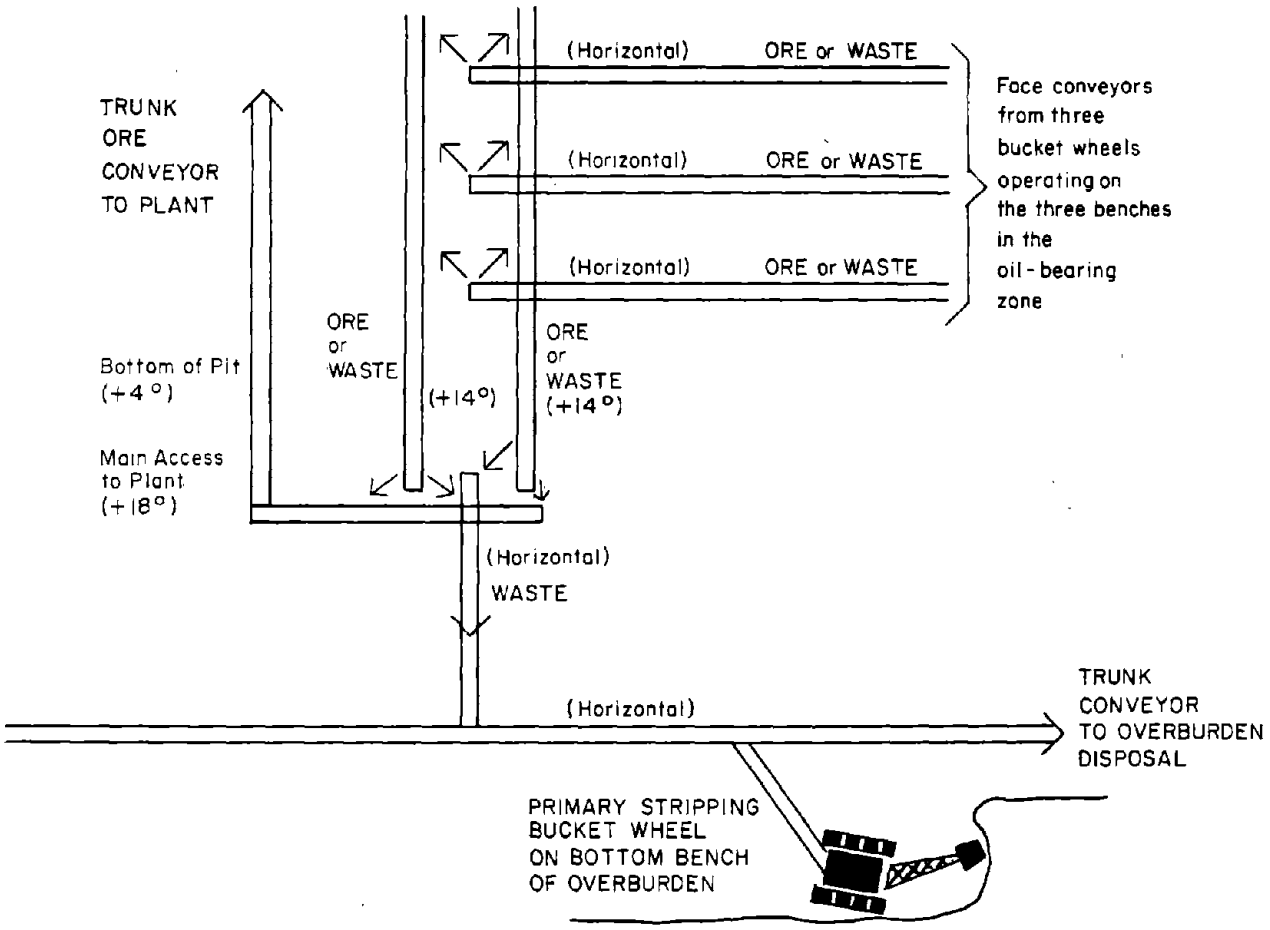
Many alternative transportation layouts are possible but considering the geometry and the scale of the proposed operations, the following system is considered best. Three bucket wheel excavator systems would be working in the oil-bearing zone with the middle unit taking the maximum cut permitting the upper and lower bucket wheels to take lower cut heights and consequently concentrating on the greater selectivity necessary to remove included waste from the ore. These three bucket wheel excavators would discharge onto their own bench conveyors which in turn would discharge onto a twin belt ramp conveyor system feeding a trunk ore conveyor. The trunk conveyor will convey the ore from the mine area to the plant (Figure 6-7). The waste material will be discharged onto a further ramp conveyor up to the main overburden conveyor on the lowest stripping bench.

TERRACE PIT MINING SYSTEM
KERN RIVER, CALIFORNIA

Figure 6-7



BENCH EXCAVATION METHOD - KERN RIVER



CONVEYOR HAULAGE LAYOUT - KERN RIVER

In order to minimize preproduction stripping and allow backfilling of the mined-out area to commence as soon as possible, the mining sequence shown in Figure 6-4 is proposed. The preproduction stripping will have to be dumped outside the pit limits. Cross-sections through the ultimate pit, showing the preproduction development indicate an average cross-sectional area in the preproduction cut of approximately one-hundred thousand square feet. The initial cut length is about 6,000 feet, giving a total preproduction stripping requirement of some 200 million cubic yards.

The volumes of material in the final pit (Figure 6-4) are as follows:

Millions of

	Cubic Yards
Ore	740
Prestripping	200
Contained waste	280
Overburden	2,380
Total	3,600

This yields an overall stripping ratio of 3.86:1 and a mining reserve of 520 million barrels of oil. Thus, if the ore mining rate is 130,000 tons per day, the following overburden and contained waste must be handled:

	millions of tons per year	thousands of tons per day	stripping ratio	thousands of cubic yards per day	millions of cubic yards per year
Ore	47	130	-	76	27.7
Contained Waste	18	50	0.38	29	11
Overburden	152	420	3.22	247	89
Total	217	600	3.60	352	127.7

Preproduction stripping therefore represents 2.2 years of primary overburden stripping at full rated capacity. Allowing for build up to full production capacity the elapsed time required for prestripping will be three years. Bucket wheel excavator delivery takes approximately two years; consequently, it will take five years from the ordering of the bucket wheel excavators to the completion of preproduction stripping.

6.2.5 Processing

The Kern River process plant feed material will be primarily sands and gravel that are both oil and water wet. The oversize material will have to be separated and crushed. A steam, hot water or solvent extraction technique would probably be used to remove the oil from the feed. The viscosity of the final oil rich product will have to be lowered by dilution with a low viscosity solvent such as naphtha.

Large samples of ore representing run-of-mine material must be obtained early in any feasibility study schedule. These samples should preferably be taken by core drilling or test shafts with care to assure that no drying or oxidation takes place prior to testing.

Bench scale tests, followed by pilot plant test work will be required to establish the general processing flow scheme. If anomalous behavior of samples from various areas of the proposed pit is found, it may be necessary to develop new technology or equipment to overcome the problems and establish production capacities for the plant modules. Only after the plant flowsheet has been determined can engineering design and meaningful cost estimates be provided. Therefore, the pilot plant testing must closely follow the detailed drilling program.

The proposed Kern River process plant will handle 47,000,000 tons of ore per year producing 19,411,920 barrels of oil.

6.2.6 Safety

No unusual safety problems or hazards are anticipated, other than those normally encountered in open pit coal mines.

6.2.7 Environmental Considerations

The ore will be conveyed to the processing plant, processed with a hot water caustic soda solution and the waste returned to the pit. Principal processing impacts are odor, dust and noise as described in Chapter 4. Spoil will be disposed of above ground with a revegetation program being necessary.

The impacts on support facilities will be minimal. The site is located five miles north of Bakersfield (population 77,000) in Kern County (population 350,000). The employment

increase of 1,000 at the mine will affect 2,000 additional support sector jobs. The total population affected will be about 7,000.

The majority of employees can be recruited from the local population minimizing the influx of new people. This will also affect the number of support employees required. The Kern River deposit is expected to have a life of 27 years so the project is long-term in nature adding stability to the area.

6.2.8 Technical Feasibility

The proposed mining method for the Kern River field is a surface terrace pit utilizing bucket wheel excavators. This method of mining has been used extensively in Europe for many decades in mining for coal. The methods utilized and equipment are well proven and the Kern River design is predicated upon known conventional equipment.

The total material, ore and waste to be moved per day, 600,000 tons, is large by world standards. This daily tonnage is considered, however, to be totally feasible since bucket wheel operations in Germany and Australia are currently achieving production rates of approximately 400,000 tons per day. The constraint on the production of these particular operations is the fact that more material is not required since the operations are generally tied to a power generating plant which requires a constant daily tonnage.

The terrace pit conveyor system is a standard method of materials handling, especially in large tonnage operations of this type. The one area of technical feasibility that does have some question is, once again, the processing. The processing of oil-bearing sands and gravels is, however, far better understood than hard reservoir rocks, since similar methods are used at the Athabasca tar sands and other places.

6.3 STRIP MINING

6.3.1 General Description

Strip mining is ideally suited to flat-lying deposits overlain with up to 180 feet of preferably medium to soft overburden. If the mineral being mined is valuable enough, the cost of blasting the overburden, if it is hard, can be tolerated. The dragline stripping system digs and directly casts the overburden into a spoil pile, hence requirng no additional overburden transportation system.

An ideal candidate for strip mining is the Santa Cruz deposit in California. The geometry of the deposit that mades this so is best illustrated in the section shown on Figure 6-8. Key properties of the Santa Cruz Field are summarized in Table 6-4. The dragline siting on the highwall casts the waste or overburden into the previously mined out "strip." In this manner the bituminous sandstone or ore is uncovered and mined out by loaders and trucks (not shown on the illustration). The trucks would haul ore to a processing plant where the oil would be separated from the sandstone. The spoil piles formed by the dragline would be graded and replanted. The sand tailings from the process plant would be either impounded in a tailings dam or, more likely, would be dewatered and returned to the mine to be dumped either between the peaks of the spoil piles or onto the bottom of the mined out portion of the working strip.

Bituminous sandstone deposits occur four to six miles northwest of the city of Santa Cruz, California, near State Highway No. 1 in T.11S., R.2W. (Mount Diablo Base and Meridian), (Figure 6-9). They are concentrated in two areas, the southwestern-most of which, the Calrock deposit, is near the Pacific coast and is the subject of this section.

The most prominent topographic feature of the area is Empire Ridge, a spur of the Santa Cruz Mountains. The ridge parallels the sea in a northwesterly trend and rises from sea level to an altitude of about 800 or 900 feet. The deposits of bituminous sandstone occur on the western slope of this ridge. The region to the the north and northwest of the area becomes somewhat more rugged.

The climate is coastal, with mild winters and moderately warm summers. The average annual rainfall is about 20 inches.

6.3.2 Geological Description

The bituminous material impregnates a bed of sandstone interbedded with the Miocene Monterey diatomaceous shale. The sandstone is massive in character and where it is impregnated with bitumen, forms steep faces in the cross-cutting canyons (Figure 6-10). The sandstone is partially cemented by calcite. The impregnation of bitumen in addition to the variable calcite cement results in a tough, moderate to hard rock which is resistant to erosion. The bituminous zones are from one to 35 feet thick.

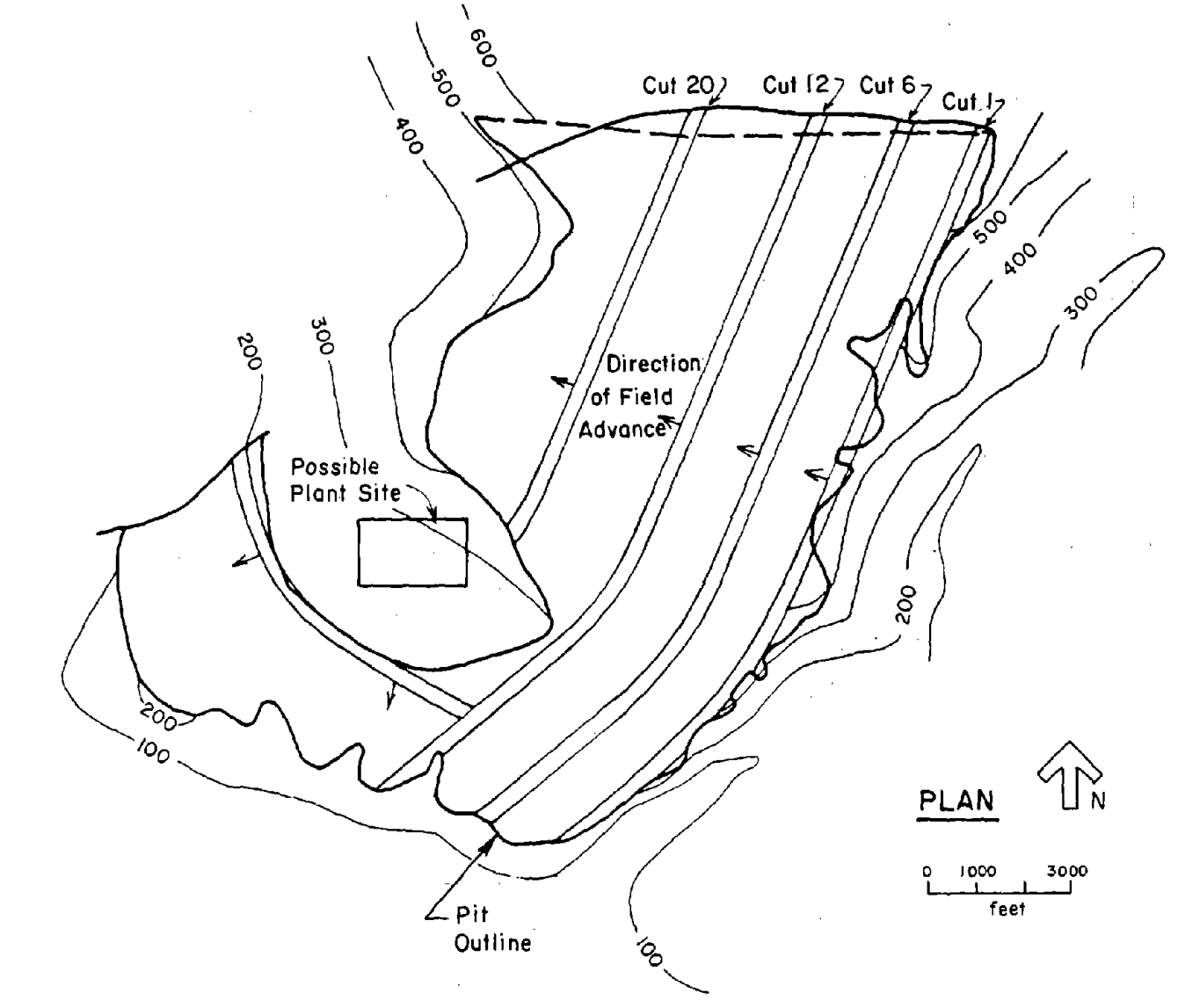
The Monterey shale is a thin-bedded diatomaceous shale. The shale in this area is siliceous and highly fractured. The Monterey shale may have been the source of the bitumen that im-

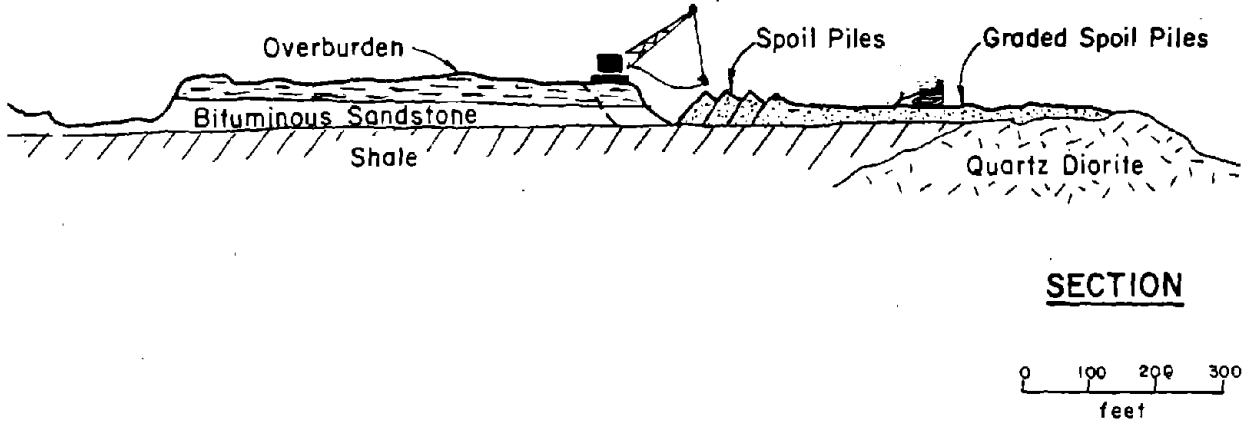
TABLE 6-4
EDNA FIELD

Permeability	Not available
Porosity (%)	36 (Bitumen-free Sand)
Oil Gravity*	15° API
In-Place Grade (bbl/T)	0.62
Depth to Top of Oil (feet)	
Minimum	0
Maximum	500
Thickness of Oil Zone (feet)	>200
Dip of Oil Zone	To 40°
Overlying Rock	
Type	Unconsolidated Alluvial Sands and Gravels
FM Name	---
Age	Quaternary
Underlying Rock	
Type	Shale with interbedded Sandstone
FM Name	Monterey Shale
Age	Miocene
Oil-Bearing Rock	
Type	Arkosic Sandstone
FM Name	Pismo
Age	Upper Miocene--Lower Pliocene

