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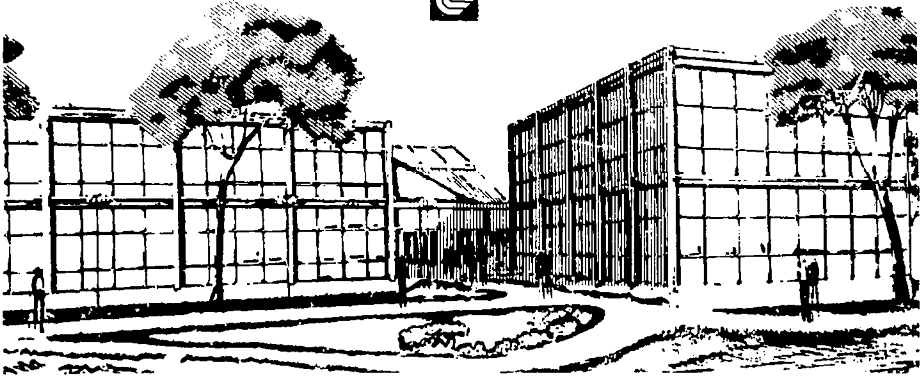

SCOPING OF FUSION-DRIVEN RETORTING OF OIL SHALE*

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Summary

In the production of synthetic fuels using fusion reactors, an initial scoping was done of the application of fusion reactors for providing economic, high temperature process heat for the high efficiency production of shale oil in underground retorts.

In the time frame beyond 2005, fusion reactors are likely to make their first appearance when the oil shale industry will probably be operating with 20% of the production derived from surface retorts operating on deep mined shale from in situ retorts and 80% from shale retorted within these in situ retorts using relatively fine shale uniformly rubblized by expensive mining methods.

We have developed a process where fusion reactors supply a 600°C mixture of nitrogen, carbon dioxide, and water vapor to both surface and in situ retorts. The surface retorts are operated at high flows and yields using water for temperature control.

The in situ production is accomplished by inert gas retorting, without oxygen, avoiding the burning of oil released from the larger shale particles produced in a simpler mining method. We found that these fusion reactor-heated gases retort the oil from four 50x50x200m in situ rubble beds at high rate of 40m/d and high yield (i.e., 95% F.A.), which provided high return on investment around 20% for the syncrude selling at $20/bbl, or 30% if sold as $30/bbl for heating oil.

The bed of 600°C retorted shale, or char, left behind was then burned by the admission of ambient air in order to recover all of the possible energy from the shale resource. The hot combustion gases, mostly nitrogen, carbon dioxide and water vapor are then heat-exchanged with fusion reactor blanket coolant flow to be sequentially introduced into the next rubble bed ready for retorting.

The advantages of this fusion-driven retorting process concept over present day concepts are a cheaper mining method, high yield and higher production rate system, processing with shale grades down to 50 ℓ/mg (12 gpt), improved resource recovery by complete char utilization and low energy losses by leaving behind a cold, spent bed.

Need for Synthetic Fuels from Fusion

There is presently within the U.S. a strong incentive to pursue an agressive synthetic fuel program to augment the dwindling supplies of refinable crude oil from our national supplies and from abroad. The time frame for a full-scale synthetic fuels industry would be expected to be beyond year 2005, with the first emergence of coal gasification, surface and in situ oil shale extraction and heavy oil production expected around 1985.

The physics of fusion is evolving nicely now as a world-wide effort, with large physics scale machines like TOKAMAKS: JT-60 JET, T-20, TFTR and MFTF MIRRORS under construction. These machines are primarily directed toward electric power production. The time frame looks like the first appearance for a demonstration fusion electric power plant to be around 2005[1,2] as in Fig. 1. Since the majority of the U.S. energy needs involve non-electric uses such as transportation, space heating and industrial process heat, there is a need for addressing synthetic fuels from fusion to serve these other energy needs. An excellent summary of the present thinking in this area has been prepared by Larry Booth[3] for DOE, where electrolytic, thermochemical and direct radiolytic cycles are addressed primarily for hydrogen production. Oscar Krikorian has broadened the scope a little in a proposal[4] outlining novel concepts for chemical process application. Professor Fred Ribe and co-workers at University of Washington have nearly completed a conceptual design for a fusion driven coal-gasification process, and a University of Connecticut group[5] is working on fusion driven electrolytic hydrogen-gasification and coal process. Recently the scope was further broadened[6] to include in addition to hydrogen production, coal-gasification and oil shale retorting.

