APPLICATION OF THE HIGH TEMPERATURE GAS COOLED REACTOR TO OIL SHALE RECOVERY

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ABSTRACT

Current oil shale recovery processes combust some portion of the products to provide energy for the recovery process. In an attempt to maximize the petroleum products produced during recovery, the potentials for substituting nuclear process heat for energy generated by combustion of petroleum were evaluated. Twelve oil shale recovery processes were reviewed and their potentials for application of nuclear process heat assessed. The High Temperature Gas Cooled Reactor-Reformer/Thermochemical Pipeline (HTGR-R/TCP) was selected for interfacing process heat technology with selected oil shale recovery processes. Utilization of these coupling concepts increases the shale oil product output of a conventional recovery facility from 6 to 30 percent with the same raw shale feed rate. An additional benefit of the HTGR-R/TCP system was up to an 80 percent decrease in emission levels. A detailed coupling design for a typical counter gravity feed indirect heated retorting and upgrading process were described. Economic comparisons prepared by Bechtel Group Incorporated for both the conventional and HTGR-R/TCP recovery facility were summarized.

INTRODUCTION

As the supplies of natural petroleum steadily decrease, the search for replacement energy sources to extend the supplies of liquid fuels will intensify. One potentially replaceable energy source is the oil and gas that is currently burned to generate industrial process heat. Either coal or uranium can be substituted for this fuel to produce the required energy. Since the projected costs of nuclear power are lower than those generated by coal[1,2,3] and the potential for processing coal to produce a petroleum feedstock exists, nuclear energy was selected as the best energy source to extend the supply of petroleum and petroleum products. Review of current nuclear technology indicated that only the High Temperature Gas Cooled Reactor (HTGR) operates at high enough temperatures to supply this replacement process heat. This process heat can be supplied either directly within 5 miles (8 km) of the reactor or indirectly with a chemical transport system up to 100 miles (160 km) from the reactor.

The General Electric Company has entered into a contract with the Department of Energy (Contract Number DE-AC03-80ET34034) to evaluate the potential for utilization of energy generatd by a HTGR for oil shale recovery. During this evaluation the existing oil shale recovery processes were reviewed and the processes with the greatest potential for HTGR energy utilization identified. A detailed process design for a 50,000 barrels per day [BPD] (7947 m^3/day) oil shale recovery operation which would begin operation near the end of this century was prepared. The design incorporated the necessary features for utilization of HTGR generated energy. This process provided the basis for an economic comparison between the conventional fossil and HTGR fueled processes.

PROCESS EVALUATION

The available literature was reviewed to obtain a basic understanding of the following oil shale recovery processes:

TOSCO II	Chevron-STB
Union B	HYTORT
Paraho	Occidental
Superior	Rio Blanco
Lurgi-Ruhrgas	Geokinetics

Selection criteria were developed to evaluate each of these recovery processes from the standpoint of utilization of HTGR energy, see Table 1. The first group includes criteria which are con-

Table 1

Oil Shale Process Screening/Selection Criteria

Criteria	Weight
Potential of HTGR Coupling	Mandatory
HTGR Satisfies Processing Requirements	Mandatory
Development Status	5
Information Availability	9
Process Simplicity	3
Shale Feed Requirements	5
Water Requirements	4
Energy Requirements	6
Liquid Yields	7
Gas Yields	6
Spent Shale Disposal	5
Economics for HTGR Coupling	7
Process Modifications of HTGR Couple	8
Environmental Improvement	6
Marketability of HTGR Yield Improvements	6

sidered mandatory for any retorting process evaluated while the second group includes those items which are highly desirable. The items in the second group were assigned weighting factors (one through ten) according to their relative importance in the nuclear process heat coupling application. Twelve processes were evaluated against this list of criteria. The mandatory criteria for each process were evaluated on a yes/no basis. In the case of the second group, each process was assigned a rating (one through ten) which indicated how well each individual evaluation criteria was satisfied. The weighting factor was multiplied by the rated value for each evaluation criteria to obtain a weighted score. The summation of these scores was utilized to establish how well each process satisfied the evaluation criteria. It was assumed that a difference of 20 percent in the weighted score would be required to demonstrate a significant difference between retorting processes.