STRIP MINING - SANTA CRUZ, CALIFORNIA
MINE PLAN

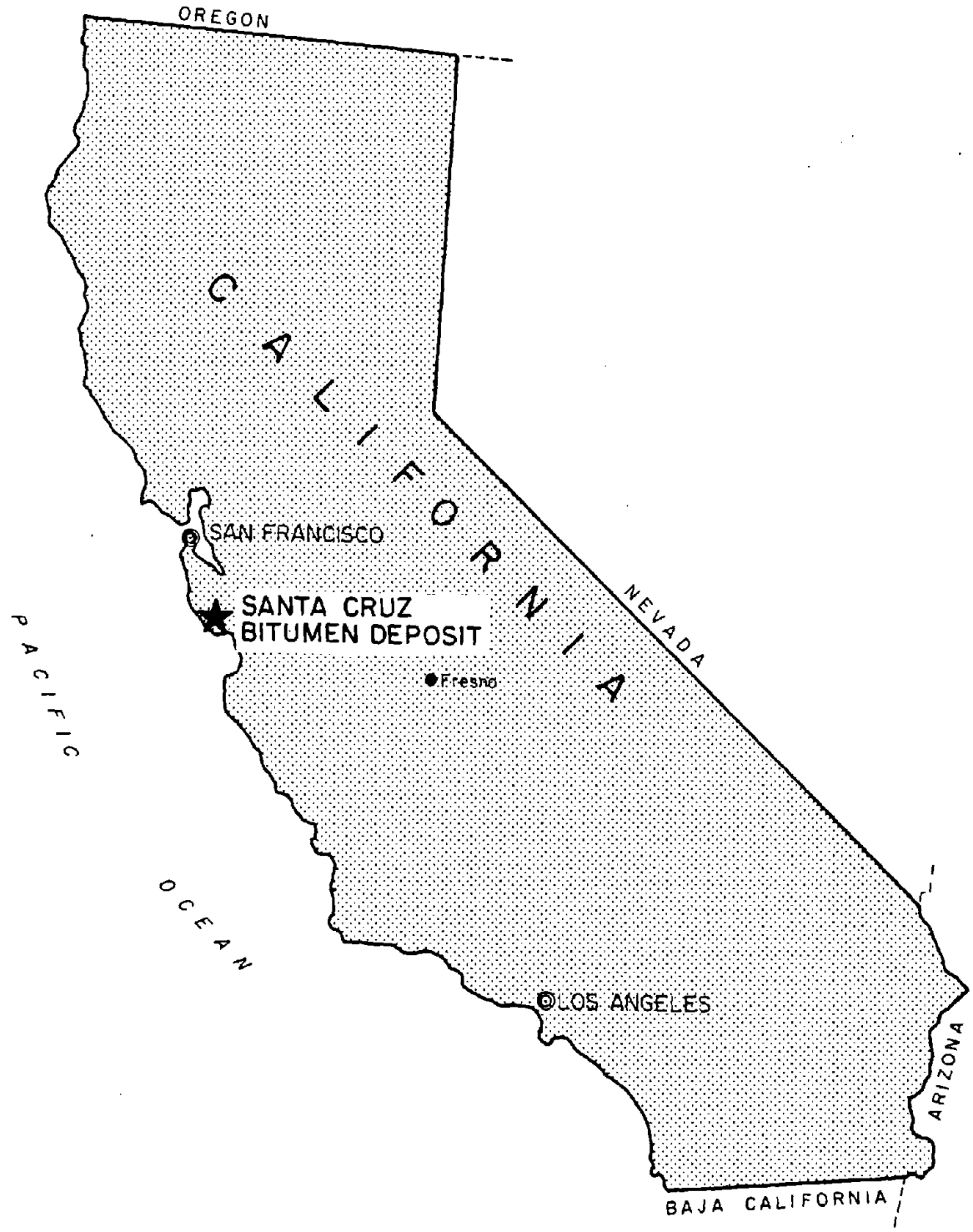
Figure 6-8





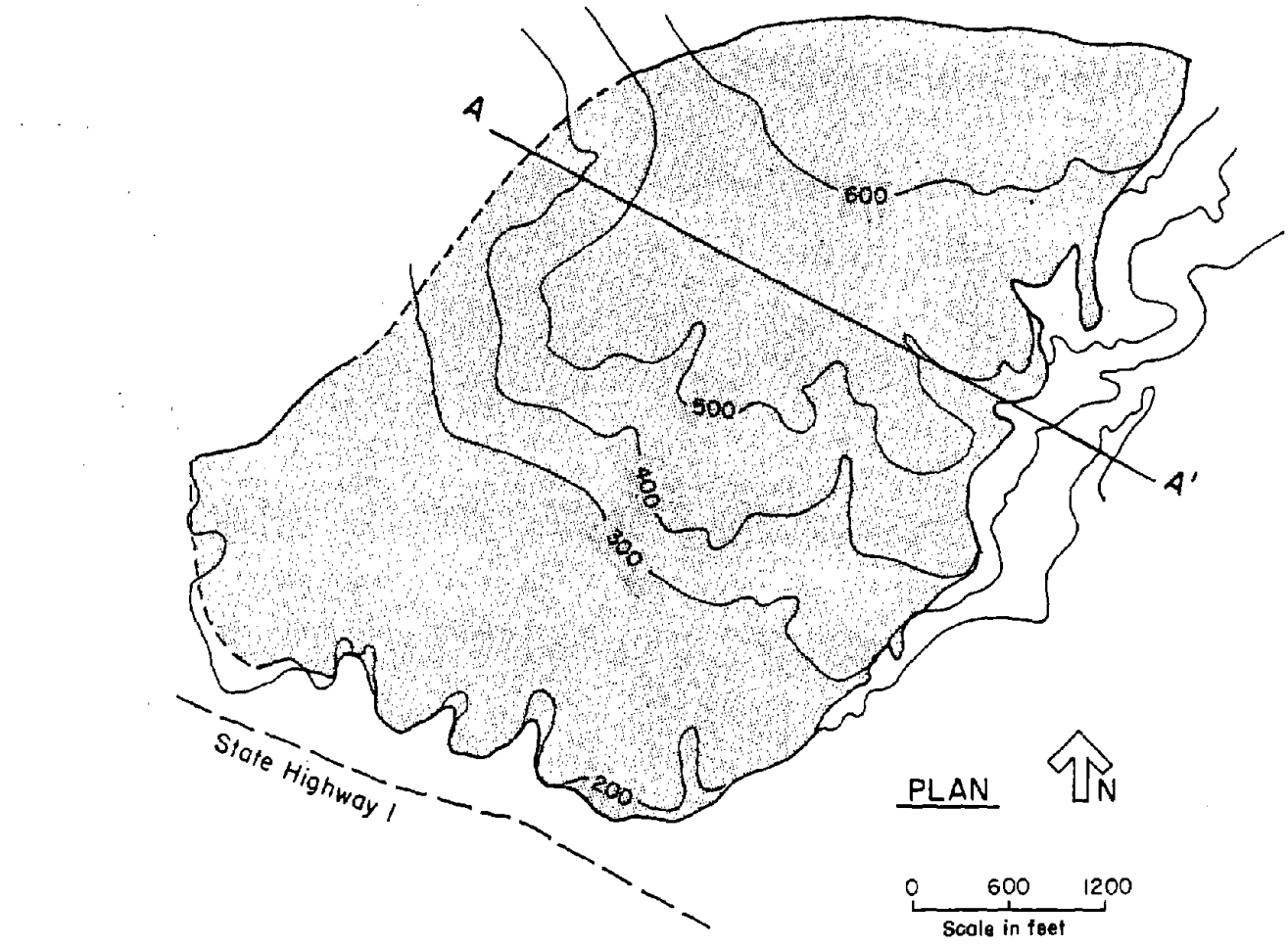
LOCATION MAP
SANTA CRUZ BITUMEN DEPOSIT, CALIFORNIA

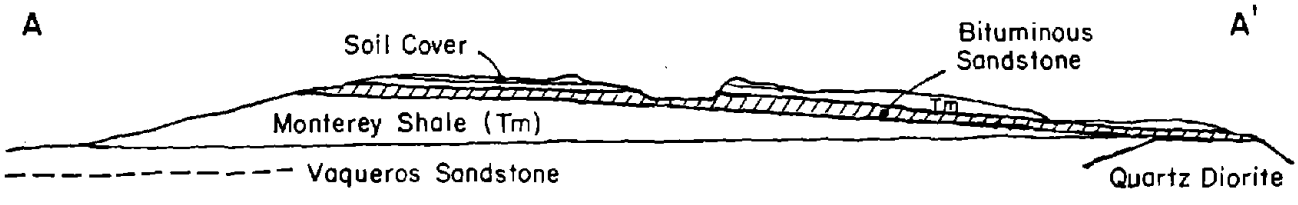
Figure 6-9



PLAN AND GEOLOGIC SECTION
SANTA CRUZ BITUMEN DEPOSIT, CALIFORNIA

Figure 6-10





SECTION

Redrawn from: Page, B., et al (1945)

pregnated the interbedded sandstone. The possibility exists that the fractured Monterey shale adjacent to the sandstone is in part impregnated with bitumen.

1. Structure

   The structure and enclosing shale dip gently, 3 degrees to 7 degrees, to the west. The general structure is that of homocline.

2. Development History

   The various bituminous sandstone deposits near Santa Cruz have been intermittently worked since 1888. Between 1888 and 1915 more than 614,000 tons of bituminous material was mined and sold for paving material.

In the period between 1915 and 1930, the district output of mined bituminous material gradually decreased, and by 1930 most operations had ceased. In or about 1930 the Calrock Asphalt Company began quarrying in the area which is the subject of this study. The Calrock plant produced paving material and pressed asphalt bricks for industrial flooring until about 1949 (Ref. 8).

During the mid-1950's, the Husky Oil Company conducted an experimental in situ project to recover oil at the Calrock quarry. Holes were drilled into the bituminous sandstone and temperature in excess of 600°F was built up in the deposit by heating with a special down-the-hole gas burner. The petroleum products were collected as vapors and put through a condenser. Total oil production achieved is reported to be 2,665 barrels of 27° gravity oil.

6.3.3 Reserves

The largest deposits of the Santa Cruz area hold published reserves of 9,300,000 cubic yards of bituminous sandstone. The sandstone contains 10 million barrels of asphalt with an average grade of 10 percent by weight.

6.3.4 Mine Design and Scheduling

The proposed mining operation at Santa Cruz has been based on assumed ore reserves of 16.7 million tons with an average grade of 10 percent or 24 gallons of bitumen per ton in the central area, plus four million tons of the same grade in the northwest and adjacent area.

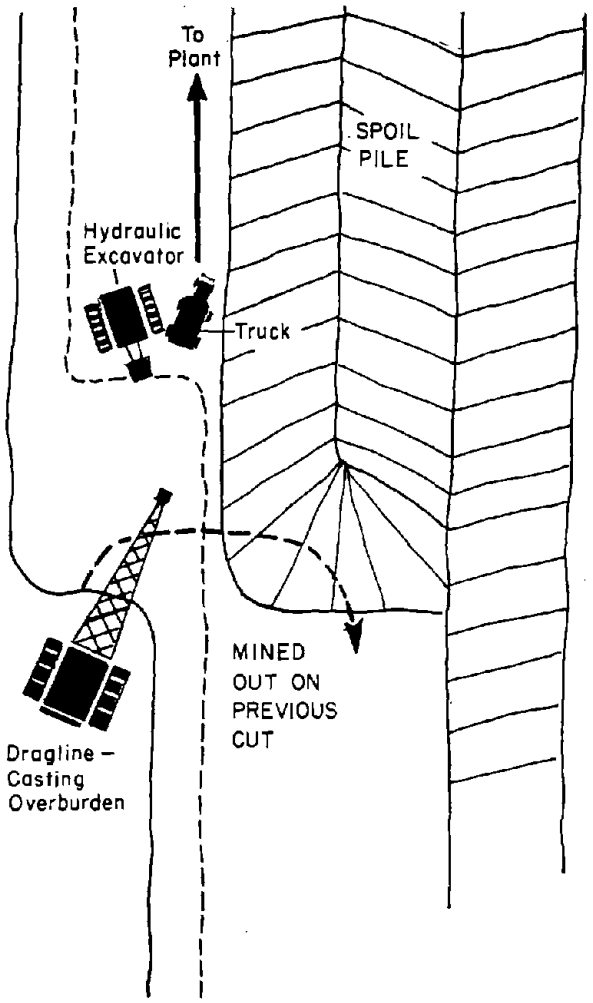
The strip mining method was selected since the Santa Cruz deposits are flat-lying and shallow, the pay zone is thin and the geometry is ideal for dragline operations (Figure 6-8). The stripping ratio was calculated to be 3.39:1 and consequently in order to achieve a production rate of 4,200 tons per day, 14,150 tons per day of waste will have to be stripped. The proposed mine would operate three shifts per day, seven days a week, for 340 days a year, producing 1,420,000 tons per year of ore and 4,811,000 ton per year of waste. Since the ore reserves are estimated to be 16,700,000 tons this would give a mine life of 12 years.

The average thickness of the overburden is 50 feet, ranging from zero to 100 feet. The overburden removal required to provide 4,200 tons per day of ore would be 2.83 million cubic yards per year. It is necessary to provide excess stripping, and therefore, the necessity of achieving three million cubic yards per year of overburden removal has been assumed. Consequently, a machine capable of producing 500 cubic yards per hour is required. Assuming: 1) a 60-second digging cycle, 2) a 25 percent material swell factor, 3) a mechanical availability of 85 percent of the scheduled operating hours and 4) an operating efficiency (the portion of the remaining time that the machine actually digs) of 80 percent, a 13 cubic yard dragline would be required.

Four-thousand two-hundred tons of ore must be mined per day. The oil-bearing material is hard and will require drilling and blasting. Six-cubic-yard capacity hydraulic shovels will match the 15-foot face and have excess capacity for the job. Since the daily ore feed required by the processing plant is so small it has been assumed that ore mining will be on a five days per week, one shift per day schedule requiring the capability of loading 1,000 tons of ore per hour. Since a 6 cubic-yard hydraulic shovel will produce 500 tons per hour, two such shovels should produce the required 1,000 tons. Six 35-ton trucks will be needed for a mining operation of this size. As shown in Figure 6-11, the dragline will dig and cast the overburden onto a spoil pile on the other side of the ore mining cut. The hydraulic shovels will trail the dragline in the mining cut, removing the ore and loading it into the trucks for haulage to the process plant. The spoil piles will be reclaimed as the strip advances.

6.3.5 Processing

The feed to the Santa Cruz process plant will be asphaltic sandstone with some oversize material. The feed will probably


To
Plant
SPOIL
PILE
Hydraulic
Excavator
Truck
MINED
OUT ON
PREVIOUS
CUT
Dragline -
Casting
Overburden

have to be passed through a toothed roll crusher to reduce the oversize material prior to treatment. It is believed that a hot water/steam process should be adequate for oil recovery. The proposed oil separation plant would operate 3 shifts per day 7 days a week, for 340 days a year and would process 4,200 tons per day of ore at a planned recovery rate of 90 percent. This will result in the production of 378 tons (2,160 barrels) of bitumen per day. This would amount to 730,000 barrels per year for a total of 8,614,000 barrels over the 12-year mine life.

6.3.6 Safety

No unusual safety problems or hazards are anticipated, other than those normally encountered in open pit coal mines.

6.3.7 Environmental Considerations

The principal impacts will be odor, dust and noise. Spoil will be disposed of above ground and revegetation will be required.

Impacts on support facilities will be minimal. Santa Cruz (population 37,000) is located about 5 miles from the site. There are several moderate sized towns within 20 miles of the site. Santa Cruz County has a population of 156,000. Additionally, Santa Cruz is a resort city and has a large number of facilities and services geared to tourism. Support services are found in greater abundance than would normally be found in a city this size.

The total population affected would be about 1,100 persons, 150 of which would be employed at the mine. This would create a minimal impact on the existing economy both during mining and after mining is completed.

There may be an adverse aesthetic impact due to the project. The proximity of the city to the site and the resort atmosphere of the general area could magnify any potential dust and visibility problems created by the facility. This could give rise to objections by the residents.

6.3.8 Technical Feasibility

The strip mining methods selected for the Santa Cruz deposits are well known and are extensively used. The proposed strip mine at Santa Cruz is very small compared to the majority of strip operations in the coal industry throughout the United States. The equipment is standard and has been available for many years.

Once again, the only area of question in the technical feasibility of this proposed operation is the processing.

6.4 OPEN PIT MINING

6.4.1 General Description

Ore deposits which come close to the surface but owing either to the topography over the deposit or to extension of the orebody with depth, cannot be mined by systems that backfill the pit. They must be mined by open pit mining systems. In these methods the overburden and ore are hauled out of the pit up haul ramps and the overburden is placed in dumps away from the pit area. An ideal candidate for the open pit method is the Edna bituminous sandstone deposits. The geometry of this deposit that makes the selection of an open pit mining system necessary is illustrated in the section shown on Figure 6-12. It can be seen on this section that the depth of the potential orebody is so great that only after an immense excavation is made (requiring many years of mining) would enough ore be mined out to permit backfilling (with tailings and in-pit waste) without unmined ore being covered.

The Edna deposits cover 410 acres in Township 31 South, Ranges 1 and 13 East (Mount Diablo Base and Meridian) in southwestern San Luis Obispo County, California (Figure 6-13). The deposits are approximately eight miles south- southeast of the city of San Luis Obispo, between the towns of Edna and Pismo. Key properties of the Edna Field are summarized in Table 6-5.

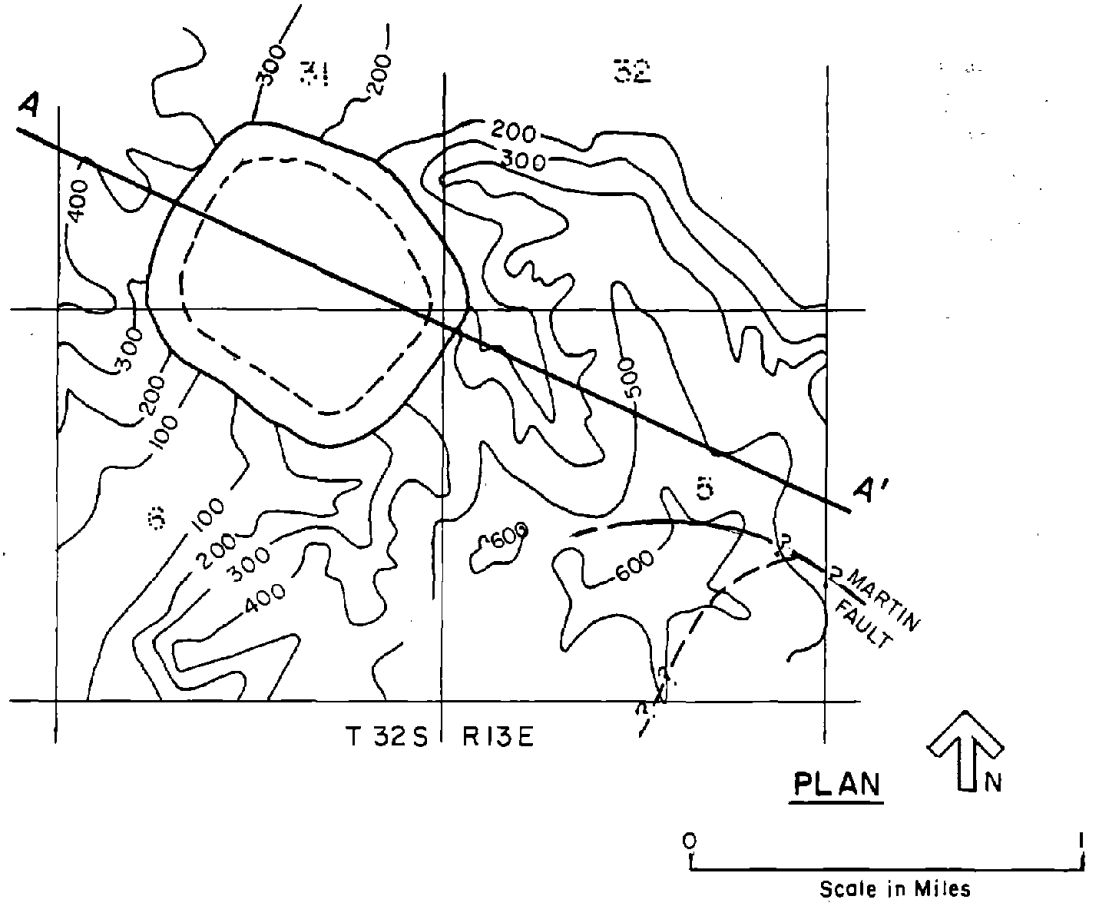
The tar sand deposits overlie the Arroyo Grande oil field (Figure 6-14). The topography consists of low hills with elevations varying from 100 to 600 feet above sea level. The areas without surface tar sands are generally gentle rolling hills. The tar sand surface exposures develop a rough terrain with steep cliffs, formed by differential erosion between the resistant bituminous sandstone and the barren, softer sandstone.

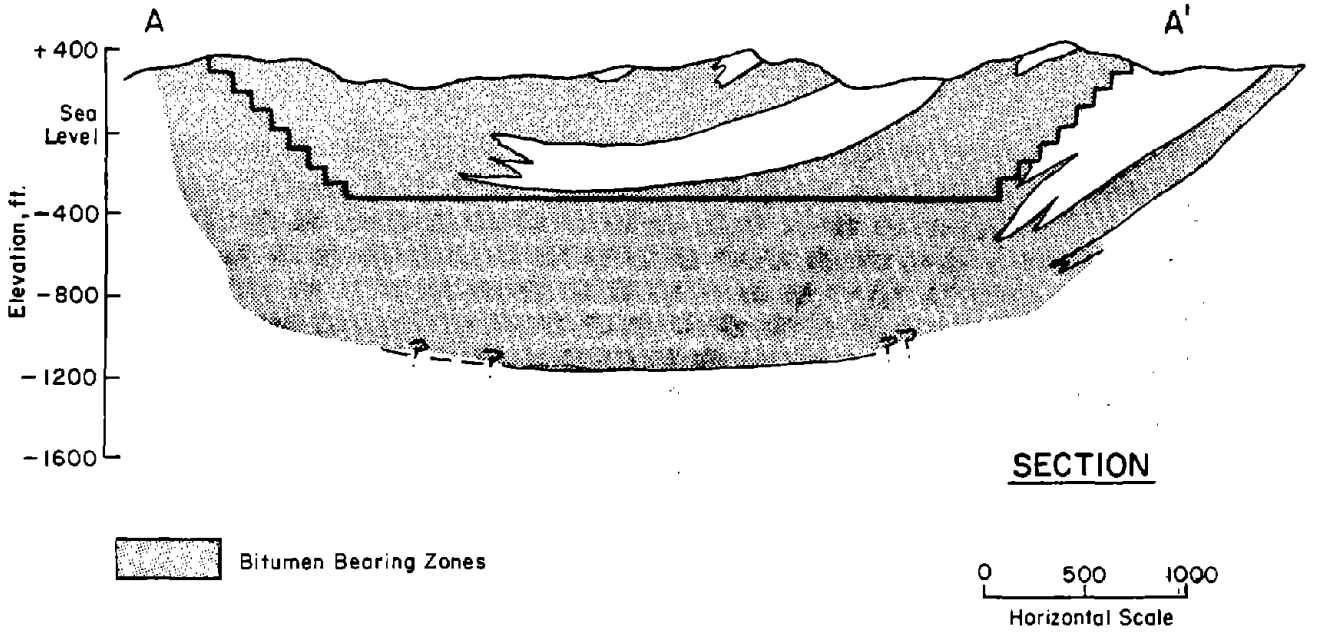
The climate is coastal, with mild winters and moderately warm to warm summers. Average annual rainfall is about 25 inches (Ref. 9).

There were small open pit asphalt mines operating in this area during the interval 1887 to 1922. One quarry measures 240 feet in length, 60 feet in width and 40 feet in depth (Ref. 10).

