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HTGR-PROCESS STEAM/COGENERATION AND HTGR-STEAM CYCLE PROGRAM

**SEMIANNUAL REPORT FOR THE PERIOD
OCTOBER 1, 1979, THROUGH MARCH 31, 1980**

**by
PROJECT STAFF**

**Prepared under
Contract DE-AT03-76ET35301
for the San Francisco Operations Office
Department of Energy**

DATE PUBLISHED: SEPTEMBER 1980

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
NTIS Price Code: Printed Copy A-05; Microfiche A-01

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**GENERAL ATOMIC PROJECT 6689
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ABSTRACT

Progress in the design of an 1170-MW(t) High-Temperature Gas-Cooled Reactor (HTGR) Nuclear Steam Supply (NSS) is described. This NSS is shown to integrate favorably into present petrochemical and primary metal process industries, into heavy oil recovery operations, and into future shale oil recovery and synfuel processes. Not only is the technical fit shown to be excellent in terms of being able to supply the required quality of steam, but the economics appear especially attractive in comparison with alternative coal-fired steam generation.

Cost estimates for central station power-generating 2240- and 3360-MW(t) HTGR-Steam Cycle (HTGR-SC) plants are updated. Cost reduction features that evolved within the HTGR-Gas Turbine design program during 1979 are incorporated into the 2240-MW(t) HTGR-SC. A 0.6 exponent cost-power scaling factor is derived through the updating of the 3360-MW(t) HTGR-SC plant cost. Supporting design work is described.

The 2240-MW(t) HTGR-SC is treated to a probabilistic risk evaluation. Compared with the earlier 3000-MW(t) design, the results predict a slightly increased risk of core heatup. This increased risk is shown to be the result of eliminating the capability of the boiler feed pump to operate at atmospheric backpressure. The differences in risk, however, are within the calculational uncertainties.

Preliminary results of the ranking of safety enhancement features for the 1170-MW(t) HTGR indicate that the following modifications offer the most promise: (1) capability for main loop rundown, (2) natural circulation core auxiliary cooling, and (3) PCRV blowdown capability through the helium purification system to minimize activity release during some core heatups.

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1. INTRODUCTION AND SUMMARY

This report describes technical work performed by General Atomic Company (GA) under the High-Temperature Gas-Cooled Reactor - Steam Cycle (HTGR-SC) program, Department of Energy (DOE) Contract DE-AT03-76ET35301, for the period October 1, 1979, through March 31, 1980. In line with current national energy objectives, the program has been largely directed toward the process steam/cogeneration application of the HTGR. This work includes the conceptual design of an 1170-MW(t) HTGR-Nuclear Steam Supply (NSS) and a study of integrating the HTGR-NSS with process industries which use large amounts of process steam and cogenerated electric power. The HTGR used in this way has been named the HTGR-Process Steam/Cogeneration plant, or HTGR-PS/C. A lesser effort involving the updating of prior HTGR-SC plant designs was also undertaken and completed for the purpose of providing benchmarks against which competing systems could be measured.

The 1170-MW(t) HTGR-NSS concept evolved from the 2240-MW(t) HTGR-SC plant designed for central station electric power generation. The 2240-MW(t) plant used four primary reactor coolant loops; the helium in each loop was circulated by means of electric-motor-driven circulators, and the steam generators did not contain the reheat feature which had been specified in earlier HTGR plant concepts. For the smaller plant, the reactor core power was reduced by about a factor of two to 1170 MW(t) and two primary reactor coolant loops were specified with the same steam generator and circulator design that was used in the 2240-MW(t) plant. However, significant modifications and improvements to other parts of the NSS were specified, primarily for purposes of scaling to a smaller core, reducing cost, or achieving commonality with the advanced HTGR applications, the HTGR-Gas Turbine and HTGR-Reformer. The changes implemented were to the fuel block, core power density, fuel handling, thermal barrier, prestressed concrete reactor vessel (PCRVR), and core auxiliary cooling system.

In the NSS-to-process application studies, a data base of potential steam-using processes was developed, the interfacing balance-of-plant (BOP) between the NSS and process was conceptualized, and the licensability and economics were evaluated. The processes explored included both existing process plants and future processes:

- Petroleum refining/chemical plants
- Primary metal plants (steel, aluminum)
- Heavy oil and oil sands recovery
- In-situ steam-retorting of oil shale

The evaluation indicated that the HTGR-PS/C could adequately provide process steam and electric energy requirements in all the applications studied and that substantial economic advantages over either coal- or oil-fired alternatives may be realized. The ratio of HTGR steam price to coal steam price was found to range from 0.23 to 0.65.

The design of the 2240-MW(t) [900-MW(e)] HTGR-SC was modified to include improvements evolving out of the advanced HTGR-Gas Turbine concept. These modifications were primarily considered for their capital cost effectiveness. The components modified included the thermal barrier, PCR/V, fuel handling system, and core auxiliary cooling system. These changes resulted in substantial cost reductions. In addition, the overall system was optimized, indicating additional cost savings will be possible.

The earlier 3360-MW(t) lead plant capital cost (1977) was updated to include the non-reheat steam generator and electric-driven main helium circulator. None of the cost reduction features mentioned above were included. The purpose of updating the 3360-MW(t) plant to the 1979 2240-MW(t) design basis was to obtain a second cost point in order to derive a cost-power scaling factor. A GA preliminary estimate of 0.6 for the NSS scaling factor is more favorable in scaling to smaller-sized plants than the 0.5 factor previously projected.

The 2240-MW(t) HTGR-SC is treated to a probabilistic risk evaluation. Compared with the earlier 3000-MW(t) design, the results depict a slightly increased risk of core heatup. This increased risk is shown to be the result of eliminating the capability of the boiler feed pump to operate at atmospheric backpressure. The differences in risk, however, are within the calculational uncertainties.

Preliminary results of the ranking of safety enhancement features for the 1170-MW(t) HTGR indicate that the following modifications offer the most promise: (1) capability for main loop rundown, (2) natural circulation core auxiliary cooling, and (3) PCRV blowdown capability through the helium purification system to minimize activity release during some core heatups.

2. 2240-MW(t) HTGR-STEAM CYCLE NSS

2.1. SYSTEMS

The systems effort for the 2240-MW(t) HTGR-SC consisted of identifying the potential for reduced NSS cost which could be considered in a revised NSS cost estimate.

The recent NSS designs have had a performance margin added to the design to provide a high probability (85%) of attaining rated thermal output [2240 MW(t)]. In addition, the hot helium temperature at the steam generator inlet has been limited to 686°C (1266°F) because at that time the benefit of higher temperatures was not considered to be worth the increased technical risks.

The potential for reducing NSS costs comes from increasing the core output by increasing core power density, using all of the circulator motor power margin (performance margin) to increase the helium coolant flow rate, and increasing the helium coolant temperature at the steam generator inlet. This corresponds to an increase in core power from 2240 MW(t) to 2440 MW(t), an increase in core power density from 7.1 to 7.7 W/cm³, an increase in helium temperature at the steam generator inlet from 686° to 710°C (1266° to 1310°F), and a decrease in the probability of attaining rated output from 85% to 50%. This can be accomplished without a substantial increase in plant capital costs. The overall result is a 7.5% reduction of plant capital cost in \$/kW(e) and somewhat higher, but acceptable, risks associated with attaining warranted output (50% probability) and with higher core power density and higher steam generator helium inlet temperature.

2.2. STRUCTURES

Through layout and materials optimizations, the PCRV diameter was reduced from 106 ft 0 in. to 102 ft 0 in. and the height was reduced from 95 ft 8 in. to 95 ft 0 in. by incorporating the following new design features:

1. Use of 55.2 MPa (8000 psi) concrete instead of 44.85 MPa (6500 psi) concrete.
2. Use of 13.34 MN (3000 kip) tendons instead of 11.02 MN (2478 kip) tendons.