It is the purpose of this paper to provide an initial scoping study of the application of fusion reactors* for providing a high temperature inert fluid for underground retorting of oil shale. We will first examine the present status of in situ oil shale extraction and identify which process steps can be improved by fusion, then lay out a fusion-driven process concept, and finally assess its merits and shortcomings.

Oil Shale Extraction -- Present Status

There are precious few overviews of the status of the U.S. oil shale program[7-15]. In summary, it can be stated that the latest estimate of economically recoverable oil is 600-700 billion barrels (out of 1.8 trillion barrels in place) in the Green River formation in the Colorado - Wyoming - Utah area. There are also massive (3 trillion barrels in place) lower grade shale deposits in the eastern U.S., called Antrim shale, only a small portion of which is economically recoverable.

The present activities of the U.S. can be broken down into (1) surface processing activities where shale is mined and brought above ground for retorting about 600°C and (2) in situ processing, where combustion driven retorting is carried out in underground mines.

Surface processing technology presently involves activities in direct heating, where either air or oxygen is introduced into the retorting vessel containing crushed shale. Oil product or residue

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* Although this study has addressed the application of fusion reactors, other high temperature gas sources can be used as well, such as high temperature gas reactors (HTGR's) and concentrating solar collector systems.

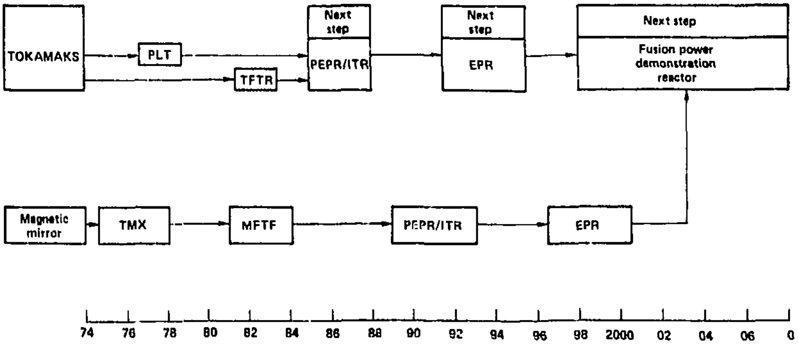

Fig. 1. General features of the Logic III reference option.

shale char is burned to supply the energy to heat the retort feed gases. There is also an indirect heating mode where a heat-carrying medium such as inert gas or recycled gas, is passed through the bed. The TOSCO process mixes externally heated hot ceramic balls with the shale to supply the heat.

Both process concepts (direct and indirect heating) for surface retorts are delayed because of serious environmental problems with disposing of the 150,000 tons/day shale per 100,000 bbl/day module in the plant and with the large amount of water consumed.

In situ processing was developed to correct many of these problems. In situ techniques can be applied to deeper deposits and to lower grade shales; thus, recovering a larger fraction of the resource in place. There is some basis for hope that shale grade down to 75 ℓ/mg (15-20 gal/ton) would be retrievable. DOE's activities are best summarized[15] as follows:

"Although in situ conversion offers several potential advantages, no single version is applicable to the full range of oil shale deposit types. Consequently, DOE's research and development program is focused on several variations of in situ retorting. In general, the variations can be grouped under two broad categories: (1) modified in situ, where a void is created by mining or leaching; and (2) true in situ, where the zone is rubblized and retorted without creating a manmade void.

"Vertical modified in situ techniques are believed to offer the most promise for early development and are especially attractive for deeper and very thick (more than 300-feet) deposits. In October 1977, DOE signed a contract for a multiphase program with Occidental Petroleum Corp.* to develop a vertical modified in situ process at Occidental's Logan Wash site in Garfield County, Colo. In Occidental's process, about 20 percent of the shale is mined to form an underground compartment. The surrounding shale is broken up and expanded by explosives to create a kind of underground chimney full of rubblized shale. From the top of the chimney, a small amount of oil is ignited and the retorting begins. Combustion in the chimney moves slowly downward as shown in Fig. 2 - typically 1-2 feet per day - and the heavy oil produced flows by gravity to the bottom where it is collected and pumped outside the mountain.

