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1170-MW(t) HTGR-SC/C APPLICATION STUDY REPORT: MODIFIED PARAHO RETORTING OF OIL SHALE

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ABSTRACT

This report describes the application of a high-temperature gas-cooled reactor (HTGR) that operates in a steam cycle/cogeneration (SC/C) mode to supply process heat and electricity for the recovery of oil from shale using a modified Paraho process. The technical and preliminary economic merits of an 1170-MW(t) HTGR-SC/C plant are assessed along with those of a very high temperature [850°C (1562°F)] process heat reactor and the standard fossil fuel-fired heat source for this application. The HTGR - process heat reactor (HTGR-PH) was previously investigated by Davy McKee Engineers and Constructors in a study for General Atomic Company (GA).

The energy requirements for the modified Paraho process were developed utilizing design parameters from the Davy McKee study which considered the HTGR-PH and conventional Paraho process (indirect gas retorting) using fossil fuel. The assumed plant location for this present study is northwestern Colorado. Ten modular Paraho retorts provide approximately 65,185 tonnes per day (71,867 tons per day) of retorting capacity and yield a net of 295 m^3/h (44,600 barrels per day) of upgraded shale oil. All mining, process, and support facilities necessary for retorting oil shale are included in the process economics assessment. A heat balance/steam cycle diagram is included showing the integration of an 1170-MW(t) HTGR-SC/C plant with the process and the cogeneration of 275 MW(e) electric power.

A preliminary cost estimate shows a price of $43.29 (1980 $, 30-yr levelized) per barrel of upgraded shale oil for a 1995 plant startup of an 1170-MW(t) HTGR-SC/C plant and $41.90 (1980 $, 30-yr levelized) per barrel with an 1170-MW(t) HTGR-PH plant. The reference fossil-fueled process shows a cost of $50.03 (1980 $, 30-yr levelized) per barrel using a consistent set of economic ground rules with fuel valued at market price. The HTGR-SC/C plant appears technically and almost economically favorable, assuming a

30-yr reactor plant economic life. The gross thermal efficiency of the plant, based on the HHV of the products, is 57.9%.

The environmental information developed indicates that using an HTGR as the primary energy source will achieve an overall plant reduction in atmospheric emissions of particulate matter, sulfur dioxide, and nitrogen oxides. Specifically, the combustion emissions from the conventional oil-fired recycle gas heaters, the hydrotreater feed preheater, and the steam/power generation will be eliminated. All generated wastewater streams will be treated as necessary for reuse on site, for dust control, for spent shale moisturization, and for retorted shale disposal.

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1. INTRODUCTION

1.1. SHALE OIL RESOURCE AND CURRENT DEVELOPMENT

Shale oil is a large energy source within the U.S. Several processes, including both above-ground and in-situ techniques, are being developed to extract shale oil in a way that is viable both commercially and economically and that at the same time satisfies environmental regulations. This report presents a preliminary study that provides technical information and evaluates the economic and environmental feasibility of using an 1170-MW(t) high-temperature gas-cooled reactor - steam cycle/cogeneration (HTGR-SC/C) heat source in conjunction with a modified Paraho process for the production of synthetic crude from oil shale.

The recoverable reserves of shale oil in the U.S. are estimated at approximately 160 Gm^3 (~1000 billion barrels); in quantity, these reserves rank second only to coal. The extraction of oil from oil shale has not seriously been pursued thus far in the U.S. because of several technical and economic uncertainties. While the future seems to be moderately encouraging for this process in view of the dwindling supply of world crude oil and the looming progressive decontrol of natural gas prices in the U.S., several uncertainties do exist today for developing an oil shale project commercially. The key restraint is development cost, as evidenced by the Exxon Company's recent decision to terminate its participation in the TOSCO Colony project. Various incentives will need to be offered by the Federal Government if private firms are to be induced to develop any future commercial synfuel projects.

Large portions of the U.S. shale oil reserves, and certainly the richest deposits, are located in the Piceance Basin of northwestern Colorado. Hence, the initial commercial development is expected to start in this area.

This report focuses primarily on developing a commercial project in northwestern Colorado.

1.2. ABOVE-GROUND RETORTING (AGR)

Feed shale for the AGR process is available from two sources: (1) from open pit mining and (2) from the chambers of the modified in-situ (MIS) process in which shale rubble must be removed to create space (Ref. 1-1 discusses the details of the in-situ process). Unlike coal, shale cannot be used for direct burning since it contains quartz, dolomite, and clay. The shale contains hydrocarbon matter (kerogen) that is pyrolized to form combustible fluids and gases. Shale AGR is generally performed at the mine site, since it is uneconomical to transport large volumes of shale while at the same time solving environmental problems concerning spent shale disposal. Retorted shale expands in volume; therefore not all of it can be returned to its point of origin. In addition, disposal of spent shale has to satisfy regulatory requirements.

Substantial quantities of water are required during several phases of the shale retorting project. The water use varies from steam/power production to dust control and revegetation. However, the regions containing shale deposits are generally arid and have limited water resources. In fact, water availability may be a key factor in determining oil shale project size. The handling of water (and the potential run-off and subsequent contamination of existing aquifers due to the AGR process waste water) could impose severe environmental constraints. It is against such a background that a commercial shale oil AGR project has to be developed.

1.3. HTGR-SC/C PLANT APPLICATION POTENTIAL FOR MODIFIED PARAHO PROCESS

Davy McKee originally studied the feasibility of integrating an 850°C (1562°F) (reactor coolant outlet temperature) HTGR-process heat (HTGR-PH) plant with the Paraho process. (The Paraho process description and the Davy McKee study details are presented in Ref. 1-2.) Davy McKee's study compared the HTGR-PH with the conventional Paraho retorting process that uses product oil as its energy supply. The study showed that integrating an HTGR-PH reactor as the energy source conserved approximately one-third of the upgraded product oil produced (13,876 bpd out of 45,042 bpd). The HTGR-PH heats up the recycle gas to about 705°C (1301°F) for retorting shale. The present study focuses on retorting shale with hot recycle gas at a lower temperature [510°C (950°F)], and the gas heating is provided by primary steam from an 1170-MW(t) HTGR-SC/C plant that is an available technology.

The oil shale AGR process has several advantages. Although the AGR process entails handling large volumes of shale rock and expensive crushing and pulverizing operations, the process can be controlled effectively and the oil and product gas yields are substantially enhanced. A recent U.S. government market forecast (Ref. 1-3) indicated that shale oil production will range from 90 m^3/day (580,000 bpd) in 1990 to 200 m^3/day (1.25 x 10^6 bpd) in 2020.

The HTGR, as a nuclear heat source, is uniquely suited for the oil shale AGR process because of its capability to provide high-temperature heat [up to 538°C (1000°F)], whereas the LWR's are constrained by design to deliver heat at $<$ 315°C (600°F).

1.4. REPORT ORGANIZATION

Section 2 of this report describes the oil shale AGR process, including raw shale oil upgrading, the basis of design, and major assumptions. Process energy requirements, the forms of energy, and heat recovery from spent shale are discussed in Section 3. Section 4 focuses on HTGR-SC/C plant integration with the oil shale process and HTGR steam cycle development. Preliminary plant economics are presented in Section 5. Section 6 covers issues relating to environmental impact and process water use and resources. A preliminary evaluation of an oil shale AGR project integrating an 1170-MW(t) HTGR-SC/C plant is given in Section 7.

REFERENCES

1-1. "Quarterly Progress Report, Occidental Vertical MIS Process for the Recovery of Oil from Oil Shale, Phase II, December 1, 1980 - February 28, 1981," DOE/LC/10036-78 (DE81024981), May 1981.

1-2. "Paraho Retorting of Oil Shale Using a Very High Temperature Reactor," Davy McKee Engineers and Constructors.

1-3. Annual Report to the Congress, Vol. III, Energy Information Administration of DOE, 1980.

2. PROCESS DESCRIPTION

2.1. SHALE PREPARATION IN THE AGR PROCESS

Approximately 68,400 tonnes per day (76,000 T/D) of mined shale are crushed and screened to produce approximately 64,800 tonnes per day (72,000 T/D) of prepared shale [pieces nominally measuring 1 cm x 7.6 cm (3/8 in. x 3 in.)] for the Paraho retorts. A general arrangement of the equipment system used for this operation is shown in Fig. 2-1. About 3600 tonnes per day (4000 T/D) of shale fines [minus 1 cm (3/8 in.)] are returned with spent shale for disposal. The sized shale is fed to twin batteries that have five Paraho retorts per battery. Each Paraho retort is a refractory-lined cylindrical vertical kiln having a capacity of approximately 6480 tonnes per day (7200 T/D). Spent shale, along with shale fines, are disposed of in an environmentally acceptable manner.

