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Slow Radio-Frequency Processing of Large Oil Shale Volumes to Produce Petroleum-like Shale Oil

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Slow Radio-Frequency Processing of Large Oil Shale Volumes to Produce Petroleum-like Shale Oil

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Abstract

A process is proposed to convert oil shale by radio frequency heating over a period of months to years to create a product similar to natural petroleum. Electrodes would be placed in drill holes, either vertical or horizontal, and a radio frequency chosen so that the penetration depth of the radio waves is of the order of tens to hundreds of meters. A combination of excess volume production and overburden compaction drives the oil and gas from the shale into the drill holes, where it is pumped to the surface. Electrical energy for the process could be provided initially by excess regional capacity, especially off-peak power, which would generate ~3×10^5 bbl/day of synthetic crude oil, depending on shale grade. The electricity cost, using conservative efficiency assumptions, is \$4.70 to \$6.30/bbl, depending on grade and heating rate. At steady state, co-produced gas can generate more than half the electric power needed for the process, with the fraction depending on oil shale grade. This would increase production to 7.3×10^5 bbl/day for 104 l/Mg shale and 1.6×10^6 bbl/day for 146 l/Mg shale using a combination of off-peak power and power from co-produced gas.

Introduction

Oil shale is an organic-rich sedimentary rock that can be mined and heated to recover a petroleum-like fluid. Various definitions of oil shale exist, but one usual factor is that the organic content is high enough that the material could conceivably be converted economically, which implies a yield greater than some threshold value, usually in the range of 100-125 l/Mg (1 bbl = 159 L). Worldwide oil-shale resources are huge—more than a trillion barrels for grades greater than 100 l/Mg—and about 60% are in the western United States.[1] For comparison, world conventional crude oil reserves are of the same magnitude, as are the amount of oil we have consumed and the predicted amount of undiscovered oil. Also, the United States has already recovered ~90% of its original 200 billion barrels of conventional crude oil, although more could be recovered with enhanced methods at a higher cost.

Despite periodic predictions that shale oil would soon be needed to replace diminishing crude oil supplies, shale oil production has actually dropped threefold since 1980.[2] Major shale oil production operations in Estonia, Scotland, and China are either gone or dwindling due to high costs relative to crude oil. A major push to develop oil shale in the late 1970s in the United States in response to a crude-oil price spike caused by a politically inspired OPEC embargo crashed in the early 1980s when the price of crude oil plummeted to historic values. The next oil shock is reasonably predicted by one to be about 2020, when half the world's ultimately discovered oil will have been produced and production is no longer able to keep up with the increasing number of automobiles in the world.[3] For reference, current crude oil consumption is 7 billion barrels per year in the US and 30 billion barrels per year worldwide.[4]

Besides the intrinsic cost barriers for producing oil shale economically, oil shale has come under considerable criticism from the environmental community. Concerns include sulfur-gas emissions, high CO_2 release per barrel of oil for modified in-situ processing, disturbance of topography from disposal of spent shale and mine tailings for conventional mining, wholesale changes in topography for open pit mining, water consumption, and degradation of ground-water quality due to mobilization of organics and inorganics in the spent shale. Such concerns played a major role in the death of the U.S. federal oil shale research program in 1994.

In view of both the economic and environmental issues associated with existing concepts for oil shale development,[5] which involve some combination of underground and open pit mining with modified in-situ and above ground retorting, it would appear that a new concept is required if we are to ever realize the benefits of the huge western US deposits, primarily in Colorado's Piceance Basin. Such a concept arises from the understandings that oil shale is merely a natural petroleum source rock that didn't get buried deeply enough to generate oil, that huge volumes of rock can be heated with essentially no mining by radio frequency (rf) waves, that oil shale heated over the course of several years generates a product very similar to natural petroleum with minimal mineral side reactions, and that overburden pressure will effectively squeeze the generated product out of the rock and into production wells.

The concept of rf processing of oil shale was developed by at IITRI in the late 1970s.[6,7,8,9] Its economics were subsequently evaluated by Mallon.[10] In both cases, the concept was to heat modest volumes of shale over a period of a few days using vertical electrode arrays shown in Figure 1 to a few months. Burnham[11] later suggested that deeper, large volumes could be processed at slower heating rates over a period of a few years to create a petroleum-like product that is extracted with conventional petroleum drilling technology. Rf processing has also been considered for enhanced oil recovery.[12,13] Additional patents found in the final stages of writing of this document include Copland[14], Bridges[15], Sresty et al.[16], Savage[17], Savage and Paap[18], Wellington et al.[19], and Zhang[20]. The latter two address non-rf methods of slow retorting in the subsurface.