"A horizontal true in situ technique being developed by DOE and the Geokinetics Oil Shale Group is currently applicable only to very shallow depth formations (less than 100 feet of overburden). Conventional mining is not used. Instead, explosives expand and rubblize a bed of shale lifting the surface of the ground noticeably. The firm, with DOE support, is conducting laboratory investigations and field development and demonstration tests through a series of progressively larger retorts in Uintah County, Utah.

"A vertical true in situ process is also under development by DOE for processing the leached zone in deep, thick shale beds in Colorado. The process uses the void space created when the water-soluble salts orginally distributed throughout the 500-foot thick seam were dissolved by naturally occurring groundwater. Because the zone is a saltwater aquifer, direct combustion methods are not applicable. The concept being tested, under a contract with Equity Oil Co., involves passing superheated steam through the full thickness of the leached zone to achieve the

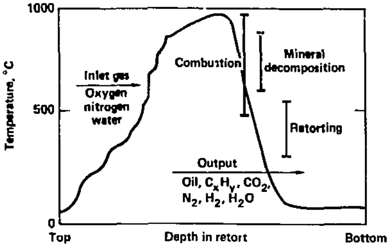

Fig. 2. Movement of the thermal wave.

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* Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

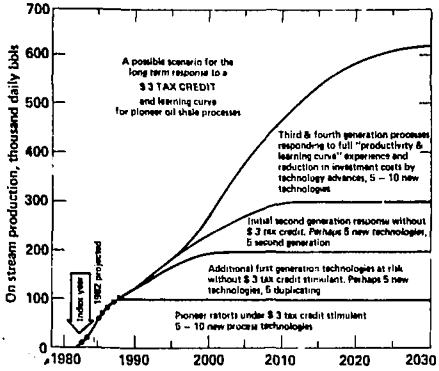

Fig. 3. Projected development of an oil shale industry.

required retorting temperatures. Tests of this process are underway in Rio Blanco County, Colo.

"In addition to these major in situ efforts, DOE is also conducting research on advanced concepts including microwave and radiofrequency processing and vacuum retorting.

"DOE has also contracted with Dow Chemical Co., Midland, Mich., to study underground gasification of the Antrim oil shale in Michigan. For the past 20 years, Dow has conducted an experimental program with this type of shale.

"Under a 4-year program with DOE which began in 1976, Dow is assessing four methods for the chemical explosive and hydraulic fracturing of Antrim shale in place. The retorting will take place underground with a minimum of disturbance to the environment.

"DOE has also begun a program to test a process for adding hydrogen to lower quality shales during the retorting process. Using this technique, useful fuels may be obtained from shale formations previously considered unlikely candidates for development due to low oil yield under normal conditions. This technique could be particularly beneficial in the East."

The timing for the deployment of an oil shale industry is best summarized in Fig. 3 by Hutchins[13]. In short, with a $3/bbl tax credit, a mature industry is expected to be in place starting by 2005 and lasting at least through 2050, when fusion technology is expected to be mature.

The key to the longer term development of a U.S. oil shale industry appears, at this time, to be the deployment of a pioneer venture modified in situ (VMIS) plant. Surface retorting is expected to occur first, once the political and environmental issues can be resolved, and then the deeper, lower grade deposits can be exploited by VMIS in combination with surface; to be followed later by pure in situ technology aimed at the even lower grade, dispersed deposits in the Eastern portion of the U.S. So it appears that a fusion-driven process ought to address the in situ processes - - first VMIS and then later, true in situ.

VMIS technology, at present, suffers from oil yield losses from oxygen penetration from behind the combustion front forward, into the retorting front. Mining improvements in rubble bed preparation are being directed toward achieving beds with more uniform flow and higher sweep efficiency and oil yield. Another approach is to utilize the existing imperfect rubble bed and by applying advanced methods of process control,[16] get an acceptable performance. These methods are directed at using preburn characterizations of the bed and manipulation of feed gas properties and compositions in order to minimize the co-mingling of oxygen with the retorted oil and the associated loss in yield. If these kinds of remedies for the VMIS process are too complex or expensive, then the U.S. effort may be redirected toward inert fluid retorting.

Both surface and in situ processing techniques can be improved with the availability of an inert (no oxygen) high temperature (600-800°C) fluid source. The advantages of inert gas retorting in surface retorts were carefully outlined by Allred[17]. The following advantages are claimed for the use of superheated water vapor; (1) increased yields of oil and gas, (2) lower retorting temperatures, (3) simplified oil recovery technology, (4) higher energy quality product gases with increased hydrogen content, and (5) more environmentally acceptable retorted shales. The key point in favor of water vapor is that it does not act merely as on inert gas, but as a chemically reactive feed that produces larger than normal quantities of hydrogen and higher yields. Comparing nitrogen and carbon dioxide with water vapor shows that oil yields of 110% of Fischer assay are achievable in a laboratory environment at temperatures of 500°C, with steam achieving this yield at temperatures as low as 450°C. Consequently, steam or mixtures with steam are particularly desirable.

