IN SITU RETORTING VIA RF HEATING

A Conceptual Design

G. D. Gould
R. R. McKinsey
Bechtel Group, Inc.

J. E. Bridges
G. Sresty
IIT Research Institute

ABSTRACT

Field test work in Utah during 1980 proved that application of radio frequency (RF) electromagnetic heating will raise Green River Formation oil shale to retorting temperatures. Laboratory results indicate that substantial permeabilities are induced at in situ retorting conditions and high oil recoveries are anticipated. Subsequently, a preliminary conceptual design for a commercial scale integrated RF retorting plant was developed. Significant advantages for in situ oil production through RF retorting are suggested by this work. Strong economic incentives and the prospect of achieving greater resource recovery warrant additional field test work. The key issue to be demonstrated is the creation of adequate permeability to accommodate induced fluid flow and achieve high oil recoveries under autogenous pressure drives at commercial operating conditions. A plan for a $20 million field test program was created and is described below.

INTRODUCTION

Vast potential oil resources exist in U.S. oil shales, tar sands, and heavy oil reservoirs. The Green River Formation oil shales alone contain 1,000 - 1,500 billion barrels of oil equivalent. Shale oil production development plans have usually focused on mining and surface retorting complexes involving huge materials handling enterprises. The environmental limitations and mitigation required for these complexes, coupled with the numerous labor and water requirements, suggest that perhaps in situ production methods should be given stronger consideration. For Colorado Green River oil shales, it is expected that oil production via the mining/surface retorting method would be limited to about 500,000 - 800,000 barrels per day (B/D) because of potential impacts on the Rocky Mountain airshed. This is inconsequential when compared to the 12 to 15 million B/D national oil consumption.

In 1981, Bechtel commenced serious studies on in situ retorting methods - both by combustion heating and by electromagnetic heating. With funding from a major oil company, a conceptual RF retorting commercial project plan was created. It emphasized radio frequency technology developed by IIT Research Institute of Chicago (IITRI). Several major potential advantages for in situ RF retorting were indicated by this plan:

- High resource recovery
- Minimum materials handling (only about 7 percent of the resource needs to be mined)
- Relatively low production costs
- Lower water requirements
- Lower labor requirements

This paper will briefly discuss the experimental background for the RF retorting concepts employed in the plan; review the basic elements of the development plan, preliminary economics, and incentives; and outline a field test program to confirm the technical viability of the RF retorting concept.

BACKGROUND

The IITRI RF in situ retorting process depends on dielectric heating (analagous to the volumetric "inside-to-outside" heating accomplished in the microwave oven). This process offers a fundamentally different way to heat oil shale without encountering many of the "surface-to-inside" heat transfer difficulties that occur with conventional shale oil recovery methods.

Non-uniform heating of the resource has been the principal difficulty with previous electrical approaches to in situ retorting of large blocks of oil shale. With these methods, the oil shale closest to the energy source tends to be overheated, which is inefficient and contributes to increased cracking and coking of the released shale oil. In addition, the oil shale furthest from the energy source tends to be underheated, leading to incomplete retorting of the kerogen (1) (2) (3). The IITRI approach overcomes this limitation by using dielectric heating within the confines of multiple rows of conductors placed in the deposit. The multiple rows of conductors simulate embedded plates, as shown in the triplate configuration in Figure 1.