The resulting PCRV layout is illustrated in Fig. 2-1.

2.3. HEAT EXCHANGERS

Thermal sizing of a "bayonet tube" core auxiliary heat exchanger (CAHE) was completed, and a general arrangement drawing for the design and cost report was issued (see Fig. 2-2).

2.4. BOP INTERFACE

Balance of plant system costs for the 2240-MW(t) HTGR-SC, produced by United Engineers and Constructors (UE&C), were reviewed and potential cost reduction areas were identified. This effort was accomplished by compiling a cost comparison summary for UE&C 2240-MW(t) and 3360-MW(t) plant data (see Table 2-1). For the BOP systems compared in Table 2-1, it is concluded that the UE&C costs were consistent with each other; that is, the 2240-MW(t) costs are lower by an amount which by judgment appears reasonable because of the reduced plant size. The exception to this is the higher costs for the fuel storage cooling water system, which can be explained by the larger storage capacity required in the 2240-MW(t) plant design.

Fig. 2-1. PCRv general arrangement, optimized four-loop plant

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TABLE 2-1
COST COMPARISON OF BOP SYSTEMS FOR 2240-MW(t)
AND 3360-MW(t) HTGR-SC (UE&C DATA) (a)

BOP System No.	System Description	3360-MW(t) Cost (\$ Jan. '77) (x 10 ⁶)	3300-MW(t) Cost (\$ July '77) (x 10 ⁶)	2240-MW(t) Cost (\$ July '77) (x 10 ⁶)
26	Condensing system without cooling tower and HR bypass	10.736	13.037	9.283
27	Feedwater system and treatment	12.050	14.689	11.153
41	Circulating water system	3.633	4.429	3.245
	Circulating water cooling tower	8.198	9.993	6.988
42	Service water system	0.854	1.041	0.820
43	Thermal barrier cooling water system	0.940	1.146	0.966
44	Domestic water system	0.147	0.179	0.160
45	Fire protection system	2.972	3.623	3.210
46	Reactor plant cooling water system	4.652	5.671	4.268
47	Core auxiliary cooling water system	8.023	9.780	5.775
	Nuclear service cooling water system	2.235	2.724	2.433
	Fuel storage cooling water system	0.380	0.465	0.830
52	Main steam system without (TR + HR)	9.590	11.690	8.439

(a) Cost escalation used: 7% for 1977, 8.5% for 1978, and 5% for January 1979 to July 1979.

For the steam turbine UE&C selected a twin TC4F 31-in. unit designed by Utility Power Corporation. Information on heat balances supplied by Utility Power Corporation indicates a TC6F 30-in. machine may be a better selection since it would provide an output 20-MW(e) greater than the one specified by UE&C.

In the BOP structures account, the results of the cost comparison using the 3360-MW(t) HTGR as the basis are as follows:

1. Reactor Service Building: Little cost change.
2. CAD Building: Significant increase due to location of building for cable routing and redesign of combined HVAC requirements.
3. Piping Vault/Annulus Building: Increase due to relocation of radioactive waste, pumps, and heat exchangers from the ultimate heat sink (UHS) structures.
4. Fuel Storage Building: Significant increase to to Gas-Cooled Reactor Associates (GCRA) 2.5 core storage requirement.
5. Radioactive Waste System: Significant increase primarily due to adoption by UE&C of light water reactor (LWR) approach in equipment and experience.

3. 3360-MW(t) HTGR-STEAM CYCLE NSS

3.1. SYSTEMS

The systems effort for the 3360-MW(t) HTGR-SC was focused on support for the plant capital-cost estimating effort. This support consisted of defining a 3360-MW(t) plant which is consistent with the 2240-MW(t) HTGR-SC design, i.e., no reheat, electric-driven circulators, and 85% probability of attaining rated thermal output without exceeding a plant operating limitation.

The NSS system components are the same for both plants except for those that scale with thermal power. The higher thermal output for the larger plant is accommodated by increasing the number of primary coolant loops from four to six. The BOP is the same for both plants, but it is scaled up in accordance with NSS thermal output.

Table 3-1 shows the rated plant performance parameters which characterize both the 2240-MW(t) and the 3360-MW(t) HTGR-SC plants. The overall effort is documented in Issue 2 of the Plant Technical Description.

3.2. STRUCTURES

3.2.1. PCRV and Liners

A study was performed to investigate the impact on the PCRV and its associated liners and penetrations of incorporating the 2240-MW(t) plant steam generator components (no gas reheat) using the side-fed feedwater penetrations. A six-loop conceptual PCRV/liner general arrangement drawing (Fig. 3-1) was prepared to incorporate the 2240-MW(t) plant steam generator for a cost comparison study. The PCRV size was increased from 111 ft 6 in.

TABLE 3-1
PERFORMANCE PARAMETERS FOR 2240-MW(t) AND 3360-MW(t) HTGR-SC PLANTS

	2240-MW(t) Plant	3360-MW(t) Plant
Primary Coolant System Data		
Number of primary coolant loops/CACS loops	4/3	6/3
Reactor power, MW(t)	2240	3360
Total heat losses from NSS heat transfer system, MW(t)	10.8	13.49
Standby parasitic CACS heat loss, MW(t)	2.16	2.16
Loss to liner cooling system, MW(t)	6.59	8.42
Miscellaneous heat losses, MW (t)	2.04	2.91
Thermal power to NSS from other sources, circulator power, MW(t)	30.8	46.3
NSS thermal power, MW(t)	2260	3393
Generator terminal power, MW(e)	933	1399
Station auxiliary power, MW(e)		
Power to helium circulator motor (and controller)	35.0	52.6
Other auxiliary power	21.3	29.9
Nominal electrical output (net), MW(e)	877	1316
Plant efficiency, %	39.13	39.17
Helium inventory (total), kg (lb)	13,381 (29,500)	19,050 (42,000)
Helium inventory (circulating), kg (lb)	8936 (19,700)	(later)
Helium flow rate, kg/s (lb/hr)	1172 (9,301,300)	1759 (13,961,200)
Helium pressure at circulator discharge, MPa (psia)	7.24 (1050)	7.24 (1050)
Total primary circuit ΔP , kPa (psi)	116.0 (16.83)	116.2 (16.85)
Reactor core, core support block, and orifice ΔP , kPa (psi)	51.1 (7.41)	51.0 (7.40)
Steam generator ΔP , kPa (psi)	51.2 (7.4)	51.2 (7.41)
Core inlet gas temperature, °C (°F)	318 (605)	318 (605)
Steam generator inlet gas temperature, °C (°F)	686 (1266)	686 (1266)
Circulator inlet gas temperature, °C (°F)	313 (596)	313 (596)
Core power density, MW/m ³	7.15	7.15
Circulator motor power margin, %	8.7	8.7
Secondary Coolant System Data		
Steam generator power, MW(t)	2260	3393
Steam flow through steam generators, kg/s (lb/hr)	925 (7,344,900)	1389 (11,022,000)
Back pressure, in. Hg	2.5	2.5
Steam generator outlet steam temperature/pressure, °C/MPa (°F/psia)	541/17.34 (1005/2515)	541/17.34 (1005/2515)
Final feedwater temperature/pressure, °C/MPa (°F/psia)	221/20.4 (430/2963)	221/20.4 (430/2964)
Main stream pipe ΔP , kPa (psi)	689.5 (100)	689.5 (100)
Number of stages of feedwater heating	6	6
Turbine	CC-4F38	CC6F-38

Fig. 3-1. PCR/V general arrangement,
six-loop plant (sheet 1 of
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in diameter by 89 ft 0 in. high to 121 ft 0 in diameter by 102 ft 0 in. high. The increase in PCRV size was due to higher maximum cavity pressure and larger steam generator components. The use of 55.2 MPa (8000 psi) concrete and 13.34 MN (3000 kip) tendons was not incorporated in this study.