Comparison of the weighted scores for each process revealed that the TOSCO II retorting process had the highest potential for coupling with a nuclear process heat source, see Table 2. The Union B and Paraho-Indirect retorting processes were ranked significantly lower but the second group still exhibited excellent potential for coupling with a nuclear heat source. The Superior-Indirect and HYTORT retorting processes were ranked in a third group with considerable potential for the application of nuclear process heat. The remaining retorting processes, although all have various applications for a nuclear process heat source, have significantly less potential than the previously mentioned retorting process.

Energy trade off evaluations were prepared for the TOSCO II, Union B, Paraho-Indirect and Superior Indirect retorting processes. In addition to these four processes which exhibited the highest potential for application of HTGR energy, the Lurgi-Ruhrgas and Chevron STB processes were evaluated because of their potential for commercialization. These energy studies along with preliminary HTGR utilization designs were utilized to identify a specific recovery process for detailed process definition and costing.

NUCLEAR POTENTIAL

Examination of the thermal profile information for the six retorting and upgrading processes with an output of 50,000 BPD (7947 m^3/day) crude shale oil were completed to establish the potential for energy applications. Two different scenarios were compared with the conventional or fossil fuel

Table 2

Process Evaluation for HTGR Process Heat Application to Oil Shale Retorting

Process	Type*	Weighted Score
TOSCO II	S	608
Union B	S	546
Paraho-Indirect	S	536
Superior-Indirect	S	483
HYTORT	S	410
Rio Blanco	MIS	361
Occidental	MIS	359
Geokinetics	TIS	356
Paraho-Direct	S	333
Superior-Direct	S	330
Chevron-STB	S	306
Lurgi-Ruhrgas	S	283

*S - Surface, MIS - Modified In Situ, TIS - True In Situ

case. The first scenario, Carbon/HTGR Fuel, utilizes the carbon on the spent shale to provide energy for retorting while the energy and hydrogen for upgrading were generated by an HTGR system. The second scenario, HTGR Fuel, provided all of the possible energy for retorting and upgrading with the HTGR system.

These energy comparisons indicated the potential HTGR process heat applications ranges from 251 to 817 MW_t, see Table 3. In addition, the electrical energy requirements were also considerable, varying from 56 to 149 MW_e depending on the particular retorting process utilized. As a result, the total potential for HTGR energy ranges from 422 to 1064 MW_t. The energy requirements for each of these retorting processes were optimized around the output streams to maximize the fossil fuel output.

NUCLEAR BENEFITS

The utilization of HTGR generated energy for oil shale recovery results in an increase in fossil products as well as a reduction in critical emissions. The two energy application scenarios, Carbon/HTGR Fuel and HTGR Fuel, were compared with the conventional or fossil fuel case to establish yield improvement information. These comparisons revealed that the yield improvement data can be divided into two basic groups. The first group represents processes which are indirectly heated with process gases and product oil which do not burn the carbon on the spent shale. These processes (TOSCO-II, Union B and Paraho-Indirect) exhibit yield increases in the 12,500 to 14,000 equivalent barrels per day [EBPD] (1987 to 2225 m^3/day) range, see Table 4. The second group of processes utilizes carbon on the spent shale and process gases as an energy source. The yields improvement for these processes (Superior-Indirect, Lurgi-Ruhrgas and Chevron-STB) exhibit yield increases in the 2,500 to 6,500 EBPD (397 to 1033 m^3/day) range, see Table 4.

