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ENVIRONMENTAL RESEARCH BRIEF

Overview of Environmental Impacts of Large-Scale Surface Mining of Oil Shale: Piceance Basin, Colorado

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This paper discusses an EPA study on the major environmental impacts of surface oil shale mining in the Piceance Basin. Mine plans are developed for operations producing at rates equivalent to 100,000 bbl/day, 400,000 bbl/day and 1,000,000 bbl/day. To facilitate analysis, a specific site is analyzed; however, selection of the site does not imply an endorsement of it. Environmental summaries are presented for each of the three operations. With regard to groundwater, much of the negative effect of surface mining may be mitigable for smaller operations which exploit only the upper rich oil shale strata.

Environmental impacts are generally less harmful with the smaller-scale operations than with larger-scale operations. Since economies of scale are not apparent for surface oil shale mining, the need for detailed economic evaluation of appropriate mine size is indicated.

Section 1

Introduction

This study helps to identify potential environmental implications of large-scale surface oil shale mining in the Piceance Creek Basin of Colorado. Three mine sizes were selected for study: mines equivalent to 100,000 bbl/day, 400,000 bbl/day, and 1,000,000 bbl/day (15,800 m^3/day, 63,200 m^3/day, and 158,000 m^3/day). Included in the study are : mine site selection, development of preliminary mining plans, determination of material movement volumes associated with the mining plans for each level of operation, determination of major environmental problems expected, discussion of these problems and, where appropriate, examples to consider for abatement.

Environmental Overview

Air, water, topography, wildlife, the health and safety of workers, and the local social and economic structure will be affected by the development of an oil shale industry. Many effects will be similar to those caused by any mining or petroleum development operation. The scale of operations of an oil shale industry and its concentration in a relatively small geographic area will create greater "local impacts" than are associated with smaller resource extraction and development operations.

The Piceance Basin, an area of approximately 2,300 square kilometers (900 square miles), includes the Piceance and Yellow Creek watersheds. The altitude in the basin ranges from 1,500 to 2,600 meters (5,000 to 8,600 feet) above mean sea level. The climate of the basin is semiarid with an average annual precipitation of about 43 centimeters (17 inches). Mean annual precipitation increases with altitude and ranges from about 29.5 to 64 centimeters (11.5 to 25 inches). About 60 percent of the precipitation occurs as snowfall during November through March. Most of the remaining precipitation results from spring and summer thunderstorms.

The surface water and groundwater systems in the basin are intimately related. Annual runoff from the basin is about 19 x 10^6 cubic meters (15,600 acre-feet). About 80 percent of the surface streamflow is supplied by groundwater discharge.[1] Recharge to the aquifer system is derived principally from spring snowmelt. Little, if any, summer rainfall percolates to the groundwater aquifer except in the alluvium. Runoff from the basin is affected by evaporation, irrigation diversions, and consumptive use by crops and native vegetation. Stream-flow depletions from irrigation are about 5.9 x 10^6 cubic meters/year (4,800 acre-feet/year).[1] The periods of lowest flow occur in spring and summer when irrigation diversions are greatest. The estimated 7-day, 20-year low flow on Piceance Creek is 232 liters/second (8.2 ft^3/s) below Ryan Gulch.

Irrigation return flows and groundwater discharge affect the quality of surface water in the basin. The concentration of dissolved solids ranges from less than 500 mg/l in the upper reaches of Piceance Creek to more than 5,000 mg/l in the lower reaches.[1] Water quality deteriorates in the downstream direction due in part to groundwater discharge from the Green River and Uinta Formations.

The groundwater system in the basin is complex but may be visualized as consisting of two principal aquifer systems separated by the Mahogany zone (of the Green River Formation) and locally interconnected by fractures and faults. Groundwater flows from the margins of the basin toward the north central part of the basin where it is discharged in the Piceance and Yellow Creek valleys. Recharge and discharge from the aquifer system are estimated to average 32 x 10^6 cubic meters/year (26,000 acre-feet per year).[1] Estimates of the volume of water in storage range from 3 x 10^9 to 3.1 x 10^{10} cubic meters (2.5 to 25 million acre-feet), which represents a significant potential resource.[1]

Sodium minerals in the aquifer below the Mahogany zone are being actively dissolved by groundwater. The Mahogany zone impedes the flow of water between the two aquifer systems, and large chemical differences have developed. Water quality in the upper aquifer system generally degrades with depth and in the direction of flow. The water can be classified as sodium bicarbonate water. The water contains moderate amounts of sulfate, and the concentrations of chloride and fluoride are low. Concentration of dissolved solids averages about 950 mg/l, ranging from 250 mg/l to more than 2,000 mg/l.[1]

The lower aquifer is classified as sodium bicarbonate water, with concentrations of dissolved solids ranging from 2,000 mg/l in the recharge areas to 30,000 mg/l in the north-central area. This water generally has low concentrations of calcium and magnesium (7.4 mg/l Ca, 9.5 mg/l Mg) and concentrations of fluoride exceeding 40 mg/l in the north-central part of the basin.[1]

Alluvial aquifers as thick as 43 meters (140 feet) and generally less than 0.8 kilometer (0.5 mile) wide are sources of water in the major stream valleys. Alluvial water quality is similar to the upper aquifer.[1]

Water quality and availability is a major concern in the Piceance Basin, particularly if the development of an oil shale industry is to proceed. Because the groundwater aquifers are the source of most streamflow and irrigation water in the basin, degradation of groundwater quality and disruption of aquifer systems is a major environmental concern. Underground mining and retorting operations present particular challenges for the control of pollutants, while both surface and underground operations may require significant pumping for dewatering, thereby lowering groundwater levels. Although shale developers are currently planning for zero discharge to streams, the potential exists for pollution of surface water by suspended solids, oil and grease, nutrients, toxic substances and microbial contamination.

Solid waste disposal and surface storage of spent and raw shale may provide sources of air and water pollutants through fugitive dust emissions, surface runoff, and leaching. Permanent surface disposal of solid wastes will affect local topography which may be difficult to stabilize and revegetate. Although revegetation has been achieved on spent shale in a number of studies, the issue of whether continuing maintenance will be required is not settled.

Waste streams associated with a shale industry may contain hazardous trace substances. In general, little is known about the hazards of shale-related waste streams. However, minor amounts of radioactivity will be released to the atmosphere during mining and processing, and a trace amount of radon gas will be released directly.

Noise levels during plant construction and operation, mining, and operation of supporting activities could be locally high if not properly controlled.

With regard to surface mining and retorting, if the operation is designed with proper consideration for the total economic, environmental, and social system, there is reason to believe that existing technologies for the control of residuals will perform adequately. Perhaps the greatest disruption to the ecology of the Piceance Basin would occur as a result of the large growth in the local human population supporting the shale industry. The outdoor recreational activities of this population may, in itself, significantly alter the environment of the basin.

Section 2

Mine Location

Introduction

In order to report on the magnitude of environmental disturbance which would be created by surface mining, it was decided to select an actual site within the basin for analysis. The advantage of this approach is that volumes of overburden and oil shale necessary to achieve oil production, and the accompanying environmental analysis would be based on actual conditions in the basin. Selection of an actual location facilitated this study but should not be viewed as a recommendation or endorsement for development at this particular site.

Procedure and Site Selection

Initially, outcrop or near-outcrop locations were considered the most likely sites for study. No such sites capable of supporting a mine as large as 1,000,000 bbl/day were located. In all cases observed, including the Suntech site,[2] the reserve base was limited because of a rapid deepening of reserves from the outcrop. The Suntech study,[2] which was performed for the Bureau of Mines, produced resource maps which were used to develop several cross sections of the basin.

Analysis of the cross sections indicated a relatively favorable stripping ratio location approximately 11 kilometers (7 miles) northeast of the center of the basin (Figure 1). This location is characterized by a gentle anticline of the underlying oil shale beds coincident with apparent erosion of overburden.

