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Gas-Cooled Reactor Associates

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HIGH-TEMPERATURE PROCESS HEAT
INTERIM DESIGN AND COST STATUS REPORT
FY 1981

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High Temperature Gas-Cooled Reactor Program

DISCLAIMER

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Introduction

Studies conducted on HTGR systems in FY 1980 were concluded in Application Study Reports to describe the preconceptual system designs to that point and discuss possible applications for three variations of the systems; the steam cycle/cogeneration plant, the higher temperature reformer plant, and the gas turbine concept.

The HTGR-Reformer Application Study was conceived and directed to evaluate the HTGR-R with a core outlet temperature of 850°C as a near-term Lead Project and as a vehicle to long-term HTGR Program Objectives. The scope of this effort included evaluations of the HTGR-R technology, evaluation of potential HTGR-R markets, assessment of the economics of commercial HTGR-R plants, and the evaluation of the program scope and expenditures necessary to establish HTGR-R technology through the completion of the Lead Project.

In addition to the configurations described above, the Nuclear Heat Source Demonstration Reactor (NHSDR) was examined as a more developmental path to HTGR demonstration. In concept, the NHSDR combines demonstration of both the HTGR-GT and HTGR-R technologies with additional potential for even higher temperature applications. As a result of the study, the NHSDR was found to be unsuitable as a lead project in its proposed configuration for the following reasons:

- HTGR-GT studies have not yet provided sufficient justification for development.

- While the size and cost of the NHSDR were of commercial scale (fixed in accordance with HTGR-GT demonstration needs), prospects for investment recovery through commercial operation were minimal due to the noncommercial configuration and projected mission in advanced systems development. Accordingly, minimal bases exist for utility/user interest and financial support.

2.0 SUMMARY OF FY 1980 APPLICATION STUDY RESULTS

The time constraints set forth in the HTGR Lead Project Identification Plan permitted consideration of the specified Lead Project configuration, including its commercial potential, but were inadequate for the development of an optimized HTGR-R commercial plant design and cost estimate. As a result, the major findings of the study indicated that:

- There was a large potential market for an energy system with the energy transmission and storage capabilities of the HTGR-R if economic goals could be met and if institutional and technical barriers could be overcome in a timely manner.

- The significant environmental benefits which are attained through offset of fossil fuels are a key market factor in the projected deployment of HTGR-R systems.

- The 850°C HTGR-R plant as configured and applied in the study has limited economic potential.

In order to properly assess the potential of the HTGR-R and the suitability of the HTGR-R as a candidate lead project, additional work beyond that completed in FY 1980 needed to be performed before a final judgment could be rendered. Design trade-off and alternative applications studies were required to determine if a commercial potential existed for the HTGR-R at 850°C. If commercial incentives were identified for the HTGR-R only with core outlet temperatures greater than 850°C, the design and development program duration and cost and the demonstration path for the HTGR-R would have to be reassessed. The FY 1981 HTGR Program addressed these issues. In addition to reforming, a potential for the application of high-temperature direct heat to synthetic fuels processes was identified during the course of the FY 1980 investigations. This potential deserved further exploration and was also included within the scope of the FY 1981 HTGR Program effort.

3.0 FY 1981 Workscope

FY 1981 studies comprised the further definition and evaluation of HTGR high temperature process heat applications. Of these studies, one element was centered upon the further development of the HTGR reforming concept in which a portion of the energy produced by the High-Temperature (850°C-950°C) Nuclear Heat Source (NHS) is utilized to convert a steam-hydrocarbon mixture to synthesis gas (H_2 and CO) using the reforming process. The synthesis gas can subsequently be employed as a distribution medium for stored reactor energy (Thermochemical Pipeline) or can be used as feedstock for a chemical process such as synfuels manufacture from coal.

An additional effort in FY 1981 was directed toward development of direct heat applications to a variety of processes as discussed below.

Integrated plant designs were produced for specific applications. Design activities were conducted in sufficient detail to establish preferred plant configurations and to facilitate technical, economic, and institutional evaluations. Additional, more detailed designs were undertaken as required to establish design data needs for selected systems and components. In completing these activities, maximum use was made of existing data developed through prior studies.