3.2.2. Thermal Barrier

Based on the PCRV general arrangement drawing shown in Fig. 3-1, thermal barrier layout drawings were prepared with sufficient information on surface areas of various zones and component quantities and sizes for cost estimating purposes (see Fig. 3-2).

3.3. HEAT EXCHANGERS

Thermal sizing of a bayonet tube CAHE was completed, and a general arrangement drawing for the design and cost report was issued (see Fig. 3-3).

The 560-MW(t) Mark IVA steam generator proposed for the 2240-MW(t) plant was reviewed for its applicability to the 3360-MW(t) plant. The following observations were made which should form the basis for additional 3360-MW(t) plant heat exchanger studies.

If the PCRV is to be optimized and therefore its height varied with core height, then the 560-MW(t) Mark IVA steam generator may have to be stretched vertically to fit the increased PCRV height. This would result in new performance sizing and seismic capability reviews.

3.4. BOP INTERFACE

Layouts of the plant general arrangement and turbine building were prepared for a six-loop 3360-MW(t) HTGR-SC featuring a non-reheat steam generator and motor-driven helium circulators (see Fig. 3-4). This

arrangement is based on the 2240-MW(t) arrangement for location and function of NSS structures. Ten-year fuel storage (approximately 50% larger in volume) was incorporated to be comparable to the 2240-MW(t) plant. The UHS and main circulator controller structures were increased by 50% over the 2240-MW(t) plant.

For the size and layout of the 3360-MW(t) turbine building (Fig. 3-5), use of two TC6F turbines, located in a common structure with each turbine serviced by its own crane, was assumed. Optimization of the turbine building may reduce cost.

3.5. NSS CAPITAL COST SCALING FACTOR

Comparison of the 2240-MW(t) and 3360-MW(t) NSS cost estimates prepared on identical bases shows a 0.6 scaling factor which is more favorable in scaling to smaller-sized plants than the 0.5 factor previously projected.

Fig. 3-2. Thermal barrier general arrangement, six-loop plant (sheet 1 of 3)

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Fig. 3-2. Thermal barrier general arrangement, six-loop plant (sheet 2 of 3)

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Fig. 3-3. Bottom-fed bayonet CAHE,
3360-MW(t) plant (sheet
1 of 2)

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Fig. 3-4. 3360-MW(t) HTGR-SC general arrangement

Fig. 3-5. Turbine size estimate for 3360-MW(t) plant (two turbines side by side as shown)

4. HTGR SAFETY

4.1. 2240-MW(t) HTGR-STEAM CYCLE [900 MW(e)] PROBABILISTIC RISK EVALUATION

In this study, the Accident Initiation and Progression Analysis (AIPA) Phase II results for the reference 1975 1160-MW(e) HTGR-SC plant are adjusted to reflect the unique design features of the 900-MW(e) HTGR-SC plant. First, the plant design differences are noted, and this information is used to construct a total loss of main loop cooling (LMLC) fault tree. The similarities between the two plants allows the loss of main loop cooling and loss of offsite power (LOSP) event trees to be used for the 900-MW(e) plant without restructuring. However, the event tree branch point probabilities are re-evaluated to reflect the plant design features. Core heatup consequence assessments for the 900-MW(e) plant are conducted using the simplified models developed for the 1160-MW(e) plant uncertainty analysis, appropriately modified to account for plant design differences.

The 900-MW(e) plant overall risk curve (Fig. 4-1) slightly exceeds the 1160-MW(e) plant curve at all meaningful frequencies. The presence of electrically driven circulators is not a major factor in the plant risk differences for the accident sequences examined. The risk benefits of eliminating the reheaters are negated by the projected increase in core heatup frequency (factor of 2) as a result of BOP changes. The increase in core heatup frequency is a direct result of eliminating the capability of the boiler feedpump to operate with atmospheric backpressure, which eliminates capability for main loop rundown. The progression of postulated core heatup accidents is similar to those determined in AIPA Phase II. The use of flapper valves rather than actuatable ring valves for main helium shutoff leads to decreased PCRV plateout in the more probable core heatup sequences and a resulting increase in consequences.

Fig. 4-1. Comparison of risk assessment curves for 1160- and 900-MW(e) HTGR-SC plants

The conclusion from this study is that the 900-MW(e) plant risk to the public is comparable to that assessed for the 1160-MW(e) plant for the initiating events examined. Slightly greater risks are assessed for the 900-MW(e) plant, but the differences are within the uncertainty of the calculations.

4.2. ENHANCED SAFETY FEATURES FOR AN 1170-MW(t) HTGR PLANT

This study utilizes probabilistic risk assessment (PRA) methodology to quantitatively rank proposed design modifications that would reduce public risk. The objective is to produce a quantitative ranking which could be input to the design.

Although the enhanced safety study is not yet completed, an indication can be given at this time regarding several promising design modifications that are under consideration for the 1170-MW(t) plant. The following three plant modifications appear to have promise:

1. Main loop rundown by, for example, improved feedwater pump turbines.
2. Natural circulation core auxiliary cooling.
3. PCRV blowdown capability.

The use of improved feedwater pump turbines is a relatively simple design change that has previously been employed, or other approaches may also be desirable to achieve a high reliability for main loop rundown.

Natural circulation of helium through an auxiliary loop offers the potential not only for reduced risk to the public but also for reduced investment risk to the utility, an important factor highlighted by the Three Mile Island event. Five different 1170-MW(t) HTGR-SC designs were analyzed from the perspective of using natural circulation to reduce core heatup frequencies. The results are summarized in Table 4-1. Although this table is predicated upon scoping calculations, it indicates that to achieve significant core heatup frequency reductions by natural circulation only, a design

TABLE 4-1
SUMMARY OF NATURAL CIRCULATION ANALYSIS

HTGR-SC Design	Flow Type	Start Method	CACWS(a) Circulation	Improvement Factor; ^(b) G
1	Downflow with shared auxiliary loops	Jet pump	Forced	2-
2	Upflow with shared main loops	Passive	N/A	1+
3	Upflow with shared auxiliary loops	Passive	Natural	2-
4	Upflow with one dedicated loop	Passive	Natural	4 to 9
5	Downflow with one dedicated loop	Jet pump	Natural	3 to 6

(a) Core auxiliary cooling water system.

(b) Improvement factors are defined as the ratio of the core heatup frequency for the base plant divided by the core heatup frequency for the plant with natural circulation capability.

incorporating auxiliary cooling loops dedicated to natural circulation is advantageous. This conclusion is based solely upon the extent that the frequencies are reduced and does not include cost, licensing, or related considerations.

The capability for an intentional PCRV blowdown following a loss of control is a feature of the Fort St. Vrain plant which would minimize activity released from the PCRV during some core heatups. The impact on development and licensing costs still needs to be considered.

As the study continues, these and other enhanced features will be assessed and ranked according to their risk reduction for the larger 900-MW(e) plant. It is anticipated that for the larger plant size, other design features, such as enhanced liner cooling and thermal radiation roles, will become important in limiting the consequences and uncertainties associated with core heatup events.

5. 1170-MW(t) HTGR-PROCESS STEAM/COGENERATION NSS

5.1. SYSTEMS

The NSS for the 1170-MW(t) HTGR-PS/C was updated to reflect the latest configuration criteria. These criteria are as follows:

1. PCRV sized for in-vessel refueling scheme.
2. Fuel block design changed from 8 row to 10 row.
3. Concrete strength changed from 45 to 55 MPa (6500 to 8000 psi).
4. CAHE changed from long configuration to short configuration.
5. Core power density changed from 7.1 to 6.6 W/cm³.

Tables 5-1 and 5-2 give the resulting NSS performance parameters. The details are documented in Issue 4 of the Technical Description.