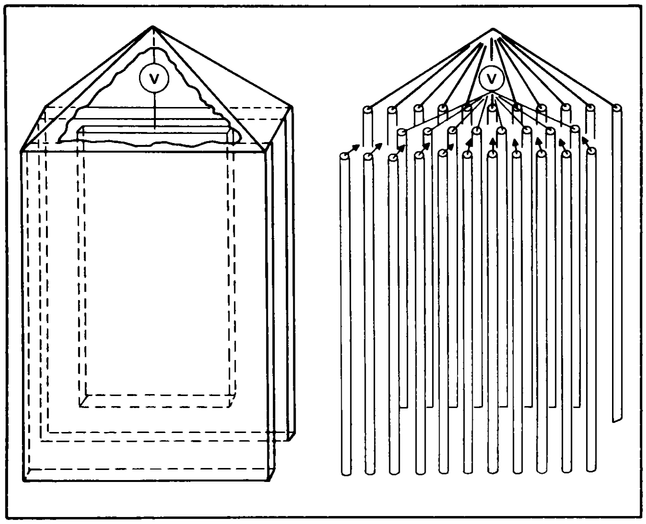

Figure 1
IITRI TRIPLATE CONCEPTUAL DESIGN

It has been demonstrated that virtually all of the electromagnetic energy supplied to the plate source structure can be contained uniformly within the outer (shield) planes, when the spacing between adjacent tubular conductors is properly chosen (4) (5). Thus, the IITRI retort module comprises alternate rows of exciter electrodes, flanked by rows of ground potential electrodes. The shale between the rows is heated slowly and uniformly as electromagnetic energy is applied.

The principle of uniform heating has been demonstrated mathematically with computer models, by measurements in pilot facilities at IITRI's labs in Chicago, and in the field tests during RF heating studies on tar sands and oil shale in Utah (6). The comparative results of the field test measurements and the computer simulation are shown in Figure 2.

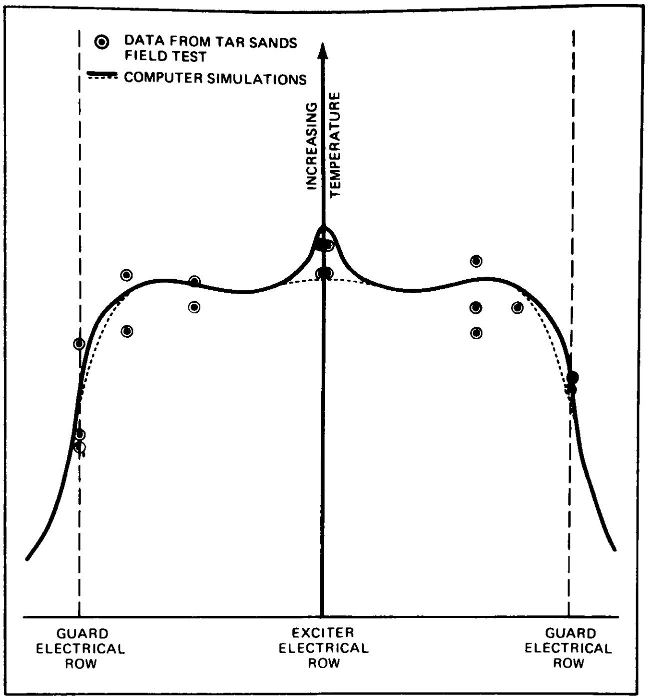

Figure 2
UNIFORM RESOURCE HEATING IN SITU BY RF ENERGY

In addition to uniform heating, RF energy also allows the oil shale to be retorted under controlled conditions and at reduced temperatures. Typically, retorting in surface facilities is accomplished by rapidly heating crushed shale particles to temperatures ranging from 425°C to 600°C. With IITRI's RF in situ technology, slow, low temperature heating is employed. An end-of-run retorting temperature level of 385°C is contemplated. In fact, experimental work carried out by IITRI suggests that high oil recoveries may be achieved at temperatures as low as 345°C (7). Slow, low temperature retorting can also minimize oil yield losses via coking of oil product and energy losses to carbonate rock decomposition.

The ultimate yield of oil from a large monolithic block undergoing RF heating has been examined theoretically by several independent groups (IITRI, Lawrence Livermore Lab, and others). The results indicate that Fischer Assay (F.A.) recoveries of 85 percent or greater are feasible and coking losses are minimal, provided that induced permeability is adequate. This estimation is largely independent of deposit depth. IITRI has simulated commercial conditions in the laboratory and, within the limitation of the shale size samples, demonstrated that adequate permeability and porosity can be induced (7). The permeability generated along the bedding planes has been measured in a lab test block under constant volume and fully constrained conditions simulating in situ retorting, as shown in Figure 3. However, a field test program will be required to demonstrate that similar permeability development will occur in a constant volume, fully constrained block of oil shale with electrodes placed at commercial hole spacings.