At higher temperatures (500 to 800° C) other reactions occur which begin to degrade the energy efficiency of the process. For example, mineral carbonate endothermic decomposition[18] begins to occur at 500°C, depending on the concentration of the steam in the feed (500°C with 65% steam and 550°C with 20% steam) as shown in Figs. 4-6. Shale char reacts with CO_2 beginning at 660°C and with steam at 600°C,[19,20] as shown in Figs. 7 and 8. These reactions reduce the amount of energy that can be released from direct carbon oxidation. There are

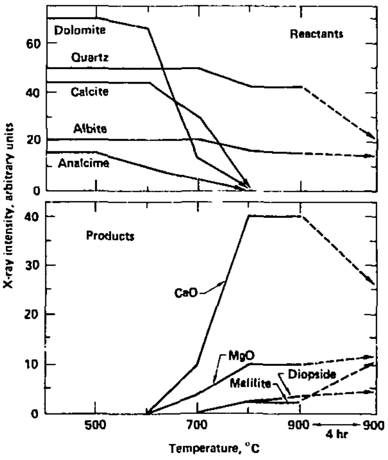

Fig. 4. Oil shale -- N_2 atmosphere.

also the endothermic decompositions of Kerogen and the release of bound water, but these are about an order of magnitude less significant in energy consumption than the mineral and char reactions.

From this discussion, it is clear that above 500°C, the energy efficiency of the process depends on the balance between the various heat sinks and the heat released by combustion of the shale carbon, released hydrogen, methane and heavier hydrocarbons and of any oil product. This balance depends strongly on the composition of the feed and product gases (i.e., water vapor and hydrogen content, etc.) and the process conditions and process control strategy used to operate the in situ retort. In general, from this evidence, a rough optimum shale particle temperature is expected to be around 600°C.

The rate of retorting[21,22] is another key process variable. As shown in Fig. 9, higher heating rates decompose the kerogen faster and remove the oil products faster before they can be coked, cracked or burned. The high heating rates are achieved by high sweep gas throughput and large temperature driving forces. The high heating rates in the range of 1,000 to 10,000°C/hr were achieved in a fluidized bed of shale and the upper point in Fig. 9 by rapid heating of a sphere. At these high heating rates, rapid heat transfer to the shale particles is required and for surface retorting, this can be achieved in a fluidized

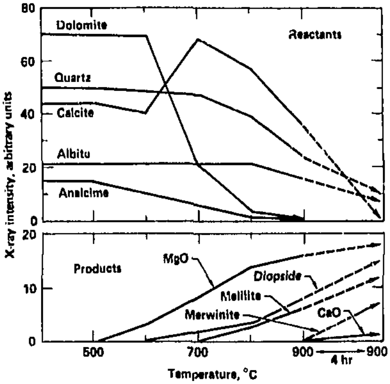

Fig. 5. Oil shale -- CO_2 atmosphere.

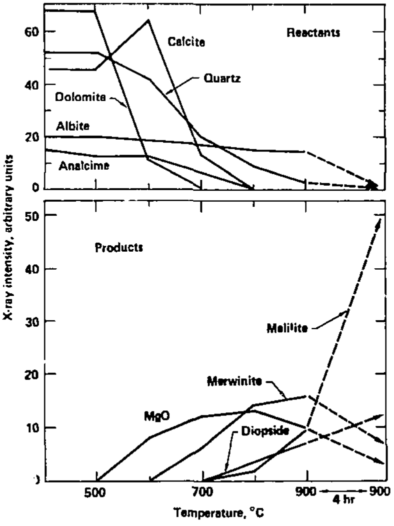

Fig. 6. Oil shale -- 95% steam atmosphere.

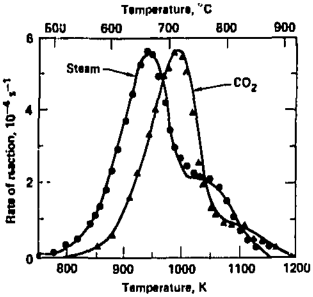

Fig. 7. Rate of reaction of steam and CO_2 in char gasification.

