HTGR HIGH TEMPERATURE GAS-COOLED REACTOR PROGRAM

BGI/GCRA 83-003

MONOLITHIC VERSUS MODULAR HTGR COST COMPARISON

PRINCIPAL CONTRIBUTORS
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COMBUSTION ENGINEERING
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GENERAL ELECTRIC CO.

ISSUED BY: BECHTEL GROUP, INC.
FOR
GAS-COOLED REACTOR ASSOCIATES
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LIST OF ABBREVIATIONS

AFUDC	Allowance for funds used during construction
BGI	Bechtel Group, Incorporated
BOP	Balance of plant
CACS	Core auxiliary cooling system
CACWS	Core auxiliary cooling water system
CAHE	Core auxiliary heat exchanger
C-E	Combustion Engineering, Inc.
CF	Capacity factor
CWS	Circulating water system
DBDA	Design base depressurization accident
DC	Direct cycle
DOE	Department of Energy (United States Government)
GA	GA Technologies, Inc.
GCRA	Gas-Cooled Reactor Assocates
GE	General Electric Company
GFY	Government Fiscal Year
HEU	High enrichment uranium
HPT	High pressure turbine
HP-TG	High pressure turbine-generator
HP/IP-TG	High pressure/intermediate pressure turbine-generator
HTGR	High temperature gas-cooled reactor
HTGR-PH	High temperature gas-cooled reactor - process heat
HTGR-R	High temperature gas-cooled reactor - reformer
HTGR-SC	High temperature gas-cooled reactor - steam cycle
HTGR-SC/C	High temperature gas-cooled reactor - steam cycle/cogeneration
HTPH	High temperature process heat
HVAC	Heating, ventilating, and air conditioning
I&C	Instrumentation and control
IDC	Indirect cycle
IHX	Intermediate heat exchanger
IPT	Intermediate pressure turbine
LEU	Low enrichment uranium
LPT	Low pressure turbine
LP-TG	Low pressure turbine-generator
LWR	Light water reactor
MRS	Modular reactor system
MRS-R	Modular reactor system - reformer
MRS-SC/C	Modular reactor system - steam cycle/cogeneration
MTBF	Mean time before failure
MTTR	Mean time to repair
MWe	Megawatts, electrical
MWt	Megawatts, thermal
NHS	Nuclear heat source
NSWS	Nuclear service water system
O&M	Operation and maintenance
ORNL	Oak Ridge National Laboratory
PCRV	Prestressed concrete reactor vessel

RCB	Reactor containment building
ROT	Reactor outlet temperature
RPCWS	Reactor plant cooling water system
SG	Steam generator
SNG	Synthetic natural gas
TCP	Thermochemical pipeline
TG	Turbine-generator
UE&C	United Engineers and Constructors

Section 1

INTRODUCTION AND SUMMARY

1.1 BACKGROUND

This summary report describes comparisons of High Temperature Gas-Cooled Reactor (HTGR) plants based on the monolithic and modular reactor concepts as sources of process steam. Contributions to this study were made during GFY 1982 by Bechtel Group, Inc. (BGI), GA Technologies, Inc. (GA), General Electric Company (GE), and Combustion Engineering, Inc. (C-E), with overall coordination by Gas-Cooled Reactor Associates (GCRA). This report presents a series of economic case studies comparing total investment requirements and steam production costs. The detailed design and technical bases for this work are described in separate reports prepared by each participant, and in integrated summary reports of the monolithic reformer and modular HTGR systems issued by GCRA (References 1-1 and 1-2). Information developed for the HTGR-SC/C Lead Plant (Reference 1-3) is also used in this report.

One of the prime objectives of the GFY 1982 HTGR development program was an economic comparison of the 2240 MWt monolithic HTGR with a modular HTGR reactor system (MRS) consisting of a number of small nuclear heat sources (NHSs) coupled in parallel. The power rating of the modules is 250 MWt in the case of the reformer concept and 300 MWt in the case of the steam cycle/cogeneration concept. Specifically, in this report the economics of monolithic and modular HTGR systems, designed for equivalent process steam availability and for production of the same quantity of process steam, are compared. The report includes monolithic versus modular comparisons for two applications of the HTGR.

- The HTGR reformer (HTGR-R) is used with the thermochemical pipeline (TCP) for energy transmission over long distances, with production of steam and electricity for on-site use plus a small amount of by-product electricity for sale. The HTGR-reformer/TCP system serves a dispersed baseloaded steam market.

- The HTGR steam cycle/cogeneration (HTGR-SC/C) unit supplies steam directly to process heat users and provides substantial amounts of by-product electricity for sale. The HTGR-SC/C serves a concentrated baseloaded steam market.

1.2 AVAILABILITY CONSIDERATIONS

Because of the high steam availability required by the typical process heat user, it was necessary to develop and apply a methodology for adding backup units to the base plants to bring the systems up to the target availability level. The steps involved in the methodology include:

- Establishing the user availability requirements for process steam (target availability)
- Identifying various candidate monolithic and modular system configurations (base plant plus backup units) which appear likely to meet the target availability and have the same steam production
- Combining the forced and scheduled outage rates for the monolithic and modular HTGR units to obtain the availabilities of the identified configurations
- Selecting for economic evaluation those configurations that are best matched in availability and steam production

Availability requirements may differ for different process heat applications. For this monolithic/modular comparison, the process steam user availability requirement was established as 99% or greater, based on a survey of steam availability requirements in the chemical industry (Reference 1-4). This target availability level is also consistent with that for many other industrial plants where three 50% gas-fired or oil-fired boilers are typically used as the steam supply (Reference 1-5).

In order to assemble systems having this target availability, it is necessary to install substantial backup capacity. This backup can be in the form of additional NHSs. Alternatively, gas-fired boilers can be used to generate backup steam at lower capital cost but higher fuel cost. System configurations were developed using different combinations of NHS and gas-fired steam generating units.

Backup provisions for the reformer/TCP concept are different from those for the steam cycle/cogeneration concept because of the different system configurations. In the reformer/TCP concept, nuclear energy is converted to chemical energy via the endothermic reforming reaction, which reacts methane and steam to form hydrogen and carbon monoxide, syngas. The syngas is then sent via the TCP to users located 60 to 100 miles away. The syngas is converted via the exothermic methanation reaction back into methane and steam, and the heat of reaction is used to generate process steam. For a typical monolithic 2240 MWt HTGR-reformer/TCP plant there are assumed to be 29 users, each with its own methanator-steam generator units. For this overall system configuration, backup HTGR-R capacity is located at the base plant site while backup gas-fired boilers are located at the user sites.

In the steam cycle/cogeneration concept, nuclear energy is converted directly into high pressure/temperature steam, which is used in a topping cycle to produce electricity, and process steam that is sent to relatively nearby users. For this system configuration, both backup HTGR-SC/C capacity and gas-fired boiler backup are located at the base plant site.

1.3 ECONOMIC COMPARISON

Economic case studies comparing monolithic versus modular steam production costs were developed using data from the reference 1982 design reports and GCRA's economic ground rules for the HTGR program for 1983. Ten configurations were evaluated, six for the reformer/TCP application and four for the steam cycle/cogeneration application. All cases satisfy the availability target.

1.3.1 Reformer Cases

Table 1-1 summarizes the cost comparisons for the reformer/TCP application. Cases 1 and 2, monolithic cases, illustrate that trading nuclear backup for gas-fired boilers as backup has virtually no effect on the process steam cost. Cases 3, 4, and 5 illustrate the same trade-off for three modular cases. Again the effect is very slight, but it suggests that eleven or twelve modules (nine module base plant, two or three backup modules) leads to the lowest process steam cost. The process steam cost for the modular cases is clearly less than that for the monolithic cases.

Case 6 shows the steam cost for a gas-fired boiler system with no nuclear component. This process steam cost is approximately 14% higher than that for the modular cases. However, the cost of process steam from an atmospheric fluidized bed (AFB) combustion system is in the \$6 to \$8/10^6 Btu range (Reference 1-6), well below the \$13/10^6 Btu for the MRS-R/TCP configurations. Thus, both modular and monolithic HTGR-R/TCP configurations lead to process steam costs that are substantially higher than that from a representative fossil fueled alternative, the AFB. Therefore, a low priority is warranted on any further near term development of the TCP application of the HTGR-R. It is noted that open cycle application of the HTGR-R to generate syngas for chemical manufacture will be addressed in the forthcoming Application Assessment Summary (Reference 1-7).

1.3.2 Steam Cycle/Cogeneration Cases

Table 1-2 summarizes the cost comparisons for the steam cycle/ cogeneration cases. Cases 7 and 8 illustrate, for the monolithic HTGR, the trade-off between nuclear and gas-fired boilers as backup units. For the SC/C systems, the use of nuclear backup reduces the use of expensive gas fuel and provides excess steam which contributes significantly to revenue in the form of an electric power credit. Thus nuclear backup, Case 7, is much more attractive than gas-fired backup, Case 8.