5.2. STRUCTURES

5.2.1. PCRV and Liners

A two-loop PCRV/liner general arrangement for a PCRV 87 ft 6 in. in diameter by 93 ft 0 in. high was prepared using the 2240-MW(t) plant steam generator and CAHE components. The maximum cavity pressure used in the design was 7.69 MPa (7.14 MPa operating) [1130 psig (1050 psig operating)]. The PCRV size was subsequently optimized by increasing the concrete strength and the prestressing tendon capacity. The PCRV size was reduced to 82 ft 0 in. in diameter by 92 ft 0 in. high (see Fig. 5-1) with the implementation of the following cost reduction features:

1. Use of 55.1-MPa (8000-psi) instead of 44.8-MPa (6500-psi) PCRV concrete.

TABLE 5-1
PRIMARY COOLANT SYSTEM DATA FOR 1170-MW(t) HTGR-PS/C

Number of primary coolant loops/CACS loops	2/3
Reactor power, MW(t)	1170
Total heat losses from NSS heat transfer system, MW(t)	8.25
Standby parasitic CACS heat loss, MW(t)	2.28
Loss to liner cooling system, MW(t)	4.34
Miscellaneous heat losses, MW(t)	1.63
Thermal power to NSS from other sources (circulator power), MW(t)	20.85
NSS thermal power, MW(t)	1183
NSS efficiency, %	99.3
Helium inventory (total), kg (lb)	7861 (17,340)
Helium inventory (circulating), kg (lb)	5789 (12,770)
Helium flow rate, kg/s (lb/hr)	615.3 (4,886,500)
Helium pressure at circulator discharge, MPa (psia)	7.24 (1050)
Total primary circuit ΔP , kPa (psi)	149.7 (21.7)
Reactor core, core support block, and orifice ΔP , kPa (psi)	78.0 (11.3)
Steam generator ΔP , kPa (psi)	55.9 (8.1)
Core inlet gas temperature, °C (°F)	321.7 (611)
Steam generator inlet gas temperature, °C (°F)	685.6 (1266)
Circulator inlet gas temperature, °C (°F)	316.1 (601)
Core power density, MW/m ³	6.6

TABLE 5-2
SECONDARY COOLANT SYSTEM DATA FOR 1170-MW(t) HTGR-PS/C

NSS thermal power, MW(t)	1182
Steam flow through steam generators, kg/s (lb/hr)	483.9 (3,842,800)
Steam generator outlet temperature/pressure, °C/MPa (°F/psia)	540.6/17.34 (1005/2515)
Feedwater temperature/pressure steam generator inlet, °C/MPa (°F/psia)	221.1/20.41 (430/2959)

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2. Use of 13.3-MN (3000-kip) instead of 11.02-MN (2478-kip) strand tendons for the linear prestressing system.
3. The new "in-vessel refueling" scheme.
4. A side exhaust short bayonet CAHE.

5.2.2. Thermal Barrier

A thermal barrier component arrangement and general layout based on the PCRV drawing shown in Fig. 5-1 was prepared. The surface areas for the various zones were generated and shown on the drawing (see Fig. 5-2). Multiple attachment coverplates were used in the preparation of these quantities.

As a result of subsequent PCRV size optimization, the thermal barrier drawing (Fig 5-2) was revised and a second issue was released. The new issue incorporated the use of single attachment fixtures instead of the multiple attachment coverplates. The in-vessel refueling in the upper plenum of the core cavity and the side exhaust bayonet CAHE were also included in the revision, and the areas and quantities were suitably adjusted.

5.3. HEAT EXCHANGERS

Thermal sizing of a bayonet tube CAHE was completed, and a general arrangement drawing for the design and cost report was issued (see Fig. 5-3).

Further optimization of the bayonet tube CAHE resulted in a smaller, less costly "compact bayonet tube" concept. This compact version was adopted for the 1170-MW(t) plant to obtain cost reduction and to provide a design basis consistent with the GCRA/GA HTGR Application Study. Thermal

sizing of this CAHE was completed, and a general arrangement drawing was issued (see Fig. 5-4).

The 560-MW(t) Mark IVA steam generator proposed for the 2240-MW(t) plant was reviewed for its applicability to the 1170-MW(t) plant. The following observations were made which should form the basis for additional 1170-MW(t) plant heat exchanger studies:

1. The 1170-MW(t) plant requires two 590-MW(t) steam generators as compared with the four 560-MW(t) units required for the 2240-MW(t) plant. Some adjustment in heat transfer surface area, helium and steam/water flow rate, or reliability will have to be made.
2. Increased helium flow velocity in the helical bundle may result in reducing maximum tube unsupported span lengths. This would be done to ensure that there is no possibility of unacceptable flow-induced vibration of the tubing.
3. Increased helium flow velocity will result in higher tube metal temperatures. Stress analysis of the tubing is required to ascertain the effect of the increased temperatures.
4. Increase in helium flow velocity may change the frequency of the acoustic wave in the diametrical mode and the frequency of vortex shedding from the tube bundle. A re-evaluation of these frequencies is required to ensure that acoustic resonance does not occur in the steam generator.

Fig. 5-2. Thermal barrier general arrangement, two-loop plant (sheet 1 of 5)

Fig. 5-2. Thermal barrier general arrangement, two-loop plant (sheet 2 of 5)

Fig. 5-2. Thermal barrier general arrangement, two-loop plant (sheet 3 of 5)

Fig. 5-2. Thermal barrier general arrangement, two-loop plant (sheet 5 of 5)

Fig. 5-3. Bottom-fed bayonet CAHE, 1170-MW(t) plant (sheet 1 of 2)

Fig. 5-4. General assembly arrangement, bayonet CAHE

6. PROCESS STEAM/COGENERATION APPLICATIONS

Work done to date includes development of a data base of processes, NSS-process plant integration, licensability studies, and economic evaluations. In situ oil recovery, coal liquefaction and gasification, chemical plant, and metal industry processes considered for application of the 1170-MW(t) HTGR-PS/C are listed below:

1. Existing Process Plants

- a. Petrochemical plant at Geismar, Louisiana.
- b. Petrochemical plant at Orange, Texas.
- c. Petrochemical plant at Port Arthur Refinery, Texas.
- d. Steel mill proposed at Lake Front near Pennsylvania/Ohio border.
- e. Alumina mill proposed in Louisiana.

2. Enhanced Oil Recovery (EOR) Projects

- a. Heavy oil recovery in California, Arkansas, Louisiana, and Texas in the U.S., Canada, and Venezuela.
- b. Oil sands in the U.S., Canada, and Venezuela.
- c. Oil shale in situ retorting in Colorado in the U.S.

3. Synthetic Fuel Projects

- a. Exxon Catalytic Coal Gasification project.
- b. Solvent Recovery from Coal (SRC II).
- c. Syncrude Oil from Coal (H-Coal).
- d. Slagging Lurgi synfuel process.

6.1. PROCESS DATA BASE EVALUATION

Data on the capacity or size of process plants, the process thermal and electric energy requirements, utility requirements provided by the HTGR-PS/C, and the number of 1170-MW(t) HTGR-PS/C units that could be used in each application are shown in Table 6-1. The evaluation to date indicates that the HTGR-PS/C could adequately provide the process steam and electric energy requirements in almost all of the applications specified. However, in a few instances, a situation could occur wherein a process waste fuel or product energy, such as product gas or fuel oil equivalent, might be required to be used in the plant utility rather than used alternatively based on economics or low heating value characteristics. Oil sands and oil shale in situ recovery projects and petrochemical plants are cases for such a possibility. In a few applications it is also possible that some special equipment or processes, such as fired heaters, would require energy at elevated temperatures [$>538^{\circ}\text{C}$ ($>1000^{\circ}\text{F}$)] which could not be provided by the HTGR-PS/C. In such cases partial use of fossil-fuel-fired systems will be necessary to provide the required high-temperature energy. Refineries, petrochemical complexes, coal gasification plants, and chemical plants, in general, have a small fraction of such high-temperature energy requirement, and a possibility of the same exists in some of the EOR crude upgrading processes.

