POTENTIAL SHALE OIL PRODUCTION PROCESSES

by

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ABSTRACT

The recovery of energy from oil shale has been investigated for well over a hundred years. Oil shale industries have existed in a number of countries including an infant industry in the eastern United States that was terminated after the discovery of petroleum in Pennsylvania. Research on oil shale processing has not kept pace with the increased demand for liquid hydrocarbons used as fuels and petrochemical feedstocks. With the present day demand for liquid hydrocarbons and the availability of petroleum, increasing interest in oil shale processing is evident. Potential shale oil production in the United States in the immediate future depends on aboveground retorts developed by the U. S. Bureau of Mines and by a limited number of private companies shortly after World War 11. Recent developments in modified in situ retorting technology may also be an alternative method for shale oil production.

INTRODUCTION

Increasing demand for hydrocarbons both for fuels and for chemical feedstocks and the current awareness of the finite nature of petroleum deposits results in renewed interest in alternate sources of fossil hydrocarbons. Oil shale is one of the alternate sources being considered because organic-bearing shales are located throughout the world. Production of oil from shale on a limited scale has occurred in several countries, but production has never reached a significant level related to the present day world requirements. In the United States, after an infant oil shale industry was terminated by the discovery of petroleum in Pennsylvania, the major activity was a research program started by the United State Bureau of Mines.

During World War 11, this research activity was intensified and it is presently being continued by the United States Energy Research and Development Administration as well as by several agencies in the United States Department of the Interior. Several private companies in the United States, and Petrobras in Brazil, are presently conducting, or were in the recent past, conducting research on oil shale retorting processes. In this paper the potential of several of these processes for the production of shale oil will be reviewed.

BACKGROUND

For well over 100 years, oil shale has been processed to produce hydrocarbon products. In 1859, a Scottish oil shale industry began using small vertical retorts to produce fuels, waxes, and chemicals. In Australia numerous operations were conducted, but the most significant was the Glen Davis plant operated in New South Wales. At one time about 100 vertical kiln retorts of the Pumpherston-Fell type were in operation processing 700 to 800 tons of 70-gallon-per-ton oil shale per day (12).[1] During World War 11, Australian operations producted over 2 x 10^8 gallons of shale oil (6).

In Sweden a wartime operation with an initial capacity of 95,000 barrels of oil per year was established. This operation utilized aboveground retorts and an in situ operation (13) . The in situ operation was based on a system of electrical heating that utilized the pressures generated by heating to force the products to recovery wells.

In China and the USSR oil shale processing has been in operation for many years. These operations produced oil and gas and, in Estonia (14-15), shale was used for firing a power plant. Data on recent operations in these countries are sparse.

A Brazilian oil shale research effort appears to be well advanced. Beginning in 1950, the Petrosix retorting process was expanded to a 2,200-ton-per-day demonstration facility by 1973.

RETORTING RESEARCH IN THE UNITED STATES

In 1944, the Synthetic Liquid Fuels Act authorized the Bureau of Mines to begin work on converting oil shale to liquid fuels. The oil shale work was divided essentially into two parts. The laboratory research and conducted at the Petroleum Experiment Station located in Laramie, Wyo., and a demonstration plant was constructed at the Anvil Points Facility near Rifle, Colo.

Development of the Gas-Combustion Retorting Process (7)

Recovery of shale oil from oil shale is based on a simple thermal decomposition of the solid organic substance in oil shale which is known as kerogen. When heated sufficiently the solid organic material decomposes to form oil, gas, and a spent shale consisting of carbonaceous and inorganic residue. These reactions have been used as a basis for a number of processes, but most of these processes have proved unsatisfactory from the standpoint of economics, or operability, or both. Oil shale retorts essentially are heat exchangers for transferring heat from a heating medium to the shale. They may be divided into four general classes based on the method of heat application.

Class	Method of Heat Application	Examples
1	Heat is transferred to the shale through a wall.	Pumpherston, Hayes, Berg
11	Heat is transferred to the shale from the combustion occurring in the retort by burning product gases and the residual carbon in the retorted shale.	N-T-U, Union Oil Co., Pintsch, Bureau of Mines gas-combustion
111	Heat is transferred to the shale by passing previously heated gases or liquids through the sale bed.	Swedish Industrial, Bureau of Mines gas-flow, Royster
1V	Heat is transferred to the shale by introduction of hot solids into the retorting bed.	Standard Oil Co. fluidized bed, Bureau of Mines hot-solids-contact, Aspeco, TOSCO

1 Underlined numbers in parentheses refer to items in the list of references at the end of this report.

The most desirable process for retorting Colorado Oil shale should meet as many of the following requirements as possible:

1. It should be continuous.
2. It should have a high feed rate per unit cross-sectional area.
3. It should have high oil recovery efficiency.
4. It should require a low capital investment, and possess a high operating time factor with low operating costs.
5. It should be thermally self-sufficient; that is, all heat and energy requirements should be supplied without burning any of the product oil.
6. It should be amenable to enlargement into high-tonnage retorts rather than to a multiplicity of small units.
7. It should require little or no water because the Green River oil shale deposits are located in an arid region.
8. It should be capable of efficiently processing oil shale of a wide range of particle sizes to minimize crushing and screening.
9. It should be mechanically simple, easily operable.