Table 1-1

SUMMARY OF MONOLITHIC/MODULAR HTGR COST COMPARISONS FOR REFORMER/TCP CASES

	Units	Monolithic		Modular			Gas
Case Number		1	2	3	4	5	6
Plant Configuration							
Base plant - HTGR	No. x MWt	1x2240	1x2240	9x250	9x250	9x250	-
- Gas		-	-	-	-	-	29x45
Backup - HTGR		1x2240	-	3x250	2x250	1x250	-
- Gas		29x45	58x45	7x45	10x45	13x45	29x45
Products							
Steam	10^{12} Btu/yr	39.1	39.1	38.8	38.8	38.8	38.9
Electric power	10^{9} kWh/yr	0.8	0.7	0.9	0.8	0.8	-
Costs							
Capital cost	$\$10^{6}$	4,915	3,977	3,793	3,628	3,461	490
Operating cost	$\$10^{6}$/yr						
Gross		696	669	573	570	579	608
Electric revenue		(47)	(37)	(49)	(48)	(45)	-
Net		649	632	524	522	534	608
Process steam cost	$\$/10^{6}$ Btu	16.6	16.2	13.5	13.5	13.8	15.6

Table 1-2

SUMMARY OF MONOLITHIC/MODULAR HTGR COST COMPARISONS FOR STEAM CYCLE/COGENERATION CASES

	Units	Monolithic		Modular	
Case Number		7	8	9	10
Plant Configuration					
Base plant - HTGR	No. x MWt	1x2240	1x2240	7x300	7x300
Backup - HTGR		1x2240	-	3x300	8x300
- Gas		1x2240	2x2240	1x600	-
Products					
Steam	10^{12} Btu/yr	57.7	57.7	54.1	54.1
Electric power	10^{9} kWh/yr	6.0	1.5	3.1	6.9
Costs					
Capital cost	$\$10^{6}$	2,546	1,620	2,229	3,078
Operating cost	$\$10^{6}$/yr				
Gross		457	418	380	512
Electric revenue		(278)	(82)	(157)	(358)
Net		179	336	223	154
Process steam cost	$\$/10^{6}$ Btu	3.1	5.8	4.1	2.8

Case 9 is a modular case which matches the process steam output of Case 7 with a minimum of excess nuclear capacity. The cost of process steam for Case 9 is well above that for Case 7 but compares favorably with the $4 to $$6/10^6$ Btu estimated for a large coal-fired cogeneration plant (Reference 1-6). Case 10 is a modular case having the same installed nuclear capacity as Case 7.

As noted in Table 1-2, Cases 7 and 10 both benefit from the revenue from electric power produced from excess nuclear capacity. Hence, the HTGR-SC/C system, both monolithic and modular, appears most attractive for base-loaded concentrated process steam markets in regions that require added electric generation capacity. A more comprehensive comparison of the HTGR-SC/C system versus the fossil alternative for different market conditions are forthcoming in the "HTGR-SC/C Economic Evaluation" (Reference 1-6).

Section 2

BASE PLANTS

This section briefly describes the essential features of individual modular and monolithic reformer/TCP and steam cycle/cogeneration units and serves as background information for understanding the overall system configurations presented in Section 3. Mechanical and operational details of the reactor systems and the balance of plant can be found in References 1-1, 1-2, and 1-3.

2.1 REFORMER UNITS

2.1.1 The Reformer/Thermochemical Pipeline Concept

In the reformer/thermochemical pipeline concept, heat from the HTGR core is used to carry out the reforming reaction in which methane and steam are converted into hydrogen and carbon monoxide (syngas). This reaction

$$CH_4 + H_2O = 3H_2 + CO$$

is highly endothermic, converting thermal energy into chemical energy. The hot syngas is cooled to ambient temperature in a series of heat exchangers, the reformer train. Water remaining in the syngas is condensed at the same time. After further drying, the syngas is compressed and introduced into the TCP. Some distance away, at the user end of the TCP, the syngas is converted via the methanation reaction, the reverse of the reforming reaction, back into methane and water. The methanation reaction releases the chemical energy as thermal energy, which is used to generate process steam. The methane is returned to the HTGR site by a return leg of the TCP. It is preheated in the reformer train and fed to the reformer, completing the cycle.

Both the modular and monolithic HTGR-R are based on the 1742°F (950°C) reactor outlet temperature, direct cycle design. Table 2-1 compares the key features of the monolithic and modular HTGR in the reforming application.

Table 2-1

MONOLITHIC/MODULAR NHS COMPARISON FOR HTGR
REFORMER PLANT

Process Heat Plant	Monolithic Configuration	Modular Reactor System
Core Thermal Rating, MWt	2240	250
Reactor Outlet Temp., °F (°C)	1742 (950)	1742 (950)
Reactor Inlet Temp., °F (°C)	932 (500)	797 (425)
System Pressure, psia (MPa)	696 (4.8)	725 (5.0)
Technology Bases	Fort St. Vrain Steam Cycle Lead Plant HTGR Technology Program	Peach Bottom 1 HTGR Technology Program
Reactor Vessel Type	Multicavity PCRV	Steel Vessel
Decay Heat Removal Capability	Dedicated CACS (3)	Passive Vessel Cooling System
Reformer, No./Location	6/in PCRV sidewalls	1/Above Core
Steam Generator, No./Location	6/in PCRV sidewalls	1/Annular
Circulator, No./Location	6/Vertical, Above SG	1/Horizontal, Vessel Bottom
Control Rod Drives	Fort St. Vrain Type (above core)	Peach Bottom Type (below core)
Refueling Arrangement	In-Vessel Refueling	Side Refueling
Reactor Core Type	HTGR Prismatic	HTGR Prismatic
Flow Arrangement	Downflow	Upflow
Fuel	LEU/Th	LEU/Th
Refueling Mode	3-Year Graded	4-Year Biennial
Power Density, W/cm^3	5.35	4.1
Active Core Diameter, ft	30.1	11.5
Active Core Height, ft	20.8	20.8
Core Orificed	Yes	No
Core Support Type	Graphite Support Posts	Metallic Forging

2.1.2 Modular HTGR-Reformer

The modular HTGR-reformer consists of a steel vessel containing a reactor core, a reformer, a steam generator, and a helium circulator. The reactor core rating is 250 MWt. The circulating helium transfers heat from the core to the reformer, supplying high temperature heat to the endothermic reforming reaction. The helium then passes through the steam generator where lower temperature heat is used to generate high pressure steam. This steam is split into two streams, one being used to generate electricity for in-house use and for sale and the other to preheat the reformer feed.

In a reformer system comprised of several modular reactors, each module has its own reformer train; however, the cooled syngas from all reformer trains is combined and compressed in a common compressor train for distribution via the TCP, and the steam from all modules is utilized in a common turbine-generator (TG) train.

2.1.3 Monolithic HTGR-Reformer

The monolithic HTGR-R consists of a multi-cavity prestressed concrete reactor vessel (PCRV) containing a reactor core and six parallel loops, each loop comprising a reformer, steam generator, and helium circulator. The core power rating is 2240 MWt. Each reformer has its own reformer train for feed-product heat exchange. The cooled syngas from all six reformer trains is combined and compressed in a common compressor train. Similarly, steam from all six steam generators is combined and fed to a common TG system.

Because each reformer loop/reformer train operates independently of the others, it is possible to continue running the reactor with a loop inoperative. However, analysis shows that failures leading to shutdown of the entire reactor system are more likely to occur than loss of single loops. Thus, in spite of the apparent modular nature of the monolithic reactor system, for all practical purposes it functions in a monolithic manner, being either totally up or totally down. Therefore, the availability analysis treats the monolithic HTGR-R as a single unit.

2.2 STEAM CYCLE/COGENERATION UNITS

2.2.1 The Steam Cycle/Cogeneration Concept

In the steam cycle/cogeneration (SC/C) concept, all of the heat from the nuclear reactor is used to generate high pressure/temperature steam. The steam passes through a high pressure turbine-generator (HP-TG) in a topping cycle. Product steam is extracted from the HP-TG exhaust and sent to the process steam user. Enough steam from the HP-TG exhaust is retained to drive a low pressure turbine (LP-TG) which supplies steam for feed water heating while generating additional electricity. Any steam not needed for these operations is sent to an intermediate pressure/low pressure turbine-generator (IP/LP-TG) to generate electricity for sale.

Table 2-2 compares the key features of the monolithic and modular HTGR in the steam cycle/cogeneration application.

2.2.2 Modular HTGR-Steam Cycle/Cogeneration

The HTGR-SC/C module consists of a steel vessel (similar in size to that of the HTGR-R module) containing a reactor core, steam generator, and helium circulator. The reactor core rating is 300 MWt. Heat is transferred from the core to the steam generator by the circulating helium. In a process steam system comprised of several modular reactors (MRS-SC/C), the steam from all modules is combined for utilization in a common TG train and for distribution to process steam users.

2.2.3 Monolithic HTGR-Steam Cycle/Cogeneration

The monolithic HTGR-SC/C configuration is based on the lead plant design which is at an advanced stage of development relative to other HTGR applications. It consists of a multi-cavity PCRV containing four parallel loops, each loop comprising a steam generator and a helium circulator. The reactor core rating is 2240 MWt. The steam from all four loops is combined and sent to a single TG train for distribution to process steam users and for generating electricity.