2.2. BASIS OF DESIGN AND MAJOR ASSUMPTIONS

The grade and characteristics of shale assumed in this study refer to the shale deposits of northwestern Colorado or their equivalent. The assumed raw shale grade has a yield of 0.12 m^3/tonne (28 gal/ton) (at 100% Fischer assay). The oil recovered, however, was estimated at 87% Fischer assay at a retorting temperature of 455°C (850°F); this Fischer assay value was extrapolated from the data presented in Ref. 2-1. The standard Paraho process has a Fischer assay value of 93.5% (Ref. 1-2). The crude shale oil is upgraded via the hydrotreating process to produce a synthetic crude having a nitrogen content less than 3000 ppm. For this study, the retort kinetic characteristics of the modified Paraho process were assumed to be the same as given in Case III of Ref. 1-2, with allowance for the fact that the recycle hot gas temperature at retort entry is lower [510°C (950°F) with the HTGR-SC/C versus 705°C (1300°F) in Case III]. The height of then retorting zone and consequently that of the retorting vessel was increased

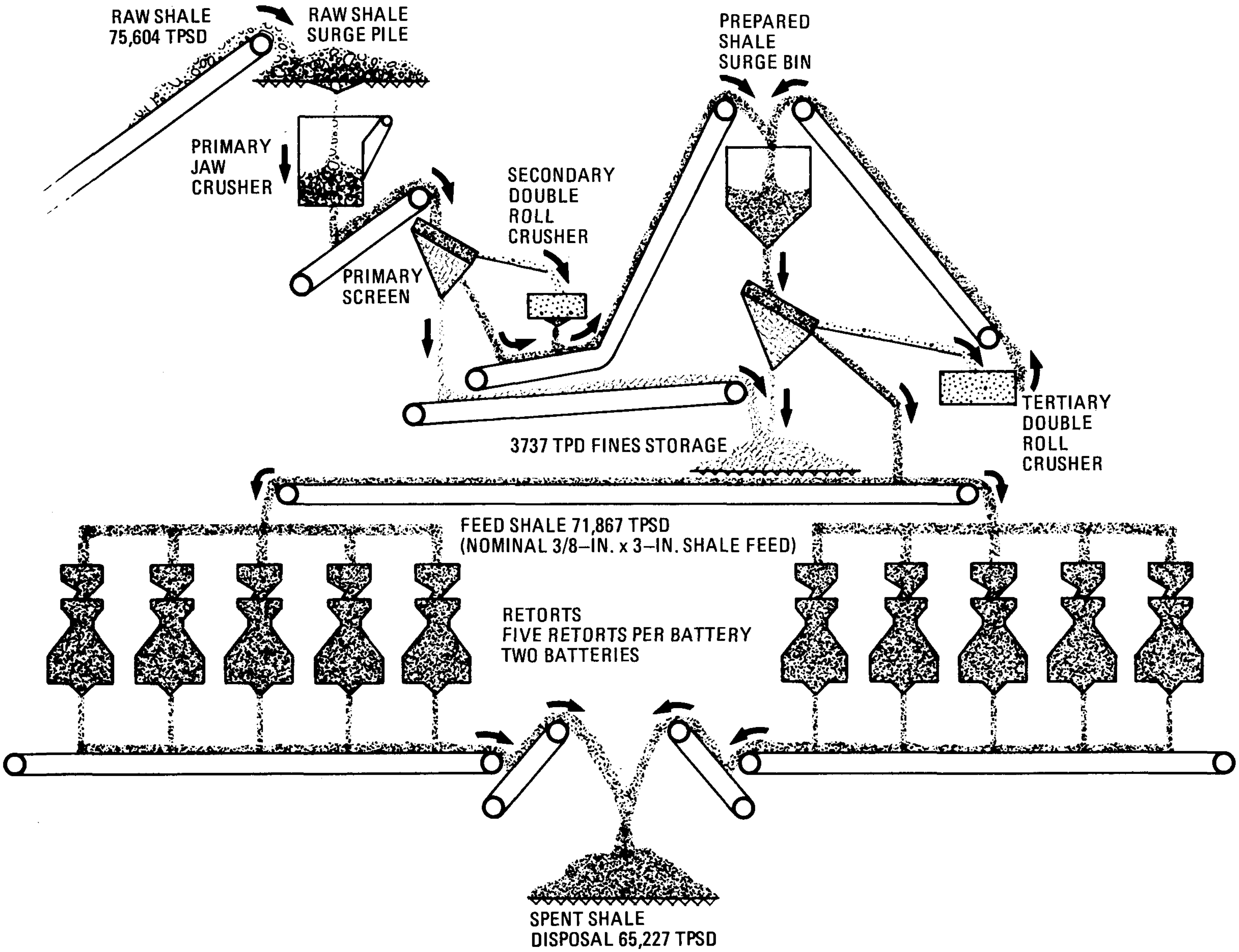

Fig. 2-1. Shale preparation and disposal scheme

by approximately 12% [from 6.7 m (22 ft) (Ref. 1-2) to 7.6 m (25 ft)] for housing the increased shale feed to make up for the lower Fischer assay (87%) and for maintaining the original crude shale oil yield of 278 m^3/h (41,683 bpd) (Case III, Ref. 1-2).

2.3. PROCESS DESCRIPTION

Raw shale enters 10 parallel trains of Paraho indirect heated retorts, each having a capacity of approximately 7200 TPD. A process block flow diagram for the indirect heated retort with major process parameters is shown in Fig. 2-2. The Paraho retort is a refractory-lined vertical kiln that acts as a countercurrent gas-to-solids heat exchanger. The moving bed of crushed shale flowing downward contacts an upward flow of hot gas that provides sufficient heat to retort the organic constituents in the shale. The heat of retorting is supplied by circulating part of the retort off-gas through recycle gas heaters and directly distributing the hot gas into the descending shale bed. Hot primary steam, supplied by the HTGR-SC/C plant at 538°C (1000°F), transfers 1090 MM BTU/h (about 27% of the total thermal HTGR-SC/C energy available) to the recycle gas and provides the necessary heat for retorting. (In the conventional Paraho process product oil was used as fuel for heating the recycle gas.) The retort off-gas, containing entrained oil mist, flows from the top of the retort and passes through the oil recovery system. The oil recovery system consists of a coalescer for initial recovery, an electrostatic precipitator for second-stage recovery, and a knock-out drum at the recycle gas compressor discharge for removal of heavy oil carry-over. About 99% of the oil in the gas is recovered to yield 278 m^3/h (41,683 bpd) of crude shale oil.

Oil-free product gas from the retort section is sent to product gas cooling, compression, and NH_3 removal. Conventional water scrubbing using stripped wash water from the Chevron wastewater treatment system removes residual NH_3 from the product gas. The sulfur content of the product gas is then removed by a Stretford sulfur recovery unit. The purified gas containing less than 1 ppmv H_2S flows to the hydrogen plant, providing feed for the

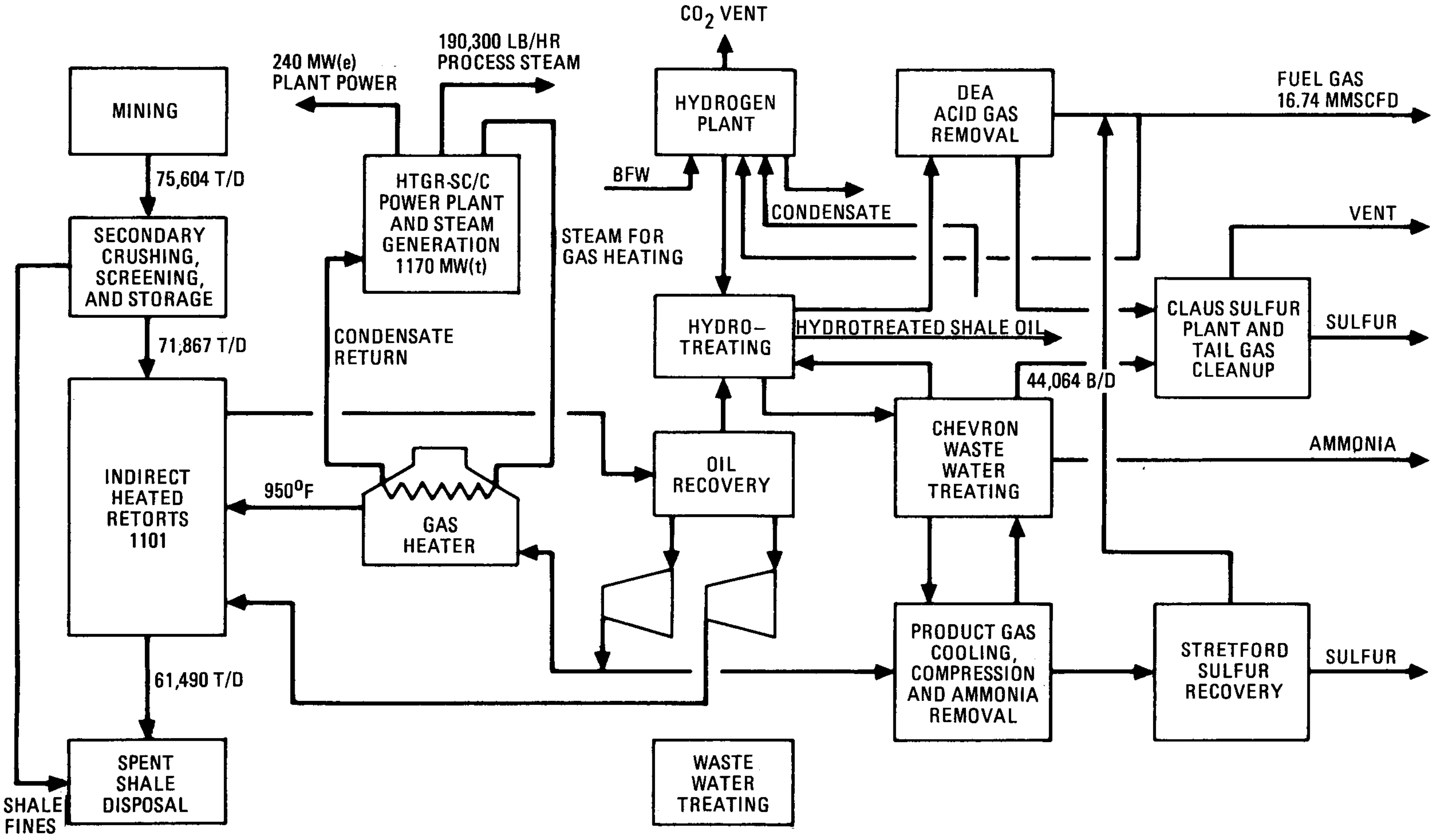

Fig. 2-2. Process block diagram for shale AGR with 510°C (950°F) recycle gas using an HTGR-SC/C plant

