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**OIL SHALE MINING COST ANALYSIS
VOLUME 1—SURFACE RETORTING PROCESS**

Final Report

MASTER

By
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January 1981

Work Performed Under Contract No. AM01-77ET12532

Ketron, Incorporated
Wayne, Pennsylvania

U. S. DEPARTMENT OF ENERGY

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by

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PREPARED FOR

U. S. Department of Energy
Carbondale Mining Technology Center

Under Contract No. U. S. DOE ET-77-C-01-8915(13)

January 1981

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FOREWORD

This report summarizes the work by KETRON, INC. on U. S. Department of Energy Contract No. ET-77-C-01-8915 (Task Order 13). It is part of a sequence of reports describing the development of a mining economic model for evaluating the production and cost consequences of oil shale development. The reports are entitled:

Oil Shale Mining Cost Analysis

1. Volume I - Surface Retorting Process
2. Volume II - Vertical Modified In Situ Process
3. Volume III - Oil Shale Mining Economic Model (OSMEM) Users Guide

Volume I is concerned primarily with underground mining of oil shale for surface retorting. Volume II describes the application of the economic model to the Vertical Modified In Situ (VMIS) retort process. And Volume III provides computer documentation.

The project was administered by the Department of Energy under the direction of Mr. Tim Zeigler, assisted by Mr. Charles Hayduk. Dr. William J. Douglas, KETRON, provided much valued management support. Kathleen Knoebel served as computer program development manager and provided assistance in directing computer program modifications. Several secretaries participated in the word processing effort, namely Robin Morby, Mary Dumont and Donna Dellaquila.

The project team would like to acknowledge the following companies who provided information pertinent to the study.

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EXECUTIVE SUMMARY

Objective

The objective of the study was to adapt presently developed economic mine models to enable the estimation of mining costs for underground mining methods to be used in conjunction with the surface retorting of oil shale.

Scope

The study included:

1. A review of resource data to establish sites representative of commercial development;
2. A review of underground mining methods to determine feasible mining techniques;
3. Development of mine designs applicable to the candidate mine sites; and
4. Simulation and financial analysis to determine underground mining costs.

The primary area of investigation concerned the costs associated with underground mining methods used in conjunction with surface retorting. Towards this end, an Oil Shale Mining Economic Model (OSMEM) was developed and executed for mining scenarios representative of commercially feasible mining operations.

Candidate Sites for Mining Scenarios

Using maps and other resource data, the essential charac-

teristics of the Piceance Creek Basin were defined and sites were selected that were representative of a range of factors affecting commercial feasibility. Factors considered most significant to economic feasibility included:

1. Grade
2. Thickness
3. Depth
4. Structure
5. Gases
6. Water
7. Non-uniformity of material properties.

Based on the above criteria, two sites from the Piceance Creek Basin were chosen. The proposed scenario sites are located across the southern portion of the basin.

Mining Methods

Potentially feasible mining systems were evaluated for the candidate mine sites. The criteria used in selecting the mining methods included: the capability of the mining method to produce the required tonnage; the state of technical development of the mining method; and potential safety and environmental impacts.

Based on the criteria, mining operations such as room-and-pillar, caving, and stoping, or natural derivatives thereof, were evaluated. The mining methods selected included:

1. room-and-pillar
2. chamber-and-pillar, with backfilling
3. sublevel stoping
4. sublevel stoping, with backfilling

Detailed mine designs were developed for each mining system. Mines were designed to extract nominally an average of 80,000 tons of oil shale per day, at full production. This tonnage corresponds to an average oil production of 47,600 bbls per day, for an average shale grade of 25 gallons per ton.

Oil Shale Mining Economic Model

An Oil Shale Mining Economic Model was developed. The model consists of a sequence of computer sub-programs which provide production and financial data necessary for evaluating the consequences of specific mine designs and production strategies.

The objectives of the model were:

1. To project annual production resulting from user-specified mine designs, production strategies, and equipment parameters;
2. To compute standard financial measure for evaluating alternative strategies;
3. To provide flexibility in analyzing a wide variety of mining scenarios; and
4. To permit sensitivity analysis of technical and financial parameters.

Economic Analysis

Costs developed for each mining scenario included all capital and operating expenses associated with the underground mining of oil shale for surface retorting processes. Each capital and operating expense was determined from individual cost elements which included:

1. Surface Preparation
2. Surface Facilities

3. Surface Utilities
4. Development Costs
5. Equipment Costs
6. Labor Costs
7. Underground Utilities
8. Operating Supplies
9. Insurance
10. Contingencies
11. Indirect Costs

An analysis of each mining scenario was performed to calculate the initial required selling price per ton. This measure represents the price required to recover all mining costs, at a specified rate of return on investment. The total required selling price of a barrel of shale oil will reflect, in addition to mining costs, the costs associated with surface processing, environmental considerations, and other cost-generating items. The initial required selling price reflects only that component of price which is necessary to recover mining costs.

Base case results indicated:

1. The maximum variation in selling price between scenarios is 62 percent (\$3.48 versus \$5.62).
2. At Site 1, the selling price for chamber-and-pillar with backfill is 49 percent greater than for room-and-pillar (\$5.20 versus \$3.48).
3. At Site 2, the selling price for sublevel stoping with backfill is 16 percent greater than for sublevel stoping without backfill (\$5.62 versus \$4.84).

Candidate factors for explaining the results included:

1. Capital expense differences.
2. Operating cost differences

3. Early production history differences
4. Steady-state production level differences

An analysis of the effects of these candidate factors suggested that capital expense difference was the primary reason for observed differences in initial required selling price among the four base case scenarios.

Parametric and sensitivity analyses also were performed. Mining costs were generated for return on investment values of 15 percent and 30 percent, in addition to the base value of 25 percent. These results indicate that at 15 percent ROI, reduction from base case values in required selling price ranged from 26 percent to 35 percent. At 30 percent, ROI increases from base case values ranged from 18 percent to 23 percent.

The sensitivity of mining cost to changes in capital costs, operating costs, return on investment, and annual escalation rates was determined. For each base case scenario, these parameters were varied one at a time, by selected percent changes relative to their base case values. These results indicate that the initial required selling price is most sensitive to the return on investment parameter.* The initial required

* Most sensitive means that the initial required selling price changes by the largest percentage for this parameter, when each parameter is changed, one at a time, by a given percent.

selling price is also sensitive to changes in capital and operating costs, but those sensitivities are less pronounced than that due to changes in return on investment. Note that this result is not inconsistent with the above analysis of differences among base case scenario results; return on investment was not varied for those cases.

1.0 INTRODUCTION

1.1 Background

The current strong interest in oil shale development reflects concern over the nation's ability to develop adequate domestic sources of liquid fuels. This concern is indicative of international conditions which suggest the need to develop capabilities for producing synthetic fuels from domestic resources. The commercial development of the extensive oil shale deposits in the Green River Formation represents one alternative.

One method suggested to hasten near-term commercialization of shale oil resources includes surface processing of mined oil shale. The deep mining of oil shale deposits, however, poses some interesting technical questions concerning the most efficient means of recovering the large amount of rock required as feedstock to the processing plant. The technical problems do not appear intractable; recent preliminary technical evaluations indicate the feasibility of large scale underground mining activity (1-3).^{*} But, in order to evaluate the effectiveness of proposed oil shale ventures so that resources can be allocated to the more promising methods, consistent economic evaluations also are required.

This report documents work by KETRON, INC. on U.S. Department of Energy Contract No. ET-77-C-01-8915 (Task Order 13) to adapt mining economic models to the estimation of mining costs

^{*} Numbers refer to references in Section 8.0.

for underground oil shale mining. The analytical model developed by KETRON, INC. represents an approach for determining the underground mining costs incurred in providing a feedstock for the surface retorting processes.

1.2 Objective

The objective of the study was to adapt presently developed economic mine models to enable the estimation of mining costs for underground mining methods to be used in conjunction with the surface retorting of oil shale.

1.3 Scope

The study included:

1. A review of resource data to establish sites representative of commercial development;
2. A review of underground mining methods to determine feasible mining techniques;
3. Development of mine designs applicable to the candidate mine sites; and
4. Simulation and financial analysis to determine underground mining costs.

The primary area of investigation concerned the costs associated with underground mining methods used in conjunction with surface retorting. Towards this end, an Oil Shale Mining Economic Model (OSMEM) was developed and executed for mining scenarios representative of commercially feasible mining operations. The modeling system for determining costs integrates a

mining development simulation model with a financial analysis program to provide an analytical tool for evaluating the production and cost consequences of proposed mine designs, production strategies, and equipment selections. Mining development scenarios were designed to recover oil shale resources to support a 50,000 barrels-per-day surface processing facility.

The results of this study are presented in the following sections. Section 2 discusses the geological resource base of the Green River Formation, based on a synthesis of existing literature. The rationale for selecting candidate mine sites is presented in Section 3. Section 4 describes the mining scenarios. Underground mining methods are discussed and detailed designs for selected operations are presented. Section 5 contains an overview of the computer model. Section 6 discusses the economic analysis of the mining scenarios. Section 7 summarizes the results of the study and presents conclusions and recommendations. Section 8 lists references cited in the body of the report.

2.0 GEOLOGY OF OIL SHALE DEPOSITS

The geological setting is a factor for both mine site selection and mining systems design. Discussed below is a compilation of current data related to the salient features of the oil shale deposits in the Western United States. Of particular interest, are the deposits located in the Piceance Creek Basin of Colorado.

2.1 Green River Formation

Although oil shale (actually kerogenitic marlstone) deposits underlie much of the United States, the richest and thickest deposits are contained in the Green River Formation. It is estimated that there are over a trillion barrels of oil contained in the Green River Formation in Colorado, Utah and Wyoming. Of these resources, less than fifty percent may be economically recoverable with current technology. This is equivalent to about 80 years of the U.S. total current petroleum consumption.

The Green River Formation is composed of five distinct basins: the Green River and Washakie Basins in Wyoming; the Uinta Basin in Utah; and the Sand Wash and Piceance Creek Basins in Colorado. Of these, three are considered to contain oil shale of sufficient grade and quantity for resource recovery -- the Green River, the Uinta, and the Piceance Creek Basins. Both the Green River and Uinta Basins have been mapped and explored geologically to determine recoverable oil shale resources, but

it is the Piceance Creek Basin in Colorado that has been explored extensively and represents the more attractive area for potential near-term commercial development. In addition to oil shale, the Piceance Creek Basin contains deposits of dawsonite, nahcolite, and other saline minerals which, as potentially recoverable by-products of oil shale extraction, enhance the economic attractiveness of resource development.

2.2 Piceance Creek Basin

The geology of the Piceance Creek Basin has been investigated extensively by others (4,5), and there are numerous reports available that discuss, in detail, its stratigraphy, physiography, and geologic history. For this study, the more important criterion is the local structure at specific mine sites that affect mine design. In a larger sense, understanding certain aspects of the Basin's structure and form are necessary to assess the impact of geological conditions in evaluating a site for commercial development.

The Piceance Creek Basin is a large asymmetric structural downwarp located in Garfield, Mesa, and Rio Blanco counties of northwestern Colorado. The low portion of this downwarp is in the north-central portion of the basin, where the beds rise rather steeply (27° maximum) until they outcrop on the northern basin rim. It generally is accepted that the major jointings run northeasterly, as indicated clearly by the drainage pattern

to the Piceance Creek. The rich oil shale is at its thinnest (approximately 60 feet) at the basin periphery and thickens towards a maximum (exceeding 2,000 feet) at the north-central low point. Associated groundwater also appears to increase in quantity along this line. The elevated areas of the Roan Plateau are major charging areas for the Upper and Lower Aquifers of the Piceance Creek Basin. The Roan Plateau provides dry mining conditions; however, mining activity may affect surface water and groundwater delivered to areas of lower elevations.

Methane is concentrated in the deeper oil shale beds (6), and hydrogen sulfide is concentrated in areas supplied by freshly oxygenated water. Hydrogen sulfide has occurred mainly in the northwest portion of the basin; although, it could exist at any peripheral point or near any major fracture. Concentrated most heavily in the northern portions of the basin are substantial quantities of nahcolite and dawsonite. These minerals may occur as individual deposits or they may be intermixed with oil shale.