Heating Geometries

The central problem being addressed by this concept is that oil shale resources in the Piceance Basin, where the majority lie, are as much as 2700 feet below the surface.[5,21] Earlier rf retorting concepts targeted shallow deposits, using shafts and rooms to emplace the electrodes. Experiments used to evaluate the concept were at atmospheric to modest pressures hydrostatic pressures and no lithostatic pressure, at which oil recovery would be by volatilization.

My initial large volume concept was to drill deep vertical wells in a hexagonal pattern at a distance so that the overlapping energy deposition contours from independent antenna in the individual wells would be roughly constant at all locations. This means that a wavelength must be chosen so that the 1/e attenuation distance is comparable to the well spacing, which one would prefer to be one hundred or more meters. However, uniform heating may be difficult with this geometry in regions of varying shale grade and aquifer salinity. Also, the pattern would have to cover a large area to minimize edge effects.

An alternative geometry was inspired by a horizontal well drilling configuration presented by Smith et al.[22] As shown in Figure 2, this enables the original waveguide concept of IITRI to be applied parallel to the bedding planes, which should enhance the uniformity of energy deposition. Of course, further investigation is required to place this conclusion on a sound basis, and still other geometries may be preferable. The horizontal drilling method was subsequently found in the 1984 patent of Copland[14]. The horizontal wellbores would probably be best placed in lean zones to minimize compaction

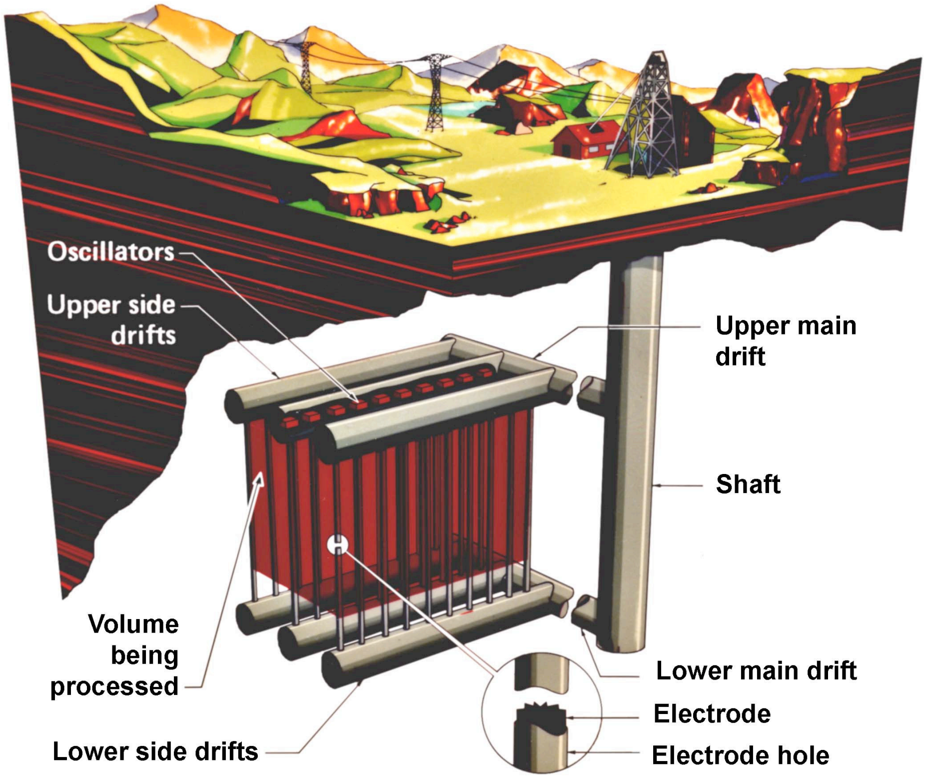

Figure 1. Conceptual design of the tri-plate rf waveguide approach to oil shale retorting as adapted by Mallon[10] from IITRI.

The proposed operating frequency for the waveguide geometry, with a total thickness of 10 m, is approximately 6-8 MHz.[10] Some adjustment will be needed for the greater the greater well spacing proposed here. While not known for certain, Mallon quotes unpublished data of J. Dubow at Colorado State University suggesting that absorption is higher in rich oil shale grades. However, that work probably used atmospheric pressure heating, which would dehydrate differently than under pressure in the subsurface. Water content in the porous parts of the formation and in fractions is also an important factor to be considered. This is a significant unknown for any feasibility assessment.