manufacture of hydrogen. About 35.4 m^3 of hydrogen/m^3 of shale oil (2000 scf of hydrogen/bbl shale oil) is consumed at the hydrotreater for the upgrading of crude shale oil. The crude shale oil is treated at a pressure of 15 MPa (2200 psig) and at a temperature of 396°C (745°F) in the hydrotreating unit, removing nitrogen, traces of sulfur, and other contaminants from the crude shale oil. About 45,042 bpd of hydrotreated shale oil flows to product storage. Off-gas from the hydrotreater flows to an acid gas removal system. Following absorption of acid gas (e.g., CO_2 and H_2S), high BTU gas [31.1 MMJ/m (835 BTU/scf), HHV] is available for other uses or export.

Reference 1-2 describes the Stretford unit, the hydrogen plant, the Chevron hydrotreating unit, the acid gas removal system, and other auxiliary process equipment.

As shown in Fig. 2-2, sensible heat from the retorted shale is recovered by cold recycle gas emerging from the oil recovery unit. The spent shale is assumed to be discharged at 176°C (350°F) for safe disposal. The recovery of sensible heat from the retorted shale is significant and is almost half of the heat required for retorting.

REFERENCE

2-1. Synthetic Fuels Data Handbook, 2nd ed., Cameron Engineers Corporation, Denver, Colorado, 1978.

3. PROCESS ENERGY REQUIREMENTS

3.1. ENERGY REQUIREMENTS AND ENERGY SUPPLY FROM HTGR-SC/C PLANT

The shale AGR process is energy intensive, with the energy required to be steam and electric power. Oil shale mining, crushing and screening, shale retorting, and oil upgrading operations are the major consumers of process energy. Since all phases of process operations are performed in remotely located shale oil fields, all forms of energy should be available on site. In the standard Paraho process, both product oil and product gas are used as fuel to generate process heat, process steam, and steam for electric power generation on site. All of the net product gas [171 MW(t)] and nearly one-third of the upgraded oil (~14,000 bpd) produced are required as fuel for retorting about 64,800 tonnes per day (72,000 T/D) of shale and for upgrading raw shale oil.

Integration of an HTGR-SC/C plant with the standard Paraho process provides almost all of the process energy required and conserves a considerable amount of product oil that would otherwise have been used as fuel in the process. The HTGR-SC/C plant primary steam, which is delivered to the process at 17 MPa/538°C (2400 psia/1000°F), provides the heat for the recycle gas retorting and for hydrotreating, and also supplies steam required at various stages of the process. Surplus steam from the HTGR-SC/C plant is expanded through power turbines, cogenerating electricity. However, the hydrogen plant also requires process heat [~203 MW(t)] at a temperature of 787°C (1450°F), which the HTGR-SC/C plant cannot provide. Fossil fuel (product oil and gas) is used to supply this process heat.

Energy required for mining, crushing, and spent shale disposal is provided by diesel-fuel-operated field equipment. This diesel fuel consumption is approximately 2.5 m^3/h (375 bpd) [~30 MW(t)].

Table 3-1 shows energy requirements at various phases of the modified Paraho process by form. It can be seen from Table 3-1 that most of the energy is required for shale retorting, followed by hydrogen production and mining operations. The thermal energy requirement shown for shale retorting is exclusive of the heat recovered from retorted shale. The electric power requirement is significant for shale retorting and oil recovery operations, mining, and hydrotreating.

Process steam from the HTGR-SC/C plant is required at 1 MPa (150 psia), dry saturated condition. A small portion of the required process steam is generated internally in the process and can be extracted from the hydrotreating unit and the Claus and Scot sulfur recovery unit.

Figure 3-1 shows the process temperature-energy (T-Q) diagram, from which it can be seen that an 1170-MW(t) HTGR-SC/C plant can supply process thermal energy at or below 538°C (1000°F); this represents about 66% of the total thermal energy requirement. The HTGR-SC/C plant also provides 100% of the process electric power requirements [~157 MW(e)].

3.2. OTHER REQUIREMENTS

The HTGR-SC/C plant can effectively replace the use of approximately one-third of the daily production of shale oil (~14,000 bpd) as fuel oil, which includes also power generation. Approximately one-half of the conserved oil is used for power generation in the standard Paraho process. Product oil can be used for a backup energy supply so that shale oil recovery and upgrading may continue when the reactor is shut down for refueling and maintenance or repairs.

The HTGR-SC/C plant for this application would be located in relatively remote parts of Colorado. The HTGR-SC/C plant can be sited relatively close to the retorting plant so that process steam transmission distances and therefore steam pressure losses would be modest.

TABLE 3-1
ENERGY REQUIREMENTS FOR A MODIFIED PARAHO PROCESS
PRODUCING 295 m^3/h (44,500 bpd) OF SHALE OIL

Section	Power (kW)	Steam[a] [Kg/s (lb/hr)]
Mining	30,636	
Secondary crushing and screening	7,350	
Retorting and oil recovery	84,685	
Spent shale disposal		
Gas cooling compression and NH_3 removal	1,361	
Stretford plant	4,246	0.5 (3,900)
Waste water treating	2,722	
Hydrotreating	16,170	[(2.62) (20,320)]
Hydrogen plant	8,810	
DEA acid gas removal	152	1.18 (9,147)
Claus and Scot plants	152	[(0.69) (5,332)]
Chevron waste water treatment	522	21.35 (165,513)
Shale oil storage		5.07 (39,200)
Total	156,806	24.79 (192,108)

(a) 1 MPa (150 psia), saturated.

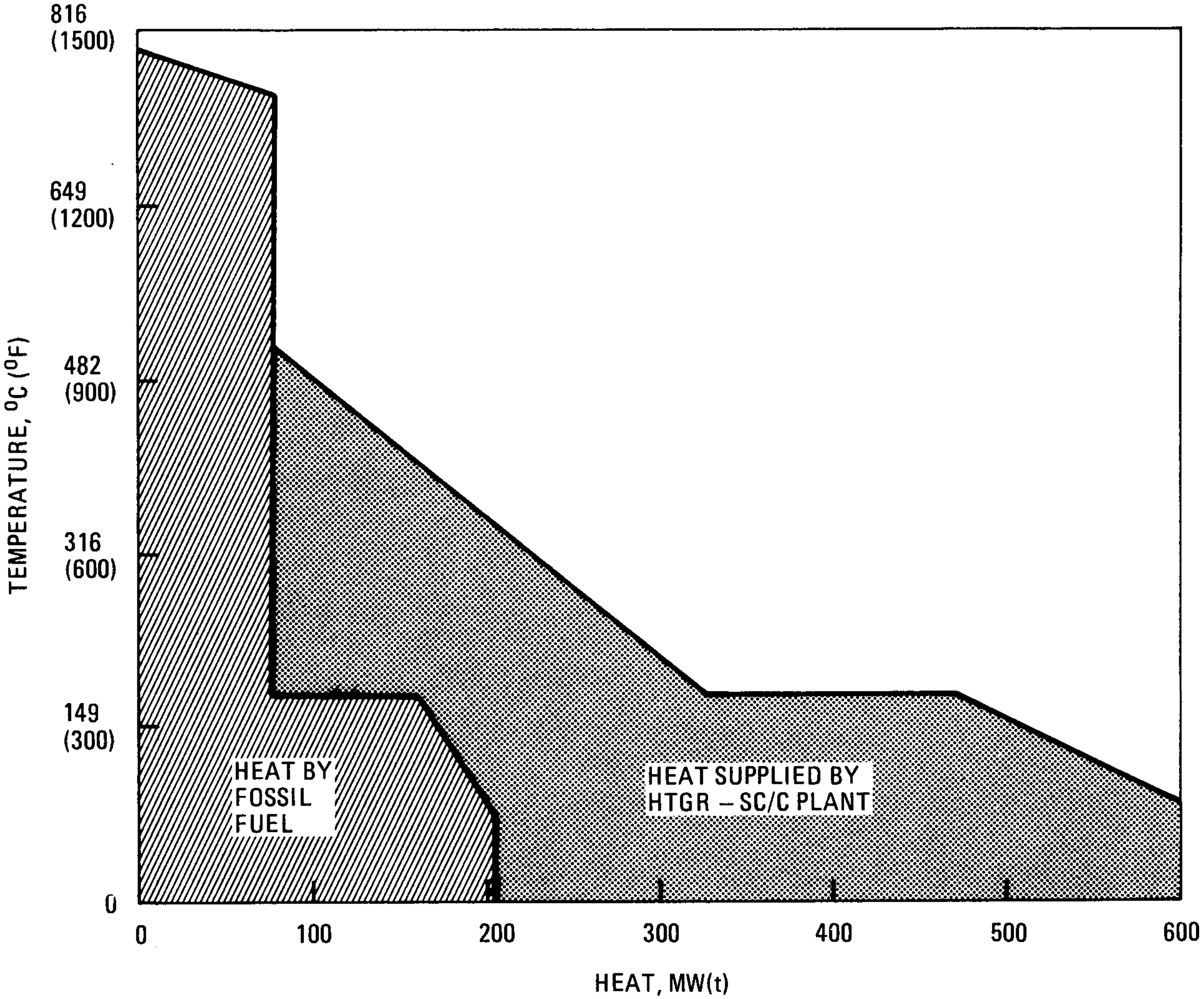

Fig. 3-1. Temperature - heat diagram for the modified Paraho process using an 1170-MW(t) HTGR-SC/C plant

