Economic Aspects of Oil Shale Production Using Radio-Frequency In Situ Retorting

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SUMMARY

In the late 1970s, IIT Research Institute (IITRI) developed the concept for retorting Green River Formation oil shale in place, using radio-frequency (RF) electromagnetic energy. The concept was proven in a field test in 1980, and in 1982 a conceptual design for a 100,000-bbl/day, commercial-scale, integrated RF retorting plant was developed. This work suggested that the RF in situ process had significant economic and environmental advantages over mining shale and processing rock in a surface retort. Petroleum sales prices needed then to return a profit were estimated at between $25/bbl and $35/bbl.

Since then, efforts continued, some as spinoffs to other applications, to make the RF oil shale process competitive with conventional petroleum processes. The technical results of this continuing work are described in a companion article (Bridges and Sresty, this volume).

Reexamining the earlier 100,000-bbl/day studies, several opportunities to improve the costs and efficiencies were noted, as follows:

- Replace the 35%-efficient coal-fired electrical power plant with a 50%-efficient gas-fired electrical power plant.
- Use high-Btu gas produced in the retorting process as the primary fuel for the electrical power plant and supplement this with purchased natural gas for power generation and product upgrading.
- Simplify the mining and electrode placement plan.
- Reduce the retorting temperature from 385°C to 345°C (725°F to 650°F).
- Use purchased electrical power at current low prices, accepting interruptible power for the bulk of the load.
- Retort higher grades of oil shale.

Based on the economic attractiveness revealed by revisiting the 100,000-bbl/day conceptual designs, several modifications were evaluated for their effects on costs, including wider electrode spacing and horizontally oriented electrodes.

These modifications to the 1982 conceptual design were analyzed, and revised cost estimates were made using sensitivity analyses. Where information was available to examine price sensitivity, the results suggest that reasonable profits can be made using the modified design when the price of oil is about $25/bbl. Leveraged financing and potential cost savings from other process improvements suggest that the required selling price may be even less than $20/bbl.

BACKGROUND

As IITRI's conceptual design for RF oil shale in situ extraction has evolved from concepts developed in the late 1970s, the economics for a potential commercial facility have evolved as well. The 100,000-bbl/day plant considered necessary in the early 1980s has given way to smaller demonstration and commercial facilities designed to prove the technology and economics and reduce risks. This economic analysis builds on work done in the early 1980s, in particular a comprehensive technical and economic study by Bechtel Group in 1982 that was partially funded by Occidental Corporation. This study was described in a paper presented at the *17th Oil Shale Symposium* (Gould and others, 1984); the design is illustrated in Figure 1. Results of that study were updated by Bowden and others (1985). This study is the basis for comparing and factoring certain costs to evaluate changes in design criteria, process concept, and industry methods and equipment.

Bowden and others (1985) concluded that the RF in situ process has very attractive economics; capital costs were only one-half to one-fourth those of competing surface processes, and oil could be profitably produced at sales prices of $25/bbl to $35/bbl, depending on project financing assumptions. The 1991 analysis included further improvements to the process that could lead to producing oil with a profitable sale price of around $20/bbl.

UPDATE OF THE 100,000-BBL/DAY PLANT

The 1991 analysis updated the 1985 cost estimate for the 100,000-bbl/day plant to reflect changes in power plant technology and purchased power costs and to escalate the estimate to 1991 dollars. The basis of the update is given in Table 1.

In 1982 two electric-power supply alternatives were evaluated—(1) a dedicated coal-fired power plant not on the oil shale facility site, and (2) purchased power from local utilities or the power grid. The 1,500-MW power plant was assumed to operate at 35% efficiency and almost doubled the capital investment required for the project. Purchased power was estimated to cost 60 mills/kWh.

Both operating and capital costs can be reduced if the coal-fired plant is replaced by a 50%-efficient, gas-fired combined-cycle plant. A gas-fired plant requires about one-half the capital investment of the coal-fired plant, on a per-kW-of-capacity basis. The gas-fired plant also is more reliable, so less installed capacity is needed. Operating cost savings are possible by using high-Btu off-gases produced by the RF process, supplemented by purchased natural gas. Much lower natural gas prices now prevail; $2/million Btu was used in this study, although this is somewhat higher than current prices. Figure 2 illustrates the energy flow for our 1991 update.