Table 2-2

MONOLITHIC/MODULAR NHS COMPARISON FOR HTGR
STEAM CYCLE/COGENERATION PLANT

Process Heat Plant	Monolithic Configuration	Modular Reactor System
Core Thermal Rating, MWt	2240	300
Reactor Outlet Temp., °F (°C)	1272 (689)	1270 (688)
Reactor Inlet Temp., °F (°C)	607 (319)	541 (283)
System Pressure, psia (MPa)	1050 (7.2)	725 (5.0)
Technology Bases	Fort St. Vrain Steam Cycle Lead Plant HTGR Technology Program	Peach Bottom 1 HTGR Technology Program
Reactor Vessel Type	Multicavity PCRV	Steel Vessel
Decay Heat Removal Capability	Dedicated CACS	Passive Vessel Cooling System
Steam Generator, No./Location	4/in PCRV sidewalls	1/Above Core
Circulator, No./Location	4/Vertical, Above SG	1/Horizontal, Vessel Bottom
Control Rod Drives	Fort St. Vrain Type (above core)	Peach Bottom Type (below core)
Refueling Arrangement	In-vessel Refueling	Side Refueling
Reactor Core Type	HTGR Prismatic	HTGR Prismatic
Flow Arrangement	Downflow	Upflow
Fuel	LEU/Th	LEU/Th
Refueling Mode	3-Year Graded	4-Year Biennial
Power Density, W/cm^3	5.8	4.9
Active Core Diameter, ft	30.1	11.5
Active Core Height, ft	20.8	20.8
Core Orificed	Yes	No
Core Support Type	Graphite Support Posts	Metallic Forging

Section 3

SYSTEM CONFIGURATIONS

3.1 DESIGN BASIS

The base plants described in Section 2 can be assembled into systems capable of producing process steam at a selected rate and availability. For both monolithic and modular systems it was the aim of this study to choose system configurations that gave comparable product rates and availabilities.

The product steam rate for the reformer/TCP cases and for the steam cycle/cogeneration cases was set by the output of one monolithic reactor. This steam rate is already large enough that the market is somewhat restricted; thus a higher steam rate did not appear to offer a practical basis for the modular/monolithic reactor comparison. At the same time it is clearly inefficient to use only part of the output of a monolithic reactor. Therefore, the monolithic reactor output became the design basis for the product steam rate, and modular systems were designed to match that rate.

The availability target that was selected was 99% at the design output.

> Note: Availability, as used in this report, means the percentage of time that the plant can provide process steam at 100% of design output rate.

Process heat users generally want assurance that the steam source will virtually never restrict or shut down their plant operation. While it is difficult to quantify such a requirement, it clearly translates to a very high availability.

One approach to defining the required availability is to interview process steam users. This has been done by Oak Ridge National Laboratory (ORNL) (Reference 1-4). They conclude that for a representative sample of the chemical industry "an energy supply system capable of meeting load demand 98-99% of the time appears reasonable." For systems comprised of several gas- or oil-fired boilers, this availability is generally achieved by having one spare boiler equal to the largest boiler in the system.

An alternative approach to defining user requirements is to examine the availability characteristics of a typical steam supply that might be provided for a new industrial plant. Several examples were found in which the process steam supply comprised two boilers, with a total output equal to the normal steam demand, plus a spare of equal size. This finding is consistent with ORNL's finding. The selected target availability of 99% seems to match the perceived demand.

In order to assemble systems having an availability of at least 99% it is necessary to install substantial excess capacity. For example, assuming 80% availability for a NHS it requires three NHSs, each having the design output, to provide a system availability of 99%. Alternatively, gas-fired boilers can be utilized to generate backup steam. System configurations were developed to illustrate different combinations of installed NHS capacity and gas-fired boiler capacity.

3.2 REFORMERS

The reformer/TCP concept delivers process steam (about 3.5×10^6 lb/hr) to customers located 60 to 100 miles from the site of the HTGR-R installation. The customers must be so located that, for the most part, the syngas can be transported via a single TCP. These customers were assumed to require 45 MWt of process steam each, so there are 29 distributed process steam user sites to consume the output of one monolithic HTGR-R, which is 1305 MWt released at the methanators.

It was judged not to be practical or economic to install a backup gas-fired reformer at the HTGR-R site. Instead, gas-fired boilers were added at the user sites.

3.2.1 Monolithic HTGR-Reformer

Two system configurations were evaluated for the monolithic HTGR-R. Case 1 consists of two monolithic HTGR-Rs backed up by 29 gas-fired boilers, one at each user site. Figure 3-1 is a block diagram of this configuration. Syngas from the two reformer trains is joined, compressed, and sent to user sites via the TCP. Here, at 29 separate stations, the syngas is methanated, and the heat of methanation is used to produce process steam. Steam from the steam generators of the HTGR-Rs, after being partially utilized to preheat the reformer feed, is joined and sent to the TG train for production of electricity.

When both HTGR-Rs are operative, they are assumed to run at half capacity, keeping each ready to take over the total duty. When neither HTGR-R is operative, the gas-fired boilers at each site supply steam to the users.

The second monolithic HTGR-R configuration, Case 2, illustrated in Figure 3-2, is one in which there is only a single HTGR-R. Because the availability of the HTGR-R block is substantially reduced for this one-reactor configuration, it proved necessary to put two gas-fired boilers at each user site in order to attain the target availability. (System availability is discussed further in the next section.) Thus, each user is supplied with process steam either via syngas from the HTGR-R or from one of two gas-fired boilers.

3.2.2 Modular HTGR-Reformer

Three similar system configurations for the MRS-R, Cases 3, 4, and 5, having about the same product steam output as the monolithic HTGR-R cases, are illustrated in Figure 3-3. The MRS consists of ten to twelve