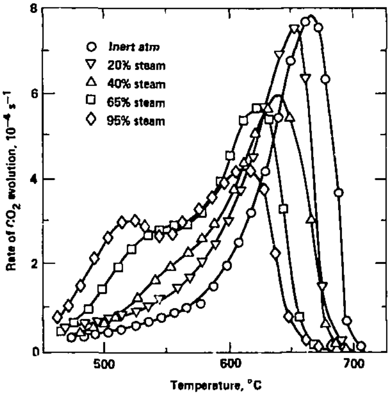

Fig. 8. Oil shale -- 95% steam atmosphere.

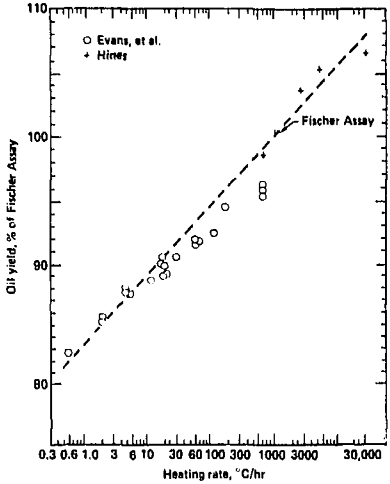

Fig. 9. Effect of heating rate on oil yield.

bed, such as used by Hines[22]. For in situ retorts, it appears that high sweep gas rates and high temperature driving forces are needed.

Fusion-Driven Retorting of Oil Shale

Now that we have established the most likely timing for a U.S. Oil shale industry and for the appearance of the demonstration fusion reactors, and we have outlined the potential areas where fusion-driven process steps appear valuable, we can propose an overall conceptual design in Fig. 10. Here, we show three rows of in situ rubble beds at different stages of the process: The first row on the left shows the rubble beds of shale (i.e., a group of four 50x50x200m) at different stages of the mining operation; the first module in the center row is being retorted with hot gases around 600°C, and in the right-hand row, a module is undergoing char combustion. Adjacent pairs are processed, moving in a zig-zag pattern down the last two rows. Start-up is planned by slowing the flow by half and feeding cool ambient combustion gases from one combustion driven retort.

The process has the following operational features: The mining operation can be done using the more economic horizontal shaft operations , where sub-level caving, stoping, or other drilling, blasting and rubblizing operations can be done on the ceiling or floor. This approach makes the best continuous use of the mining machinery in horizontal tunnels (avoiding costly hauling operations of this equipment to and from the surface) and avoids the costly intermittent operations that would be involved if one retort were mined and then burned. This arrangement also maintains a physical separation between retorts undergoing combustion and those undergoing mining -- thus, minimizing the opportunity for contaminating the mining worker's breathing atmosphere through leaks of carbon monoxide or hydrogen sulfide.

After the first pair of modules in the second and third rows is processed, the flow is switched about once a week to the next pair for processing. This assures continued use of the fusion plant heat and allows added time and operational flexibility.

The shale rubble is first subjected to hot combustion gases at 600°C without any oxygen. We have shown[16] that this approach eliminates the problems associated with oxygen "fingering" into (and destroying) the oil product. As the retorting front moves down the retort at superficial velocities around 40m/day, cool (i.e., 80°C) gases plus oil product pass out the bottom of the retort. The oil product consists of a liquid phase which is collected and removed and a vapor-mist phase which is fed to a series of cooled gravity and demister separators, designed to capture 99% of the fine oil mist. These exit gases will remain cool until the retorting front approaches the bottom of the rubble bed, at which point the temperature will start to climb toward 600°C. The retorting operation would be terminated when the temperature reached 500-550°C.

A hot spent shale bed is left after the retorting operation is completed. The shale remaining contains a substantial amount of carbon that was not carried off in the retorted oil. This carbon is left over when a portion of the kerogen is unconverted or as some of the oil is coked. This combination of carbon sources leftover is called char, and can be further processed to recover a significant fraction of additional energy. In addition, this spent bed of shale is hot, 600°C, and we do not want to leave this energy wasted in the ground. We believe the heat balance is favorable enough for a 600°C bed with gases exiting around 350°C, so that char can be combusted down to very low carbon levels.