Another major beneficial change is that excess power-generation capacity currently exists in Utah and Colorado. Based on discussions with utilities and power brokers, commercial contracts are available for interruptible power for 30 to 35 mills/kWh. For this study, 35 mills/kWh is used. Enough capacity is available to energize an RF shale oil industry at production rates between 300,000 and

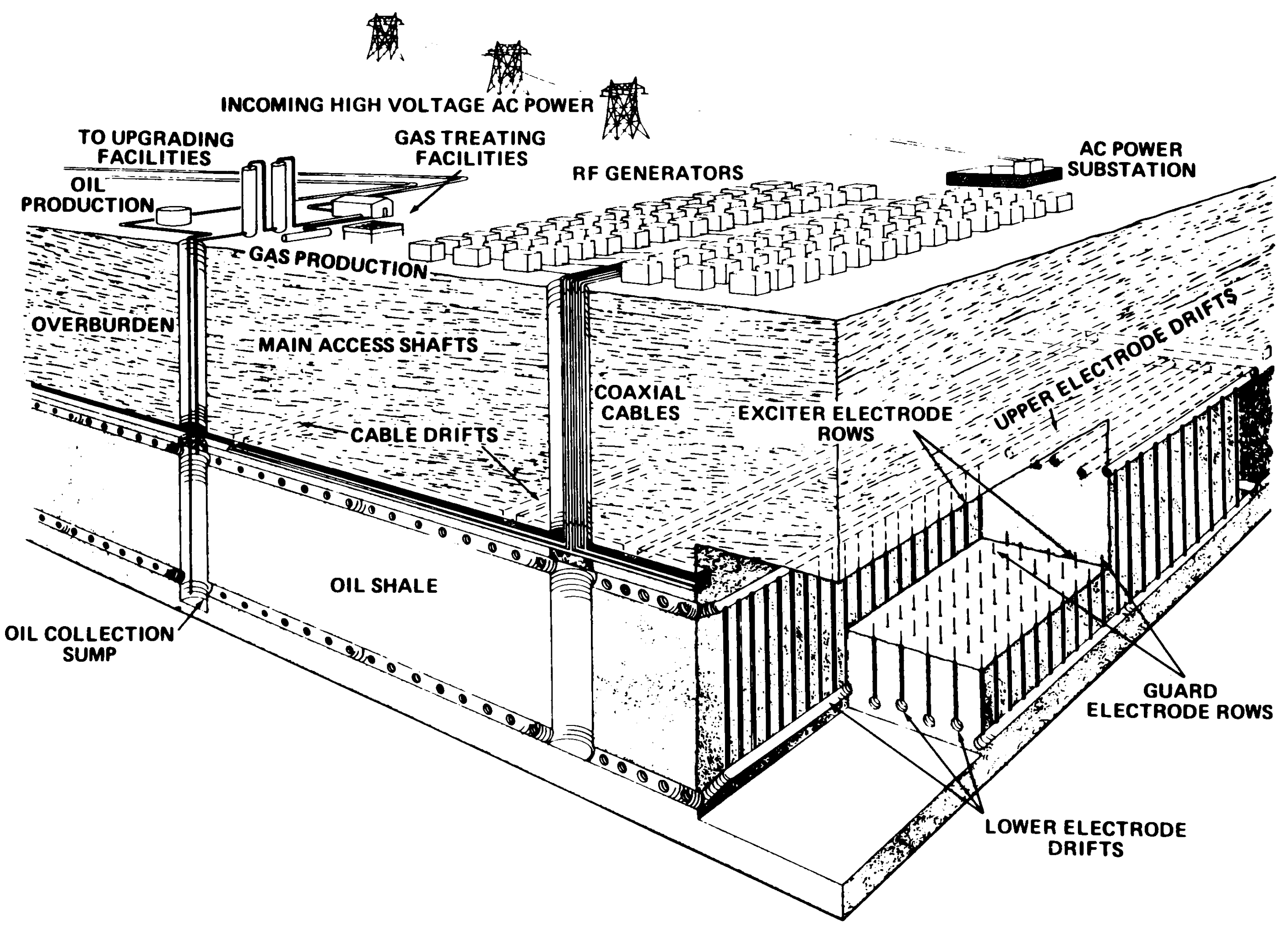


Figure 1. Cutaway view of a conceptual commercial RF retorting facility.