6.2. PLANT INTEGRATION

For each process a balance-of-steam plant was conceptualized. In all cases, the HTGR-PS/C NSS was assumed to operate at a rated output of

TABLE 6-1
HTGR-S/C APPLICATIONS DATA BASE

No.	Process	Plant Size	Utility Requirements ^(a) (MW)	Utility Requirements Met By HTGR-PS/C ^(a) (MW)	Percent Energy Supplied by HTGR-PS/C [(met/req'd) x 100]	No. of HTGR-PS/C Units
1	Heavy oil in situ steam drive (Fig. 6-9(b))	35,000 B/D	<u>Steam</u> • Injection steam 644 to 853 P = 3.45 (500) T = 247 (467) • Dewatering 140 P = 0.69 (100) T = 164 (328) • Water treatment plant Later <u>Electric</u> 1 Total 785 to 894	<u>Steam</u> • Injection steam 664 to 853 P = 3.45 (500) T = 247 (467) • Dewatering 140 P = 0.69 (100) T = 164 (328) • Water treatment Later <u>Electric</u> 1 Total 785 to 995 Other uses (electric) (losses) 158 (18)	<u>Steam</u> • Injection steam 100 • Dewatering 100 • Water treatment Later <u>Electric</u> 100 Total 100	One 1170 MW(t)
2	Oil Sands in situ steam drive	160,000 B/D (bitumen)	<u>Steam</u> • Injection steam 3112 P = 13.79 (2000) T = 336 (636) • Steam for upgrading 266 P = 6.21 (900) T = 278 (532) • Water treatment 76 P = 6.21 (900) T = 278 (532) • Auxiliaries 349 P = 6.21 (900) T = 278 (532) <u>Electric</u> 288 Total 4091	<u>Steam^(c)</u> • Injection 3112 P = 13.79 (2000) T = 336 (636) • Upgrading 266 P = 6.21 (900) T = 278 (532) • Water treatment 76 P = 6.21 (900) T = 278 (532) • Auxiliaries 349 P = 6.21 (900) T = 278 (532) <u>Electric</u> 288 Total 4091 Other uses (electric) (losses) 164 (425)	<u>Steam</u> • Steam (all uses) 100* * Assumed that in all processes limiting steam temperature will be $\leq 538^{\circ}\text{C}$ ($\leq 1000^{\circ}\text{F}$) (To be ascertained when process flow diagram is available) <u>Electric</u> 100 Total 100	Four 1170 MW(t)

TABLE 6-1 (Continued)

No.	Process	Plant Size	Utility Requirements ^(a) (MW)	Utility Requirements Met By HTGR-PS/C ^(a) (MW)	Percent Energy Supplied by HTGR-PS/C [(met/req'd) x 100]	No. of HTGR-PS/C Units
3	Oil shale	32,600 B/D	<u>Steam</u> • Injection steam 1090 P = 10.34 (1500) T = 538 (1000) (approx.) • Upgrading Later • Water treatment Later <u>Electric</u> Later Total 1090	<u>Steam</u> • Injection steam 1090 P = 10.34 (1500) T = 510 (950) • Upgrading Later • Water treatment Later <u>Electric</u> Later Total 1090 Other uses (electric) 64 (losses) (16)	<u>Steam</u> • Injection steam 100 ^(d) • Upgrading Later • Water treatment Later <u>Electric</u> Later Total 100	One 1170 MW(t)
4	Petrochemical complex at Geismar, Louisiana (Fig. 6-1)	3510 MW(t)	<u>Steam</u> • Process 162 P = 1.99 (290) T = 265 (509) • Process 1908 P = 4.76 (690) T = 360 (680) • Process 144 P = 6.69 (970) T = 408 (767) <u>Electric</u> 348 Total 2562	<u>Steam</u> • Process 162 P = 1.99 (290) T = 265 (509) • Process 1908 P = 4.76 (690) T = 360 (680) • Process 144 P = 6.69 (970) T = 408 (767) <u>Electric</u> 348 Total 2562 Other uses (electric) 354 (losses) (594)	<u>Steam</u> • Process 100 P = 1.99 (290) T = 265 (509) • Process 100 P = 4.76 (690) T = 360 (680) • Process 100 P = 6.69 (970) T = 408 (767) <u>Electric</u> 100 Total 100	Three 1170 MW(t)

TABLE 6-1 (Continued)

No.	Process	Plant Size	Utility Requirements ^(a) (MW)	Utility Requirements Met By HTGR-PS/C ^(a) (MW)	Percent Energy Supplied by HTGR-PS/C [(met/req'd) x 100]	No. of HTGR-PS/C Units
5	Petrochemical complex at Orange, Texas (Fig. 6-3)	1170 MW(t)	<u>Steam</u> • Process 547 P = 4.41 (640) T = 351 (663) • Process 269 P = 1.99 (290) T = 264 (507) <u>Electric</u> 215 Total 1031	<u>Steam</u> • Process 547 P = 4.41 (640) T = 351 (663) • Process 269 P = 1.99 (290) T = 264 (507) <u>Electric</u> 215 Total 1031 Other uses (electric) 4 (losses) (135)	<u>Steam</u> • Process 100 P = 4.41 (640) T = 351 (663) • Process 100 P = 1.99 (290) T = 264 (507) <u>Electric</u> 100 Total 100	One 1170 MW(t)
6	Refinery/ petrochemical complex at Port Arthur, Texas	390,000 B/SD	<u>Steam</u> • Process 348 P = 9.52 (1380) T = 452 (845) • Process 1157 P = 4.79 (695) T = 353 (685) • Process 425 P = 1.59 (230) T = 248 (479) • Fired heater 448 <u>Electric</u> 111 Total 2489	<u>Steam</u> • Process 348 P = 9.52 (1380) T = 452 (845) • Process 1157 P = 4.79 (695) T = 363 (685) • Process 425 P = 1.59 (230) T = 248 (479) • Fired heater 0(e) <u>Electric</u> 111 Total 2041 Other uses (electric) 217 (losses) (83)	<u>Steam</u> • Process 100 P = 9.52 (1380) T = 452 (845) • Process 100 P = 4.79 (695) T = 363 (685) • Process 100 P = 1.59 (230) T = 248 (479) • Fired heater 0 <u>Electric</u> 100 Total 82	Two 1170 MW(t)

TABLE 6-1 (Continued)

No.	Process	Plant Size	Utility Requirements ^(a) (MW)	Utility Requirements Met By HTGR-PS/C ^(a) (MW)	Percent Energy Supplied by HTGR-PS/C [(met/req'd) x 100]	No. of HTGR-PS/C Units
7	Steel mill, (Lake Front, at the border of Ohio and Pennsylvania)	7.2 x 10 ⁶ T(LIQ)/yr	<u>Steam</u> • Process 296 P = 4.99 (725) T = 365 (689) <u>Electric</u> 240 Total 536	<u>Steam</u> • Process 296 P = 4.99 (725) T = 365 (689) <u>Electric</u> 240 Total 536 Other uses (electric) (losses) (239)	<u>Steam</u> • Process 100 P = 4.99 (725) T = 365 (689) <u>Electric</u> 100 Total 100	One 1170 MW(t)
8	Alumina mill, Louisiana (Fig. 6-15)	800,000 ST/yr	<u>Steam</u> • Process 317 P = 5.45 (790) T = 381 (718) <u>Electric</u> 94 Total 411	<u>Steam</u> • Process 317 P = 5.45 (790) T = 381 (718) <u>Electric</u> 94 Total 411 Other uses (electric) (losses) (526)	<u>Steam</u> • Process 100 P = 5.45 (790) T = 381 (718) <u>Electric</u> 100 Total 100	One 1170 MW(t)
9	SRC II (solvent refined coal Mod II, Gulf Oil) (modified)	26,800 ST/day	<u>Steam</u> • Slurry heater 476 P = 16.65 (2415) T = 538 (1000) • Superheaters 83 P = 16.65 (2415) T = 538 (1000) • Steam to process 280 P = 10.45 (1515) T = 513 (956) • Steam to process 148 P = 4.59 (665) T = 258 (497) <u>Electric</u> 122 Total 1109	<u>Steam</u> • Slurry heater 476 P = 16.65 (2415) T = 538 (1000) • Superheaters 83 P = 16.65 (2415) T = 538 (1000) • Steam to process 280 P = 10.45 (1515) T = 513 (956) • Steam to process 148 P = 4.59 (665) T = 258 (497) <u>Electric</u> 84 ^(f) Total 1071 (losses) (99)	<u>Steam</u> • Slurry heater 100 P = 16.65 (2415) T = 538 (1000) • Superheaters 100 P = 16.65 (2415) T = 538 (1000) • Steam to process 100 P = 10.45 (1515) T = 513 (956) • Steam to process 100 P = 4.59 (665) T = 258 (497) <u>Electric</u> 69 Total 966	One 1170 MW(t)

(a) P = pressure, MPa (psia); T = temperature, °C (°F).