At the Anvil Points Facility, the Bureau of Mines began an investigation that led to the development of the gas-combustion retorting process. This investigation included a study of the N-T-U process, the Royster process, and the gas-flow process before the gas-combustion process was developed. Of all of the processes studied, the gas-combustion process comes closest to fitting the above-listed desirable characteristics.

The gas-combustion retorting process is characterized by its use of continuous gravity flow of shale, direct gas-to-solids heat exchange, and heat supply by internal combustion. The essentials of the process are illustrated in figure 1. The retort is a vertical, refractory-lined shaft equipped with shale- and gas-handling devices. It is convenient to divide the retort into four functional zones, although there is no physical separation, and no definite dividing line between these zones.

Crushed and sized shale moves downward as a bed through the retort vessel, passing through the product cooling zone where the solid particles are heated almost to retorting temperature by the rising gases from the retorting zone. It then passes downward into the retorting zone where the organic matter is decomposed by heat to liberate oil vapor and gas. A carbonaceous residue from this reaction remains as part of the retorted shale particles. The retorted shale next proceeds to the combustion zone, where the sustaining heat for the process is produced by burning the organic residue on the shale plus a part of the product gas which is returned to the system. From this hot zone, the shale moves down through the heat recovery zone where its heat is transferred to the rising stream of recycle gas. The cooled, spent shale is discharged from the retort mechanically at a controlled rate, which governs the retort throughout.

Recycle gas is injected at the bottom of the vessel and rises through the spent shale in the heat recovery zone. In effect, this zone is a simple countercurrent, gas-to-solids heat exchanger. An air distribution device is located near the center of the retort where air, diluted with part of the circulating retort gas, is injected. This mixture is heated quickly by the hot spent shale; reaction of the oxygen with combustibles produces a hot flue

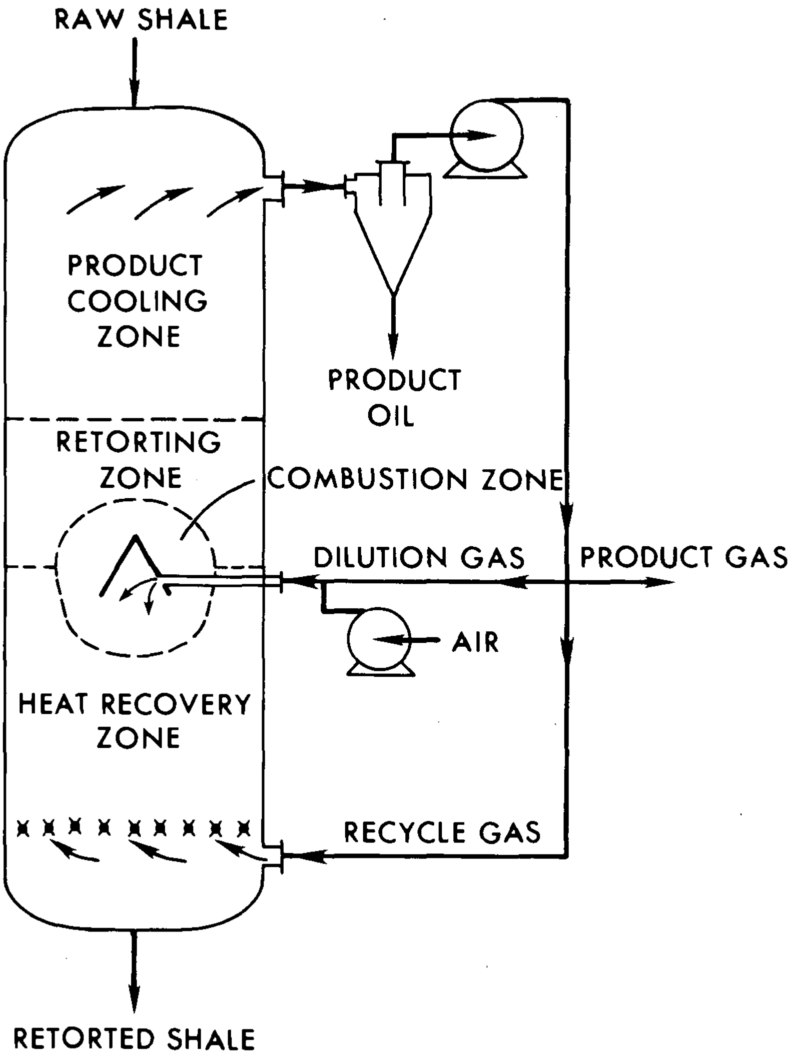


FIGURE 1. - GAS-COMBUSTION PROCESS.

gas. The hot flue and recycle gases rise in contact with the descending raw shale in the retorting zone, and the solids are heated enough to effect theremal decomposition of the kerogen in the shale. The liberated gases and oil vapors, commingled with the upward rising gas stream, are cooled by the entering raw shale. In the product cooling zone,the gas stream is cooled and the oil condenses as a fine mist or fog and is carried out of the top of the retort. Both the retorting and cooling zones are, in effect, countercurrent gas-to-solids heat exchangers. However, their functioning is complicated by retorting reactions and by oil condensation.