4. HTGR-SC/C PLANT INTEGRATION AND HEAT BALANCES

4.1. INTEGRATED PLANT DESIGN

As stated in Section 3, process steam is required at ~1 MPa (150 psia) dry saturated condition, for the Paraho process, and the process also requires substantial electric power [~157 MW(e)]. About 75% of the primary steam exiting the HTGR-SC/C plant at 16.65 MPa/538°C (2415 psia/1000°F) is used for heating the recycle gas and is then expanded through power turbines, cogenerating electric power. The exhaust steam from the high-pressure turbine is adjusted to meet the process steam condition and flow rate. In this study, the heat cycles were so arranged that, after providing heat for the heating of recycle gas, steam was expanded through power turbines to maximize electric power production. Any primary steam remaining in excess of its use for process purposes was expanded through a condensing turbine-generator (T-G) unit to enhance electric power production.

4.2. NUCLEAR STEAM SUPPLY (NSS) DESIGN

The 1170-MW(t) HTGR-SC/C NSS design heat source is described in Ref. 4-1.

4.3. HEAT CYCLE

Figure 4-1 shows the HTGR-SC/C heat cycle for the modified Paraho process. This heat cycle uses split heat exchangers (HX's) to heat the recycle gas from 138° to 510°C (280° to 950°F). The gas is heated to 388°C (730°F) in HX 1 and from 388° to 510°C (730° to 950°F) in HX 2. On the steam side, steam is desuperheated in HX 2 from about 536° to 438°C (996° to 820°F). In HX 1, the steam is further desuperheated, condensed, and subcooled as shown in the heat transfer diagram of Fig. 4-2. The drain temperature of the condensate from HX 1 was selected to match the feedwater

ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	157	13.4
STEAM POWER	394	33.7
SUBTOTAL	551	
OTHER USES		
ELECTRIC POWER	83	7.1
LOSSES		
CONDENSER	501	42.8
OTHER	35	3.0
TOTAL REACTOR POWER OUTPUT	1170	100.0

P = PSIA
F = °F
W = 10^3 LB/h
h = BTU/LB, ENTHALPY

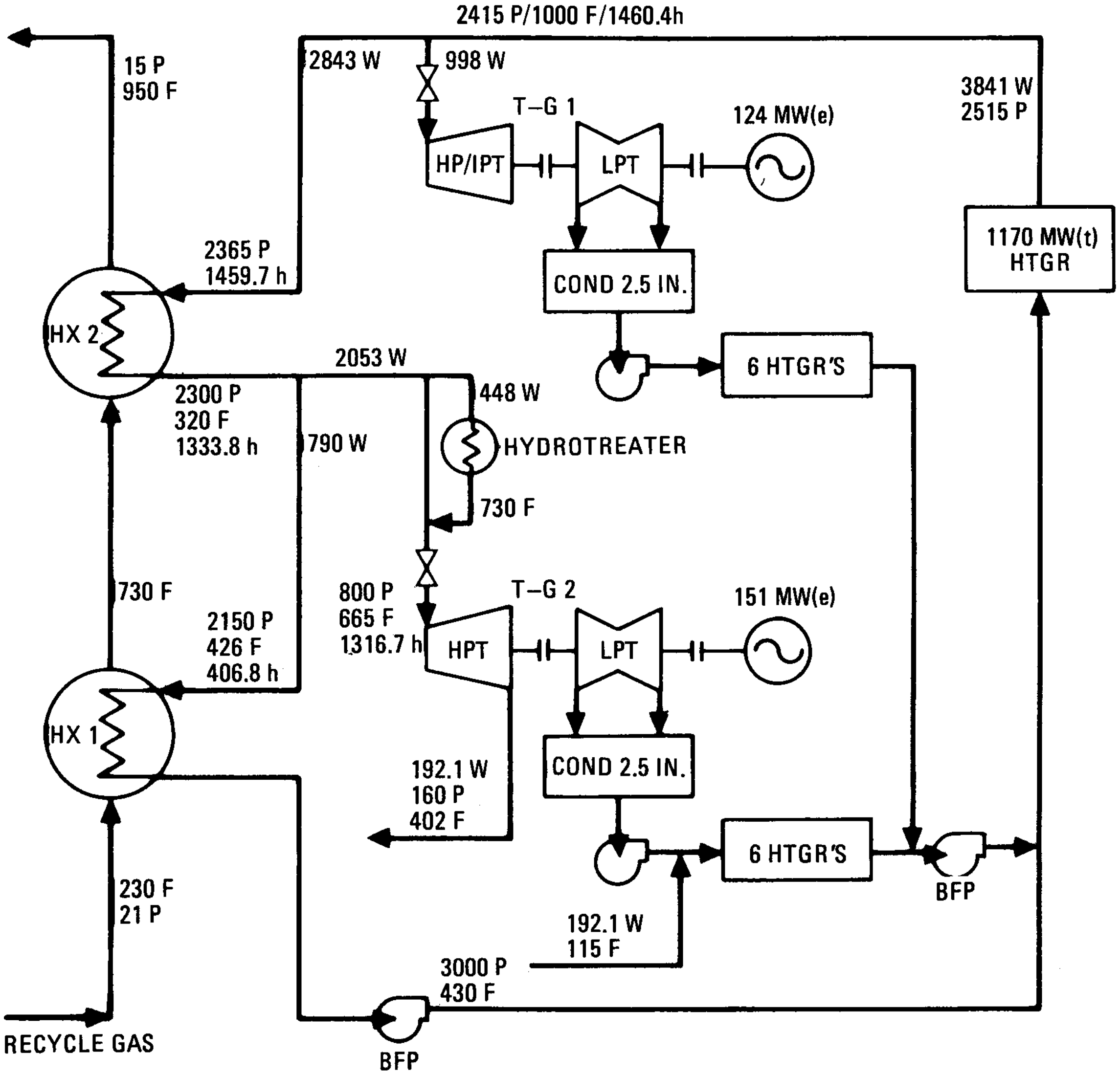

Fig. 4-1. 1170-MW(t) HTGR steam cycle for hot recycle gas [510°C (950°F)] retorting of oil shale