OPEN PIT – PLAN AND SECTION OF MINE
EDNA, CALIFORNIA

Figure 6-12





LOCATION MAP
EDNA BITUMEN DEPOSIT, CALIFORNIA

Figure 6-13

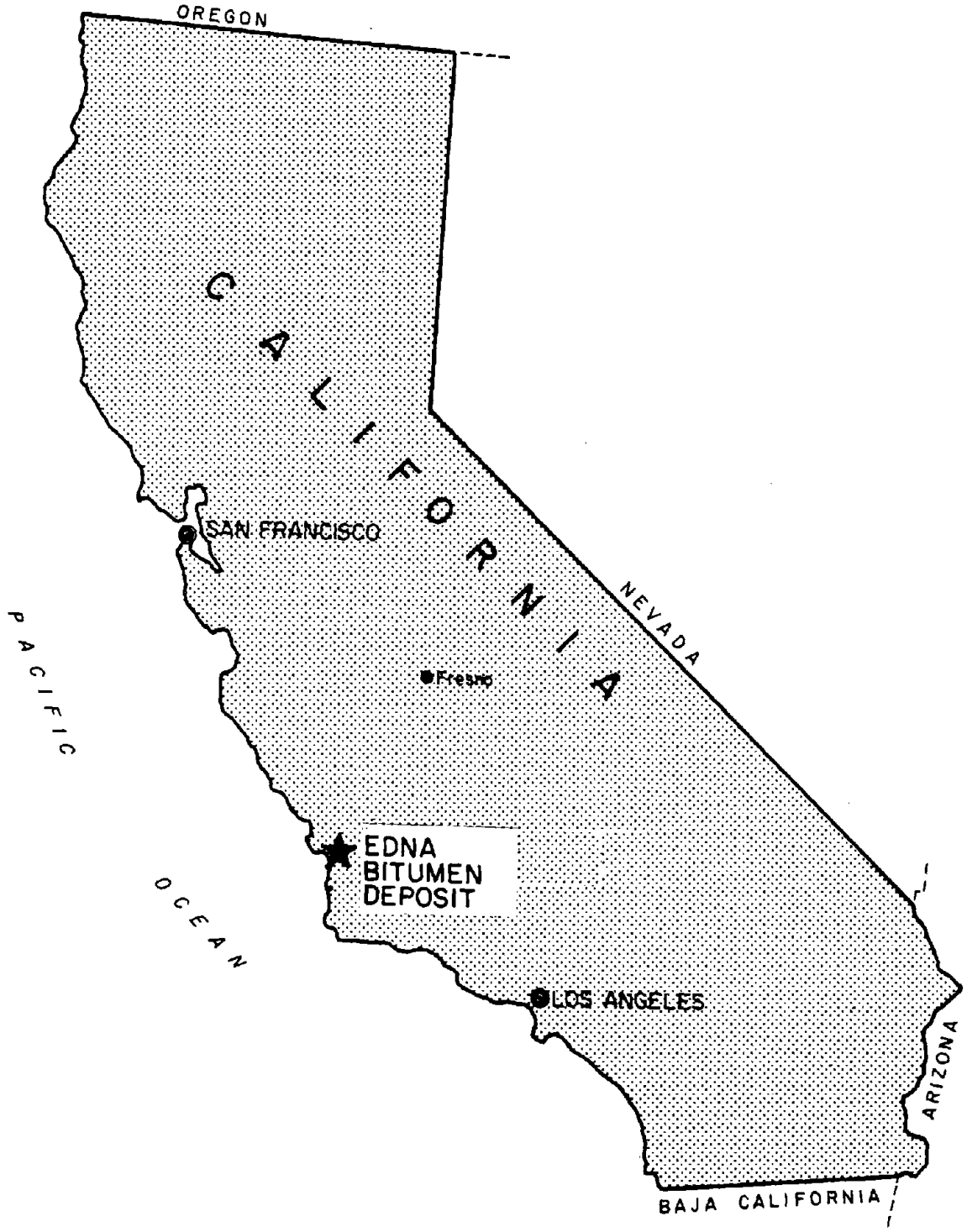


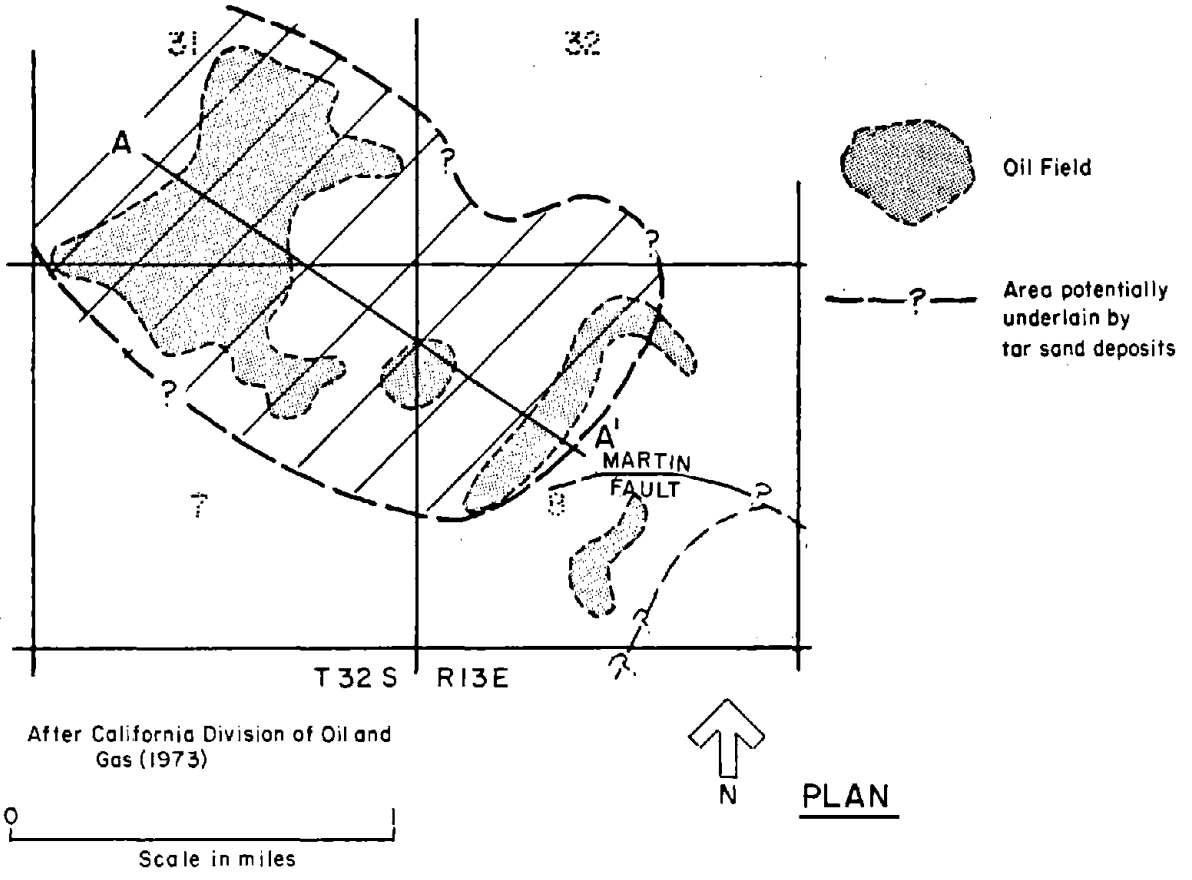
TABLE 6-5

SANTA CRUZ FIELD

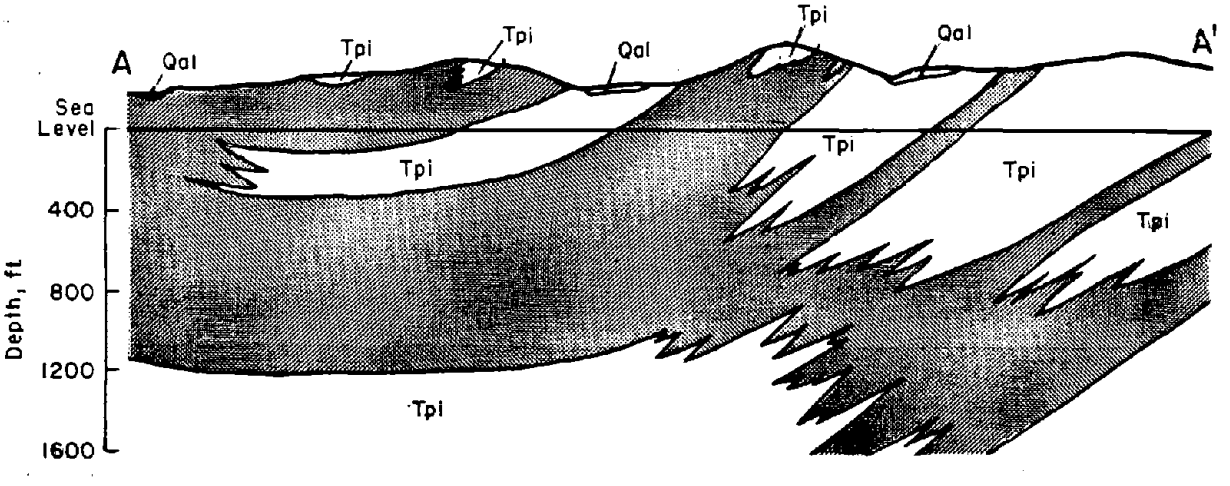
Permeability	Not available	
Porosity (%)	Not available	
Oil Gravity	27°	
In-Place Grade (bbl/T)	0.57	
Depth to Top of Oil (feet)		
Minimum	0	
Maximum	100	
Ave.	50	
Thickness of Oil Zone (feet)	1 to 35	
Dip of Oil Zone	3° to 7° W	
Overlying Zone		
Type	Soil and Marne Terrace Deposits	
FM Name	---	
Age	Quaternary	
Underlying Rock		
Type	Sandstone	Quartz Diorite
FM Name	Vaqueros Sandstone	---
Age	Miocene	Pre-Cretaceous
Oil-Bearing Rock		
Type	Sandstone interbedded wtih Diatomaceous Shale	
FM Name	Monterey Shale	
Age	Miocene	

PLAN AND GEOLOGIC SECTION
EDNA, CALIFORNIA

Figure 6-14



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6.4.2 Geological Description

The upper Miocene-lower Pliocene Pismo formation is the bitumen-bearing zone. This is more than 200 feet thick and is composed of variable marine sediments. The Pismo formation overlies the Monterey shale.

The lithologic character of the Pismo formation is extremely variable within short distances. Individual beds cannot be traced with certainty for any distance on the surface, nor can they be correlated accurately between the wells in the oil field. Good examples of this phenomenon can be observed in road cuts along the road from Pismo Beach to Edna. Here rapid changes in grain size and lithology occur within a few feet.

The arkosic sandstone beds vary in grain size from fine to coarse, and are locally conglomeratic. The sandstone is variably impregnated by oil at depth and by tar in the near surface environment.

The bituminous impregnations are irregular and discontinuous. Some of the bituminous deposits follow the bedding, but these frequently terminate abruptly along the strike. It is unsafe to assume continuity between outcrops. The texture of the bituminous sandstone varies, but it is usually medium- to coarse-grained and tends to be slightly coarser-grained than the rest of the Pismo sandstone. While large bodies of rock are of reasonably uniform character, beds or thin zones of gritty sandstone or conglomerate are a common occurrence within a predominantly medium-grained mass (Ref. 9). The water content of the bituminous sandstone is low, ranging between one and three percent by weight. Porosity of non-bitumen impregnated sandstone is approximately 36 percent (Ref. 11).

The bituminous sandstones are more resistant to weathering and erosion than the barren parts of the Pismo formation. These outcrops vary from "rich, black, completely saturated tar sand, which in warm weather gives rise to small asphalt seepages" (Ref. 9) to "slightly bituminous sandstones, to which traces of organic matter impart a light-brown color"(Ref. 9). The most common grade of tar sand is of intermediate quality, dark brown in color. The grade of the sandstone varies within each deposit, and in some outcrops changes from clean, white sandstone to completely saturated sandstone within a distance of five to 25 feet. The higher-grade bituminous sands are somewhat plastic.

Moderately rich sandstones are hard and tough, being essentially cemented by tar. The lower-grade, pale-brown sandstones are usually soft and friable. The weathered and oxidized out-



crops of the bituminous deposits are dry, and light to medium brown, and sometimes reddish in color. This material is reported to grade downward into bituminous saturated sandstone at depths as shallow as 3 to 20 feet below the surface (Ref. 9). The bituminous sandstone outcrops contain between 9 and 16 percent bitumen by weight (Ref. 12). Bulk sample analyses averaging 11 percent by weight (26 gallons of bitumen per ton) were collected by the U.S. Bureau of Mines (Ref. 13).

The bitumens impregnating the Pismo formation probably originated in the underlying Monterey shale, which is bituminous. The oil would have migrated upward following the more sandy members which contained few permeability barriers. Open fractures, joints, bedding-plane joints, and shear zones are observed controlling distribution of the bitumen in outcrop, and probably partially controlled migration within the deposit as well. As the oil reached the near surface environment it lost its more volatile constituents. The bitumens accumulated an asphaltic residue forming a seal and preventing the further escape of oil. Permeability appears to have exerted the primary control for the localization of the bitumens.

Overlying the Pismo formation there is from zero to more than 30 feet of unconsolidated alluvial sands and gravels and sporadic patches of sandy soil (Ref. 9).

1. Structure

The main structural feature of the area is the narrow northwest-trending, assymetrical Pismo syncline, the northeast limb of this syncline dips up to 30 degrees while the southwest limb dips 45 degrees to 60 degrees (Ref. 10). Minor anticlines and synclines occur superimposed upon the limbs of the Pismo syncline, but these are inconsequential features. The bituminous deposits on the northeast side of the axis of the Pismo syncline are larger than those on the southwest side.

2. Development History

"The bituminous sandstone deposits were quarried for paving material beginning in 1887. By 1890, more than 80,000 tons of rock were shipped from the district, and from 1890 to 1915 about 75,000 tons were shipped. The rate of production declined during the latter period, however, and in 1915 only one quarry was still producing. In 1922 the California Oil Mining Company began oil recovery operations by the solvent extraction process at or near quarries. A small processing plant was erected, and several short adits were driven in

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the saturated sandstone, which, in the richer parts, contained about one barrel of oil per ton. This operation was unsuccessful (Ref. 9).

3. Reserves

Reserve estimates (Ref. 9) apply to moderately to highly bituminous deposits in existing exposures. Slightly bituminous deposits are not included.

In 1944, 13.35 million cubic yards of "measured reserves" of immediately accessible bituminous rock were revealed by measurements of existing outcrops and quarries. An additional 76.15 million cubic yards of "indicated reserves" were estimated to occur where geologic evidence suggested the deposits continued at depth, and a further 76.9 million cubic yards were "inferred" to be present where geologic evidence was favorable, and deep quarrying was thought to be possible. Depths assigned to "measured" reserves ranged from 5 to 70 feet, "indicated" ranged up to 150 feet, and "inferred" up to 250 feet. Material at depth greater than 250 feet, or covered by greater than 50 feet of overburden, was not included in these rough reserve estimates. Total estimated reserves in all classes was 166.4 million cubic yards, or approximately 282.88 million short tons, (Ref. 9).

For the purposes of this study a reserve of 200,000,000 tons at grade of 0.62 barrels of bitumen per ton was assumed.

6.4.3 Mine Planning and Scheduling

The stripping ratio at Edna is 1:1 and the postulated orebody lends itself to a truck and shovel open pit. The pit has been designed to produce 50,000 tons of ore per day for 340 days per year. At the 1:1 stripping ratio this will require the daily removal of 100,000 tons of ore and waste.

The ultimate pit would be almost three-quarters of a mile in diameter at the perimeter and 350 feet deep at its deepest point (Figure 6-12). The major problems that could be encountered with this operation will be grade control due to the known extreme variations in bitumen content that occur at Edna, and the problem of trafficability on the high bitumen material. The latter problem can be overcome with the use of high flotation tracks on the shovels and bulldozers and high flotation tires on the trucks.

Since the distribution of included waste in the Edna deposit is not well known at this time, it is not possible to present a detailed production schedule in this report. However, the annual overall production will be 17,000,000 tons of ore and an equivalent amount of waste. Based on standard operating efficiency parameters, it is estimated that three 21-cubic yard electric shovels with a 15-cubic yard front-end loader as backup will be required for the entire operation. The mine would operate with 50-foot benches using standard open pit drilling and blasting techniques as required in the harder areas. It is estimated that three rotary drills of the Bucyrus Erie "R" Class would be necessary. To achieve the appropriate production level it was estimated that thirteen 170-ton end-dump off-highway haulage trucks would be necessary. The majority of the waste that makes up the 1:1 stripping ratio is included waste within the ore. Only five million tons of prestripping would be necessary because of the outcropping nature of the bitumen zone, an extremely favorable situation for early startup.

The waste would initially be dumped outside the pit, although later, after detailed mine design and scheduling, in-pit waste dumping could be achieved.

6.4.4 Processing

The processing plant for the Edna deposit would utilize the same extraction method as proposed for Santa Cruz. As in that case, the Edna plant will require a crushing circuit for the oversize material, and will handle 17,000,000 tons of ore per year to produce 9,500,000 barrels of oil.

A preliminary report (Ref. 11) has presented the results of laboratory research into the adaptation of the hot-water separation process to the recovery of hydrocarbons from bituminous sandstones of the Edna deposits near San Luis Obispo, California. The report describes the construction and operation of the laboratory separation plant and discusses the problems involved and the results obtained in treating the Edna bituminous sandstones. The utilization of the recovered bitumen as a source of motor fuels, diesel fuels and fuel oils also is discussed, and data on cracking, analytical distillation, and its asphalt properties are summarized. The studies have demonstrated that the hot-water method of separation may be applied satisfactorily to separating hydrocarbons from the Edna bituminous sandstones, although the presence of mineral salts and fine silt in the deposits complicates the operation. Certain operating problems still remain to be solved but, unquestionably, further study and experimental work will lead to their solution. Although the work has not been advanced to the pilot-plant stage and does not permit estimates to be made of separation costs, the small-scale

studies have provided much valuable information of a fundamental nature on the recovery of bitumen from the Edna bitumenous sandstones by the hot-water separation method.

6.4.5 Safety

No unusual safety problems or hazards are anticipated, other than those normally encountered in open pit coal mines.

6.4.6 Environmental Considerations

The principal impacts associated with processing are odor, dust and noise. There will be an increase in truck traffic on roads between the mine and processing plant. Spoil will be disposed of above ground with revegetation necessary.

Impacts related to support activities from increased employment will be moderate. Edna is located three miles northeast of Pismo Beach (population 5,000), 7 miles southwest of San Luis Obispo (population 33,000) and 18 miles northwest of Santa Maria (population 33,600) in San Luis Obispo County (population 129,000).

Employment will be about 600 persons. This will create an additional 1,200 service and support jobs and affect a population of about 4,200 people.

A large number of employees will probably come from the local area damping the influx from outside the area. The surrounding area has sufficient population and service infrastructure to absorb the mining activity with little impact on support functions. At the end of the 12-year life of the project it will experience moderate increases in unemployment which may be temporary depending on the economy of the area at that time.

6.4.7 Technical Feasibility

The proposed open pit method to be used for the Edna deposit is a conventional open pit mining approach, using conventional readily available equipment.

The tonnages involved would put this operation into the small- to medium-size open pit class. The proposed mining system is totally technically feasible, but as with the other proposed methods in this report, the processing system is the one area of questionable technical feasibility.

As stated above, this is due to the fact that no pilot plant testing or full-scale plant operation of this type has been tried before.

CHAPTER 6
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7.0 ECONOMIC EVALUATION

7.1 SYNTHESIS OF COSTS

Based on the mine designs described in the previous chapters capital and operating costs were derived. The method of computation is described in this section, together with any significant assumptions or simplifications that were found necessary. It should be noted that for the costing of the proposed operations, it has been assumed that the end point of the operation is the storage of an oil product or concentrate ready for shipment. Since the aim of this study is to compare the cost of producing oil by mining techniques to the cost of conventional production at the wellhead, no costs have been estimated for transporting or refining the product.

The total capital cost of each operation including replacement capital and contingency have been amortized on a straight line basins over the recoverable barrels of oil in each deposit. This yields a capital cost per barrel. The total annual operating cost has been apportioned to the designed annual production to give an operating cost per barrel.

Each of the proposed oil mining methods has been evaluated on a cost basis. In order to make these costs comparable to the current and possible future selling prices of oil, it was necessary to introduce a factor to recognize the need for payment of interest, redemption of loans, and achievement of profit. To this end a factor of 10 percent of the total initial capital investment has been added to the operating cost for each year for all the operations described. This allowance has been shown as a separate item on the cost presentations made in this section.

It has been assumed throughout this report that oilfields which are producing oil conventionally at a profit would not be purchased for oil mining. Only in those fields where the oil cannot be produced commercially with conventional techniques should consideration be given to mining. Consequently, no allowance has been made in the costing for acquisition of such fields since it is assumed that the current owners would be those who would wish to develop an oil mining facility if it were to make a currently uneconomic resource viable.

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The costs presented in this report were derived from various sources. In the underground studies:

- Capital equipment costs were taken from recent manufacturers listed prices:
- Prerevenue mine development (shaft sinking, etc.) and underground and surface facilities were based on preliminary construction estimates.
- Underground operating labor costs were based on manpower estimates, and operating materials and supplies were estimated as a factor of the labor costs, based on recorded experience in operating mines.

In the surface mine studies:

- Capital equipment items were obtained from recent manufacturers listed prices:
- Prerevenue mine development (development drilling, prestripping, road construction, etc.) was based on gross estimates obtained from recently completed similar projects.
- Operating costs (labor, materials and supplies) were based on unit costs obtained from mines with similar operations.

7.1.1 Capital Costs

All capital and preproduction costs have been calculated at current price levels and in 1977 dollars. Wherever possible, known prices for equipment, construction activities, etc., have been used in the basic costs.

Since the capital costs of items outside the mining and processing complexes such as the major infrastructure for new towns and highways vary widely and have no relation to the oil mining techniques used, the costs for such items as related to the specific fields examined have not been included. However, the direct mine and plant related infrastructure such as power and water supply within the mine-plant complex have been included in the process plant and mine plant costs.

The replacement capital requirements have been estimated utilizing industry-accepted useful lives for equipment and installations. In all cases it has been assumed that the original process plant will last the life of the operation; however, a replacement allowance calculated as a percentage of

the initial capital cost of the process plant has been added in for each year of operation.

1. Process Plant

The estimated capital cost for the construction of the complete process plant includes construction and the cost of equipment for the process plant. Engineering and design costs are also included. These costs have been derived by an experienced specialist in this field based on limited knowledge of relevant mineralogy and, of course, without the benefit of detailed design or bench testing. They do, however, to the greatest degree possible, reflect the characteristics of the various deposits and are factored to allow for the different scales of operation.