The depositional formation containing commercially recoverable oil shale deposits in the Piceance Creek Basin is the Green River Formation. The Green River Formation is overlain by the Uinta Formation which forms the surface of most of the basin's interior and which is composed essentially of sandstone, siltstone, barren marlstone, and shale. The Green River Formation has three stratigraphic members: the Douglas Creek

Member, consisting primarily of sandstone, shale, and limestone; the Garden Gulch Member, composed of laminated shales and marlstone, thin beds of sandstone, and limestone; and the Parachute Creek Member, which contains most of the oil shale bearing zone (Figure 2-1).

The strata in the basin are divided into a number of zones, each having distinguishing characteristics which are useful for correlating stratigraphical sequences at different areas within the basin. The zones generally are grouped as: the upper zone; the mahogany zone; the middle zone; and the lower zone. The upper zone contains the Uinta Formation and the upper Parachute Creek Member, and is composed of both rich and lean oil shale sequences. The mahogany zone underlies the upper zone and is bound by relatively thin barren horizons known as the A-groove above the zone and the B-groove below the zone (Figure 2-2). Its thickness ranges from less than 100 feet to over 225 feet and it contains shale oil grades generally exceeding 20 gallons per ton (gpt) throughout the basin. The middle zone contains the leached zone consisting of fractured porous oil shale from which saline minerals have been leached. The lower zone consists of rich oil shales containing nahcolite, dawsonite, and other saline minerals.

FIGURE 2-1

South-North Diagrammatic Cross-Section of the Green River Formation in Colorado's Piceance Creek Basin

Source: Smith, J.W., et. al., "Colorado's Primary Oil Shale Resource for Vertical Modified In Situ Processes", LERC/RI - 78/2, Laramie Energy Research Center, 1978.

Section measured on
south side of Long Point
Secs. 7, 18, 19, T. 7 S.,
R. 97 W.

FIGURE 2-2
Typical Core Sample From
The Piceance Creek Basin

3.0 SITE SELECTION

3.1 Site Selection Rationale

There are many possible combinations of variables that constitute the mining environment, and it would be unrealistic to account for all of them in selecting candidate sites. A reasonable alternative is to select sites that are representative of values associated with the factors described below in Section 3.2. For this study, mine scenario selection has been restricted to sites in the Piceance Creek Basin, since this deposit is the most attractive for near-term commercialization.

Using maps and other resource data (7,8), the essential characteristics of the Piceance Creek Basin were defined. Some of the more important characteristics are:

1. The thickness of oil shale deposits tends to increase from the periphery of the basin towards a maximum at the structural center (also the low point) of the basin.
2. Average richness of the Mahogany Zone and total in-place reserves increase from the periphery towards a maximum at the structural center of the basin.
3. Overburden thickness follows the same general pattern observed in seam thickness and grade, although to a lesser degree.
4. Groundwater increases in quantity and importance from the southern portion to the northern portion of the Piceance Creek Valley.

5. Methane, of sufficient concentration to impact development methods, occurs in the deep (central) portion of the basin.
6. Hydrogen sulfide may be a problem in areas supplied by fresh water, such as areas near outcrops or areas near faults that may transmit oxygenated surface water to deep areas.

3.2 Factors Affecting Mine Scenario Development

A criterion established for selecting candidate sites was that each site be representative of commercially recoverable deposits. Sites were selected to be representative of a range of factors affecting commercial feasibility. Factors considered most significant to economic feasibility include: grade; thickness; depth; structure; gases; water; and non-uniformity of material properties. Other factors, such as the potential for accessory mineral recovery, were not considered, although their importance in overall mining economics should not be discounted. Presented below is a brief description of each factor involved in defining scenarios for this study.

3.2.1 Grade

The grade of oil shale generally is regarded as the primary determinant of the economic viability of oil shale projects. Variations in mining methods, developments in technology, and changes in the economy determine an appropriate range of oil shale grade that can be recovered economically.

3.2.2 Thickness

Oil shale thickness generally varies from a few feet to hundreds of feet; although in some cases, thicknesses over a thousand feet have been recorded. The oil shale thickness will impact economic considerations, since it affects the choice of mining method. Underground mining methods generally are workable in any ore body thickness. But specific methods may be practical realistically only within a limited thickness range.

3.2.3 Depth

Depths to the oil shale zone may range from zero at outcrops to over 3000 feet at some points in the basin. Deposit depth will affect the choice of mining method. Economic and technical considerations caused by extreme depth may reduce the feasibility of resource recovery. For example, recent studies have indicated that the compressive strength of oil shale often decreases with increasing depth. Since some deep beds will have only half the strength of the overlying material, the need to maintain stable entries may limit recovery potential.

3.2.4 Structure

Geological features, such as joints, faults, and fractures, will affect the orientation of a mine, and possibly limit the choice of mining method. As noted below in Section 3.2.5, faults also may be a factor in producing hydrogen sulfide gas.

3.2.5 Gases

Methane has been encountered in oil shale, and may be present in sufficient quantity to be a mining consideration. A U.S. Bureau of Mines (USBM) experimental shaft encountered heavy concentrations of methane. Recently, the Federal Oil Shale Lease Tract Cb was classified as gassy. This possibility may exist for all deep sites. Also, at the Federal Oil Shale Lease Tract Ca, significant quantity of hydrogen sulfide was encountered in the groundwater. It is speculated that hydrogen sulfide may be present near the edge of the basin and close to major faults. The gas appears to be the result of microbial activity and may be expected in those areas where fresh, oxygen bearing water is available to the micro-organisms.

3.2.6 Water

Water must be considered as: a drainage problem in active workings; a needed resource in mining/processing operations; and, a renewable resource that must not be damaged. Each of these factors is highly site-specific and should be considered on a site-by-site basis. Within reasonable limits, underground mining operations are possible within some water-bearing strata.

3.2.7 Non-Uniformity of Material Properties

Many material properties that remain constant in other ores do not remain uniform in oil shale. As mentioned previously

(paragraph 3.2.3), compressive strength varies with depth. Compressive strength also varies with grade; and, permeability decreases with increasing depth and grade. Laterally, however, the deposits are uniform across the basin as a whole; but, between specific individual mine-sites this uniformity may not be maintained. Local variation of material properties may increase the difficulty of developing workable mine designs at specific sites; however, unless material properties vary widely within a mine site, the use of average properties should be sufficient to develop mine designs.

3.3 Candidate Sites

Site-specific data were organized to delineate resource characteristic variations throughout the basin. Gradual transitions of resource characteristics occur from the periphery of the basin inward towards the structural center. Site selection criteria include the more important characteristics of the Piceance Creek Basin (section 3.1), the factors affecting the mine scenario development (section 3.2), and the following:

1. Proposed sites should be in an area of commercial interest.
2. Proposed sites should account for the changing trend of resource characteristics from the periphery to the structural center.
3. Proposed sites should be near publicly available corehole data to ensure an accurate representation of site characteristics.

4. Unique situations such as steeply pitching beds, which may limit the feasibility of conventional mining methods, should be avoided.

Based on the above criteria, two sites from the Piceance Creek Basin were chosen as representative of commercially feasible mining sites. The proposed scenario sites are located across the southern portion of the basin, as shown in Figure 3-1. Site 1 is on the southern rim of the basin where the Mahogany Zone outcrops, and will afford easy access and limited overburden. Site 2 is located high on the Roan Plateau at a point where the drainage basins divide. Dry mining conditions should exist at this point.

FIGURE 3-1
Piceance Creek Basin, Colorado -- Sites 1 and 2

4.0 MINING METHODS

Potentially feasible mining systems were evaluated for the candidate mine sites. The criteria used in selecting the mining methods include: the capability of the mining method to produce the required tonnage; the state of technical development of the mining method; and potential safety and environmental impacts. In selecting the candidate mining methods, an attempt was made to obtain a cross-section of both technically and economically feasible approaches.

4.1 Underground Mining Methods For Surface Retort Processes

Feasible mining systems for oil shale development have been investigated by several researchers. Cameron Engineers (1) investigated and evaluated potential underground systems for mining the deeper deposits of oil shale and associated minerals in the Piceance Creek Basin. Using a set of factors associated with technical feasibility, mining cost, resource recovery, reclamation and environmental impact, and health and safety, Cameron Engineers selected four mining methods showing merit for exploiting the deposits. Aerospace Corporation (2) compiled information from various reports to estimate mine cost data for surface, underground, and modified in situ mining operations. Information concerning the underground mining systems was extracted from the Cameron Engineers study. Cleveland-Cliffs Iron Co. (3) presented designs and specifications for a prototype oil shale

demonstration mining program to be undertaken in the Piceance Creek Basin. Four underground mining systems were specified. These essentially were scaled-down versions of the mining methods suggested by Cameron Engineers. Dravo Corporation (9) provided a comprehensive summary of larger scale non-coal mining methods. The report presented detailed statistics on underground mining systems in current practice, the methods and problems, and needed technological improvements.

After a careful review of the available information,* mining methods were proposed which represented commercially attractive mining systems. Much of the selection rationale was drawn from prior studies. It was concluded at the outset of the study that the selection of mining methods should come from the body of mining techniques workable with either existing technology or with minor, and technically feasible, extensions to existing technology. Based on this rationale, mining operations such as room-and-pillar, caving, and stoping, or natural derivatives thereof, were evaluated. The mining methods selected to provide feedstock in support of surface retorting processes are:

1. room-and-pillar
2. chamber-and-pillar, with backfilling
3. sublevel stoping,
4. sublevel stoping, with backfilling

* The available information included, among others, discussions with cognizant individuals and related technical reports (see References).

The room-and-pillar and chamber-and-pillar mining methods are proposed as potentially workable mining systems at Site 1. These methods appear particularly suited to sites with high-grade oil shale zones less than 100 feet thick. For sites with larger mining horizons, such as Site 2, the sub-level stoping methods seem more appropriate. A brief description of each mining operation is presented below.

4.1.1 Room-and-Pillar

Room-and-pillar mining is the most common underground mining method in the United States for coal, and may be an attractive method for mining some of the thinner oil shale deposits. Its advantage comes from being highly flexible, highly mechanized, and highly productive. It is suited to deposits that have not been greatly folded or deformed, are relatively flat, and contain ore that is relatively uniform over a wide area. Extraction percentages for room-and-pillar systems will vary depending on structural considerations and depth. Using coal mining as an example, extraction percentages between 30 percent and 60 percent are not uncommon (without pillar extraction). In oil shale mining, extraction percentages greater than 60 percent potentially can be achieved, given the improved width-to-height entry ratios available in thicker ore bodies. An illustration of this method is shown in Figure 4-1.

FIGURE 4-1
Room and Pillar Mining

Source: Dravo Corporation, Analysis of Large Scale Non-Coal Underground Mining Methods," U.S. Department of Interior, PB-234555, 1974.

4.1.2 Chamber-and-Pillar, with Backfilling

This mining method is a modification of room-and-pillar mining in which crosscuts, driven perpendicular to the entries, are enlarged into chambers. One advantage of this method is that most mining design specifications (i.e., height, length, extent) can be adjusted to the geological constraints of the deposit and still produce an economically viable mining system. Within the mining horizon, extraction percentages of 60 percent to 70 percent are possible with current technology. The primary advantage of the chamber-and-pillar method is that the chambers provide an excellent area for the underground disposal of spent shale. Chamber and pillar mining is illustrated in Figure 4-2.

4.1.3 Sublevel Stoping

Sublevel stoping theoretically can yield an extraction percentage approaching 100 percent. Sublevel stoping is followed by pillar recovery after the initial stope is complete. After a stope is mined, pillars are blasted into the stope and the overburden is allowed to cave. This method permits the development of relatively small stopes and relatively large pillars to afford maximum safety during development and stoping operations. Mining of the blasted rock proceeds until dilution of the shale and overburden material makes continued mining economically unattractive. This method is illustrated in Figure 4-3.

FIGURE 4-2
Chamber and Pillar Mining

Source: Cameron Engineers, "A Technical and Economic Study of Candidate Underground Mining Systems for Deep, Thick Oil Shale Deposits," Cameron Engineers, Inc., Denver, CO, 1976.

FIGURE 4-3
Sublevel Stoping

Source: Cameron Engineers, "A Technical and Economic Study of Candidate Underground Mining Systems for Deep, Thick Oil Shale Deposits," Cameron Engineers, Inc., Denver, CO, 1976.