(b) Figures are flow cycle diagrams included in Section 6.2.

(c) The process produces three forms of by-product energy, and their energy contents are:

1. Coke: 31 MW(t)
2. Fuel oil Eq (FOE): 1019 MW(t)
3. Gas: 128 MW(t)

(A) If coke should be used in utility to raise steam, HTGR-PS/C will supply 99.18% of required steam.

(B) As in (A) + FOE, HTGR-PS/C supplies 72.4% of required steam.

(C) As in (B) + gas, HTGR-PS/C supplies 69.02% of required steam.

(D) This amount of energy is envisioned for the Cold Lake commercial project.

(d) One of the by-products of the process is low-grade gas, having an energy equivalent of 42 MW(t); if this is used for generating steam, energy supplied by HTGR-PS/C $\approx$ 96%.

(e) A combination of waste fuel and energy at high temperature [$>538^{\circ}\text{C}$ ($>1000^{\circ}\text{F}$)] precludes energy from HTGR-PS/C for fired heaters.

(f) It is possible to generate the additional 36 MW(e) by increasing the reactor power from 1170 MW(t); otherwise an alternate source has to be found for this additional power requirement.

1170 MW(t). In this concept feedwater is supplied to the steam generators at 20.79 MPa (3015 psia) and 221.1°C (430°F), and the product steam conditions for each NSS are 484.1 kg/s (3,833,900 lb/hr) at 16.65 MPa (2415 psia) and 537.8°C (1000°F).

Information from the process plant data base (Section 6.1) provided the requirements for electrical power and process steam. Depending upon the required steam pressure and temperature, process steam was expanded through a turbine to the required pressure or throttled from the main steam. In several cases, a desuperheater was employed to reduce the temperature to meet process requirements. In all cases, an extraction turbine, either condensing or non-condensing, was used to provide steam for the feedwater heating train.

6.2.1. Petrochemical Plant at Geismar, Louisiana

1. Three 1170-MW(t) HTGR-PS/C units supplied process steam through expansion turbines at three pressure levels and produced cogenerated electric power. In this case, the process steam was that specified in the data base and any excess power was used to produce electric power. (See Fig. 6-1.)
2. Same as application 1, except that the production of process steam was maximized. (See Fig. 6-2.)

6.2.2. Petrochemical Plant at Orange, Texas

1. A single 1170-MW(t) HTGR-PS/C supplied the prescribed process steam flows through expansion turbines and produced cogenerated electric power. Excess energy was used to produce electric power. (See Fig. 6-3.)

Fig. 6-1. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for Geismar, Louisiana petrochemical complex application with condensing cycle

ALLOCATION OF REACTOR POWER OUTPUT		MW	%
PROCESS USES			
ELECTRIC POWER		348.0	9.9
STEAM POWER TO PROCESS		2214.2	63.1
SUBTOTAL		2562.2	73.0
OTHER USES			
ELECTRIC POWER		150.6	4.3
STEAM POWER		752.5	21.4
LOSSES		44.7	1.3
TOTAL REACTOR POWER OUTPUT		3510	100

LEGEND

W = FLOW KG/S (10⁶ LB/HR)
P = PRESSURE MPa (PSIA)
T = TEMPERATURE °C (°F)

Fig. 6-2. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for Geismar, Louisiana petrochemical complex application (maximum process steam)

ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	214.5	18.3
STEAM POWER TO PROCESS	816.0	69.8
SUBTOTAL	1030.5	88.1
OTHER USES		
ELECTRIC POWER	3.6	0.3
LOSSES		
CONDENSER	120.1	10.3
OTHER	15.8	1.3
TOTAL REACTOR POWER OUTPUT	1170	100

LEGEND

W = FLOW KG/S (10^6 LB/HR)
P = PRESSURE MPa (PSIA)
T = TEMPERATURE °C (°F)

Fig. 6-3. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for Orange, Texas petrochemical complex application with condensing cycle

6.2.3. Recovery from Oil Sands

1. An 1170-MW(t) HTGR-PS/C supplied steam to a non-condensing turbine-generator with the exhaust steam cooled and condensed in a reboiler, which in turn supplied saturated steam for oil recovery. The condensate from the reboiler was heated by a portion of the turbine exhaust steam before returning to the HTGR steam generators. (See Fig. 6-4.)
2. Same as application 1, except that the steam extracted for condensate heating was expanded through another non-condensing turbine-generator before reaching the feedwater heater. Steam to the process was reduced 2.6%, but cogenerated electric power increased 25,700 kW (26.1%).
3. In this application, the reboiler was eliminated and saturated process steam was provided directly from the turbine exhaust through a desuperheater. A low-pressure, non-condensing, extraction turbine was used to heat the condensate and makeup returned from the oil fields. The flow of process steam was reduced from application 1 by 8.2%, but the cogenerated electric power was increased 120%. (See Fig. 6-5.)

6.2.4. Exxon Catalytic Coal Gasification Process

1. An 1170-MW(t) HTGR-PS/C was used to cogenerate electric power and to supply process steam at two pressure levels plus heat for an air preheater. High-pressure turbine exhaust steam provided one process flow, while the other process steam at a lower pressure was expanded through a mechanical drive turbine. The air preheater was heated by steam extracted from the high-pressure turbine. A low-pressure, non-condensing, extraction turbine-generator was used to heat all condensate to steam generator requirements. (See Fig. 6-6.)

ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	29.0	2.5
STEAM POWER TO PROCESS	1115.4	95.3
SUBTOTAL	1144.4	97.8
LOSSES	25.6	2.2
TOTAL REACTOR POWER OUTPUT	1170	100
ENERGY SUPPLIED BY REACTOR	1144.4	94.3
TOTAL ENERGY REQ'D BY PROCESS	1358	

LEGEND

W = FLOW KG/S (10^6 LB/HR)
P = PRESSURE MPa (PSIA)
T = TEMPERATURE $^{\circ}$ C ($^{\circ}$ F)

Fig. 6-4. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for 46,700 B/SD in situ oil sands recovery project application (with reboilers)

ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	63.8	5.5
STEAM POWER TO PROCESS	1090.4	93.2
SUBTOTAL	1154.2	98.7
LOSSES	15.8	1.3
TOTAL REACTOR POWER OUTPUT	1170	100
ENERGY SUPPLIED BY REACTOR	1154.2	
TOTAL ENERGY REQ'D BY PROCESS	1339.0	86.2

LEGEND

W = FLOW KG/S (10^6 LB/HR)
P = PRESSURE MPa (PSIA)
T = TEMPERATURE °C (°F)

Fig. 6-5. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for 46,000 B/SD in situ oil sands recovery project application

Fig. 6-6. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for 18,000 T/SD Exxon catalytic coal gasification (ECCG) process application

6.2.5. Shale Oil Recovery

1. An 1170-MW(t) HTGR-PS/C supplied high-pressure, high-temperature steam used to extract shale oil. A reboiler for the process steam was heated by main steam from the reactor. A non-condensing, extraction turbine was used for feedwater heating and generation of electric power. (See Fig. 6-7.)