2. Mine Plant

The capital costs of the mine plant for the underground operations are divided into two categories. The first category, Surface Mine Plant, contains all the capital costs and any preproduction operating costs for the construction of the mine plant, including such surface items as headframes, hoist houses, workshops, warehouses, miners' change house, offices, etc. All underground installations such as crushers, permanent fans, shafts and skip pockets, are combined into the category of Mine Plant-Underground.

This cost element includes all capital costs and preproduction operating costs incurred in developing the mine on-site infrastructure. This would include such items as warehouses, workshops, garages, and general office.

3. Mine Equipment

This cost element covers all the mining equipment such as drill jumbos, ring drilling equipment, LHD units and rail haulage units, for underground mines, and shovels, conveyors, bucket wheel excavators, trucks, dozers etc. for the surface operations. In all cases, the equipment selection and costing has been predicated on having spare equipment capacity available.

4. Advance Development

Advance development includes all capital and preproduction operating costs incurred in advance development

underground prior to production startup. The equivalent for the surface mines is prestripping, which includes all the operating labor, materials and supplies costs incurred in stripping waste material prior to ore production.

7.1.2 Operating Costs-Underground Mines

The operating costs for the underground operations are divided into 13 cost elements.

1. Development

   This includes all operating labor, materials and supplies for the development of haulage drifts, crosscuts, sublevel development, orepasses and ventilation raises, etc., during the mining operation.

2. Stoping

   This cost element includes all operating labor, materials and supplies incurred in stoping operations in the direct mining methods. This would include stope access raises, production drilling and blasting.

3. Drilling/Drainage

   This includes all operating labor, materials and supplies incurred in the drilling and preparation of drainage holes in those mining systems utilizing a drainage approach. The costs of fragmentation of the oil bearing zone prior to drainage, and steam stimulation where used, are also included under this heading.

4. Rock Transport

   This cost element includes all operating labor, materials and supply costs incurred in the transportation of mined material from the stopes to the skip pockets at the shaft.

5. Product Handling

   This heading covers all operating labor, materials and supplies incurred in the handling of oil produced from drainage-type operations. This would include the collection of the oil in underground sumps, any necessary initial separation, and its transportation from the collection point to the surface.

6. Ventilation

This cost element includes all operating labor, materials and supplies incurred in the operation of the ventilation systems. This would include the operation of the main fans and any secondary ventilation or volatile gas control required. The operation of air doors, bulkheads, seals, etc. is also included in this category.

7. Pumping

This cost element includes all operating labor, materials and supplies incurred in the collection, settling and pumping to surface of water inflows into the mine.

8. Hoisting

This cost element includes all operating labor, materials and supplies incurred in the hoisting of oil-bearing rock to surface and the operation of service shafts. Also included is the cost of hoisting barren development rock.

9. Backfilling

The cost element includes all costs incurred in the backfilling of stopes for support purposes.

10. Processing

This cost element covers all operating labor, materials and supplies incurred in the process plant but does not include the cost of transport of the final product from the plant to the refinery.

11. Waste Disposal

This cost element would include all operating labor, materials and supplies incurred in the disposal of both waste rock and tailings on the surface.

12. Environment

This cost element would include all operating labor, materials and supplies incurred in environmental control including air and water quality, noise, dump reclamation, etc.

13. General and Administration

This cost element includes all operating labor, materials and supplies incurred in the control and supervision of the mining operation. This would include such items as accounting, safety control, day-to-day engineering, warehousing, etc.

7.1.3 Operating Costs-Surface Mines

The cost elements for the operating costs of the surface mines are divided into 15 categories. They are as follows:

1. Drilling-Overburden

This includes all operating labor, materials and supplies incurred in the drilling of blastholes in the overburden material.

2. Blasting-Overburden

This cost element covers all operating labor, materials and supplies incurred in loading and blasting the blastholes in the overburden.

3. Loading-Overburden

This cost element includes all operating labor, materials and supplies incurred in the loading of the broken overburden material into haulage units. In the case of bucket wheel operations, this would include only the cost of the bucket wheel itself and not the cost of the bench and trunk conveyors.

4. Transport of Overburden

This cost element includes all operating labor, materials and supplies incurred in the hauling of the overburden to a discharge point at a waste dump.

5. Miscellaneous-Overburden

This cost element includes all operating labor, materials and supplies incurred in miscellaneous operations in the overburden stripping, such as mine dewatering, communications, lighting, safety, and maintenance, general mine cleanup, brush and scrub removal, etc.

6. Drilling-Ore

This cost element includes all operating labor, materials and supplies incurred in the drilling of blastholes in the ore material.

7. Blasting-Ore

This includes all operating labor, materials and supplies incurred in the loading and blasting of blastholes in the ore.

8. Loading-Ore

This cost element covers all operating labor, materials and supplies incurred in the loading of the ore material onto the haulage system.

9. Transport Ore

This cost element includes all operating labor, materials and supplies incurred in the transportation of ore from the loading face to the processing plant.

10. Miscellaneous Ore

This cost element includes all operating labor, materials and supplies incurred in miscellaneous activities such as mine dewatering, communications, lighting, etc., in the oil mining operation.

11. Pumping

This cost element includes all operating labor, materials and supplies incurred in the collection of water and pumping out of the pit.

12. Processing

This cost element includes all operating labor, materials and supplies incurred in the processing plant.

13. Waste Disposal and Reclamation

This cost element includes all operating labor, materials and supplies involved with the disposal of overburden waste material and tailings to waste dumps or impoundments, or back into the pit as is the case in some of the suggested methods. This cost element also

includes all costs incurred in the reclamation of waste dumps, tailings ponds, and the mine itself.

14. Environmental

This cost element includes all operating labor, materials and supplies costs involved with environmental control. This includes such items as control of air quality, water quality, noise, etc.

15. General and Administrative

This cost element includes all direct operating labor, materials and supplies costs incurred in the control and supervision of the operation. This includes such items as accounting, warehousing, supervision, management, etc.

7.2 ESTIMATED COSTS

7.2.1 Direct Stoping Methods

The estimated capital and annual operating costs of the Circle Ridge oil mine are shown in Table 7-1.

1. Capital Costs

This operation employs an extraction system in which all the ore is brought to surface for processing, and the process plant represents the largest single item, 72.0 percent, of the initial capital cost. This cost is based on a figure of $3,065 per daily ton of installed capacity. Both mining methods considered at Circle Ridge are highly mechanized and consequently the underground mine plant and mine equipment together represent almost one-fifth of the initial capital, at 9.9 percent and 8.3 percent respectively. However, since the majority of the development is done in the orebody and production starts fairly quickly, the amount of advance development necessary is small, at 0.6 percent of the initial capital.

The estimated cost for the exploration, feasibility and design stage is 7.5 percent of the initial capital investment. This includes fairly extensive drilling to delineate and sample the two formations and a great deal of process design work will be required.

Table 7-1

ESTIMATED TOTAL CAPITAL COSTS

	$(,000's)	TOTAL $(,000's)
Preproduction Capital		
Process Plant	184,000	
Mine Plant Surface	4,420	
Mine Plant Underground	25,253	
Mine Equipment	21,121	
Advance Development	1,640	
Exploration and Feasibility	19,219	
		255,653
Replacement Capital		44,191
Contingency (15%)		44,977
TOTAL CAPITAL COST		344,821

ESTIMATED ANNUAL OPERATING COSTS

	$(,000's)	
Mine Production		
Development	13,908	
Stoping	34,873	
Drilling / Drainage	—	
Rock Transport	11,961	
Ventilation	7,866	
Pumping (Water)	9,866	
Hoisting	6,036	
Backfilling	20,216	
Miscellaneous Mining	19,517	
		124,243
Processing		
Processing	6,961	
Product Handling	—	
		6,961
Waste Disposal and Environmental		
Waste Disposal and Reclamation	853	
Environmental	395	
		1,248
General and Administrative		3,483
Contingency (15%)		20,390
TOTAL ANNUAL OPERATING COST		156,325

SUMMARY - COST PER BARREL

	$
Capital Amortization Cost	9.76
Operating Cost	44.67
Allowance for Interest and Profit	7.32
TOTAL COST PER BARREL	61.75

The total initial capital requirement at Circle Ridge will be $255,653,000. Since the mine has a short life, 11 years, only a minor amount of replacement capital is required, and this is estimated to be $44,191,000. A standard 15 percent contingency, equivalent to $44,977,000, is added to the initial and replacement capital cost to give a total capital cost for the project of $344,821,000, this representing a direct capital cost of $9.76 per recoverable barrel of oil.

2. Estimated Annual Operating Costs

Mining Costs - At Circle Ridge all the development for both the Phosphoria and the Tensleep areas is in the oil-bearing zones. The combined development for both mining methods represents 11.2 percent of the annual mine operating cost and is based upon an average cost of development of $240 per foot. The largest single cost item in the annual mining operating cost is the stoping representing 28.1 percent of all mining costs.

Since the operations will be carried out in the hazardous environment of the oil-bearing zone, considerable ventilation costs will be incurred, 6.3 percent of the total annual mining cost. The Tensleep formation is to be backfilled, which will cost $1.06 per ton of ore or 16.3 percent of the total mining cost. Miscellaneous mining costs for such items as safety, communications, etc., will be sizeable because of the hazardous type of mine involved, and have been estimated at $1.04 per ton of ore or 15.7 percent of the total mining cost.

The total annual mining cost is therefore estimated to be $124,243,000 or $6.63 per ton of ore, 79.5 percent of the total annual operating cost.

Processing Costs - Process plant operating costs are estimated at $0.37 per ton of ore for an annual operating cost of $6,961,000 or 4.5 percent of the total annual operating cost.

Waste Disposal, Reclamation and Environmental - The disposal of tailings and reclamation of the ponds is estimated to cost $0.05 per ton of ore, and the costs of environmental control for the operation will be $0.02 per ton of ore.

General and Administrative - An annual sum of $3,483,000 has been estimated for the general and administrative cost for Circle Ridge.

Total Annual Operating Cost - Including a 15 percent contingency the total annual operating cost is estimated at $156,325,000, or $44.67 per barrel. This is equivalent to $8.34 per ton of ore.

The total cost per barrel for the Circle Ridge oil mining operation, excluding taxes, is therefore estimated to be $61.75 per barrel.

7.2.2 Block Caving

The estimated capital and annual operating costs of the Casmalia oil mine are shown in Table 7-2.

1. Capital Costs

Casmalia is a block caving operation in which the ore is removed from the mine to a surface processing plant. The processing plant represents the largest single item, 60.8 percent, of the initial capital cost. This cost is based upon $3,300 per daily ton of installed capacity.

The block caving mining method is moderately mechanized with the underground mine plant and the mine equipment representing approximately 18 percent of the initial capital. Since the majority of the development is done in the footwall and a large amount of advance development is required to bring the mine into production, the estimate for advance development represents 3.5 percent of the initial capital.

The total initial capital requirement at Casmalia will be $174,517,000. The daily tonnage produced is less than Circle Ridge and the mine is less mechanized, consequently the replacement capital is considerably less at $27,510,000. A 15 percent contingency is added to the initial and replacement capital cost to give a total capital cost for the project of $232,331,000, representing $3.80 per recoverable barrel of oil in the Casmalia fields.

2. Estimated Annual Operating Costs

Mining Costs - At Casmalia the largest single operating cost item is the actual block caving (stoping)

ESTIMATED TOTAL CAPITAL COSTS

	$(,000's)	TOTAL $(,000's)
Preproduction Capital		
Process Plant	106,250	
Mine Plant Surface	6,501	
Mine Plant Underground	17,260	
Mine Equipment	14,449	
Advance Development	6,156	
Exploration and Feasibility	23,901	
		174,517
Replacement Capital		27,510
Contingency (15%)		30,304
TOTAL CAPITAL COST		232,331

ESTIMATED ANNUAL OPERATING COSTS

	$(,000's)	
Mine Production		
Development	1,943	
Stoping	15,342	
Drilling / Drainage	—	
Rock Transport	6,929	
Ventilation	7,393	
Pumping (Water)	6,073	
Hoisting	4,477	
Backfilling	—	
Miscellaneous Mining	8,207	
		50,364
Processing		
Processing	12,468	
Product Handling	—	
		12,468
Waste Disposal and Environmental		
Waste Disposal and Reclamation	1,190	
Environmental	422	
		1,612
General and Administrative		3,466
Contingency (15%)		10,187
TOTAL ANNUAL OPERATING COST		78,097

SUMMARY - COST PER BARREL

	$
Capital Amortization Cost	3.80
Operating Cost	24.79
Allowance for Interest and Profit	5.54
TOTAL COST PER BARREL	34.13

operation. This represents 30.5 percent of the total mining cost or $1.40 per ton of ore. The development cost, $15.54 per ton of waste or 3.9 percent of the total mining cost, covers block development only and does not include any of the sublevel operations costs.

Since the operations will be primarily carried out in the oil-bearing zone, ventilation-related costs will be high, 14.6 percent of the total annual mining cost. It also appears likely that considerable water exists in the oil-bearing zone, and a high mine inflow can be expected, with consequently high water pumping costs at 12.1 percent of the total annual mining costs. Miscellaneous mining costs for such items as safety, communications, etc., will also be inflated by the potentially hazardous type of mine involved, and have been estimated at $0.75 per ton of ore, 16.3 percent of the total annual mining cost.

The total annual mining cost is estimated to be $50,364,000 or $4.61 per ton of ore, representing 64.5 percent of the total annual operating cost.

Processing Costs - Process plant operating costs are estimated at $1.14 per ton of ore for a total of $12,468,000 per year or 16 percent of the total annual operating cost.

Waste Disposal, Reclamation and Environmental Costs - The disposal of the tailings, and the reclamation of waste dumps and tailings ponds, and the control of subsidence areas, is estimated to cost $0.11 per ton of ore. The costs of environmental control for the operation will be $0.04 per ton of ore.

Total Annual Operating Cost - A 15 percent contingency has been added to the annual operating cost to yield a total annual operating cost of $78,097,000, $7.14 per ton of ore, or $24.79 per barrel.

3. Summary

The total production cost per barrel for the Casmalia oil mining operation, excluding taxes, is estimated to be $34.13 per barrel.

7.2.3 Shatter and Drain Method

The estimated capital and annual operation costs of the Yates oil mine are shown in Table 7-3.

ESTIMATED TOTAL CAPITAL COSTS

	$(,000's)	TOTAL $(,000's)
Preproduction Capital		
Process Plant	87,145	
Mine Plant Surface	6,191	
Mine Plant Underground	23,371	
Mine Equipment	21,384	
Advance Development	4,632	
Exploration and Feasibility	22,550	
		165,273
Replacement Capital		43,525
Contingency (15%)		31,320
TOTAL CAPITAL COST		240,118

ESTIMATED ANNUAL OPERATING COSTS

	$(,000's)	
Mine Production		
Development	13,094	
Stoping	—	
Drilling / Drainage	9,367	
Rock Transport	4,662	
Ventilation	4,175	
Pumping (Water)	2,993	
Hoisting	3,941	
Backfilling	—	
Miscellaneous Mining	7,150	
		45,382
Processing		
Processing	5,955	
Product Handling	6,067	
		12,022
Waste Disposal and Environmental		
Waste Disposal and Reclamation	662	
Environmental	736	
		1,398
General and Administrative		3,843
Contingency (15%)		9,397
TOTAL ANNUAL OPERATING COST		72,042

SUMMARY - COST PER BARREL

	$
Capital Amortization Cost	4.27
Operating Cost	27.41
Allowance for Interest and Profit	6.31
TOTAL COST PER BARREL	37.99

1. Estimated Capital Costs

This operation will produce 31 percent of its oil by extraction and surface processing of the ore, with the remainder produced by drainage from the oil-bearing rock following shattering with explosives. Even though the oil produced by processing is less than one-third of the total production, the process plant still represents the largest single item, 52.8 percent, of the initial capital cost, computed on a cost per daily ton of installed capacity of $4,360.00. The proposed mining method involves the use of a large amount of mobile mining equipment and consequently the underground mine plant and mine equipment together represent in excess of a quarter of the initial capital, at 14.2 percent and 12.9 percent respectively.

The total initial capital requirement for this operation will be $165,273,000. Since the mine utilizes a great deal of mobile equipment, the replacement capital required will be high at $34,525,000. A 15 percent contingency is added to the initial and replacement capital cost for give a total capital cost for the project of $240,118,000. This represents $4.27 per recoverable barrel of oil.

2. Estimated Annual Operating Costs

Mining Costs - The largest of the mine operating costs is the cost of development, which accounts for 28.8 percent of the mine operating cost and is based on an average cost of $337 per foot. Drilling and blasting to shatter the reservoir rock is another major cost item representing 20.6 percent of the annual mining cost.

Since the operations will be carried out in the hazardous environment of the oil-bearing zone, considerable ventilation costs will be incurred, 9.2 percent of the total annual mining cost.

Miscellaneous mining costs for such items as safety, communications, etc., will be substantial because of the hazardous type of mine involved, and these costs have been estimated at $1.17 per ton of ore, or 15.8 percent of the total annual mining cost.

The total annual mining cost is therefore estimated to be $45,382,000 or $17.32 per barrel which represents 63.1 percent of the total annual operating cost.

Processing Costs - Process plant operating costs are estimated at $0.98 per ton of ore for a total annual cost of $5,955,000. The handling of drained oil and its transportation to surface for water and suspended solids removal is estimated to cost $6,067,000. The total processing and product handling costs represent 16.7 percent of the total annual operating costs.

Waste Disposal, Reclamation and Environmental - The disposal of tailings and the reclamation of the ponds is estimated to cost $662,000 per year. The costs of environmental control for the operation will be $736,000 per year.

General and Administrative - A sum of $3,843,000 has been estimated for the annual general and administrative cost.

Total Annual Operating Cost - A 15 percent contingency has been added to the annual operating costs to yield a total of $72,042,000 per year, or $27.41 per barrel.

The total cost per barrel for the shatter and drain operation, excluding taxes, is estimated to be $37.99 per barrel.

7.2.4 Drainage with Steam

The estimated capital and annual operation costs of the Irma oil mine are shown in Table 7-4.

1. Estimated Capital Costs

This operation involves steam stimulation from development headings driven over the oil-bearing zone. As such, no ore is removed for processing; however, a treatment plant for oil/water, oil/gas and suspended solids separation is required, and is estimated to cost $1,714,000 for 5,000 barrels per day. The mine plant and mine equipment capital costs are a high proportion of the total (see sheet), representing 71.2 percent of the initial capital cost. Development of the headings, the drilling of wells and stimulation holes, the steam generation and injection equipment, and oil collection system are the major components of this cost. In order to expose enough area of the oil-bearing zone for

ESTIMATED TOTAL CAPITAL COSTS

	$(,000's)	TOTAL $(,000's)
Preproduction Capital		
Process Plant	1,714	
Mine Plant Surface	2,479	
Mine Plant Underground	11,119	
Mine Equipment	10,043	
Advance Development	1,080	
Exploration and Feasibility	3,296	
		29,731
Replacement Capital		16,295
Contingency (15%)		6,904
TOTAL CAPITAL COST		52,930

ESTIMATED ANNUAL OPERATING COSTS

	$(,000's)	
Mine Production		
Development	3,972	
Stoping	—	
Drilling/Drainage	9,456	
Rock Transport	788	
Ventilation	1,000	
Pumping (Water)	710	
Hoisting	2,854	
Backfilling	—	
Miscellaneous Mining	8,137	
		26,917
Processing		
Processing	758	
Product Handling	605	
		1,363
Waste Disposal and Environmental		
Waste Disposal and Reclamation	166	
Environmental	110	
		276
General and Administrative		1,467
Contingency (15%)		4,503
TOTAL ANNUAL OPERATING COST		34,526

SUMMARY - COST PER BARREL

	$
Capital Amortization Cost	2.55
Operating Cost	19.73
Allowance for Interest and Profit	1.70
TOTAL COST PER BARREL	23.98

drilling, a considerable amount of advance development is required. This represents 3.6 percent of the initial capital cost.

An extensive prefeasibility drilling program will be required to delineate the field, and considerable design of the stimulation and collection system and the treatment plant will be necessary. The estimated cost for exploration, feasibility and design is 11.1 percent of the initial capital investment.

The total initial capital investment requirement is therefore estimated at $29,731,000. Since the mine utilizes a large amount of mobile equipment, and the steam generation equipment is expected to require replacement at frequent intervals, the replacement capital requirement is high at $16,295,000. A standard 15 percent contingency is added to the initial and replacement capital cost to give a total capital cost for the project of $52,930,000. This represents $2.55 per recoverable barrel of oil.

2. Estimated Annual Operating Costs

Mining Costs - The main operating costs of the Irma operation will be for drift development, and for drilling and steaming the reservoir. The first of these elements represents 14.8 percent of the annual mining cost and is based on $216 per foot of development. The drilling costs are the largest single item, 35.2 percent, of the annual mining cost. The fact that a great number of relativley large diameter injection and production wells must be drilled accounts for the high proportion of cost attributed to drilling. Ventilation is less critical in this scheme than any of the other four underground schemes presented because the operations will be carried out above and away from the oil-bearing zone, and ventilation costs account for only 3.7 percent of the overall annual mining cost. Miscellaneous mining costs, which category includes the cost of producing and injecting the steam and the maintenance of the injection and collection system, safety and communications will be sizeable and have been estimated at $8,137,000 per year, or 30.2 percent of the total annual mining cost.

The total annual mining cost is therefore estimated to be $26,917,000 or $15.38 per barrel, which represents 78.1 percent of the total annual operating cost.