The overhead stream from the retort passes first through oil-mist separators to recover the shale oil. The oil-lean gas then enters a blower from which it leaves at higher pressure and is divided into three streams. One part (dilution gas) is injected with air into the center of the retort. Another part (recycle gas) enters the bottom of the retort, and the remainder (net product gas) is vented from the system.

The typical material balance and pertinent temperatures are shown in table 1. These data reflect an actual test period during which 2,000 pounds

TABLE 1. - Typical gas-combustion retort material quantities and temperatures

	Weight, pounds	Volume, std cu ft	Temperature, °F
Material in:			
Shale	2,000	--	60
Recycle gas	1,134	14,850	129
Dilution gas	148	1,940	129
Air	294	3,840	91
Material out:			
Retorted shale	1,611	--	166
Product oil	196	--	129
Total retort gas	1,769	23,170	129

of raw shale, assaying 26.7 gallons per ton, were charged to the retort at 60°F. Under the retorting conditions of this test, 1,611 pounds of retorted shale were discharged at a temperature of 166°F, and 25.2 gallons of oil weighing 196 pounds were produced. The total volume of recycle gas, dilution gas, and air injected to the retort was 20,630 scf. The total gas discharge was 23,170 scf, representing a volume increase of 2,540 cu ft as the result of various reactions within the retort, such as the evolution of gas from cracking organic matter, and production of carbon dioxide from decomposing mineral carbonates. Net product gas vented amounted to 6,380 scf. The heating value of this gas varied from 80 to 100 Btu per scf and, with preheating, the gas could be used as fuel for gas turbines or waste-heat boilers. The weight of gas moved by the gas blower was about the same as the weight of raw shale charge.

Most of the studies were made at mass shale rates between 200 and 300 lb/(hr) sq ft. retort bed area. This is equivalent to a shale bed movement of about 3 to 4.5 feet per hour.

The reactions within the gas-combustion retort are complex, and a study of this phase of retorting was not completed when the project was terminated. Numerous combustion and related reactions are possible among the various gases, liquids, and solids present. These materials include air, carbon dioxide, carbon monoxide, hydrogen, water vapor, hydrocarbon gases, shale oil and bitumens, carbon, and various sulfur- and nitrogen-bearing materials, in addition to many minerals.

Because of the complexity of the combustion and thermal decomposition reactions, it was necessary to assume simplified conditions in calculating heat balances. Decomposition of part of the magnesium and calcium cabonates in the shale is an important endothermic reaction. Estimation of the extent of this reaction was relatively simple through comparison of the amount of carbon dioxide in the vent gas with that expected from combustion reactions. Other mineral reactions also may take place, such as oxidation of pyrites in the shale to produce sulfur dioxide or sulfates, and combination of silicates with calcium or magnesium oxides.

The gas-combustion process is notable for its high thermal efficiency. Because a large part of the sensible heat of the retorted shale is recovered, it is necessary to add only about 400,000 Btu per ton of shale. This low heat requirement is a distinct advantage, because it may be met by combustion of the easily burned portion of the carbonaceous residue near the surface of the retorted shale particles, and by combustion of a part of the gas. There is no indication that combustion rates limit the capacity of the gas-combustion process. The limits seem rather to be in such factors as increasing pressure drop through the bed, and the tendency for fine shale particles to become entrained in the gas stream as throughput is increased.

The endothermic carbonate decomposition reactions absorb about 160,000 Btu per ton of shale under normal gas-combustion retorting conditions. Thus the presence of mineral carbonates helps dissipate excess heat, when processing difficulties might otherwise result in temperatures high enough to cause severe fusion of shale. In general, carbonate decomposition tends to limit the maximum shale temperature to about 1,600°F, several hundred degrees below the fusion point of the inorganic matter that is present.

The mechanical simplicity of the gas-combustion retort is a particularly advantageous feature. The retort vessel is simple, and both gas and shale distribution devices are stationary. Raw and spent shale handling presents few problems because of the low temperatures and mechanical forces involved. The air distributor at the combustion zone is the most critical part of the system, and this requires special considerations in design. arrangement, material selection, and operation technique.

From the outset of the experimental work at Anvil Points, it was observed that the gas streams from retorts usually contained shale-oil mist. However, the potential benefit of the phenomenon was not realized until tests showed that the product oil could be removed as a mist carried in the gas stream. This discovery, a fundamentally new concept in oil shale retorting, suggested an approach to retorting and oil recovery that led to the development of the gas-combustion process.