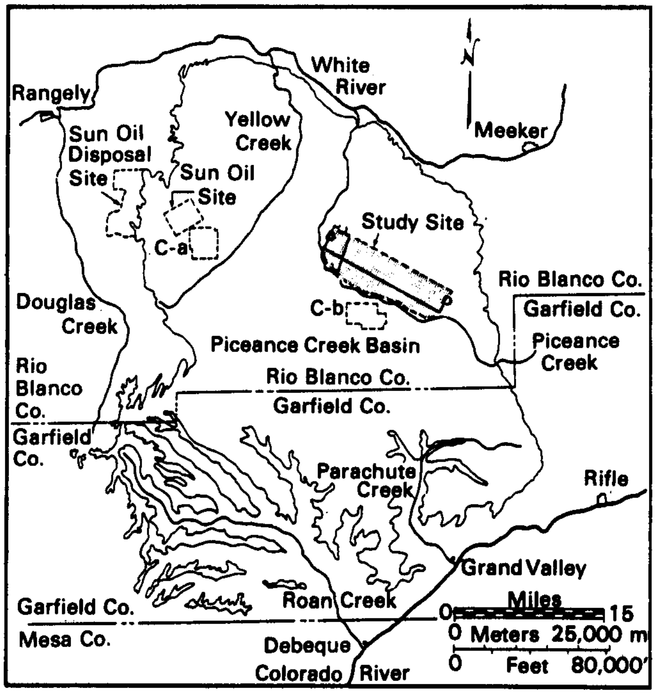

Figure 1. Area map.

Permanent storage of initial pit material appears to be available at a distance of approximately 7 kilometers (4.3 miles) north of the mine site. Whether permanent storage is appropriate is questionable. If not, initial pit material could be temporarily stored above ground near the mine site.

The study area shown in Figure 1 over which the overburden remains constant or increases only gradually consists of approximately 130 square kilometers (50 square miles). Underlying this area is an oil shale thickness of 300 meters (1,000 feet), with an average grade of 85+ liters of oil per tonne (20+ gallons/ton (excluding leaner strata). This indicates a reserve base of nearly 50 billion barrels (7.9 billion m³), which is sufficient to support a 1,000,000 bbl/day mine for 140 years.

Because of the site's location in and near the Piceance Creek valley, water is assumed to be available from the underground aquifers. The site is, however, more suitable to an effective water control plan because of its proximity to Piceance Creek.

Site Characteristics

Overburden/Oil Shale Characteristics

Profiles of the selected site within the study area were prepared both across and along the site (cross sections CC and DD, Figures 2 and 3). Typical of the basin, the profiles show overburden, the Mahogany oil shale stratum, a thin oil-less zone (B-groove), and 11 underlying oil shale strata alternately rich and lean (R-6 to R-1 and L-5 to L-1). Table 1 lists the range of thickness of the overburden and rich oil shale strata in the mining area. Table 2 lists the range of oil shale grades (Fisher assay) for the Mahogany and R-strata.

Site Hydrology

The study site lies north of Piceance Creek opposite Tract C-b. Both the upper and lower aquifers may be intersected by the mining pit, and mine dewatering will have a significant impact on the hydrologic regime. Local effects of mining on the groundwater system would be the most significant hydrologic impact of the operation.

Dewatering flow rate estimates range from 5,700 liters/minute (1,500 gpm) at Tract C-b,[3] to 57,000 liters/minute (15,000 gpm).[1] Groundwater quality and flow have not been clearly established for the basin, however, and the figures cited in this study are principally for purposes of illustrating potential groundwater impacts related to surface mining. If the latter estimates are true, excess water will be produced. Several disposal alternatives are possible: (1) reinjection, perhaps in northern, more brackish areas of the aquifer; (2) transfer to areas of water shortage; (3) treatment and disposal; or (4) a combination of the above.

Dissolved solids concentrations of the mine water should be less than 1,000 mg/l for the upper aquifer and less than 5,000 mg/l for the lower aquifer.[1] The mine site will be dewatered by drawing down the site aquifers with pumping of perimeter wells. Mine discharge will not

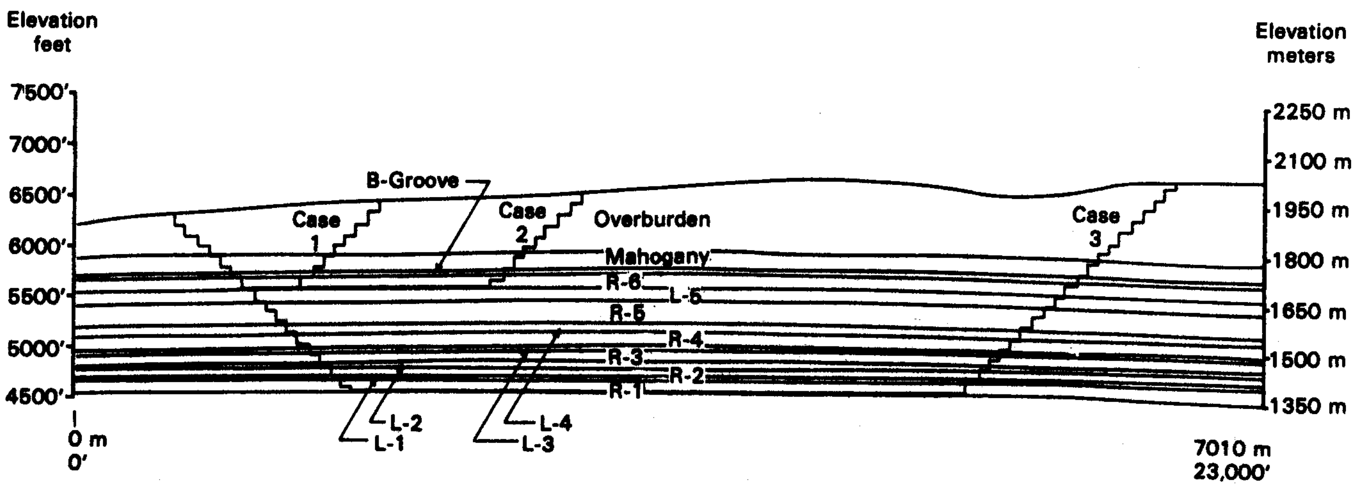

Figure 2. Cross section cc of study site.