Processing Costs - The annual costs of operating the oil separation plant are estimated to be $758,000, or $0.43 per barrel, with handling costs for getting the oil from the mine to the separation plant are estimated to be $605,000 or $0.35 per barrel.

Waste Disposal, Reclamation and Environmental Costs - The disposal and reclamation of the waste rock brought to the surface from the underground development is estimated to cost $0.30 per ton. The environmental control costs for the entire Irma operation will cost $110,000 per year or $0.06 per barrel.

General and Administrative Costs - A sum of $1,467,000 has been estimated for the general and administrative cost for Irma.

Total Annual Operating Cost - A 15 percent contingency has been added to the annual operating cost to yield a total of $34,526,000 or $19.73 per barrel.

The total cost for the Irma oil mining operation, excluding taxes, is estimated to be $23.98 per barrel.

7.2.5 Gravity Drainage Operation

The estimated capital and annual operating costs of the Wheeler Ridge oil mine are shown in Table 7-5.

1. Capital Costs

Wheeler Ridge is a gravity drainage operation carried out from access drifts driven below the oil-bearing zone. As such, no ore is removed for processing; however, a treatment plant for oil/water, oil/gas and suspended solids separation is required at a cost of $1,000,000 for 6,660 barrels per day. Both the mine plant underground and the mine equipment capital costs represent major portions of the costs, 34.0 percent and 22.9 percent respectively of the initial capital cost, because the development of the headings, the drilling of drainage holes, and the oil collection system are the major part of the operation. In order to expose enough area of the oil-bearing zone for drilling, a considerable amount of advance development is required. This represents 2.6 percent of the initial capital cost.

The total initial capital requirement will be $11,720,000. Since the mine uses mobile equipment such

ESTIMATED TOTAL CAPITAL COSTS

	$(,000's)	TOTAL $(,000's)
Preproduction Capital		
Process Plant	1,000	
Mine Plant Surface	1,291	
Mine Plant Underground	3,980	
Mine Equipment	2,684	
Advance Development	302	
Exploration and Feasibility	2,463	
		11,720
Replacement Capital		7,401
Contingency (15%)		2,868
TOTAL CAPITAL COST		**21,989**

ESTIMATED ANNUAL OPERATING COSTS

	$(,000's)	
Mine Production		
Development	2,255	
Stoping	—	
Drilling / Drainage	3,009	
Rock Transport	436	
Ventilation	1,673	
Pumping (Water)	1,018	
Hoisting	2,482	
Backfilling	—	
Miscellaneous Mining	3,718	
		14,591
Processing		
Processing	1,300	
Product Handling	2,827	
		4,127
Waste Disposal and Environmental		
Waste Disposal and Reclamation	242	
Environmental	148	
		390
General and Administrative		714
Contingency (15%)		2,973
TOTAL ANNUAL OPERATING COST		**22,795**

SUMMARY - COST PER BARREL

	$
Capital Amortization Cost	0.48
Operating Cost	9.87
Allowance for Interest and Profit	0.51
TOTAL COST PER BARREL	**10.86**

as drills, LHD units, etc., with reasonably short operating lives, the replacement capital is moderately high at $7,401,000. A standard 15 percent contingency equivalent to $2,868,000 is added to the initial and replacement capital cost to give a total capital cost for the project of $21,989,000. This represents a capital cost of $0.48 per recoverable barrel of oil.

2. Estimated Annual Operating Costs

Mining Costs - The main operating costs will be those for development and for drilling the reservoir. The first of these elements represents 15.5 percent of the annual mining cost and is based on $170 per foot of development. The drilling costs are the largest item, 20.6 percent of the annual mining cost. Ventilation is quite critical in the Wheeler Ridge mine since the actual operations will be carried out below the oil-bearing zone and the oil will be flowing into the workings for collection. The ventilation costs account for 11.5 percent of the overall annual mining cost.

Miscellaneous mining costs includes the cost of supervision and maintenance of the ore collection system as well as costs for safety, communications, etc., and will be fairly sizeable. These costs have been estimated at 25.4 percent of the total annual mining cost. The total annual mining cost is therefore estimated to be $14,591,000 or $6.32 per barrel which represents 64.1 percent of the total annual operating cost.

Processing Costs - The costs of operating the oil separation plant are estimated to be $0.56 per barrel. Product handling costs for getting the oil from the mine to the separation plant are estimated at $1.22 per barrel.

Waste Disposal, Reclamation and Environmental Costs - The disposal and reclamation of the waste rock brought to surface from the underground development is estimated to cost $2.25 per ton, and environmental control will cost $0.06 per barrel.

General and Administrative Costs - A sum of $714,000 has been estimated for the general and administrative costs.

Total Annual Operating Cost - A 15 percent contingency equivalent to $2,973,000 has been added to the annual

operating cost to yield a total annual operating cost of $22,795,000 or $9.87 per barrel.

The total cost per barrel for the gravity drainage oil mining operation, excluding taxes, is estimated to be $10.86 per barrel.

7.2.6 Modified Terrace Pit Mining

The estimated capital and operating costs for the proposed Sunnyside open pit are presented in Table 7-6.

1. Capital Costs

The proposed Sunnyside modified terrace open pit oil mine is the most capital intensive of the fields presented in this report requiring a Total Capital Cost, including replacement and contingency, of $1,103,568,000. The processing plant at Sunnyside is the largest factor in the initial capital cost at $442,100,000 or 70 percent of the initial capital requirements. The estimated capital cost for the plant is calculated as $4,421 per ton of daily installed capacity. This cost per daily ton of installed capacity is relatively high (when comparing with the plant cost at Kern River) owing to the fact that the Sunnyside ore would require extensive crushing and grinding prior to treatment.

The estimated cost for prestripping of $25,200,000, or 4 percent of the initial capital requirement, is based upon removing 100,000,000 tons prior to startup of production. The $25,200,000 includes only the cost of labor and operating supplies to perform this function. The capital cost of the equipment is covered elsewhere. As no revenue would occur during the prestripping phase, this operating cost would have to be capitalized. This prestripping will expose enough ore to permit ongoing ore recovery while normal operational stripping proceeds. A reasonably large estimate of $51,000,000 or 8.1 percent of the capital has been made for exploration, feasibility and design. Such a fairly detailed drilling program will be necessary to delineate the orebody and fairly extensive design work would have to be done for both the process plant and the overland conveyor system.

The total initial capital cost for the Sunnyside operation is therefore $632,050,000. Since the modified terrace pit system using trucks and shovels has been selected, considerable replacement costs will be

Table 7-6

ESTIMATED TOTAL CAPITAL COSTS

	$(,000's)	TOTAL $(,000's)
Preproduction Capital		
Process Plant	442,100	
Mine Plant	24,466	
Mine Equipment	89,284	
Pre-Stripping	25,200	
Exploration and Feasibility	51,000	
		632,050
Replacement Capital		327,574
Contingency (15%)		143,944
TOTAL CAPITAL COST		1,103,568

ESTIMATED ANNUAL OPERATING COSTS

	$(,000's)	
Mine Production		
Overburden		
Drilling	2,166	
Blasting	1,444	
Loading	7,222	
Transport	48,390	
Miscellaneous	13,001	
Ore		
Drilling	1,416	
Blasting	944	
Loading	4,721	
Transport	37,755	
Miscellaneous	8,498	
Pumping	1,200	
		126,757
Processing		66,640
Waste Disposal and Environmental		
Waste Disposal and Reclamation	12,675	
Environmental	4,225	
		16,900
General and Administrative		4,785
Contingency (15%)		32,262
TOTAL ANNUAL OPERATING COST		247,344

SUMMARY - COST PER BARREL

	$
Capital Amortization Cost	2.45
Operating Cost	14.61
Allowance for Interest and Profit	3.73
TOTAL COST PER BARREL	20.79

encountered throughout the 28-year life of the operation. This replacement capital cost has been estimated as $327,574,000. A 15 percent contingency equivalent to $143,944,000 has been added to the initial and replacement capital cost to yield a total capital cost for the project of $1,103,568,000. This represents a total capital cost of $2.45 per recoverable barrel of oil in the Sunnyside deposit.

2. Estimated Annual Operating Costs

Mining Costs - The Sunnyside open pit will be mined with conventional mobile open pit equipment. The overburden and ore are hard and will require conventional drilling and blasting, 2.8 percent of the total annual mining cost. The major operating cost for the overburden is the haulage cost. The overburden must be hauled a considerable distance to the waste dump at an estimated cost of $0.575 per ton or 38.2 percent of the total annual mining operating cost.

The highest operating cost in the ore mining operation is, as with the overburden, the haulage cost. The ore is hauled to a crusher and then transferred by an overland conveyor to the process plant. This represents 29.8 percent of the overall mining cost or $1.144 per ton of ore.

A certain amount of water will collect in the open pit and will have to be pumped out. An allowance of $0.036 per ton of ore or 1 percent of the overall mining cost has been made for the pumping. The total annual mining cost is estimated to be $126,757,000 or $3.841 per ton of ore. This represents 51.3 percent of the overall total annual operating cost.

Processing Costs - The processing plant operating cost is estimated at $2.02 per ton of ore for a total processing plant annual operating cost of $66,640,000 or 27 percent of the total annual operating cost.

Waste Disposal, Reclamation and Environmental Costs - The overburden will be dumped outside the pit area and the process plant tailings material will be impounded in a tailings pond. Waste disposal and reclamation costs have been estimated at $12,675,000 or $0.108 per ton of total material removed from the pit. An annual cost of $4,225,000 or $0.036 per ton of total material has been allowed for environmental control throughout the operation. The waste disposal, reclamation and environmen-

tal costs account for 6.8 percent of the total annual operating cost.

General and Administrative Costs - A sum of $4,785,000 or $0.041 per ton of total material has been estimated for general and administrative costs at Sunnyside. This is 1.9 percent of the total annual operating cost.

Total Annual Operating Cost - A 15 percent contingency has been added to the annual operating costs giving a Total Annual Operating Cost of $247,344,000 or $2.111 per ton of total material or $14.61 per barrel.

The total cost per barrel for the Sunnyside operation, excluding taxes, is therefore estimated to be $20.79 per barrel.

7.2.7 Terrace Mining with Bucket Wheel Excavators

The estimated capital and annual operating costs of the Kern River oil mine are shown in Table 7-7.

1. Estimated Capital Costs

Even though the Kern River field is the largest operation presented in this report in terms of material moved, it is not the most capital-intensive. The initial capital required for this 130,000 tons of ore per day operation is approximately $28,000,000 less than for the 100,000 ton per day operation at Sunnyside. The primary reason for this difference is the cost of the process plant which is estimated at $2,023 per ton of daily installed capacity. This cost per ton of daily installed capacity is quite low compared with many of the other process plants presented. However, since the Kern River deposit is an oil and water, wet sand and gravel, it is considered to be a simpler material to process than the harder materials encountered in other fields. The process plant represents 43.5 percent of the total initial capital cost.

Because of the extremely large and extensive bucket-wheel excavator-conveyor-stacker installations, the capital requirements for the initial mine equipment are large compared to the other surface operations. They represent 35.3 percent of the total initial capital. In addition, fairly extensive workshops, warehousing facilities, etc., are necessary to maintain the

ESTIMATED TOTAL CAPITAL COSTS

	$(,000's)	TOTAL $(,000's)
Preproduction Capital		
Process Plant	263,000	
Mine Plant	26,000	
Mine Equipment	213,000	
Pre-Stripping	50,000	
Exploration and Feasibility	52,000	
		604,000
Replacement Capital		54,000
Contingency (15%)		98,700
TOTAL CAPITAL COST		756,700

ESTIMATED ANNUAL OPERATING COSTS

	$(,000's)	
Mine Production		
Overburden		
Drilling	—	
Blasting	—	
Loading	9,320	
Transport	17,260	
Miscellaneous	2,560	
Ore		
Drilling	—	
Blasting	—	
Loading	3,220	
Transport	9,010	
Miscellaneous	1,810	
Pumping	1,251	
		44,431
Processing		62,386
Waste Disposal and Environmental		
Waste Disposal and Reclamation	19,210	
Environmental	6,410	
		25,620
General and Administrative		9,783
Contingency (15%)		21,333
TOTAL ANNUAL OPERATING COST		163,553

SUMMARY - COST PER BARREL

	$
Capital Amortization Cost	1.61
Operating Cost	9.12
Allowance for Interest and Profit	3.36
TOTAL COST PER BARREL	14.09

equipment; hence, the mine plant capital cost is also reasonably high though it only represents 4.3 percent of the initial capital cost.

The $50,000,000 estimated capital cost for prestripping is based upon the preproduction removal of 200 million cubic yards to give an initial cut length of about 6,000 feet. The prestripping represents 8.3 percent of the total initial capital cost. Exploration feasibility and design of the Kern River operation has been estimated at $52,000,000 or 8.6 percent of the total initial capital cost. The aerial extent of the field is quite considerable, and the field has been very extensively drilled by the present producers. Considerable information should be available from the existing drillholes to assist in delineating the overall orebody and establishing an accurate grade; however, a fairly extensive drilling and sampling program will be required prior to the design stage.

The total initial capital cost is therefore $604,000,000, and owing to the mining method selected, the replacement capital requirement is reasonably low at $54,000,000. The bucket-wheel excavator-conveyor-stacker systems, even though expensive initially, have a very long operating life and do not require total replacement throughout the life of the proposed Kern River operation. A standard 15 percent contingency equivalent to $98,700,000 has been added to the initial and replacement capital cost to yield a total capital cost for the project of $756,700,000. This represents a total capital cost of $1.61 per recoverable barrel of oil in the Kern River field.

2. Estimated Annual Operating Costs

Mining Costs - The Kern River oil field material was examined and found to be suitable for bucket-wheel excavators. Consequently, no drilling and blasting will be required in overburden or ore. The loading of overburden by the bucket wheels is estimated to be 21 percent of the total annual mining cost and represents a cost of $0.052 per ton of overburden. The transportation of the overburden by the terrace conveyors initially to external waste dumps, and once full production has started, to the in-pit dump is estimated to be 38.8 percent of the annual mining cost or $0.094 per ton of overburden. Miscellaneous costs for overburden mining such as preparation of roads, moving of

equipment, etc., represent 5.8 percent or $0.014 per ton of overburden.

The loading of ore by the bucket-wheels represents 7.2 percent of the total annual mining cost or $0.069 per ton of ore. The transportation of the ore by conveyor to the process plant is 20.3 percent of the total annual mining cost or $0.192 per ton of ore. Miscellaneous ore mining costs as described above amount to 4.1 percent of the total annual mining cost or $0.0385 per ton of ore.

It would appear that a considerable amount of groundwater will be encountered and will need to be pumped out of the pit. The operating cost for pumping is estimated to be 2.8 percent of the total annual mining cost or $0.027 per ton of ore. The total annual mining cost is therefore estimated to be $44,431,000 or $0.945 per ton of ore, which represents 27.2 percent of the total annual operating cost.

Processing Costs - The processing plant operating cost is estimated at $1.33 per ton of ore for a total processing plant annual operating cost of $62,386,000 or 38.1 percent of the total annual operating cost.

Waste Disposal, Reclamation and Environmental Costs - The overburden material will be dumped back into the disused part of the pit and the clean sand and gravel discharge from the process plant will be placed on top. An annual cost of $19,210,000 has been allowed for waste disposal and reclamation. This represents $0.084 per ton of total material removed from the pit. An annual cost of $6,410,000 or $0.028 per ton of total material has been included for environmental control throughout the operation. The waste disposal, reclamation and environmental costs are 15.7 percent of the total annual operating cost.

General and Administrative Costs - General and administrative costs have been estimated to be $9,783,000 or $0.043 per ton of total material or 6.0 percent of the total annual operating cost.

Total Annual Operating Cost - A 15 percent contingency has been added to the annual operating costs to yield a total annual operating cost of $163,553,000 or $0.717 per ton of total material, or $9.12 per barrel.

The total cost per barrel for the Kern River operation, excluding taxes, is estimated to be $14.09 per barrel.

7.2.8 Strip Mining

The estimated capital and annual operating costs of the Santa Cruz oil mine are shown in Table 7-8.

1. Estimated Capital Costs

The Santa Cruz operation is very small compared to the other surface potentials presented in this report. As with all the other surface mining potentials, the process plant is the largest item of initial capital investment. The Santa Cruz plant represents 60.5 percent of the total initial capital. The plant cost has been based upon a cost of $5,000 per ton of daily installed capacity. The mine equipment is the second largest item, 17.2 percent at Santa Cruz. The mine plant, workshops, etc., represent 8.6 percent of the total capital which is quite a lot higher than the other surface mines and is due to the fact that Santa Cruz is a very small operation, but still requires the basic facilities for good maintenance and support. Very little prestripping is required, approximately 750,000 tons, which represents 0.5 percent of the total initial capital cost. Exploration, feasibility and design account for 13.2 percent of the initial capital cost, considerably greater than for the other surface mines. This is, however, a function of the small size and total capital investment for the project. The total initial capital investment is therefore $34,779,000.

Because of the short life and the small size of the operation, the required replacement capital is very small at $1,800,000 or 4.3 percent of the total capital cost. A standard 15 percent contingency equivalent to $5,487,000 has been added to the initial and replacement capital cost to give a total capital cost for the project of $42,006,000. This represents a total capital cost of $4.88 per recoverable barrel of oil in the Santa Cruz field.

2. Estimated Annual Operating Costs

Mining Costs - The Santa Cruz field was found to be an ideal candidate for dragline stripping. The overburden material, though, will have to be drilled and blasted before the dragline can cast the material. The drill-

ESTIMATED TOTAL CAPITAL COSTS

Preproduction Capital	$(,000's)	TOTAL $(,000's)
Process Plant	21,000	
Mine Plant	3,000	
Mine Equipment	6,000	
Pre-Stripping	179	
Exploration and Feasibility	4,600	
		34,779
Replacement Capital		1,800
Contingency (15%)		5,487
TOTAL CAPITAL COST		42,066

ESTIMATED ANNUAL OPERATING COSTS

Mine Production	$(,000's)	
Overburden		
Drilling	200	
Blasting	100	
Loading	624	
Transport	—	
Miscellaneous	176	
Ore		
Drilling	91	
Blasting	54	
Loading	90	
Transport	341	
Miscellaneous	127	
Pumping	36	
		1,839
Processing		2,556
Waste Disposal and Environmental		
Waste Disposal and Reclamation	761	
Environmental	251	
		1,012
General and Administrative		600
Contingency (15%)		901
TOTAL ANNUAL OPERATING COST		6,908

SUMMARY - COST PER BARREL

	$
Capital Amortization Cost	4.88
Operating Cost	9.46
Allowance for Interest and Profit	4.76
TOTAL COST PER BARREL	19.10

ing and blasting cost for the overburden is $0.063 per ton of overburden and represent 10.9 percent and 5.4 percent of the total annual mining cost respectively. The dragline loading and casting is estimated at $0.130 per ton of overburden and is 33.9 percent of the total annual mining cost. No transport costs are associated with the overburden due to the direct casting of the dragline.

The ore at Santa Cruz must be drilled and blasted and these costs have been estimated as $0.102 per ton of ore. These costs are 8.0 percent of the overall annual mining cost. Truck haulage of the ore to the process plant has been determined to be $0.240 per ton of ore or 18.5 percent of the total annual mining cost. Some water will collect in the pit area and will need to be removed. An allowance of $0.025 per ton of ore or 1.9 percent of the total annual mining cost has been made for pumping. The total annual mining cost at Santa Cruz is therefore estimated to be $1,839,000 or $1.295 per ton of ore or 26.6 percent of the total annual operating cost.

Processing Costs - The operating cost of the processing plant at Santa Cruz has been estimated at $1.80 per ton, giving an annual processing cost of $2,556,000 or 37.1 percent of the total annual operating cost.

Waste Disposal, Reclamation and Environmental Costs - Reclamation of the spoil piles and maintenance of a tailings impoundment have been estimated at $0.122 per ton of total material. Environmental control operating costs have been calculated to be $0.040 per ton of total material. The reclamation, waste disposal and environmental costs represent 14.6 percent of the total annual operating cost at Santa Cruz.

General and Administrative Costs - A sum of $600,000 or $0.096 per ton of total material has been estimated for the general and administrative costs at Santa Cruz. This is 8.7 percent of the total annual operating cost.

Total Annual Operating Cost - A 15 percent contingency, $901,000, has been added to annual operating costs to give a total annual operating cost of $6,908,000 or $1.109 per ton of total material, or $9.46 per barrel.

The total cost per barrel for the Santa Cruz operation, excluding taxes, is therefore estimated to be $19.10 per barrel.

7.2.9 Open Pit Mining

The estimated capital and annual operating costs of the Edna oil mine are presented in Table 7-9.

1. Estimated Capital Costs

Edna is an open pit with a 1:1 stripping ratio mining 34 million tons of total material per year. As with all the surface mines presented in this report, the largest item of initial capital cost is the processing plant. The Edna processing plant represents 70.9 percent of the initial capital requirement and is based on a value of $5,000 per ton of daily installed capacity. This value is slightly higher than the cost per daily ton for Sunnyside and is the same as for Santa Cruz. Sunnyside's lower unit cost is, in the main, due to the economies of scale.

The geometry of the orebody and the overall stripping ratio permit a fairly limited prestrip of approximately five million tons which represents only 0.8 percent of the initial capital cost. Considerable definition of the Edna orebody is required and extensive design work would be necessary for the processing plant; consequently, 12.2 percent of the initial capital is for exploration, feasibility and design.