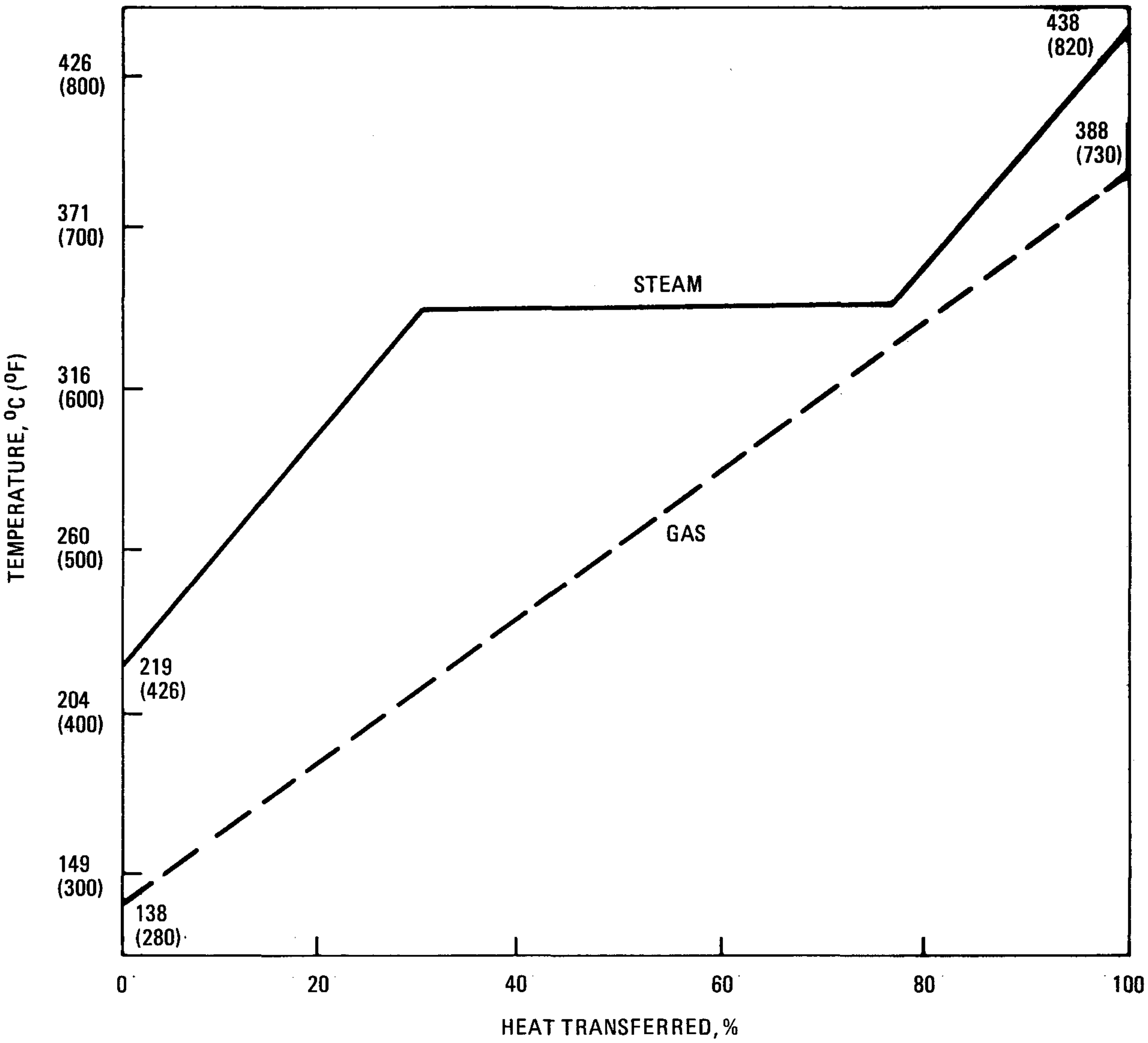

Fig. 4-2. Heat load versus temperature for heat exchanger (HX 1), 510°C (950°F) hot recycle gas retorting process

temperature requirement of the HTGR steam generators. The heat exchangers were assumed to be located about 0.8 km (1/2 mile) from the reactor plant, and a 0.34-MPa (50-psi) pressure loss in transmission piping was estimated. That pressure loss, combined with a piping heat loss of about 1.75 MJ/kg (3/4 Btu/lb) of steam, results in a steam temperature of 536°C (996°F) at the HX 2 inlet.

Also shown in Fig. 4-1 is the extraction of 87,318 kg/h (192,100 lb/hr) of steam at 14 MPa (160 psia) from turbogenerator T-G 2 for process use. Additionally, some steam from the HX 2 outlet is used in the hydrotreating process to heat fluid from 368° to 396°C (695° to 745°F). That heat load was specified to be 10.3 MW(t).

Steam at the T-G 2 inlet is shown as 5.5 MPa/352°C (800 psia/665°F). It has been throttled to those conditions after it leaves the heat exchangers in order to limit turbine exhaust moisture to the same level as in the straight steam cycle turbines which have 16.65 MPa/538°C (2415 psia/1000°F) steam at the inlet.

T-G 2 would probably be located in the shale retorting plant. Its output of 151 MW(e) (generator terminals) is only slightly short of the specified 157 MW(e) requirements of that plant. The output of T-G 1 [124 MW(e)] supplies the 35 MW(e) auxiliary load of the HTGR plant plus 6 MW(e) to the shale plant, leaving a surplus of about 83 MW(e) for alternate uses or export.

HX 1 was arbitrarily selected to have a minimum pinch-point-temperature difference of about 14°C (25°F), as shown in Fig. 4-2. Using this pinch-point value, other heat exchanger alternates for heating recycle gas were considered. These alternatives were based on the use of a single heat exchanger instead of a split design and used varying amounts of subcooling of the condensed steam. The plot of heat exchanger performance (Fig. 4-3) shows the maximum hot gas temperature available for a range of condensate drain temperatures up to the saturation temperature of 341°C (646°F). The

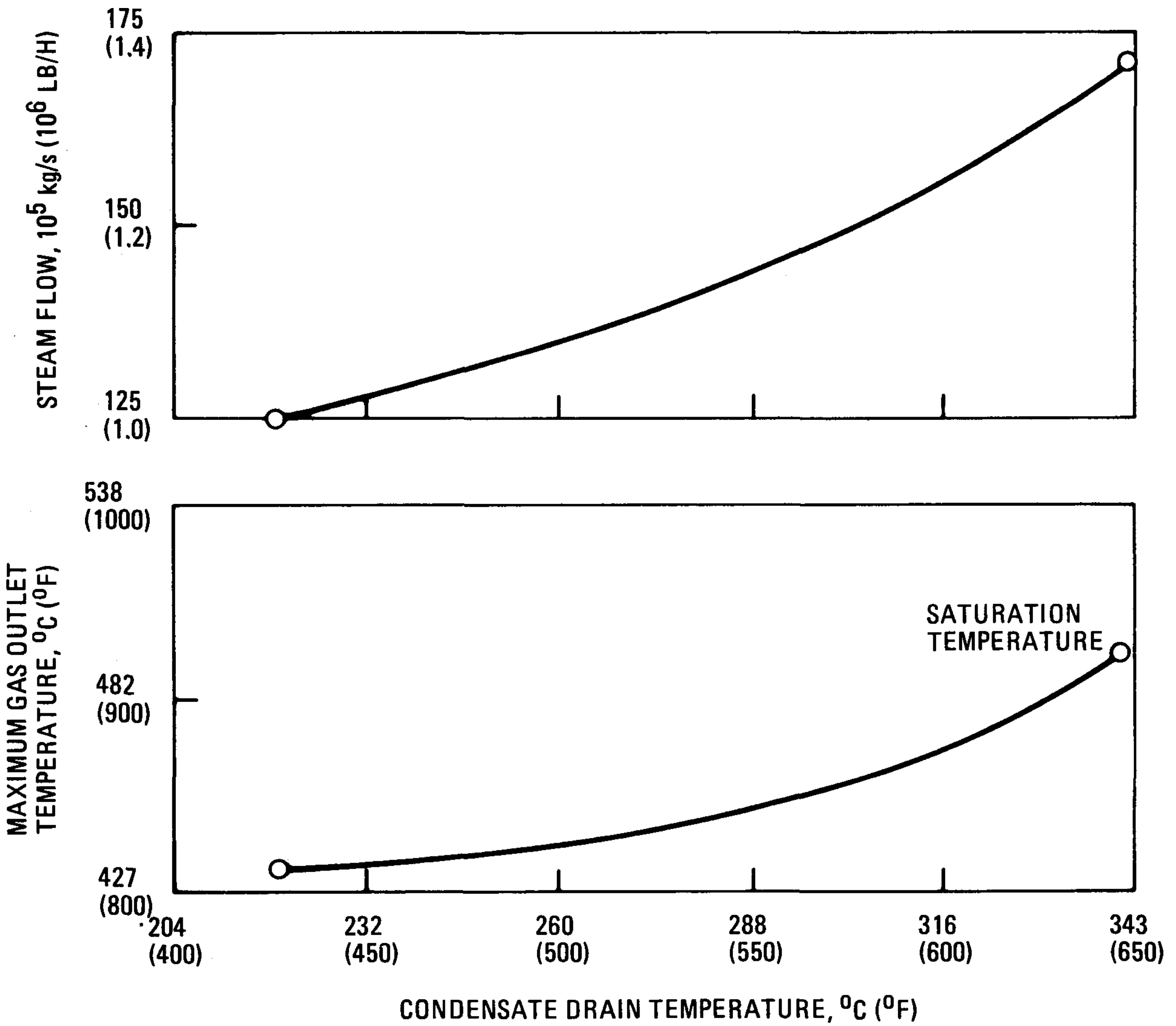

Fig. 4-3. Single heat exchanger alternative for gas heating with steam from an 1170-MW(t) HTGR-SC/C plant

maximum hot gas temperature available from complete condensation of the steam, without subcooling, is 493°C (920°F).

The net electric power produced is 83,000 kW as summarized below:

	kW(e)
Gross generator output	275,000
Less: HTGR auxiliary power	-35,000
Net electric power	240,000
Less: Shale plant electric power requirements (See Table 3-1)	-157,000
Electric power for other uses or export	83,000

REFERENCE

4-1. "1170-MW(t) HTGR Steamer Cogeneration Plant NSSS Design Report," DOE Report GA-A15222, General Atomic Company, August 1980.

5. ECONOMICS

5.1. COST ESTIMATES

A preliminary cost estimate was made of the modified Paraho process to obtain a cost comparison with the Davy McKee study based on the use of an HTGR-PH (VHTR) reactor plant (Ref. 1-2). The process plant cost estimate was derived or extrapolated from Davy McKee cost data and had no detailed input from cost engineering.

The following paragraphs highlight the Davy McKee basis and general terms used in developing the plant economics.

The capital costs include plant investment, engineering services, construction expenses, contingency, and working capital. An order-of-magnitude capital cost was developed based on such information as process flow diagrams, major equipment sizes, in-house pricing for process packages, budget prices based on other similar projects, and published cost data.

For determining direct capital costs of major plant sections, the six-tenths exponent rule was applied to the scaling of plant capacities. The Chemical Engineering Plant Cost Index escalation factors were used as a method to update plant costs. Single-source quotations from previous studies were used to determine the costs of major equipment such as furnaces, compressors, turbogenerators, towers, heat exchangers, and pumps. Recommended exponents were used for scaling equipment costs, and the Marshall and Swift Equipment Cost Index was used to update the cost. All costs were based on January 1, 1980, dollars. Power plant costs for the 1170-MW(t) HTGR-PH and 1170-MW(t) HTGR-SC/C plants were developed by GA in cooperation with United Engineers & Constructors and Bechtel Group Inc. and formed the basis for the cost study. Systems and components were modified to suit Paraho shale retorting process application design requirements. These systems and components included structures and improvements and equipment pertaining to the reactor plant, the turbine plant, the electric plant, and other related components. All costs were based on January 1, 1980, dollars.