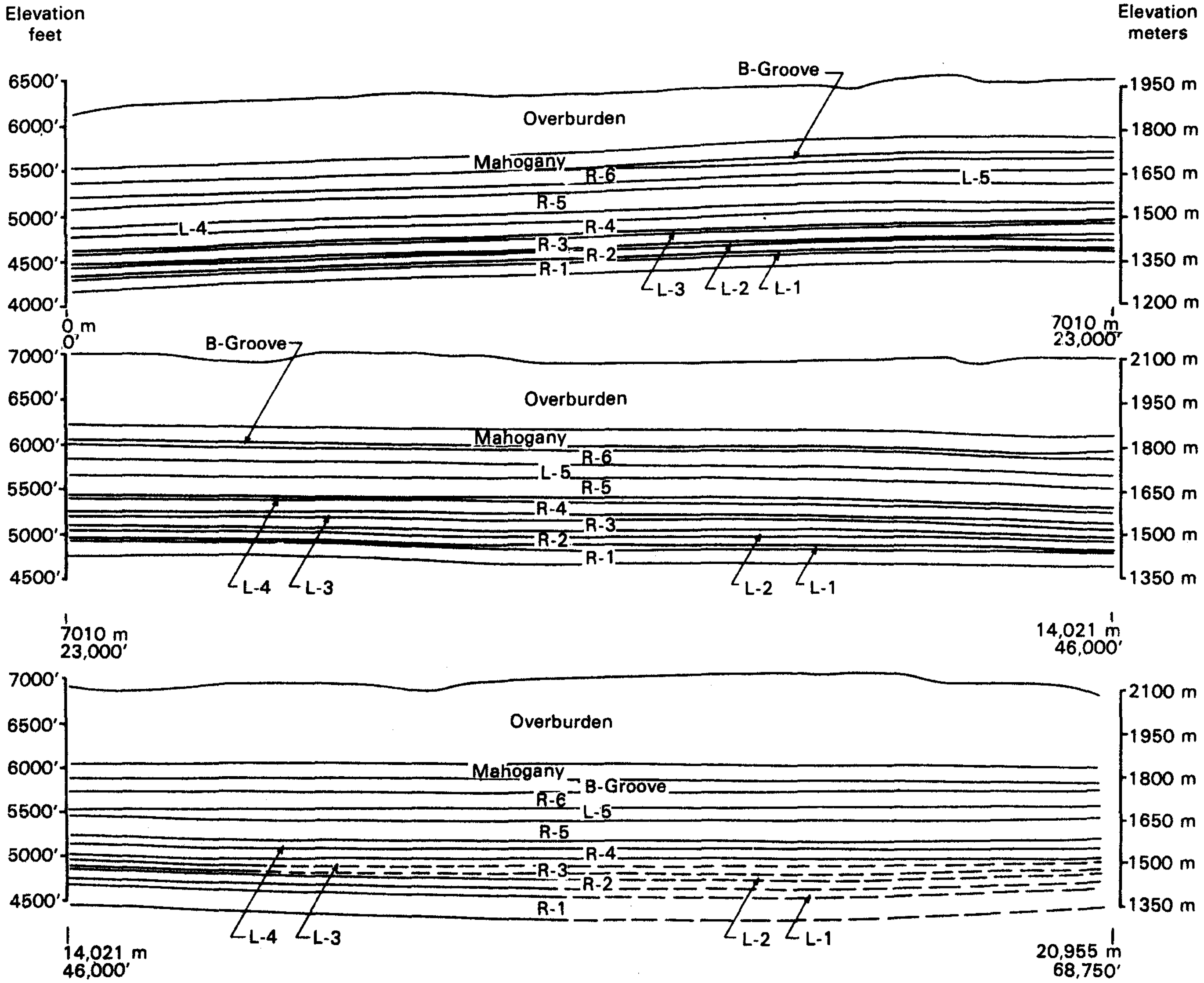

Figure 3. Cross section dd of study site.

contact raw shale rubble. Treatment of all or part of the excess water would allow utilization for a variety of purposes and may be the least disruptive method to obtain water to meet the demands of an oil shale industry, agriculture, and an expanded population. Costs of this water development strategy have been estimated to be $0.02 to $0.50/cubic meter ($20 to $600 per acre-foot) depending on the level of treatment required.[4]

Optimal treatment levels for mine water, and gas condensate and retort water are a function of mine water production, the retort process, and end use. Both solid and liquid residue streams should remain segregated to ensure economical and environmentally sound treatment. Following removal of organics and reduction in inorganic concentration levels, process waste water quality would be comparable to mine water.

Table 1. Range of Thickness of Strata at Mine Study Site[2]

Stratum	Max. Thickness Meters	Min. Thickness Meters
Overburden	375 (1,230 ft)	101 (330 ft)
Mahogany	64 (210 ft)	43 (140 ft)
B-groove	49 (160 ft)	8 (25 ft)
R-6	61 (200 ft)	37 (120 ft)
R-5	73 (240 ft)	66 (215 ft)
R-4	49 (160 ft)	27 (90 ft)
R-3	37 (120 ft)	15 (50 ft)
R-2	30 (100 ft)	18 (60 ft)
R-1	87 (285 ft)	27 (90 ft)

Table 2. Range of Oil Shale Strata Grades at Mine Study Site[2] (Fisher Assay)

	Maximum		*Minimum*	
Stratum	liters/tonne	gal/ton	liters/tonne	gal/ton
Mahogany	117	28	92	22
R-6	100	24	92	22
R-5	133	32	58	14
R-4	125	30	92	22
R-3	92	22	75	18
R-2	125	30	92	22
R-1	108	26	75	18

Section 3

Three Surface Mines

Introduction

This section postulates three surface mines capable of producing oil shale at 100,000, 400,000 and 1,000,000 bbl/day, respectively. They are described as Case 1, Case 2, and Case 3.

Assumptions which are common to all three cases are:

1. The entire mining area is adequately represented by cross sections CC and DD (Figures 2 and 3).
2. Data on thickness, depth, and grade of all strata are primarily from the Suntech report.[2]
3. B-groove stratum above the R-6 is mined selectively as waste on the same bench level as the bottom half of the Mahogany stratum.
4. Mining recovery (within the pit) of oil shale is 100% and shale oil recovery is 100% Fisher assay.
5. Initial overburden removed to open the pit is permanently stored off-site or temporarily stored near the mine.
6. Mining benches are 30.5 meters (100 feet) high and 61 meters (200 feet) wide.
7. Primary crushing of oil shale occurs at the bottom of the pit.
8. Unimpeded aquifer flow rate through dewatering is 38,000 liters/minute (10,000 gpm), treated mine water is reinjected, and there is zero discharge to surface streams.

Case 1—100,000 BBL/Day Surface Mine

Specific assumptions for Case 1 used in developing a mining plan are:

1. Truck and shovel mining is assumed because it is the current predominant mining method for deep deposits.
2. Pit floor dimensions are 244 meters (800 feet) (in the direction of mining) by 335 meters (1,100 feet).

Oil Shale Strata Mined

Overall pit dimensions must be larger for a deeper pit which requires that both overburden and ore must be hauled farther and lifted higher. Haulage capital and operating costs, which are major cost components of deep pit mining, increase with depth. Because deeper pits require more benches, relatively more ore is lost under the benches; therefore, the effective stripping ratio (the ratio of actual overburden to ore) relative to the in-place ratio of overburden to ore is higher and total resource recovery is lower for deeper pits than for shallow pits.

Surface mining upper strata does not preclude using underground methods for lower strata. The incremental cost of mining deeper reserves by strip mining must be compared to the cost of development by underground methods which include modified *in-situ* and underground mining. The cost of underground mining also increases with depth, but probably at a slower rate than surface mining.

For these reasons, detailed economic evaluations should be made to determine whether surface mines to the bottom of the oil shale strata are appropriate. This study assumed for both the 100,000 and 400,000 bbl/day (15,800 and 63,200 m^3/day) study mines that only the Mahogany and R-6 strata are surface mined. The bottom of the R-6 makes a convenient cutoff point because it abuts the low-grade L-5 stratum which might require a difficult wasting operating for a layer of interburden ranging in thickness from 18 to 60 meters (60 feet to 200 feet) and averaging 46 meters (150 feet).

Mining Plan

Figures 4 and 5 show plan and section views of a hypothetical mature truck and shovel pit capable of producing 100,000 bbl/day (15,800 m^3/day). After the initial pit is opened, overburden is mined on benches, 30.5 meters high, 61 meters wide (100 feet high, 200 feet wide) carried along the bench, and backstacked in the original sequence. Oil shale is carried along the bench to chutes for transport to the bottom of the pit where it is subjected to primary crushing. Then it is loaded on trucks and hauled out of the pit to retorting facilities assumed to be 1.6 kilometers (1 mile) from the pit. B-groove material, which is interburden, is conveyed to the bottom of the pit and used to form the permanent pit floor. Spent shale is returned to the pit directly from the retort by truck, dumped, wetted, and compacted. Table 3 lists pertinent annual mining statistics for the mature operation.

The effective stripping ratio of 4 tonnes waste/tonne oil shale for this operation is primarily a function of the size of the pit, which was designed to remain in low overburden and to maintain short haul distances. However, the narrowness of the pit, from the standpoint of resource recovery, is inefficient because relatively large amounts of oil shale are left under the development benches as the mine advances. A wider pit, even at the cost of significantly increasing average overburden height, because of a proportionately smaller amount of ore being lost under the mine benches, would reduce the stripping ratio (see Case 2).