Table 1. Summary of basis used for conceptual design and economics in 1991 update of RF in situ facility.

1. Western Resource Green River oil shale
2. Shale quality 25 gal/ton average in 1.80-ft-thick bed
3. Shale oil recovery of 85% of Fischer assay
4. Plant size 100,000-bbl/day raw shale oil yields 104,000 bbl/day of upgraded oil
5. Stream factor of 90%
6. Shale from mining disposed of above ground with no further processing
7. Minimal water intrusion into the shale being processed
8. Return on equity is 20% when project is 100% equity financed, and return is 25% when project is financed with combination of debt/equity
9. Interest on debt is 15%
10. Main power supplied by 50%-efficient gas-fired combined-cycle plant, or
11. Power is purchased at 35 mills/kWh
12. Natural gas is purchased at $2/million Btu
13. 1.7 million Btu/bbl of off-gas is supplied to gas turbine for power generation
14. 0.7 million Btu/bbl of natural gas purchased for upgrading
15. Retort temperature of 385°C (725°F)
16. RF produced in solid-state generators 1 MW in size with 92% AC to RF efficiency.

500,000 bbl/day. Use of off-gas for power generation would allow even greater shale oil production. The off-gas has a high energy content and can be delivered by pipeline to a remote power plant, thereby avoiding onsite combustion. Interruptible power is acceptable for nearly all the large power loads. Off-peak power can be considered but at the expense of added capital equipment.

Except for mine equipment and development and infrastructure, capital costs were escalated by 20% to be stated in first-quarter 1991 dollars. The 20% escalation is considered conservative, as several cost indexes showed only 13% to 15% escalation from 1985 to mid-1990. Mine equipment and development costs were not escalated because a simplified mine plan reduces capital requirements, and new mine excavating and support equipment is available that improves productivity and reduces costs. Offsite infrastructure costs were not escalated because new roads, housing, and other facilities were constructed in the 1980s and remain in service.

The results of the 1991 cost update, as well as a comparison with the 1985 cost estimate, are shown in Table 2 for capital costs and Table 3 for operating costs.

Table 4 compares the 1985 and 1991 updated costs for each of the design cases—dedicated power plant and purchased power. The 1991 updated costs are lower than those for 1985 because of more efficient power-plant technology and less expensive purchased power. If capital costs were calculated using leveraged financing, then a required selling price of $20/bbl to $25/bbl of oil would be indicated.

REVISED DESIGN BASIS

Two sensitivity cases in the 1985 study indicated likely prospects for improving the oil shale extraction process. These two cases were (1) to reduce the retorting temperature from 385°C to 3450C (725°F to 650°F); and (2) to increase the grade of oil shale retorted from 25 gal/ton to 28 gal/ton. The ability to retort kerogen at lower temperatures has been shown by IITRI in the laboratory and should be possible in a commercial operation.

Table 2. Estimated capital investment costs (in million 4th-quarter 1985 dollars and 1st-quarter 1991 dollars) for gas-fired combined-cycle power plant.

	Dedicated Plant		Purchased Power	
Facility Operation	11/15/85	1/15/91	11/15/85	1/15/91
Mining preproduction	224	224	224	224
Mining	146	146	146	146
RF surface	682	818	682	818
RF underground	296	355	296	355
Power plant	1,850	800	–	–
Upgrading	553	664	553	664
Offsites	262	262	262	262
Property access	14	17	14	17
Plant prestartup	55	66	55	66
Total [a]	4,083	3,352	2,233	2,552
$ per bbl/day	40,830	33,520	22,330	25,520

a. Totals may not add due to rounding.

Table 3. Estimated operating costs (in $/bbl, 4th-quarter 1985 dollars and 1st-quarter 1991 dollars) for gas-fired combined-cycle power plant.