4.1.4 Sublevel Stopping, with Backfilling

A disadvantage of sublevel stopping is the potential surface damage which may preclude the method from serious consideration where local conditions do not permit such damage. A modification of this method, sublevel stopping with backfilling, may mitigate potential surface effects. However, this modification also may reduce extraction percentage to 50 percent or 60 percent of the mining horizon. In sublevel stopping with backfilling, mining may proceed on advance instead of on retreat. Stopes are back-filled with spent shale, thereby minimizing surface damage and significantly reducing the amount of spent shale disposed on the surface. An illustration of this method is shown in Figure 4-4.

4.2 Detailed Mine Design

Detailed mine designs were developed for the four mining systems described above. Key parameters for these scenarios are listed in Table 4-1. Advance rates and production rates for each system represent estimates based on tabulated data, current industry practices, and the collective judgement of in-house mining engineers. Independent verification of the estimates was obtained prior to their use.

Mines were designed to extract nominally an average of 80,000 tons of oil shale per day, at full production. Simulated

FIGURE 4-4

Sublevel Stoping with Backfill

Source: Cameron Engineers, "A Technical and Economic Study of Candidate Underground Mining Systems for Deep, Thick Oil Shale Deposits," Cameron Engineers, Inc., Denver, CO, 1976.

TABLE 4-1
Summary of Mine Parameters

Mine Parameters	Scenario			
	Room and Pillar	Chamber and Pillar	Sublevel Stoping	Sublevel Stoping with Backfilling
Mine Site	1	1	2	2
Average Overburden Depth (Ft.)	600	600	800	800
Tract Size (Miles)	3 by 3	3 by 3	1 by 2	1 by 3
Average Grade (gpt)	25	25	23	20
Access Method	Drift	Shaft	Slope	Shaft
Mining Horizon (ft)	75	80	200	280
Target Production (tpd)	80,000	80,000	80,000	80,000
Simulated Production (tpd)	87,500	80,250	86,000	87,500
Extraction Percentage	55%	47%	73%	54%
Mine Life (Years)	26	24	17	26

production from these mines was up to ten percent greater than this target value.*

As a result of mining production variations and differences in average shale grade within the respective mining horizons, shale oil yield for the four mining scenarios ranged from 42,000 to 52,000 barrels per day.

4.2.1 Room-and-Pillar

Site 1 was chosen for the development of an oil shale mine using the room-and-pillar mining system. The average shale mined is 25 gallons per ton (gpt). The average grade shale is located within the Mahogany Zone, which averages 100 feet in thickness.** The depth of overburden ranges from zero to 800 feet, with an average of about 600 feet.

4.2.1.1 Layout Specifications

The property considered is a square tract, three miles on a side. Access to the mining area is achieved by drifting in at an outcrop located on the southern edge of the property. Figure 4-5 illustrates the mine layout. A barrier pillar, 450 feet wide, is left between the outcrop and room-and-pillar

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- * These variations are the consequence of two interacting factors:
- 1) The inherent difficulty in designing a mine to produce exactly at a precise, pre-selected target rate.
 - 2) The discipline of the mine simulation model (e.g., advance and production rates are constants for a given segment type, only full crews are used, etc.), and the quantizing effects that result.

** The mining horizon is 75 feet.

FIGURE 4-5
Layout of Room-and-Pillar Mine

panels. Protection barriers, 285 feet wide, are left between main entries and room-and-pillar panels. Submains are shielded by 90-foot barriers, and a 180-foot wide block of in-place shale is left between successive panels. An equipment service area is located conveniently near the entrance of the mine.

Main entries are developed through the center of the property, and consist of five parallel 20-foot high by 30-foot wide entries with 75-foot long crosscuts of the same dimensions driven on 430-foot centers (Figure 4-6). The center entry will be used to support a rail haulage system that will transport supplies and workers. A 60-inch main haulage belt will transport mined oil shale to the surface. The other four entries are developed to provide air circulation throughout the mine. Main entries are designed with the capability of handling 88,000 tons of oil shale per day and three million cubic feet of air per minute. Three million cubic feet of air per minute is determined by assuming ventilation requirements of 125 cfm for each underground diesel horsepower and 100 cfm for each miner, in accordance with standard mining industry practice. Also in accordance with standard mining practice, shafts and airways are sized so that shaft air speeds do not exceed 2500 feet per minute (fpm).

Submains are driven perpendicular to the mains to provide access to the room-and-pillar panels. Submain layouts showing their position relative to the panels and main entries are illustrated in Figure 4-7 through Figure 4-10. The submains consist of

FIGURE 4-6
Main Entry Configuration,
Room-and-Pillar Mining System

FIGURE 4-7
Submain Entry Configuration Adjacent to
Main Entry. Room-and-Pillar Mining System.

FIGURE 4-8

Submain Entry Configuration Adjacent to
Room-and-Pillar Panels.. Room-and-Pillar Mining System.

FIGURE 4-9

Submain Entry Configuration Between Successive
Room-and-Pillar Panels. Room-and-Pillar Mining System.

FIGURE 4-10

Room-and-Pillar Panel Showing Relationship
with Submains and Exhaust Airways

three parallel entries; the middle entry is used for belt and track haulage, while the other two entries are for ventilation. The dimensions of all entries in the submains, including the crosscuts, are 20-feet high by 30-feet wide. The exhaust airways (Figure 4-10) are constructed to direct contaminated air out of the room-and-pillar panels. They are driven through the center of the panels at a level 55 feet above the floors of the main and submain entries. This level is achieved by developing a ramp with a ten percent grade (550 feet long) and leveling off at the top of the ramp. The elevated entry enables the air to sweep across the roof of the panel where methane and other contaminants might collect. The return air is exhausted through the rear of the panel where it is directed down another entry leading to the exhaust entries of the mains.

The room-and-pillar panels are accessible through three entries which provide intake air and haulageways. The center entry leads to the exhaust airway driven through the center of the panel. The panel dimensions are 1680-feet wide and 3570-feet long. Pillar dimensions are 75-feet wide, 75-feet long and 75-feet high. A maximum allowable extraction percentage of 72 percent was determined, assuming an oil shale yield stress of 3150 pounds per square inch (psi) and an average overburden depth of 800 feet. Driving 60-feet wide entries between pillars yields a total recovery of 69 percent in the panels, which is within the maximum safe extraction limit of 72 percent. This

entry size also provides a safe working area for employees by minimizing the width of exposed roof.*

4.2.1.2 Mine Operation

The mining operation starts by drifting in at the outcrop on the south side of the property. The main entries are driven up the center of the property, a total of 4230 feet, where submains are started. At the same time, the exhaust airway for the first panel is developed off the mains and panel access entries are driven. Upon completion of the operations, the first panel is opened for production. Additional panels are developed by driving the submains and main entries to the property line along with development of panel access entries. However, after the first panel is developed, the exhaust airways are driven off the submains to avoid locating a working place in return air.

Production from the panels is achieved by mining on two levels. The base of the upper level is 45 feet above the submain floor, where lifts are 30-feet high by 60-feet wide by 30-feet deep.** The face is drilled by a dual boom jumbo drill, blasted, and mucked out using a 15 cubic yard front-end loader. A single

* The room-and-pillar mine being developed at the Colony site is at a depth of 600 to 850 feet, and has 58 feet by 58 feet pillars. Entries are 55 feet wide and 60 feet high. In general, long-term stability has been very good, indicating that the slightly more conservative pillar-to-entry ratio used in this design should be more than adequate.

** The lifts taken are slightly larger than current practice, but feasible with existing technology. The intent here is to reduce the labor requirements by substituting larger lifts and larger haulage equipment.

lift nets about 3,700 tons and a total of three lifts can be cycled from the upper level of one panel in one day. Lower level production progresses in a similar manner, except drilling is done from the top by a track-mounted rotary percussive downhole drill. The material is blasted to the floor level and mucked out using two 12-yd³ front-end loaders. The dimensions of a lift are 60 feet wide by 45 feet high by 30 feet deep. This volume yields 5560 tons of oil shale. Three lifts can be cycled from the lower level of a panel in one day, in addition to the three upper level lifts.

The oil shale is loaded onto 35-ton rear dump trucks by front-end loaders, and is hauled to a conveyor belt centrally located in the panel. The material is dumped onto feeder breakers and transferred out of the panels using a 42-inch conveyor belt. The crushed rock is transferred to another 42-inch conveyor belt in the submains and eventually to a larger 60-inch belt in the mains, where it subsequently is transported to the surface.

Full production is achieved with the simultaneous mining of three panels and the development of an additional three panels. Total daily production out of the three panels is estimated at 81,500 tons, with an additional 6,000 tpd being mined through development. This yields a total average daily production of 87,500 tons, which is slightly higher than the nominal design value. The mine will be under development for a total of three years before full production is attained. At that rate, the

mine will be active for 26 years with approximately 55 percent of the resources in the mining horizon recovered.

4.2.2 Chamber-and-Pillar, With Backfilling

Site 1 was chosen for the development of an oil shale mine using the chamber-and-pillar mining method. The average grade of shale mined is 25 gallons per ton (gpt). The shale is located within the Mahogany Zone, which averages 100 feet in thickness.* Overburden depth ranges from zero to 800 feet with an average of about 600 feet.

4.2.2.1 Layout Specifications

The property considered is a square tract, three miles on a side. Access to the mining area is by shafts driven at the center of the property. The shaft area is protected by a large block of shale which extends about 1800 feet to the nearest production chamber. Barrier pillars of 200 feet and 270 feet are left between main access entries and chamber crosscuts as shown in Figure 4-11. The difference in barrier pillar size allows the haulage entries for individual chambers to alternate on each side of the submain. An adequate protection barrier of 100 feet also is provided between submains and the boundary of finished chambers (Figure 4-12). A shop area is centrally located to provide services for both halves of the mine. A layout of the shaft and shop areas is illustrated in Figure 4-13.

* The mining horizon is 80 feet.

FIGURE 4-11

Main Entry and Submain Intersection Showing Location of Chamber Crosscuts - Chamber and Pillar Mining System

FIGURE 4-12

Plan View of Production Chambers -
Chamber and Pillar Mining System

FIGURE 4-13
Shaft and Shop Area for Chamber and Pillar Mine

A total of six shafts are sunk to a depth of 800 feet to meet production and ventilation requirements. Shafts and airways are sized on an estimated ventilation requirement of three million cubic feet per minute (cfm). The ventilation requirement is based on providing 125 cfm for every diesel horsepower underground, as well as providing 100 cfm for each miner.

Two 28-foot diameter production shafts are designed to hoist 88,000 tons per day (tpd) using friction hoists and 64-ton skips. Another 28-foot diameter shaft is used for hoisting men and equipment and for intake ventilation. A fourth 28-foot diameter shaft is used exclusively for intake ventilation. Two additional 28-foot diameter exhaust ventilation shafts are driven to intersect the return air entryways of the mains.*

In addition to production and ventilation shafts, two 8-foot diameter shafts are raise-bored from the center of the property to provide a chute through which spent shale may be dumped. Shaft locations are shown in Figure 4-13.

The main entryways (Figure 4-14) are driven from the center of the property to both the northern and southern boundary lines. They consist of three parallel passageways with 75-foot long crosscuts on 365-foot centers. The main haulage entry is 20

* An alternative approach would be to sink smaller diameter shafts using technology currently being developed. The number of shafts required to maintain adequate ventilation would increase, however, and the cost-tradeoff between the two approaches would have to be assessed.

FIGURE 4-14

Main Entry Configuration - Chamber and Pillar Mining System

feet x 20 feet, as are all main crosscuts. The other two entries are 20 feet x 30 feet intake and return airways.

Submain entries are driven on 1420-foot centers, perpendicular to the main entries. They extend to within 200 feet of the property line. Submains consist of three parallel 15 feet x 15 feet entries with 15 feet x 15 feet crosscuts driven on 140-foot centers. These crosscuts are offset to correspond with chamber crosscuts, as shown in Figure 4-11. Offsetting of crosscuts should minimize waiting delays encountered at the dump points in the haulage entry of the submains.

Chamber crosscuts are driven perpendicular to the submains, as shown in Figure 4-12. The dimensions are 15 feet x 30 feet with a development length of 630 feet. Chamber crosscuts are 30 feet wide to allow two front-end loaders (FEL) to work simultaneously in each crosscut.

Exhaust airways (Figure 4-12) are driven to connect the ends of the chamber crosscuts to the main entries. In this manner, ventilation consists of intake air coming in through the mains, passing up through the submains, filtering through the chamber crosscuts to the exhaust airway, and exhausting by way of the exhaust main airway.