In addition to the fossil yield improvements, the use of HTGR energy to replace conventional energy sources for an oil shale retorting and upgrading facility results in an overall reduction in emission levels. The emission levels for the Carbon/HTGR Fuel and HTGR Fuel scenarios were

Table 3
HTGR Energy Applications to Oil Shale Recovery

Process	Retorting Site		Upgrading Site			Total[a]
	Electrical (MW_e)	Process Heat (MW_t)	Electrical (MW_e)	Process Heat (MW_t)	Hydrogen (MW_t)	(MW_t)
TOSCO-II	72	530	21	77	178	1064
Modified TOSCO-II[b]	72	-	21	77	178	534
UNION B	35	481	21	78	176	903
Modified UNION B[b]	35	-	21	78	176	422
PARAHO-INDIRECT	39	555	25	80	182	1009
Modified PARAHO-INDIRECT[b]	39	139	25	80	182	593
SUPERIOR-INDIRECT	35	127	23	78	179	558
LURGI-RUHRGAS	128	-	21	77	174	698
CHEVRON-STB	128	-	21	77	181	705

[a] Assume 3 MW_t = 1 MW_e

[b] Assumes combustion of carbon on spent shale.

Table 4
Potential HTGR/R/TCP Benefits[a]

Process	Yield Increase (EBPD)				Emission Reductions (Percent)					
	Carbon/HTGR		HTGR		Carbon/HTGR			HTGR		
	Oil	Gas	Oil	Gas	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2
TOSCO-II	5688	7520	5688	7520	80	63	(202)	80	63	78
UNION-B	6022	6745	6022	6745	80	62	(227)	80	62	77
PARAHO-INDIRECT	5145	3205	5498	8333	80	64	(225)	80	64	77
SUPERIOR-INDIRECT	-	4808	-	6207	70	54	8	70	54	10
LURGI-RUHRGAS	-	4704	-	-	24	28	10	-	-	-
CHEVRON-STB	-	2794	-	-	24	29	10	-	-	-

[a] Based on conventional fuel replacement

compared with the conventional or fossil fuel emissions for the six selected oil shale processes. Review of the emission data for critical pollutants (NO_x, SO_2 and CO_2), see Table 4, revealed two different levels of emission reductions for the Carbon/ HTGR Fuel energy scenario. The first group of processes (TOSCO-II, Union B and Paraho-Indirect) which are indirectly heated exhibited 60 to 80 percent reductions for NO_x and SO_2 emissions which resulted from replacing conventional fossil combustion processes with nuclear heat. The 200 to 230 percent emission increases for CO_2 associated with these processes resulted from combustion of the carbon on the spent shale. The second group (Superior-Indirect, Lurgi-Ruhrgas, and Chevron STB) exhibited 10 to 70 percent reduction for NO_x and SO_2 emissions which again resulted from the replacement of conventional fossil combustion process. Changes in the CO_2 emissions were not observed in the second case because the fossil or conventional process normally combust the carbon on the spent shale. The critical pollutants for the HTGR energy scenario revealed nearly identical emission reduction which ranged from 50 to 80 percent with one exception, see Table 4. The exception is the small (10 percent) reduction in CO_2 emission associated with the Superior-Indirect process. This process is designed to combust the carbon on the spent shale so the CO_2 emission reduction anticipated is very minimal.

HTGR UTILIZATION

The High Temperature Gas Cooled-Reformer/Thermochemical Pipeline (HTGR-R/TCP) system, see Figure 1, is well-suited for the long distance transport of process heat energy. This concept is based on conversion of the thermal energy from the HTGR core to a gaseous chemical form by the endothermic steam-methane reforming reaction producing principally hydrogen and carbon monoxide. The resulting reaction products are transmitted by pipeline for use at some distant location. The heat of the reaction products can then be released in an exothermic methanation reaction in the form and quantity required by the user. Further, an open pipeline concept could supply synthesis gas as a hydrogen feedstock to the petrochemical industry.

Review of the HTGR process heat potential information and the detailed processing temperature requirements indicated that the Union B oil shale recovery process exhibits an excellent application for a HTGR-R/TCP system. Since it appears that the Union B technology will be the first retorting process to reach the commercial scale, the process should provide an excellent engineering basis for developing a detailed HTGR-R/TCP system design. As a result, the Union B retorting process was utilized as a base case for possible application of the HTGR-R/TCP system for oil shale recovery.