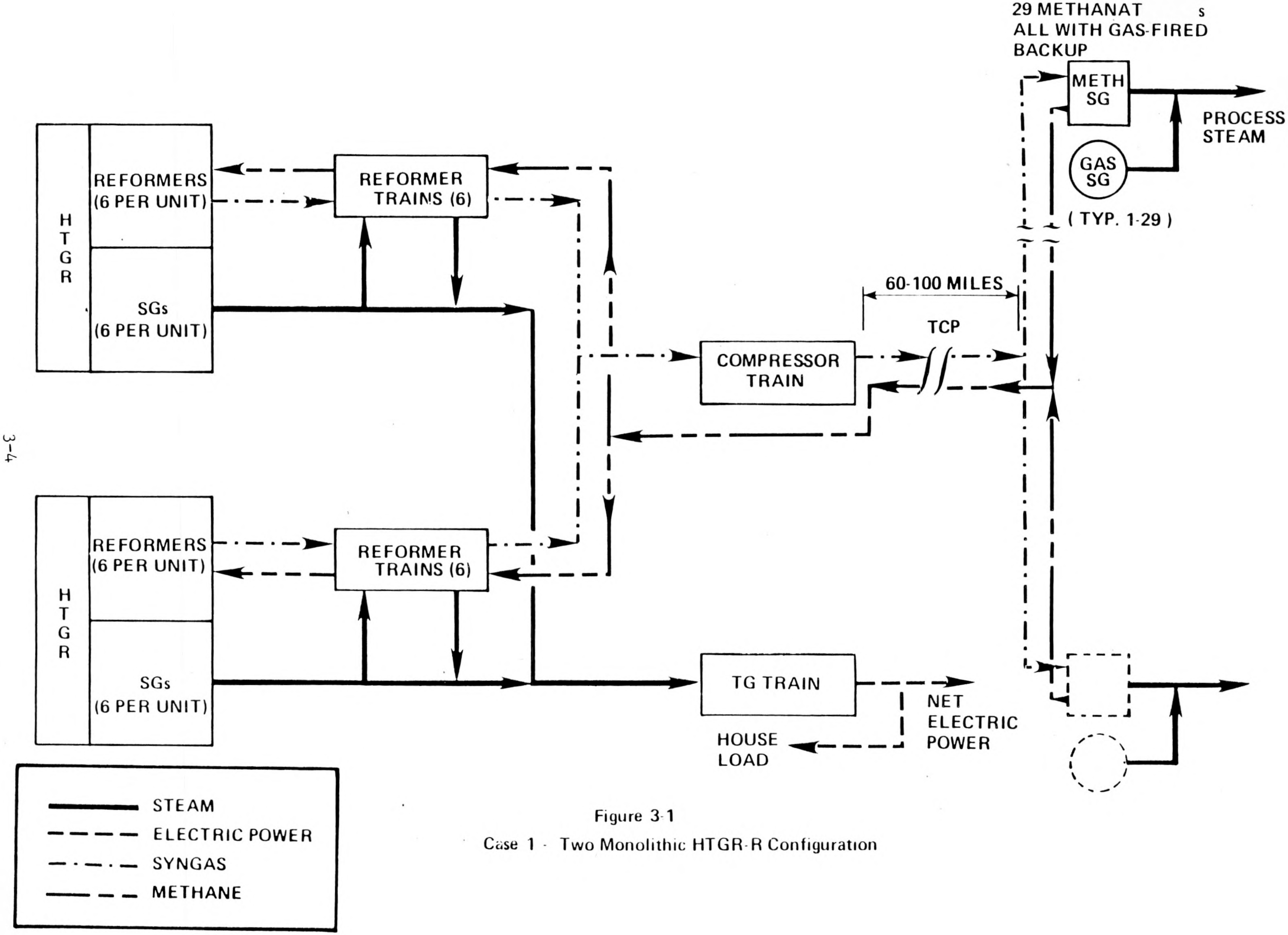

Figure 3-1

Case 1 - Two Monolithic HTGR-R Configuration

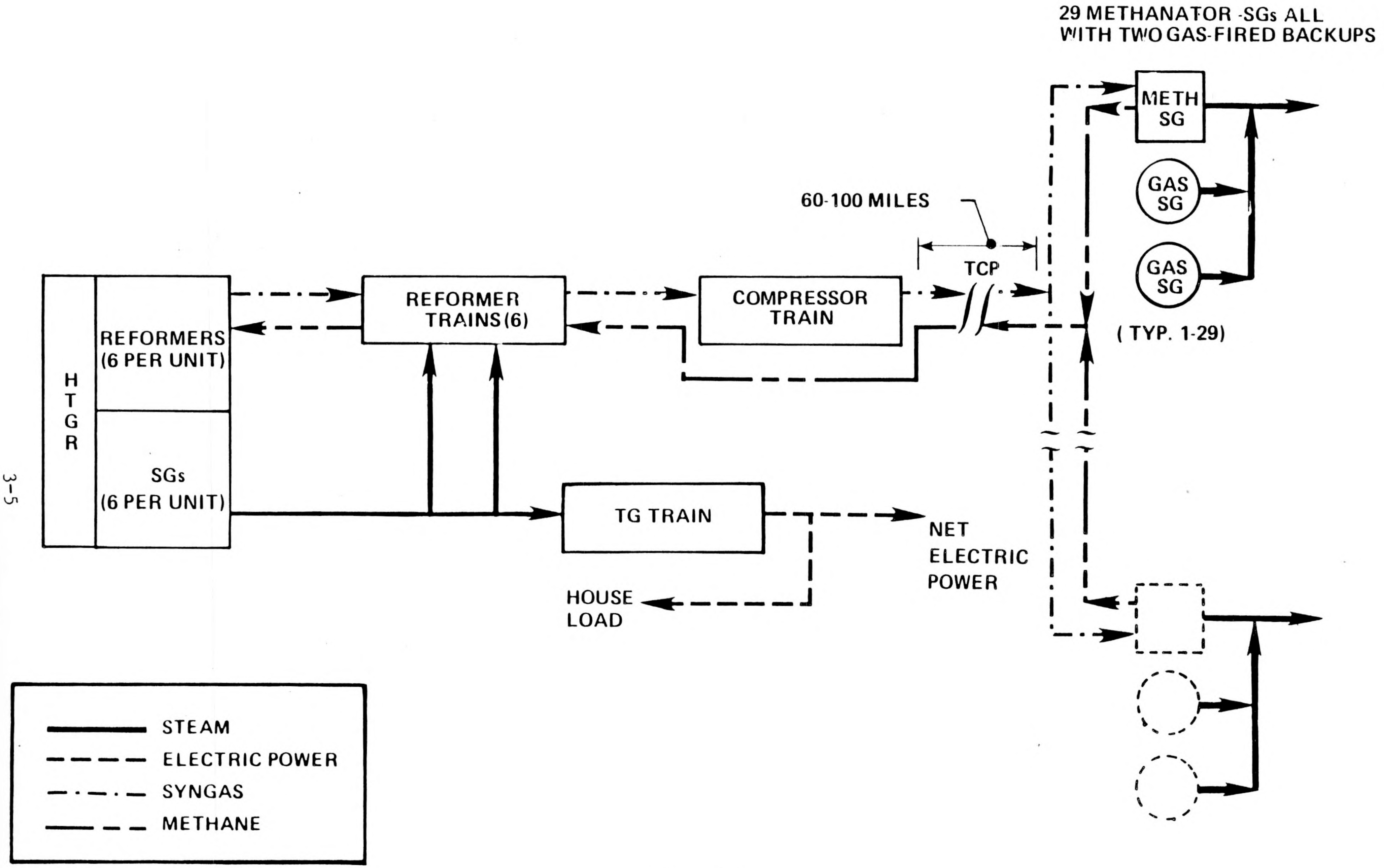

Figure 3-2

Case 2 - One Monolithic HTGR-R Configuration

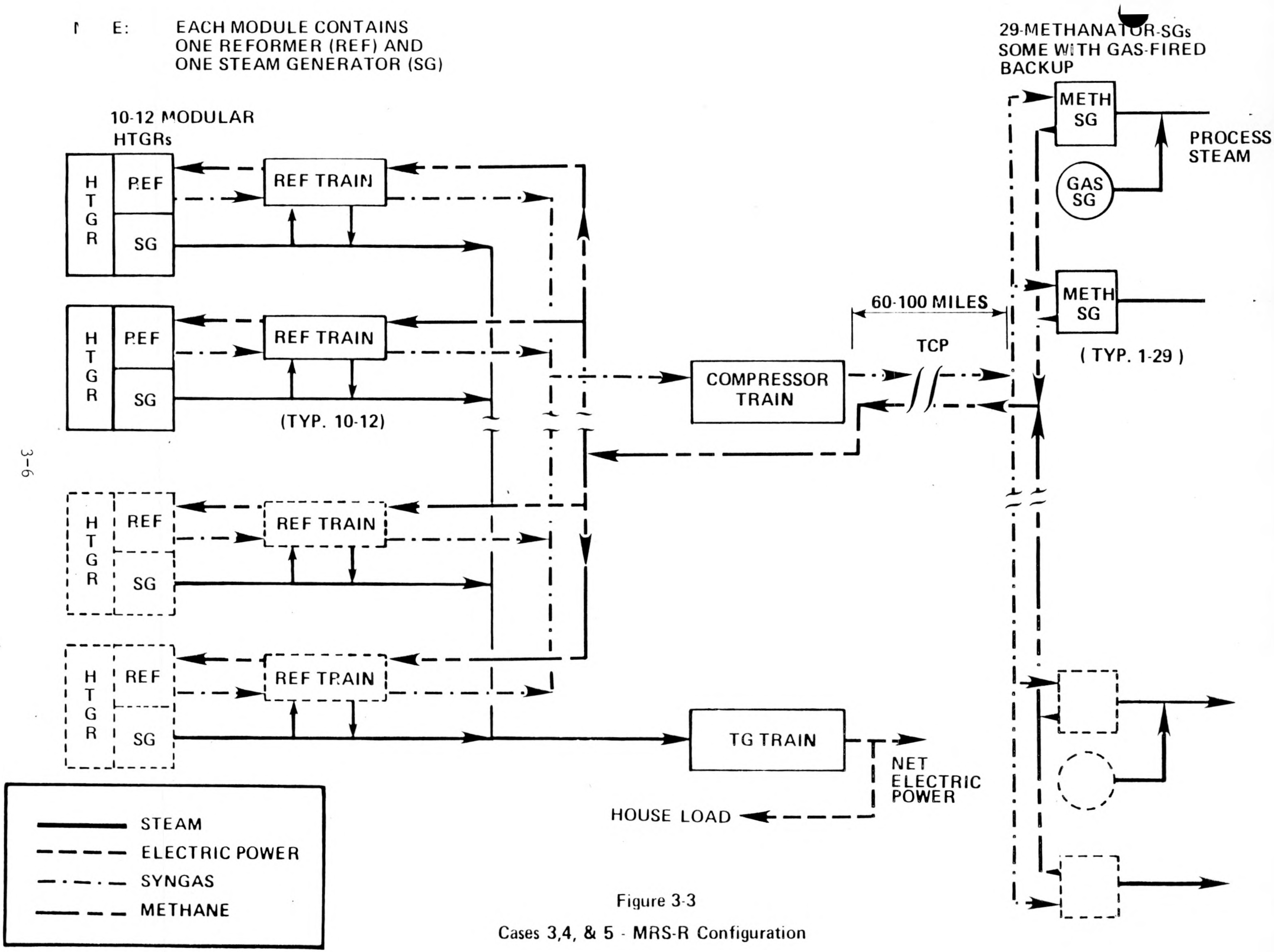

Figure 3-3

Cases 3,4, & 5 - MRS-R Configuration

modules. The output of nine modules is required for the design load. The remainder can be regarded as backup capacity. The syngas from all of the reformer trains is joined and sent via the TCP to the user stations, where it is converted back to methane, the heat being used to generate steam.

When fewer than nine modules are operating, the amount of syngas being made will be inadequate to supply the users' steam demands. However, some of the modules will always be operating. It will be shown later that at least half of the modules are available more than 99% of the time. Therefore, there will always be some syngas being sent along the TCP so that there is no need to provide gas-fired boilers at every user site. Instead, when there is a shortage of syngas, certain preselected sites will cease to use syngas and rely on their gas-fired boilers, thus making it possible to continue to supply syngas at full design rate to the other user sites.

The option of partial gas-fired boiler backup is not available to the monolithic HTGR-R cases since the syngas supply from the monolithic systems is either 100% or 0% of demand.

Case 6 (not illustrated) is comprised only of two gas-fired boilers at each user site. There is no NHS. This case is used to provide an economic standard to compare against the various HTGR reformer cases.

In summary, these are the reformer/TCP cases which were evaluated:

REFORMER/TCP CONFIGURATION

	Monolithic		Modular			Gas
Case Number	1	2	3	4	5	6
Energy Source (No. x MWt)						
Primary - HTGR	1 x 2240	1 x 2240	9 x 250	9 x 250	9 x 250	-
- Gas	-	-	-	-	-	29 x 45
Backup - HTGR	1 x 2240	-	3 x 250	2 x 250	1 x 250	-
- Gas	29 x 45	58 x 45	7 x 45	10 x 45	13 x 45	29 x 45

3.3 STEAM CYCLE/COGENERATION

The HTGR-SC/C concept delivers process steam (about 5 x 10^6 lb/hr) to users located within about 15 miles of the nuclear heat source. Since there is a single steam source (as contrasted with the dispersed methanator-steam generators of the reformer/TCP concept), the practical way to back up the nuclear source is to use one or more large gas-fired boilers located at the HTGR-SC/C site.

3.3.1 Monolithic Steam Cycle/Cogeneration

Two monolithic HTGR-SC/C cases were examined. Figure 3-4 illustrates Case 7, a configuration of two HTGR-SC/C units and a gas-fired boiler. The process steam demand is the output of one HTGR. When both HTGRs are operating, there is a large amount of excess steam, which is used in the HP-TG and the IP/LP-TG to generate electricity for sale. When only one HTGR is operating, only the HP-TG and LP-TG are used. When neither HTGR is operating, process steam is supplied by the gas-fired boiler, but no electricity is generated.