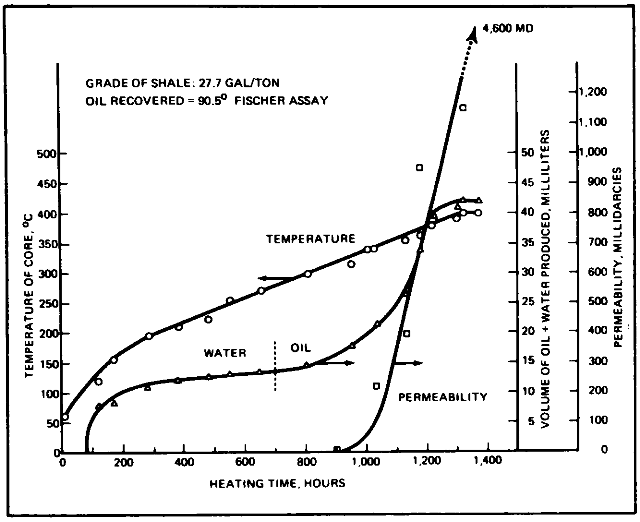

Figure 3
PERMEABILITY AND PRODUCT RECOVERY PARALLEL TO BEDDING PLANE

CONCEPTUAL DESIGN BASIS

Bechtel, on behalf of a major oil company, developed a conceptual design for a nominal 100,000 B/D commercial shale oil facility at a site-specific location in the Piceance Basin. As part of the conceptual design, Bechtel examined:

- Mine preparation shafts and main drifts
- Bore hole drilling
- RF generation system
- Underground cable distribution system
- Retorting strategy
- Product recovery
- Oil upgrading
- Effluents treating
- Electric power generation and delivery
- Support facilities

Infrastructure was addressed but not included as part of the design or the economics. Environmental management was also discussed but the costs associated with permitting, siting studies, water rights, etc., were not included.

The conceptual design presented in Figure 4 illustrates a possible commercial version of the IITRI process. Initially, three vertical access shafts are mined out to reach the 55 m thick shale layer that is to be retorted. From these access shafts, a series of horizontal drifts and crosscuts are formed above and below the shale layer. Rows of vertical boreholes are created from the crosscuts and expendable tubular electrodes are inserted into them. Commercial row spacing is contemplated to be about 10 m, with electrodes spaced 3.5 - 4.5 m apart along each row. Heated zones are separated by unreacted pillars to provide roof support.

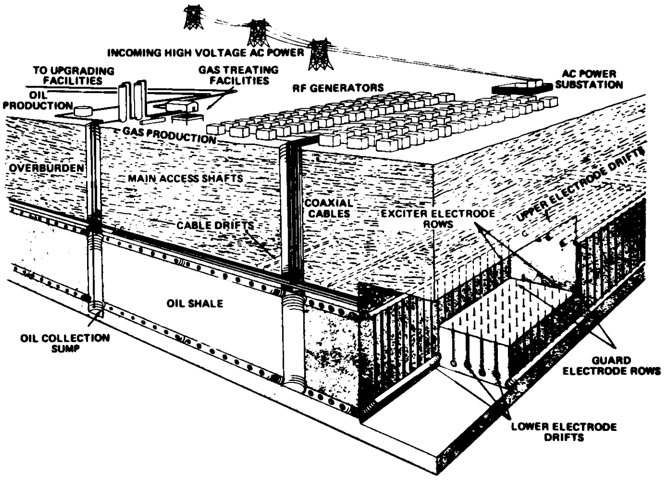

Figure 4
CUTAWAY OF CONCEPTUAL COMMERCIAL RF RETORTING FACILITY

The RF generators, which are on the surface, are connected to the electrodes by expendable coaxial cables. Electric power is supplied from offsite generation facilities, and is usually coal-fired. Oil and gas production occurs via migration to the nearest electrode hole and then by gravity drainage to a product collection sump underlying the triplate module being heated. The collection sump products are brought to the surface through the main access shaft and are upgraded into synthetic crude oil by hydroprocessing in aboveground facilities.

Bechtel's preliminary commercial design included an assessment of the Net Energy Ratio

(NER), using coal as fuel for the electrical generating facility. Each unit operation employed in the production of syncrude oil has been examined, and favorable results are expected (Figure 5). The energy quantities shown are normalized to produce one barrel of syncrude. In other words, one ton of coal fed to the power plant converts to seven barrels of high quality syncrude via the IITRI in situ retorting process.