The HTGR-R/TCP system designed to provide energy to the Union B oil shale recovery process includes two methanation systems for process heat and a hydrogen purification system to provide process hydrogen. The energy flows shown in Figure 2 were utilized to develop the detailed coupling concept for the HTGR-R/TCP system. The first methanator system replaces the gas heater in the Union B retorting process. Five methanator process heat plant modules[4] were required to provide the 1000°F (538°C) recycle gas for a nominal 50,000 BPD (7947 m^3/day) commercial sized facility. The second methanator system provided the process heat and hydrogen required for an upgrading operation. The methanator system process heat plant system[4] includes two methanators which supply energy to the upgrading facility. This energy is divided between hydrogen purification, delayed coking and hydrotreating. The hydrogen requirements for the process are supplied by a purification system which removes the CO_2 and CO from the syn gas received from the TCP.

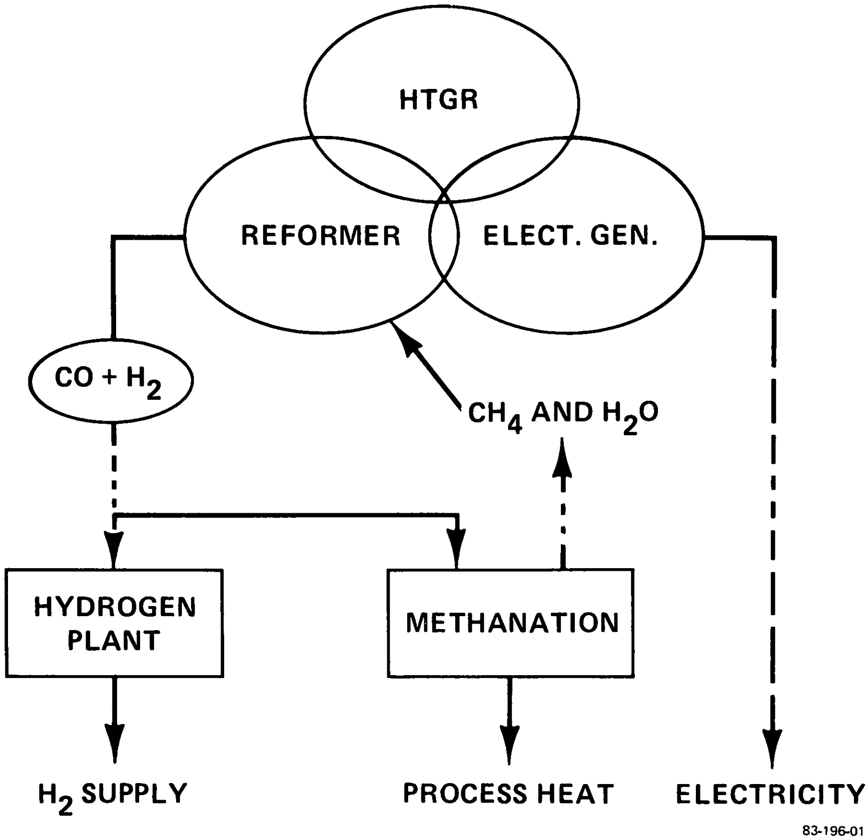

Figure 1 HTGR-R/TCP SYSTEM

ECONOMIC EVALUATION

Application of the HTGR-R/TCP system as an energy source to a counter gravity feed indirect heated retorting system with conventional upgrading was evaluated by Bechtel Group Incorporated to determine the cost effectiveness of this application. This system supplies energy through methanators producing either hot gas or steam coupled directly to process vessels to provide the required process heat. The system supplies hydrogen to a hydrogen purification system fed by syngas taken directly from the TCP. In addition, the system provides electricity at the nuclear plant which is fed directly into the electrical grid.