	Dedicated Plant		Purchased Power	
Facility Operation	11/15/85	1/15/91	11/15/85	1/15/91
Mining	1.49	1.50	1.49	1.50
RF retorting	0.95	1.20	0.95	1.20
Power plant	4.42	1.00	–	–
Purchased power	–	–	16.64[b]	8.82[c]
Upgrading & support	2.98	4.00	2.98	4.00
Replaceables	0.51	0.60	0.51	0.60
Total [a]	10.34	8.30	22.56	16.12

a. Totals may not add due to rounding.
b. Based on cost of 60 mills/kWh, 11/15/85.
c. Based on cost of 35 mills/kWh, 1/15/91.

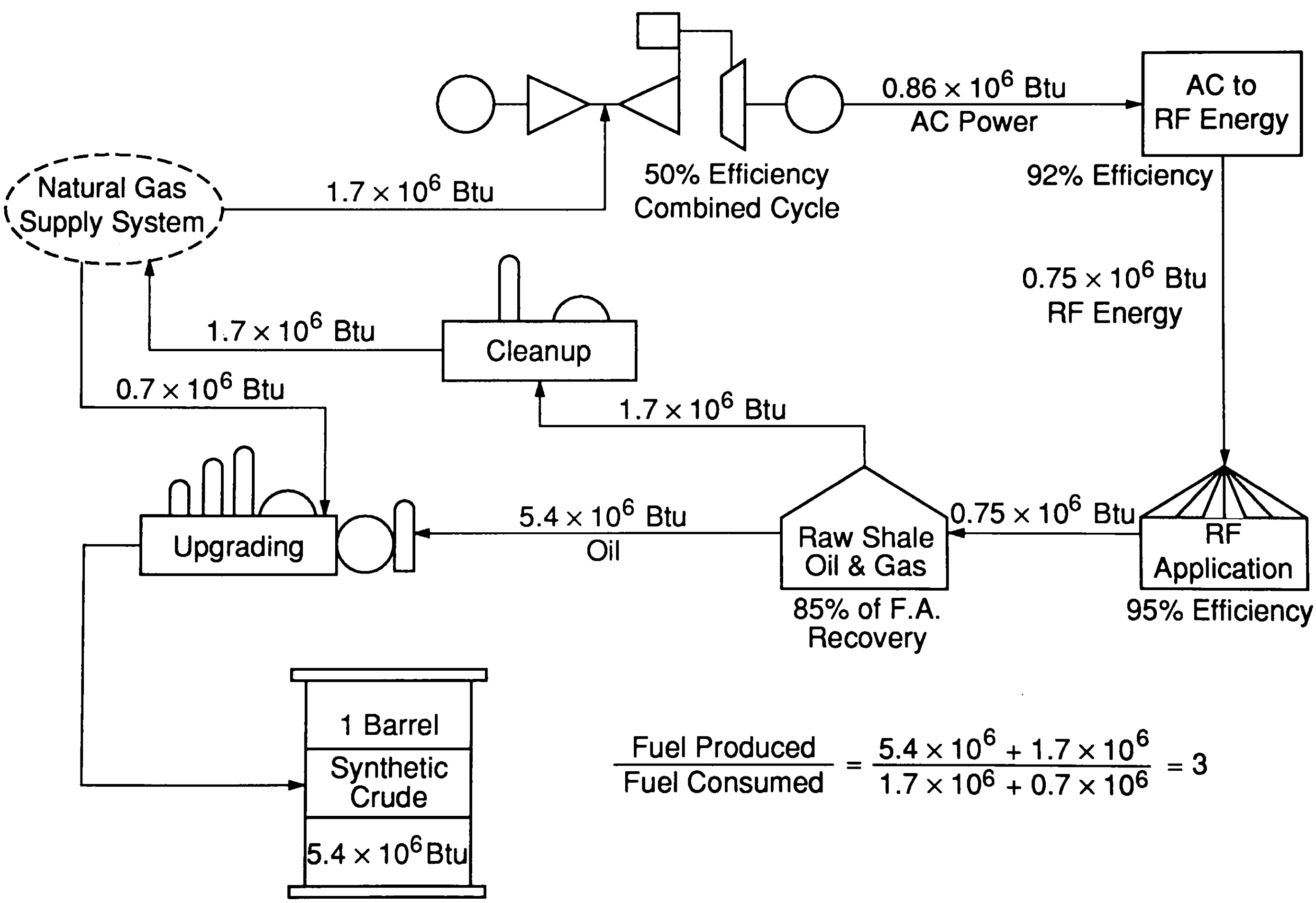
Table 4. Combined capital and operating costs for RF in situ facility using dedicated power and purchased power (in $/bbl, 4th-quarter 1985 dollars and 1st-quarter 1991 dollars).