So cool air can be admitted to this spent shale bed, as shown in Fig. 10, wereupon ignition will spontaneously occur[23] and combustion will begin. The combustion front will be driven down the bed by means of the cool air being fed to the bed. Combustion of char occurs evenly and does not exhibit the serious non-uniformities[24] in air combustion driven retorts. The hot gases leaving the spent shale beds consist mainly of nitrogen, carbon dioxide and water at about 350°C and are fed to the fusion plant heat exchangers for further heating to 650°C so they can then be fed to rubble beds for retorting. These spent beds are burned until the exit oxygen concentration reaches 5% or so. We do not wish to go higher since we want to avoid oxygen in the inert gas retort operation.

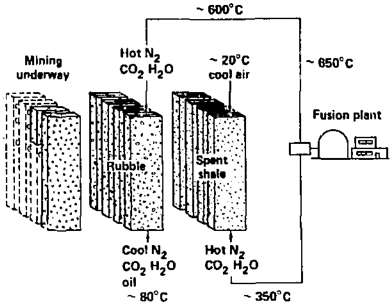

Fig. 10. Concept of fusion-driven oil-shale-retorting process.

Assessment

Now that we have presented the process concept, let us briefly examine the economic implications. We have used the basic 1GW$_{(e)}$ Tandem Mirror Reactor (TMR) costs[25] (1977 dollars) of \$980 (Kw$_{(e)}$) for the higher beta central-cell and design minus the generating turbines, condensers, cooling towers and associated hardware. The optimized point design plant operates at an overall thermodynamic efficiency of 0.34. We assume that the thermal power normally fed to the electric-generating turbine system of 2.844 GW$_{(t)}$ would be available to heat these gases at the same thermodynamic efficiency and the electric power from the direct converters of 620MW$_{(e)}$ is available for plant use and for grid. This gives us a thermal energy cost of \$350/Kw$_{(t)}$ to feed the oil shale process.

If we assume that the average grade of the rubblized bed to be retorted is 100 ℓ/mg (24 gal/ton), and we operate in the temperature range around 550°-600°C, then the thermal requirements will basically involve kerogen decomposition (0.045 GJ/Mg) and the release of bound water from the various minerals (0.041 GJ/Mg). Since we are designing for low temperature (i.e., 550-600°C) and rapid retorting rates, we plan to avoid any significant mineral decomposition.

The rates of retorting can be approximated simply[26], as was done for steam. Then, the retorting rate necessary to compute oil production rate is given approximately by the following expression:

$$V_{rf} = \frac{\rho_g C_{pg} V_g}{(1-\varepsilon)\rho_s C_{ps}} \qquad (1)$$

Where g and s denote gas and shale phases, ρ the density, Cp the heat capacity, ε the bed voidage and V_g the superficial gas velocity fed to the bed. Thus, the oil production can be calculated[23] as follows:

$$P = SE\ Y\ G\ V_{rf}\ \rho_s(1-\varepsilon)$$

$$P = SE\ Y\ G\ \rho g V g\ \frac{C_{pg}}{C_{ps}} \qquad (2)$$

Where SE is the sweep efficiency of the rubble mine, Y is the retorting yield, G the shale grade, and P is the production rate in Mg/m^2-day (equivalent to 29,000 bbl/acre-day).

In order to use this expression, we need to use the process concept in Fig. 10. First, the fusion plant heats the N_2, O_2, H_2O gas stream from 350 to 650°C using 85%[1] of the 2.844 GW$_{(t)}$ available heat, which corresponds to a total gas mass flow of $\rho_g V_g$=7.5 Mg/s. For a sweep efficiency of 85% and a yield of 60%, Eq. 2 produces an oil production rate of 32,000 m^3/day (or 235,000 bbl/day), this corresponds to a retorting rate (via Eq. 1) of 415,000 m^3/day. If one were to use the retort modules in Fig. 10 with a 10,000m^2 cross section, the rate would be 41.5m/d, which is ten times that in our present combustion-driven pilot retorts[16] that have been operated up to 4.4m/d. Surface retorts, on the other hand, have been operated up to 60m/d[27]. An example is Brazil's Petrosix retort[27] operating at a shale solids throughput of 2,000 Mg/d using inert gas at 30 m/d. This significant difference in rates is the result of the smaller, more uniform shale particles and the temperature control used in surface retorts and the lack of oxygen which would otherwise destroy oil. We also note that in inert gas retorting higher heating rates are beneficial as shown in Fig. 9. Our typical heating rates for field-scale combustion retorting are expected to be around 50°C/h; whereas, inert gas retorting can achieve 1000°C/h, or so. When we try to push combustion driven retorting faster, we find we must use increasing amounts of steam in order to keep the combustion peak temperatures below the sintering temperature of 1100°C.

