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INTRODUCTION

The solvent refined coal (SRC-II) process is an advanced process being developed by Gulf Mineral Resources Ltd. (a Gulf Oil Corporation subsidiary) to produce a clean, non-polluting liquid fuel from high-sulfur bituminous coals. The SRC-II commercial plant will process about 24,300 tonnes (26,800 tons) of feed coal per stream day, producing primarily fuel oil plus secondary fuel gases. This summary report describes the integration of a high-temperature gas-cooled reactor operating in a process steam/cogeneration mode (HTGR-PS/C) to provide the energy requirements for the SRC-II process.

The HTGR-PS/C plant was developed by General Atomic Company (GA) specifically for industries which require energy in the form of both steam and electricity. General Atomic has developed an 1170-MW(t) HTGR-PS/C design which is particularly well suited to industrial applications and is expected to have excellent cost benefits over other sources of energy. Because the HTGR produces high-temperature, high-pressure steam at conditions identical to those from fossil-fired boilers, there can be fairly direct substitution for existing large oil-or gas-fired industrial boilers and maximum flexibility in establishing cogeneration heat cycles to produce steam at conditions required for process use.

APPLICATION REQUIREMENTS

The SRC-II process flow diagram is shown in Fig. 1 and gives the steam conditions at various stages of the process where the HTGR-PS/C steam has been substituted for steam and direct-fired duties. The base case design included process steam being generated by direct gas-fired boilers and