Although current oil shale project estimates are based on lead plant first-of-a-kind analysis, the HTGR-R/TCP system estimates are based on Nth plant applications. The TCP has an equivalent design length of 60 miles (97 km). Estimates are prepared in accordance with the economic ground rules adopted by Gas Cooled Reactor Associates, La Jolla, California, for the FY82 HTGR Program, issued June 14, 1982. Costs are at the January 2, 1982 price level with commercial plant operation anticipated in January 2005. Industry ownership was assumed for the shale oil project and utility ownership was assumed for the HTGR-R/TCP system.

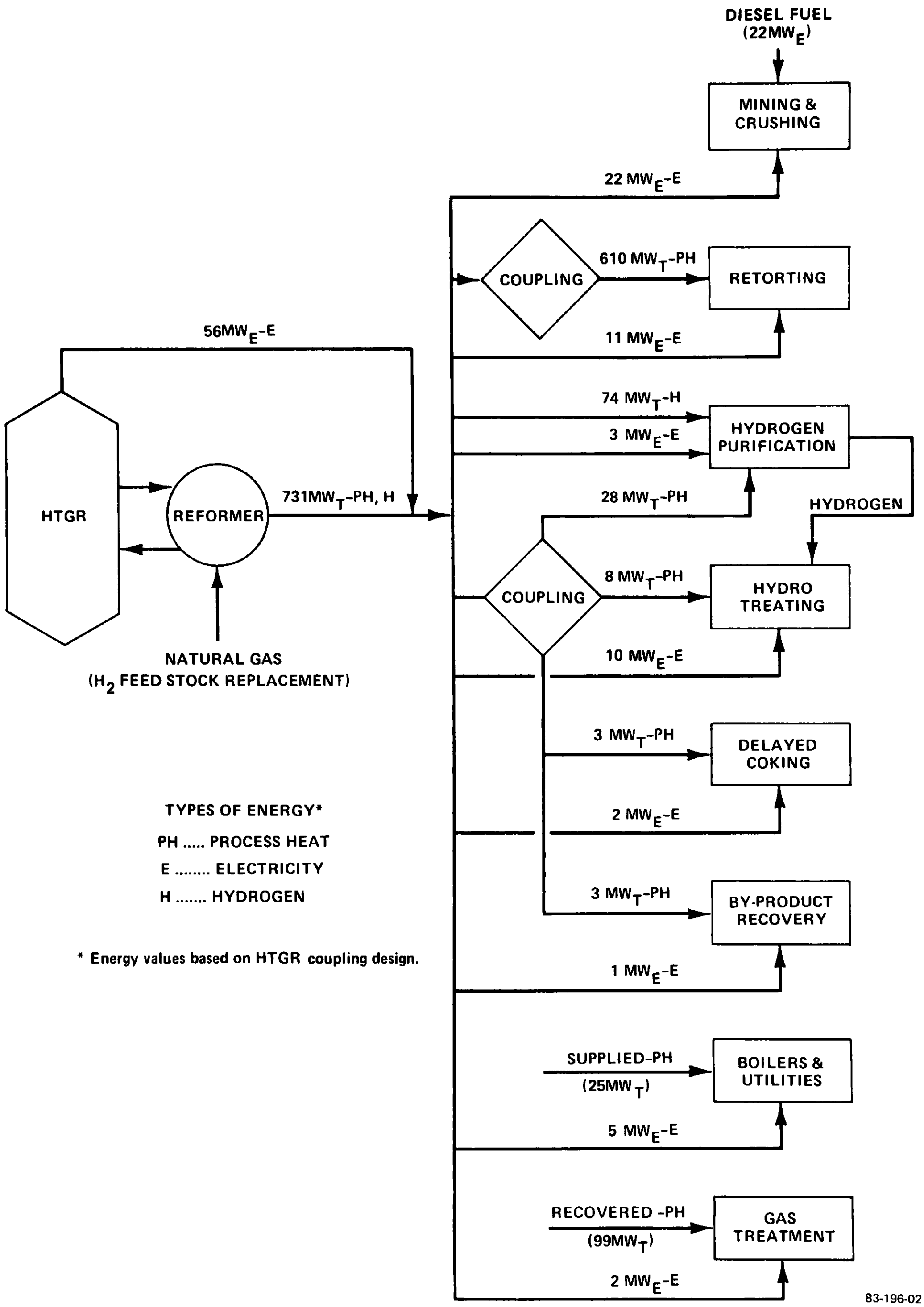

Figure 2 HTGR-R/TCP ENERGY FLOW DIAGRAM (50,000 BPD Crude Shale Oil)