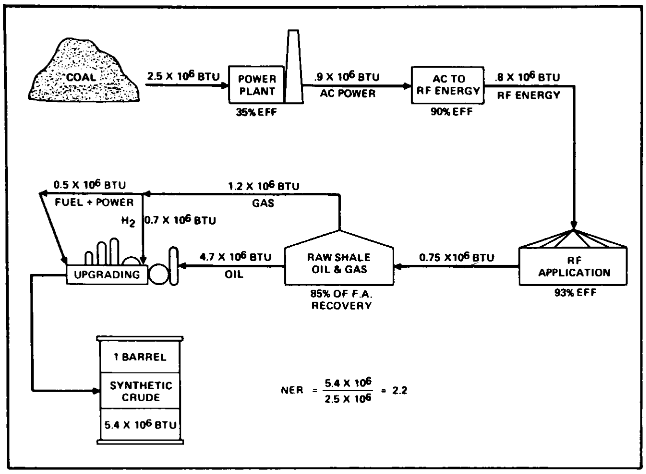

Figure 5
NET ENERGY FOR IN SITU OIL SHALE PRODUCTION
RF HEATING METHOD

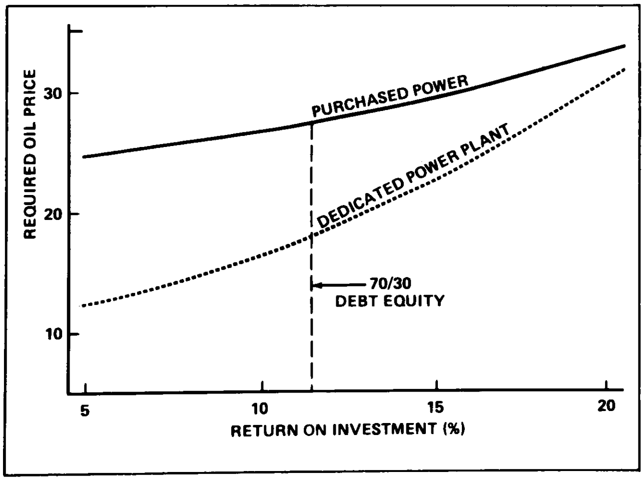

Figure 6
REQUIRED OIL PRICES FOR IN SITU OIL SHALE PRODUCTION
RF HEATING METHOD (LATE 1981 $/BBL)

The expected properties of the shale oil produced by the IITRI process as compared to properties of shale oil produced in typical surface retorting facilities are shown in Figure 6. Preliminary laboratory tests of the IITRI oil indicate that it has a markedly higher gravity, lower pour point, and higher percentage of light ends than conventional shale oils. These properties are presented in Table 1.

Table 1
PRODUCED OIL PROPERTIES

PROPERTY	IITRI PROCESS	SURFACE RETORTING
RAW SHALE OIL		
GRAVITY, °API	34.4	21
NITROGEN, WT%	0.97	1.8
SULFUR, WT%	0.56	0.65
C/H WT RATIO	6.92	7.38
POUR POINT, °C	5	30
ASTM CUT, LV%		
C_5+ NAPHTHA	15	2
KEROSENE	29	7
GAS OIL	26	38
RESIDUUM	30	53
	100	100
OFF GAS, DRY (SCF/BBL) NH_3 AND H_2S FREE	1,750	1,200

ECONOMICS OF RF HEATING

Included in the conceptual design of the facility is an estimate of capital and operating costs as well as an estimate of the project economics. The estimated costs were based on a nominal 100,000 B/D facility which would receive power from a dedicated 1,500 MW coal-fired power plant located in the Piceance area but not necessarily at the site of the process facilities. An alternative to this plan would involve the purchase of power from electric utilities in the area. A summary of major design and cost parameters used is presented in Table 2.

The estimated capital investment costs for these two options are itemized in Table 3. It is worth noting that the capital requirements, especially for the purchased power alternative, are significantly lower than those figures normally associated with conventional facilities employing surface retorting with room and pillar mining. In fact, the estimated $19,500 installed cost per B/D rivals some of the published costs associated with deep well oil production and off-shore platforms (Table 4).

