OIL SHALE AS A POTENTIAL ENERGY SOURCE

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INTRODUCTION

Although the physical exhaustion of petroleum resources appears to be many years away, the increasing demand for petroleum has led to concern for adequately meeting future demand. The conversion of oil shale to a synthetic crude oil, which can be accomplished by various systems under consideration, is one of the several alternative ways to supplement petroleum requirements.

An oil shale processing complex consisting of three mines, three retorting plants, and a prerefinery has been proposed for the production of 100,000 barrels per calendar day of semirefined oil. Included are the equipment and installation for mining and retorting in the Roan Creek area in Colorado and the pipelining of the gas and crude oil to the prerefinery in DeBeque, Colo. In addition, the cost of chemicals and catalyst, interest during construction (plants), interest during development (mine), startup expenses, and working capital have been taken into account. The complex is designed to process 174,820 tons per stream day or 157,335 tons per calendar day (CD) of raw oil shale assaying 30 gallons of oil per ton of shale. Figure 1 is a block diagram of the total complex.

MINE DEVELOPMENT AND GENERAL MINING PLAN

Three mines will be operated to produce the required tonnage. At each mine, development will begin by driving three headings from the outcrop in the top bench of the minable section of the oil shale. These headings will be 30 feet wide by 31 feet high with 60-foot barriers between headings. One heading will be the main return airway, the center heading will be the belt haulage, and the right heading will be the intake airway and haulageway for men and supplies.

It is assumed that the development headings can be turned to the right at 600 feet and be clear of any weathering along the outcrop. The development headings will consist of three entries similar in size and functions to the main heading. The production panels will start operations as the development has advanced the required distance. It is estimated that 200 days will be required to open the first panel.

The mining plan is to mine the right side of the mine until the limits of mining are reached. The left side will be mined on the retreat. Under this system the mine will go into full production in the shortest possible time. It also means that the working area will be concentrated and better control of ventilation, haulage, and supervision will result.

Sufficient places will be provided to load tonnage. The crews will be equipped with a heading jumbo, scaling and bolting rig, bulldozer, front-end loader, and trucks.

The production panels are 1,860 feet by 1,020 feet and are mined using a 33-foot thick heading round and 28-foot bench round. The headings are 60 feet wide. Sixty-foot square pillars, regularly spaced, are left for support. A ramp will provide haulageway from the bench round to the main haulage level. Production panels will be equipped with a heading jumbo, a bench jumbo, scaling and bolting rigs, bulldozers, front-end loaders, and trucks.

The ore will be transported to portable crushers located at the mouth of the panel. These crushers will discharge onto a 60-inch belt that will carry the ore to the main haulage 60-inch belt.

The roof will be supported by roof bolts on 6-foot centers. Sixty-foot barriers will be left between panels and development on main headings.

Ventilation will be provided by 1 million cfm dual fans at the main portals. Direction of the airflow is controlled by crosscuts, regulators, and overcasts. Portable blowers with tubing provide secondary ventilation.

PRIMARY CRUSHING AND SCREENING PLANT

The run-of-mine shale is conveyed directly to the receiving hoppers at the crushing plant; one plant is provided for each of the three mines. The underground concrete hoppers are sized to provide 24-hour surge storage. The shale from the bottom of the hopper is conveyed to the primary-crusher feed bin at a rate of 58,272 tons per stream day or 2,428 tons per hour. A 90-percent onstream factor is assumed for the plants. Three conveyors, 48 inches wide and 200 feet long, are required. The shale is dumped into three parallel storage bins which are sized for 1/2-hour holdup. From the storage bins the shale is fed by magnetic vibratory feeders to the primary gyratory crushers where the size of the shale is reduced to minus 10.5 inches. The crushed shale is conveyed to underground surge bins (sized for 24-hour holdup).

The shale from the bottom of the surge bins is transported to the secondary crusher feed bins on 48-inch-wide belt conveyors.

SECONDARY AND TERTIARY CRUSHING AND SCREENING PLANTS

The shale at a rate of 58,272 tons per stream day is fed from the storage bins to three double hopper feed bins in the secondary crushing system. From each surge bin the shale is fed by two magnetic vibratory grizzly bar screens (six operating in parallel). The minus 4.5-inch material (47 percent of the total) falls through the screen to the product conveyor from the secondary crushers. The plus 4.5-inch material feeds to the secondary crushers (six crushers in parallel) and is crushed to minus 4.5 inches. The shale is then conveyed back under the screens, picking up the material that originally passed through the vibrating grizzlies, and is transported to tertiary crushing.