Reference Case	Capital Charge[1] ($/bbl)	Operating Cost[2] ($/bbl)	Total ($/bbl)	1985 Update[3] 100% Equity	1985 Update[3] 70%/30% Debt/Equity
Dedicated Power					
11/85	24.86	10.34	35.20	36.00	25.00
1/91	20.40	8.30	28.70	NA	NA
Purchased Power					
11/85	13.60	22.56	36.16	35.60	29.60
1/91	15.54	16.12	31.66	NA	NA

1. Simplified calculation $ = $/bbl/day (Table 2) × 0.2 Capital rate × 1/365 day × 1/0.9 utilization
2. Operating cost, Table 3.
3. 1985 update (Reference 3)—Required selling price using economic model.

Combined, these two sensitivity cases reduced the required selling price by about $5.00 in the 1985 study, about 14% of the total price of $36.00/bbl. A comparable reduction in the 1991 update would reduce the dedicated power-plant case by $4.02 and the purchased-power case by $4.43.

Increasing the oil shale grade even more is possible by retorting a thinner horizon, presumably in the Mahogany



$$\frac{\text{Fuel Produced}}{\text{Fuel Consumed}} = \frac{5.4 \times 10^6 + 1.7 \times 10^6}{1.7 \times 10^6 + 0.7 \times 10^6} = 3$$

Figure 2. Energy flow diagram for in situ oil shale production RF heating method.

zone. Grades of 34 gal/ton can be retorted if the horizon thickness is reduced to 80 ft. Increasing the grade of oil shale reduces the cost of electrical and RF functions in nearly inverse proportion to grade. Mining costs fluctuate depending on the thickness of the richer grade horizon and the mining plan. All other costs, such as upgrading and infrastructure, are not affected significantly.

Processing 34-gal/ton shale, as opposed to the base case of 25 gal/ton, reduces power costs by about 20% rather than the 30% implied by the change in grade because of the added energy to pyrolyze the kerogen. For the conditions listed in Table 1 and shown in Figure 2, the power and RF system-related cost reductions would be about $2.84 for the dedicated power plant and about $3.40 for the purchased-power option at 35 mills/kWh.

REVISED PROCESS CONCEPTS

Several other methods of improving the economics for the RF in situ process have been considered, of which three are discussed here—(1) wider spacing of electrodes and a slower heating cycle; (2) horizontally oriented electrodes; and (3) pillar robbing for improved recovery of oil from room-and-pillar mining operations. These alternatives deviate from the basic concepts of the 1982 study; therefore, only qualitative comparisons can be made regarding improvements in the required sales price.

Wider Spacing of Electrodes/Slower Heating

IITRI has evaluated the possibility of increasing electrode spacing, which has the effect of decreasing electromagnetic field strength and slowing the heating and retorting process. Their analysis indicates no problems associated with this approach and considerable economic benefits. Only limited laboratory data are available to evaluate the effects of the wider spacing; additional tests would be needed before field-scale experiments could be conducted.