The second monolithic HTGR-SC/C case, Case 8, is illustrated in Figure 3-5. This case comprises one HTGR and two gas-fired boilers. This case contains no IP/LP-TG, because there is no excess steam to be utilized. One gas-fired boiler operates when the HTGR is not running, but no electricity is generated in this mode.

3.3.2 Modular Steam Cycle/Cogeneration

The MRS-SC/C configurations, Cases 9 and 10, are illustrated in Figure 3-6. The output of seven modules is required to supply the process steam demand equivalent to that supplied by one monolithic HTGR-SC/C. When more than seven modules are operating, the excess steam is used to generate additional electricity for sale. When fewer than seven modules are operating, the deficiency in process steam is made up by the gas-fired boiler.

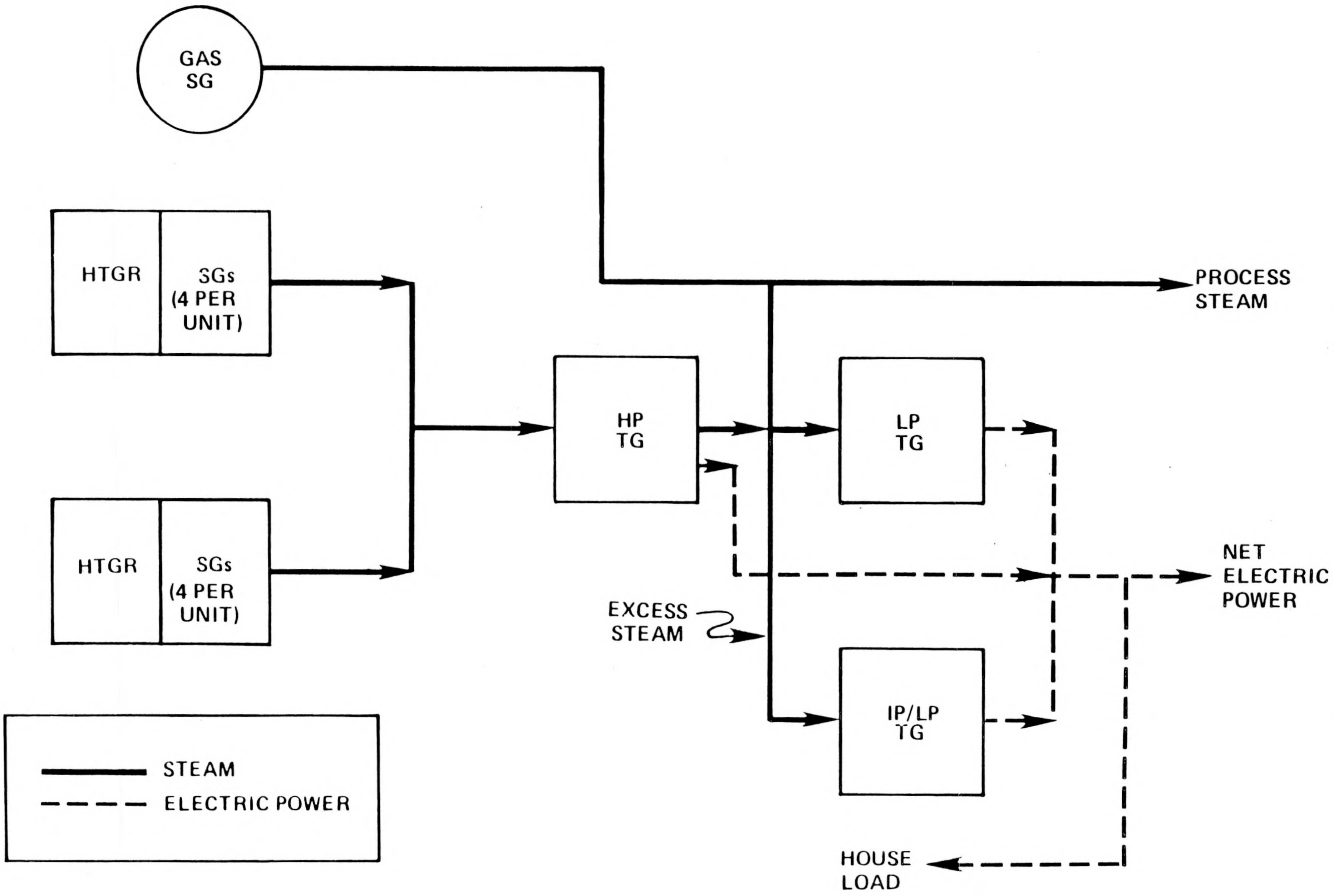

Figure 3-4

Case 7 - Two Monolithic HTGR-SC/C Configuration

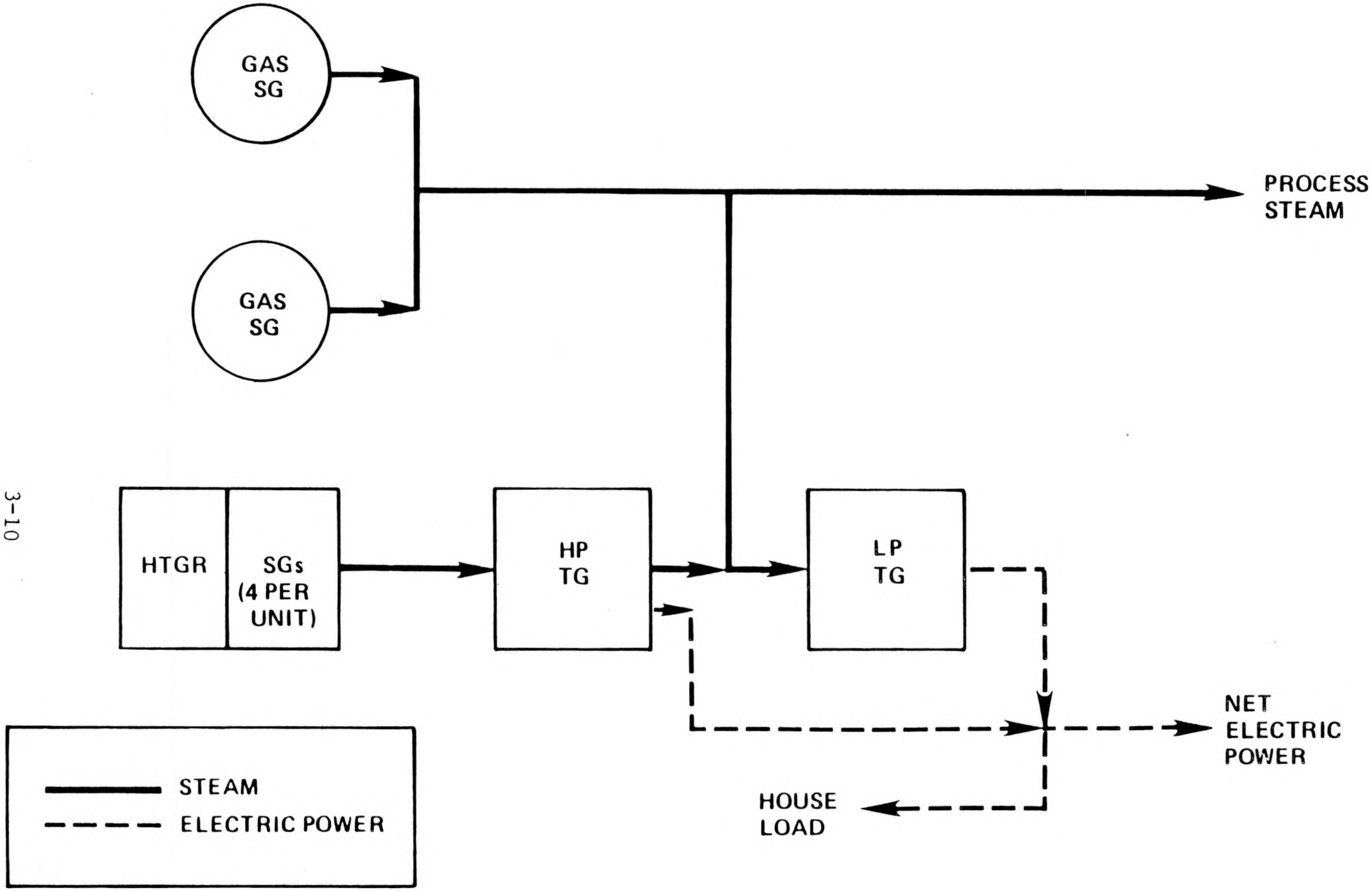

Figure 3-5

Case 8 - One Monolithic HTGR-SC/C Configuration

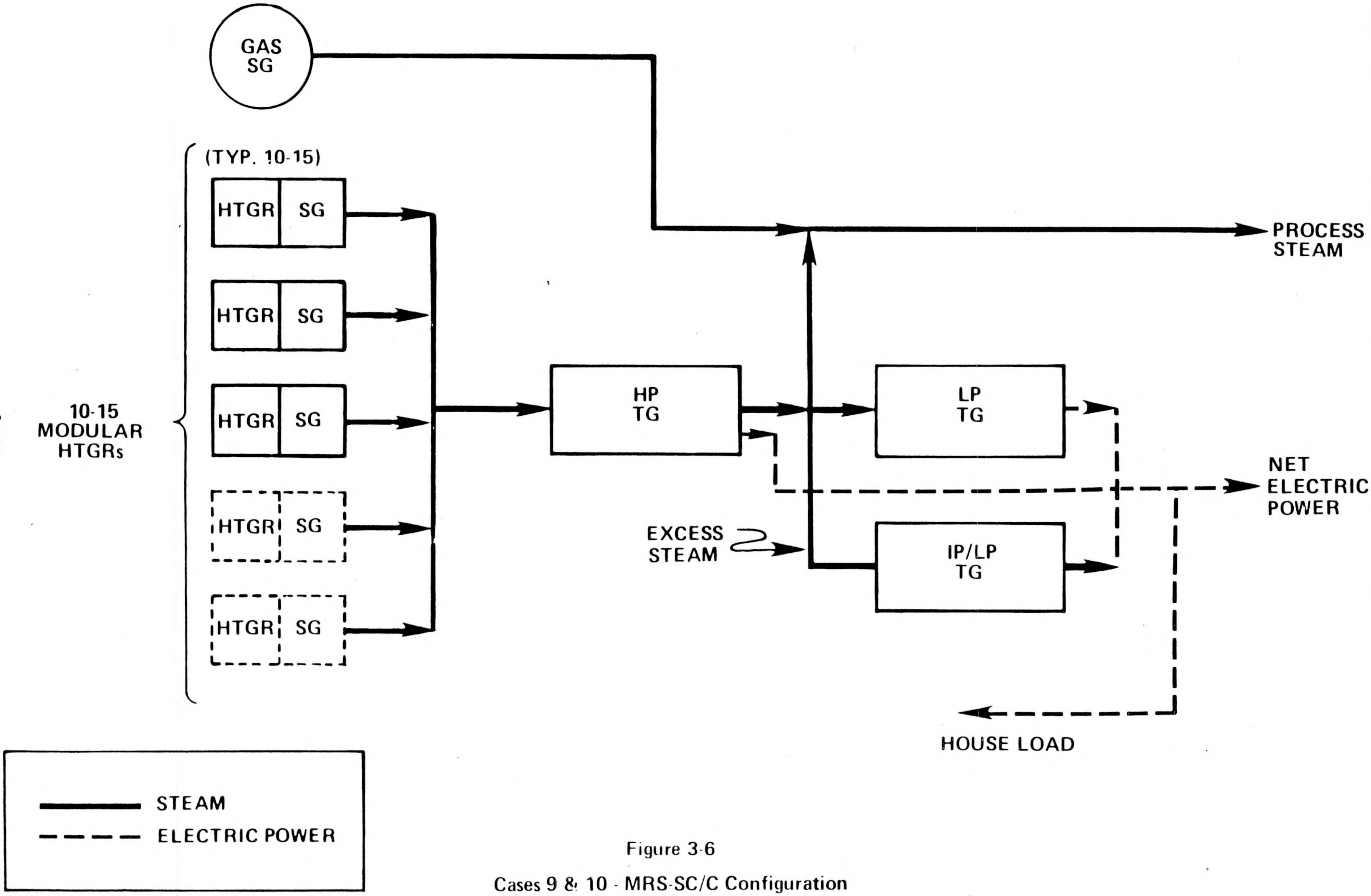

Figure 3-6

Cases 9 & 10 - MRS-SC/C Configuration

With the ten-module system, Case 9, there will virtually always be at least five modules operating. Therefore the gas-fired boiler need only be large enough to supply steam equivalent to the output of two modules. With the fifteen-module system, Case 10, there will always be at least seven modules available, so that no gas-fired boiler is required.

In summary, these four steam cycle/cogeneration cases were evaluated:

STEAM CYCLE/COGENERATION CONFIGURATIONS

	Monolithic		Modular	
Case Number	7	8	9	10
Energy Source (No. x MWt)				
Primary - HTGR	1 x 2240	1 x 2240	7 x 300	7 x 300
Backup - HTGR	1 x 2240	-	3 x 300	8 x 300
- Gas	1 x 2240	2 x 2240	1 x 600	-

3.4 AVAILABILITY

3.4.1 Methodology

GFY 1983 Economic Ground Rules have assigned values for the unit steam availability as follows:

	Availability, %	
Unit	SC/C	Reformer
Monolithic HTGR	80	75
Modular HTGR	85	80

These values are based on experience from existing plants and ongoing availability analyses within the HTGR program.

The outage rates corresponding to the above unit availabilities were split into forced and scheduled outage rates by assuming these to be equal. Data from the National Energy Reliability Council (NERC) suggest that this is a reasonable split. The reason for splitting the outages is that the calculated availability for a group of units is more rational if the computational method recognizes that unit scheduled outages will not occur simultaneously. For example, in a group of two monolithic HTGRs the refueling outages would not be scheduled for the same time. Forced outages, on the other hand, are treated as being entirely random among those units not on scheduled outage.

The system availabilities were calculated using the combinatorial method, sometimes referred to as the binomial method.

Gas-fired boilers were assumed to have an availability of 95%. This high availability is felt to be reasonable in view of the fact that these units are used only for backup and will only infrequently be operated at full design rates.

In calculating electric power output, the turbine-generator units were assumed to be available 95% of the time that steam was available to drive them.

3.4.2 Availability Results - Reformer Cases