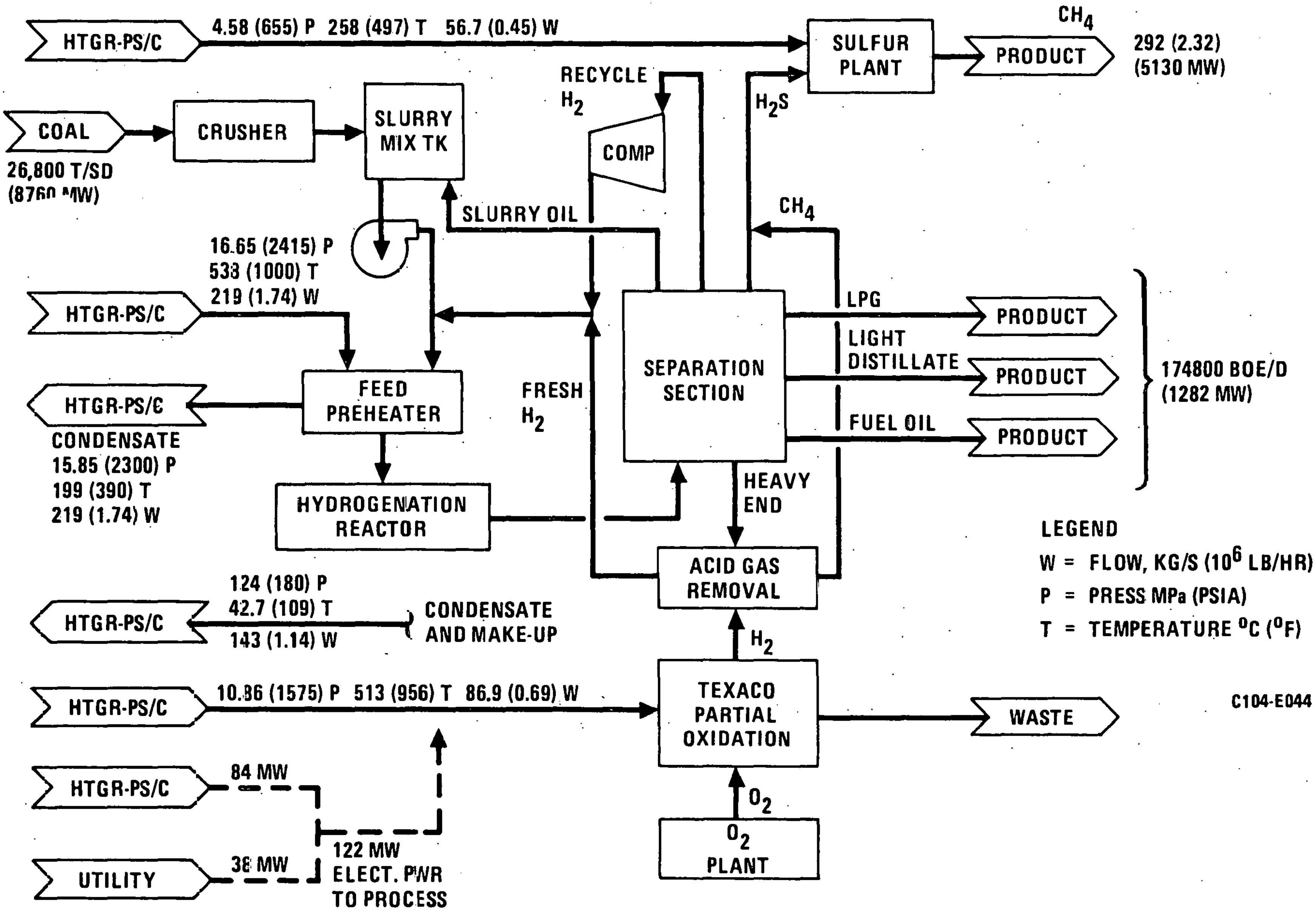


Fig. 1. Process flow diagram for 24,300 tonne (26,800 ton) per stream day SRC-II coal liquefaction application using an 1170-MW(t) HTGR-PS/C

process heating by direct gas firing. The fuels utilized are hydrocarbon-rich gas, CO-rich gas, and purified syngas (i.e., no feed coal is used for fuel). Table 1 presents the energy requirements, both thermal and electric, for an expanded SRC-II plant that processes about 24,300 tonnes (26,800 tons) of feed coal per stream day. Table 1 also gives the approximate quantities of gaseous fuels required for the SRC-II process. A review of Table 1 shows that a single HTGR-PS/C unit can supply these thermal requirements principally by substituting for the fuel gases previously employed. The displaced gases may be marketed or alternatively used.

All system thermal energy requirements in the form of process steam generation, steam superheating, and slurry heating are provided by the HTGR-PS/C plant with its high-pressure [16.65 MPa (2415 psia)], high-temperature [538°C (1000°F] steam supply. The 1170-MW(t) HTGR does not generate all the required electrical energy, and a deficit of about 38 MW electric power results.

PLANT DESIGN

The SRC-II heat loads and mechanical/electrical power loads are shown in Table 1. The 10.45-MPa (1515-psia) steam is supplied by throttling the main steam from 16.65 MPa (2415 psia). After throttling, the steam temperature is 513°C (956°F). The required 4.58-MPa (665-psia) saturated steam is supplied from the high-pressure turbine exhaust, which is desuperheated using condensate return. The remaining four heat requirements are supplied by main steam through separate heat exchangers as shown in Fig. 2. The high-pressure condensate from these heaters, at 15.86 MPa (2300 psia) and 199°C (390°F), is mixed with the other feedwater between the boiler feed pump and the top feedwater heater. The HTGR-PS/C plant cycle diagram for this service is shown in Fig. 3.

All the SRC-II plant steam and heat requirements are satisfied either directly or through the heat exchangers. The excess steam supplies a