Three feed hoppers in tertiary crushing provide 20-minute holdup and receive the shale at a rate of 805 tons per hour for each hopper. Magnetic vibratory feeders (6 in parallel) are used to feed the vibrating screens (6 in parallel); the minus 3-inch material is screened out and falls on the product conveyors from the tertiary crushers. The plus 3-inch material (35 percent of the total) then feeds to the tertiary crushers (6 in parallel) where it is reduced in size to minus 3 inches. The shale is then transported by the return conveyors, picking up the material that passed through the 3-inch screens, to the main conveyor and is conveyed to three surge storage hoppers (3-day holdup).

From the surge storage hoppers 57,600 tons per stream day of shale is fed to the splitter in the screen house. Sixty-five percent of the shale bypasses the screens and feeds directly to the surge bin for feed to the retorting plant. The double-deck screens (three in parallel plus one spare) remove the minus 1-inch material on the top screen and minus 3/16-inch material on the bottom screen. The screens are fed by vibratory feeders. The shale from the top of the screens feeds to the conveyor that transports the bypass to the retorting plant and the fines from the screens (2,256 tons per stream day) are conveyed to the briquetting plant.

The overall dust losses in the crushing and screening operations are estimated to be 1.32 percent of the shale handled. Half of this loss is assumed to occur in crushing and transporting and the balance in screening.

BRIQUETTING PLANT

The fines are conveyed to the briquetting surge bin No. 1 on a 20-inch belt conveyor. The fine shale is then fed by vibratory feeders to two parallel hammer mills where it is reduced in size to minus 14 mesh. From the mills the shale is conveyed to surge bin No. 2. A vibratory pan feeder is used to feed the milled shale to two parallel double-paddle horizontal mixers where it is mixed with crude shale oil (binder). From the mixers the material flows by gravity into the briquetting machines.

The briquettes are then sent by conveyor to surge bin No. 3 and are then conveyed back to the retort feed conveyor.

RETORTING PLANT

The three retoring plants, each consisting of four 56-foot diameter units, will be located in close proximity to the three mine locations. The retorts are scaled up from smaller unit data but are assumed operable to facilitate this study.

The shale from the 3-hour surge bins and the briquettes from the briquetting plant are fed to the retort feed hoppers (atop the retorts). Each of the plants uses one belt conveyor equipped with an automatic tripper to feed the retorts.

The retorts are equipped with Cameron and Jones[1] improved feeding and discharge mechanisms. The feeding and discharge mechanisms are described in detail ("Quarterly of the Colorado School of Mines," v. 60, No. 3, July 1965) in a paper presented to the Second Oil Shale Symposium.[2]

Each retort processes 14,376 tons per stream day of shale and briquettes and produces 9,693.5 barrels per stream day of crude shale oil, 86,242,000 standard cubic feet per day of excess low-Btu gas, and 11,160 tons per stream day of spent shale.

The shale bed in the retorts is maintained at a depth of approximately 18 feet. The fresh feed at the top of the unit is preheated by the off gases from the retort combustion zone. The shale, at a rate of 500 pounds per hour per square foot of cross sectional area, moves through the preheat zone of the retort. The combustors, located near the midpoint of the shale bed, use recycled low-Btu gas burned with air to provide the heat needed for retorting.

About 82 percent of the recycled gas is fed to the bottom of the retort and is utilized to cool the spent shale to about 200° F prior to discharge. The remainder of the recycled gas, together with the combustion air, is fed directly to the combustors.

The gases from the top of the retorts, with entrained crude shale oil, flow through rotoclones and electrostatic precipitators for separation of gases and oil. The crude is then pumped to storage tanks located at the retorting site. The low-Btu gas is compressed either for recycle or to supply other plant fuel requirements.

The spent shale is fed to a common conveyor belt for discharge into a canyon. The mines and retort plants are located to provide dry canyons for the spent shale disposal. It is assumed that mined out areas will be utilized as soon as they become available. The crude shale oil from the retorts, 116,322 barrels per stream day, flows by pipeline to the refinery storage tanks near DeBeque, Colo.

PREREFINERY

The crude oil from storage is charged to a distillation column. The crude is heated in a furnace enroute to distillation. The crude charge is decomposed into a heavy fraction and vapors, about 50 percent bottoms and 50 percent overhead. The residual heavy fraction from the bottom of the distillation column is fed to the coke drums. The overhead product is cooled and depropanized to yield a distillate product, 55,100 barrels per stream day. The uncondensed gases, consisting of C_3 and lighter gases, are utilized for plant fuel. The liquid hydrogenated product, 42° API, is pumped to storage.