4.2.2.2 Mine Operation

Mining proceeds on a half-advance, half-retreat pattern, as shown in Figure 4-15. Main access entries are driven up the

FIGURE 4-15

Mine Layout Showing Half-Advance, Half-Retreat
Mining Scheme - Chamber and Pillar Mining System

center of the property to the required distance, and submains are driven perpendicular to the mains. After submain development progresses 200 feet, the first chamber crosscut is driven. At the same time, an exhaust airway is driven to connect the tail end of the chamber crosscut to the return air entry in the mains. This cycle repeats for all chambers in the submain. Successive chambers are developed on both sides of the submains, and exhaust airways from successive chambers are driven to connect those of the previous chamber.

Major production is achieved by enlarging the 15 feet x 30 feet crosscut to a 100 feet wide by 80 feet high chamber with a completed length of 500 feet. This is achieved by fan drilling and blasting. Fan drilling is done on retreat from the exhaust airway to the submains. Twenty-five foot slices are drilled, blasted and mucked-out using two 10 yd³ load-haul-dump (LHD) vehicles. The oil shale is dumped onto feeder/breakers located at the end of the chamber crosscuts where it is broken to 12-inch lumps and fed onto a 42-inch belt in the submain.* The oil shale is transferred to a larger 60-inch belt in the mains where it is conveyed to the production shaft bottom and hoisted to the surface. One complete cycle of drilling, blasting, and loading takes two days working three 8-hour shifts each day. An entire chamber is completely mined out in 42 days.

* Feeder-breakers capable of handling large quantities of oil shale presently are being developed by the mining industry.

Full production is achieved with the mining of twelve individual chambers -- six in each half of the mine -- along with the development of an additional two chambers. Development for a chamber must be completed every seven days in each half of the mine in order to maintain full production. This rate is achieved using four development crews for each half of the mine. At full production, a total of 72,250 tpd is mined out of the chambers. An additional 8000 tpd is obtained from development work. The life of the mine is estimated to be 24 years, and extraction of 47 percent of the mining horizon is expected. Production chambers are illustrated in Figure 4-16 and Figure 4-17.

4.2.2.3 Spent Shale Backfilling

After the oil shale has been retorted at the surface, spent shale is transported back into the mine to be used as backfilling material. In the chamber-and-pillar mine, two eight foot diameter shafts (one shaft for each half of the mine) are raise bored from the main entries located near the shaft area. Spent shale is fed into a shaft from the surface where it falls to a surge bin at the bottom of the shaft. The shale is then fed to conveyor belts that transport it to a mined-out chamber. A bucket elevator is attached to the belt tailpiece located in the chamber to allow the shale to be piled higher during the operation. The backfilling then can retreat from the exhaust end of the chamber to the chamber entrance near the submains.

FIGURE 4-16

End View of Production Chambers Showing Dimensions
and Fan Drilling Pattern - Chamber and Pillar Mining System

FIGURE 4-17

Side View of Production Chamber Illustrating the Mining Scheme - Chamber and Pillar Mining System.

Backfilling was incorporated into the mine design for the dual purpose of protecting against surface damage and mitigating problems associated with spent shale disposal. Although the mine was designed to minimize surface effects, long-term surface disturbances caused by pillar failure are a possibility. Backfill material strengthens pillars by providing lateral support to the walls. Under current legislation, mining plans resulting in subsidence are permitted in Colorado; but the surface of disturbed land must be restored to at least its original condition. Most plans currently under consideration are designed to result in a slow uniform surface lowering. Plans such as sublevel stoping (with full subsidence) also have been considered; however, the surface is reclaimed by filling the depression with spent shale, covering with topsoil, and revegetating.

4.2.3 Sublevel Stoping

Site 2 was chosen for the development of an oil shale mine using sublevel stoping. The average grade of shale mined is approximately 23 gallons per ton (gpt). The shale mined is a contiguous two hundred foot section of strata which includes: the Mahogany Zone (averaging 120 feet in thickness and 27 gpt); the A-Groove (averaging 10 feet in thickness and 9 gpt); and Unit I shale (averaging 70 foot and 17 gpt). Overburden depth ranges from 600 feet to 1,200 feet with an average depth of approximately 800 feet.

4.2.3.1 Layout Specifications

The area mined in Site 2 is one mile wide and two miles long. Access to the mining area is through a slope which is driven 2,750 feet, at an angle of 17 degrees, to a depth of 800 feet where it intersects the base of the Mahogany Zone. The slope is used for intake ventilation, ore haulage, and transporting men and equipment to and from the surface. Two large slope belts (60 in.) are used for ore haulage, while men and equipment are transported by means of a slope hoisting device.

Four 25-foot diameter shafts* (Figure 4-18) sunk to a depth of 800 feet, along with the 20 foot by 30 foot slope, provide the necessary ventilation to the working areas of the mine. Sizing the shafts and airways was based on an estimated ventilation requirement of three million cubic feet per minute. The ventilation requirement is calculated on the basis of providing 125 cfm for every diesel horsepower underground and 100 cfm for each miner. As shown in Figure 4-19, two of the shafts are driven to intersect intake airways, and two are driven to intersect exhaust airways. The two exhaust shafts are equipped with four 800,000 cfm exhaust ventilation fans with a combined capacity of 3,200,000 cfm. In the shaft area,

* The intake air shafts are sized so that the maximum air velocity in the shafts does not exceed 2500 feet per minute. These intake shafts have a smaller diameter than the shafts designed for the chamber and pillar mine because there is no service hoist to obstruct air movement. Also, additional intake air is provided by the slope.

FIGURE 4-18
Plan View of Lower Level Sublevel Stopping Mine -
Sublevel Stopping Method

FIGURE 4-19
Plan View of Shaft and Shop Area - Sublevel Stopping Method

an underground maintenance shop is developed for equipment storage and servicing. The shaft area is protected by a large block of shale that extends at least 1,500 feet to the nearest caving operation.

The main entryways (Figure 4-20) consist of parallel haulage and exhaust entries with 75-foot long 20 foot x 20 foot crosscuts driven on 320-foot centers. The haulage entry, also used for intake ventilation, is 20 feet high and 30 feet wide, while the exhaust entry is 20 feet high and 20 feet wide. In order to ensure safety, a 200-foot barrier pillar is left to separate the main entries from the stope development.

Haulage and exhaust crosscuts are driven on 480-foot centers to connect the main entryways, as shown in Figure 4-21. A series of crosscuts consists of one haulage crosscut driven between a pair of exhaust crosscuts. Within a series of crosscuts, a total of fifty-four stopes will be developed.* Lower level stope development (Figure 4-21) consists of a series of alternating front-end loader haulageways and stope drawpoints driven perpendicular to each other on both sides of a haulage crosscut.

The sublevel lies at an elevation 120 feet higher than the floor of the lower level. Access to the sublevel is through

* A total of nine series of crosscuts will be developed during the life of the mine, providing a total of 486 stopes to be mined.

FIGURE 4-20
Main Entry Configuration - Sublevel Stopping Method

FIGURE 4-21

Lower Level Stope Development -
Sublevel Stopping Method

a ramp having a five percent grade with its base intersecting an intake airway connecting the two intake shafts, as shown in Figure 4-19. All sublevel access ways, including the ramp, consist of three parallel 15 feet x 15 feet entries with 75-foot long 15 feet x 15 feet crosscuts on 320-foot centers, as shown in Figure 4-22. Stope access ways (Figure 4-23) are driven perpendicular to the main sublevel access ways to a distance of 4,565 feet. Upon development of a stope access way, consisting of a pair of parallel 15 feet x 15 feet openings, sublevel stope development can proceed (Figure 4-24). Haulage of oil shale mined from the development of the sublevel is achieved by using a 36-inch conveyor belt that transfers the rock onto railcars at the base of the sublevel ramp.

4.2.3.2 Mine Operation

Initially, the shaft and slope are developed to the bottom of the mining horizon. Upon completion of the shaft bottom, shop areas are ready for development (Figure 4-19). Main entries are driven up the sides of the mine to a distance of 8,640 feet. Simultaneously, the access ramp and main access ways are driven to an equivalent distance on the sublevel. Haulage and exhaust crosscuts are driven on the lower level as shown in Figure 4-18, and sublevel stope access ways are driven to a distance of 4,565 feet. Upon completion of the access ways, stope development is started simultaneously on both levels. The order of mining operations within a single series of stopes

FIGURE 4-22
Main Sublevel Access-way Configuration -
Sublevel Stopping Method

FIGURE 4-23
Sublevel Stope Access Ways - Sublevel
Stoping Method

FIGURE 4-24

Sublevel Stope Development - Sublevel Stoping Method

is illustrated in Figure 4-25. Each operation -- development, stope mining, and pillar mining -- is separated by an area in which no activity occurs. These idle areas are left for safety purposes to protect working personnel from the effects of blasting or sudden caving of weakened support.

Production is achieved by fan drilling and blasting on both operating levels, as shown in Figure 4-26. Each blast takes a 26-foot linear section of the stope. The blasted ore collects in an ore chute, is directed onto stope drawpoints (Figure 4-21), and is mucked-out with front-end loaders and transported to railcars located in the lower level haulage cross-cuts. The ore is transported out of the stope area to the haulage entry where it is hauled by rail to crushing facilities located at the base of the slope. After reduction to -6" size, it is fed onto slope conveyor belts and is transported to the surface.

Pillar recovery is achieved by fan drilling and blasting in passageways surrounding the mined out stope on the sublevel. End pillars (Figure 4-26) and side pillars (Figure 4-27) are blasted out in a single blast. Crown pillars are left over all entries on the lower level, except the stope drawpoints where the blasted ore collects. Ore haulage out of the mine proceeds in the same manner as was the case with the stopes.

Full production is achieved with the simultaneous mining of three stopes, the clearing of three sets of pillars, and the

FIGURE 4-25
Order of Operations - Sublevel Stoping

FIGURE 4-26

Side View of Production Stope Showing Fan Drilling and End Pillars - Sublevel Stoping Method

FIGURE 4-27

Sublevel Stopping Operation Showing End View of Stopes and Side Pillars -
Sublevel Stopping Method

development of an additional two stopes. After the mining cycle proceeds to a predetermined point in a row of stopes, crews will be sent to develop additional haulage and exhaust crosscuts on the lower level, and additional stope accessways on the sublevel (Figure 4-28). Mining proceeds until a total of nine rows of stopes are mined to completion.

Full production will be attained during the third year. At this point, a total of 34,000 tpd can be expected out of the stopes, an additional 46,000 tpd will be mined through pillar recovery, and 6,000 tpd will be obtained through development. This gives a total average daily production of 86,000 tpd. At this rate, a mine life of 17 years can be expected with a rate of extraction of 73 percent of the mining horizon.

4.2.4 Sublevel Stoping, With Backfilling

Site 2 was chosen for the development of an oil shale mine using a sublevel stoping mining technique which includes backfilling of spent shale in order to ensure minimal surface damage.* The average grade of shale mined is about 20 gallons per ton.** The thickness of the shale mining horizon is 280 feet

* The lateral support provided by backfilling, as discussed in Section 4.2.2.3, is of greater importance in sublevel stoping because of the additional height of the stopes.

** The difference between the average grade for sublevel stoping (Section 4.2.3) and this method is due to the change in mining horizon.

FIGURE 4-28
Sublevel Layout - Sublevel Stoping Method

with a fill level developed 60 feet above the mining horizon. The total thickness includes: the Mahogany Zone, which averages 120 feet in thickness and 27 gpt; the A-Groove, which averages 10 feet in thickness and 9 gpt; Unit I oil shale, which averages 110 feet in thickness and 17 gpt; and Unit II oil shale, which averages 100 feet in thickness and 17 gpt. Overburden depth ranges from 600 to 1200 feet with an average of approximately 800 feet.

4.2.4.1 Layout Specifications

Although the property is a square tract, three miles on a side, the actual area mined is a one-by-three mile tract, with a 1000 foot by 2000 foot area located on a long side. This additional area includes the shafts, shop area, and surface facilities. A total of six 28-foot diameter shafts are sunk to a depth of 800 feet to provide both production and ventilation requirements. Shafts and airways are sized on an estimated ventilation requirement of three million cubic feet per minute. This requirement is based on providing 125 cfm for every diesel horsepower underground and 100 cfm for each miner. Two 28-foot production shafts are designed to hoist 88,000 tpd using friction hoists and 64 ton skips. Another 28 foot diameter shaft is used for hoisting men and equipment, and also for intake ventilation. A fourth 28-foot diameter shaft is used exclusively for intake ventilation. Two 28-foot diameter exhaust ventilation shafts are sunk to intersect the exhaust airways that lead into the

mains. A total of four exhaust ventilation fans, each with the capacity of pulling 800,000 cubic feet per minute, will be located at the top of the two exhaust air shafts. Shaft locations are shown in Figure 4-29.