Pit width optimization is a matter of balancing benefits of decreasing the stripping ratio against the increased hauling costs required for a wider pit. Figure 2 shows the outline of all three study mines on section CC.

Mining Equipment Required

Table 4 estimates the major mining equipment required for the Case 1 mine.

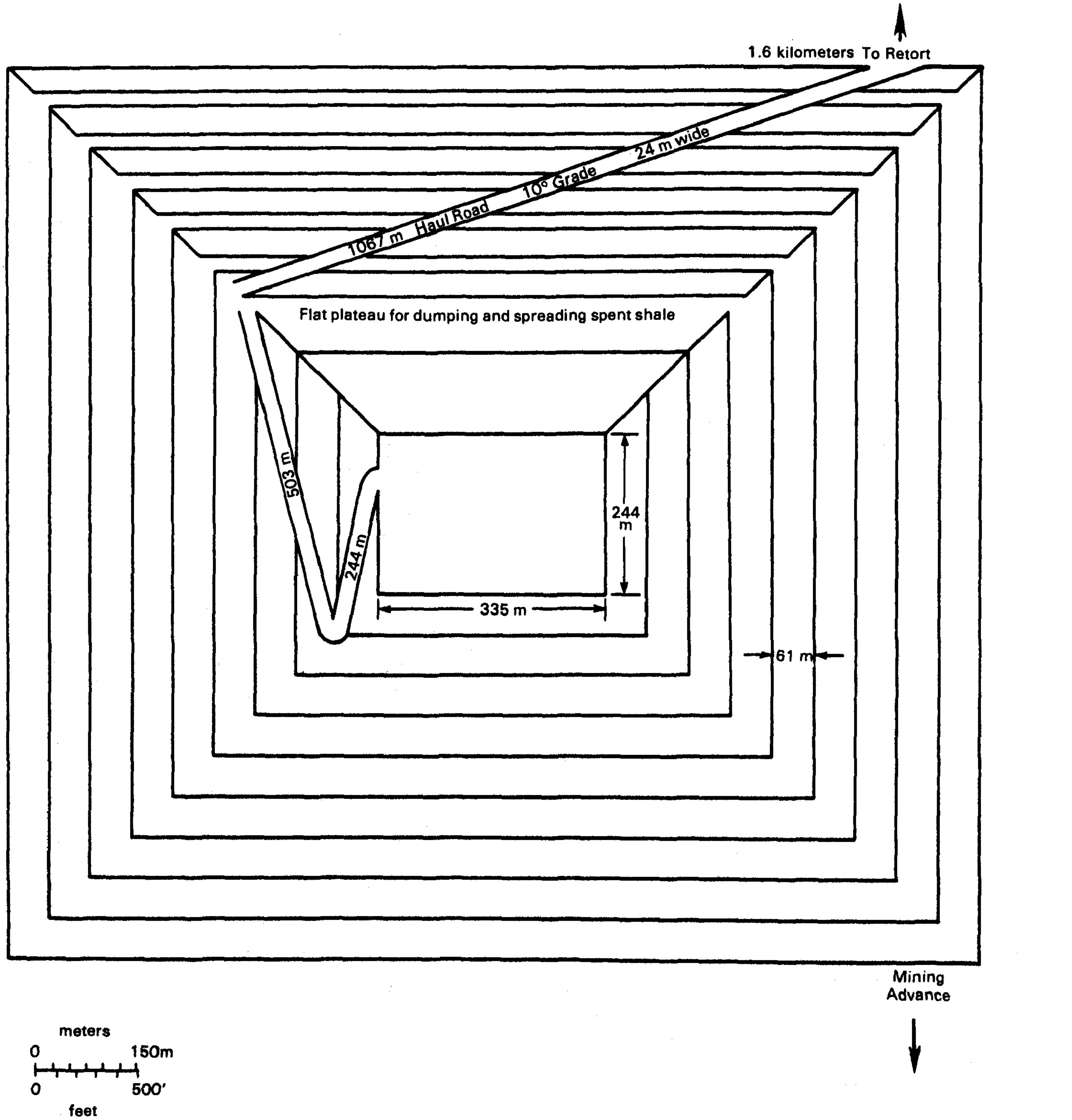

Figure 4. Plan view of mature pit — Case 1.

Other support equipment will include scrapers, graders, front-end loaders, and miscellaneous vehicles. Fuel consumption of the support equipment is estimated to be an additional 1,900 liters/hour (500 gallons/hour). In addition, approximately 53,000 tonnes/year (58,000 tons/year) of ammonium nitrate and fuel oil (ANFO) are required for blasting.

Reclamation

Backfilling the pit area would be performed by selective

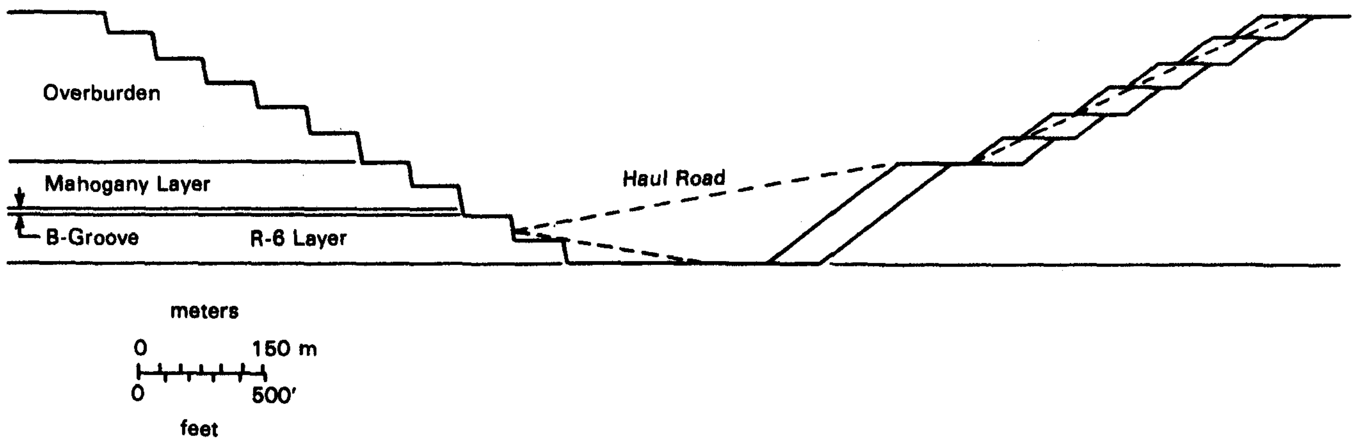

Figure 5. Mature pit cross section — Case 1.

Table 3. Mining Statistics - Case 1, Mature Pit

Overburden — thousand tonnes/day (thousand tons/day)	646	(711)
Interburden — thousand tonnes/day (thousand tons/day)	13	(14)
Total Spoil — thousand tonnes/day (thousand tons/day)	659	(725)
Oil Shale — thousand tonnes/day (thousand tons/day)	161	(178)
Oil Shale — average grade, liters/tonne (gallons/ton)	98.6	(23.6)
Shale Oil — thousand bbl/day (thousand m^3/day)	100	(15.8)
Stripping Ratio — tonnes spoil/tonne oil shale	4:1	
Mining Advance — meters/year (feet/year)	432	(1420)
Surface Disturbance — hectares/year (acres/year)	62	(153)

Table 4. Case 1, Major Mining Equipment

Type	Size	Number Required	Power D-diesel fuel E-electric	Diesel Fuel Consumed (liters/hr)	(gallons/hr)
Shovels	23 cubic meters (30 cubic yards)	15	E	n/a	
End-dump Trucks	155 tonnes (170 tons)	150	D	18,200	4,810
Bulldozers	$3x10^5$ joules/second (740 horsepower)	50	D	2,800	740
Rock Drills	25 centimeters (9.75 inches)	6	E	n/a	

placement of the overburden and compacted spent shale in the original strata sequence. All spent shale would be returned to the pit. The shale would be moistened and compacted for cementation in layers about 46 centimeters (18 inches) thick. The return of the compacted spent shale to its approximate original position should provide a relatively impermeable zone between the upper and lower aquifer systems. In this sense, the groundwater system would be returned to pre-mining conditions. This restoration is, of course, contingent upon the impermeability of the compacted spent shale to leaching. Laboratory- and field-compaction tests on spent shale indicated that permeabilities as low as 10^{-7} cm/s can be obtained.[5] Others[6,7,8] have found that spent shale cannot always be made impermeable. Returning the spent shale to its original stratigraphic position, juxtaposed to the Mahogany zone and associated Bird's Nest aquifer, would place much of the waste material — possibly including solid residuals, catalysts, chemicals, sewage and refinery-type sludge — below the static water table. Given enough time, the spent shale would become saturated. Leaching will occur through this material relative to the degree or permeability and the significance of occurrence of fracturing or other conduit formation.