Shale-oil mist forms in the retort just above the retorting zone, which in effect is a countercurrent heat exchanger. The downward moving oil shale is heated almost to retorting temperature, and the rising gases and vapors are

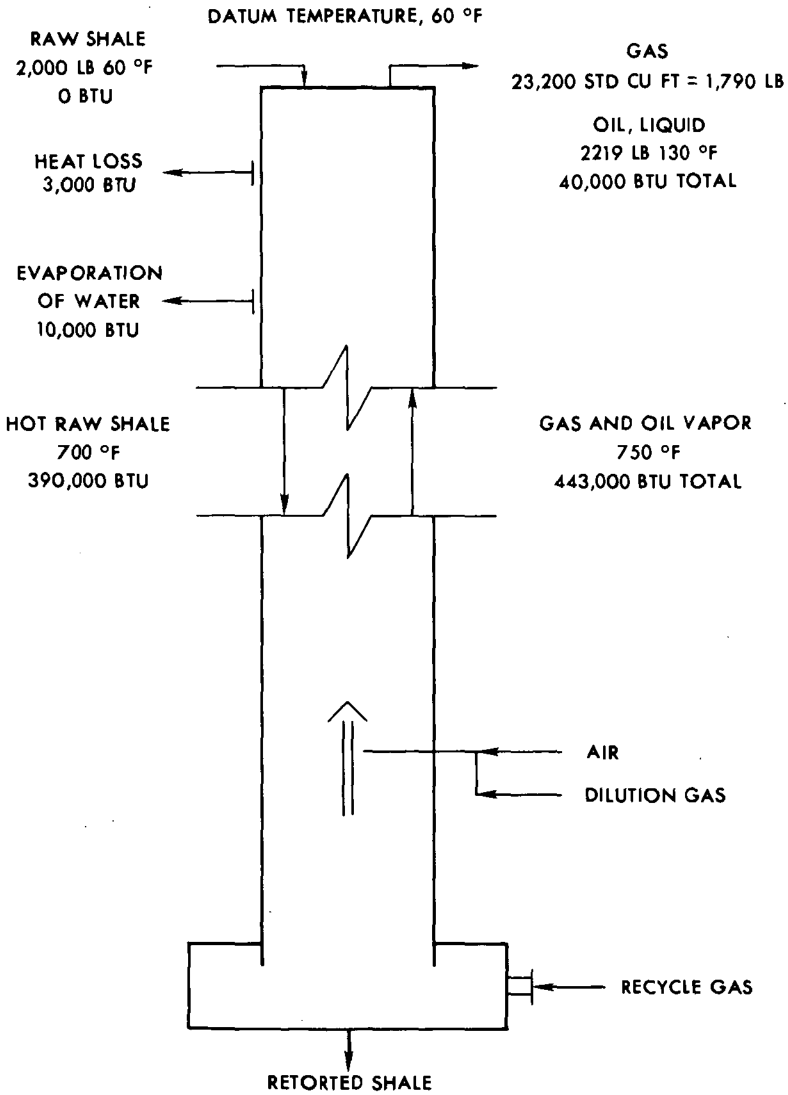


FIGURE 2. - MIST FORMATION SECTION OF THE GAS-COMBUSTION RETORT.

are cooled to the temperature of the retort outlet. Figure 2 is a diagram of this section. Conditions at the upper end are known because they can be measured directly, but there is no sharp separation of the zones of retorting and product cooling. For purposes of this discussion, a shale temperature of 700°F has been assumed as a dividing point. This is about the temperature at which the rate of kerogen decomposition becomes appreciable, so it may be considered the place at which the retorting zone begins.

Typical conditions existing around the mist-formation section are noted on figure 2. About 400,000 Btu's of heat are transferred from the gas stream to each ton of shale. Condensation of the oil vapor represents a substantial portion of this heat quantity, about 100,000 Btu. For the present purpose, it is assumed that no water vapor condenses in the upper part of the mist-formation section, even though this assumption probably is not always correct.

If the retort is operating satisfactorily, oil condenses in the upper section as a fine mist which is easily carried out with the gas.

The general requirements for efficient removal of mist from a retort can be determined from study of the upper section of the retort. The usual principle of mechanical entrainment does not operate because the gas velocity is too low to carry large oil drops, and any condensed oil deposited on shale particles will descend to the retorting zone with the moving bed. If the oil is to leave the retort as mist in the offgas stream, the droplets must be formed in the spaces between the shale particles, and must be small enough so that inertial separation does not occur as they are carried upward by the gases through several feet of shale bed.

Some condensation and deposition of oil on the pieces of shale is considered unavoidable. It is believed that even under the best conditions a thin film of oil is present on all particles of shale entering the retorting zone. A refluxing problem occurs when the amount of oil on the shale is great enough to drop or flow down through the bed of shale.

Oil on the pieces of shale is subjected to increasing temperature as the bed moves toward the retorting zone, and part of the oil redistills. However, the heavier fractions are thermally cracked before reaching their boiling point. Only about half of a gas-conbustion crude oil distills at atmospheric pressure in the standard laboratory distillation test. Cracking of the heavier fraction forms lighter oil, gas, and coke. Most of the lighter oil is recoverable, but the gas and coke represent a loss in yield of primary product. Thus, refluxing, if uncontrolled, can result in substantial losses and altered products.