The total initial capital cost estimate for Edna is $352,694,000. Due to the short life of the pit, 12 years, which is less than the useful life of the mine equipment, the replacement capital cost is very moderate at $15,300,000. A standard 15 percent contingency cost equivalent to $55,199,000 is added to the initial capital cost and replacement capital cost to give a total capital cost for the Edna project of $423,193,000. This represents a total capital cost of $4.72 per recoverable barrel of oil in the Edna field.

2. Estimated Annual Operating Costs

Mining Costs - The deposit will be mined by conventional open pit techniques. Truck haulage of the overburden will cost $0.277 per ton and is 23.1 percent of the total mining cost, the highest overburden associated cost.

Table 7-9

ESTIMATED TOTAL CAPITAL COSTS

	$(,000's)	TOTAL $(,000's)
Preproduction Capital		
Process Plant	250,000	
Mine Plant	10,000	
Mine Equipment	47,000	
Pre-Stripping	2,694	
Exploration and Feasibility	43,000	
		352,694
Replacement Capital		15,300
Contingency (15%)		55,199
TOTAL CAPITAL COST		423,193

ESTIMATED ANNUAL OPERATING COSTS

	$(,000's)	
Mine Production		
Overburden		
Drilling	637	
Blasting	630	
Loading	672	
Transport	4,712	
Miscellaneous	1,272	
Ore		
Drilling	1,104	
Blasting	982	
Loading	1,355	
Transport	5,924	
Miscellaneous	1,863	
Pumping	1,221	
		20,372
Processing		34,000
Waste Disposal and Environmental		
Waste Disposal and Reclamation	2,635	
Environmental	845	
		3,480
General and Administrative		2,000
Contingency (15%)		8,978
TOTAL ANNUAL OPERATING COST		68,830

SUMMARY - COST PER BARREL

	$
Capital Amortization Cost	4.72
Operating Cost	7.25
Allowance for Interest and Profit	3.71
TOTAL COST PER BARREL	15.68

Since the hardness of the Edna ore is very variable, the drilling and blasting costs per ton are much higher than the overburden drilling and blasting costs and represent 10.2 percent of the overall annual mining cost. Truck haulage of the ore to the process plant will cost $0.349 per ton or 29.2 percent of the total mining cost. Miscellaneous costs attributable to ore mining will be $0.110 per ton of ore or 9.1 percent of the total mining cost. A reasonably large amount of water could collect in the Edna pit and an allowance of $0.072 per ton of ore has been made for pumping, which represents 6.1 percent of the overall mining costs. The total annual mining cost is estimated to be $20,372,000 or $1.198 per ton of ore. This represents 29.6 percent of the overall total annual operating cost.

Processing Costs - The processing plant operating cost is estimated to be $2.00 per ton of ore for a total processing plant annual operating cost of $34 million or 49.4 percent of the total annual operating cost.

Waste Disposal, Reclamation and Environmental Costs - Reclamation of the waste dumps and maintenance of the tailings pond are estimated to cost $0.078 per ton of total material. Environmental control costs are based on a cost of $0.025 per ton of total material. The waste disposal, reclamation and environmental costs represent 5.1 percent of the total annual operating cost.

General and Administrative Costs - A sum of $2 million or $0.059 per ton of total material has been estimated for the general and administrative costs and represents 2.9 percent of the total annual operating cost.

Total Annual Operating Cost - A 15 percent contingency, $8,978,000, has been added to the annual operating costs to yield a total annual operating cost of $68,830,000 or $2.024 per ton of total material, or $7.25 per barrel.

The total cost per barrel for the Edna operation, excluding taxes, is estimated to be $15.68 per recoverable barrel.

7.3 COST OF CONVENTIONAL OIL PRODUCTION

The costs of producing oil by conventional methods vary widely and are dependent upon many factors. Lifting costs, the

cost of lifting the crude oil from the reservoir rock to the surface, are much lower in flowing wells than in pumping wells. Also, the rate of production is generally much higher in flowing wells than in pumping wells. For instance, if a well is capable of flowing 100 barrels per day or 3,000 barrels per month at a cost of $500.00 per month, lifting cost would be about $.17 per barrel. If, on the other hand, a well was pumped from about the same depth, the cost might run $900.00 per month and if the production rate was three barrels a day or 90 barrels per month, lifting cost would be $10.00 per barrel.

Lifting cost does not include amortization of the well cost or depreciation of the equipment. Lifting cost is only that cost involved in lifting the oil from the reservoir to the stock tank where it is stored for sale to the pipeline company. The economic limit is reached when the lifting cost exceeds the revenue realized from the sale of production. A stripper well is defined as a well capable of producing less than 10 barrels of oil per day. Wells producing large quantities of water with the oil production and wells at great depths frequently cannot produce 10 barrels of oil a day economically. In any event, production costs as shown on Table 7-10 do not include capital costs or amortization of capital necessary to establish oil production.

The Joint Association Survey (Ref. 1) has published the total expenditures by the oil industry on exploration, development and production of U.S. oil. The API Basic Petroleum Data Handbook (Ref. 2) shows the new reserves proved during this period and the barrels of oil produced. It is therefore possible to estimate the cost of exploration, development and production per barrel. It is virtually impossible to separate out the cost for crude oil and natural gas; consequently, gas is shown as equivalent barrels on the basis that ten MCF of gas are equivalent to one barrel of crude oil. Since the cost of production is much greater for oil than for gas, it has also been assumed that approximately 80 percent of the production cost was for oil. The results of these calculations are shown in Table 7-10 and Figure 7-1.

It is apparent that the cost of finding new oil reserves is increasing at an extremely rapid rate and is the main reason for pushing the total finding and producing cost up. The production cost has also increased but not at the same pace. This leads to the following conclusions:

- The oil industry is not finding and developing new reserves sufficiently rapidly to replace annual production. The short fall was about 2.3 billion equivalent barrels in 1971 increasing to about 2.6 billion equivalent barrels in 1975.

TABLE 7-10

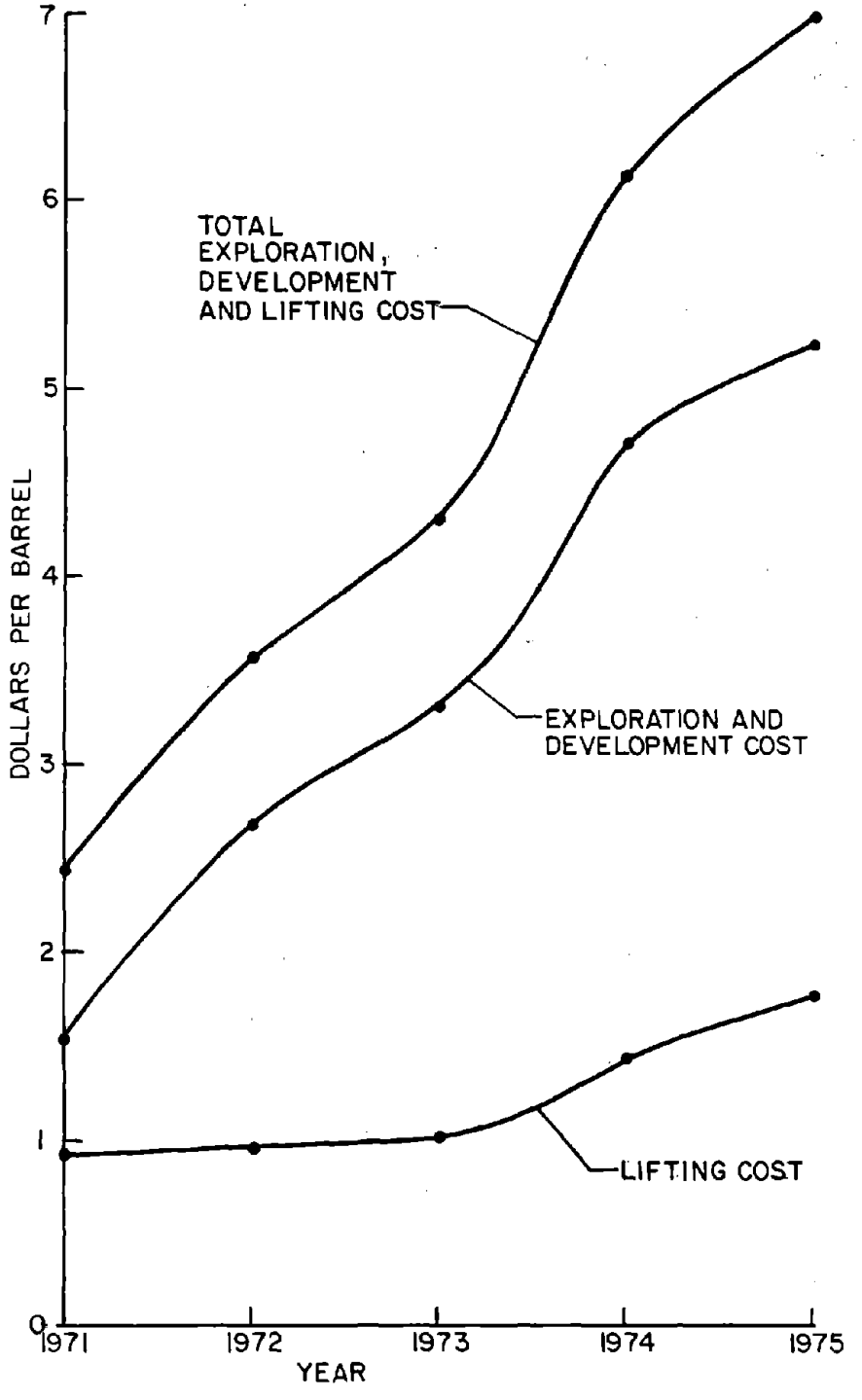
EXPLORATION, DEVELOPMENT AND LIFTING COSTS (1971-1975) - CONVENTIONAL PRODUCTION

ITEM	UNITS	1971	1972	1973	1974	1975
Annual Exploration Cost	$ (Millions)	2,393	3,672	5,865	8,901	5,779
Annual Development Cost	$ (Millions)	2,671	3,093	3,255	4,476	6,983
Total Annual Exploration and Development Cost	$ (Millions)	5,064	6,765	9,120	13,377	12,762
New Reserves - Crude Oil	Bbl (Millions)	2,318	1,558	2,146	1,994	1,318
New Reserves - Natural Gas	Eq.Bbl (Millions)	1,014	979	647	850	1,019
Total New Reserves	Eq.Bbl (Millions)	3,332	2,537	2,793	2,844	2,337
Exploration and Development Cost per Equivalent Barrel	$/Bbl	$1.52	2.67	3.27	4.70	5.46
Annual Production Cost	$ (Millions)	3,851	3,912	4,235	5,685	6,683
Production - Oil	Bbl (Millions)	3,454	3,455	3,361	3,203	3,052
Production - Natural Gas	Eq.Bbl (Millions)	2,208	2,251	2,261	2,132	1,972
Total Production	Eq.Bbl (Millions)	5,662	5,706	5,622	5,335	5,024
Lifting Cost per Equivalent Barrel	$/Bbl	0.69	0.69	0.75	1.07	1.33
Lifting Cost for Oil Assume 80% Total Cost	$ (Millions)	3,081	3,130	3,388	4,548	5,346
Lifting Cost per Barrel of Oil	$/Bbl	0.89	0.91	1.01	1.42	1.75
Exploration, Development and Lifting Cost per Barrel of Oil	$/Bbl	2.41	3.58	4.28	6.12	6.95

Golder Associates

EXPLORATION, DEVELOPMENT AND LIFTING COSTS.
CONVENTIONAL PRODUCTION TECHNIQUES

Figure 7-1



- The rate at which new reserves are found and developed is declining.

- The cost for exploration, development and production is increasing rapidly.

- The total expense for exploration and development increased rapidly until 1974 and leveled out in 1975. This means that capital for exploration and development is not becoming available.

- In contrast to the above, gas prices for intra-state gas started to increase dramatically in 1972 and 1973. This resulted in increased exploration and increased discovery of gas reserves.

The National Petroleum Council has carried out a number of studies on potential future production of crude oil within the United States from known fields and has evaluated in detail the potential for enhanced recovery. Figure 7-2 shows the general decline of primary production, secondary production and production from existing enhanced oil recovery projects gradually declining from a current level of approximately 7.35 million barrels per day to approximately one-half million barrels per day by the year 2000. Superimposed upon this is additional production which could be achieved by various enhanced oil recovery techniques based upon a selling price of both $15 per barrel and $25 per barrel. As can be seen from this figure, assuming the addition of no new fields, the incremental production from enhanced oil recovery techniques is needed immediately to maintain a reasonable supply of oil for the United States.

The conclusion of the National Petroleum Council study (Ref. 3) was that the potential for enhanced recovery involves complex relationships among technology, economics and government policy, but valid generalizations are difficult. The National Petroleum Council draws three interrelated conclusions from the study. These are:

- The enhanced recovery processes, if technically successful and broadly applied, could have a significant impact on oil production from known U.S. reservoirs during the years 1985 to 2000.

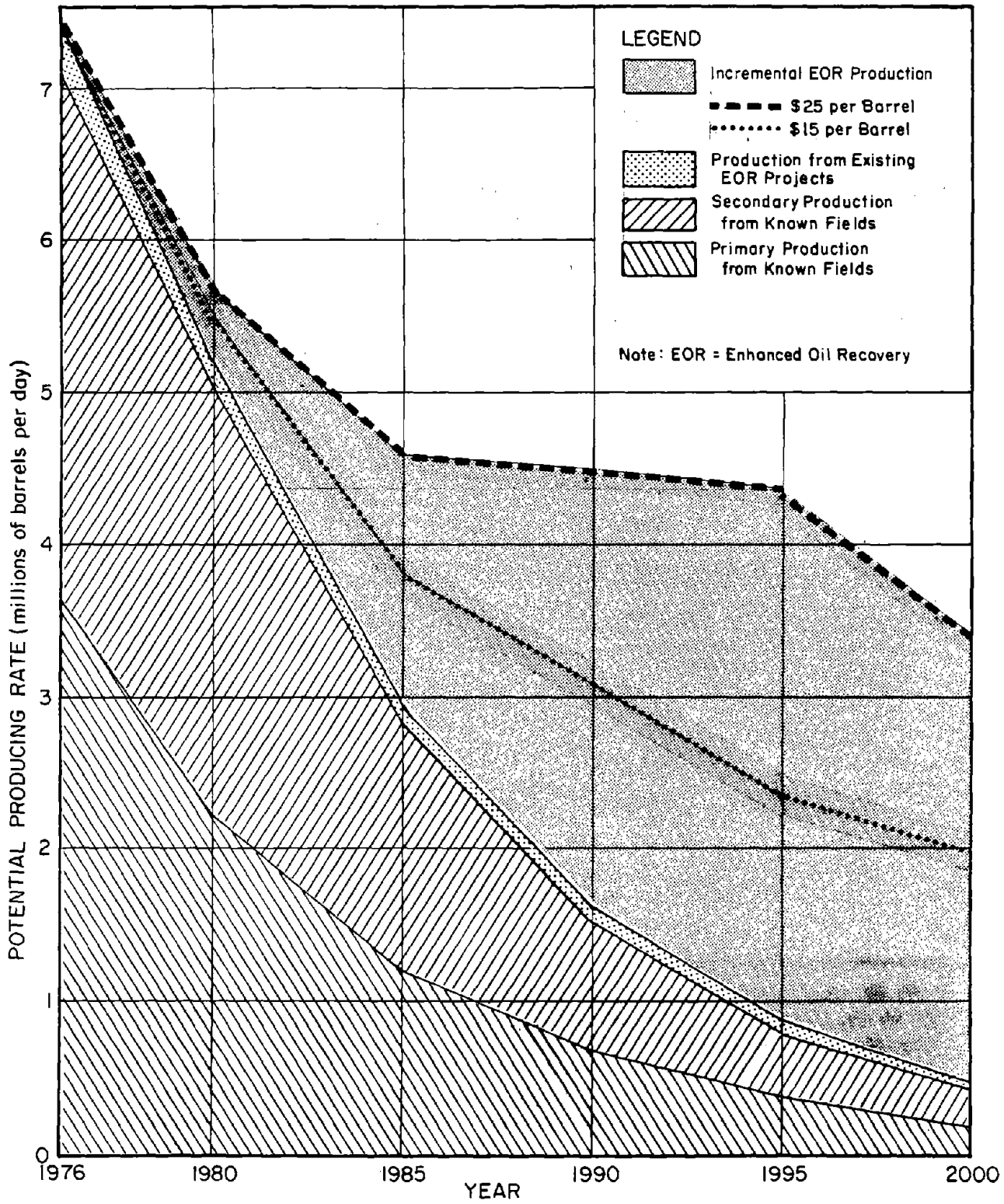
- The potential of enhanced recovery processes is uncertain at this time.

- Incremental alternate recovery and the potential producing rate for enhanced recovery are highly dependent on oil price and other economic factors.

In the body of the API study it becomes apparent that enhanced oil recovery costs would be on the order of $20 to $25 per barrel if reasonable volumes of oil are to be recovered.

POTENTIAL U.S. CRUDE OIL PRODUCTION RATE
FROM KNOWN FIELDS

Figure 7-2



FROM: "Enhanced Oil Recovery – An Analysis Of The Potential For Enhanced Oil Recovery From Known Fields In The United States – 1976 to 2000" By The National Petroleum Council, December 1976.

The results of this study into oil mining's economic potential have therefore to be viewed against a conflicting and uncertain economic background. On the one hand, domestic demand for petroleum products currently exceeds domestic production by a substantial margin, and will continue to do so for the foreseeable future. If national policy permits this imbalance to be reflected in free market behavior, there is little doubt that incremental oil costing $25 per barrel, as discussed above, could be profitably produced. Such a situation would make several of the oil mining options described here appear attractive investments. On the other hand, a continuance of the present pricing compromise between domestic costs and those of imported crude would defer the prospects of many, but not all, oil mining schemes for one or more decades. It hardly needs saying that a reversion to pre-1973 price levels would even more conclusively defer the development of a major oil mining industry, although it would perhaps increase its eventual inevitability.

To enable readers of this report to form their own judgements of the implications of the oil mining costs presented here, several of the key current and possible oil prices have been marked on Figure 7-3 for ease of comparison. They are:

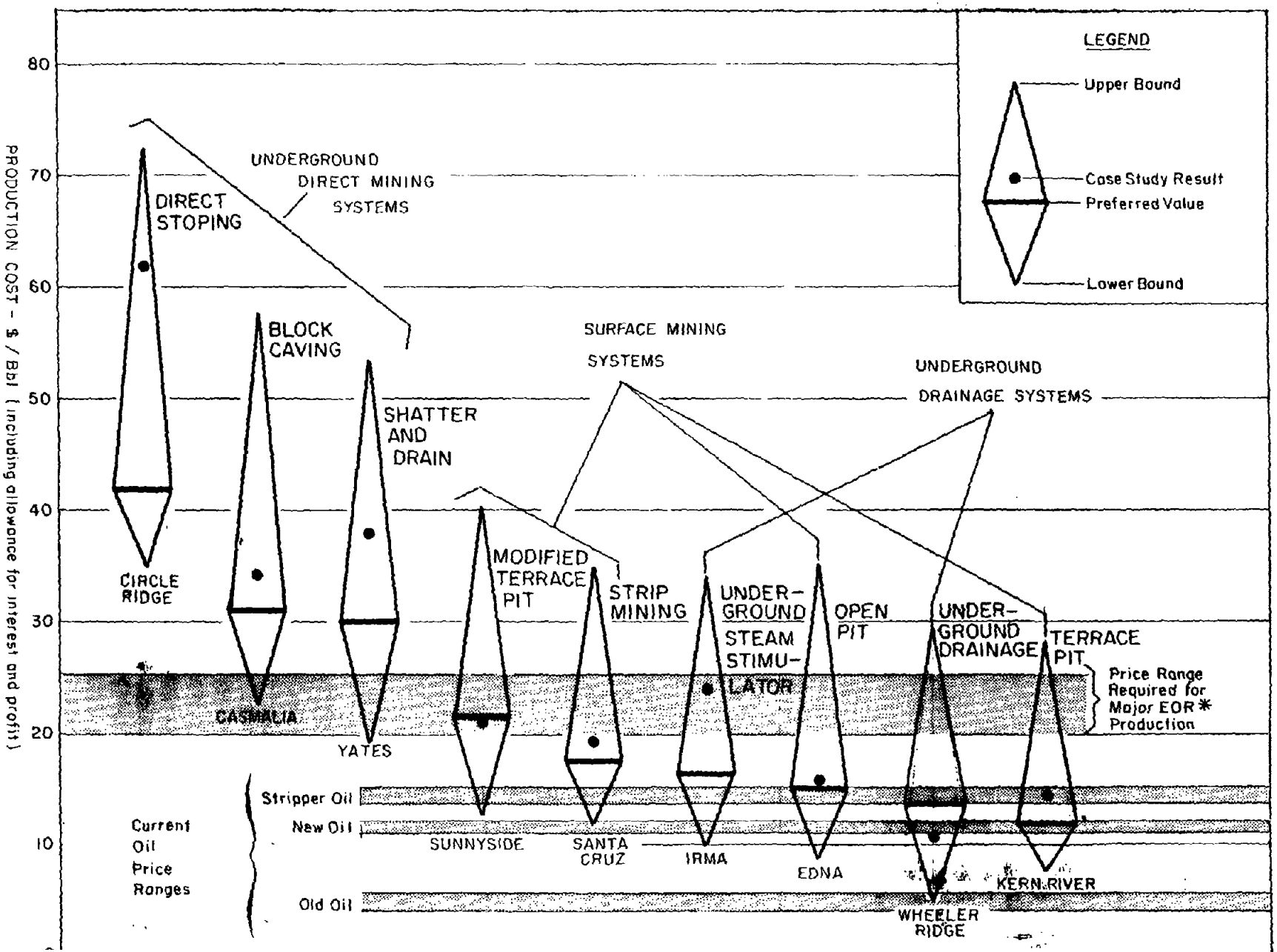
Stripper Oil - $13.75 to $14.85
New Oil - $11.00 to $12.00
Old Oil - $4.00 to $5.50

7.4 DISCUSSION OF ECONOMIC FEASIBILITY

The results of the economic side of this study are summarized on Figure 7-3. For each method considered, this chart shows the estimated range of possible production costs, the actual value determined from the specific case studied, and the single value considered most likely to be attained in a favorable situation. The methods are ranked in order of increasing cost attractiveness. In order to provide a frame of reference, the conventional production costs discussed in the preceding section are also marked on the chart.