Miscellaneous solids residuals, such as catalyst and chemicals, sewage, and sludges, may be produced at a rate of about 5 percent that of spent shale, or about 6,850 tonnes/day (7,550 tons/day). Products in this waste stream from which no secondary benefits can be derived will have to be disposed of in conformance with federal and state regulations. One possibility may be to isolate the material between layers of compacted spent shale in the pit.

Topsoil salvaged during the mining operation would be placed on reclaimed land to be revegetated.

Continuous backfilling and reclamation during mining operations will minimize material exposure times. All material will be returned to the pit with the exception of 122,000,000 cubic meters (160,000,000 cu yds) of overburden removed during the initial pit development. Because waste and spent shale will occupy more volume after disturbance, reclaimed land will be higher than the original contour. Side slopes of the reclaimed land surface must be planned so that surface runoff is controlled to minimize leaching of the spoil and erosion of the surface.

Two alternative methods are available for filling the final pit. First, the initial pit overburden can be stored in the area of the initial pit and at the end of mining be transported to the final pit for fill. Along cross section DD, the mine life will be 45 years and the final pit will be 21 kilometers (13 miles) from the initial pit. The advantages of this approach are short haul distances for development of the pit and possible postponement of reclamation costs. Both advantages have a favorable financial impact in the early stages of surface mining. A disadvantage is the requirement for much longer haul distances to transport the initial overburden to the final pit. This disadvantage might be somewhat mitigated by the availability of hauling equipment upon cessation of mining. The second method is to permanently store the initial overburden about 11 kilometers (7 miles) from the site on rugged terrain and withhold a portion of overburden spoil, and as mining approaches the area of the final pit, stockpile the spoil and use it to fill the final pit. Because both overburden and spent shale swell, adequate amounts of spoil will be available. This alternative method would decrease the distance to haul fill for the final pit, but it may require additional trucks.

Leaving a typical open pit mine, after covering backfilled spent shale with adequate overburden, would require careful planning to ensure that the final configuration of the reclaimed pit has minimal adverse impact on groundwater levels, quantity, and quality in the basin.

Water Management

Table 5 lists the inorganic salt concentrations of the upper and lower aquifers and compares the salt concentrations of these aquifers with the TOSCO wastewater. If the wastewater from the TOSCO process were treated to remove organic contaminants (and possibly some metals and inorganic contaminants), the remaining water probably could be reused or reinjected into the lower aquifer. Figure 6 depicts this water management plan. Within economic restraints, this plan suggests that wells be drilled into the aquifers in such a manner that water is allowed to enter the pit, through fractures in the walls, only in quantities sufficient to maintain low dust levels. If the remaining water were treated to remove salts, it could be sold to process developers or reinjected into the surrounding aquifers to help maintain groundwater levels.

If the assumed aquifer flow rate of 38,000 liters/minute (10,000 gpm) is realized, and if oil shale processing requires 3 barrels of water per barrel of shale oil produced (a high estimate), the aquifer water would be sufficient to provide the required water for 100,000 bbl/day of shale oil, and minimal use of surface water would be required by this operation.

Dust

A recent EPA report titled "Environmental Perspective on the Emerging Oil Shale Industry"[9] lists five estimates of atmospheric particulate emissions from oil shale mining. In terms of tonnes of dust per tonne of oil shale mined, these estimates vary from 1.2×10^{-4} to 6.3×10^{-3}, a very wide range.

As a source of dust generated during mining and processing, limestone is a relatively high producer. EPA has

Table 5. Water Quality: Upper and Lower Aquifers and TOSCO Wastewater, (mg/l)

Inorganics	Aquifer[1] Upper (mean values)	Aquifer[1] Lower (mean values)	TOSCO[8] Wastewater
Ca	50	7.4	280
Bicarb	550	9,100	100
Carbonate	n/a	n/a	360
Cl	16	690	570
TDS	960	9,400	3,100
Fl	1.4	28	<1
Mg	60	9.5	100
Na	210	3,980	670
Sulfate	320	80	850
K	1.5	11	<1

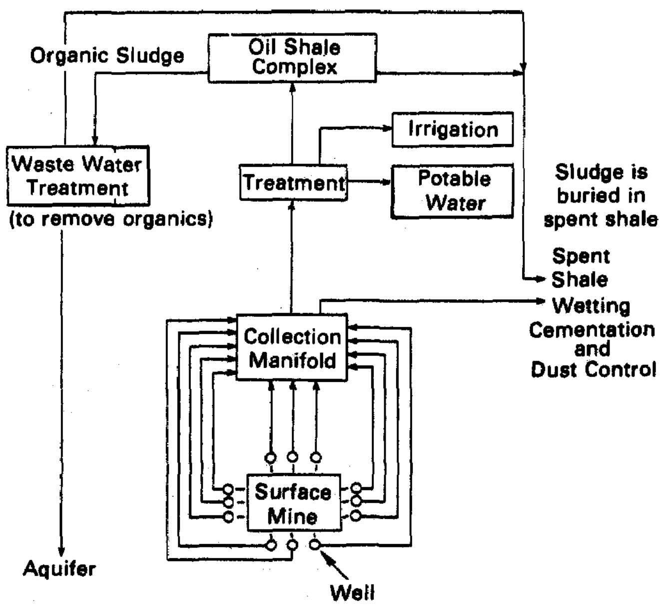

Figure 6. Water management plan.

studied limestone emissions, reported in "Source Assessment: Crushed Limestone, State of the Art"[10] and published the data shown in Table 6 relating mass particulate emissions from limestone to various stages of mining and processing operations. Total limestone dust emissions of 3.5 grams/tonne are equivalent to 3.5×10^{-6} tonnes of particulates per tonne of ore mined.

Assuming similar dusting characteristics for oil shale (which is dolomitic marlstone), Table 7 is constructed. Predicated on the above assumption, a 100,000 bbl/day surface mine would emit 2.13 tonnes (2.35 tons) of particulate dust per day with partial controls (primarily on roads). The principal source of dust would be vehicular traffic between the pit floor and plant and reclamation areas.

Environmental Summary — Case 1

Impacts on air quality at the mine site could result from dust generation and gaseous emissions from mining equipment. Data from comparable limestone operations were extrapolated, with the associated degree of uncertainty, and indicate particulate dust emissions of 2.13 tonnes per day (2.35 tons/day). The principal source of dust results from vehicular traffic. Fuel consumption by mining and support equipment is estimated to be 550,000 liters (145,000 gallons) of diesel fuel per day. Based on emission data (Table 8) this would result in the following diesel engine emission rates per day:

SO_2	3.4 tonnes/day	(3.7 tons/day)
NO_2	7.4 tonnes/day	(8.1 tons/day)
Aldehydes and Ketones	0.7 tonnes/day	(0.8 tons/day)
Total Hydrocarbons	13.5 tonnes/day	(14.9 tons/day)
Total particulates	8.1 tonnes/day	(8.9 tons/day)

The 100,000 bbl/day operation may not have a large impact on water resources, but drawdown of groundwater in the vicinity of the pit would result from dewatering. Oil shale processing water requirements (3 bbl water/bbl shale oil or 33,100 liters (8,750 gallons) per minute water) would be provided by the dewatering operation which produces 38,000 liters/minute (10,000 gpm). Excess water would be treated and sold or reinjected, with zero discharge to streams. Comparison of salt concentrations in TOSCO wastewater and aquifer water indicate that it may be possible to treat the process wastewater and reinject it into the lower aquifer.