Table 5-1 shows itemized process plant capital costs for the Paraho process using an 1170-MW(t) HTGR-PH plant, the standard Paraho retorting plant, and the modified Paraho process using an 1170-MW(t) HTGR-SC/C plant. An equilibrium HTGR-PH plant was assumed in the economic analysis. A cost difference of approximately 78 million dollars (January 1980 $) [1837 M$ (HTGR-PH) versus 1759 M$ (HTGR-SC/C)] exists between the two nuclear plant cases, and this is mainly attributable to the HTGR-PH plant, which represents an advanced technology. The standard Paraho plant cost is about two-thirds that of a Paraho/HTGR plant capital cost, primarily because of the lower fossil-fuel-fired power plant cost.

5.2. ECONOMIC ANALYSIS

5.2.1. Methodology

The revenue requirement method (Ref. 5-1) was selected as the method for evaluating the alternative projects. This technique, which is commonly accepted by the electric utility industry for evaluating long-lived power plant projects, determines the revenue needed by the firm as compensation for all expenditures fixed and variable. Hence, the revenue requirements of the firm are the costs to the consumer of the process steam cogenerated.

Under the revenue requirement technique, the concept of levelization is used to convert a stream of escalating costs to a single "level" cost stream, or equal payment annuity. Such a technique explicitly accounts for the time value of money to the firm (discount rate), the escalation (inflation) rate, and the life of the project.

TABLE 5-1
PARAHO PROCESS PLANT/HTGR PLANT COST DATA

	Paraho HTGR-PH (Source: Ref. 1-2)	Modified Paraho HTGR-SC/C	Standard Paraho Fossil Fuel-Fired (Source: Ref. 1-2)
Plant Specifications			
Thermal ratings, MW(t)	1170	1170	1311
Electrical ratings			
Gross, MW(e)	215	275	137
Net, MW(e)	130	240	137
Heat to Process, MW(t)	532	598	600
Direct Costs ($ million, 1/80)			
Mining	116	126	116
Secondary crushing and screening	64	70	64
Retorting and oil recovery	198	234	210
Spent shale disposal	23	25	23
Gas cooling compression and NH_3 removal	3	3	3
Stretford plant	10	11	10
Wastewater treating	8	9	7
Hydrotreating	74	74	75
Hydrogen plant	0	44	44
DEA acid gas plant	2	2	2
Claus and Scot plant	4	4	4
Chevron wastewater treatment	13	14	13
Shale oil storage	10	10	8
Power plant	602[(a)]	446	73
Water supply	11	11	9

TABLE 5-1 (Continued)

	Paraho HTGR-PH (Source: Ref. 1-2)	Modified Paraho HTGR-SC/C	Standard Paraho Fossil Fuel-Fired (Source: Ref. 1-2)
Off-site	67	70	73
Direct cost	1205	1153	734
Construction service	241	231	147
Home office engineering service	174	167	106
Contingency	217	208	132
Total base cost	1837	1759	1119

(a) Equilibrium HTGR-PH plant.

Base year capital costs are escalated through plant construction, and interest during construction is added to arrive at a total capital cost in commercial operation year dollars. A fixed charge rate is applied to the total capital cost to arrive at an annual fixed charge to which are added the levelized annual fuel costs, levelized annual operation and maintenance (O&M) costs, and a credit for the levelized value of cogenerated power to arrive at a total levelized annual cost.

5.2.2. Assumptions

Table 5-2 shows the new economic assumptions used in this study. Table 5-3 shows the financial assumptions employed in the study. The economic analysis was based on private industries ownership. Oil and gas used as fuel in the standard and modified Paraho processes were assumed purchased at the world market price.

5.3. RESULTS

Table 5-4 shows the economic results for the modified Paraho process using an 1170-MW(t) HTGR-SC/C plant. The table also shows the results of the Davy McKee economic study, which included an 1170-MW(t) HTGR-PH (VHTR) plant and the standard Paraho plant. The standard Paraho plant consumes a considerable amount of fuel oil in the power plant. Therefore, the annual fuel cost of the standard Paraho process, as shown in Table 5-4, is high, although the retorting plant capital cost is significantly lower than either of the two Paraho/HTGR plants. The resulting product price - oil ($/bbl) and gas ($/GJ) - is significantly higher (16%) than the product price of the two Paraho/HTGR plants.

The economic assumptions shown in Table 5-2 were established by GA in cooperation with Gas Cooled Reactor Associates (GCRA). While these ground rules are consistent with private industry practice, they are subject to modification by a specific developer. Additional economic advantages, if any, depend on the ground rules of a specific developer.

TABLE 5-2
ECONOMIC ASSUMPTIONS

Commercial plant basis	Nth plant	
Capacity factor	70%	
Base date for all costs	January 1980	
Date of operation for all plants	January 1995	
Investment life for all plants	30 yr	
Credit value for electric power	34 mills/kW/h	
1995 fuel cost projections (January 1980 $)		
Uranium	\$88.88/kg (\$40/lb)U_3O_8	
Conversion	\$6/kg UF_6	
Separative work (0.2% tails)	\$120/SWU	
Nuclear fuel cycle	HEU/TH recycle	
Oil/gas	\$5.01/10^6 BTU	
Operation and maintenance costs (January 1980 $)	Fixed (10^6 \$/yr)	Variable [mills/kW(t)-h]
HTGR-SC/C	(12.2)	(0.95)
HTGR-PH (R)	12.0	0.45
Common cost factors, private industry-owned facility	Percent	
Weighted cost of capital	7.4	
Levelized fixed charge rate	13.0	
Allowance for funds during construction	6.9	
Real escalation rates		
Construction	1.0	
O&M	1.0	
Electric power	2.0	
Fuel (all)	3.0	
Private industry-owned facility	Constant Dollars	
O&M	1.114	
Electric power	1.247	
Fuel (all)	1.403	

TABLE 5-3
FINANCIAL ASSUMPTIONS ASSUMING ZERO INFLATION RATE

	Public Corporation (%)
Capital Structure	
Debt	25
Preferred equity	--
Common equity	75
Financing costs	
Bond yield	4.1
Preferred equity yield	--
Common equity yield	8.5
Weighted cost of capital	7.4
Property taxes and insurance	2.0
Effective tax rate	50.0
AFDC rate	6.9
Resulting fixed charge rate	13.0
Plant investment life (years)	30
Plant tax life (years)	20
Depreciation method	Accelerated SYD

TABLE 5-4

ECONOMIC ANALYSIS OF MODIFIED PARAHO SHALE PROCESS WITH AN HTGR/SC PLANT IN COMPARISON WITH DAVY MCKEE RESULTS USING AN HTGR-PH PLANT AND A STANDARD PARAHO PLANT

	Paraho Process with HTGR-PH Plant	Modified Paraho Process with HTGR-SC/C Plant	Standard Paraho Fossil Fuel-Fired
Heat input to cycle, MW(t)	1,170	1,170	1,311
Shale feed, tonnes/day	59,490	65,180	59,490
Heat to process, MW(t)	530	598	600
Net electrical power output after process, MW(e)	0	83	0
Capital costs, M$			
Base capital cost, 1/80 $	1,837	1,759	1,119
Escalation through construction	250	240	154
Interest during construction	329	315	181
Total capital costs, M$	2,416	2,314	1,454
Annual costs, M$/yr[a]			
Fixed charges	314	301	189
Fuel costs - nuclear	22	22[b]	--
Fuel costs - oil	--	8	232[c]
Fuel costs - gas	--	35	32
O&M costs (power plant)	20	25	3
O&M costs (process)	144	157	143
Credit for electric power[d]	0	<29>	0
Total annual costs	500	519	599
Product			
Oil (bpd)	45,042	45,042	45,042
Gas MMSCFD	13.6	16.79	14.43
(bpd, FOE)	(1,713)	(2,115)	(1,817)
Total (bpd)	46,755	47,157	46,859

TABLE 5-4 (Continued)

	Paraho Process with HTGR-PH Plant	Modified Paraho Process with HTGR-SC/C Plant	Standard Paraho Fossil Fuel-Fired
Product price			
Oil $\$/m^3$ (\$/bbl)	263.51 (41.90)	272.25 (43.29)	314.64 (50.03)
Gas \$/GJ ($\$10^6$ Btu)	6.63 (6.99)	6.84 (7.19)	7.92 (8.35)
Ratio of product price based on HTGR-SC/C plant	0.97	1.00	1.16

(a) 1995 projection in 1/1980 \$, levelized over 30 yr.

(b) Includes nuclear fuel, 443 bpd of fuel oil, and 16.79 MMSCFD of fuel gas.

(c) Includes 13,876 bpd of fuel oil and 13.60 MMSCFD of fuel gas.

(d) Power credit at \$0.034/kW(e)-h, 1/80 \$.

REFERENCE

5-1. "EPRI Technical Assessment Guide," Electric Power Research Institute Report EPRI PS-1201-SR, July 1979.