The HTGR-R/TCP was assumed to be part of a larger utility installation having the capacity to provide process heat to fully meet the requirements for several shale oil projects. Specific sites for the oil shale project and the HTGR-R/TCP have not been selected. Crude shale oil production of 50,000 BPD (7947 m^3/day) from the retorting process was selected as the project size for this study. About 61,538 tons per day [TPD] (55,815 tonnes/day) of crushed shale feed was required for retorting and 38,257 BPD (6081 m^3/day) of upgraded shale oil and 2,262 EBPD (358 m^3/day) of propane gas was produced by conventional processing. All of the high BTU gas produced in the conventional process was consumed to provide energy for the retorting and upgrading. Production was increased to 44,279 BPD (7038 m^3/day) of upgraded shale oil and 9,007 EBPD (1432 m^3/day) of high BTU gas with the utilization of the HTGR-R/TCP system. All of the gas produced in this processing scheme was available for resale.

Energy furnished to the oil shale project by the HTGR-R/TCP totaled 731 MW_t, see Figure 2. This included 610 MW_t for the retorting processes and 47 MW_t for the upgrading processes. (Includes 3 MW_t process heat for byproduct recovery which was not included in the 44 MW_t Methanator Process Heat Plant design). An additional 74 MW_t was provided as hydrogen and the electrical requirements are 56 MW_e (168 MW_t). Total energy delivered to the HTGR-R/TCP system was 899 MW_t.

Constant dollar estimates of 30-year levelized costs per barrel for the upgraded shale oil equivalent at January 1982 price levels showed costs for the conventional plant at $32.30 per barrel oil equivalent (BOE) versus $29.30 per BOE for the plant coupled with the HTGR-R/TCP system. The cost summaries and product costs are shown in Table 5. These costs assume that the high BTU gas has the same value per million BTUs as oil. No by-product credit was taken for sulphur, coke, ammonia, or the shale fines. The shale fines were estimated at 3,200 TPD and contain about 2,670 barrels of oil which is recoverable using a fine retorting process such as the TOSCO II, Lurgi-Ruhrgas or Chevron STB processes.

Sensitivity analyses were performed to determine the effect on product costs for changes in capital costs and operating costs. The current analysis resulted in a conventional plant capital cost of $52,470 per daily barrel of oil equivalent (DBOE) which is consistant when compared to the approximately $50,000/DBOE[5] value being projected for a similar plant being constructed at Parachute, Colorado. The comparable HTGR-R/TCP coupled plant capital cost was $51,990/DBOE. If the oil shale project costs are assumed to be $100,000/DBOE[6] (Exxon/TOSCO Colony Project capital costs prior to termination) and the HTGR project capital position was constant, the conventional plant produces upgraded oil products at a cost of $46.60 per BOE versus $37.70 per BOE for the HTGR-R/TCP coupled plant. The conventional plant product costs were 24 percent more than the coupled plant product. When both the oil shale and coupled plants were assumed to have project costs of $100,000/DBOE, the upgraded oil from the conventional plant still costs $46.60 per BOE while the coupled plant oil cost increased to $41.60 per BOE, resulting in a conventional plant cost which is still 12 percent higher than the coupled plant.

The current product cost estimate of $32.30 per BOE for the conventional plant was 10 percent higher than the product from an HTGR-R/TCP plant. If it was assumed that the HTGR coupled plant product cost was also $32.30 per BOE then an equivalent annual operating cost of $564 million results. To reach this cost level, the HTGR-R/TCP system nuclear costs could increase by 30 percent.