Oil and gas generation and expulsion

During the 1980s, it became generally recognized that the chemical kinetics of natural petroleum formation are basically the same as those for generating shale oil in the laboratory or factory. Although the concepts discussed here are general, we will only give results for Green River formation oil shale. Oil generation kinetics derived by Campbell et al for modeling in-situ retorting,[23,24] as modified by Burnham and Braun,[25] were later applied by Sweeney and Burnham,[26] with minor revision, to account for oil generation in Utah's Uinta Basin. The modified reaction network included rate expressions for gas generation from both kerogen and oil cracking.

Oil generation curves from Green River oil shale are given for a few relevant heating rates in Figure 3. At the highest heating rate of 3°C/h, the oil generation is essentially complete at ~400°C, or in about 5 days. At the middle heating rate of 3°C/day, oil generation is complete at ~350°C, or in about 3.5 months. At the slowest heating rate of 3°C/month, oil generation is complete at ~300°C, or in about 7.6 years. In all cases, oil generation starts in earnest at about 75% of the time for completion.

An important advantage of the lower temperature generation is improved oil quality. A summary of oil properties from a self-purging reactor[27] at various heating rates and pressures is given in Table 1. Nitrogen and sulfur contents are half that in Fischer assay shale oil at conditions closest to rf processing. Gas chromatograms of a few selected samples are shown in Figure 4. In the case most like in-situ rf processing, the improvement in yield comes with a 25-30% loss in oil yield, as shown in Figure 5. Similarly, expelled oil from hydrous pyrolysis experiments using Green River shale is also much more like natural petroleum than conventional shale oil.[28] Huizinga[19] reports 6 wt% oil yield from Green River oil shale containing 10.6% organic carbon, which corresponds to 73% of Fischer assay. Slightly higher yields may be possible at lower temperatures and higher pressures, which would reduce oil cracking.[29]