In the 1982 study, electrodes were spaced every 4 m along the rows, with 10-m separated rows of exciter and guard electrodes. In a more widely spaced array, a pattern of 12-m by 30-m spacing is possible. Several dollars per barrel would be saved in reduced mine development and electrode-placement capital and operating costs. The RF

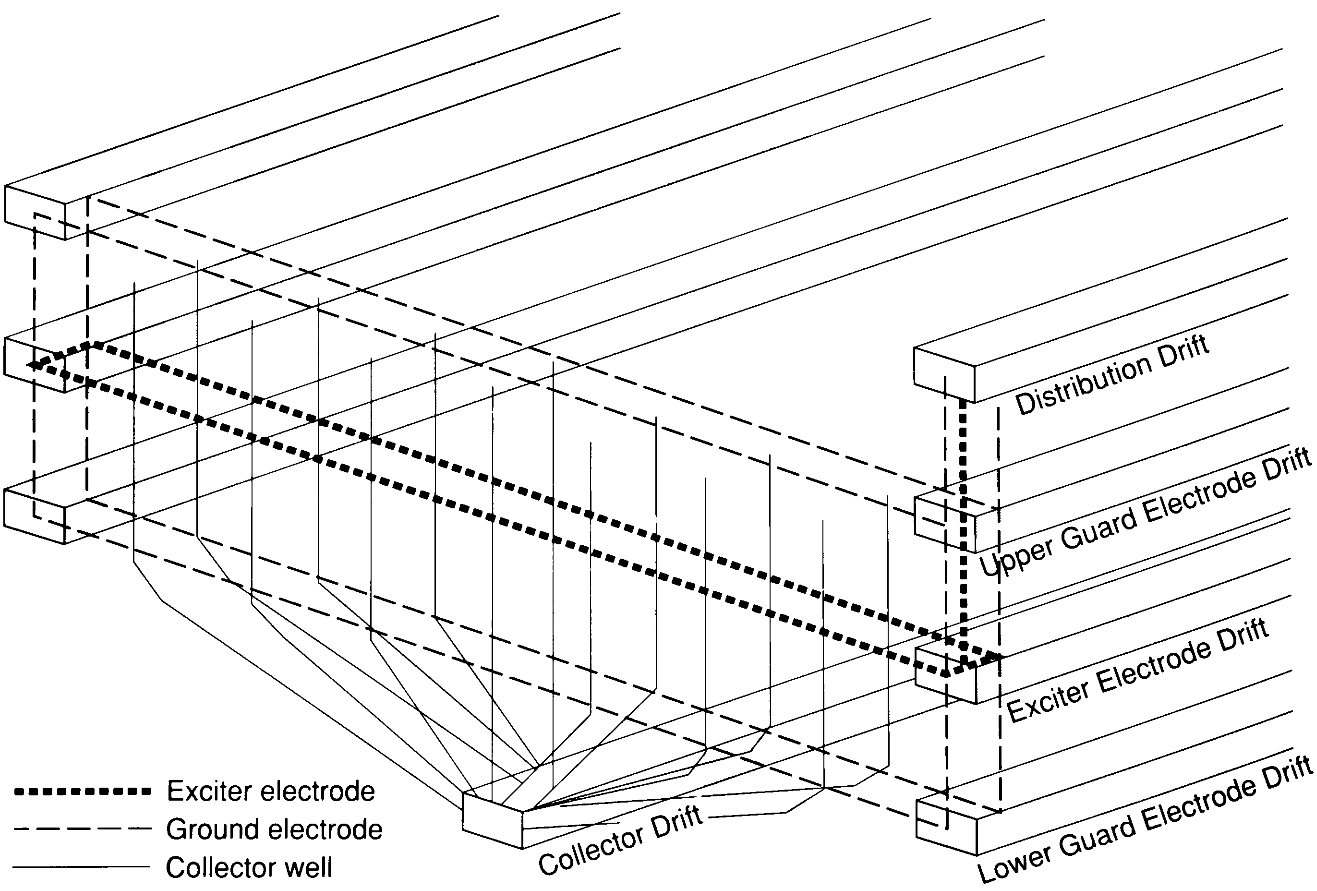


Figure 3. RF oil shale horizontal electrode orientation.