The bottoms from the distillation column are fed through a preheat furnace to the delayed coking units. The feed is preheated prior to being charged to the drums. The product from the top of the coker, the coker distillate, is cooled and depropanized and then, together with the distillation overheads, is charged to hydrogenation. The coke from the drums, 1,710 tons per calendar day, is stored for sale. The hydrocrackers operate at 835° F and 1,500 psig and produce a product containing about 45 volume percent material in the gasoline boiling range.

The gas streams from the hydrogenation, delayed coking, and distillation contain the sulfur and nitrogen available for recovery, the recoverable materials being in the form of hydrogen sulfide and ammonia. The streams are processed as follows: An ammonia-water wash is used to remove the hydrogen sulfide from the coker and distillation gases, and a water wash is used to extract the ammonia and hydrogen sulfide from the hydrogenation gas. The combined ammonia-hydrogen sulfide-water solution is then heated to 170° F to drive off the hydrogen sulfide which is scrubbed with sulfuric acid to remove traces of ammonia. The hydrogen sulfide is reacted with air in a Claus kiln to form sulfur (85.5 tons per calendar day) which is recovered as a hot liquid and stored for sale. The ammonia-water solution is pressurized to 230 psig and heated to 330° F to liberate the ammonia (275.5 tons per calendar day), which is cooled, condensed, and stored for sale in liquid form.

About 89 percent of the washed gas from the gas treating plant is steam reformed to produce the hydrogen needed for hydrocracking. The gas used for hydrogen generation is converted to produce 76 percent of the hydrogen theoretically available with complete conversion of the gas. A small amount of methane is purchased to augment the fuel supply. Using methane as an example (other hydrocarbons in the coker gas react in an analogous manner), the conversion involves the two following steps:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad (1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (2)$$

with the following overall result:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \qquad (3)$$

The first reaction takes place in tubes at 50 psig and 1,400° to 1,500° F using a nickel catalyst and an excess of steam. The endothermic heat of reaction is supplied by burning retort gas in the furnace surrounding the tubes. The hydrogen yield then is increased by catalytic water-gas shift conversion at 800° F as illustrated by equation 2. A hypersorber is used for hydrogen purification before compression and introduction to the hydrocracking unit. The hydrogen requirement is 1,662 standard cubic feet per barrel of product. Twenty-five percent excess hydrogen is produced to provide for surges and losses.

CAPITAL INVESTMENT

Table 1 is a summary of the estimated total capital investment required to develop the mines and to install the equipment to process 174,820 tons per stream day of oil shale. Included are initial catalyst and chemicals, interest during construction, startup expense, and working capital. The total estimated capital investment is $426,216,400.

WORKING CAPITAL

Working capital requirements are detailed in table 2. Interest during construction assumes a two-year construction period. An allowance of $11,033,100 is included for startup expenses.

The cost of providing steam, power, cooling water, sanitary water, compressed air, etc., is included in plant utilities. The cost of administrative buildings, roads, fences, rolling stock, etc., is included in plant facilities. A summary of utility and facility costs is given in table 3.

OPERATING COST

Table 4 is a summary of the estimated annual operating costs. Included in operating costs are labor, labor supervision, administration and general overhead, raw water charges, annual catalyst and chemicals, taxes, insurance, and depreciation. The annual operating cost is $85,543,000 before credit for the byproducts and $78,434,600 after credit.

FINANCIAL ANALYSIS

Table 5 shows the method of determining financial analysis based on a 12-percent discounted cash-flow rate which takes into account the present value of capital expenditures (both before and after startup). The present value of the positive cash flow includes the effect of changes after depreciation is taken. A selling price of $3.74 per barrel for the semirefined oil (30-gallon shale) is required to balance the present value of the capital expenditure with the present value of the positive cash flow, using a 12-percent compound and discount factors and a 20-year life.

Figure 2 illustrates the effect of varying the debt equity segment of the capital investment and the relationship of different values for the interest rate on the debt portion of the investment. This relationship is based on a selling price of $3.74 per barrel for the semirefined oil.

REFERENCES

1. Reference to specific makes or models of equipment is made to facilitate understanding and does not imply endorsement by the Bureau of Mines.