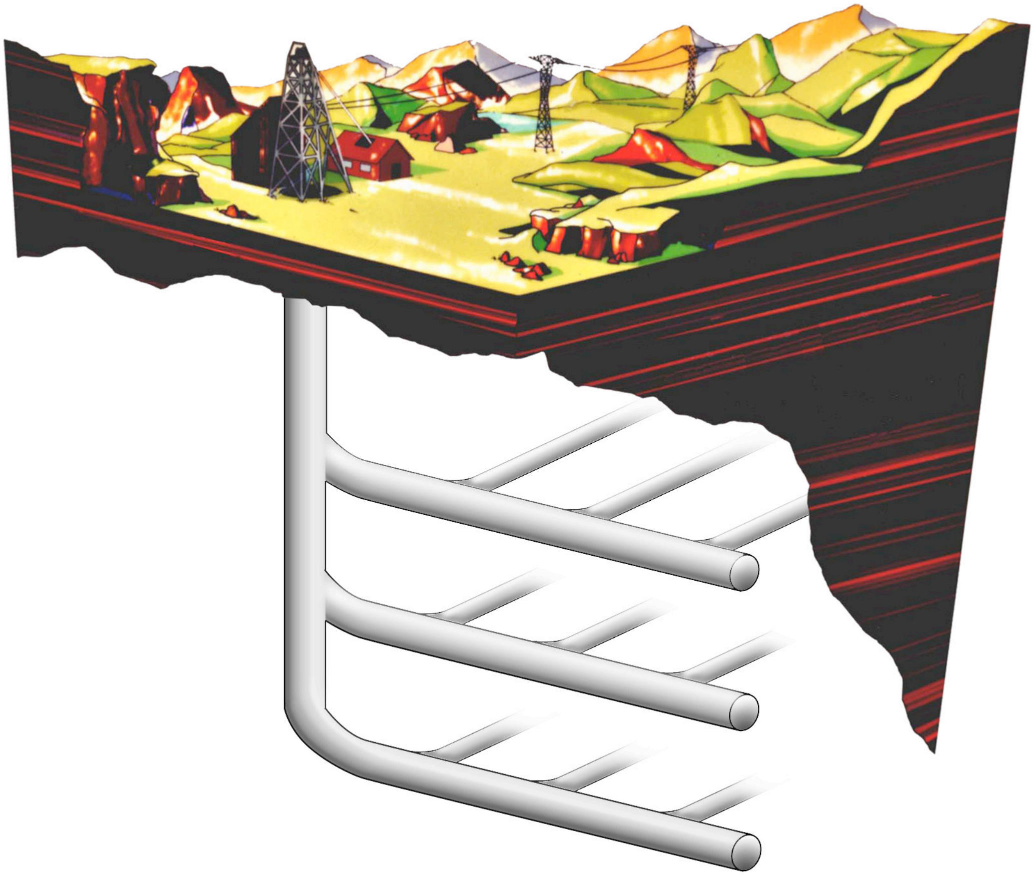

Figure 2. Adaptation of the IITRI tri-plate rf retorting process to horizontal drilling technology to enable heating of large volumes of shale in the subsurface with a minimal number of boreholes at the surface.

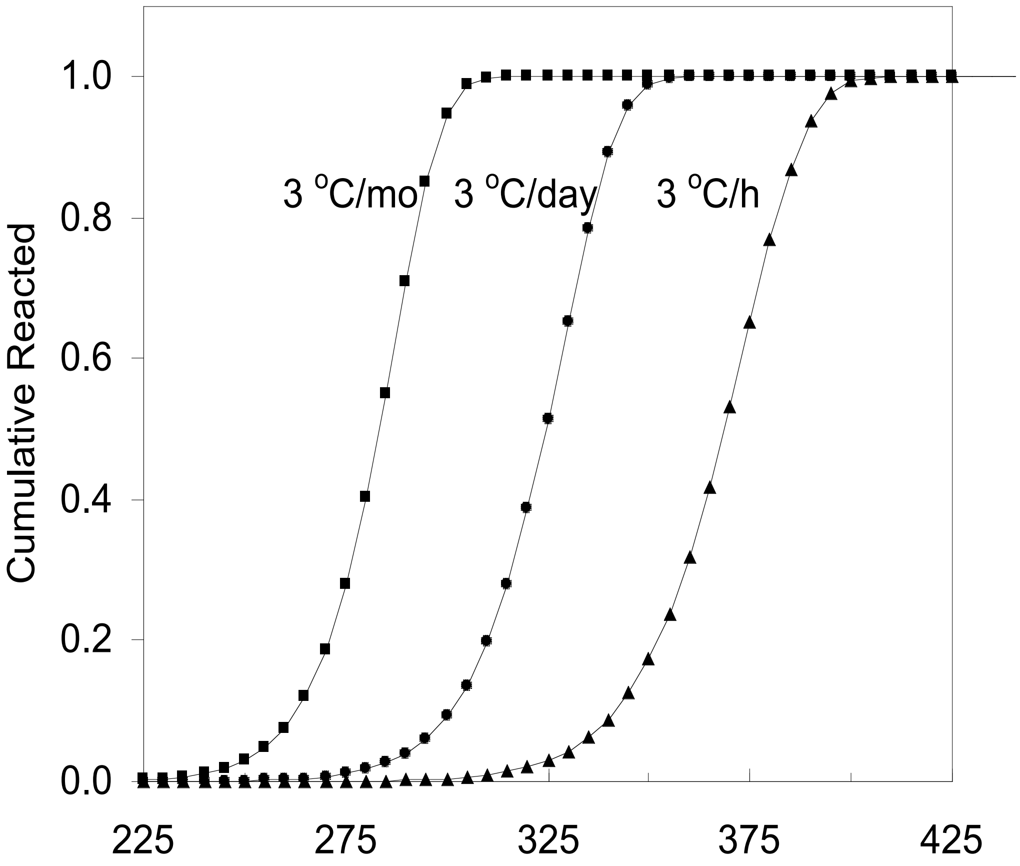

Figure 3. Calculated oil generation curves for Green River oil shale at three heating rates of interest for in-situ retorting.

Table 1. Summary of shale oil properties at the extremes of conditions examined by Burnham and Singleton.[27]

Conditions	Density, g/cm^3	H/C ratio	Wt% N	Wt% S	90% distilled, °C
12 °C/min, 1 atm	0.906	1.61	2.7	0.66	504
1 °C/h, 27 atm	0.826	1.90	1.5	0.36	395