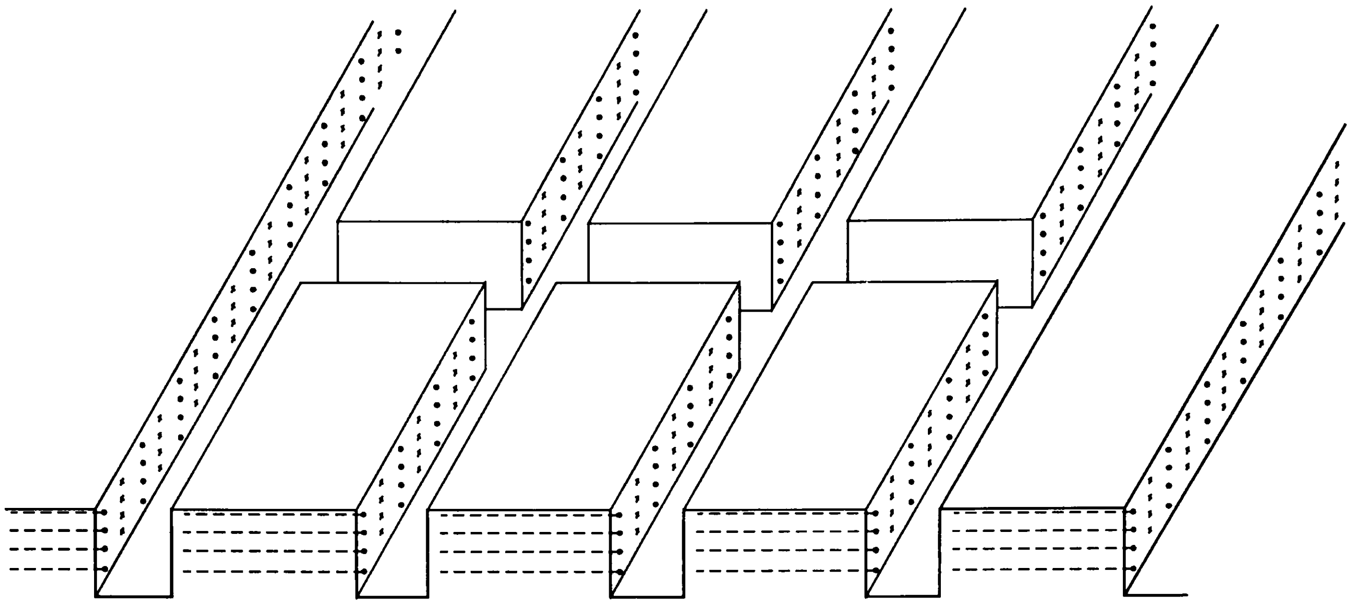


Figure 4. Pillar recovery from mined workings with horizontal electrodes.

and power systems would not be affected. The retorting time, which would increase from a 120-day cycle to about 200 days, would only affect initial startup, and would be offset by faster mine development startup. Once steady-state operations were achieved, there would be no difference.

Horizontal Electrodes

In a horizontally oriented configuration, guard electrodes would be placed along the top and bottom of the retorting zone, with exciter electrodes placed in the center (Figure 3). The capital and operating costs for mining and electrode placement would be less in this case, with a corresponding decrease in the required selling price.

With this system, however, is the additional risk that less oil will be recovered. The retorting process creates porosity and permeability within the dolomitic limestone matrix, and the gas that is produced drives the oil toward collection wells. Oil recovery will be assisted by gravity drainage within the formation, but low-grade horizontal layers within the shale beds may be less permeable and block vertical flow of the oil. With vertically oriented electrodes, gas and oil will be driven to the vertical boreholes and will drain to a lower collection level. For the horizontal configuration, oil collection may be more difficult.

It is relatively easy to enhance oil collection in the horizontal case by drilling vertical wells through the formation from a lower collection drift, as shown in Figure 3. These wells are inexpensive and would reduce the risks associated with this alternative.

Pillar Robbing

The third alternative considered is a method of recovering shale oil left in pillars after room-and-pillar mining is performed to feed a surface retort. Both vertical and horizontal electrode orientations are possible in a pillar-robbing system. Figure 4 illustrates one horizontal system.

Oil could be recovered both from the pillars within the panel and from the barrier panels between panels, with nearly complete recovery of oil in that horizon. The design of the room-and-pillar system would need to be modified, however, because in situ retorting would reduce pillar strength. A smaller room-and-pillar extraction ratio and larger pillars would be necessary to maintain ground stability.