2. Russell J. Cameron. Cameron and Jones Vertical Kiln for Oil Shale Retorting. Pp. 131-146.

TABLE 1. - Capital investment summary, 30-gallon shale

Mine:	
Initial investment	$24,609,400
Present worth of deferred expense (discounted at 12 percent)	14,518,900
Retort plant:	
Retorting	115,381,100
Crushing and screening	12,316,000
Briquetting	1,582,000
Refinery	113,339,700
Utilities	41,469,400
Facilities	30,898,200
Total	354,114,700
Initial catalyst	9,517,700
Total plant cost	363,632,400
Interest during construction (plant)	16,225,200
Interest during development (mine)	561,700
Startup expense (plant)	11,033,100
Subtotal for depreciation	391,452,400
Working capital	34,764,000
Total	426,216,400

TABLE 2. - Working capital, 30-gallon shale

		Dollars
Cash	30 CD operating cost	6,952,800
Accounts receivable	90 CD operating cost	20,858,400
Inventory	30 CD operating cost	6,952,800
		34,764,000[1]

[1] Includes $5,944,100 for mine.

TABLE 3. - Summary, utilities and facilities, 30-gallon shale

	Utilities	Facilities
Retorting plant:		
Generator	$3,375,000	
Turbine	8,160,000	
Startup diesel generator set	1,080,000	
Power distribution	4,125,000	
Air compressor	3,582,000	
Gas compressor	1,582,200	
Steam generation and distribution	333,000	
Site preparation, etc		$1,500,000
Administration building		750,000
Subtotal	22,237,200	2,250,000
Refinery:		
Powerplant	9,100,000	
Power distribution	3,850,000	
Steam generation	5,200,000	
Air compression plant	750,000	
Telephone system	332,200	
Warehouse		480,100
Maintenance & operating building		266,700
Central shops		3,683,600
Intermediate gathering system		1,945,000
Water treatment and distribution (includes cooling water)		8,983,300
Condensate system		1,540,100
Laboratories		1,149,500
Operating unit buildings		2,937,600
Other refinery buildings		638,600
Refining site, roads, and fences		1,053,700
Sewage and refuse system		5,970,000
Subtotal	19,232,200	28,648,200
Total	41,469,400	30,898,200

TABLE 4. - Annual operating cost, 30-gallon shale

	Annual cost, dollars
Natural gas--3,610 Mscf/CD x 365 days/yr x $0.25/Mscf...	329,400
Charge for use of water (Colorado)... ...480 M gph x 8,760 hr/yr x $0.026/M gal...	109,300
Annual catalyst and chemicals...	5,335,000
Direct labor plant...	2,980,900
Direct labor supervision plant...	540,000
Direct labor mine...	5,282,500
Direct labor supervision mine...	378,000
Maintenance labor plant...	4,325,000
Maintenance labor supervision plant...	420,000
Maintenance labor mine...	1,526,300
Maintenance labor supervision mine...	315,000
Operating supplies, mine...	10,102,400
Operating supplies, plant (20% of plant maintenance)...	1,814,000
Maintenance materials, plant (100% of maintenance labor)	4,325,000
Payroll overhead, mine (35% of payroll)...	2,625,600
Payroll overhead, plant (25% of payroll)...	2,066,500
Administration and general overhead, plant...	1,235,900
Administration and general overhead, mine...	1,293,800
Taxes (land valued at $1,000/acre, 6 sq miles) at 68 mills per dollar of evaluation...	261,100
Taxes on improvement at mine (at 68 mills per dollar on 1/3 the cost)...	557,800
Insurance, mine, 2% of investment...	492,200
Taxes (retorting, crushing and screening, and interplant pipelines) at 68 mills per dollar on 1/3 the cost...	3,485,300
Insurance (retorting, crushing and screening, and interplant pipelines) at 2% of investment...	3,075,300
Taxes (refinery) at 68 mills per dollar on 1/3 the cost.	3,870,000
Insurance (refinery) at 2% of investment...	3,414,800
Depreciation ...	25,381,900
Annual operating cost...	85,543,000