Key issues addressed within the context of the High Temperature Process Heat Study included the following:

- Configuration of the Nuclear Heat Source - Principal options addressed were direct vs. indirect cycle reforming, secondary pressure vessel configuration (indirect cycle-steel vessels vs. PCPV), and primary and secondary heat exchanger design options.

- Nuclear Heat Source operating parameters - Core outlet temperatures of up to 950°C were considered. Other key parameters investigated included reformer/steam generator crossover temperature and core temperature rise.

- Evaluation of the HTGR for application to a wide range of potential market opportunities in the areas of energy distribution (Thermochemical Pipeline and related applications) and direct heat (hot helium) input to integrated chemical processes (coal gasification and liquefaction, shale oil recovery, synthesis gas production, etc.)

In addressing the issues identified above, the High Temperature Process Heat Study was comprised of three principal elements which were conducted in parallel: Nuclear Plant Design and Evaluation, HTGR Applications Screening, and Utility/User Applications.

The Nuclear Plant Design and Evaluation element addressed configurational issues and provided an input to the selection of operating parameters. Additionally, the capital cost data developed provided a basis for extrapolation to various applications as an input to computing total product costs. Within this element, designs were developed for both the direct cycle and indirect cycle versions of the HTGR-R on the basis of open cycle reforming. Included in the study was the Nuclear Heat Source (NHS) and the balance of plant (BOP) through the reformers and steam generators. The turbine plant and piping to the nuclear site boundary were also included. Representative input and output parameters were selected so as to provide a consistent basis for comparison. From a basic design point in the case of each configuration, parameters of interest, notably including core outlet temperature, reformer/steam generator crossover temperature, and core temperature rise, were extrapolated over a range of interests. The extrapolation took into account performance effects as well as major design impacts on systems and components (e.g., materials changes, lifetimes, etc.). Other designs developed within this element addressed various direct heat applications and were derived from the basic indirect cycle reformer design. Through the use of coordinated Architect/Engineering support, the direct and indirect cycle designs were evolved on a consistent basis of safety and reliability and cost estimates were developed using consistent economic ground rules. In addition to providing the basic data required to address configurational issues, the capital cost estimates resulting from this element were a basis for extrapolation to various specific applications. Parametric data to be developed formed a basis along with application requirements for selecting operating parameters.

A second principal element included within the High Temperature Process Heat Study was HTGR Applications Screening. Within this element, a wide variety of potential applications were addressed. Notable examples are various coal gasification and liquefaction processes, oil recovery from shale and tar sands, synthesis gas production from light hydrocarbons, Thermochemical Pipeline concepts and others. Based upon existing data, a coordinated effort was undertaken by an Application Screening Committee (consisting of representatives from study participants) to identify high-interest candidates and to set priorities. For selected processes, in-depth investigations were conducted to evaluate process systems and subsystems and to determine the potential impact of substituting HTGR derived energy. Key elements addressed were conventional and nuclear energy interfaces with the process, process modifications required, present and planned use of waste streams, etc. Based upon these investigations, projections have been made regarding the feasibility of incorporating HTGR derived energy and the impact on product cost, resource requirements, environmental impact, etc. The effort described within this element of the study was coordinated with application studies addressing the Steam Cycle/Cogeneration and Sensible Energy Transmission and Storage concepts to derive a common basis for comparison. Data regarding conventional processes were also developed on a consistent basis for comparison.

The third principal element of the Reforming Application Study was Utility/User Applications. Within this element, specific utilities/users were identified which expressed an interest in a site-specific study. Primary participants in these studies included Public Service Electric and Gas Company, and a two-party combination of Idaho Power and Light Company and Idaho Nuclear Engineering Laboratory. The scope of the site-specific studies are similar in concept to the detailed screening studies described above.