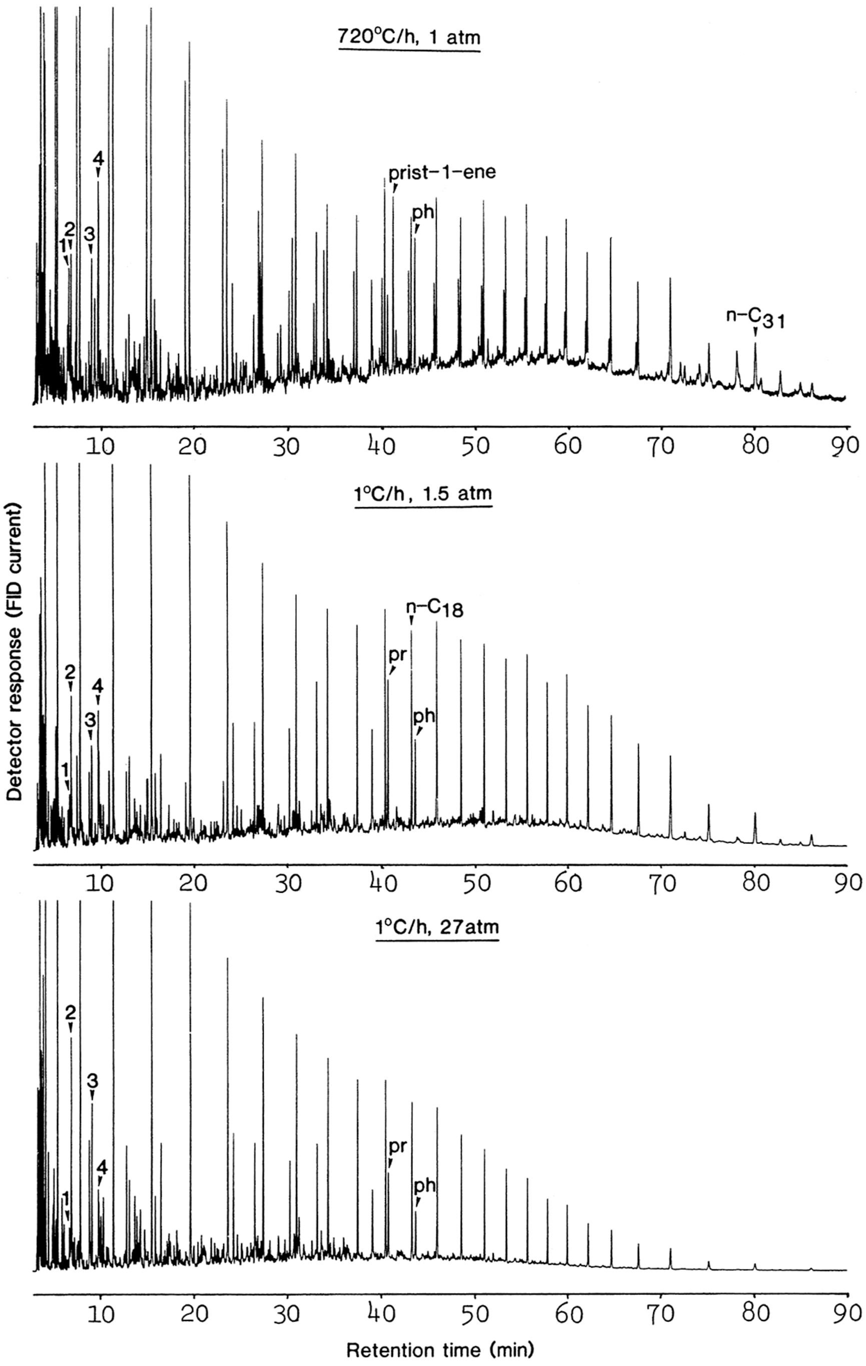

Figure 4. Gas chromatograms of shale oils produced at three different pyrolysis conditions (from Burnham and Singleton[27]). Slower heating rates and increased pressure generate more petroleum-like shale oil. Numbered compounds are (1) toluene, (2) branched C_8H_{18}, (3) trimethyl cyclohexane, and (4) m, p-xylene.