6.2.6. Heavy Oil Recovery

1. An 1170-MW(t) HTGR-PS/C was used to supply high-pressure saturated steam to recover very heavy oil (tar sands). A reboiler heated by main steam was employed, and a non-condensing, extraction turbine-generator provided feedwater heating and cogenerated electric power. (See Fig. 6-8.)
2. Same as application 1, except that the reboiler was eliminated. Main steam was throttled and desuperheated for process use. Essentially the same amount of saturated steam and 120% more cogenerated electric power were produced. (See Fig. 6-9.)

6.2.7. Solvent Recovery of Coal (SRC II)

1. This application was rather complex since six different heat requirements plus electrical power were involved. A single 1170-MW(t) HTGR-PS/C was able to supply all heat requirements through reboilers and heat exchangers and all but 25,000 kW of the electrical load. (See Fig. 6-10.)

6.2.8. Syncrude Oil from Coal

1. In this application, electric power and high-pressure saturated steam were required plus heat for the H-Coal reactor preheater and

ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	18.6	1.6
STEAM POWER TO PROCESS	1119.8	95.7
SUBTOTAL	1119.8	96.3
LOSSES	31.7	2.7
TOTAL REACTOR POWER OUTPUT	1170	100

LEGEND

W = FLOW KG/S (10⁶ LB/HR)
P = PRESSURE MPa (PSIA)
T = TEMPERATURE °C (°F)

Fig. 6-7. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for 32,600 B/SD in situ oil shale recovery project application (with reboilers)

ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	1.0	0.1
STEAM POWER TO PROCESS	1037.9	88.7
SUBTOTAL	1038.9	88.8
OTHER USES		
ELECTRIC POWER	110.3	9.4
LOSSES	20.8	1.8
TOTAL REACTOR POWER OUTPUT	1170	100
ENERGY SUPPLIED BY REACTOR	1038.9	
TOTAL ENERGY REQ'D BY PROCESS	1038.9	100

LEGEND

W = FLOW KG/S (10⁶ LB/HR)
P = PRESSURE MPa (PSIA)
T = TEMPERATURE °C (°F)

Fig. 6-8. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for 36,500 B/SD heavy oil recovery project application (with reboilers)

ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	1.0	0.1
STEAM POWER TO PROCESS	993.4	84.9
SUBTOTAL	994.4	85.0
OTHER USES		
ELECTRIC POWER	156.9	13.4
LOSSES	18.7	1.6
TOTAL REACTOR POWER OUTPUT	1170	100
ENERGY SUPPLIED BY REACTOR	994.4	
TOTAL ENERGY REQ'D BY PROCESS	994.4	100

LEGEND

W = FLOW KG/S (10^6 LB/HR)

P = PRESSURE MPa (PSIA)

T = TEMPERATURE °C (°F)

Fig. 6-9. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for 35,000 B/SD heavy oil recovery project application

ALLOCATION OF REACTOR POWER OUTPUT		MW	%
PROCESS USES			
ELECTRIC POWER		98.8	8.4
STEAM POWER TO PROCESS		138.8	11.9
SLURRY HEATER		476.0	40.7
SUPERHEATERS		279.4	23.9
SUBTOTAL		993.0	84.8
LOSSES			
CONDENSER		161.2	13.8
OTHER		15.8	1.4
TOTAL REACTOR POWER OUTPUT		1170	100

LEGEND

W = FLOW KG/S (10⁶ LB/HR)

P = PRESSURE MPa (PSIA)

T = TEMPERATURE °C (°F)

Fig. 6-10. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for 26,800 T/SD SRC II (coal liquids) process application (with reboilers)

the fluidized bed dryer. A reboiler heated by main steam was used and a condensing, extraction turbine-generator produced power and heated the feedwater. A novel split feedwater train was employed to handle the high- and low-pressure condensate streams. All the heat and steam requirements were supplied, but 71,400 kW of outside electric power was required. (See Fig. 6-11.)

6.2.9. Steel Mill

1. A single 1170-MW(t) HTGR-PS/C was used to supply process steam and electric power to a steel mill. Exhaust steam from the high-pressure turbine was used for the process. Feedwater heating and additional electric power generation were accomplished with a low-pressure, condensing, extraction turbine-generator. All the steel mill steam and electric power requirements were supplied. Excess energy was supplied as additional steam [135 kg/s (1,070,000 lb/hr)] to other users. (See Fig. 6-12.)
2. Same as application 1, except that excess energy was used to generate additional electric power (114,700 kW) for other users. (See Fig. 6-13.)

6.2.10. Alumina Mill

1. A single 1170-MW(t) HTGR-PS/C was used to supply process steam and electric power to an alumina mill. Exhaust steam from the high-pressure turbine was used for the process. Feedwater heating and additional electric power generation were accomplished in a low-pressure, non-condensing, extraction turbine-generator. All the alumina mill steam and electric power requirements were supplied. Excess energy was supplied as additional steam [236 kg/s (1,870,000 lb/hr)] and electric power (44,600 kW) to other users. (See Fig. 6-14.)

ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	179.6	15.4
STEAM POWER TO PROCESS	193.0	16.5
FEED HEATER	427.0	36.5
FLUIDIZED BED DRYER	135.0	11.5
SUBTOTAL	934.6	79.9
LOSSES		
CONDENSER	219.3	18.7
OTHER	16.1	1.4
TOTAL REACTOR POWER OUTPUT	1170	100

W = FLOW KG/S (10⁶ LB/HR)
P = PRESSURE MPa (PSIA)
T = TEMPERATURE °C (°F)

Fig. 6-11. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for 30,000 T/SD H-Coal (coal liquid) process application (with reboilers)

ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	240.0	20.5
STEAM POWER TO PROCESS	295.9	25.3
SUBTOTAL	535.9	45.8
OTHER USES		
STEAM POWER	395.1	33.8
LOSSES		
CONDENSER	216.9	18.5
OTHER	22.1	1.9
TOTAL REACTOR POWER OUTPUT	1170	100

LEGEND

W = FLOW KG/S (10^6 LB/HR)

P = PRESSURE MPa (PSIA)

T = TEMPERATURE °C (°F)

Fig. 6-12. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for 7,200,000 T(LIQ)/yr steel mill application (tailored cogenerated electrical power)

ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	240.0	20.5
STEAM POWER TO PROCESS	295.9	25.3
SUBTOTAL	535.9	45.8
OTHER USES		
ELECTRIC POWER	114.7	9.8
LOSSES		
CONDENSER	492.1	42.1
OTHER	27.3	2.3
TOTAL REACTOR POWER OUTPUT	1170	100

LEGEND

W = FLOW KG/S (10⁶ LB/HR)
P = PRESSURE MPa (PSIA)
T = TEMPERATURE °C (°F)

Fig. 6-13. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for 7,200,000 T(LIQ)/yr steel mill application (maximum cogenerated electrical power)

ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	94.0	8.0
STEAM POWER TO PROCESS	27.1	2.4
SUBTOTAL	121.1	10.4
OTHER USES		
STEAM POWER	59.6	5.2
ELECTRIC POWER	44.6	3.9
LOSSES	17.8	1.5
TOTAL REACTOR POWER OUTPUT	1170	100

W = FLOW KG/S (10⁶ LB/HR)
P = PRESSURE MPa (PSIA)
T = TEMPERATURE °C (°F)

Fig. 6-14. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for 800,000 ST/yr alumina mill application (maximum process steam)

2. Same as application 1, except the low-pressure turbine was condensing and all excess energy was supplied as additional electric power (232,600 kW) to other users. (See Fig. 6-15.)