Consequently, this fusion-driven process can be superior economically to combustion driven retorting, if we strive for considerably higher rates. The seam thickness rarely exceeds 200m and to maintain a reasonable aspect ratio of the bed for high sweep efficiencies, we have aimed for four retort modules of dimensions of approximately 50x50m, with an upper limit of around 70x70m. There are also problems with room and pillar mining in supporting the top roof with larger dimensions. This then places the retorting rate for a single retort module in the range 20 to 100m/d. If we introduce the added complexity of feeding hot gas to say four 50x50m retort modules, we could operate at 40m/d. The complexity of multiple modules in mining operations and process control would undoubtedly add somewhat to the cost. However, there is the advantage of individual flow control to the four separately.

Next we have to examine the heat requirements of a typical process module consisting of four 50x50x200m retorts operated on a 5 day cycle. As we presented earlier, the heats of kerogen decomposition and release of bound mineral water total 0.086 GJ/Mg. If we operate our process with 2.4 GW$_{(t)}$ of fusion heat at a thermal efficiency of 85%, which is typical of surface retorts, at a retorting rate processing 900,000 Mg/d (1 million tpd) of shale, we will produce 37,000 M^3/d (235,000 bbl/day) of oil product with a heat consumption of only 0.93 GW$_{(t)}$ for kerogen and bound water. If any mineral carbonates are decomposed in the process, owing to excess steam or temperature "hot spots", a portion of the 0.6 GJ/Mg endothermic carbonate decomposition heat would quickly consume the remaining process heat. For example, if about 20% of the carbonates were decomposed, the energy would balance. We believe this is a reasonable expectation for rubble beds that will exhibit flow non-uniformities. In this operational concept, the mineral provides a sort of "safety" temperature control.

Now, with this basis, we can examine the economic implications for the fusion-driven oil shale retorting process. The bases for the economic analysis are given in Table 1 and compare favorably with others[27,28] reported. Standard economic practices have been used[29]. The price of the syncrude or fuel oil product will depend on political and market factors, such as the congressional passage of a \$3/bbl tax subsidy for shale oil, prevailing interest rates, the cost of prerefining or upgrading of syncrude suitable for conventional refinery feedstock (i.e., \$8 to 10/bbl) or fuel oil, the OPEC and/or spot market prices of crude, etc. These and other factors, as they influence an oil shale industry, are discussed elsewhere[27].

Another critical factor in this analysis is the rather considerable delay of income cashflow during mine development and plant construction. It is of great economic importance to carry out as much as possible of this construction in parallel. One of the key advantages of this fusion-driven process concept involving inert gas retorting in situ is that most of the mine development and plant construction can be done in parallel. A proposed project plan is envisaged in Fig. 11. Mine development we visualize as involving a large initial stage (from \$500 to \$1600 million dollars) where major vertical shafts are sunk

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[1] *85% is a typical thermal efficiency of surface inert gas retorts.*

and major horizontal drifts and tunnels constructed; followed by a much lower level phase where individual modules are rubblized and completed at a rather rapid rate. Detailed discussion of mining methods is beyond the scope of this report; however, they are summarized elsewhere (5, 7-9, 27 and 28). There are several mining methods that could fit this kind of timeline.

TABLE 1. Economic Assumptions (July 1979 Dollars)

1. Start-up 2005.
2. 20-year plant.
3. 25% loan at 12% interest (75% equity).

4. Price of synthetic crude increases 14% per year.
5. Surface plant cost: $400M.
6. Fusion plant capital cost less generating turbines, condensers, cooling water tanks, and converted hardware: $995M.

7. 4% of capital for reclamation, environmental costs, land taxes, royalties, etc.

8. Mining and rubblized costs at $8/bbl and escalating at 8% per year.

9. Financing at $132M.

10. Operation, maintenance, administration and other burden $2/bbl and escalating at 8% per year.

11. No investment tax credit.
12. No depletion allowance.
13. No production or severance taxes.
14. Mine development: 4 years.
15. Plant construction: 4 years.

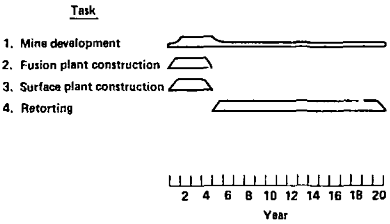

Fig. 11. Timeline for proposed project.