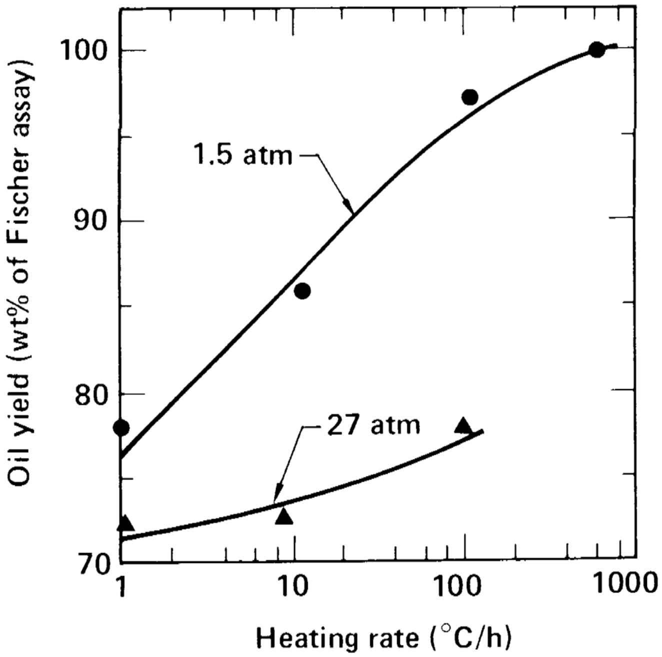

Figure 5. Effect of heating rate and pressure on oil yield (from Burnham and Singleton[27]). The effect of pressure is probably greater than in the subsurface because liquid oil cracking rates are lower and because evolution of oil from the self-purging reactor used in this experiment requires volatilization.

Raw oil shale has very little permeability, both because it is a fine-grained rock and because organic matter to some extent is a pore filling material. Consequently, external reactants or heating fluids cannot penetrate very far. However, the low permeability is not a significant constraint for escape of generated product. Under normal high temperature retorting, the gas and oil vapors, which have a volume much greater than the kerogen from which they are formed, escape readily through the porosity generated by the kerogen conversion. Under natural petroleum generation conditions, oil and gas are in a single fluid phase, and the excess volume generated is too small to expel much of the generated fluid. However, the additional porosity formed is greater than can be withstood by the lithostatic overburden, so the rock compacts and expels the fluid. If the permeability is insufficient to expel the oil and gas at the rate it is expelled, the rock fractures and releases the product via high-permeability cracks. Compaction-driven expulsion does not appear to be considered by IITRI.

To our knowledge, there are currently no generation-compaction models available to quantitatively calculate the rate of oil release over the broad range of interest for rf-generation. Our first computer code for this application, PYROL, coupled a chemical reaction network to a gas-liquid equilibrium calculation and leaky compacting reactor with a pressure relief valve.[30] The chemical reaction model was calibrated largely on the data of Burnham and Singleton,[27] which were collected under conditions thought to be close to those under the rf generation conditions of Mallon.[10] Unfortunately, the PYROL expulsion is incorrect in certain aspects of the compaction-expulsion model.

PMOD is a subsequent computer code that has greater flexibility in the chemical reaction network and included an equation-of-state model for water.[31] PYROL calculations had shown that the organic fluids were single phase above 90°C and 25 MPa, which corresponds to a depth of about 3 km. Since natural petroleum formation occurs below that depth, PMOD included only single-phase organic volumetric calculations. Otherwise, it is also a compacting leaky reactor, as shown in Figure 6. The conditions used for rf processing may involve shallower depths and lower pressures, so the single phase approximation may not be valid. Further, rf processing will occur at higher temperatures at which water solubility in the organic phase cannot be ignored. Including these effects in PMOD would be fairly straightforward, but not without effort.

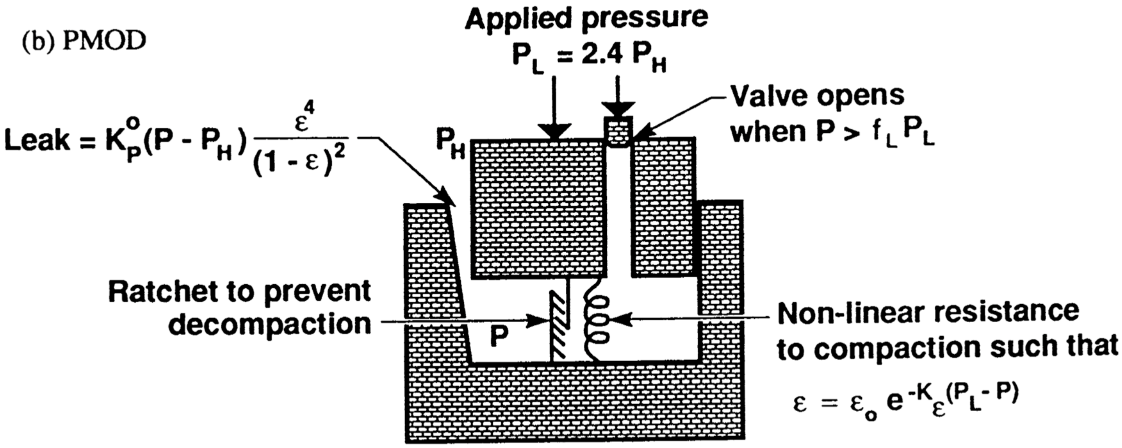

Figure 6. Schematic diagram of the compaction model in PMOD. Compaction in the absence of excess pore pressure is exponential. If fluids cannot escape by permeation, the rock fractures and releases fluid though the equivalent of a pressure relief valve. The rock cannot decompact, but porosity can increase during conversion of kerogen to oil and gas if the generated pore pressure is sufficient to prop open the new porosity.