Separating the shafts from the production stopes is a 2000-foot barrier pillar, within which lies the shop area and main accessways to the stoping area. The main haulage level is at the base of the Mahogany Zone. The total operation requires the use of three levels. A plan view of the shaft and shop area is illustrated on Figure 4-29. The main accessways consist of five parallel 20 feet x 30 feet entries separated by 50-foot wide pillars with 20 feet x 20 feet crosscuts driven at varying intervals, as shown on Figure 4-30. The middle entry is used for ore haulage out of the mine as well as for intake ventilation. The two entries adjacent to the haulage entry also are used for intake ventilation, while the two outside entries on both sides of the mains are used for exhaust ventilation.

The submain entries on the haulage level are driven perpendicular to, and on both sides of, the main entries. They consist of three parallel 20 feet x 20 feet entries separated by 30 foot pillars of varying lengths (Figure 4-31). The center entry is used for haulage out of the stopes to the main entryways. All three entries supply intake air.

FIGURE 4-29

Shaft and Shop Area -- Sublevel Stoping
Mining Method with Spent Shale Backfilling

FIGURE 4-30
Main Entry Configuration -- Sublevel
Stoping Mining Method with Spent Shale Backfilling

FIGURE 4-31

Main Haulage Level Stope Development --
Sublevel Stoping Mining Method with Spent Shale Backfilling

The front-end loader haulageways and stope drawpoints are driven perpendicular to the submains. The front-end loader haulageways are 20 feet x 30 feet entries driven on both sides of the 20 feet x 20 feet stope drawpoints. Crosscuts are driven at various intervals to connect the stope drawpoints with the front-end loader haulageways. These crosscuts allow the loaders to muck-out the stopes without being exposed to unsupported roof. Access to the first sublevel, 180 feet above the haulage level, is through a ramp consisting of three parallel 15 feet x 15 feet entries. The ramp is developed on a ten percent grade and has a length of 1800 feet. The center entry is used for intake ventilation and haulage, while the two outside entries are used for exhaust ventilation. After the ramp is developed to its full length, a set of sublevel mains (Figure 4-32) are driven. These mains consist of three parallel 15 feet x 15 feet entries separated by 212 feet x 75 feet pillars. Small 15 feet x 15 feet crosscuts are driven between the pillars to connect the entries.

Sublevel drifts are driven perpendicular to the mains to provide access to the stopes for fan drilling. These drifts consist of two parallel 15 feet x 15 feet entries separated by 30-foot pillars with conveniently located crosscuts, as shown in Figure 4-33. These entries are used to provide intake air to the drill crews working on the sublevel.

The fill level accessways are developed off the two production shafts at a height of 320 feet above the haulage level.

FIGURE 4-32

Sublevel Main Entry Configuration -- Sublevel Stopping
Mining Method with Spent Shale Backfilling

FIGURE 4-33

Sublevel Stope Development -- Sublevel Stoping
Mining Method with Spent Shale Backfilling

The accessway to the stope area is by a single 15 feet x 15 feet entry used for intake ventilation and spent shale haulage into the stopes (Figure 4-34). After this single entry is driven to the stope area, the fill level drifts can be developed. These drifts consist of two parallel 15 feet x 15 feet entries separated by 75-foot pillars with crosscuts conveniently located, as shown on Figure 4-35. A ventilation raise is driven to connect the fill level with the sublevel, allowing the second entry on the mains to be used for exhaust ventilation. Single entry passageways are driven to access the stopes for backfilling.

The mine plan utilizes three levels of operation to realize total production. The haulage level is used for fan drilling, blasting, and oil shale removal. The sublevel is used specifically for fan drilling and blasting, while the fill level, constructed above the stopes, enables topfilling of the stopes. Each level of the mine is shown in Figure 4-36 through Figure 4-38.

4.2.4.2 Mine Operation

After the shafts are sunk, the shop area is developed by two mining crews using drill jumbos and 9 yd³ load-haul-dump vehicles. The haulage level mains, sublevel ramp and mains, and the fill level accessways then will be developed. Two crews will be used to develop the mains and two additional crews will be used to drive the sublevel ramp and mains. One crew will be sufficient to drive all headings on the fill level. Haulage of oil shale is by rail on the haulage level, and by belt on the

FIGURE 4-34

Fill Level Main Entry Configuration -- Sublevel
Stoping Mining Method with Spent Shale Backfilling

FIGURE 4-35

Fill Level Backfilling Scheme -- Sublevel
Stoping Mining Method with Spent Shale Backfilling

FIGURE 4-36

Line Diagram. Plan View of Haulage Level -- Sublevel Stoping Mining Method with Spent Shale Backfilling

FIGURE 4-37

Line Diagram. Plan View of Sublevel --
Sublevel Stoping Mining Method with Spent Shale Backfilling

FIGURE 4-38

Line Diagram. Plan View of Fill Level --
Sublevel Stopping Mining Method with Spent Shale Backfilling

sublevel and fill level. After main entry development on all levels proceeds to a certain point, development of the stopes is started. On the haulage level, this includes development of the submains, stope drawpoints, front-end loader haulageways, and exhaust airways (Figure 4-31). On the sublevel, stope development includes submains, stope crosscuts and exhaust airways (Figure 4-33). Stope development on the fill level includes submains and fill crosscuts (Figure 4-35).

Upon development of a stope, production out of the stopes is conducted by fan drilling a section of the stope, blasting the section, and loading out the fragmented oil shale using front-end loaders. Fan drilling is done from both the haulage level and sublevel as shown on Figure 4-39. Lower level fan drilling is done to ensure proper fracturing of the rock when blasting so that a chute is formed that will direct the fragmented oil shale to the stope drawpoints.

After a section of a stope is blasted, the oil shale is mucked-out using two 15 yd³ front-end loaders per stope. This will yield an average daily production rate of 10,000 tons per day out of each stope. The oil shale is hauled to the submains by the front-end loaders, where it is dumped onto railcars. Locomotives then transport the shale to the production shafts via the main haulageway where it is hoisted to the surface. A total of eight stopes can be mined at one time, with four stopes

FIGURE 4-39

Side View of Production Stopes -- Sublevel
Stoping Mining Method with Spent Shale Backfilling

under production on each side of the mains. A stope cross-section showing haulage drifts and fill drifts is illustrated in Figure 4-40.

The mining of eight stopes simultaneously yields a full production of 80,000 tons per day. Production from the development of two additional stopes yields an additional 7500 tons per day, giving a total daily production of 87,500 tons per day. The mine will have an operating life of about 26 years and will extract about 54 percent of the available resource in the mining horizon.*

After a stope has been mined, backfill can begin from the fill level. This is accomplished, simultaneous with other mining operations, using large pipes to convey the spent shale through the shafts to the fill level, and then transporting it to the stopes by belt. The spent shale then is poured into the stopes through chutes bored into the stope roofs.

* The extraction percentage is lower than the stoping method without backfilling) because the support pillars are made larger to provide added strength required for long-term support.

FIGURE 4-40

End View of Production Stopes --
Sublevel Stopping Mining Method with Spent Shale Backfilling

5.0 DESCRIPTION OF THE MODEL

The objective of the study was to develop a mining economic model to determine mining costs associated with various strategies for developing oil shale resources for surface processing. The Oil Shale Mining Economic Model (OSMEM) consists of a sequence of computer sub-programs which provide production and financial data necessary for evaluating the consequences of specific mine designs and production strategies. The objectives of the model are:

1. To project annual production resulting from user-specified mine designs, production strategies, and equipment parameters;
2. To compute standard financial measures for evaluating alternative strategies;
3. To provide flexibility in analyzing a wide variety of mining scenarios; and
4. To permit sensitivity analysis of technical and financial parameters.

The model is executed in two phases. The first phase consists of a simulation of an operating underground oil shale mine; it provides the annual operating results of the mine design. Yearly production and advance may be analyzed for a mine life up to one hundred years. The second phase performs the financial analysis, using cost and revenue streams to determine cash flows and to compute the mining portion of the selling price required to recover capital and operating expenses at a desired rate of return. Financial analysis may be performed for a period up to

thirty-five years; estimates of financial scenarios beyond this point are considered not meaningful, due to the uncertainty associated with financial parameter values over that long a period.

Discussed in the following sections is an overview of the computer model. A more detailed discussion of the model, its structure and input requirements, is presented in a companion document: "Oil Shale Mining Cost Analysis - Volume III: Oil Shale Mining Economic Model (OSMEM) User Guide".

5.1 OSMEM Production Sub-System

The production sub-system defines a set of interconnected "elements" representing unique operating segments of the mine. A mine element can be a shaft, main, submain, entryway, section, etc.; it is differentiated further by design parameters and by equipment selections. A mine element type is defined uniquely by the following set of parameters: element configuration and dimensions, advance rate, production rate, equipment requirements, and operating costs. For simulation purposes, a mine design is reduced to a set of segments, many of which may have the same mine element type. It is the interrelationship between element types which defines the allowable sequence of operations. This determines the manner in which mining proceeds.

5.1.1 Input

The simulation process requires a specification of a mine

design. Although this need not be a detailed design, the mine layout, entryway and other dimensions must be realistically estimated. The design is translated to a single line diagram which represents the order in which each element is executed. Through consistent changes in the mine design, by reformulating the order in which elements are executed, the impact of variations in development and production strategies can be evaluated.

The line diagram subsequently is reduced to a strategy tree structure to facilitate input to the computer model. Each unique mine element type appearing in the strategy tree is distinguished by two important variables: the element's advance rate in feet per shift, and, the production rate in tons of oil shale mined per shift. Production is related to the advance rate but depends on both the mine geometry and strategy tree specification. These variables, currently computed external to the model, apply to all elements of a unique element type.

5.1.2 Processing

Once the mine element parameters have been defined, the mine strategy tree is processed by executing individual elements in sequential order. The criteria to be met prior to element execution are:

1. All predecessor elements have been executed.
2. All equipment required for the element type is available.

If either of the criteria is not met, an element is queued, to be serviced when the appropriate deficiency has been satisfied.

5.1.3 Output

The production sub-system provides output reports which include:

1. The tons produced, feet advanced, and shifts required for each segment type for the year, and cumulatively over all years.
2. The number of initial equipment requests and initial denials by equipment type, and the sum over all equipment types for the year.

In addition to these reports, the production sub-system generates a file of data elements subsequently used by the financial sub-system in developing economic performance measures.

5.2 OSMEM Financial Sub-System

The financial analysis sub-system accepts inputs generated by the production sub-system to provide various economic measures of project performance. The financial sub-system performs a discounted cash flow return on investment analysis based on cost and revenue streams computed from data merged from three sources:

1. User input
2. Production sub-system
3. Program default values

The financial analysis conforms to the guidelines published by The Engineering Societies Commission on Energy, Inc. (ESCOE). The guidelines are defined in "Guidelines for Economic Evaluation of Coal Conversion Processes" (10).

5.2.1 Input

The structure of the financial sub-system permits some degree of flexibility in specifying parameters associated with mining operations. Financial input parameters used by the program include: fixed and variable cost data, such as capital and operating expense for each element type; pre-mining expenditure data, such as mineral right and development costs; and supplementary cost data, such as royalties, escalation rates, and discount rate (minimum acceptable rate of return on investment). Additional input parameters allow for decisions concerning depreciation method, equipment purchases, and equipment retirement.

The financial sub-system has the following characteristics:

1. Development and mineral rights costs occur in year 0.
2. Development costs are treated as expenses in the years in which they are incurred.
3. Initial mining capital expenditures are assumed to occur in year 0.
4. State severance tax is computed when applicable.
5. County-level taxes are not included.

5.2.2 Processing

In the financial sub-model simulation-generated annual production and cost streams are merged with other financial parameters to compute economic performance measures.

First, revenue streams are determined. These data are used to calculate annual profit. Second, the yearly cash flow is computed by adding back annual non-cash expense to annual net profit. Then, the net present value of the investment is determined from the present value of yearly cash flow and present value of capital expenditures. Finally, a break-even analysis is performed to calculate the initial required selling price* (IRSP), given in dollars per ton mined. This measure is a key result of interest in that it represents the price required to recover all mining costs, at a specified rate of return on investment (ROI). Note that in addition to mining costs, the price of a barrel of shale oil will reflect the costs associated with processing, environmental considerations, and other cost-generating items.