Table 2

SUMMARY OF BASES USED FOR CONCEPTUAL DESIGN AND ECONOMICS

GENERAL

- The western resource Green River oil shale
- Shale quality 25 gal/ton average
- Shale oil recovery 85 percent of Fischer Assay
- The plant size 100,000 B/D raw shale oil which yields 104,000 B/D of upgraded oil
- The stream factor 90 percent
- Main power supplied by three 500 MWe coal-fired steam power units using low sulfur western coal
- The retort temperature 385°C
- Excess gas not used for H_2 manufacture or process boilers is used for fuel to two gas turbines
- RF is produced in solid state generators 1 MW in size having an efficiency of 90 percent
- Shale from drilling is disposed of aboveground with no further processing
- Water intrusion into the shale being processed is minimal

ECONOMICS

- Project operating life of 25 years
- Discount rate fixed at 20 percent on equity
- Interest on debt of 15 percent
- Investment tax credit of 10 percent with immediate application
- Synfuels tax credit of 10 percent of capital through retorting, excluding power generation and product upgrading
- Inventories: Coal - 60 days
  Product oil - 7 days
- Synthetic fuel tax credit not considered
- No by-product credit

Table 3

ESTIMATE OF CAPITAL INVESTMENT

(Millions 4th Quarter Dollars)

FACILITY OPERATION	DEDICATED POWER PLANT	PURCHASED POWER
MINING PRE-PRODUCTION	204	204
MINING	133	133
RF SURFACE	620	620
RF UNDERGROUND	269	269
POWER PLANT	1.920	–
UPGRADING	503	503
OFFSITES	238	238
PROPERTY ACCESS	13	13
PLANT PRE-STARTUP	50	50
TOTAL	3,950	2,030
$ PER BARREL/DAY	38,000	19,500

Table 4

SHALE PROJECT CAPITAL COST COMPARISONS

OIL RECOVERY ALTERNATIVES	$/BARREL DAY CAPACITY
RF INSITU	
DEDICATED POWER PLANT	40,000
PURCHASED POWER	20,000
ROOM AND PILLAR MINING/SURFACE RETORT	
GETTY STUDY	52,000
UNION	65,000
COLONY	80,000
OFF SHORE PETROLEUM – DEEPWATER	
BRITISH PETROLEUM	22,000
EXXON	32,000

*Oil and Gas Journal

The operating costs presented in Table 5 assume a delivered coal price of about $20 per ton. Although low, this price reflects published costs given for the Rocky Mountain area mines. The effect of increased coal cost was determined by re-estimating the operating costs using $40 per ton coal. The effect on the final price required for the product shale oil was about $3 higher per barrel.

Table 5

ESTIMATE OF OPERATING COSTS

(Dollars Per Barrel)

FACILITY OPERATION	DEDICATED POWER PLANT	PURCHASED POWER
MINING	1.35	1.35
RF RETORTING	.86	.86
POWER PLANT	4.02	–
PURCHASED POWER*	–	16.64
UPGRADING AND SUPPORT	2.71	2.71
REPLACEABLES	.46	.46
TOTAL	9.40	22.02

*Based on 1982 cost of 60 mills/kW

The results of Bechtel's economic analysis are presented in Figure 6. The required oil price of $31 - $33 per barrel based on 100 percent equity financing is comparable to world market crude prices. It is also favorable compared to estimates for shale oil from conventional oil shale retorting facilities using surface retorting with room and pillar mining. If debt/equity financing is used, the project appears even more attractive. The costs associated with a 70/30 debt/equity scenario are highlighted in Figure 7. In this case, the required purchase price for a 20 percent return on investment is only $18.10 per barrel, assuming that a dedicated power plant is built as part of the project.

It should be noted that while the economic analysis was based on an 85 percent F.A. oil recovery, it was also assumed that an additional 10 percent of the resource was unrecovered for unspecified reasons.

One of the advantages of RF retorting is the ability to start with a small facility and expand it as a positive cash flow is established. An estimate of the effect of plant size on investment capital is illustrated in Figure 7.