Heat requirements

Central to any feasibility analysis of is the amount of energy needed for the process and the cost and availability of that energy. The largest heat requirement is for sensible heat in the residual shale. A fundamental advantage of slow rf processing of oil shale is that the oil is extracted at a lower temperature, 325°C ± 25°C for heating over a few months to a few years. If the fluids are extracted as liquids at high hydrostatic pressure, the heat of vaporization is also saved.

The first calculation is merely one describing the amount of energy needed as a function of oil shale grade and heating rate, using algorithms from the literature.[32,33] This is given in Table 2. An important issue is whether co-generated gas has enough energy content to provide the energy for the process. For comparison, Fischer assay retorting generates gas with an energy content of 422 MJ/Mg of 104 l/Mg oil shale and 591 MJ/Mg of 146 l/Mg oil shale.[34]

Table 2. Ideal energy and power required to retort two grades of oil shale at three different heating rates achievable in situ.

Heating rate	Final T (°C)	MJ/Mg (104 l/Mg shale)	kW-h/Mg of shale	kW/Mg of shale	MJ/Mg (146 l/Mg shale)	kW-h/Mg of shale	kW/Mg of shale
3°C/mo	300	302	83.8	0.0012	347	87.4	0.0013
3°C/day	350	364	101.2	0.038	400	105.6	0.040
3°C/h	400	428	119.0	0.94	454	124.2	0.98

However, the yield of oil and gas under slow retorting conditions is not the same as under Fischer assay. Gas compositions reported by Burnham and Singleton for slow, modest-pressure retorting indicate that energy content of the gas could be as much as 70% greater than for Fischer assay. This increase has at least three sources of uncertainty: (1) possible leaks in their gas collection system at the slowest heating rate at elevated pressure, (2) difficulty in recovering light hydrocarbons dissolved in the oil at elevated pressure, and (3) the likelihood that oil cracking at higher geological pressures in the liquid phase are less than in the self-purging reactor, which requires volatilization for expulsion. Nevertheless, it is likely that the gas yields will be higher for methane due to oil coking reactions, which was the main reason for the 70% increase, so it is likely that slow rf retorting would generate gases with ~650 MJ/Mg for 104 l/Mg shale and 900 MJ/Mg for 146 l/Mg shale.

Does the co-produced gas have enough energy to supply the production at steady state? The answer depends on the efficiencies of electricity generation, conversion to rf, and coupling to the shale. For the moment, I assume the same values for these as Mallon, namely 0.43, 0.80, and 0.85, for a total efficiency of 0.29. This means that the gas can deliver 190 MJ/Mg to the 104 l/Mg shale and 263 MJ/Mg to the 146 l/Mg shale. These are half the required energy for the 104 l/Mg shale at 3°C/day and 75% of the required energy for the 146 l/Mg shale at 3°C/mo. The remaining electrical energy would have to come from other fuels or a renewable energy source.

(As an aside, these calculations assume the shale starts at 25°C. The shale could be substantially warmer if deeply buried--geothermal gradients are ~20°C/km). The reduced energy needed to retort deep oil shale may more than compensate for the extra drilling costs. Also, one may be able to take advantage of thermal conduction over long time scales preheating alternate layers or injection of water into the wells to recover energy in the form of steam for electrical energy generation.)

Development Concept

As originally proposed by Mallon, initial electricity for the process would be provided by off-peak power from existing area power stations. Mallon lists four major generation facilities with a combined capacity of 7.3 GW. Roughly 2.5 GW, averaged over the day, might be available for this purpose. One needs to assume efficiencies for conversion to rf energy and coupling to the formation, which we again take as 0.80 and 0.85. The resulting masses of shale that could be processed at any given time are given in Table 2. Also given are the cross-sectional areas involved for a thickness of 20 m, assuming a density of 2.2 Mg/m^3. Given that areas of order km^2, depending on depth, would probably have to be involved to take advantage of compaction-driven expulsion, the $3^oC/h$ heating rate does not appear to be viable for this concept.