5.2.3 Output

Using the information obtained from the production simulation, the financial sub-system computes the costs and revenue streams associated with the mine design and operation strategy.

* The initial required selling price represents the first year selling price required to recover all costs of production, at a specified rate of return.

From these data, various financial indicators are computed and output in the reports described below.

5.2.3.1 Capital Costs

The capital cost report shows capital expenditures per year, by capital item, for up to thirty-five years. Capital items include mineral rights costs, development costs, and capital costs. The report also includes the present value (year 0) of all capital expenditures, discounted at the minimum acceptable return on investment.

5.2.3.2 Production and Revenue

Production and revenue items include annual and total production, annual gross revenues (based on the estimated initial selling price), annual royalties, and the annual net revenue. The report also includes the present value of all gross revenues, royalties and net revenue, discounted at the minimum return on investment.

5.2.3.3 Cash Operating Costs

The cash operating cost report includes the cash operating costs per mine element per year. Typical cash operating costs include direct labor, operating supplies, and maintenance supplies. The report also includes the present value of all cash operating expenses, discounted at the minimum return on investment.

5.2.3.4 Non-Cash Operating Expenses

Non-cash operating expenses consist of depletion, depreciation, and allocated costs. Such costs represent the usage over time of capital items, and are used in the calculation of income taxes. The present value of all non-cash operating expenses is reported, discounted at the minimum rate of return.

5.2.3.5 Net Profit Per Year

Net profit per year is calculated as in a standard corporate income statement. The sum of all operating expenses, i.e., cash and non-cash, and any tax losses carried forward, are subtracted from taxable income. The non-cash operating costs are "expensed", i.e., equipment is depreciated, and development expenses are used to offset taxable income (and to generate tax losses carried forward). Taxes are charged to the taxable income and a net profit per year is reported.

5.2.3.6 Cash Flow Per Year

The yearly cash flow is calculated by adding back the yearly non-cash expenses (i.e., depreciation, depletion and allocated development expense) to the yearly net profit. The program performs this calculation for each year of the mine's life and then determines the present value, discounted at the minimum return on investment.

5.2.3.7 Summary Statistics

The results of the financial computations are tabulated. The required selling price is output and the program calculates the net present value of the investment. This is computed by subtracting the present value of capital expenditures from the present value of yearly cash flow. The program calculates a payback period for all initial capital investments and determines the effective tax rate over the 35 year period (or the mine life, if less than 35 years).

6.0 ECONOMIC ANALYSIS

The model was used to analyze the four base case mining scenarios described in Section 4. This section provides cost input details for these runs and presents base case, parametric, and sensitivity analyses.

6.1 Cost Estimates

Costs developed for each scenario include all capital and operating expenses associated with the underground mining of oil shale for surface retorting processes. Cost of surface support facilities and pre-mining activities are included. The analysis does not include costs associated with the surface retorting process, nor does it include costs associated with the surface disposal of spent shale.

Each capital and operating expense is determined from individual cost elements which include:

1. Surface Preparation
2. Surface Facilities
3. Surface Utilities
4. Development Costs
5. Equipment Costs
6. Labor Costs
7. Underground Utilities
8. Operating Supplies
9. Insurance
10. Contingencies
11. Indirect Costs

Federal tax, state tax, state severance tax, depletion allowance, and depreciation are handled internally by the model.

Costs were compiled from various sources, the details of which are described below.

6.1.1 Capital Cost

Capital cost elements include pre-mining preparation and development, surface facilities, equipment, surface utilities, contingencies and indirect costs. Costs excluded from the analysis are mineral rights, cost of land, surface disposal of raw shale, and oil shale processing costs. Each cost element is described below. Price estimates were obtained from existing reports (1,11), in-house data, or equipment manufacturers. Capital cost elements include:

1. Surface Mine Support Facilities. The cost element includes Maintenance Shop, Warehouse, Dispensary, Changehouse, Administrative Offices, Mine Offices, Gatehouses, and Explosive Storage.
2. Surface Fuel/Service Station.
3. Surface Utilities. The cost element includes electric power, communications, fire protection, and sewage disposal.
4. Surface Sitework. The cost element includes sitework, roads, parking, drainage and fencing.
5. Surface Water Facility. The cost element includes minewater storage and treatment.
6. Preliminary Site Development. The cost element includes design engineering, equipment mobilization, exploration, environmental studies, and other preproduction mining development.

The cost elements described above were assumed to be the same for each mining scenario. Other capital cost items are

specific to each mining scenario. These include shaft sinking,* service shaft and facilities, production head frames, slope development, and an outside ore pass. Costs for these items also were estimated from existing studies or from in-house data. Contingencies were determined as nine percent of the total capital expenses, excluding mining equipment.

Mining equipment was selected for each mining scenario on the basis of a seven-day, three-shift operation. Sufficient spares of critical equipment types were specified to account for equipment availability. Equipment costs for most major items are based on vendor quotes. Some items for which vendor quotes were unavailable, were estimated from past studies. All costs are in 1980 dollars. A summary of required equipment for each scenario is presented in Table 6-1.

Indirect costs are estimated as six percent of the total capital investment.

6.1.2 Operating Cost

Operating cost elements include: supervisory labor; underground labor; surface labor; utilities; operating supplies; indirect costs; and insurance.

The supervision and labor force were determined from the production and equipment requirements specified for each mining scenario. Manpower requirements were based on a continuous

* Some items categorized as capital costs, such as shaft-sinking, were "expensed" in the financial analysis. That is, they were treated as expenses in the year they occurred.

TABLE 6-1

Required Equipment and Unit Cost

Equipment	Unit Cost (In Thousand Dollars)	Quantity			
		Chamber And Pillar, With Backfilling	Room And Pillar	Sublevel Stoping	Sublevel Stoping With Backfilling
Face Drill Jumbo	205.0	10	11	10	16
Fan Drill Jumbo	229.6	26	0	9	19
Front-End Loader - 12 yd ³	510.0	0	8	20	0
Front-End Loader - 15 yd ³	581.0	0	4	0	20
LHD - 8 yd ³	186.0	10	8	8	16
Bench Drill	150.0	0	4	0	0
LHD - 15 yd ³	581.0	26	0	0	0
Roof Bolter	160.0	6	9	6	9
Scaling Machine	140.0	6	9	6	9
Locomotive	99.5	6	6	20	20
Railcar	15.2	95	30	320	320
Flat Bed	8.5	10	10	10	10
Fuel Tank Car	15.0	0	5	5	6
Track (in miles)	40.83	10	1	28	20
ANFO Loading Truck	30.0	4	5	6	7
Water Truck	58.0	2	2	2	3
Lubrication/Fuel Truck	50.0	4	5	4	4
Ventilation - 800000 cfm	291.5	4	4	4	4
Ventilation - 60000 cfm	8.0	18	11	6	10
Personnel Carrier	26.75	3	0	4	4
Portal Bus	33.0	12	14	5	5
Jeep	24.0	4	4	5	5
Fire Chemical Truck	50.0	3	3	3	4
Track Cleaner	63.7	0	0	1	1
Track Tamper	64.7	0	0	1	1
Underground Maintenance Facility	3,397.0	1	1	1	1

TABLE 6-1 (CONTINUED)

Required Equipment and Unit Cost

Equipment	Unit Cost (In Thousand Dollars)	Quantity			
		Chamber And Pillar, With Backfilling	Room And Pillar	Sublevel Stoping	Sublevel Stoping With Backfilling
Mine Dewatering	1,900.0	1	1	1	1
Belt Conveyor - 30 in.	0.2375/ft	17,250 ft	0	0	0
Belt Conveyor - 36 in.	0.25/ft	0	0	15,500 ft	20,000 ft
Belt Conveyor - 42 in.	0.2625/ft	20,000 ft	16,500 ft	0	0
Belt Conveyor - 54 in.	0.2875/ft	0	0	0	20,000 ft
Belt Conveyor - 60 in.	0.30/ft	20,000 ft	30,000 ft	0	0
Feeder/Breaker	205.0	14	6	0	16
High Voltage Cable Plus Accessories	0.025/ft	40,000 ft	30,000 ft	30,000 ft	40,000 ft
Underground Pumping Station	10.7	0	0	2	2
Raise Borer	170.0	0	0	0	4
Air Compressor (16,000 cfm)	450.0	1	1	1	1
Mine Safety Equipment	169.0	1	1	1	1
Backfill Equipment	12,500.0	0	0	0	1
Spent Shale Disposal Equipment	820.0	1	0	0	0
Underground Crusher -2000 TPH	400.0	0	0	4	2
Underground Crusher -1000 TPH	355.0	0	0	0	2
Truck - 35 ton	160.0	0	30	0	0

seven-day, three shift operating schedule. Additional underground workers were added to the requirements to allow for vacation time, sick leave, and absenteeism. Supervision and labor wage rates were estimated from existing studies and information obtained from the Denver area average salaries. Underground and surface labor wage rates were estimated at \$25,000 per year, including fringe benefits. An additional five percent of the total payroll was added to account for overtime payments. Fringe benefits of thirty-five percent were added to total supervisory labor costs. All wage rates were adjusted to 1980 using a yearly escalation rate of ten percent. Manpower requirements and annual wage rates for each mine scenario are tabulated in Table 6-2 through Table 6-4.

Material costs, utilities, fuel and lubrication costs were estimated from the existing reports and adjusted to 1980 dollars. Explosive costs were estimated using a bulk rate vendor quote. A powder factor of 1.4 was assumed.

Contingencies were computed as nine percent of operating supply costs (fuel and lubrication, explosives, materials). Indirect costs were estimated from the sum of all labor costs, exclusive of fringe benefits, and operating supply costs. Insurance was computed as one percent of the direct costs (utility, labor, operating supplies). Cost summaries for each mining scenario are documented in Table 6-5 through Table 6-8.

TABLE 6-2

Supervisory Labor Requirements

Job Classification	Annual Salary	Quantity			
		Chamber And Pillar, With Backfilling	Room And Pillar	Sublevel Stopping	Sublevel Stopping With Backfilling
General Superintendent	55,000	1	1	1	1
Mine Foreman	49,500	1	1	1	1
Assistant Mine Foreman	38,500	1	1	1	1
General Shift Foreman	31,000	4	4	4	4
Assistant Shift Foreman	27,500	4	4	4	4
Production Foreman	27,500	12	12	12	16
Development Foreman	27,500	16	8	16	28
Fill Foreman	27,500(1)	0	0	0	4
Raise Boring Foreman	27,500(1)	0	0	0	0
Maintenance Superintendent	44,000	1	1	1	1
Chief Mechanical Foreman	33,000	1	1	1	1
Shift Mechanical Foreman	31,000	4	4	4	4
Chief Electrical Foreman	33,000	1	1	1	1
Shift Electrical Foreman	31,000	4	4	4	4
Belt Crew Supervisor	27,500(1)	4	4	0	0
Chief Mining Engineer	42,000	1	1	1	1
Senior Mining Engineer	33,000	1	1	1	1
Development Engineer	31,000	1	1	1	1
Ventilation Engineer	31,000	1	1	1	1
Production Engineer	31,000	1	1	1	1
Rock Mechanics Engineer	31,000	1	1	1	1
Chief Surveyor	27,500	1	1	1	1
Surveyor	18,000	4	4	4	5
Surveyor	17,500	4	4	4	5
Technician	15,500	2	2	2	2

TABLE 6-2 (CONTINUED)

Supervisory Labor Requirements

Job Classification	Annual Salary	Quantity			
		Chamber And Pillar, With Backfilling	Room And Pillar	Sublevel Stoping	Sublevel Stoping With Backfilling
Draftsman	15,500	2	2	2	2
Safety Director	28,500	1	1	1	1
Safety Inspector	24,000	4	4	4	4
Nurse	18,000(1)	1	1	1	1
First-Aid Attendant	15,500	4	4	4	4
Purchasing Supervisor	23,000(2)	1	1	1	1
Purchasing Agent	16,500(2)	2	2	2	2
Chief Accountant	20,000(2)	1	1	1	1
Accountant	18,000	1	1	1	1
Bookkeeper	15,000(2)	1	1	1	1
Personnel Administrator	23,000(1)	1	1	1	1
Labor Relations	23,000(1)	1	1	1	1
Clerk	15,000(2)	8	8	8	8
Warehouse Supervisor	23,000(2)	1	1	1	1
Warehouseman	15,000(2)	4	4	4	4
Executive Secretary	15,000(3)	1	1	1	1
Secretary	12,500(3)	8	8	8	8
Receptionist	12,500(3)	1	1	1	1
Watchman	13,000(2)	4	4	4	4