Surface environmental impacts would be minimized by compacting spent shale and residual solids in the pit beneath replaced overburden. Continuous backfilling and reclamation, with topsoil material replacement, would limit disturbed surface exposure to about 62 hectares (153 acres). Overburden from initial pit development (122,000,000 cubic meters) (160,000,000 cubic yards) would be stored and revegetated off-site, with possible subsequent transport of some of the material to fill the final pit.

During the 45-year mine life, 4,050-8,100 hectares (10,000-20,000 acres) would be altered by mining and ancillary activities. This could have a large impact on zoological species in and adjacent to the area. The significance of this impact beyond relocation of local populations is unknown and requires further study. Vegetative disruption would be temporally shorter, and

Table 6. Mass Emissions from Various Operations in the Crushed Limestone Industry

Operation	Particulates (grams particulate/tonne limestone)*
Drilling	0.11
Blasting	0.075
Loading at the quarry	0.0015
Vehicular traffic	2.3
Primary crushing	0.56
Primary screening	0.0016
Secondary crushing	0.14
Secondary screening	0.0009
Conveying	0.32
Stockpile	nil
Unloading at stockpile	nil
Total	3.5

*Parts per million or pounds per million pounds.

Table 7. Estimated Dust Emissions from Various Oil Shale Surface Mining Operations-Case 1

Operation	Rock Processed (000 tonnes/day)	Rock Processed (000 tons/day)	Particulate Dust Emissions (tonnes/day)	Particulate Dust Emissions (tons/day)
Drilling	820*	903	0.09	0.10
Blasting	820*	903	0.06	0.07
Loading at the pit	820*	903	nil	nil
Vehicular traffic	820*	903	1.89	2.08
Primary crushing	161**	178	0.09	0.10
Primary screening	161**	178	nil	nil
Secondary crushing	-†	-	-	-
Secondary screening	-†	-	-	-
Conveying	-†	-	-	-
Stockpile	-†	-	-	-
Total			2.13	2.35

*Total rock mined—overburden and oil shale.
**Oil Shale only.
†Retorting process—not applicable to this study.

Table 8. Typical Diesel Fuel Emissions[11]

	grams/gram diesel fuel
SO_2	0.0075
NO_2	0.0165
Aldehydes and Ketones	0.0016
Total Hydrocarbons	0.030
Total Particulates	0.018

Diesel = 820 grams/liter (S.G. = .82)

native or introduced species should adapt to the reclaimed area within a reasonable time.

Vehicular energy requirements would be 0.035 bbl diesel fuel/bbl shale oil. Approximately 1.5 kg (3.3 lb) of ANFO per barrel of shale oil would be required for blasting.

Case 2 — 400,000 BBL/Day Surface Mine

Case 2 is a 400,000 bbl/day (63,200 m³/day) surface mine in the study site area. In addition to the general assumptions made for all study cases, the specific assumptions for Case 2 are:

(1) Truck or enclosed conveyor and shovel mining.
(2) Pit floor dimensions are 245 meters (800 feet) by 1,435 meters (4,700 feet).
(3) Mahogany and R-6 oil shale strata only are mined.

Except for the option of enclosed conveyors instead of trucks, Case 2 is an extension of Case 1 to a larger scale. The life of the Case 2 mine in the study area is 35 years.

Mining Plan

The mining plan for Case 2 is substantially the same as for Case 1. Overburden is mined on 61-meters wide (200-ft.) benches, carried along the benches, and backstacked in the original sequence. Oil shale is carried along the bench by trucks or conveyors to chutes where it is transported to the bottom of the pit for primary crushing (for which the requirements are greater for the conveyor operation). Next, it is loaded on trucks or conveyors and hauled out of the pit to the retort. As in Case 1, B-groove material is conveyed to the bottom of the pit and used for the permanent pit floor. Spent shale is returned and dumped, wetted and compacted on the pit floor. Table 9 lists pertinent annual mining statistics for the mature operation.

The stripping ratio of 3:1 for Case 2 is 25% less than Case 1, notwithstanding an increase of approximately 10% in overburden thickness (see Figure 2) because of increased resource recovery associated with the wider Case 2 pit.

Mining Equipment Required

Table 10 estimates the major conventional mining equipment required for the Case 2 mine.

The number of shovels per unit for shale oil output is less for Case 2 than for Case 1 in proportion to the stripping ratios for the two cases. On the other hand, the number of trucks per unit of shale oil for the truck haulage operation is greater because of longer haul distances, in spite of the 25% reduction in stripping ratio.

Table 9. Mining Statistics-Case 2, Mature Pit

Overburden — thousand tonnes/day (thousand tons/day)	1,855	(2,040)
Interburden — thousand tonnes/day (thousand tons/day)	47	(52)
Total Spoil — thousand tonnes/day (thousand tons/day)	1,902	(2,092)
Oil Shale — thousand tonnes/day (thousand tons/day)	652	(719)
Oil Shale — average grade, liters/tonne (gallons/ton)	97.4	(23.4)
Shale Oil — thousand bbl/day (thousand m³/day)	400	(63.2)
Stripping Ratio — tonnes spoil/tonne oil shale	3:1	
Mining Advance — meters/year (feet/year)	562	(1,843)
Surface Disturbance — hectares/year (acres/year)	153	(378)

Table 10. Case 2, Major Mining Equipment

Type	Size	Number Required	Power D-diesel fuel E-electric	Diesel Fuel Consumed (liters/hr)	(gallons/hr)
Shovels	23 cubic meters (30 cubic yards)	45	E	n/a	
End-dump Trucks	155 tonnes (170 tons)	650	D	78,700	20,820
or Conveyors				n/a	
Bulldozers	$3x10^5$ joules/ second (740 horsepower)	220	D	12,500	3,305
Rock Drills	25 centimeters (9.75 inches)	20	E	n/a	

Support equipment shows fuel consumption increased an additional 8,300 liters/hour (2,200 gallons/hour). Approximately 164,000 tonnes/year (180,000 tons/year) of ANFO are required for blasting.

Reclamation

Reclamation for Case 2 would be the same as Case 1 except on a larger scale. The amount of initial pit overburden which must be stored permanently or temporarily is 279,000,000 cubic meters (336,000,000 cu yds). The same options regarding the final deposition of the initial pit overburden are available for Case 2 as for Case 1.

Water Management

Aquifers intercepted by the pit in Case 2 are the same as those for Case 1. The water management plan would be similar to Case 1 (Figure 6). Water usage requirements for the 400,000 bbl/day operation would, however, be 132,000 liters/minute (35,000 gallons/minute) based on 3 bbl of water /bbl of shale oil. Groundwater pumping in addition to the pit dewatering operation may be required to meet the water needs. Since the quality of the waters will be similar to Case 1, post-use treatment and disposal would be the same.

Dust

Table 11 lists estimated dust particulate emissions for the Case 2 truck haulage operation. These estimates are based primarily on the methodology used in Case 1 (Table 2) with a significant adjustment for dust generated by vehicular traffic because of that source's predominant proportion of total emissions generated. If the methodology of Case 1 were adhered to, the increase in dust from vehicles for Case 2 over Case 1 would be a factor of 3:1. Because of the larger pit and longer haul distances, Case 2 requires an estimated 650 trucks compared to Case 1's requirement of 150, a ratio of 4.3:1. It is reasonable to assume that dust generated by vehicles will depend more directly on the number of operating vehicles than on the production tonnage. Therefore, vehicular dust for Case 2 was assumed to be 4.3 times that for Case 1. An estimated 8.97 tonnes per day (9.87 tons/day) of dust particulates would be emitted, of which 91% is attributable to vehicular traffic.