The amount of low level tritium contamination of the inert retort gas appears to be acceptable since the blanket coolant is heat exchanged with the inert retort gas at about 650°C and at this low temperature tritium permeation out of the blanket coolant will be under 10 Ci/day[30]. The blanket coolant is processed with a slip-stream scavenger system to keep the blanket coolant tritium level down to acceptable levels.

The economic results are shown in Table 2. We included the cash flows in Table 3 and gave a sample calculation for the first case of $6/bbl. We costed the mining, plant, operations and maintenance, financing and burden in a parametric study with varying syncrude or heating oil price (July 1979 dollars). The results show that the project is attractive (i.e., DCFROR between 15 and 30%) for syncrude or heating oil prices from $17 to 30/bbl. We also looked at the sensitivity to a U.S. Federal $3/bbl tax subsidy applied at production (4 years after project beginnning) and found the incentives to be very modest.

These results in Table 2 compare favorably with the Colony Study[27], which found for in situ extraction and some surface retorting a DCFROR between 10 and 13% when the syncrude price (corrected by 8% per year to July 1979 dollars) was between $19 and 24/bbl. In 1974, this was not considered good enough for continuing the Colony program. Today (Sept. 1979), prime interest rates are running as high as 14%, consequently, corporate investments would probably not be made unless DCFROR 14% depending on the degree of risk. And today there are several programs[31] looking at the feasibility of selling shale oil as a heating oil (after denitrification) for around $30/bbl for use in special low NO_x combustors. Thus, $20/bbl at a DCFROR 20% for syncrude or $30/bbl at 30% should be attractive for a fusion-driven process, given the pre-existence of a fusion reactor, that was the premise for this study.

This is approximately the economic position that the syncrude oriented oil shale industry is in today. If we add roughly $8/bbl for prerefining or upgrading costs in order to produce a refinery feedstock crude that will be purchased, the price of around $28/bbl is close to the present spot market price. And the use of shale oil as a heating fuel oil appears to be new and upcoming. So a fusion-driven oil shale retorting process is significantly better, and certainly no worse, than the present conventional oil shale "industry".

This brief scoping study has shown that the fusion-driven retorting of oil shale looks attractive enough at this rough early stage, that comments and suggestions from the technical community and further, more detailed conceptual design studies should be made.

TABLE 2. Economic Results.

	Syncrude Price ($/bbl)							
	6	8	10	13	17	20	25	30
Payout period (years)	17	13	10	9	8	7	6	5
DCF ROI (%) w/O subsidy	2.42	5.36	7.74	11.3	16.1	19.7	24.6	30.3
DCF ROI (%) w/ subsidy	2.86	6.00	8.54	12.4	17.4	21.2	26.5	32.6

TABLE 3. Cash Flows (Millions of July 1979 Dollars).

Year	Income $/bbl +14% Annual	Income $/bbl +14% Accum.	Mining & Retorting $8/bbl + 8%	O & M $2/bbl + 8%	Financing	Accum. Costs	Cash Flow
1980	0	0	500	0	174	674	-674
1981	0	0	1200	5	174	2053	-2053
1982	0	0	1600	10	174	3837	-3837
1983	0	0	1600	30	174	5641	-5641
1984	800	800	730	80	174	6625	-5825
1985	912	1712	788	86	174	7673	-5961
1986	1039	2751	851	93	174	8791	-6040
1987	1185	3936	919	101	174	9985	-6049
1988	1350	5286	992	109	174	11260	-5974
1989	1540	6826	1071	117	174	12622	-5974
1990	1755	8581	1156	126	174	14078	
1991	2001	10582	1249	136	174	15637	
1992	2221	12863	1349	147	174	17307	
1993	2601	15464	1457	159	174	19097	
1994	2965	18429	1574	171	174	21016	
1995	3380	21809	1699	185	174	23074	
1996	3853	25662	1835	200	174	25283	
1997	4393	30055	1982	216	174	27655	
1998	5009	35064	2140	233	174	30202	
1999	5710	40824	2312	252	174	32940	
2000	6509	47334	2497	272	174	35883	
2001	7420	54754	2696	294	174	39047	
2002	2459	63213	2912	318	174	42451	
2003	9644	72857	3145	343	174	46113	

ROI = 2.42%

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