6. ENVIRONMENTAL AND WATER CONSIDERATIONS

6.1. ENVIRONMENT

Davy McKee has performed an in-depth environmental study of the Paraho process used in conjunction with an 1170-MW(t) HTGR-PH plant, comparing that process with the standard indirect Paraho retorting process in which all process heat is supplied by firing upgraded product oil; the results of the comparative study are included in Ref. 1-2. A few highlights from the Davy McKee study, along with environmental data pertinent to the modified Paraho process using an HTGR-SC/C plant, are presented in this section. Environmental considerations primarily extend to four areas: (1) air, (2) water, (3) solid waste, and (4) thermal impact. Each of these areas is discussed in the following subsections.

6.2. AIR

Atmospheric emissions will occur from several sources during oil shale processing. The major source of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and carbon monoxide (CO) will be fuel combustion for process heat, predominantly at the reforming furnace. Sulfur dioxide will also be emitted in the sulfur recovery and tailgas clean-up operations. Particulate matter emissions will occur from fuel combustion, raw and spent shale dust in process streams, raw and spent shale handling and disposal, mining and blasting, and other site activities that generate fugitive dust.

Particular emissions from fuel combustion and fugitive dust from spent shale may emit potentially hazardous substances. Pyrolysis of oil shale will produce polycyclic organic material (POM). POM compounds could be released to the atmosphere during shale retorting, disposal, and handling of retorted shales or during combustion of shale-derived oils. Gaseous ammonia (NH_3), hydrogen sulfide (H_2S), and volatile organics may be released during moisturizing and subsequent cooling of the retorted shale. Trace metals may also be released to the atmosphere from fuel combustion. Fugitive dust emissions are expected from spent shale handling and during catalyst regeneration, handling, and final disposal. The exact consequences of releasing the above contaminants into the atmosphere are presently not known and they need further study. However, it is likely that the emission of such pollutants can be held to acceptable levels through control technology.

Table 6-1 presents an overall emission summary for the modified Paraho process, which uses an HTGR-SC/C plant as its energy source. Table 6-2 shows a summary of air emissions from a standard Paraho retorting plant for comparison. The commercial oil shale plant is assumed to be located in an "attainment area," defined as an area where the ambient air quality is currently cleaner than defined in the National Ambient Air Quality Standards (NAAQS) for SO_2, CO, total suspended particulates, photochemical oxidants (O_x), nitrogen dioxide (NO_2), or lead (Pb). If the shale plant is located in a nonattainment area (i.e., in an area where the ambient air quality is not cleaner than defined in the NAAQS), regulatory requirements will then apply with regard to the allowable emissions. For pollutant-producing operations in attainment areas, the United States Environmental Protection Agency (USEPA) has established a monitoring program. The objective of the program is to "prevent significant deterioration" of the air quality concentrations up to the NAAQS. The monitoring program includes gathering data on the regulated pollutants emitted in excess of the "de minimis" values. The "de minimis" values for the regulated pollutants established on the basis of a single plant operation are given in Table 6-3. The EPA will scrutinize the pollutant data with respect to the "de minimis" values and will consider permissible variances or initiate appropriate actions.

There are at present no federal emission standards specifically covering oil shale production. The State of Colorado, however, has enacted a few regulations directed to the shale oil industry on air emissions. One requires commercial operations [producing more than 6.7 m^3/h (1000 bpd)] to

TABLE 6-1
AIR EMISSION SUMMARY FOR THE MODIFIED PARAHO PROCESS USING AN 1170-MW(t) HTGR-SC/C PLANT [kg/h(lb/day)]

	Particulates	SO_2	NO_x	HC	CO	CO_2	H_2S
Mining[a]	12 (640)	--	2 (87)	--	22 (1,145)	--	--
Shale preparation[b]	17 (915)	--	--	--	--	--	--
Retorting	11 (568)	16 (840)	118 (6,248)	5.4 (284)	27 (1,420)	0.1×10^6 (5.38×10^6)	4 (212)
Spent shale treatment and disposal	26 (1,349)	--	--	--	--		--
Upgrading	0.3 (18)	0.5 (26)	4 (197)	0.20 (9)	0.9 (45)	3,831 (202,705)	--
Ammonia and sulfur recovery		--	--	52 (2,726)	1,290 (68,275)	--	--
Product storage		--	--	1.4 (72)	--	--	--
Steam and power	8 (404)	4 (187)	54 (2,870)	1.1 (58)	5.5 (288)	0.02×10^6 (1.21×10^6)	--
Hydrogen production	5 (234)	7 (345)	49 (2,569)	2 (117)	11 (584)	0.1×10^6 (5.6×10^6)	--
Total[c]	78 (4,128)	26 (1,398)	226 (11,971)	62 (3,266)	1,356 (71,757)	0.2×10^6 (12.4×10^6)	--

(a) Does not include mobile mine equipment.
(b) Does not include hauler emissions.
(c) It should be noted that emissions are regulated on a process basis and are not generally regulated as one large point source emission for the entire process area.

TABLE 6-2

AIR EMISSION SUMMARY FOR A 60,000-TONNE/DAY (66,000-T/D)
STANDARD PARAHO RETORTING PLANT [kg/h(lb/day)]

	Particulates	SO_2	NO_x	HC	CO	CO_2	H_2S
Mining[a]	11 (584)	-	1.5 (79)	-	20 (1,045)	-	-
Shale preparation[b]	16 (835)	-	-	-	-	-	-
Retorting	10 (518)	14 (766)	106 (5,702)	5 (259)	24 (1,296)	0.1×10^6 (4.91×10^6)	-
Spent shale treatment and disposal	23 (1231)	-	-	-	-	-	-
Upgrading	0.3 (16)	0.4 (24)	3 (180)	0.15 (8)	0.7 (41)	3426 (185,000)	-
Ammonia and sulfur recovery	-	-	-	50(2,726)	1264(68,275)	-	212
Product storage	-	-	-	1.3 (72)	-	-	-
Steam and power	37 (2,016)	17 (936)	266(14,352)	5 (288)	26 (1,440)	0.11×10^6 (6.06×10^6)	-
Hydrogen production	5 (234)	6 (345)	48 (2,569)	2 (117)	11 (584)	0.1×10^6 (5.6×10^6)	-
Total[c]	102 (5,434)	38 (2,071)	424(22,882)	64(3,470)	1346(72,681)	0.3×10^6 (16.8×10^6	-

(a) Does not include mobile mine equipment.
(b) Does not include hauler emissions.
(c) It should be noted that emissions are regulated on a process basis and are not generally regulated as one large point source emission for the entire process area.

TABLE 6-3
"DE MINIMIS" VALUES FOR THE REGULATED POLLUTANTS

Regulated Pollutants	"De Minimis" Values [kg/yr (tons/yr)]
Sulfur dioxide (SO_2)	36,288 (40)
Total suspended particulates (TSP)	22,680 (25)
Carbon monoxide (CO)	90,718 (100)
Nitrogen oxides (NO_x)	36,288 (40)
Ozone (volatile organic compounds)	36,288 (40)
Lead (Pb)	544 (0.6)
Asbestos	6.35 (0.007)
Beryllium	0.36 (0.0004)
Mercury	90.7 (0.1)
Vinyl chloride	907 (1)
Fluorides	2,722 (3)
Sulfuric acid mist	6,350 (7)
Total reduced sulfur (including H_2S)	9,070 (10)
Reduced sulfur compounds (including H_2S)	9,070 (10)
Hydrogen sulfide (H_2S)	9,070 (10)

restrict themselves to 0.85 kg SO_2/m^3 (0.3 lb SO_2/bbl) of oil production plus an equal amount for the refining operation. Similarly, hydrogen sulfide emission is limited to 10 ppm based on a one-hour average ambient air concentration. Any plan for developing a commercial oil shale operation in the State of Colorado requires filing an Air Containment Emission Notice and securing an emission permit prior to construction.

A review of Tables 6-1 and 6-2 shows a considerable reduction in pollutant emission from a Paraho/HTGR-SC/C plant as compared with a standard Paraho retorting plant. This reduction occurs primarily because of a substantial reduction in the use of the product oil as fuel. The particulates and SO_2 emissions are reduced to approximately two-thirds of the standard plant emission and the NO_x is reduced by 50%. Thus, the integration of the HTGR-SC/C plant as an energy source for the Paraho process offers environmental advantages.

6.3. WATER

There are four sources of water available in the shale oil fields of Colorado:

1. Surface water.
2. Mine water.
3. Well water.
4. Run-off water.

However, water availability from these sources is not abundant and is a major concern in developing the shale oil industry in Colorado. The shale oil fields generally are in arid areas; indeed, any large-scale commercial oil shale operation in Colorado may be limited by water availability. Therefore, it is necessary that water use and management be given paramount importance in shale industry development. Wastewater streams resulting from surface retorting facilities are treated for reuse as well as for dust control, spent shale moisturization, and shale disposal on site. A summary of wastewater effluents from a surface retorting process is given in Ref. 1-2. Figure 6-1 shows the wastewater utilization scheme.

Based on environmental considerations, contaminated wastewater streams from shale surface retorting facilities could have access to aquifers and ground water, resulting in fouling. The USEPA has established national effluent limitations on what a point source can discharge into the aquifers or ground water. Depending upon the pollutant, an effluent limitation may permit some level of pollutant discharge or may prohibit any discharge of the pollutant. The State of Colorado issues discharge or disposal permits for the sources of pollutants to ensure that all effluent limitations and other requirements are complied with.