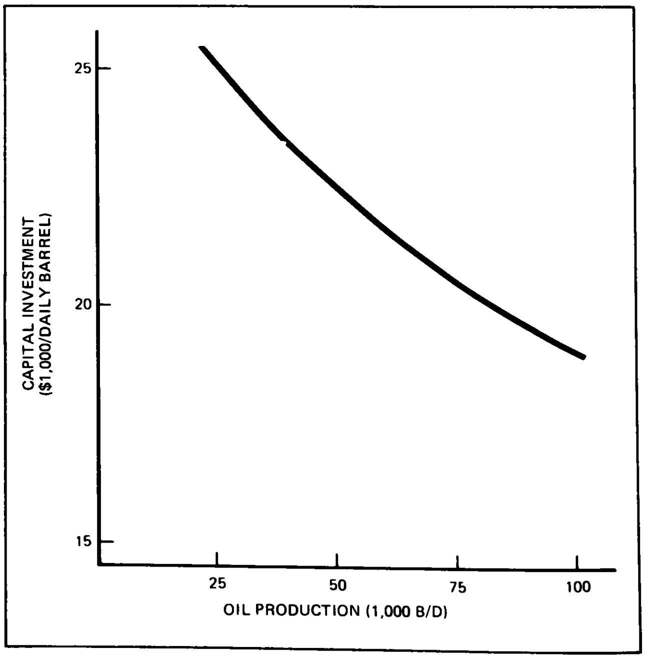

Figure 7

EFFECT OF SIZE ON CAPITAL INVESTMENT

As part of the economic study of a commercial RF retorting facility, Bechtel examined the sensitivity of the required purchase price to several variables. Included in the analysis were the effects of adding a surface retort (derived from the shaft and tunneling development) to process the mined shale; reducing the final retorting temperature to 345°C; and using a higher average grade of shale (28 GPT). The results of this sensitivity analysis are displayed graphically in Figure 8.

The effect of reducing the in situ retort end-of-run temperature shows the significant investment savings and production cost savings that can accrue if the electric power required to retort the shale is reduced. The study made by Bechtel assumed that the spent shale was left hot with no attempt to recover any residual heat. The effect of recovering just 10 percent of the heat left in the spent shale is also shown in Figure 8.

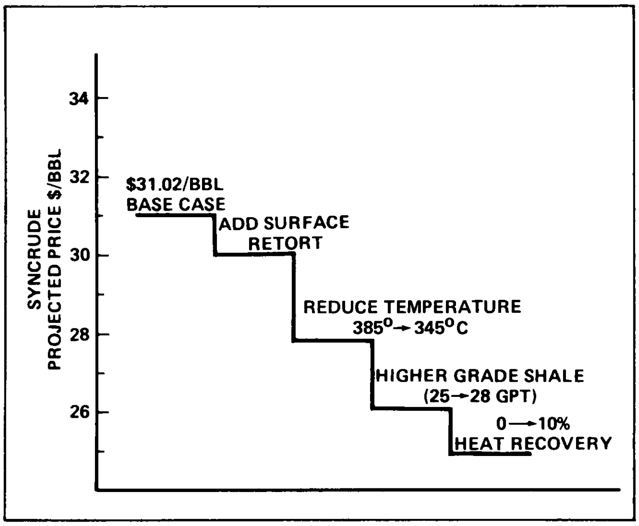

Figure 8
SENSITIVITIES FOR THE DEDICATED POWER PLANT CASE BASED ON 100 PERCENT EQUITY

During the course of the study, Bechtel discovered several other beneficial factors attributable to the IITRI in situ RF retorting method. When compared to other in-house studies involving conventional aboveground retorting with room and pillar mining, RF in situ retorting was found to require about half the operating staff and had less than a third of the onsite water requirements (Tables 6 and 7). The lower staffing levels and water consumption will help reduce the overall project impact on the local infrastructure and environment.