TABLE 1
DATA BASE FOR SRC-II PROCESS ENERGY REQUIREMENTS FOR 24,300 TONNES (26,800 TONS) OF FEED COAL PER STREAM DAY

A. Utility Energy Requirements[a]	MW	B. Energy Requirements Provided by HTGR-PS/C	MW	C. Percent Provided by HTGR-PS/C (B/A)
1. Process heat for slurry heating: Slurry T_{in} = 177°C (350°F) Slurry T_{out} = 399°C (750°F) W_{slurry} = (later) Heating provided by direct fuel firing	476	Provided by heat exchange with steam at: P = 16.65 MPa (2415 psia) T = 538°C (1000°F) W = 189 kg/s (1.5 x 10^6 lb/hr)	476	100
2. Process steam superheating by direct-fired fuel to: P = 10.45 MPa (1515 psia) T_2 = 513°C (950°F) T_1 = 314°C (598°F) W = 83 kg/s (657,400 lb/hr)	56	Process steam superheating provided by heat exchange with steam at: P = 16.65 MPa (2415 psia) T = 538°C (1000°F)	56	100
3. Process steam superheating to: P = 4.24 MPa (615 psia) T_2 = 399°C (750°F) T_1 = 258°C (497°F) W = 41 kg/s (325,387 lb/hr)	18	Process steam superheating provided by heat exchange with steam at: P = 16.65 MPa (2415 psia) T = 538°C (1000°F)	18	100
4. Process steam superheating to: P = 1.83 MPa (265 psia) T_2 = 227°C (440°F) T_1 = 217°C (422°F) W = 163 kg/s (1.29 x 10^6 lb/hr)	9	Process steam superheating provided by heat exchange with steam at: P = 16.2 MPa (2350 psia) T = 327°C (620°F)	9	100
5. Steam to process at: P = 10.45 MPa (1515 psia) T = 513°C (950°F) W = 87 kg/s (690,000 lb/hr)	280	Steam to process: Supplied by pressure breakdown of HTGR-PS/C 16.65 MPa (2415 psia), 538°C (1000°F) steam	280	100
6. Steam to process at: P = 4.59 MPa (665 psia) T = 257°C (495°F) W = 57 kg/s (449,100 lb/hr) Generated by direct gas-fired boilers)	148	Steam to process: Supplied by HTGR-PS/C after turbine expansion and desuperheating	148	100
Subtotal (Direct Fired)	987		987	100
Fuel sources for direct-firing process heat and steam generation: syngas, 7.9 m^3/s (24 x 10^6 SCFD); CO-rich gas, 23.6 m^3/s (72 x 10^6 SCFD); HC fuel gas, 18.0 m^3/s (55 x 10^6 SCFD)				
7. Electric power (purchased from the grid)	122	Electric power	84[b]	69
Total	1109		1071	96.6

[a] P = pressure, T = temperature, W = flow.

[b] A total of 115 MW(e) is cogenerated by the HTGR-PS/C. Of this, 84 MW(e) is available after HTGR-PS/C auxiliary requirements.