Runs may be classified either as refluxing or nonrefluxing, depending on the properties of the product and on operating characteristics. Equilibrium is stable under either type of operation, so that substantial changes are needed to shift from one type to the other. Within some operating ranges a refluxing type of equilibrium may exist or not depending upon conditions at the outset of a run. Data from runs 236 and 241, shown in table 2, illustrate this phenomenon. Run 241 was planned to duplicate 236, but the results were quite different even though the operating conditions apparently were matched. Comparison of the two runs shows that oil from run 241 was lighter, the viscosity and the carbon residue were lower, and the oil yeild was greatly reduced. All of these differences indicate more cracking.

TABLE 2. - Comparison of refluxing and nonrefluxing tests

	Test number	
	236	241
Type of test	Nonrefluxing	Refluxing
Operating conditions:		
Shale grade, gpt	21.1	20.8
Shale size, in.	1/2 to 1	1/2 to 1
Raw shale rate, lb/hr	616	616
Air quantity, scf/ton shale	4,210	4,020
Recycle gas quantity, scf/ton shale	17,000	16,800
Results:		
Oil gravity, ° API	19.7	22.8
Oil viscosity at 130° F SSU	132	61
Oil Remsbottom carbon, wt-pct	5.2	.6
Oil yield, vol-pct Fischer assay	93	72
Retorted shale assay, gpt	.5	1.8
Product gas temperature, ° F	125	161

Secondary cracking in the retort produces a lighter, less viscous oil that has some quality advantages, but these are outweighed by the loss of yield. In addition, refluxing causes operational difficulties in that the coke that forms tends to bond the shale particles into large agglomerates, interfering with, and sometimes completely stopping, the flow of shale.

Refluxing also causes marked changes in the temperatures in the retort. Under refluxing conditions, there is an oil stream that moves downward through the shale bed. The volume of this oil may be appreciable. This downward flow of oil alters the heat distribution in the mist-formation section because of the thermal effects of revaporization and secondary cracking. The void space pattern in the shale bed also is affected by refluxing, even to the extent of causing as channeling, and the heat transfer coefficient between the hog gas and shale is reduced by the oil film. In comparison with nonrefluxing operation, refluxing conditions tend to increase the temperature near the top of the bed because of heat release through condensation, and to decrease the temperature lower down because of the heat load imposed by vaporization. Cracking reactions and other thermal effects, such as change in offgas temperature and carbonate decomposition, also affect the picture. It is apparent that formation of a stable mist is an essential part of the gas-combustion process, and that an understanding of the factors controlling mist formation is important for effective operation of the process.

A summary of the results of operations by the Bureau of Mines at Anvil Points using two different sized retorts are shown in table 3. Examination of this table shows that the oil yield in volume-percent of Fischer assay was about 7 to 11 percent lower for the 150-ton-per-day plant than for the 6-ton-per-day plant. Since the runs shown are representative of smooth,

TABLE 3. - General data summary, evaluation runs on the 150 ton/day plant

	150 ton/day plant						6 ton/day plant	
Test number	25(1-5)	26(1-2)	26(3-5)	27(1-3)	28(1-4)	28(5-6)	222(A-J)	304(A-D)
Length of test, hours	120	48	72	72	96	48	240	72
Rates and quantities:								
Shale size, in.	3/8-3	1-2	1-2	1-2	1-2	1-2	¼-1¼	¼-1¼
Bed height, ft and in.	9,11	9,11	9,11	9,11	7,2	7,2	7,0	7,0
Raw shale rate, $lb/(hr)ft^2$	299	222	299	350	299	300	233	229
Air rate, scf/ton shale	3,940	4,230	3,910	3,840	4,010	4,290	3,760	3,840
Dilution gas rate, scf/ton shale	2,860	3,800	2,950	3,140	3,100	4,040	--	1,940
Recycle gas rate, scf/ton shale	13,340	12,400	12,650	12,660	12,500	10,260	16,620	14,850
Temperatures, ° F:								
Product outlet	162	142	141	143	141	126	123	129
Retorted shale out	376	348	356	345	378	447	185	166
Raw shale in	40	34	32	30	28	25	--	85
Recycle gas	241	247	250	246	224	213	122	129
Dilution gas	83	90	92	92	79	86	--	129
Air	128	129	131	144	110	98	84	91
Yields:								
Oil, vol-pct Fischer assay	82.8	92.3	86.2	86.7	85.1	86.1	94.1	95.0
Gas, scf/ton shale	6,040	6,440	6,000	6,020	6,100	6,090	5,810	6,380
Retorted shale, wt-pct of raw shale	81.8	82.9	82.3	82.1	83.3	83.0	77.9	76.5
Liquid water, lb/ton shale	.2	5.0	.9	1.1	4.9	11.2	25.7	18.8
Miscellaneous:								
Retort pressure drop, in. H_2O/ft bed	.90	.37	.73	1.02	.58	.45	.34	.40
Carbonate decomposition, wt-pct	24.9	24.1	26.9	25.6	23.3	23.6	26.1	37.6