Table 6
MANPOWER COMPARISON
100,000 B/D SHALE OIL PROJECT

CATEGORY	ROOM AND PILLAR MINING PLUS SURFACE RETORTING	RF INSITU RETORTING
SITE MANAGEMENT	4	4
MINING	1,678	650
MATERIALS HANDLING		
RETORT PREPARATION	133	12
SHALE DISPOSAL	251	22
RETORTING	239	256
OIL UPGRADING	62	56
SUPPORT FACILITIES	56	40
ADMINISTRATION	134	96
TECHNICAL SERVICES	95	68
MAINTENANCE	505	364
SUBTOTAL	3,157	1,568
POWER PLANT		
OPERATIONS	–	29
MAINTENANCE	–	85
SUBTOTAL	–	114
TOTAL	3,157	1,682

Table 7
WATER REQUIREMENTS
(Gallons/Minute)

BASIS: 100,000 B/D SHALE OIL PROJECT
NO GROUND WATER RECLAMATION

FACILITY OPERATION	CONVENTIONAL PROJECT WITH SURFACE RETORT AND ROOM AND PILLAR MINE	RF INSITU RETORT WITH COAL FIRED POWER PLANT
MINE OPERATIONS	100*	300*
PROCESS REQUIREMENTS		
COOLING TOWER MAKEUP	4,300	1,300
OTHER CONSUMPTIONS	1,500	1,200
SHALE DISPOSAL AND DUST CONTROL	4,900	300
SUBTOTAL ONSITE	10,800	3,100
POWER PLANT, OFFSITE	2,500	12,600
TOTAL RAW WATER MAKEUP	13,300	15,700

*Does not include internally recycled water from mine drainage used for dust and fire control

One of the strongest factors in support of the RF in situ technique is the increased resource recovery, as shown in Table 8. Conventional methods can only recover up to 39 percent of the thicker oil shale beds that predominate in the Piceance Basin. On the other hand, RF in situ retorting can recover about 58 percent of the shale oil, or almost 50 percent more oil from a given resource property holding. The figures presented in Table 8 exemplify the significance of this increase when applied to a 5,000 acre block containing a 55 m bed of 25 GPT oil shale. The increase in production amounts to 300 million barrels of oil worth over $10 billion (at a value of $35 per barrel).

Table 8
INCREASED RESOURCE RECOVERY FROM RF IN SITU RETORTING

BASIS: 100,000 B/D RAW SHALE OIL
55 M SHALE BED (25 GPT)

CATEGORY	ROOM AND PILLAR MINING PLUS SURFACE RETORTING	RF INSITU RETORTING
MINED SHALE, T/D	175,000	13,000
RESOURCE RECOVERY		
EXPLOITABLE BED THICKNESS	67%	100%
DEVELOPABLE AREA	60%	75%
F.A. OIL RECOVERY	95%	85%
LOSSES	–	10%
	39%	58%
BARRELS PRODUCED FROM 5000 AC BLOCK	613 MILLION	912 MILLION
INCREMENTAL VALUE AT $35/B	$10.46 BILLION	

REQUIRED TEST PROGRAM

The key questions identified by Bechtel relate to demonstrating by a full scale design module in the field that about 85 percent of the F.A. oil content can be recovered as a high quality oil. Other issues of importance regarding the commercialization of this process are the operability of the RF delivery system, and the integrated operation of the project elements. The work program suggested as a next step is intended to resolve uncertainties surrounding the product oil recovery and quality issues.

A phased approach is recommended. Initially, small-scale field tests should be carried out to confirm the workability of equipment concepts and fluid flow mechanisms for fully constrained underground test blocks. Following this, a large block of shale will be retorted, employing triplate electrode array(s) with anticipated commercial electrode hole spacing. The specific program steps are:

- Phase 0 – Design of Field Test Program and Facilities
- Phase I – Preliminary Small-Scale Test
- Phase II – Proof of Concept Step

Future programs would:

- Confirm the viability of the integrated RF energy delivery system
- Demonstrate the commercial project design criteria

Phase I - Preliminary Small-Scale Test

It is anticipated that the Phase I test would be conducted in a fully constrained block of oil shale approximately 800 m^3 in size with a simulated triplate array of electrodes. Figure 9 shows one possible design which will be considered for the test. The heated shale block will be constrained at the sides by the shale deposit, and the top and bottom of the test block will be constrained by special refractory cement. Electrode hole spacing will be closer than for a commercial module plan. Because of the small size of this first test block, additional production holes may be drilled and provisions may be added to compensate for heat losses. It is estimated that the block will contain about 1,200 barrels of