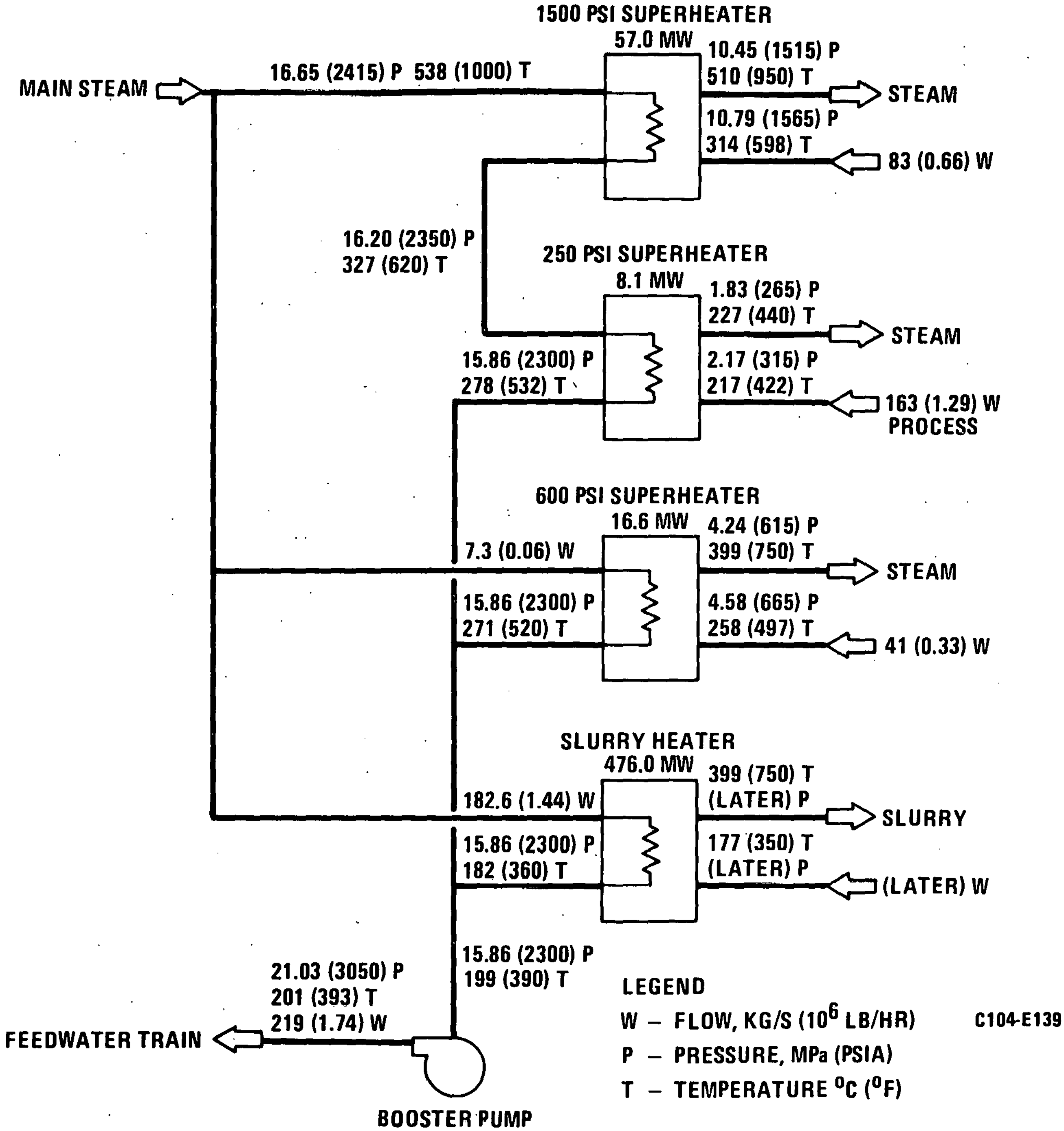
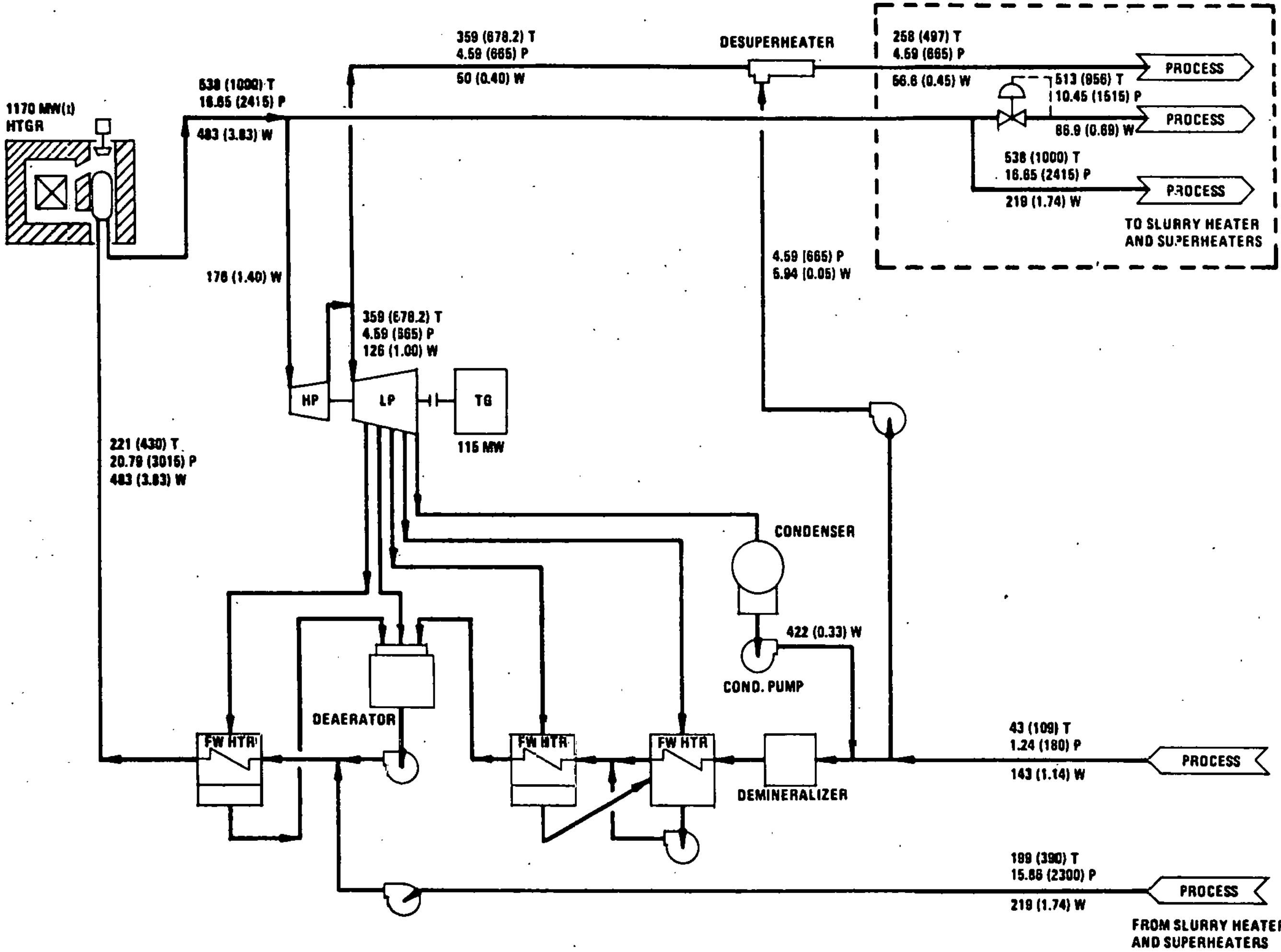