Because of substantial reduction in vehicular traffic, enclosed conveyor haulage of shale and overburden produces significantly less dust than truck haulage. We have assumed a reduction of 85% in the emission factor listed in Table 6 for vehicle-generated dust for the conveyor haulage option, and added a conveyor-mining emission source.[10] Table 12 lists the estimated particulate dust emissions for the Case 2 enclosed conveyor option.

Summary — Case 2 Environmental Impacts

Air quality impacts of the 400,000 bbl/day operation were estimated using substantially the techniques of Case 1. Dust emissions for the 400,000 bbl/day truck haulage operation are estimated to be 8.97 tonnes/day (9.87 tons/day). Using enclosed conveyors for haulage instead of trucks reduces particulate emissions 72% to 2.54 tonnes/day (2.80 tons/day).

For the truck haulage operation, fuel consumption by mining equipment is estimated to be 2,390,000 liters (630,000 gallons) of diesel fuel per day. Based on the emission data of Table 8, this would result in the following diesel engine emission rates per day:

SO_2	14.7 tonnes/day	(16.2 tons/day)
NO_2	32.3 tonnes/day	(35.5 tons/day)
Aldehydes and Ketones	3.1 tonnes/day	(3.4 tons/day)
Total hydrocarbons	58.8 tonnes/day	(64.7 tons/day)
Total particulates	35.3 tonnes/day	(38.9 tons/day)

Emissions from diesel-operated equipment would decrease by 79% for the enclosed conveyor operation because primary haulage equipment would be electrically powered.

Water requirements of the 400,000 bbl/day operation could have a considerable effect on the groundwater regime of the upper Piceance basin. Treatment and disposal to Piceance Creek may be required to maintain pre-mine flow rates. Groundwater levels would be lower over a larger area (10-12 times) of the upper basin than in Case 1. Treatment and disposal of process water would be similar.

Table 11. Estimated Dust Emissions from Various Oil Shale Surface Mining Operations-Case 2, Truck Haulage

Operations	Rock Processed (thousand tonnes/day)	Rock Processed (thousand tons/day)	Particulate Dust Emissions (tonnes/day)	Particulate Dust Emissions (tons/day)
Drilling	2,554*	2,810	0.28	0.31
Blasting	2,554*	2,810	0.19	0.21
Loading at the pit	2,554*	2,810	nil	nil
Vehicular traffic	2,554*	2,810	8.13	8.94
Primary crushing	652**	719	0.37	0.41
Primary screening	652**	719	nil	nil
Secondary crushing	-†	-	-	-
Secondary screening	-†	-	-	-
Conveying	-†	-	-	-
Stockpile	-†	-	-	-
Total			8.97	9.87

*Total rock mined — overburden and oil shale.

**Oil shale only.

†Retorting process — not applicable to this study.

Table 12. Estimated Dust Emissions from Various Oil Shale Surface Mining Operations - Case 2, Enclosed Conveyor Haulage

Operation	Rock Processed (thousand tonnes/day)	Rock Processed (thousand tons/day)	Particulate Dust Emissions (tonnes/day)	Particulate Dust Emissions (tons/day)
Drilling	2,554*	2,810	0.28	0.31
Blasting	2,554*	2,810	0.19	0.21
Loading at the pit	2,554*	2,810	nil	nil
Conveying-Mining	2,554*	2,810	0.82	0.90
Vehicular traffic	2,554*‡	2,810	0.88	0.97
Primary crushing	652**	719	0.37	0.41
Primary screening	652**	719	nil	nil
Secondary crushing	-†	-	-	-
Secondary screening	-†	-	-	-
Conveying	-†	-	-	-
Stockpile	-†	-	-	-
Total			2.54	2.80

*Total rock mined —overburden and oil shale.
**Oil shale only.
†Retorting process—not applicable to this study.
‡Reduced emission factor listed in Table 6 by 85% because of no truck haulage.

although greater in magnitude, to that for the 100,000 bbl/day operation.

The disposal and reclamation of overburden, spent shale, and residual solids for Case 2 would be similar to Case 1. The disturbed surface exposure for the 400,000 bbl/day operation would be about 153 hectares (378 acres). Off-site storage would be required for 279,000,000 cubic meters (336,000,000 cubic yards) of initial pit overburden.

Vehicular energy requirements would be 0.038 bbl of diesel fuel per bbl shale oil for the truck haulage operation and 0.008 bbl of diesel fuel per bbl of shale oil for the conveyor haulage operation. Approximately 1.2 kg (2.6 lbs) ANFO/bbl shale oil would be required for blasting.

Case 3 — 1,000,000 BBL/Day Surface Mine

Case 3 is a 1,000,000 bbl/day (158,000 m^3/day) surface mine in the study area and differs in two important respects from both Cases 1 and 2: mining equipment and strata mined. In addition to the general assumptions made for all case studies the specific assumptions for Case 3 are:

(1) Enclosed conveyor/shovel mining.

(2) All rich oil shale strata down to the R-1 stratum are mined.*

(3) Pit floor dimensions are 244 meters by 3,500 meters (800 feet by 11,600 feet).

(4) Mine life is 100 years.

Shovel/Conveyor Mining

For Case 3, the mining method selected is electric power shovels loading both overburden and oil shale into feeder-breakers which, in turn, load onto conveyor belts. This method was selected principally because the scale of this mine would cause very large traffic congestion problems for a truck/shovel operation.

Oil Shale Strata Mined

As in cases 1 and 2, overburden is mined and carried along the mining benches and backstacked in the original sequence. The dimensions of the mining benches are the same as the previous cases: 30.5 meters high by 61 meters wide (100 feet high by 200 feet wide). Overburden, interburden, and oil shale are conveyed along the benches to main lines. Overburden and oil shale are conveyed out of the pit: oil shale to the retort and overburden to the backstack area. Interburden is conveyed to a position on top of the compacted spent shale. Spent shale is conveyed from the retort back to the pit bottom, and is wetted and compacted.

Table 13 lists pertinent mining statistics for Case 3. The average stripping ratio is 1.35 tonnes of overburden per tonne of oil shale. The improved stripping ratio is a result of mining the deeper oil shale strata and improved resource recovery because of a wider pit. These two factors overcome the effect of increasing overburden thickness.

Mining Equipment Required

Table 14 lists the major conventional mining equipment estimated to be required for Case 3.

Support equipment would add an estimated 30,300 liters/hour (8,000 gallons/hour) of fuel consumption. Approximately 273,000 tonnes/year (300,000 tons/year) of ANFO are required for blasting.

Reclamation

Other than scale, the major reclamation difference between Case 3 and the previous cases is that compacted and wetted spent shale is placed directly on the pit floor, and interburden which is primarily lean oil shale is stacked above the spent shale. Overburden is placed on top of the interburden. All transportation is provided by conveyors and compaction is done by dozers.

*This study does not consider processing of the lean shale zones. It may, however, be feasible to process these zones either for the shale oil only or for the shale oil and associated minerals such as nahcolite and dawsonite. In this study, B-groove and zones L5-L1 are considered interburden.