As a means of focusing the Technology Program, a reference HTGR-Process Heat design was required. As an interim assumption, the baseline design was identified to be the 850°C Indirect Cycle HTGR which is documented in the HTGR-Reforming Application Study: Interim Report completed during FY 1980. Based upon the reference design, Data Needs Packages were prepared as input to the establishment of Development Plans and the subsequent identification of a Technology Program Baseline.

Results of the Project Screening Phase of the High Temperature Process Heat application studies will be documented through a comprehensive Concept Evaluation Report to be published in FY 1983. Additional documentation will be provided through appropriate supporting topical and periodic reports.

Summary Results of FY 1981 Studies

Beyond the near term applications of the HTGR using steam cycle technology, an incremental potential may be identified for advanced HTGR systems providing direct process heat. An HTGR NHS configured for such applications is depicted in Figure 1.

HTGR REFORMER (PROCESS HEAT) SYSTEM
1170 MWt

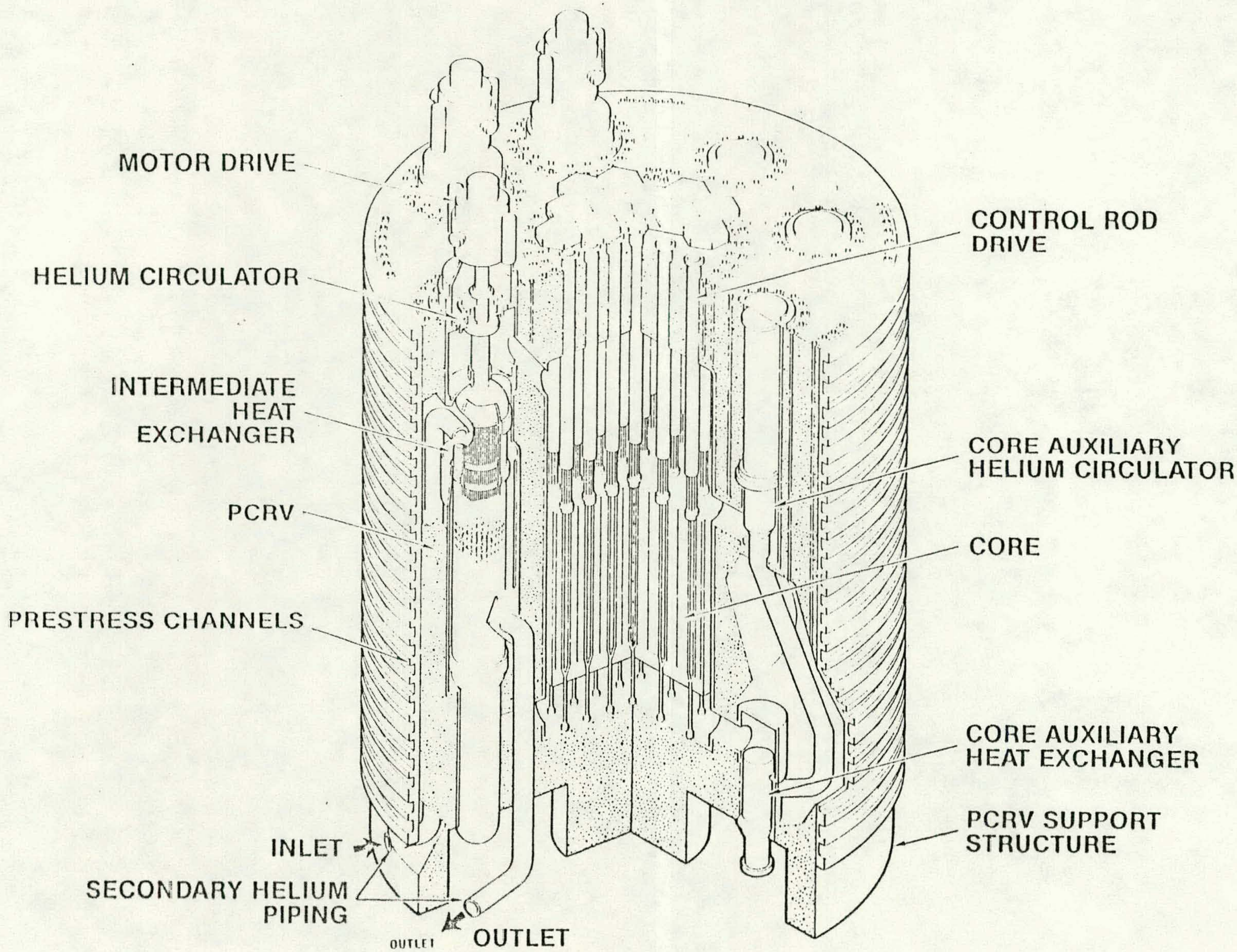

Figure 1

The incremental potential of such a system may be illustrated through a typical example which was explored during FY 1981. In this example, the HTGR facility was configured to provide both process energy (in the form of direct heat and steam) and electrical energy for the Exxon Catalytic Coal Gasification (ECCG) process. The product of the ECCG process is methane (called Substitute Natural Gas or SNG).

The ECCG process uses alkali metal salts as catalysts mixed directly with the feed coal to promote low-temperature gasification. Use of this catalyst also increases the rate of steam gasification, reduces agglomeration of caking coals, and promotes the achievement of gas compositions closely approaching gas phase methanation equilibrium. The process utilizes a fluidized bed gasification system that operates in a well-mixed mode approaching isothermality, the fluidizing gas being steam and recycle hydrogen and carbon monoxide.

Figure 2 shows the ECCG process heat requirements that have potential for HTGR coupling. Up to 997 MWt of energy at temperatures ranging from 472°F to 1575°F could be coupled to a plant designed to gasify 12,000 tons/day of coal. This process also consumes electrical power in the amount of 190 MWe. Four process steps show potential for coupling: 1) the gas preheat furnace for the gasifier, 2) the coal/catalytic drier (2nd drying stage), 3) the raw coal drier (1st stage drier), and 4) offsite boilers supplying process steam.

The use of HTGR-derived heat to replace combustion in the ECCG process results in significant savings to the environment and of coal and product gas including:

- 2940 tons/day of coal not burned,
- 230 tons/day of product methane not burned,
- 265 tons/day of ash not generated, and,
- 6908 tons/day of carbon dioxide not emitted.