The results of these economical analysis show that the HTGR-R/TCP coupled oil shale project can compare favorably with present conventional processes. Site specific and company specific factors

Table 5
Economic Summary

Case	Conventional Plant	Coupled with HTGR-R/TCP
Crushed Shale Feed	61,540	61,540 TPD
Product Output Upgraded Shale Oil		
Conventional Barrel/Day	38,260	44,280
Equivalent Barrel/Day	40,500	53,200
Equivalent Barrel/Yr	13.30×10^6	17.48×10^6
Total Capital Requirement $\$10^6$ (Jan. 1982 Price Level)		
Shale Oil Project	2,125	1,633
HTGR & Methanator Plants	-----	1,133
Total Capital Requirement	2,125	2,766
Annual Operating Cost $\$10^6$ (Jan. 1982 Dollar)	30-Yr. Lev.	30-Yr. Lev.
Fixed Charges		
Shale Oil Project @ 9.9%	$ 210.4	$ 161.7
HTGR & Methanator @ 6.7%	---	75.9
Nuclear Fuel Cost	---	58.5
O&M Cost		
Shale Oil Project	218.7	175.3
HTGR & Methanator Plants	---	40.9
Total Annual Operating Costs	$ 429.1	$ 512.3
Cost of Upgraded Oil (Per Equivalent Barrel)	$ 32.30	$ 29.30

should be included in any further refinement of such cost evaluations to provide the most realistic assessment of the oil shale application. Industry practices for project analyses will vary from company to company resulting in the need for participative evaluation with those companies whose processes seem most likely candidates for application of HTGR-R/TCP process heat.

SUMMARY AND CONCLUSIONS

Twelve oil shale retorting processes were summarized and ranked according to their ability to utilize the High Temperature Gas Cooled-Reformer/Thermochemical Pipeline (HTGR-R/TCP) system to provide process heat as an energy source. The potential for application of nuclear process heat for six selected processes ranged from 400 to 1100 MW_t for a 50,000 BPD (7947 m^3/day) commercial oil shale recovery facility. A detailed HTGR-R/TCP system coupling design was developed for a commercial oil shale facility which utilized a Union B retort and a typical upgrading facility as a basis.

Nuclear energy from the HTGR-R/TCP system can be used for production of shale oil. Major benefits obtained in this application are conservation of the oil shale resource and reduction in emissions. With energy from the HTGR-R/TCP system, the oil shale project produces approximately 31 percent more fossil fuel from a given amount of mined shale. Associated benefits are the reduction in mining and spent shale disposal problems inherent for any given level of production based on conventional technology. Gaseous emissions to the environment are significantly reduced with sulfur dioxide, nitrous oxides, and carbon dioxide emission reductions of approximately 60 percent, 80 percent and 75 percent, respectively.

Application of the HTGR-R/TCP system as an energy source to a counter gravity feed indirect heated retorting system with conventional upgrading indicated upgraded shale oil product from a conventional plant cost $32.30 per BOE. This cost was 10 percent higher than the HTGR-R/TCP coupled plant cost of $29.30 per BOE. The HTGR related costs can rise by 30 percent before a cost parity of $32.30 per BOE was reached for the HTGR-R/TCP system coupled plant. Sensitivity studies show that higher HTGR-R/TCP system capital costs would decrease its competitive position, but that a 68 percent increase would be required to raise the product oil cost to $32.30 per BOE.

Studies to date have been based on existing data and reports generally available to the public and have required use of engineering judgments for assessment of coupling requirements and energy usage. Site specific studies are needed to provide perspectives on siting, plant interfaces, economic assumptions, and other factors which require a more comprehensive input from actual participants in oil shale development.

Timely interaction with companies actively developing oil shale technology could result in definition of HTGR and oil shale systems which better integrate the strengths of each system. Since current oil shale technology is at the pre-commercial stage, there exists a unique opportunity for timely integration of the HTGR into the commercial scale oil shale plants of the future.

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