This would be a very economical oil recovery system because it would be an incremental expansion to an existing plant, and the mine development would be provided without additional cost.

CONCLUSIONS

The IITRI RF oil shale extraction process can be made to produce oil at attractive selling prices. More efficient power-generation equipment, high-production mining equipment, reduced retorting temperatures, and higher grade shale reduce capital and operating costs. Simpler and better designs for mine development and electrode placement offer more productivity and lower costs. Currently, low prices for purchased power and natural gas also contribute to making this process very competitive with other oil shale

Table 5. Summary of selling price changes for 1985 base case and 1991 update.

Case	$/bbl
1985 base case	36.00
1991 update	- 6.50
	29.50
Decrease retorting temperature and increase shale grade to 28 gal/ton	- 4.00
	25.50
Increase grade to 34 gal/ton, wider spacing, horizontal electrodes	??
Leveraged financing	- 6.00
Total	< 20.00

Table 6. Profitable sale prices ($/bbl) for in situ RF produced and upgraded shale oil.

Shale Grade	70/30 Debt Equity ($/bbl)	100% Equity ($/bbl)
1985 Update Cost Estimate		
25 gal/ton shale, 725°F retort temp.	25	36
28 gal/ton shale, 650°F retort temp.	22	31
1991 Update Cost Estimate*		
25 gal/ton shale, 725°F retort temp.	~20	39
28 gal/ton shale, 650°F retort temp.	<20	26

processes and potentially attractive in current and future oil markets.

Using sensitivity analyses and costs factored from a comprehensive study performed in 1982, we have estimated the order-of-magnitude costs that might be incurred for developing a facility using the RF in situ process. Table 5 summarizes the steps taken to reduce the estimated1985 sales price of $36.00/bbl to our estimate of $25.50/bbl. For the 1991 update, the effect of leveraged financing was estimated based on the cost reduction achieved by leveraging the 1985 estimate. For the 1985 estimate, leveraging reduced the required selling price by about 30% for the dedicated-power-plant case. Applying this reduction to the $25.50/bbl gives a selling price below $20.00/bbl.

Table 6 summarizes the estimated selling price required to make an RF oil shale facility profitable. Our analysis shows that, even after inflation, the improvements made in the system reduce the estimated costs from $25 to $35 to a range of $20 to $26, and perhaps slightly lower.

An important factor that has changed since 1982 but was not included in this analysis is taxes. Corporate tax rates, credits for synthetic fuels production, and other rules have been modified in ways that should improve project economics, although it was not possible to quantify their effects on required selling price.

We recognize that extrapolating and factoring costs based on the 1985 update is not necessarily accurate, in particular, because of the higher cost of purchased power used in that study. However, we feel that the errors are small, and we have been conservative in our changes. In addition, other process improvements not included in our analysis offer other opportunities to improve project economics.

Some of the risks for a RF project have been eliminated. Continued development of RF heating technology (as described in Bridges and Sresty, this volume) has proven the effectiveness of radio-frequency electromagnetic heating. High capital-cost equipment items already have been engineered, tested, and put into operation.

Gas-fired electrical power generators and the AC-to-RF solid-state convertors, still under development in the early 1980s, are now proven technologies. Whatever risk remains is whether adequate oil can be recovered from large blocks of oil shale. This risk can be resolved only by a field testing program.

Another feature that makes development of the RF process attractive is that production capacity can be added on an incremental and modular basis. When testing is concluded, a small-scale plant can be built to produce several hundred barrels of oil per day, followed by steps to achieve commercial size. While there are efficiencies in size, the investment at each stage is such that the risk can be limited until the process is proven and the economics confirmed. Ongoing incremental process improvements also are fairly easy to achieve because the entire process lends itself to modular operation, and each module can benefit from the experience gained on the previous one.

In summary, the major components of the RF in situ oil shale extraction process are proven and commercially available; economic analysis indicates that profits can be made at competitive and attractive oil prices, and a large resource is available to which this technology can be applied. Therefore, we believe that this process merits the next step toward commercial production—an RF field demonstration program should be a priority in an on-going oil shale research program.

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