extended operating periods in both plants, the data shown are indicative of the maximum yields that could be expected at the stage of process development from the equipment and procedures used in this study. Yields from the 150-ton-per-day plant were improved by using a narrow-sized-range shale. However, the performance still did not equal that achieved with the smaller unit. The reason for this decrease in yield in the larger unit appears to be primarily the result of secondary cracking. Some evidence of secondary cracking was shown by differences in oil properties. The gravity of the oil produced in the large plant was 21° API or greater while that produced in the small plant was 20° API or less. The viscosities and Ramsbottom carbon contents of the oils also indicated more extensive cracking in the 150-ton-per-day plant. Comparison of the product gas streams from each of these two retorts also indicated that the larger retort may have been troubled by extensive secondary cracking. The 150-ton-per-day retort produced a gas containing more light hydrocarbons than the 6-ton-per-day retort.

Secondary cracking not only forms light gases, but also forms coke which contributed to the greater quantity of carbon which was found on the spent shale from the 150-ton-per-day retort.

Another problem related to the operation of a moving bed retort is the flow of solids through the retort vessel. Because of segregation of various particle sizes, wall effects, the resistance to solid flow of air/gas distributors, and other operational problems, there is a tendency for localized heating to result in clinker formation. These clinkers further impede the flow of solids and ultimately result in bridging which completely stops the flow through the retort vessel. The bridged material must be removed mechanically before the retorting process can be continued.

By the mid-1950's, work by the Bureau of Mines on the gas-combustion process was terminated; however, in 1964, the Anvil Points Facility was reactivated and operated under contract to the Government by six major oil companies (10-11). This work further defined the effects of operating variables and continued to indicate that the gas-combustion process is technically feasible. The Anvil Points Facility was again leased in the early 1970's to Development Engineering, Inc. for development and demonstration of the Paraho Oil shale retorting process.

The Paraho Process

The Paraho process is very similar to, and can be considered, a further development of the gas-combustion process. Major improvements of the Paraho process over the gas-combustion process are related to better process control, including solid and fluid flow. This more precise control tends to minimize operational problems such as bridging and loss of liquid product by refluxing on the cold shale. The Paraho process can also be successfully operated in an externally heated mode where the energy for the process is provided by burning part of the recycle gas stream in an external heater.

In the externally heated mode, the quality of the recycle gas can be improved. Liquid oil recoveries remain essentially unchanged.

The Union Oil Company Process

To overcome the problems of bridging and secondary cracking of product oil, Union Oil Co. devised a retorting process based on a retort which utilizes a rock pump. This rock pump is a piston-type feeder which forces solid oil shale particles upward into an inverted, cone-shaped vessel which is open to the atmosphere at the top. Spent shale solids overflow the retort vessel's top rim after having been retorted in the lower regions of the vessel.

Air enters the moving bed at the top of the vessel and flows downward countercurrent to the flow of solids. Because of the influence of gravity refluxing is less likely to occur and secondary cracking is much less of a problem. The rock pump tends to break up any bridging in the material and forces spent shale from the vessel. Over the years the Union Oil process has been modified. In 1974, Union Oil Co. announced an improvement to the process that was called the SGR process.

The SGR process, which stands for steam-gas-recycle, uses essentially the same retort design as the internally heated process except thatthe top of the retort was covered to prevent air from being admitted. The spent shale was transferred to a separate vessel where oxygen and steam reacted with the residual carbon left on the spent shale. The hot synthesis gas that was produced in this upper vessel was injected into the shale in the retort to provide all necessary heat for retorting the incoming shale.

In the Union "B' process, heated recycle gas is used to provide the necessary heat for retorting oil shale.

The TOSCO 11 Retorting Process

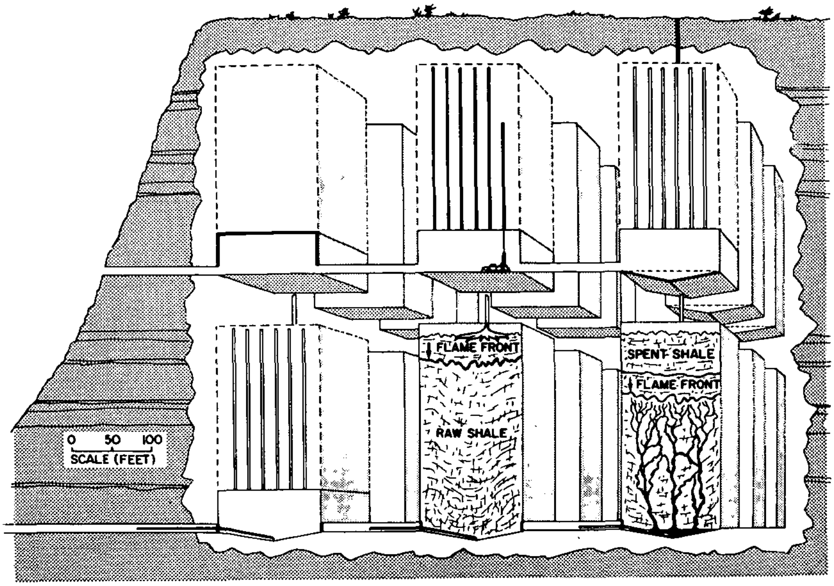
The TOSCO 11 retorting process is also an externally heated process. In this process the retorting vessel was a rotating drum in which raw oil shale is heated by being contacted with ceramic balls that are used as a heat transfer medium. The balls are heated in an external vessel by burning residual carbon on spent shale particles. Because combustion air is not admitted into the retorting vessel, the gases produced are not diluted with nitrogen and, therefore, have a higher heating value. The oil product tends to have a slightly higher API gravity and a lower pour point than shale oil from the gas-combustion process. The recovery of hydrocarbon values from the raw shale is high.