Table 13. Mining Statistics - Case 3, Mature Pit

Overburden - thousand tonnes/day (thousand tons/day)	1,715	(1,886)
Interburden - thousand tonnes/day (thousand tons/day)	740	(814)
Total Spoil - thousand tonnes/day (thousand tons/day)	2,455	(2,700)
Oil Shale - thousand tonnes/day (thousand tons/day)	1,822	(2,004)
Oil Shale - average grade, liters/tonne (gallons/ton)	87.4	(21.0)
Shale Oil - thousand bbl/day (thousand m^3/day)	1,000	(158)
Stripping Ratio - tonnes spoil/tonne oil shale	1.35:1	
Mining Advance - meters/year (feet/year)	189	(620)
Surface Disturbance - hectares/year (acres/year)	120	(297)

Table 14. Case 3, Major Mining Equipment

Type	Size	Number Required	Power D-diesel fuel E-electric	Diesel Fuel Consumed (liters/hr)	(gallons/hr)
Shovels	23 cubic meters (30 cubic yards)	80	E	n/a	
Bulldozers	$3x10^5$ joules/second (740 horsepower)	800	D	45,400	12,010
Rock Drills	25 centimeters (9.75 inches)	32	E	n/a	
Conveyors/ Feederbreakers			E	n/a	

Initial pit overburden and interburden, which must be permanently or temporarily stored is 2,388,000,000 cubic meters (3,129,000,000 cu yds) - a very large amount.

Water Management

Open pit operations for the 1 million bbl/day production requires mining to depths of 725 meters (2,400 feet). Water requirements for Case 3 are 331,000 liters/minute (87,500 gallons/minute) based on 3 bbls water/bbl shale oil. Because of the pit depth, aquifer systems above and below the Mahogany zone will be impacted and demetered to some extent.

Dust

Table 15 lists estimated dust emissions from the Case 3 mine based on the same methodology used for the Case 2 conveyor operation. The vehicular emission factor (Table 6) has been reduced by 85% to account for the absence of truck haulage, and a conveying-mining function has been added because of the substitution of conveying for truck haulage.

The elimination of truck haulage, the major contribution to dust emissions, could reduce the estimated levels of dust for Case 3 to slightly more than twice the level of Case 1, although the shale oil production of Case 3 is ten times that of Case 1 and the total rock mined is five times that of Case 1.

Summary-Case 3 Environmental Impacts

Estimates of dust emissions for Case 3 are 4.53 tonnes/day (4.98 tons/day). Fuel consumption by mining equipment is estimated to be 1.82×10^6 liters (480,000 gallons) of diesel fuel/day. Based on emission data (Table 8), this would result in the following emission rates per day:

SO_2	11.2 tonnes/day	(12.3 tons/day)
NO_2	24.6 tonnes/day	(27.1 tons/day)
Aldehydes and Ketones	2.4 tonnes/day	(2.6 tons/day)
Total hydrocarbons	44.8 tonnes/day	(49.3 tons/day)
Total particulates	26.9 tonnes/day	(29.6 tons/day)

The 1,000,000 bbl/day open pit operation would have major impacts on the water resources in the upper basin. The stratified pre-mining local geology would be replaced by a more-or-less homogeneous medium after backfilling. The interface between the upper and lower, more saline, aquifer would thereby be removed. Also, without substantial pretreatment and maintenance of flow to Piceance Creek, the quantity and quality of surface water in the lower basin would be reduced. Many of the potential impacts on the hydrology of the basin could be irreversible, but with proper design and control, many of these impacts can be kept to a minimum.

Table 15. Estimated Dust Emissions from Various Oil Shale Surface Mining Operations - Case 3

Operation	Rock Processed (thousand tonnes/day)	(thousand tons/day)	Particulate Dust Emission (tonnes/day)	(tons/day)
Drilling	4,277*	4,704	0.47	0.52
Blasting	4,277*	4,704	0.32	0.35
Loading at the pit	4,277*	4,704	0.01	0.01
Vehicular traffic	4,277*‡	4,704	1.37	1.51
Primary crushing	1,822**	2,004	1.48	1.63
Primary screening	1,822**	2,004	nil	nil
Secondary crushing	-†	-	-	-
Secondary screening	-†	-	-	-
Conveying	-†	-	-	-
Stockpile	-†	-	-	-
Total			4.67	5.14

*Total rock mined—overburden and oil shale.
**Oil shale only.
†Retorting process—not applicable to this study.
‡Reduced emission factor listed in Table 6 by 85% because of no truck haulage.

Surface environmental impacts of the 1,000,000 bbl/day operation might not be as significant as other impacts. Spent shale and residual solids would be buried at the pit floor. Reclamation activities would limit disturbed surface exposure to 120 hectares (296 acres); less than that for the 400,000 bbl/day operation due to the deeper pit. Storage requirements for initial pit interburden and overburden would be substantial, 2,388,000,000 cubic meters (10 square miles to a depth of 300 feet).

A substantial relocation of zoologic species could occur directly from mining and from the large influx of mine and support personnel. Vehicular energy requirements would be 0.011 bbl diesel fuel/bbl shale oil. Electric powered conveyors would be the major energy consumers in production. Since these would not be conventional equipment, quantified energy requirements are not available. Approximately 0.8 kg (1.7 lb) ANFO per bbl shale oil would be required for blasting.

Section 4

Summary

Analysis of the projected impacts of surface mining at the levels of 100,000 bbl/day, 400,000 bbl/day, and 1,000,000 bbl/day indicates that the scale of the mining operation plays an important role in pollutant generation and environmental impacts. Truck and shovel mining may be well suited for smaller operations, but truck transport may become unmanageable in Cases 2 and 3. Reclamation activities also present some unanswered questions based on the scale of the projected mines and amounts of materials to be moved, stored, and replaced.

Water-related impacts appear to be minimal for the Case 1 mine with only some local dewatering taking place. At the Case 2 and 3 levels, water requirements for mining, retorting, and spent shale disposal exceed projected mine dewatering rates. In this situation, additional damage may result in area or basin-wide groundwater depletion and aquifer mixing.

Particulate emissions are generated primarily by haul-road traffic and diesel engine exhaust. Using conveyers instead of trucks for Case 2 yields a reduction of approximately 7 tons/day of dust emissions and 30 tons/day of diesel engine particulates. The most promising areas for improvement in levels of particulate emissions appear to be in reducing truck traffic and in improving the emission characteristics of diesel engines.

Economies of scale, both with respect to output and final pit depth are not apparent. In view of the relatively favorable environmental impacts associated with smaller operations, detailed economic evaluations of mine size should be performed to determine the appropriate scale of operations.

References

1. Weeks, John B., George H. Leavesley, Frank A. Welder, and George Saulinier, Jr., "Simulated Effects of Oil Shale Development on the Hydrology of Piceance Basin, Colorado," Geological Survey Professional Paper 908, 1974.
2. "Technical and Cost Evaluation of Candidate Large-Scale Open Pit Oil Shale Mining Methods in Colorado," Suntech, Inc., for U.S. Bureau of Mines, Contract No. 50241046, July 1976.
3. Miller, Glen A., telephone communication to Arnold H. Pelofsky, June 23, 1981.
4. Office of Technology Assessment, *An Assessment of Oil Shale Technologies,* Washington, DC, June 1980.
5. Heistand, R.N., and W.G. Holtz, "Retorted Shale Research," 13th Oil Shale Symposium Proceedings, Colorado School of Mines, 1980.
6. Harbert, H.P., and W.A. Berg, *Vegetative Stabilization of Spent Oil Shale,* EPA-600/7-78-021, 1978.
7. Nevers, T.D., *et al., Predicted Cost of Environmental Controls for a Commercial Oil Shale Industry, Vol. 1,*

D.R.I., University of Denver, Report COO-5107-1, prepared for U.S. Department of Energy, July 1979.

8. Crawford, K.W., *et al., Preliminary Assessment of the Environmental Impacts from Oil Shale Developments,* Table 3-11, EPA-600/7-77-069, July 1977.
9. Bates, Edward R., and Terry L. Thoem, Editors, *Environmental Perspective on the Emerging Oil Shale Industry,* Table 3-1, EPA-600/2-80-205a, 1980.
10. Chalekode, P.K., T.R. Blackwood, and S.R. Archer, *Source Assessment: Crushed Limestone, State of the Art,* Table 1, EPA-600/2-78-004e, April 1978.
11. Stern, A.C. *et al. Fundamentals of Air Pollution,* Academic Press, 1973.