Cost, dollars/barrel of oil = 85,543,000 ÷ 36,500,000 = 2.34

$$\text{Cost, dollars/barrel of oil after byproduct credit} = \frac{85{,}543{,}000 - 7{,}108{,}400}{36{,}500{,}000}$$

$$= 2.15$$

TABLE 5. - Financial analysis, 30-gallon shale

Year	Estimated capital investment	Positive cash flow, oil at $3.74/bbl, dollars	Discount or compound factors, 12 percent	Present value investment, dollars	Present value cash flow, dollars	Federal income tax, dollars
-2	58,126,100	-	1.2544	72,913,400		
-1	269,549,100	-	1.120	301,895,000		
0	64,022,300	-	1.000	64,022,300		
1	-	61,011,100	.893		54,482,900	22,446,200
2	-	61,011,100	.797		48,625,800	22,446,200
3	-	61,011,100	.712		43,439,900	22,446,200
4	-	61,011,100	.636		38,803,100	22,446,200
5	5,481,200	61,011,100	.567	3,107,800	34,593,300	22,446,200
6	-	61,011,100	.507		30,932,600	22,446,200
7	-	61,011,100	.452		27,577,000	22,446,200
8	-	61,011,100	.404		24,648,500	22,446,200
9	-	61,011,100	.361		22,025,000	22,446,200
10	32,403,200	61,011,100	.322	10,433,800	19,645,600	22,446,200
11	-	61,011,100	.287		17,510,200	22,446,200
12	-	61,011,100	.257		15,679,900	22,446,200
13	-	61,011,100	.229		13,971,500	22,446,200
14	-	61,011,100	.205		12,507,300	22,446,200
15	6,369,600	61,011,100	.183	1,165,600	11,165,000	22,446,200
16		61,011,100	.163		9,944,800	22,446,200
17		50,018,500	.146		7,302,700	33,438,800
18	3,111,600	50,018,500	.130	404,500	6,502,400	33,438,800
19		50,018,500	.116		5,802,100	33,438,800
20	-34,764,000	50,018,500	.104	-3,615,500	5,201,900	33,438,800
Total				450,326,900	450,361,500	

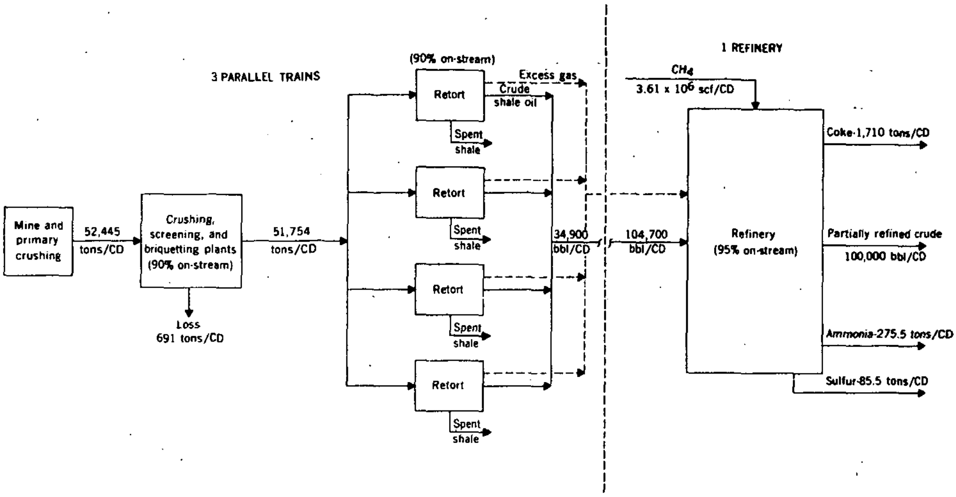

FIGURE 1. - General Block Diagram - Oil Shale Project, 100,000 Barrels per Calendar Day

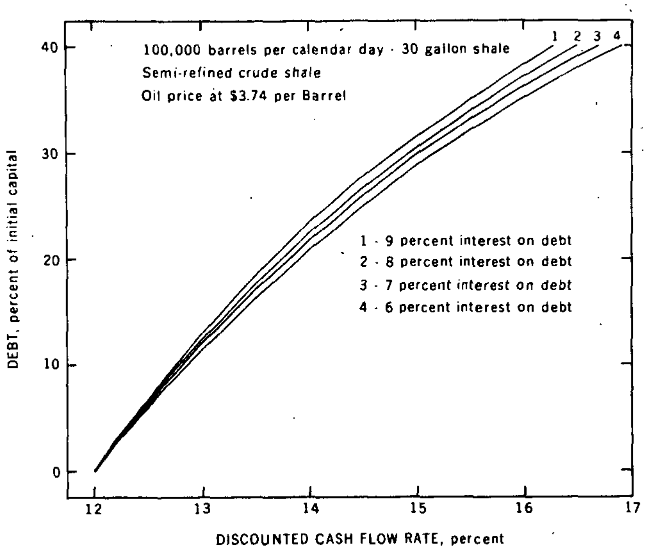

FIGURE 2. - The Effect of Debt-Equity Split on DCF at Various Interest Rates on Debt