The intrinsic oil yield at the slow high-pressure retorting conditions should be of order 0.75 of Fischer assay, and one might assume an expulsion-recovery fraction of 0.8, giving a total yield of 0.6 of Fischer assay. The production rates given in Table 2 are calculated with these efficiency factors and with the shale masses for each grade rather than the average given in Table 3. The average oil production rates are of order 1% of the US daily consumption.

Table 3. Amounts of shale that can be processed by off-peak power in the near-Colorado region and average production rate for 2.5 GW of electrical power.

Heating rate	Total shale processed at any time, Mg	Area processible for 20 m thickness, km^2	Production rate from 104 l/Mg shale, bbl/day	Production rate from 146 l/Mg shale, bbl/day
$3^oC/mo$	2.0×10^9	46	2.6×10^5	3.5×10^5
$3^oC/day$	6.4×10^7	1.5	2.3×10^5	3.1×10^5
$3^oC/h$	2.6×10^6	0.059	2.0×10^5	2.7×10^5

The oil production rate depends primarily on the power input and the shale grade. The slight decreases at the higher heating rates are due to the higher temperature (lower thermal efficiency) needed to complete retorting. One might also envision fewer long-term environmental problems with the lower final shale temperature. Oil is produced only during the last quarter of the heating time. Consequently, one would envision four blocks in process at any given time to maintain a constant production rate, even though only one would be producing at a given time.

The cost of the off-peak power is envisioned to be ~\$0.02/kW-h.[10] Recalling that the total efficiency of electricity into shale heating is 0.68, this corresponds to \$2.46-3.65/Mg shale for Fischer assay yield. However, we estimate recovered oil yields of ~60% of Fischer assay, implying a yield of 0.39 bbl/Mg for the leaner shale and 0.55 bbl/Mg for the richer shale (1 bbl=159 l). This results in electricity costs of \$6.30/bbl for the leaner shale and \$4.70/bbl for the richer shale when retorted over a few years. The electricity costs for retorting over a few months are about 20% higher. Improvements in conversion, delivery, and recovery efficiencies would reduce these costs. Also, these calculations ascribe no electricity costs to the co-produced gas, which contains ~20% of the product heating value according to our yield assumptions.

After oil and gas generation starts, the produced off-gas could be used for additional power. The yield of electrical power depends on the method used, but we will start with a relatively conservative assumption of 50% efficiency for current technology. Along with the rf generation and deposition efficiencies, roughly one third of the heating value of the offgas would be used beneficially for retorting. Recall that slow in-situ rf retorting will likely generate gases having heat content of ~650 MJ/Mg shale for 104 l/Mg shale and 900 MJ/Mg for 146 l/Mg shale, and from Table 2, that the corresponding energy requirements are 333±30 and 375±25 MJ/Mg, respectively, for the range of the lower two heating rates. Consequently, the leaner shale can provide ~65% of its energy requirements from offgas, and the richer shale can provide ~80% of its energy requirements.

In other words, the total oil production rates could be increased by 3 times for the leaner shale and 5 times for the richer shale for the same amount of imported power. This implies steady state oil production rates of 7.3×10^{5} bbl/day from 104 l/Mg shale and 1.6×10^{6} bbl/day from 146 l/Mg shale. Production rates could be increased to even higher levels using specially built natural gas, coal, solar, wind, or nuclear capacity. For comparison, Lewis estimated a production rate of 5×10^{6} bbl/day for a pit mine advancing at a rate of _ mile per year along an 11-mile front.

Areas of Needed Research

This paper presents a conceptual study, not a feasibility study. There are several areas of research that are needed to do a feasibility study. First, the rf attenuation distances as a function of shale organic content, water content, water salinity, temperature, and extent of reaction are not known adequately for high pressure retorting. These are needed to accurately calculate the energy deposition profiles using state-of-the-art electromagnetic codes. Next, thermal diffusion calculations must assess both beneficial (heat smoothing) and detrimental (heat loss) affects as a function of shale composition and heating rate. Next, improved multiphase equation-of-state models are needed in computer codes such as PMOD to calculate source rock pore pressures and compaction during generation. Also, 3D-compaction codes must be used if the geometry does not support the use of a 1D-compaction model based on overburden pressure. Finally, an assessment is required of the effectiveness of boreholes in various geometries to collect and produce the oil before it dissipates into the formation.

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