The Petrosix Retorting Process

The Petrosix retorting process, which was developed in Brazil, is also an externally heated process similar to the gas-combustion process and also to the externally heated Paraho process.

In Situ Retorting Processes

Retorting oil shale underground by in situ methods has been considered because this method appears to have several potential advantages over aboveground processing. Many shale deposits are deeply buried and may be too lean, or the strata may be too thin to be produced economically by ordinary mining techniques. These deposits can only be produced by some in situ



1

20% OF ANTICIPATED MODULE VOLUME IS REMOVED FROM BASE

2

MODULE IS DRILLED IN PREPARATION FOR FRACTURING

3

A SHALLOW SLOPING PIT IS MINED OUT AND A SHAFT IS DRILLED INTO BLOCK FROM ABOVE

4

PIPING SYSTEM FOR OIL RECOVERY IS PLACED IN PIT AND SHAFT OPENINGS ARE SEALED

5

MODULE IS DETONATED AND BROKEN SHALE IS IGNITED FROM ABOVE WITH NATURAL GAS

6

COMPRESSED AIR FORCES FLAME FRONT DOWN AND SHALE OIL IS RELEASED BELOW THIS BURNING ZONE

FIGURE 3. - SIMPLIFIED SEQUENCE FOR MODIFIED IN SITU OIL SHALE RETORTING.

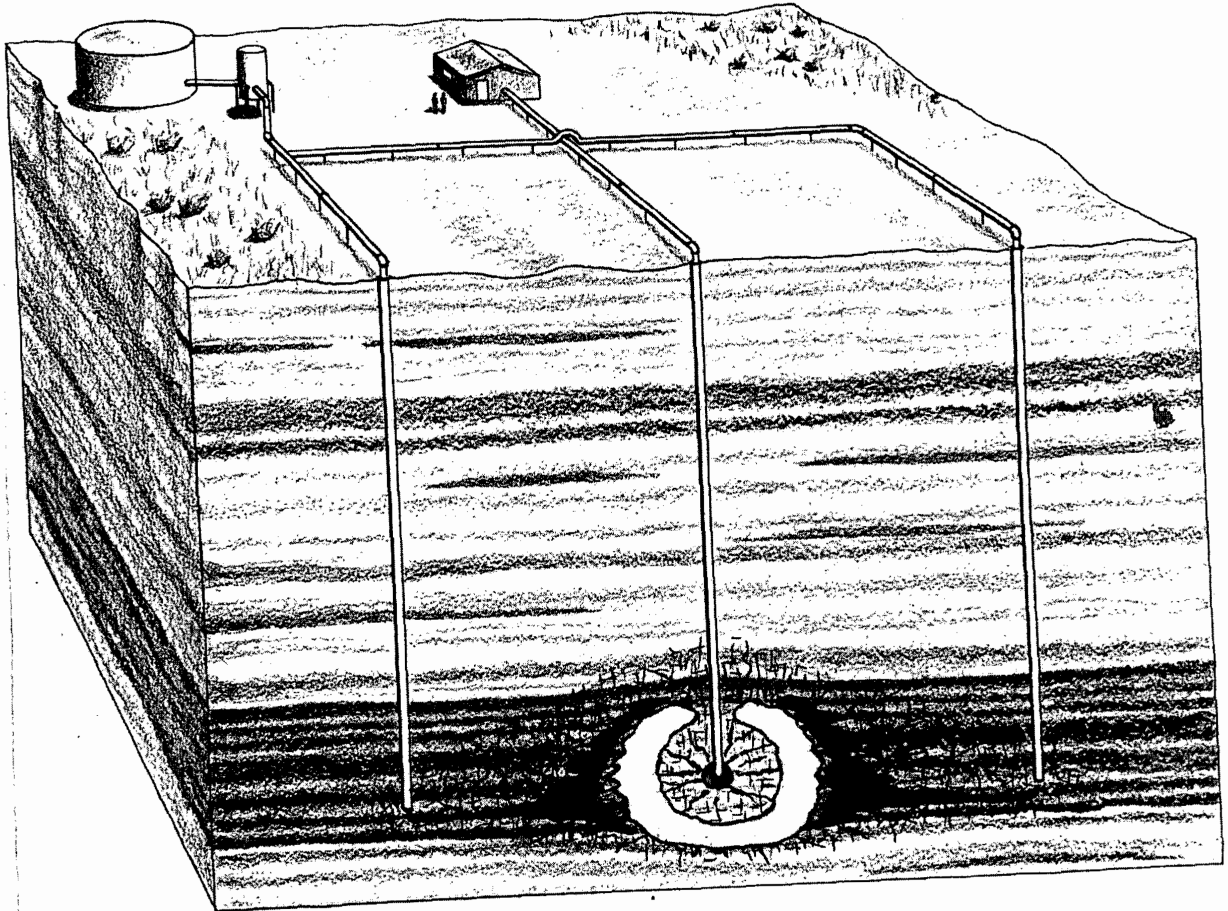


FIGURE 4. - TRUE IN SITU RETORTING PROCESS.