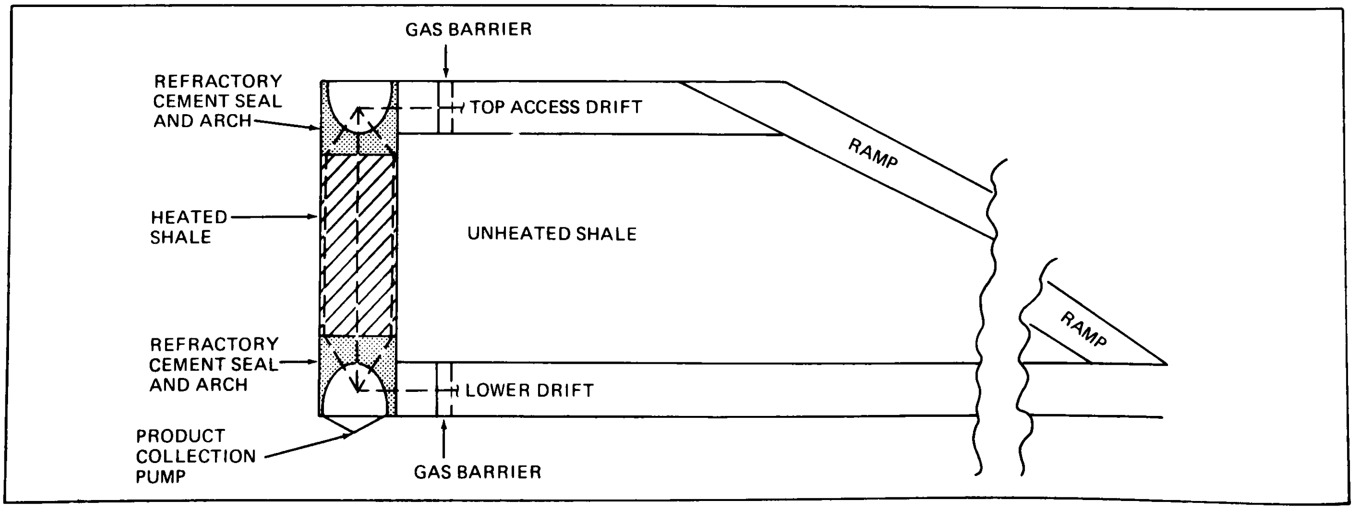

Figure 9
POSSIBLE DESIGN FOR 800 m^3 RF OIL SHALE FIELD TEST

potential shale oil in place. The anticipated maximum production level is about 75 B/D for a brief period during the two- to three-month test.

This work will verify systems design concepts; materials selection; data measurement apparatus; scaling models; production and RF generation equipment; test procedures; yield and loss mechanisms; temperature distribution and dielectric behavior for the test site resource rock; integrity of the electrode holes as producers; and the effects, if any, of jointing planes and induced cracks in the heated block. The validity of the production drive mechanism will be tested and the need for secondary drive mechanisms will be evaluated. Approximate type data will be obtained on the quantity and quality of recovered oil. It should be recognized that "edge effects" (cool zones) may invalidate the development of quantitative oil recovery and energy utilization information in Phase I. However, post-retort core drilling may help interpret the results.

Phase II - Proof of Concept Test

It is anticipated that at least one test will be conducted on a large block, about 5,000 - 10,000 m^3 in size, and containing about 7,000 - 15,000 barrels of shale oil in place. The test layout would be a segment of the contemplated commercial retort design and would employ commercial electrode row spacing; i.e., rows about 10 m apart. Approximate commercial electrode hole spacing will be applied.

The product flow paths in the test block will be representative of those expected in the commercial scale conceptual design. The block size should be large enough that thermal outflow over a 120-day heating period will not adversely affect recovery. However, provisions for guard heaters will be made if design studies indicate that they are justified. The anticipated maximum production level is about 600 B/D for a brief period during the three-month test.

Results of this $20 million program should provide a more reliable basis for judging commercial development prospects for RF in situ retorting.

CONCLUSIONS

Bechtel's and IITRI's engineering studies to date indicate favorable prospects for employing RF retorting of shale oil production in an environmentally acceptable system.

Favorable economics have been calculated based on the conceptual design of a commercial 100,000 B/D facility.

Uncertainties that have been identified will require field test work to obtain proof of concept information that cannot be developed through laboratory work. A modest cost test program has been developed to obtain the needed information.

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