The calculated steam availabilities for the five reformer cases are shown in Table 3-1. Looking first at the two monolithic HTGR-R cases, it is clear that the steam availability is much higher for Case 1 than for Case 2. It is the high fraction of time at zero output, 25%, that necessitates having two gas-fired boilers at each user site in order to achieve the target availability for Case 2.

The three modular cases illustrate the availability characteristic of the modular system. Availability at design output is mediocre. However, it is extremely unlikely that fewer than half the modules are operating. Thus, it is necessary to supply gas-fired boilers to back up only two modules for the twelve-module case since at least seven modules are operating 99.3% of the time. Similarly, for the eleven-module case, at

Table 3-I

STEAM AVAILABILITY SUMMARY FOR REFORMER/TCP SYSTEMS

Case	System Configuration	State, Units Operating	Output, % of Design	State Availability	Cumulative Availability	
1	Two 2240 MWT HTGR-R	2	200	0.549	0.549	
	Twenty-nine 45 MWT Gas-Fired Boilers	1*	100	0.402	0.951	(0.998)**
	at Users' Sites	0	0	0.049	1.000	
2	One 2240 MWT HTGR-R	1*	100	0.750	0.750	(0.999)**
	Fifty-eight 45 MWT Gas-Fired Boilers	0	0	0.250	1.000	
	at Users' Sites					
3	Twelve 250 MWT HTGR-R	11(a)	122	0.215	0.215	
	Seven 45 MWT Gas-Fired Boilers	10	111	0.366	0.581	
	at Users' Sites	9*	100	0.268	0.849	(0.992)**
		8	89	0.113	0.962	
		7	78	0.031	0.993	
		6	67	0.006	0.999	
		5	56	0.001	1.000	
4	Eleven 250 MWT HTGR-R	10(a)	111	0.275	0.275	
	Ten 45 MWT Gas-Fired Boilers	9*	100	0.383	0.658	(0.997)**
	at Users' Sites	8	89	0.235	0.893	
		7	78	0.084	0.977	
		6	67	0.019	0.996	
		5	56	0.004	1.000	
5	Ten 250 MWt HTGR-R	9*(a)	100	0.346	0.346	(0.994)**
	Thirteen 45 MWt Gas-Fired Boilers	8	89	0.390	0.736	
	at Users' Sites	7	78	0.195	0.931	
		6	67	0.057	0.988	
		5	56	0.011	0.999	
		4	45	0.001	1.000	

*Design state
**Availability at 100% of design with gas-fired boilers included
(a) There is always at least one module on scheduled outage

least six modules operate 99.6% of the time, requiring backup for three modules. For the ten-module case, five modules operate 99.7% of the time, and backup for four modules is needed. In each case, each nuclear module removed requires gas-fired backup at three more user sites.

3.4.3 Availability Results - Steam Cycle/Cogeneration Cases

The availability results for two monolithic HTGR-SC/C cases and two MRS-SC/C cases are shown in Table 3-2. Both of the monolithic cases have very high steam availability when the gas-fired boiler backup is included. However, Case 8, with a single HTGR, operates only 80% of the time on nuclear power and will consume a large quantity of gas. Case 7, with two HTGRs, consumes little gas, and, because both reactors are operating 63% of the time, produces much excess steam for generating electricity.

The availability for the ten-module case, Case 9, is nearly high enough (97.7%) without gas-fired boiler backup. However, a gas-fired boiler is included for consistency with the availabilities of the other cases.

The modular case with fifteen modules, Case 10, was included to compare the modular and monolithic systems at the same installed nuclear capacity, in this instance, about 4500 MWt. Since the steam demand has been assumed constant at the output of seven modules, there will be a large amount of excess steam for generating electricity. Also, the availability of steam is essentially unity without any gas-fired boiler backup.