All labor rates are based on R.M. Parsons Company report escalated by 10% to 1980 salary levels, except for:

- (1) Estimated Annual Salary
- (2) Cameron Engineers data x 1.64
- (3) Denver area 1979 salary base x 1.1

TABLE 6-3

Underground Labor Requirements

Job Classification	Annual Salary	Quantity			
		Chamber And Pillar, With Backfilling	Room And Pillar	Sublevel Stoping	Sublevel Stoping With Backfilling
Drill Operator	All wage rates	48	48	52	116
Drill Operator Helper	including	48	48	52	116
Front-End Loader Operator	fringe benefits	0	36	60	64
LHD Operator	are assumed	56	24	24	52
Powderman	\$25,000 per yr.	40	48	48	36
Beltman	Rates are based	16	20	0	20
Rock Bolt Machine Operator & Helper	on R.M. Parsons Company report	48	54	48	72
Locomotive Operator/Supplyman	adjusted by 10% to 1980 levels.	16	16	64	72
Trackman		5	5	16	5
Mechanic		48	24	48	48
Mechanic Helper		48	24	48	48
Electrician		12	8	8	8
Electrician Helper		12	8	8	8
Welder		4	4	8	4
Machinist		4	4	8	4
Machinist Helper		4	4	8	4
Ventilation Crewman		8	8	16	8
Pipeman/Pumper		24	4	4	4
Laborer		80	40	48	
Truck Driver		0	96	0	
Crusher Operator		0	0	4	8
Dispatcher		4	0	4	4
Raise Boring Crewman		0	0	0	3
Fillman		0	0	0	16
Fuelman		16	0	0	0

TABLE 6-4

Surface Labor Requirements

Job Classification	Annual Salary	Quantity			
		Chamber And Pillar, With Backfilling	Room And Pillar	Sublevel Stoping	Sublevel Stoping With Backfilling
Mechanic	All wage rates including fringe benefits are assumed \$25000 per year. Rates are based on R.M. Parsons Company report adjusted by 10% to 1980 levels.	4	4	4	4
Mechanic Helper		4	4	4	4
Surface Mobile		8	8	8	8
Equipment Operator		4	4	4	4
Lampman		4	4	4	4
Janitor		4	4	4	4
Supplyman		8	4	4	8
Electrician		4	4	4	4
Surface Fuel/Service Station Operator		4	4	4	4
Miscellaneous Operators		12	12	12	12
Hoist Operator		12	0	4	12

TABLE 6-5

Cost Summary -- Room and Pillar

<u>Capital Costs</u>	<u>(In Thousand Dollars)</u>
Surface Mine Support Facilities	20,981.
Surface Fuel/Service Station	558.
Surface Utilities	44,027.
Surface Sitework	8,351.
Surface Water Facility	10,061.
Preliminary Site Development	28,500.
Outside Ore Pass	1,000.
Contingency (9%)	10,213.
Equipment Cost	43,206.
Indirect Cost (6%)	10,014.
	<u>176,911.</u>
 <u>Annual Operating Costs</u>	
Supervisory Labor	3,480.
Underground Labor	13,729.
Surface Labor	1,260.
Utilities	4,125.
Operating Supplies	
- Fuel and Lubrication	3,744.
- Explosives	4,000.
- Material	3,500.
- Contingency (9%)	1,012.
Indirect Cost	1,501.
Insurance	349.
	<u>36,700.</u>

TABLE 6-6.

Cost Summary -- Chamber and Pillar

<u>Capital Costs</u>	<u>(In Thousand Dollars)</u>
Surface Mine Support Facilities	20,981.
Surface Fuel/Service Station	558.
Surface Utilities	44,027.
Surface Sitework	8,351.
Surface Water Facility	10,061.
Preliminary Site Development	28,500.
Service Shaft and Facilities	25,987.
Production Headframe (2)	25,002.
Shafts (5)	27,519.
Contingency (9%)	17,189.
Equipment Cost	57,740.
Indirect Cost (6%)	15,227.
	<u>281,142.</u>
 <u>Annual Operating Costs</u>	
Supervisory Labor	3,777.
Underground Labor	15,251.
Surface Labor	1,680.
Utilities	6,022.
Operating Supplies	
- Fuel and Lubrication	4,156.
- Explosives	4,000.
- Material	3,716.
- Contingency (9%)	1,068.
Indirect Cost	1,605.
Insurance	397.
	<u>41,672.</u>

TABLE 6-7

Cost Summary -- Sublevel Stoping

<u>Capital Costs</u>	<u>(In Thousand Dollars)</u>
Surface Mine Support Facilities	20,981.
Surface Fuel/Service Station	558.
Surface Utilities	44,027.
Surface Sitework	8,351.
Surface Water Facility	10,061.
Preliminary Site Development	28,500.
Shaft Sinking (4)	17,313.
Contingency (9%)	12,271.
Equipment Cost	40,303.
Indirect Cost (6%)	<u>11,342.</u>
	200,368.
 <u>Annual Operating Costs</u>	
Supervisory Labor	3,628.
Underground Labor	15,120.
Surface Labor	1,365.
Utilities	6,411.
Operating Supplies	
- Fuel and Lubrication	3,066.
- Explosives	4,000.
- Material	3,758.
- Contingency (9%)	974.
Indirect Cost	1,522.
Insurance	<u>383.</u>
	30,227.

TABLE 6-8

Cost Summary -- Sublevel Stoping, With Backfilling

<u>Capital Costs</u>	<u>(In Thousand Dollars)</u>
Surface Mine Support Facilities	20,981.
Surface Fuel/Service Station	558.
Surface Utilities	44,027.
Surface Sitework	8,351.
Surface Water Facility	10,061.
Preliminary Site Development	28,500.
Service Shaft and Facility	25,987.
Contingency (9%)	17,189.
Equipment Cost	70,992.
Indirect Cost (6%)	<u>15,227.</u>
	294,394.
 <u>Annual Operating Costs</u>	
Supervisory Labor	4,456.
Underground Labor	19,950.
Surface Labor	1,680.
Utilities	6,533.
Operating Supplies	
- Fuel and Lubrication	3,993.
- Explosives	4,000.
- Material	3,318.
- Contingency (9%)	1,018.
Indirect Cost	2,200.
Insurance	<u>449.</u>
	47,597.

6.1.3 Depreciation and Depletion

Annual depreciation costs were calculated using either the straight-line (SL) method or the sum-of-the-year digits (SYD) methods. Surface facility costs were depreciated using the straight-line method. Equipment cost was depreciated using the sum-of-the-year digits method.

Surface facility costs were depreciated over the life of the mine assuming zero salvage value. Equipment types were aggregated into two groups. The first group consisted of equipment to be depreciated over the life of the mine. A second group consisted of equipment depreciated over an eight year life, and replaced at the end of this period. Zero salvage value was assumed.

Once production begins, certain costs can be recovered through depletion allowance. Depletion may be taken as either a cost depletion or a percent depletion; each is computed by the mine model. For a given year, the method resulting in the larger deduction was used. A depletion allowance of fifteen percent was used in the analysis.

6.1.4 Taxes

Federal income tax, state income tax, and state severance tax are computed by the model based on applicable tax schedules. Not included in the analysis were royalties, rents, bonus bid payments, county taxes, and inspection fees.

6.2 Results of Economic Analysis

An analysis of each mining scenario was performed using the cost data presented in section 6.1 to demonstrate the utility of OSMEM. Table 6-9 summarizes the baseline parameter values and key results associated with each mining scenario. The start-up production histories for these scenarios are plotted in Figure 6-1.

6.2.1 Analysis of Base Case Results

Comparison of the Initial Required Selling Price results (Table 6-9) for each base case scenario is a way of assessing OSMEM's utility. Review of these base case IRSP results indicate:

1. The maximum variation in IRSP between scenarios is 62 percent.
2. At Site 1, the IRSP for chamber-and-pillar with backfill is 49 percent greater than for room-and-pillar.
3. At Site 2, the IRSP for sublevel stoping with backfill is 16 percent greater than for sublevel stoping (without backfill).

Candidate factors for explaining these results include:

1. Capital expense differences
2. Operating cost differences
3. Early production history differences
4. Steady-state production level differences

TABLE 6-9

Summary of Baseline Values

Parameter	Scenario			
	Chamber and Pillar	Room and Pillar	Sublevel Stopping	Sublevel Stopping With Backfilling
Mine Site	1	1	2	2
Shale Grade (gpt)	25	25	23	20
Capital Investment*				
- Equipment Cost	\$ 57,704	\$ 43,206	\$ 40,303	\$ 70,992
- Development Expense	132,106	69,092	96,452	132,106
- Surface Facilities	91,296	64,613	63,613	91,296
Total	\$281,142	\$176,911	\$200,368	\$294,394
Annual Operating Cost*	\$ 41,672	\$ 36,700	\$ 40,227	\$ 47,597
Annual Escalation Rate	7%	7%	7%	7%
Rate of Return of Investment (ROI)	25%	25%	25%	25%
Required Selling Price (\$/ton)	\$ 5.20	\$ 3.48	\$ 4.84	\$ 5.62
Required Selling Price(\$/bbl)**	\$ 8.74	\$ 5.85	\$ 8.84	\$11.80
Time to Full Production (years)	2.5	2.5	5.0	3.8
Full Production Averages				
- Tons per Day	80,250	87,500	86,000	87,500
- Barrels per Day	48,000	52,000	47,000	42,000

* Cost in thousands of 1980 dollars

** Mining portion of required per barrel selling price, based on shale grade

FIGURE 6-1
YEARLY PRODUCTION LEVELS TO FULL PRODUCTION

Capital and operating cost differences appear to be major factors in explaining the observed IRSP results. Differences in capital expenditures arise from differences in access method, differences in equipment requirements, and costs associated with backfilling.* Differences in operating expenditures arise from differences in manpower requirements, utility costs, and operating supplies.

The impact of capital and operating costs on the IRSP is seen by comparing the room-and-pillar mining scenario with the sublevel stoping with backfill scenario, where the IRSP differs by 62 percent. In this case, the capital and operating costs differ by 66 percent and 30 percent, respectively. This effect also is observable between scenarios at a given site. For example, at Site 1 the IRSP differs by 49 percent. Capital and operating costs differ by 60 percent and 14 percent, respectively. And at Site 2, a capital and operating cost difference of 47 percent and 18 percent, respectively contributes to a 16 percent variation in IRSP. Differences in production history at Site 2 appear to mitigate the effects of capital and operating cost differences, as explained below.

* Backfilling costs represent an expenditure for spent shale disposal not included in the room-and-pillar scenario and the sublevel stoping without backfill scenario. In order to estimate roughly the incremental expenditure for the surface disposal of spent shale, the average operating cost for spent shale disposal determined by the Mitre Corporation (12) for the Paraho process may be useful as an indicator of a lower bound (since capital expense is not included). The average operating cost of \$2.58 per barrel (in 1979 dollars) translates to \$1.54 per ton for the room-and-pillar mining scenario and \$1.41 per ton for the sublevel stoping scenario.

Early production history differences are also a factor in explaining base case IRSP differences. Early production generates early revenue, which is discounted less than later revenue. Thus, a scenario whose production begins, for example, two years before another scenario's production can generate the same ROI at a lower selling price, assuming other factors are equal. Production history differences contribute partly to the observed variations in IRSP between scenarios, and are a factor in explaining the relatively small difference in IRSP at Site 2. This effect does not appear to be significant at Site 1, because the difference between the two production histories is comparatively minor.

Differences in actual steady-state (full) production levels generated by the model make small contributions to between-case IRSP differences, since they produce differences in annual operating revenues. However, these steady-state production differences are small (up to 9 percent) compared with price differences, and their effects are diminished significantly by the (25%) discount factor, after a few years of steady-state production.

6.2.2 Parametric Analysis

Analyses were performed to estimate the influence of selected parameters on mining cost. For this study, two parameters were considered: return on investment (ROI) and oil shale quality. Selling price was determined for return on investment ranging from 15 to 30 percent. The results for each scenario are shown in Figure 6-2. At 15 percent ROI, reduction from base case values in required selling price ranged from 26 percent to 35 percent.