6.2.11. Multi-Purpose Plant

1. This application was developed as a general case based on typical requirements seen for a range of specific applications. Process steam was supplied from the high-pressure turbine exhaust at 4.48 MPa (650 psia) and 356°C (672°F). Only enough steam was diverted to the low-pressure, non-condensing turbine to heat all feedwater to steam generator requirements. About 345.4 kg/s (2,736,000 lb/hr) of process steam was produced plus 150,000 kW cogenerated electric power. (See Fig. 6-16.)
2. An application similar to application 1, but using a coal-fired boiler, was studied. This cycle produced roughly the same output (steam and electric) at slightly higher input to the boiler. (See Fig. 6-17.)

6.3. LICENSING REQUIREMENTS

Initial work under this task involved collecting and summarizing siting criteria pertinent to nuclear plants located near industrial process plants. With the exception of external industrial hazard considerations, the requirements for cogeneration plants are the same as those for condensing nuclear electric power plants. The inherent safety feature of the HTGR should assist in resolving siting matters. The safety/licensing issues applicable to the SC/electric plant also generally apply for PS/C plants.

When current criteria regarding population density are applied, the exclusion area and low population zone (LPZ) are such that existing industrial complexes appear to be acceptable applications.

ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	94.0	8.0
STEAM POWER TO PROCESS	316.9	27.1
SUBTOTAL	410.9	35.1
OTHER USES		
ELECTRIC POWER	232.6	19.9
LOSSES		
CONDENSER	480.6	41.1
OTHER	45.9	3.9
TOTAL REACTOR POWER OUTPUT	1170	100

LEGEND

W = FLOW KG/S (10^6 LB/HR)
P = PRESSURE MPa (PSIA)
T = TEMPERATURE °C (°F)

Fig. 6-15. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for 800,000 ST/yr alumina mill application (maximum cogenerated electrical power)

ALLOCATION OF REACTOR POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	151	12.9
STEAM POWER TO PROCESS	1001.2	85.6
SUBTOTAL	1152.2	98.5
LOSSES	17.8	1.5
TOTAL REACTOR POWER OUTPUT	1170	100

LEGEND

W = FLOW KG/S (10^6 LB/HR)
P = PRESSURE MPa (PSIA)
T = TEMPERATURE °C (°F)

Fig. 6-16. Cycle diagram of 1170-MW(t) HTGR-PS/C plant for multi-purpose applications

ALLOCATION OF PLANT POWER OUTPUT	MW	%
PROCESS USES		
ELECTRIC POWER	157.5	11.5
STEAM POWER TO PROCESS	1000.4	73.2
SUBTOTAL	1157.9	84.7
LOSSES	136.0	10.0
OTHER	72.1	5.3
TOTAL BOILER HEAT INPUT	1366	100

LEGEND
W = FLOW KG/S (10⁶ LB/HR)
P = PRESSURE MPA (PSIA)
T = TEMPERATURE °C (°F)

Fig. 6-17. Cycle diagram of coal-fired PS/C plant for multi-purpose applications

Regulatory Guide 4.7, "General Site Suitability Criteria for Nuclear Stations," contains a guideline for population density, which requires special attention to alternate sites if the population density, including weighted transient population, at the time of initial operation exceeds 500 persons per square mile averaged over any radial distance out to 30 miles, or similarly if the projected population over the lifetime of the facility exceeds 1000 persons per square mile. The guide further states that the Nuclear Regulatory Commission staff has found that a minimum exclusion distance of 0.4 mile is usually acceptable and that a distance of 3 miles to the outer boundary of the LPZ is usually adequate.

When external industrial hazards are considered, the analysis must be very site and process plant specific, and no work of this scope is included in the current program.

Regulatory Guide 4.7 requires that potentially hazardous facilities and activities within 5 miles of a proposed site be identified and evaluated. Hazards include those from explosions, flammable vapor clouds, toxic chemicals, missiles, and incendiary fragments. Consideration is to be given to nearby industrial, military, and transportation facilities. If the probability of a given accident is not sufficiently low and if the potential consequences exceed specified limits (for some types of events), it may be required that plant design features be incorporated to mitigate the consequences of the accident.

Industrial hazards have not played a large part in the siting of nuclear generating stations, but in at least one case a site has been rejected in part because of external hazards. In this instance the hazards were a rail line and an adjacent military proving ground.

Recommendations included in the "Report of the Siting Policy Task Force" (NUREG-0625) could have a significant effect on PS/C plant siting. However, it is too early to know what recommendations will be adopted and

whether the technical differences between HTGR and LWR units will be acknowledged.

6.4. PRELIMINARY ECONOMIC EVALUATIONS

Ground rules for economic evaluations have been agreed on by GA, GCRA, and UE&C, and base case economics have been developed. The economic studies are based on input of capital costs developed for the HTGR-PS/C plant and competing coal- and oil-fired units. The methodology and ground rules used in the economic studies are discussed briefly below.

The revenue requirement method was selected as the method for evaluating the alternative projects. This technique, which is commonly accepted by the electric utility industry to evaluate 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. Base capital costs are escalated up 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 obtain an annual fixed charge, to which is added the levelized annual fuel costs, levelized annual operation and maintenance costs, and a credit for the levelized value of cogenerated power to obtain a total levelized annual cost. This annual cost is then converted to a levelized cost per million Btu, a figure which represents, in present value terms, the "average" cost of the cogenerated process steam for the project life. In economic terms, the project with the lowest cost per million Btu of process steam is the project with the greatest economic merit.

Key ground rule assumptions used in the studies are as follows:

Commercial operation of all plants: 6/1/95

Capacity factor: 70%

Levelizing period: 30 yr and 15 yr

Electric power credit: 22 mills/kW-hr (1980 \$)

Discount rate: 10%/yr

Fixed charge rate: 18%/yr

Interest during construction: 10%/yr (simple interest)

Coal cost escalation: 8%/yr

Fuel oil escalation: 9%/yr

All other escalation: 6% yr

Construction period: 6 yr for all plants (2 yr for No. 6 fired oil plants)

U₃O₈ (yellowcake) cost: \$45/lb in 1990, rising to \$120/lb in 2030

Separative work unit (SWU) cost: \$100/SWU (1980 \$)

Tails assay: 0.2%

Coal cost: \$1.36/MBtu (1980 \$)

No. 2 oil cost: \$5.33/MBtu (1980 \$)

No. 6 oil cost: \$3.95/MBtu (1980 \$)

HTGR fuel cycle cost: \$3.23/MBtu (6/95 \$ levelized over 30 yr)
\$2.62/MBtu (6/95 \$ levelized over 15 yr)

PWR fuel cycle cost: \$3.00/MBtu (6/95 \$ levelized over 30 yr)

The preliminary economic study results (Table 6-2) show the HTGR-PS/C plant to be significantly lower in product steam cost than the coal-fired alternative. This is true for the reference multi-purpose plant application and for all other applications studied. The ratio of HTGR steam price to coal steam price is shown to range from 0.23 to 0.65.

TABLE 6-2
HTGR-PS/C AND COAL-PS/C APPLICATION COMPARISON (\$/MBtu)
(30-yr Levelization)

	Multi-Purpose	Steel Mill No. 1	Steel Mill No. 2	Alum. Mill No. 1	Alum. Mill No. 2	Heavy Oil Recovery	SRC 11	Tar Sands	H-Coal	Exxon Catalytic Coal	Orange with Cond.	Orange without Cond.	Geismar with Cond.	Geismar without Cond.
HTGR-PS/C	10.73	10.16	7.48	11.05	10.74	10.49	13.59	13.07	12.38	11.06	9.81	--	8.10	--
Coal-PS/C	18.33	21.16	32.91	18.61	34.71	18.16	21.60	20.03	22.93	19.28	18.66	17.69	18.74	17.57
Existing No. 2 oil plant	63.27	--	--	--	--	--	--	--	--	--	63.27	--	63.27	--
Small No. 6 oil boiler plant	55.32	--	--	--	--	55.25	--	--	--	--	--	--	--	--

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