method. There may be advantages of in situ methods in richer, thicker deposits of oil shale also. Because the aboveground installation is less expensive and less complicated, the in situ process is less capital intensive. Because the spent material remains underground there is less problem associated with the disposition of waste products. To be successful, an in situ retort requires sufficient permeability to permit the flow of retorting fluids into and out of the retort, so that heat may be distributed evenly throughout the shale bed. This permeability must be maintained throughout the life of the retort and it must be limited so that the flow of fluids can be contained within the desired volume.

Recently, the term "modified in situ retorting" have come to be applied to an in situ retort in which a part of the material has been removed to allow for expansion furing fracturing of the oil shale bed. The term would also be applied to underground retorts prepared by solution mining of soluble salts, either by natural or artificial means.

The remaining in situ processes where very little or no material is removed prior to fracturing have come to be termed "tru in situ processes." For the true in situ process, fracturing and maintaining permeability is a much more difficult problem. Some limited work was performed by Sinclair Oil Co. on a true in situ process in Green River oil shale (4). These tests were conducted at Haystack Mountain near Grand Valley, Colo., and have been described, but no technical results were presented.

Extensive experimental work on this process has been conducted by the Laramie Energy Research Center under the Bureau of Mines and the Energy Research and Development Administration. These tests, conducted in Green River oil shale near Rock Springs, Wyo., have been reported extensively in the literature (1-3,8-9,16). These experiments have not produced large quantities of oil but have demonstrated that underground combustion can be initiated and sustained and liquid products can be produced from this type of processing. The outstanding example of modified in situ processing is the work conducted by Occidental Oil Co. (5). In this method, underground mining is used to remove sufficient material to allow for proper expansion of oil shale rubble during the formation of the retort. Figure 3 presents an artist's concept of how a modified in situ retorting sequence could be developed underground. Figure 4 is a concept of how a true in situ oil shale retort might operate. After fracturing, the oil shale is ignited in a central well and combustion is sustained by injecting air. The heated combustion products flow outward toward recovery wells retorting the oil shale and forcing the shale oil to flow in the same direction.

DISCUSSION

The technical feasibility of producing liquid hydrocarbon products from aboveground retorts has been established. Many of these processes, the gas-combustion process, the Paraho process, the Union Oil process, and the TOSCO 11 process have operated successfully at rates as high as approximately 1,000 tons per day. The Petrosix process has been operated at rates above 2,000 tons per day.

To make significant contributions to today's energy demand, these processes must be scaled up by approximately 10 to 20 times. This scale-up would result in a commercial-sized module and a successful operation of a module would produce realistic data that could be used to develop an economic analysis of an oil shale retorting process. Scaling a process up by a factor of 10 to 20 is not unusual, but a retort handling 20,000 tons per day of broken oil shale has never been constructed and operated. The problems connected with the flow of this amount of solids countercurrent to a flow of retorting fluids will require extensive engineering development. This development will require time and if oil shale is to make a significant contribution to our energy requirements in the near term, the development work should be started as soon as possible.

The picture, as far as in situ retorting is concerned, is roughly similar to aboveground retorting. Modified in situ methods show great promise and are applicable to many shale deposits, especially formations that are thick and readily accessible for the required mining operation. True in situ methods require a great deal more research before they can be considered for commercial application.

Shale oils produced by all of these retorting methods have many similar characteristics. The most extensive work has been done on gas-combustion crude oils and these oils are made up of about 40 percent hydrocarbons and the remaining 60 percent are organic compounds containing oxygen, nitrogen, and sulfur. The oils are deficient in gasoline boiling range material and only about half of it can be recovered overhead during distillation. The crude shale oil could be used directly as burner fuel and this may well be one of the uses during the early stages of development. Because the most urgent needs are for finished fuels required for transportation, gasoline, jet fuels, diesel fuel, and others, research on upgrading and refining to these products is essential.

CONCLUSIONS

In conclusion, oil shale has been known and processed for more than one hundred years. It is widely distributed throughout the world and could well be an abundant substitute for the diminishing supply of petroleum. There are engineering development problems that must be solved before this resource can compete in the marketplace. Technical feasibility has been shown by several aboveground retorting processes and by modified in situ retorting. All of these processes must be demonstrated on a larger scale to prove operability and to provide reliable economic data. As the retorting processes are developed, refining methods must also be developed to convert this valuable resource to the desired hydrocarbon products.

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