FIGURE 6-2
The Effect of Return on Investment on Mining Cost

At 30 percent ROI, increases from base case values ranged from 18 percent to 23 percent.

The effect of oil shale grade and return on investment on the mining cost per barrel also was determined. An evaluation was performed for oil shale grades ranging from 20 gpt to 30 gpt,* and for return on investment ranging from 15 percent to 30 percent. The results for each scenario are shown in Figure 6-3 through Figure 6-6. The mining portion of selling price per barrel decreases non-linearly with decreasing return on investment. The selling price also decreases non-linearly with increasing grade, at a fixed ROI. For example, for room-and pillar mining, the selling price is approximately \$5.24 per barrel at 20 gpt and \$3.61 per barrel at 30 gpt, at 15 percent ROI. The price reduction is a consequence of the increase in shale oil output as grade increases, for a fixed tonnage rate (see footnote).

6.2.3 Sensitivity Analysis

An analysis was performed to determine the sensitivity of mining costs to changes in capital costs, operating costs, return on investment, and annual escalation rates. For each scenario, these parameters were varied one at a time by selected percent changes relative to their base case values. Table 6-10 indicates the parameters varied, their variations and the resulting IRSP for

* In the computations, the tonnage mined remained constant while the average grade of shale varied. The intent is to show the impact of grade on mining costs for a given production rate. Since barrels produced is a function of both the grade and the production rate, changes in the daily production rate of barrels will vary directly with changes in oil shale grade (for a fixed tonnage rate).

FIGURE 6-3
Effect of Return on Investment and Grade
on Mining Cost - Room and Pillar

FIGURE 6-4
Effect of Return on Investment and Grade on
Mining Cost - Chamber and Pillar with Backfilling

FIGURE 6-5

Effect of Return on Investment and Grade
on Mining Cost - Sublevel Stoping

FIGURE 6-6

Effect of Return on Investment and Grade on
Mining Cost - Sublevel Stoping with Backfilling

TABLE 6-10

Sensitivity Analysis

Initial Required Selling Price for Parameter Variations

Parameter	Case	% Change	Value	Initial Required Selling Price (\$/ton)			
				Chamber and Pillar	Room and Pillar	Sublevel Stopping	Sublevel Stopping With Backfilling
Return on Investment	Low	-40	15%	3.44	2.58	3.29	3.68
	Base	0	25%	5.20	3.48	4.84	5.62
	High	+20	30%	6.35	4.09	5.94	6.94
Capital Investment	Low	-25	See Table 6-9	4.32	2.97	4.06	4.83
	Base	0		5.20	3.48	4.84	5.62
	High	+50		6.96	4.48	6.42	7.70
Annual Operating Cost	Low	-25	See Table 6-9	4.85	3.21	4.51	5.20
	Base	0		5.20	3.48	4.84	5.62
	High	+50		5.89	4.07	5.53	6.40
Inflation - Costs	Base	0	7%	5.20	3.48	4.84	5.62
	High	100	14%	6.25	4.45	5.75	7.45
Escalation - Price & Costs	Low	-100	0%	6.75	4.29	6.36	7.45
	Base	0	7%	5.20	3.48	4.84	5.62
	High	+50	10.5%	3.81	2.86	3.81	4.29

each scenario. These results are displayed in Figure 6-7 through Figure 6-10, which show the sensitivity of the required selling price to various percent changes in the base case parameter values for each scenario.

The initial required selling price is most sensitive to changes in return on investment. When the base ROI was increased by 20 percent (to 30 percent ROI) the required selling price increase ranged from 18 percent for the room-and-pillar mining scenario to 24 percent for the sublevel stoping with backfill scenario. When the base ROI was reduced by 40 percent (to 15 percent ROI) the required selling price decrease ranged from 26 percent for room-and-pillar mining to 35 percent for sublevel stoping with backfill.

Capital and operating cost changes did not cause equivalent percent changes in the initial required selling price; although changes in capital expenditure appear to have a more pronounced effect on mining cost than changes in annual operating expense. For example, in the room and pillar mining scenario a 50 percent increase in capital costs resulted in a 29 percent increase in mining costs, whereas a 50 percent increase in operating expense yielded only a 17 percent increase in mining cost.

When the selling price is allowed to escalate annually at the same rate as capital and operating costs escalates ("escalation"), IRSP changes are inversely proportional to changes in

FIGURE 6-7
Sensitivity Analysis - Room and Pillar

FIGURE 6-8
Sensitivity Analysis - Chamber and Pillar with Backfilling

FIGURE 6-9
Sensitivity Analysis, - Sublevel Stopping

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FIGURE 6-10
Sensitivity Analysis - Sublevel Stoping with Backfilling

the escalation rate. For example, when the base case escalation rate (7 percent) was increased by 50 percent (to 10.5 percent) IRSP reductions ranged from 11 percent room-and-pillar mining to 14 percent for chamber-and-pillar mining. This effect occurs because annual increases in selling price escalation rate have a greater positive effect on ROI than the negative effects caused by the same percentage increases in capital and operating costs.

When costs are allowed to increase faster than the selling price ("inflation"), the effect is to raise the initial required selling price. Thus, when the escalation factor for costs was increased 100 percent (to 14 percent), while selling price was escalated only at 7 percent, IRSP increases ranged from 19 percent for sublevel stoping with backfill to 28 percent for room-and-pillar mining.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The objective of the study was to adapt presently developed economic mine models to enable the estimation of mining costs for underground mining methods to be used in conjunction with the surface retorting of oil shale. The Oil Shale Mining Economic Model (OSMEM) developed for this study was demonstrated for four commercially feasible mining scenarios. The mining scenarios include: room-and-pillar mining, chamber-and-pillar mining (with backfill), sublevel stoping (without backfill), and sublevel stoping (with backfill). The scenarios were based on developing the oil shale resources at two areas in the Piceance Creek Basin (see Figure 3-1). Emphasis was placed on providing a mix of mining and access methods for recovering the resources at each site.

Costs used in the financial analysis were determined from vendor quotes, in-house data, or estimated from existing studies. All costs are in 1980 dollars. The mining cost portion of the initial required selling price was determined for each scenario. These prices are estimates based on computer analysis and best available information. The results are useful for research and development planning and for decisions for establishing technology development priorities. However, actual oil shale mining costs for a given scenario may differ somewhat from the costs computed using the input data available for this study.

Capital and operating costs for each scenario are summarized in Table 6.5 through Table 6.8. Baseline parameters and key

results for each scenario are tabulated in Table 6.9. Output results are illustrated in Figure 6.2 through Figure 6.10.

In this preliminary study, capital expenditures range from \$176,911,000 for room-and-pillar mining with drift access to \$294,394,000 for sublevel stoping (with backfilling) with shaft access. The corresponding unit mining costs range from \$3.48 per ton for room-and-pillar mining to \$5.62 per ton for sublevel stoping (with backfilling). These values do not include costs associated with surface processing of oil shale, nor do they include costs associated with the surface disposal of spent oil shale.

The model* for evaluating the economic consequence of oil shale mining provides the Department of Energy with a useful tool for evaluating the cost and efficiency of proposed oil shale projects and for establishing technology development priorities. The computer program represents an initial effort at merging simulation and financial models to enable the estimation of production and cost consequences of proposed mine designs, production strategies, and equipment strategies under different technological and financial scenarios. Refinements to the model which will improve its effectiveness are:

* The model is discussed more thoroughly in a companion document "Oil Shale Mining Cost Analysis - Volume III: Oil Shale Mining Economic Model (OSMEM) User Guide".

o Computer Generated Mine Design

The mine economics model is driven by the tree processor which computes production history and associated costs based on a mine design and a strategy for developing the property. The procedure involved in transferring the mine design to input requirements for the model requires distinct steps, many of which are amenable to automation. By automating some, if not all, of the process by which the tree structure is defined, much of the burden for generating input data can be lessened and the risk of generating input errors can be reduced. Ultimately, it may be possible to generate a mine design from a few key parameters, such as geological conditions, areal extent, mining method, etc. This capability would greatly enhance the ease with which different mine designs can be evaluated.

o Computer Generated Advance and Production Rates

Because of limited data available on cyclical underground operations associated with hard rock mining activity in geological conditions similar to the Piceance Creek Basin, the most practical method of determining advance and production rates is to have the user compute them. To enhance further the utility of the model, it is recommended that information be developed concerning the unit operations and associated times for representative underground activities. These data may be used to develop an algorithm for predicting advance and production rates to be incorporated into the mine model.

o Computer Generated Equipment Requirements

In the current version, equipment and associated crew requirements are estimated in connection with the mine planning process which generates model inputs for a given scenario. This preliminary effort could be reduced by having the computer model determine numbers of pre-specified equipment types (and crews) needed to meet the target product on rate. This approach would also yield the appropriate time-phasing of capital equipment purchases.

o Uncertainty Analysis

The computer program could be enhanced to provide an optional capability to generate a mining cost distribution that would reflect uncertainties associated with input cost elements. The approach would involve a Monte Carlo simulation based on known or assumed distributions of individual cost elements. The results would provide the user with a mining cost probability distributions; i.e., the probability that mining cost per ton will be less than or equal to any specified amount.

In addition to refinements to the model, it also is recommended that the current model be exercised to determine the financial impact of various technological concepts. These include:

1. The impact of changes in equipment characteristics.
2. The impact of various haulage configurations.
3. The impact of technological innovation affecting advance and production rates.

As a concluding observation, it is noted that the isolation of oil shale mining costs from processing, disposal and reclamation costs can be a difficult and judgmental task in many cases. This is particularly true where surface facilities support more than one of these functions. It is also true where the mining method involves backfilling with spent shale, since this approach affects both mining and disposal costs.

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APPENDIX

GLOSSARY OF TERMS

Base Case or Baseline Study. The set of estimates and parameters for an economic evaluation. The estimate of the most probable outcome. It is used as a reference point in sensitivity analysis.

Cash flow. The cash inflow and outflow of a company between two given dates or accounting periods. Cash flow in financial analysis means net income after adding back expense items that currently do not use funds, such as depreciation and depletion.

Development Costs. Once it has been determined that a project is commercially viable, the development stage begins. For tax purposes, development costs are only costs from this time on which are in excess of any net receipts from production. This is not to be confused with continuing mining development expenses.

Depreciation. A systematic and rational way of allocating cost, less salvage value, of a tangible asset over the useful life, modified by tax regulation practices. Also, the annual amount allocated. An allocation, not valuation.

Discounted Cash Flow Return on Investment. A method of analyzing investments in which future cash flows are discounted, or converted to their present values. Also known as time adjusted return, internal rate of return, project rate of return, and investor's method.

Discount Rate. The rate of change in value of a transacted amount over a unit of time, usually expressed as percentage annually and used to determine the equivalent value over time.

Escalation. A price change of an item over time for any reason, including inflation. It applies to expenses and revenues.

Extraction Percentage. The percent of material derived through mining and/or retorting of total available resources within the property boundaries and economical mining limits.

Inflation. A persistent rise in prices not accompanied by an offsetting rise in productivity. An average of all commodities, goods, or services which have escalated or de-escalated.

IRSP. The initial required selling price calculated by OSMEM. This is the starting value for the annual escalation of the required selling price.

Minimum Rate of Return on Investment. The minimum acceptable rate of return on investment given the cost of money and the risk perceived in the investment. An input to OSMEM.

Mining Horizon. The vertical extent of productive mining.

OSMEM. The Oil Shale Mining Economics Model.

Parameters. A set of values of variable which determine the characteristics or behavior of something. The financial analysis parameters determine the relationship of the required selling prices based on cost estimates.

Powder Factor. The ratio of pounds of explosive used to tons of material to be rubblized.

Present Value. The present value of a future amount is the amount of capital at the start of a definite period of time which, at a stated discount rate per year, will accumulate to a specified sum at the end of that period. Mathematically, present value equals future amount multiplied by $(1 \text{ plus discount factor})^{-T}$, where T is the number of years.

Present Value Ratio. The present value of the cash flow divided by the present value of the capital expenditures. This ratio is convenient for ranking the economic efficiency of alternate investments.

Required Selling Price. A calculated price which will pay all costs of the operation, including all operating expenses, taxes and a specified return on the capital investment. It is sometimes referred to as a minimum selling price, required revenue price, or a cost-based price.

Return on Investment. See Discounted Cash Flow Return on Investment.

Severance Tax. A state tax imposed upon the removal of minerals.

Surface Retorting Process. Above ground processing of oil shale to recover shale oil.