Three methods stand out as offering little hope of viability under any reasonably foreseeable price situation. They are the three methods which involve an element of direct mining of the reservoir rock and have the following major economic disadvantages:

- High capital cost associated with very large mines and processing plants.
- High operating costs compared to surface mines.
- Major problems and cost areas associated with ventilation and water handling.


PRODUCTION COST - $ / Bbl (including allowance for interest and profit)
80
70
60
50
40
30
20
10
LEGEND
Upper Bound
Case Study Result
Preferred Value
Lower Bound
UNDERGROUND DIRECT MINING SYSTEMS
DIRECT STOPING
BLOCK CAVING
SHATTER AND DRAIN
SURFACE MINING SYSTEMS
UNDERGROUND DRAINAGE SYSTEMS
MODIFIED TERRACE PIT
STRIP MINING
UNDER-GROUND STEAM STIMU-LATOR
OPEN PIT
UNDER-GROUND DRAINAGE
TERRACE PIT
CIRCLE RIDGE
CASMALIA
YATES
SUNNYSIDE
SANTA CRUZ
IRMA
EDNA
WHEELER RIDGE
KERN RIVER
Price Range Required for Major EOR * Production
Current Oil Price Ranges
Stripper Oil
New Oil
Old Oil

- extreme difficulty in ensuring safe working conditions particularly with regard to risks from explosive and/or toxic gases;

- substantial costs associated with waste disposal and environmental problems.

The worst of the three is the direct stoping operation.

One of the main reasons for these high costs is the low grade of rock which is expected to be suitable for such an operation. As can be seen from Figure 7-4, this method, in common with all the others, is extremely sensitive to reserve grade, particularly in the lower range. It is considered very unlikely indeed, however, that any deposit will be found to combine the needed favorable qualities of rock competence for safe stoping conditions with a high enough grade to produce attractive cost levels.

The Casmalia block caving method appears, as one would expect, somewhat better than the stoping method, but still appears very likely to become of economic interest.

The shatter and drain prospect shares all of the problems of the pure direct mining operations, including their sensitivity to ore grade and the efficiency of the drainage system, and the need for basically competent rock.

In summary, therefore, one conclusion of this study is that none of the underground direct mining systems demonstrates the potential of becoming economically feasible. This aptly parallels the conclusion reported earlier that each of them had serious problems of technical feasibility, notably in the safety area.

All of the six other methods considered, however, show some potential for economic success, even at current price levels, and could become even more attractive if the price of oil approaches or exceeds $20/bbl. Four of these are surface mining options and two are underground drainage methods.

The four surface mining options all suffer from high initial capital cost, particularly on the process plants, and from substantial problems in waste disposal and mitigation of environmental impacts. They all overcome this to a greater or lesser degree, however, due to the inherent economy of the large-scale earthmoving techniques employed.

The most expensive of these is the modified terrace open pit designed for Sunnyside, which is the only one in competent enough rock to require drilling and blasting of all the material, and

which has extremely long haul distances for both ore and waste. In spite of these handicaps, however, it would not require too large an increase in the real price of oil for such a mine to become attractive.

The methods used at Santa Cruz and Edna, strip mining and open pit mining respectively, both give results that border on the attractive. Edna has the best grade of the fields studied and a favorable stripping ratio, whereas Santa Cruz is penalized by its small size, giving a reduced operating life and consequent high amortization cost per barrel.

The Kern River terrace pit operation, employing bucket-wheel excavators, is the best of the surface operations from an economic standpoint, and appears to be viable now if the product is classified as "stripper" oil, and very nearly so if rated as "new" oil. It should be noted that one thing very clear from Figure 7-3 is that any designation of mined oil as "old" would make such developments a very remote possibility. Kern River is an immense deposit which warrants exploitation on a very large scale, thus giving low unit costs for both mining and processing.

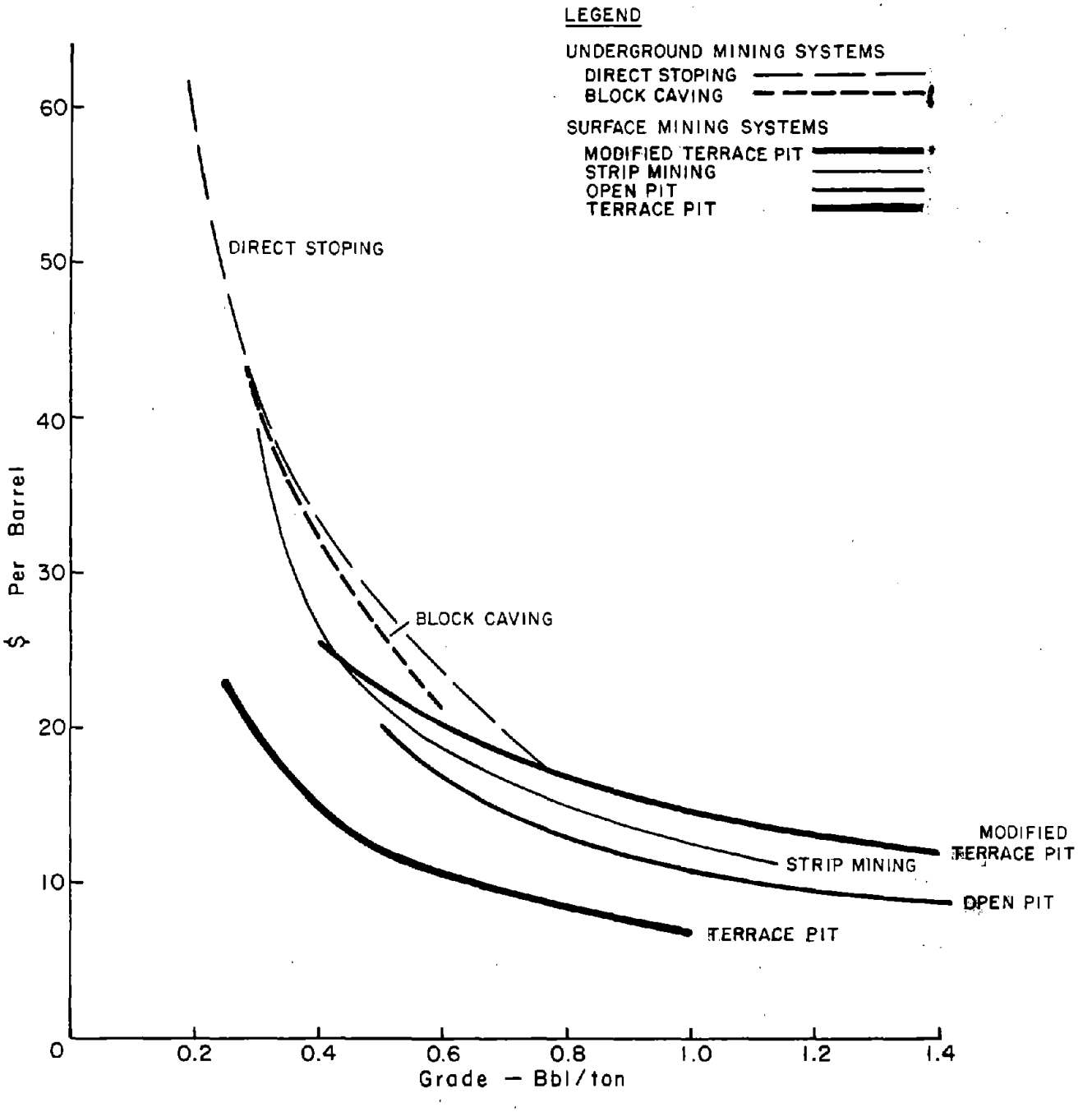
All of the methods studied are very sensitive to low ore grade, as can be seen from Figures 7-4 and 7-5, and this is the main factor which produces the range of possible costs displayed on Figure 7-3. Other major factors include stripping ratios and rock hardness for the open pit mines and processing costs for all direct mining systems.

The two underground systems, which rely purely on drainage as the production system, are also in the competitive range of cost. The steam stimulation system used for the Irma field promises costs in the $16/bbl range even in a thin deposit, and could be substantially more economical in a thicker deposit, as shown on Figure 7-5.

The evaluation of gravity drainage at the Wheeler Ridge field was made on very optimistic assumptions--that 50 percent of the contained oil would be recovered by pure drainage to the drillholes, with no expense incurred for stimulation, steam, etc. If this situation is indeed true, this system would be very attractive economically, in fact the best of all the systems studied. It is far more realistic, however, to expect that recoveries would be lower, or that stimulation would be required, and these possibilities are recognized in the curves on Figure 7-5 and in the preferred cost value shown on Figure 7-3. Even a thoroughly pessimistic view of the results to be expected, however, still produces costs which could be of substantial interest.

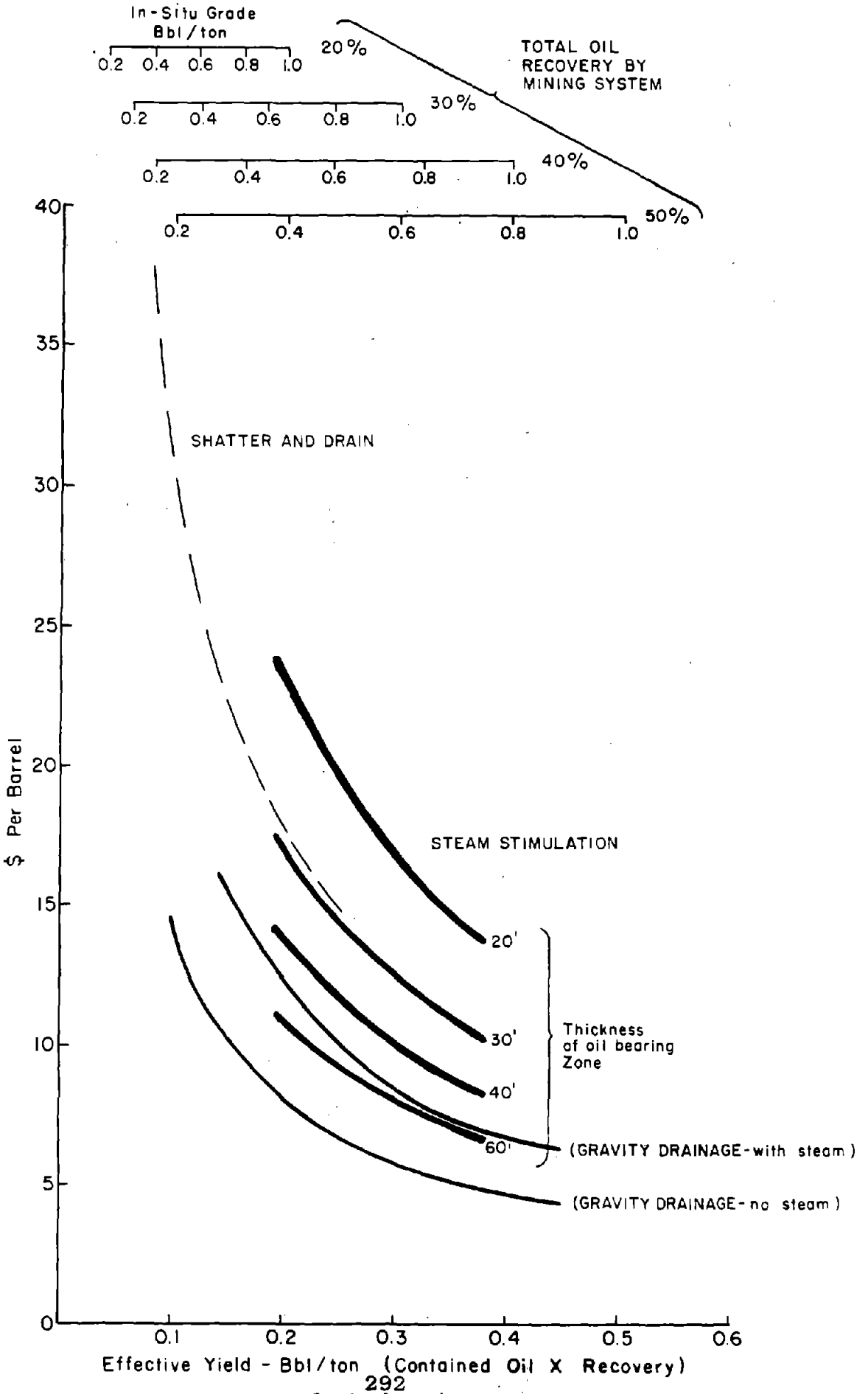
SENSITIVITY OF DIRECT MINING METHODS
TO GRADE OF ORE (Bbl/Ton)

Figure 7-4



SENSITIVITY OF UNDERGROUND DRAINAGE METHODS
TO GRADE (Bbl/Ton) AND YIELD

Figure 7-5



The general conclusions resulting from these economic results, together with some suggested specific courses of action, are presented in the next chapter.

CHAPTER 7
REFERENCES

1. American Petroleum Institute. Joint Association Survey of the U.S. Oil and Gas Producing Industry, 1971-1975. Washington, D.C.: American Petroleum Institute, 1977.

2. American Petroleum Institute. Basic Petroleum Data Handbook. Washington, D.C., American Petroleum Institute, 1977.

3. National Petroleum Council. Enhanced Oil Recovery. Washington, D.C., U.S. Department of the Interior, December 1976.

8.0 DISCUSSION OF RESULTS

8.1 GENERAL CONCLUSIONS

In 1932, George S. Rice stated his conclusions on the future of recovery of oil by underground methods in USBM Bulletin 351 (Ref. 1) and these conclusions have changed little in the intervening 46 years. They are, in fact, still so relevent as to form a useful basis for discussion of the underground prospects considered in this report. Mr. Rice stated in his conclusions that:

> "1. Where conditions are favorable, mining methods in depleted oil fields may bring large financial returns and recover oil that might otherwise be lost."

There is still no doubt that such mining operations appear to represent the only technically viable way of recovering vast quantities of known petroleum reserves, and the significance of this in broad national and strategic terms has grown immensely in recent years. The potential for "large financial returns" from underground operations is, however, less well established. Major inadequacies in data and in the level of proof of some elements of production technology limit the degree of confidence that this study can express. There is no doubt, however, that this study has strongly reaffirmed the very real potential that, even at current price levels, oil production by underground drainage is promising enough to deserve pursuit.

Mr. Rice proceeded to define "favorable conditions" as follows:

> "2. Favorable conditions mean:
> a) That there is remaining, in at least one oil sand, sufficient oil, of which at least 5,500 barrels may be recovered per acre, by drainage or by repressuring systems.
> b) That there is a tight, firm shale stratum more than 20 feet thick within 30 feet of the oil sand.
> c) That the price of crude oil at the top of the shaft is at least $2.25 per barrel.

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3. That under favorable natural conditions the mining method for depleted area gives cheaper production of oil at depths down 1,500 feet than wells for repressuring or flooding, and the advantage in favor of mining appears to increase rapidly with depth to perhaps 3,000 feet.

4. That at 4,000 feet depth the limit of practical or commercial mining is being approached, due to high temperature for mine workers, and the cost entailed by increasing ground pressure."

The fundamental soundness of these conclusions is unchanged although this study has not revealed the existence at this time of a reliable basis for establishing specific critical depths or other dimensions. The need to establish the presence of a high concentration of recoverable oil has, however, remained unchanged. Inflation has raised the 1932 required price to some $15 per barrel.

Mr. Rice's next conclusion was:

"5. There are also limitations in the pressures that can be safely used in repressuring and flooding from mine passages because of the possible leakage through fissures or permeable places in the shale or rocks in which or below which the mine entries are made, or by breaking down the roof or upheaving the floor, or bursting pipes or fittings."

The safety limitations on reservoir pressurization have been aptly demonstrated by the problems encountered in the Russian Yarega project where the steam pressures had to be reduced to avoid blowouts.

Mr. Rice further stated:

"6. That mining methods should not be used as a primary method of oil extraction from an oil field; the inflammable and sometimes toxic vapors and gases at high pressure would make it too dangerous for mine workers. The gas and oil pressure would have to be relieved by prior drilled and operated wells and must be kept under low pressure limits in repressuring and flooding."

Passage of time and improving technology have done nothing to weaken the conclusiveness of this statement. It is clear from the economic results of this study that only a superbly

efficient direct underground mining operation would have a chance of profitability and this would require extreme mechanization and concentration of operations. At present in the geological environments considered favorable for major mining operations, the available fragmentation and ore handling technologies simply do not provide adequate security against explosion and toxic gas risks. Even if individual deposits can be identified which offer the possibility of satisfactory operation using direct underground mining methods, it seems most unlikely that the total suitable resource will be extensive enough to warrant the major expenditures required to develop and demonstrate the technology.

A major factor here is the well established relationship between rock strength and grade. The very qualities of rock competence which could lead to efficient stoping-type operations preclude high oil contents in all but the most exceptional cases. Perhaps the only underground mining method which can escape this rationale is block caving.

Mr. Rice's next conclusion was:

> "7. That under favorable strata conditions, to be tested by core drilling, driving mine passages in tight impervious shale should present no greater problems than driving entries in a gassy coal mine; in fact, less so than in a bituminous mine, as the dust would not be explosive in air as it is in a bituminous-coal mine."

This recommendation is still extremely valid and forms the basis for the confidence expressed in this report that underground drainage operation can be safely undertaken with reasonable safety.

The conclusions related to underground mining can therefore be summarized as follows:

- Underground operations involving direct mining cannot be contemplated at this time with adequate confidence in their safety or economic feasibility. There is no obvious way of improving this situation markedly by any readily identifiable research or test project.

- Underground operations involving drainage of oil offer important attractions. Such projects would have the favorable features of low capital requirements and minimum environmental impact. Considerable further study is needed, however, to establish with confidence the potential yields to be expected from such

operations, and specific recommendations for this work are made later in this chapter.

Bulletin 351 specifically addressed underground operations, but it is a strong conclusion from the present study that surface mining offers comparable or better economics and greatly superior demonstrable technical feasibility, at least in the mining elements and should therefore by pursued with at least as much rigor as the underground prospects.

The main areas where additional work is required to further this possibility are in the fields of determination of mineable reserves and the design of oil separation plants. Even with the currently available technology, however, there is no reason why a deposit like Kern River could not now be subjected to full commercial preliminary feasibility study.

No major mining operation can be undertaken without producing substantial and varied effects on the environment. The methods studied here are no exception to this rule, although the underground drainage methods are substantially less of a problem than the others. The impacts of the surface plants, both mine and processing, and the socioeconomic aspects are, however, all within the range of normal major industrial environmental technology. Disposal of the large quantities of mined waste material can be more of a problem and there may be no reasonable way of making the surface subsidence and hydrological impacts of methods such as block caving acceptable.

8.2 RECOMMENDATIONS FOR FURTHER STUDIES

During the course of this study, many areas have been identified where additional effort is necessary before mining of oil can become an industry of major importance to the national economy. These areas are discussed in this section and some specific recommendations made as to how the problems should be approached.

8.2.1 Factors Relevant to All Types of Operation

1. Inventory of Mineable Oil Resources

The conclusions of this study are generally optimistic about the potential of several types of oil mining systems and a number of types of hydrocarbon deposits have been identified as deserving further attention. The ability of both public and private sectors to pursue these prospects is, however, limited and it is essential to ensure that these efforts are as efficiently focused as is possible.

A major step in this direction would be a thorough inventory of the resources within the United States which appear to be amenable to recovery by mining. Such a study would indicate whether the potential production is of national importance and thus deserving of support from public funds, or whether it is relatively minor and should take its place in the array of candidates for normal commercial exploitation.

The suggested categories for such a study are:

- Heavy oils, tar sands, etc. This group would consist of shallow deposits, suitable for surface mining, where conventional production has not been significantly attempted due to problems of viscosity.

- Oils bound in diatomites, etc. This category would consist of oil reserves which have probably never been considered for production and possibly never explored at all, due to unfavorable bonding in the host rock. They also would be shallow fields suited to surface mining.

- Depleted shallow fields. This group includes field at shallow, surface mineable depths where exploitation by conventional well techniques is either complete to economic limits or can be advantageously replaced by mining.

- Depleted deeper fields. These prospects would lie at depths below the economic range of surface mining and would have been depleted to some extent, and certainly depressurized, by conventional well production techniques. They would have characteristics making improved productive potential by drainage from underground access points a strong possibility, and would have competent impermeable formations either over or underlying them suitable for mine development.