Table 3-2

STEAM AVAILABILITY SUMMARY FOR STEAM CYCLE/COGENERATION SYSTEMS

Case	System Configuration	State, Units Operating	Output, % of Design	State Availability	Cumulative Availability	
7	Two 2240 MWT HTGR-SC/C	2	200	0.631	0.631	
	One 2240 MWT Gas-Fired Boiler	1*	100	0.338	0.969	(0.998)**
	at HTGR Site	0	0	0.031	1.000	
8	One 2240 MWt HTGR-SC/C	1*	100	0.800	0.800	(0.999)**
	Two 2240 MWt Gas-Fired Boilers	0	0	0.200	1.000	
	at HTGR Site					
9	Ten 300 MWt HTGR-SC/C	10	143	0.098	0.098	
	One 600 MWt Gas-Fired Boiler	9	129	0.458	0.556	
	at HTGR Site	8	114	0.317	0.873	
		7*	100	0.104	0.977	(0.999)**
		6	86	0.020	0.997	
		5	72	0.003	1.000	
10	Fifteen 300 MWt HTGR-SC/C	14(a)	200	0.266	0.266	
	No Gas-Fired Boiler	13	186	0.375	0.641	
		12	171	0.238	0.879	
		11	157	0.092	0.971	
		10	143	0.024	0.995	
		9	129	0.004	0.999	
		8	114	0.001	1.000	
		7*	100	0.000	1.000	

*Design State
**Availability at 100% of design with gas-fired boilers included
(a) There is always at least one module on scheduled outages

Section 4

ECONOMIC COMPARISON

Economic comparisons of total capital requirements, 30-year levelized operation and maintenance costs, and the product cost of steam are presented in this section for five reformer cases and four steamer cases. Regulated utility ownership is assumed for all plants. The cost estimates and the approaches used to develop them are described in the following subsections.

4.1 ECONOMIC GROUND RULES

Estimates are prepared in accordance with the economic ground rules adopted by GCRA for the GFY 1983 HTGR Program unless indicated to the contrary. Costs are at the January 1, 1983 price level, with commercial plant operation in January 2005. Estimates are based on Nth Plant engineering and construction.

4.2 CAPITAL COST ESTIMATES

Capital cost estimates for the plants described in the preceding sections of this report are summarized in Tables 4-1 and 4-2. Estimates are based on inputs and comments from GCRA, GA, GE, C-E, and existing cost estimates by UE&C. Bechtel made appropriate adjustments of the UE&C estimates for the size and number of turbine-generator units and associated facilities as defined in this study and given in the tables.

For the reformer/TCP cases, the pipeline cost is based on a 60-mile long TCP. Contingency allowance for the MRS-SC/C cases and for all reformer/TCP cases is 20%, as specified in the GFY 1983 economic ground rules. Contingency allowance for the monolithic HTGR-SC/C cases is 10%, reflecting their more advanced state of development. (The all gas-fired plant, Case 6, also uses 10% contingency.)

Table 4-1

CAPITAL COST SUMMARY FOR REFORMER/TCP CASES

Case	1	2	3	4	5	6
Energy Source, No. x MWt: HTGR	2 x 2240	1 x 2240	12 x 250	11 x 250	10 x 250	-
Gas	29 x 45	58 x 45	7 x 45	10 x 45	13 x 45	58 x 45
TG's, No. x MWe: HP	1 x 220	1 x 220	1 x 155	1 x 155	1 x 155	-
IP-LP	-	-	-	-	-	-
LP	1 x 96	1 x 96	1 x 76	1 x 76	1 x 76	-
Energy Input, 10^{12} Btu/yr						
Nuclear	63.73	50.26	65.84	63.75	59.82	-
Gas	2.33	11.91	1.03	2.50	5.26	47.50
Product Output,						
Steam, 10^{12} Btu/yr	39.07	39.07	38.77	38.77	38.77	38.92
Electricity, 10^9 kWh/yr	0.83	0.66	0.88	0.85	0.80	-
Acct Category			**Capital Costs, $\$10^6$ - Jan 1983 Price Level**			
21 Struct & Improvements	392	279	421	392	364	-
22 Reactor Plant	738	369	583	535	486	-
23 Turbine Plant	72	72	59	59	59	-
24 Electric Plant	67	67	55	55	55	-
25 Misc. Plant	23	23	19	19	19	-
26 Main Cond & Heat Rej	17	17	13	13	13	-
28 Reform Plant	620	310	373	343	312	-
Start-up "Support"	7	7	7	7	7	-
31 TCP	224	224	224	224	224	-
41 Methanation Plants	208	208	208	208	208	-
Gas-Fired Boilers	177	354	45	64	84	354
Total Direct Cost	2,545	1,930	2,007	1,919	1,831	354
Cons. Serv. & Field Eng	509	482	401	384	366	42
Total Field Costs	3,054	2,412	2,408	2,303	2,197	396
Eng Serv & Fees	366	362	289	276	264	18
Contingency	684	555	539	516	492	41
Total Plant Investment	4,104	3,329	3,236	3,095	2,953	455
Owner's Cost	123	166	97	93	89	14
AFUDC @ 4.4%/yr	688	482	460	440	419	21
Total Capital Requirement	4,915	3,977	3,793	3,628	3,461	490

Table 4-2

CAPITAL COST SUMMARY FOR STEAM CYCLE/COGENERATION CASES

Case	7	8	9	10
Energy Source, No. x MWt: HTGR	2 x 2240	1 x 2240	10 x 300	15 x 300
Gas	1 x 2240	2 x 2240	1 x 600	-
TG's, No. x MWe: HP	1 x 425	1 x 227	1 x 300	1 x 420
IP-LP	1 x 699	-	1 x 282	1 x 658
LP	1 x 82	1 x 82	1 x 77	1 x 77
Energy Input, 10^{12} Btu/yr				
Nuclear	107.21	53.61	76.30	114.43
Gas	2.19	14.07	0.28	-
Product Output,				
Steam, 10^{12} Btu/yr	57.67	57.67	54.05	54.05
Electricity, 10^9 kWh/yr				
- Firm	2.92	1.46	2.26	5.44
- Nonfirm	3.09	-	0.80	1.42

Acct	Category	Capital Costs, $\$10^6$ - Jan 1983 Price Level			
		7	8	9	10
21	Struct & Improvements	327	155	384	516
22	Reactor Plant	636	318	515	772
23	Turbine Plant	208	71	135	203
24	Electric Plant	86	41	60	84
25	Misc. Plant	21	12	17	20
26	Main Cond & Heat Rej	34	9	11	33
	Gas-Fired Boiler	126	252	57	-
	Total Direct Cost	1,438	858	1,179	1,628
	Cons. Serv. & Field Eng	288	214	236	326
	Total Field Costs	1,726	1,072	1,415	1,954
	Eng Serv & Fees	207	161	170	234
	Contingency	193	123	317	438
	Total Plant Investment	2,126	1,356	1,902	2,626
	Owner's Cost	64	68	57	79
	AFUDC @ 4.4%/yr	356	196	270	373
	Total Capital Requirement	2,546	1,620	2,229	3,078

4.3 STEAM PRODUCT COST ESTIMATES

Steam product cost estimates are based on GFY 1983 economic ground rules. These differ from the GFY 1982 ground rules in four major respects:

- Nuclear fuel cost for the modular reactors - Preliminary economic studies had shown the fuel cost for the MRS to be much higher than for the monolithic system. This was due largely to the 4-year refueling interval used for the MRS compared to the 1-year refueling interval of the monolithic HTGR. Reducing the MRS refueling interval to 2 years has brought the fuel cost more in line with that for the monolithic system.

- Price level cost basis - The price level cost basis is January 1983 instead of January 1982. This represents a 4% escalation.

- Fixed charge rate - The fixed charge rate is 8.5% instead of 6.7% as in the GFY 1982 economic ground rules.

- Electric power credit - Electric power is divided into two categories, firm and nonfirm. Firm power has a forced outage rate not exceeding 15%; nonfirm power has a forced outage rate greater than 15%. Firm power is credited at 53 mills/kWh and nonfirm power at 33 mills/kWh. This recognizes the lower value of the interruptible nonfirm electric power.

4.4 DISCUSSION OF RESULTS

4.4.1 Reformer Cases

The steam cost calculations for the reformer cases are summarized in Table 4-3. Since the life of the reformer is estimated to be 15 years, or half of the project life, a sinking fund has been provided to replace the reformer after 15 years.

Cases 1 and 2, the two monolithic cases, show essentially equal process steam cost, about $\$16/10^6$ Btu. The lower capital cost and operating and maintenance costs for Case 2 are offset by the cost of its higher gas consumption.

Table 4-3

STEAM COST SUMMARY FOR REFORMER/TCP CASES

Case		1	2	3	4	5	6
Energy Source, No. x MWt:	HTGR	2 x 2240	1 x 2240	12 x 250	11 x 250	10 x 250	-
	Gas	29 x 45	58 x 45	7 x 45	10 x 45	13 x 45	58 x 45
Steam Produced, 10^{12} Btu/yr		39.07	39.07	38.77	38.77	38.77	38.92
Total Capital Requirement, $\$10^6$		4,915	3,977	3,793	3,628	3,461	490
Annual Operating Cost, $\$10^6$ - 30 Yr. Levelized							
Fixed Charges @ 8.5%		418	338	322	308	294	41
Fuel - Nuclear		101	79	118	114	107	-
Gas		26	134	12	28	59	535
Operation & Maintenance							
Fixed							
HTGR, Ref, & TG		90	60	75	75	75	
TCP & Methanation		13	13	13	13	13	-
Gas-Fired Boilers		9	19	2	3	4	29
Variable							
HTGR, Ref, & TG		11	9	12	11	11	-
TCP & Methanation		9	7	9	9	8	-
Gas-Fired Boilers		-	-	-	-	-	3
Reformer Sinking Fund		19	10	10	9	8	-
Total Operating Cost-Gross		696	669	573	570	579	608
Electrical Revenue							
Firm @ 53 x 1.06[a] mills/kWh		(47)	(37)	(49)	(48)	(45)	-
Net Operating Cost		649	632	524	522	534	608
Process Steam Cost, $\$/10^6$ Btu		16.6	16.2	13.5	13.5	13.8	15.6

(a) Levelizing factor per GFY 1983 Economic Ground Rules

The three MRS-R/TCP cases, Cases 3, 4, and 5, show that the minimum product cost case is the twelve or eleven module configuration, although the cost difference is not significant. The calculated cost for process steam, about $\$13/10^6$ Btu, is somewhat lower than for the monolithic cases. Therefore, if there is to be future work on the HTGR-R/TCP concept, the modular approach should be emphasized.