Fig. 2. Interfacing arrangement: HTGR-PS/C to SRC-II process



ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	83.6	7.1
STEAM POWER TO PROCESS	428.0	36.6
SLURRY HEATER	476.0	40.7
SUPERHEATERS	81.7	7.0
SUBTOTAL	1069.2	91.4
LOSSES		
CONDENSER	85.6	7.3
OTHER	15.2	1.3
TOTAL REACTOR POWER OUTPUT	1170	100

Fig. 3. Heat cycle for 24,300 tonne (26,800 ton) per stream day SRC-II coal liquefaction plant using an 1170-MW(t) HTGR-PS/C

condensing steam turbine-generator that produces 115 MW and heats all the feedwater for return to the steam generators. The net electrical output of the plant is 83.50 MW.

For completeness, studies were also conducted on utilizing steam-to-steam reboilers to isolate the primary steam from process steam. The cycle developed for this case supplies slightly less process heat, but somewhat more electric power, than the cycle without reboilers.

ECONOMIC ASSESSMENT

The revenue requirement method was selected as the economic tool for evaluating alternative application projects, since it is appropriate for evaluation of long-lived coal and nuclear cogeneration power plants. The revenue requirement method determines the revenue needed by the firm as compensation for all expenditures, fixed and variable. Hence, the revenue requirements of the user are the cost to the consumer of the process steam cogenerated.

Table 2 shows the economic evaluation results for the 1170-MW(t) HTGR-PS/C plant and for comparable coal-fired PS/C plants. A clear advantage of the HTGR-PS/C over a coal-fired plant is seen for this SRC-II process application. The analysis is based on economic assumptions used for evaluation of utility cogeneration projects in work being performed for the DOE. Such work is being carried out by General Atomic in coordination with Gas Cooled Reactor Associates (GCRA). Table 3 gives the principal assumptions of the economic analysis, a key one being the 18% fixed charge rate for capital use/recovery. Such a rate may be higher when industrial ownership ground rules are applied. Therefore, the economics should be determined using the economic ground rules specific to the SRC-II application. Industrial user input is being developed regarding possible alternate economic ground rules that should be utilized.