2. Improved Technology for the Evaluation and Documentation of Unrecovered Oil Remaining in Place

The petroleum industry has the technology available to obtain good estimates of the quantity of oil that can be produced conventionally from a reservoir unit. These estimates are usually most accurate for three-phase systems (gas-oil-water) where there is a reasonable production history for the field or individual pool

within the field. Estimates of the oil remaining in place after depletion are, however, of a lower order of confidence. This knowledge is based on the limited number of widely spaced core holes where oil content has been measured, augmented by porosity measurements, by geophysical techniques and flow permeability studies. In very uniform reservoir rocks, where there are no radical small scale variations of the porosity, permeability, grain size, etc., these estimates may well be reasonable.

As a basis for design and evaluation of a mining operation, however, very few oil deposits as currently delineated and sampled would be able to demonstrate ore tonnages and grades to satisfy conventional mining standards. It seems possible that, even in the densely drilled Kern River field, the highest ore reserve classification that could be expected would be "indicated", and the typical field would more probably be in the lowest reserve category, "inferred."

Two main factors contribute to this problem:

- Lack of direct validation of total residual oil content estimates.

- Lack of experience of residual oil distribution patterns within a reservoir.

Methods of study anticipated include the drilling of a series of closely spaced holes within a "depleted" oil field. These holes would be cored in part using large diameter equipment, to develop good estimates of the oil saturation remaining in the reservoir and the physical nature of the oil contained in the pores. Drilling of a grid of reasonably closely spaced holes, possibly augmented by whipstocked deflections, would allow a detailed non-petroleum engineering approach to resource evaluation. Geostatistical studies could also be performed on these data to evaluate the distribution characteristics of the reserves. The results obtained would be compared with estimates generated from pre-existing data using the best available reservoir evaluation techniques.

3. Rock Property Determination

In normal oil field production technology there is only occasional need for determination of the types of

rock property which may be absolutely critical to the design and evaluation of a potential mine. Such determinations are a basic part of the normal exploration program for a mine, particularly where underground operations are contemplated.

Reasonable estimates of rock strength are required, coupled of course with a good understanding of the distribution of the various lithologic units. Perhaps more important, however, is a reasonable understanding of internal rock structure. Major structures such as faults are obviously very significant, but equally so, particularly for underground mines, is a knowledge of the lesser structures such as joints and bedding planes which play a fundamental role in defining the fabric of a rock mass and determining its strength.

Such a study should critically assess the value of existing oil field data for this purpose and include the drilling of additional holes, cored to high geotechnical standards.

4. Byproduct Considerations

Although not a basic ingredient in the evaluation of oil mining, it is possible that important byproducts could be recovered from some such operations. As an example, uranium is known to occur associated with some asphalt deposits and oil fields, and the potential for byproduct production uranium from oil mining operations should be investigated. Examples of areas with such potential include fields in California, parts of Texas, and the Joplin tristate area.

8.2.2 Factors Relevant to Potential Surface Operations

In order to bring the mining of oil deposits by surface methods closer to commercial realization, it is recommended that two substantial studies be undertaken.

1. Study of the Kern River Deposit

In the majority of the fields reviewed, the sequence of events required to bring an operation into production would stretch over many years. A substantial portion of this time would elapse before an evaluation could be made even to normal commercial prefeasibility standards. This time would be spent on preliminary reconnaissance/target identification activities and,

almost certainly, on exploration drilling to raise ore reserve estimation to mining standards.

The Kern River field, however, appears to offer a unique opportunity to begin the process further along the chain, with a immediate preliminary feasibility study. This is largely due to the density of drilling in the field and its long production history.

A preliminary mining/processing feasibility study should therefore be made of the Kern River oil deposit. The objective of this proposed project would be to produce an evaluation, to normal feasibility study standards, of surface mining and processing the oil-bearing sands of the Kern River oil field. The general approach recommended would include:

- The geometry and grade of the field would be defined and delineated based on a full and detailed examination of existing data.
- A mine would be designed capable of producing sufficient ore to a feed process plant to supply 50,000 bbls/day of petroleum stock.
- Mining equipment would be selected and the capital and operating costs of mining estimated.
- An oil extraction process would be chosen that appears to offer the most economic advantage. Equipment and plant would be selected, and capital and operating costs estimated.
- All additional cost elements would be estimated in specific detail. This would include environmental considerations including disposal of all wastes, water quality impacts, etc; infrastructure and associated socioeconomic studies; and land ownership/unitization costs.
- A financial evaluation would be made aimed at determining the overall cost of production and a price level for refinery stock required to realize a reasonable return rate. This evaluation should be based on a specific corporate financial model and should include debt structuring, tax analysis etc.

No significant additional field work is expected to be required as a basis for this study.

2. Studies of Oil Processing Plant Technology

Processing plants represent a major portion of the cost of the surface mining options, and a large proportion of the technical uncertainty. There is therefore a need for a study that would have as its objective the generation of conceptual design and costs of construction and operation for oil processing plants, capable of handling the following types of oil-bearing rock: oil sands, tar sands, and oil impregnated diatomaceous earth.

This study would rely heavily upon technology already developed for the Canadian tar sands but would incorporate the modifications necessary to enable oil to be recovered from the above general types of oil deposits. The overall objective of the study would be to develop conceptual flow sheets and material balances for the several important major types of oil-bearing deposits and to estimate the costs of these plants.

8.2.3 Factors Relevant to Potential Underground Operations

1. Drainage Production Studies

Development of the methodology for making a more accurate estimate of the quantity of oil recoverable in an underground drainage operation, and the rate of its recovery, is essential as a prelude to specific feasibility studies. Progress toward such a situation will include further study of the following topics.

- A review of existing reservoir data. In particular, data from partially and fully depleted reservoirs should be reviewed to understand of transient changes in reservoir properties resulting from oil production. Important parameters include: temperature, pressure, viscosity, gas/oil ratios, fluid saturations, permeability, porosity, production history, effects of secondary and tertiary recovery techniques, and their spatial variations within a potential reservoir.

- The effects of an underground excavation on reservoir properties. The properties listed above should be re-examined with respect to the physical environment resulting from an oil mine. This environment may be substantially different from those encountered in conventional petroleum

engineering practice, and existing petroleum engineering methodology may therefore require significant modifications. Potential problems associated with adverse water or gas saturations or pressures should also be considered.

- A study of recovery mechanisms including:
  - straight gravity drainage
  - gravity drainage with viscosity and/or permeability enhancement

  An understanding of the flow physics of the possible various proposed recovery techniques is essential for yield determinations. This will almost certainly necessitate the development of new or improved analytical and modeling techniques for reservoir analysis.

- Acquisition of additional reservoir data. This could involve both laboratory and field testing. For example, drainage tests on core, increased monitoring of areal drawdowns in producing oil fields, and pump tests using closely spaced observation wells or piezometers would produce important data for yield determination.

2. Hydrological Studies

Relatively detailed hydrologic data are needed for reliable mine inflow and environmental impact considerations. In most oil fields current hydrologic data on overlying and underlying formations is poor or nonexistent and additional testing is probably needed. Important hydrologic properties of the overlying and underlying strata include: permeability, pressure, specific storage, definition of aquifer zones, areal extent of aquifers, and current water use practices.

CHAPTER 8
REFERENCES

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APPENDIX A

GRAVITY DRAINAGE METHODOLOGY AND ANALYSIS

An estimate of the average oil production rate from a pattern of vertical boreholes drilled from a mine zone into an overlying oil-bearing zone was needed in order to evaluate the Wheeler Ridge mining scenario. The method used to obtain the production rate estimate is outlined below.

MECHANISM

Oil recovery by gravity drainage into a borehole at atmospheric pressure is not normally encountered in petroleum engineering practice. The usual methods of estimating oil production by solution gas drive, gas expansion drive, water drive and gravity separation drive are not directly applicable to gravity drainage into boreholes. The mechanism of drainage is very similar to that encountered in water seepage and drainage problems. The oil must drain downward and into the borehole due to the force of gravity, being replaced by air or gas as it drains. Pressure at the air-oil boundary will be atmospheric, comparable to water table conditions in situations involving groundwater flow. It is assumed that all confining pressure on the oil has been relieved prior to mining.

The estimate of oil production rate was made using the basic equation for radial steady state flow to a well, treating the oil as the flowing phase. A series of steady state solutions was used in order to incorporate the transient effects resulting from the lowering of the air-oil boundary. No-flow boundaries occur at the midpoint between boreholes which define the radius of influence of the boreholes.

METHOD OF ANALYSIS

The steady state radial flow equation is:

$$Q_o = \frac{2\pi \; Mavg \; \rho_o g k_o (h_e - h_w)}{\mu_o \; \ln(r_e / r_w)} \qquad (1)$$

where:

Q_o = flow rate of oil

Mavg = average thickness of oil saturated reservoir

ρ_o = density of oil

g = gravitational constant

pages 308 thru 310 are blank.

k_o = effective permeability to oil

μ_o = viscosity of oil

r_e = radius of influence of borehole

r_w = radius of borehole

h_e = head (expressed in feet of oil) at radius of influence

h_w = head at borehole

A simpler form of equation is:

$$Q_o = \frac{2\pi \text{ Mavg } K_o(h_e - h_w)}{1n(^r e/r_w)} \quad (2)$$

where K_o is the hydraulic conductivity to oil defined by:

$$K_o = \frac{\rho_o g k_o}{\mu_o} \quad (3)$$

A further simplification of equation (2) is possible by recognizing that for the situation being considered

$$h_e = 2h_w \quad (4)$$

and

$$\text{Mavg} = \frac{h_e + h_w}{2} \quad (5)$$

Equation (2) can then be written in terms of h_w as:

$$Q_o = \frac{2\pi K_o (h_w)^2}{1n(^r e/r_w)} \quad (6)$$

Since the air-oil boundary is constantly lowering as oil drains, the flow rate, Q_o, will decrease with time. To account for this effect, flow rates are calculated for incremental decreases in h_w, as indicated in Figure A-1. The volume of reservoir drained as the head at the borehole decreases from h_{w1} to h_{w2} is indicated by the hatched area. The average flow rate at which this incremental volume is drained is:

$$Q_{avg} = \frac{Q_1 + Q_2}{2} \quad (7)$$

The volume of reservoir drained for each incremental lowering of the head at the borehole is equal to the volume found by revolving the hatched area in Figure A-1 about the axis of the borehole. Analytically, the volume is equal to:

$$\text{Vol.} = 2\pi \int_{r_w}^{r_e} r \left[h_1(r) - h_2(r) \right] dr \qquad (8)$$

where:

r = radial distance from center of borehole

$h_1(r)$ = head as a function of radius for flow rate Q_1

$h_2(r)$ = head as a function of radius for flow rate Q_2

The functions $h_1(r)$ and $h_2(r)$ are defined by:

$$h_1(r) = h_{e1} - \frac{Q_1}{2\pi M_1 K_o} \ln(r_e/r) \qquad (9)$$

$$h_w(r) = h_{e2} - \frac{Q_2}{2\pi M_2 K_o} \ln(r_e/r) \qquad (10)$$

M_1 and M_2 represent the average thickness of flow for the oil level at positions 1 and 2. Substituting equations (4), (5), (9), and (10) into equation (8) and performing the integration yields:

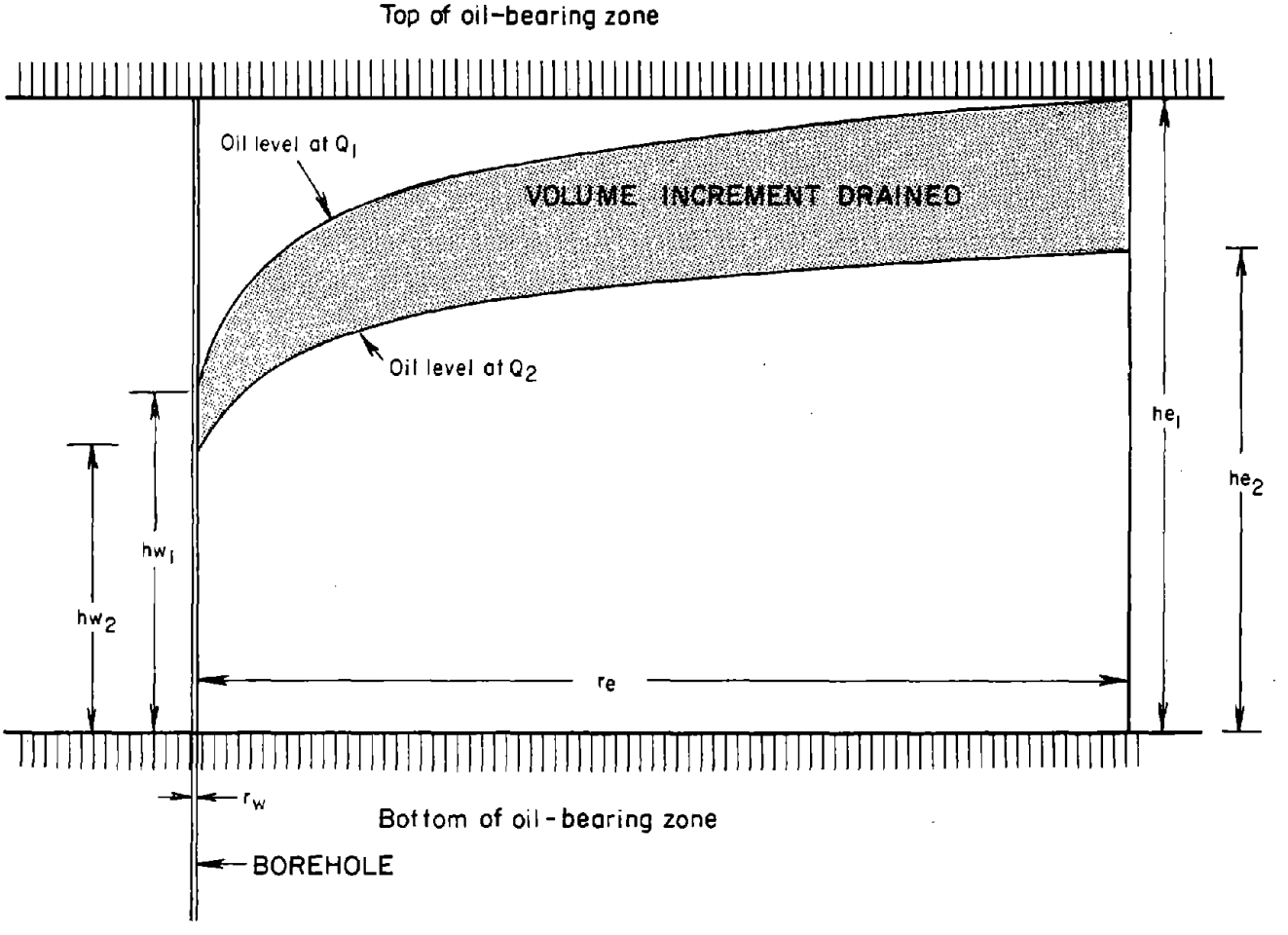
$$\text{Vol.} = 2\pi(h_{w1} - h_{w2})(r_e^2 - r_w^2) + \frac{1}{3K_o} \left(\frac{h_{w1}Q_2 - h_{w2}Q_1}{h_{w1}h_{w2}} \right) \left[\frac{r_e^2 + r_w^2}{2} \left(\frac{1}{2} + \ln r_w - \ln r_e \right) \right] \qquad (11)$$

which, by neglecting r_w, can be simplified to:

$$\text{Vol.} \approx 2\pi r_e^2 (h_{w1} - h_{w2}) + \frac{r_e^2}{6K_o} \left(\frac{h_{w1} Q_2 - h_{w2} Q_1}{h_{w1} h_{w2}} \right) \qquad (12)$$

EFFECT ON FLOW RATE, Q, DUE TO DECREASES IN HEAD AT THE BOREHOLE, hw

Figure A-1



The volume between the initial oil level and the oil level for flow rate Q_1 can be found in a similar manner by integrating:

$$\text{Vol.} = 2\int_{r_w}^{r_e} r\,(h_e - h_1(r))\,dr \qquad (13)$$

to give:

$$\text{Vol.} \quad \frac{Q_1 r_e^{\,2}}{2H_{w1}K_o} \qquad (14)$$

after neglecting insignificant terms.

The variation of production rate with time can be found by decreasing the head at the borehole, h_w, in increments and finding the average flow rate, Q_{avg}, and volume drained for each increment.

RESULTS

The parameters necessary to calculate flow rates from equation (6) include the hydraulic conductivity, head at the borehole, radius at the borehole, and radius of influence. The mining scenario at Wheeler Ridge sets the geometry and defines the following parameters:

h_w = 85 feet initially, which is half the thickness of the oil-bearing zone

r_w = 0.17 feet (4-inch diameter)

r_e = 25 feet, assuming the boreholes are spaced at 50-foot centers

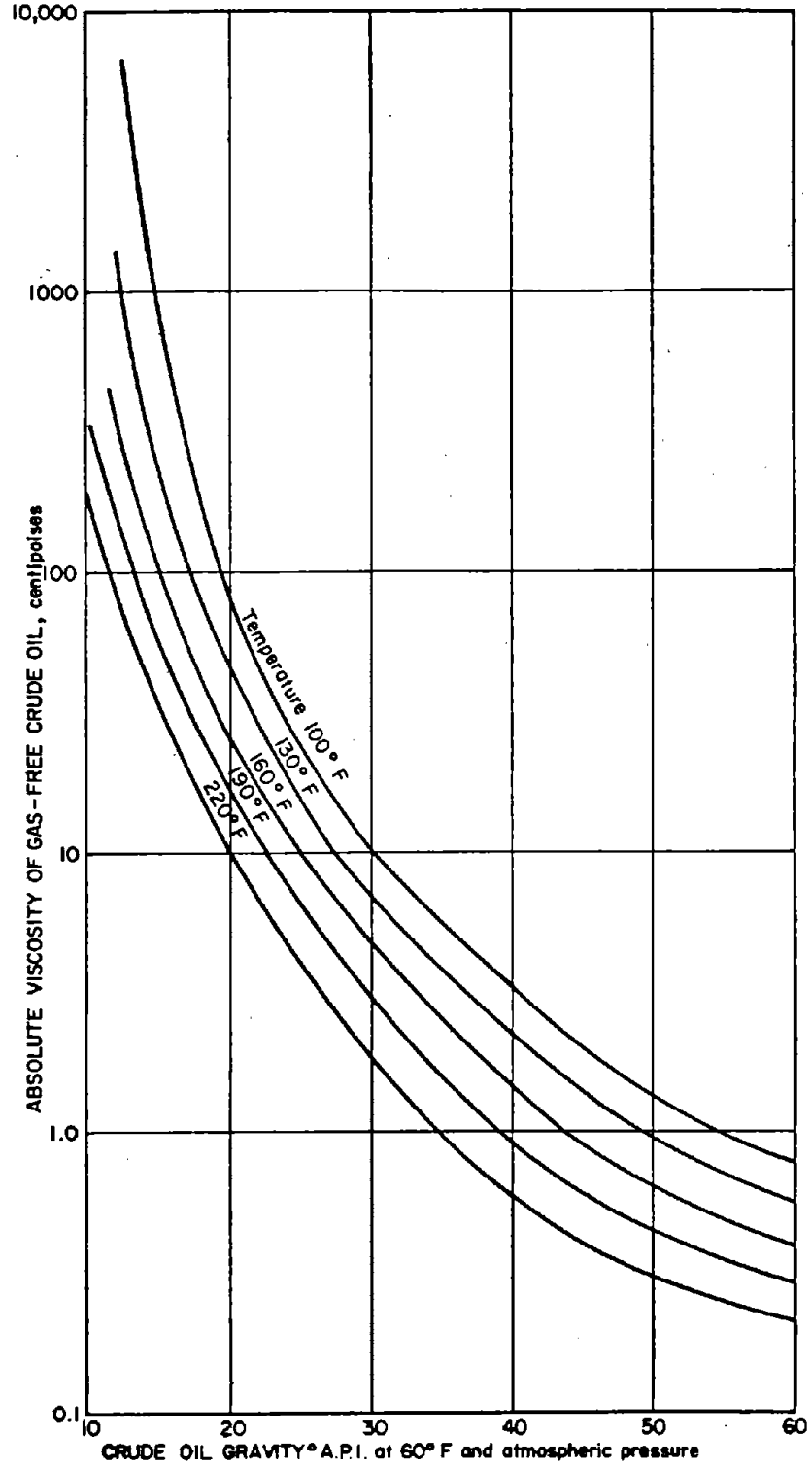
The hydraulic conductivity used in equation (3) is computed based on an assumed effective permeability and a measured API gravity. An effective permeability to oil of 10^{-11} cm^2 (100 millidarcies) at an existing water saturation of approximately 30 percent (also an assumed value) is used as an assumed value. The density and viscosity of the oil are estimated from the measured API gravity, 22.3°, and equation (15) and Figure A-2 respectively.

$$\text{API Gravity} = \frac{141.5}{\text{Spec. Grav. @60°F}} - 131.5 \qquad (15)$$

Assuming a reservoir temperature of approximately 60°F, the numerical values are ρ_o = 0.92 g/cm^3 and μ_o = 100 centipoise. Gravity, g, is 980 dyne/g. The above parameters give a hydraulic conductivity to oil of 2.56×10^{-3} feet/day.

RELATIONSHIP BETWEEN GRAVITY AND
ABSOLUTE VISCOSITY FOR VARYING TEMPERATURES

Figure A-2



The variation of the calculated oil production rates with time shown in Figure A-3 for total recoveries of 50 percent, 30 percent and 10 percent of the remaining oil content (882 barrels per acre/foot).

OIL PRODUCTION VS. TIME FOR
VARYING RECOVERIES

Figure A-3