6.4. SOLID WASTE

Solid waste disposal from oil shale processing presents one of the major problems associated with commercial development of the oil shale industry. The predominant source of solid waste will be shale-derived, including spent shale, raw shale fines, and mined raw shale. At present, no solid waste resulting from shale surface retorting facilities has been classified as hazardous by federal or state agencies. However, the management of solid waste disposal will need to incorporate the following actions as an inherent part of the waste disposal process:

- Preparation of the disposal site.
- Transport of the waste to the disposal site.
- Construction of a stable waste pile.
- Minimization of wind and water erosions of pile surface.
- Rehabilitation of the disposal site to compatibility with surrounding undisturbed land.

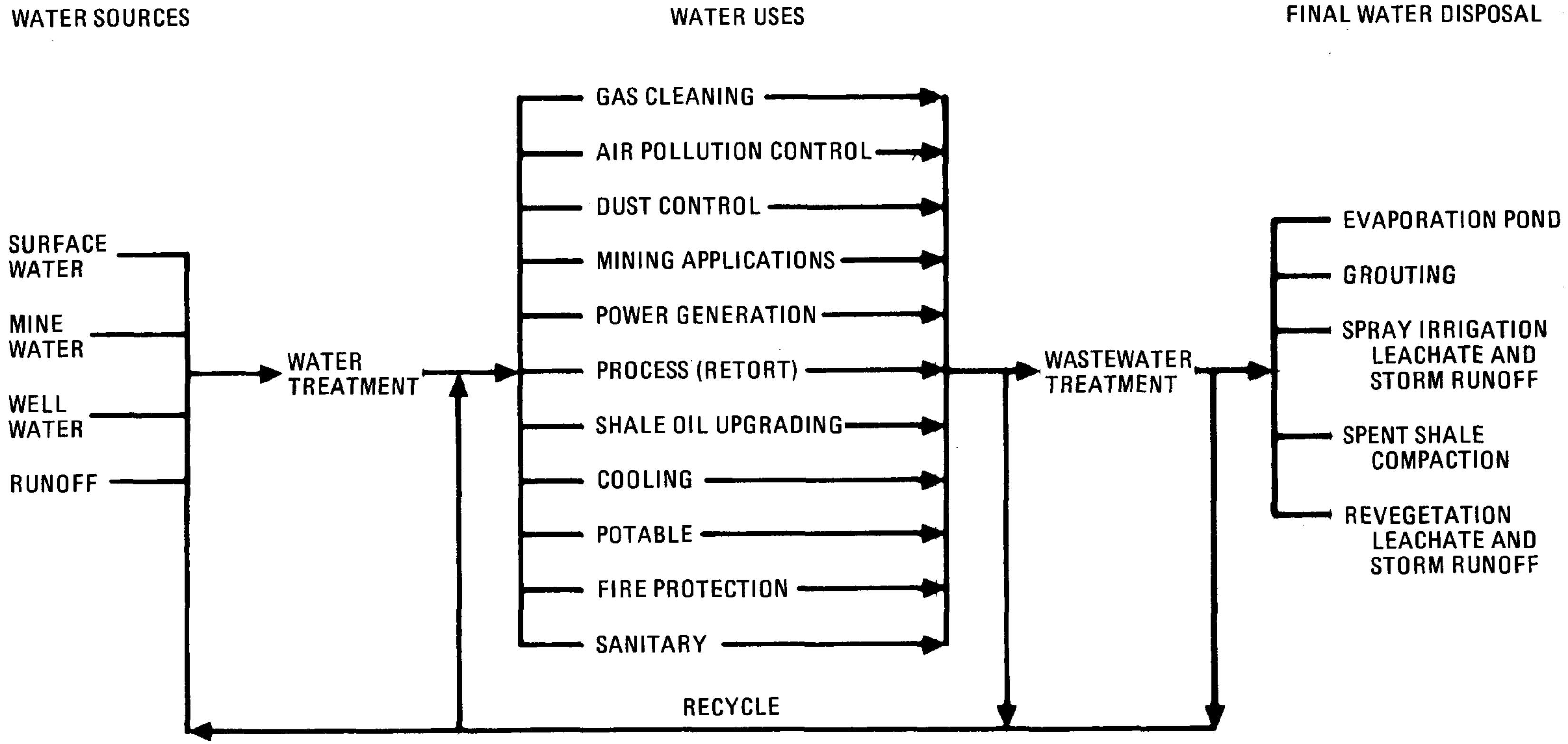

Fig. 6-1. Wastewater utilization in a surface shale retoring process

6.5. THERMAL IMPACT

The thermal pollution of Colorado waters under the aquatic life classification is limited, generally, to a maximum 3°C increase over a minimum of a four-hour period, lasting for 12 hours maximum. Where temperature increases cannot be maintained within this range using best management practice, the Colorado Department of Health will determine whether the resulting temperature increases preclude an aquatic life classification. Recreational, agricultural, and domestic water classifications do not have express thermal limitations.

The foregoing discussion on environmental effluents pertains primarily to shale retorting and process side. Table 6-4 shows the environmental effluents (air emissions, solid wastes, and liquid effluents) from an 1170-MW(t) HTGR plant; they are within limits set by the Federal Nuclear Regulatory Administration.

TABLE 6-4
ENVIRONMENTAL EFFLUENTS FROM AN 1170-MW(t) HTGR PLANT

Air emissions	
Noble gases, Ci/yr	99[(a)]
Iodine and particulates, Ci/yr	0.01
Solid wastes	
Miscellaneous radioactive material, Ci/yr	7570[(b)]
Liquid effluents	
Mixed fission products (no tritium), Ci/yr	0.0021

[(a)] Includes 0.09 Ci/yr of Tritium.

[(b)] Includes Tritium contained in soidified high-specific-activity liquids.

7. CONCLUSIONS

The modified Paraho shale surface retorting process integrating an 1170-MW(t) HTGR-SC/C plant has several advantages over the standard Paraho indirect retorting process, which uses about one-third of the product oil as fuel. It also compares favorably with the indirect Paraho process that integrates an HTGR-PH plant as described in Davy McKee's study (Ref. 1-2). The modified Paraho/HTGR-SC/C process requires approximately 10% more shale feedstock than the Paraho/HTGR-PH process because it retorts shale at a lower temperature [455°C versus 510°C (850°F versus 950°F)] and has attendant lower Fischer assay yields (87% versus 93.5 %); however, the results of the economic analysis presented in Section 5 show that the price difference per barrel of upgraded oil between the two processes is only marginal. Thus, it appears that developing a lead HTGR-PH plant (which represents an advanced technology) as an energy source solely for this application is not necessary; an HTGR-SC/C plant (which represents an available technology) could serve the same purpose at nearly the same oil price. Both Paraho/HTGR plants have a definite economic advantage (~16%) over the standard Paraho process based on the product price.

In comparison with the standard Paraho process, the Paraho/HTGR-SC/C process not only serves the national interest by conserving valuable liquid synthetic fuel and enhancing domestic production, but also by conserving an important resource: shale feedstock.

A surface shale retorting process utilizing nuclear heat considerably reduces the environmental burden associated with the burning of oil such as occurs in the standard Paraho process. It could be argued that emissions due to oil burning have only an incremental impact over the process environmental releases. However, this impact could well mean that the amount of shale that could be retorted would have to be limited so as to offset the emissions from oil burning.

It appears from the foregoing discussion that the HTGR-SC/C plant is well suited as an energy source for the shale surface retorting process; however, the future of recovering oil from shale itself is not clear. Several technological and economic uncertainties exist for commercial development of shale operations. (This is evidenced by the Exxon Company's termination of participation in the now defunct Tosco Colony project.)

Coal has not been considered as an alternative source of energy for shale operations in Colorado, since coal has to be imported and transported to remotely located shale oil fields. Coal transportation costs and environmental impact problems are additional uncertainties in considering coal as an energy source in shale operations.

In summary, the following statements can be made on HTGR-SC/C applicability to the modified Paraho process.

- The HTGR-SC/C is an available technology that can be integrated as the source of energy with the modified Paraho process.
- The HTGR-SC/C plant as an energy source conserves considerable amounts of product oil that would otherwise be burned in the standard indirect Paraho shale retorting process.
- The HTGR-SC/C plant reduces the environmental burden significantly in comparison with the oil-burning standard Paraho process.
- One 1170-MW(t) HTGR-SC/C plant can supply approximately 67% of the process thermal energy and all of the on-site electrical power requirements and has a surplus of electric power [~83 MW(e)] for export or other uses.
- In the Paraho/HTGR-SC/C process, shale is retorted at a lower temperature compared with the Paraho/HTGR-PH process or the standard Paraho process, thus requiring more feedstock (approximately 10%) and a larger retort.

- Preliminary economic analysis favors the Paraho/HTGR-SC/C process over the standard Paraho process on the basis of product price. The Paraho/HTGR-PH process also has an economic advantage over the standard Paraho process. However, the developmental cost associated with an HTGR-PH plant for providing high-temperature heat to the process is significant, whereas the HTGR-SC/C plan is an available technology.

REFERENCE

7-1. Hopwood, G.R., et al., "HTGR Application Comparative Assessment Study," DOE Report GA-A16525, General Atomic Company, April 1982.