Case 6, Table 4-3, shows the cost for supplying steam at 29 user sites using only gas-fired boilers. For this latter case it was assumed that two gas-fired boilers would be needed at each site to achieve the target availability. In effect, this is Case 2 without the HTGR-R/TCP.

The cost difference between the MRS-R/TCP cases and the gas-fired boiler case, Case 6, favors the MRS-R/TCP by about $\$2/10^6$ Btu. However, the cost of process steam from an atmospheric fluidized bed (AFB) process combustion system is in the $\$6$ to $\$8/10^6$ Btu range (Reference 1-6), well below that for the MRS-R/TCP concept. Therefore, there is no economic incentive for pursuing the development of the MRS-R/TCP concept in the near term for the production of distributed process steam.

There is another potential application for the HTGR-R, namely open cycle reforming to augment the energy content of natural gas or to generate a feedstock for manufacture of hydrogen, methanol, or other chemicals. This subject will be addressed in the Applications Assessment Summary Report to be published in the spring of 1983.

For most HTGR-R configurations there is some installed excess HTGR-R capacity. When not needed for backup, this excess capacity could be used to produce syngas and steam. However, it is difficult to construct a scenario in which it would be practical and economic to utilize this added product because of its poor availability. Therefore, the reformer/TCP cases described above have taken no credit for this potential revenue source.

Two subcases were evaluated in the attempt to show the HTGR-R/TCP in its most favorable light. For these subcases, variants of Cases 1 and 3, it was assumed that the HTGR-R capacity that would otherwise be on standby could at least be operated at reduced rate to produce its full output of steam. This excess steam would be handled as shown in Figure 3-4 for Case 7, passing through the HP turbine and an IP/LP turbine to generate electricity.

In making this calculation only the value of the electric power (nonfirm), the cost of added capital equipment to generate electricity, and the added nuclear fuel cost were taken into account. For Case 1, the cost of process steam would be reduced to $\$16.0/10^6$ Btu and for Case 3 to $\$13.3/10^6$ Btu. The effect is greater for Case 1, because, as shown in Table 3-1, it has more excess capacity. However, in neither case is the cost of process steam decreased enough to change the above conclusion regarding non-competitiveness with alternative fossil-fired steam supply systems.

4.4.2 Steam Cycle/Cogeneration Cases

The steam cost calculations for the steamer cases are summarized in Table 4-4. The best configurations, Cases 7, 9, and 10, show process steam costs in the range of $\$3$ to $\$4/10^6$ Btu. For comparison, steam from a coal-fired cogenerator is estimated to be in the $\$4$ to $\$6/10^6$ Btu range (Reference 1-6).

The case with two monolithic HTGRs, Case 7, has a product steam cost that is clearly less than that of the case with one HTGR, Case 8. The higher capital and operating costs of Case 7 are more than offset by the value of the co-produced electricity.

The two MRS-SC/C configurations, Cases 9 and 10, have different rationales. The ten-module case, Case 9, is designed to supply process steam at a rate to match the output of one monolithic reactor with a minimum of either gas-fired boiler backup or excess installed nuclear ıbl 4

STEAM COST SUMMARY FOR STEAM CYCLE/COGENERATION CASES

Case		7	8	9	10
Energy Source, No. x MWt:	HTGR	2 x 2240	1 x 2240	10 x 300	15 x 300
	Gas	1x 2240	2 x 2240	1 x 600	-
Steam Produced, 10^{12} Btu/yr		57.67	57.67	54.05	54.05
Total Capital Requirement, $\$10^6$		2,546	1,620	2,229	3,078
Annual Operating Cost, $\$10^6$ - 30 Yr. Levelized					
Fixed Charges @ 8.5%		216	138	189	262
Fuel - Nuclear		143	71	127	190
Gas		25	158	3	-
Operation & Maintenance					
Fixed					
HTGR & TG		60	40	50	50
Gas-Fired Boiler		4	6	4	-
Variable					
HTGR & TG		9	5	7	10
Gas-Fired Boiler		-	-	-	-
Total Operating Cost - Gross		457	418	380	512
Electrical Revenue					
Firm @ 53 x 1.06[a] mills/kWh		(164)	(82)	(127)	(305)
Nonfirm @ 33 x 1.13[a] mills/kWh		(114)		(30)	(53)
Net Operating Cost		179	336	223	154
Process Steam Cost, $\$/10^6$ Btu		3.1	5.8	4.1	2.8
with 50% of electrical revenue		5.5	6.5	5.6	6.2

(a) Levelizing factor per GFY 1983 Economic Ground Rules capacity. This case shows only a slightly lower capital requirement than Case 7, the two-HTGR monolithic configuration, and the lower quantity of co-produced electricity leads to a higher process steam cost. The fifteen-module configuration, Case 10, matches Case 7 on the basis of total installed nuclear plant capacity. This case generates a large amount of excess steam from which to produce electric power. Table 3-2 shows that twelve modules, five more than needed for process steam, are available 88% of the time. Therefore, most of the excess steam produces firm electric power (forced outage rate less than 15%), which receives a high value. As a result, even though the capital cost of Case 10 is higher than that of Case 7, these two cases produce process steam at essentially the same cost.

Comparison of Cases 7 and 8 and of Cases 10 and 9 illustrate the economic benefit of maximizing cogenerated electricity. In effect, the electric power credit is subsidizing process steam cost. However, in order to realize this benefit, Cases 7 or 10 must serve a large market for both process steam and electric power. In other scenarios, capital budgeting constraints may be more of a driving factor than absolute lowest cost of production.

The sensitivity of product costs to credit for electricity is illustrated in the last line of Table 4-4. If the electric power revenue is assumed to be reduced by 50%, the resulting process steam costs for Cases 7 and 9 become equal at about $\$5.5/10^6$ Btu. The loss in electric power revenue increases the process steam cost for Case 10 to $\$6.2/10^6$ Btu. Clearly the value assigned to electric power is a critical parameter.

Section 5

CONCLUSIONS FROM MONOLITHIC VERSUS MODULAR COMPARISON

The following conclusions can be made from the economic comparison of monolithic and modular HTGR concepts for the reformer/thermochemical pipeline and steam cycle/cogeneration applications:

- HTGR - Reformer/Thermochemical Pipeline serving a dispersed baseloaded steam market

  - Steam product costs for either the monolithic or modular plants are not sensitive to the backup strategy. Nuclear and gas-fired backup lead to the same cost for process steam.

  - Capital investment and steam product costs are clearly lower for the modular concept.

  - Steam product cost ($\$16/10^6$ Btu) for the monolithic-reformer/TCP plant concept are basically the same as for a comparable distributed natural gas-fired system ($\$15.6/10^6$ Btu).

  - Steam product cost ($\$13/10^6$ Btu) for the modular-reformer/TCP plant is marginally competitive with a comparable distributed natural gas system. However, it is not competitive with alternative small coal-fired systems such as the atmospheric fluidized bed (AFB) combustion system ($\$6$ to $\$8/10^6$ Btu).

  - Considering the above, further development of the HTGR-R/TCP application is not warranted in the near term.

- HTGR - Steam Cycle/Cogeneration serving a concentrated baseloaded steam market

  - Steam product costs ($\$3$ to $\$4/10^6$ Btu) for both the monolithic and modular systems are competitive with gas- and coal-fired systems.

- Steam product costs for both HTGR systems are sensitive to the revenue from the sale of electricity. In cogeneration markets needing large amounts of electricity with sufficient electricity credit, the monolithic and modular systems become increasingly competitive with fossil systems.
- Considering the favorable economic potential of the modular HTGR-SC/C concept, further development is warranted. This is in addition to the ongoing development of the monolithic HTGR-SC/C Lead Plant.

Within the next few months two GCRA reports that are significant in the ongoing evaluation of the modular and monolithic HTGR concepts will be issued. The first report, entitled "HTGR-SC/C Economic Evaluation" (Reference 1-6), will elaborate on the comparative economics of the two HTGR system configurations as well as alternate coal-fired systems. The impact of market size and the sensitivity to economic factors such as electric credit and unit availability will be investigated. The second report, entitled "Application Assessment Summary" (Reference 1-7), will summarize the application/comparison of the HTGR-SC/C and the HTGR-R for petroleum recovery, synfuel manufacture, etc. The economic incentives for the open reforming cycle will be included.

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1-2 "Modular HTGR Systems Design and Cost Summary," prepared by Bechtel Group, Inc. for Gas-Cooled Reactor Associates, January 1983.

1-3 "HTGR-Steam Cycle/Cogeneration, Lead Plant Design Cost Report, Volume 1: Summary," issued by GCRA, July 1982.

1-4 "Potential Market for Industrial Process Steam From an HTGR Cogeneration Facility," Sherman A. Reed, ORNL Gas-Cooled Reactor Programs, ORNL/GCR - 80/13.

1-5 "Small-Scale Modular HTGR for Steam Cogeneration," S. Golan, et al., of Bechtel Group, Inc., presented at 1982 Utility/User Conference on the HTGR.

1-6 "HTGR-SC/C Economic Evaluation," to be issued by GCRA in April 1983.

1-7 "Application Assessment Summary," to be issued by GCRA in April 1983.