TABLE 2
ECONOMIC ANALYSIS OF HTGR-PS/C AND
COAL-FIRED PS/C PLANTS FOR SRC-II PROCESS APPLICATION

	HTGR-PS/C SRC-II	Coal-PS/C SRC-II
Heat input to cycle (MW)	1170.0	1230.2
Heat output in process steam (MW)	985.7	985.7
Net electrical power output (MW)	83.5	85.0
Capital Costs ($ x 10^6)		
Base capital cost (1/80 $)	544	356
Escalation through construction	542	403
Interest during construction	341	151
Total capital cost (1/95 $)	1427	910
Annual Costs ($ x 10^6/year)[a]		
Fixed charges	257	164
Fuel costs	81	299
O&M costs	63	69
Credit for electric power	(87)	(88)
Total annual costs	314	444
Process Steam Cost [mills/kW(t)-hr ($/MMBtu)]	51.93 (15.22)	73.60 (21.52)

[a] 1/95 $ levelized over a 30-year period.

TABLE 3
KEY ECONOMIC ASSUMPTIONS FOR HTGR-PS/C SRC-II APPLICATIONS

Commercial operation of all plants	1/1/95
Capacity factor	70%
Levelizing period	30 years
Electric power credit	22 mills/kW-hr (80 $)
Discount rate	10%/year
Fixed charge rate	18%/year
Interest during construction	10%/year (simple interest)
Coal cost excalation	8%/year
Fuel oil escalation	9%/year
All other escalation	6%/year
Construction period	6 years for all plants (2 years for No. 6 oil-fired plants)
U_3O_8 (yellowcake) cost	\$121/kg (\$55/lb) in 1990, rising to \$264/kg (\$120/lb) in 2030
Separative work unit (SWU) cost	\$100/kg-SWU (80 \$)
Tails assembly	0.2%
Coal cost	4.64 mills/kW(t)-hr (\$1.36/MMBtu) (80 \$)
No. 2 oil cost	18.2 mills/kW(t)-hr (\$5.33/MMBtu) (80 \$)
No. 6 oil cost	13.5 mills/kW(t)-hr (\$3.95/MMBtu) (80 \$)
HTGR fuel cycle cost	11.2 mills/kW(t)-hr (\$3.29/MMBtu) (1/95 \$ levelized over 30 years)

Ultimately, the method of economic analysis will be determined by the nuclear cogeneration plant ownership arrangement. Three ownership possibilities that should be considered are (1) industrial ownership with connection to the utility grid for backup electric power and sale of excess power [per recent Federal Energy Regulatory Commission (FERC) rulings regarding a more favorable arrangement for industry], (2) utility ownership with both steam and cogenerated electric power sold to nearby industry, and (3) consortia ownership and sale of energy to industry and local utilities.

The substantial advantage of the HTGR-PS/C over coal, indicated in Table 2 is primarily due to the much lower fuel cost of the nuclear plant despite its higher capital cost. This advantage is enhanced by long levelization periods, which in effect provide a smaller fixed charge rate for the use/recovery of capital. The fixed charge rate can also be reduced if shorter periods for depreciating the plant are permitted for tax purposes, which may be quite possible in view of the national goal to reduce imported oil/gas use.

The technical risk for the HTGR-PS/C for the subject application is considered small. The timescale for development is satisfactory, and the licensing risk should be relatively modest since the plant is likely to be relatively remotely located and since the licensing risk is only an increment upon already extensive licensing requirements for the process plant itself. The HTGR-PS/C is particularly suited for this application, which requires significant quantities of steam at conditions of 10.45 MPa (1500 psig) and 510°C (950°F) that cannot be obtained from an LWR without fossil superheating.