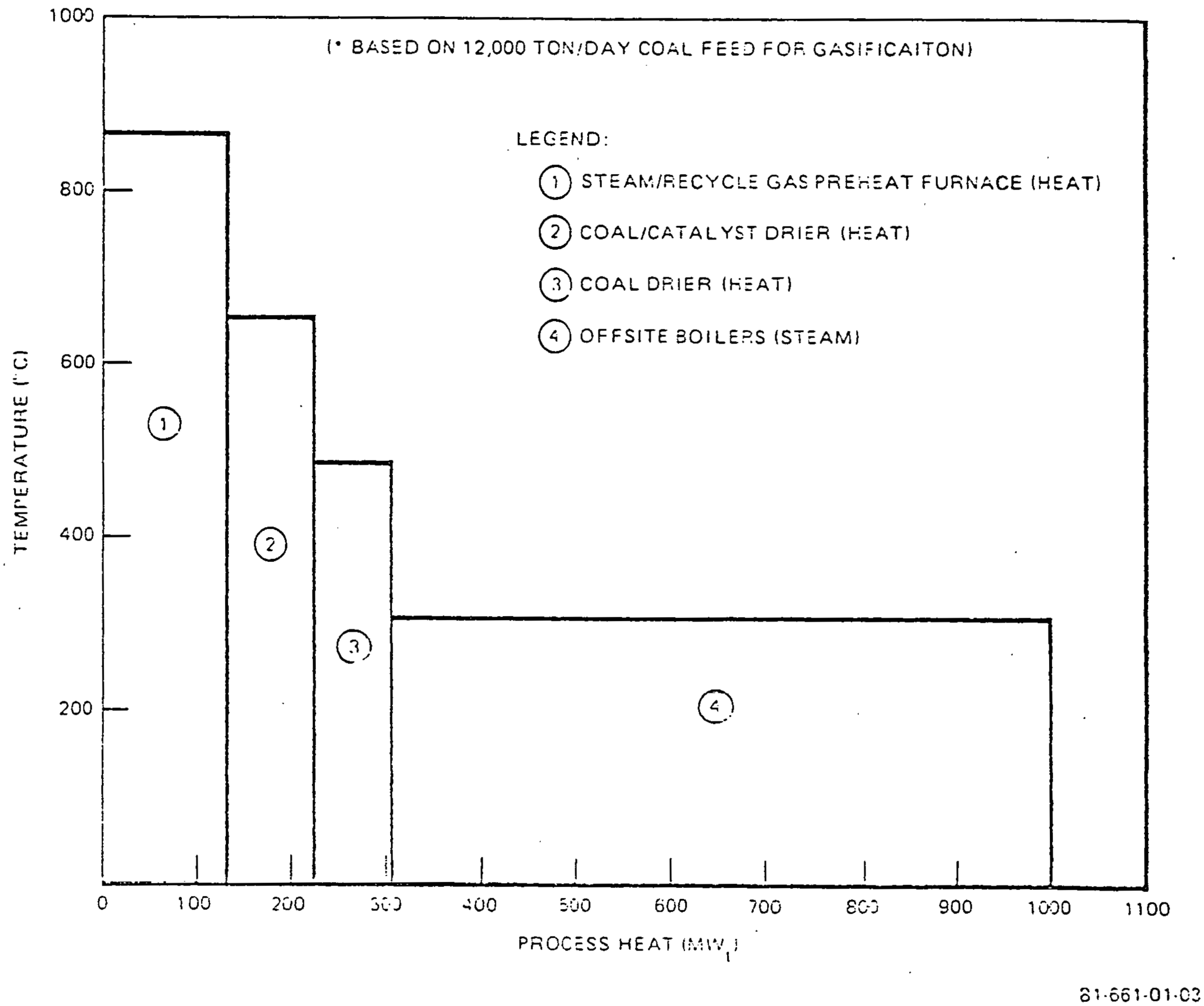

Figure 2 Exxon Catalytic Coal Gasification Process - Process Heat Needs with Potential for HTGR Coupling

The technical and economic implications of high temperature direct heat applications such as the above continue to be assessed in the U.S. HTGR Program. Future emphasis will be placed upon reducing the relatively high capital costs which appear to be associated with such systems. Unless such cost reductions can be realized, the incremental capabilities of high temperature direct heat systems may not be warranted except in specialized circumstances.

Steam Methane Reforming and the Thermochemical Pipeline

The HTGR is unique among nuclear energy systems in that it can operate at temperatures high enough (850°C to 1000°C) for efficient steam reforming of methane. The high temperature helium coolant is used to drive the reformer to produce hydrogen in the form of syngas and thereby chemically store the nuclear heat from the HTGR. The syngas product can be transported long distances to dispersed process heat users. Using the reverse (methanation) reaction a closed loop energy system, or thermochemical pipeline (TCP), can be formed to deliver nuclear energy to small dispersed industrial process heat users with methanators added at the user sites. Water and methane are returned from the methanator plants to the HTGR-R plant. This TCP concept is depicted in Figure 3. Furthermore, for an open loop reforming system the hydrogen in the syngas can be used as a feedstock or as a fuel for a variety of dispersed applications such as production of coal derived liquids, ammonia, and methanol and the processing of steel. FY 1981 studies indicate that implementation of the HTGR-R in these types of applications could both increase the supply of, and substitute for, fluid fuels and thus have a major impact on all global energy systems.

The benefits of such a system have been evaluated and show that the TCP energy system concept has the potential to compete with nuclear electricity and with fossil energy systems such as substitute natural gas (SNG) and local fluidized bed coal combustors for one and two shift process heat operations. Energy delivery cost projections show that at distances approximating 30 miles or greater the TCP may be the lowest cost system for delivery of energy including direct transmission of nuclear generated steam. This relationship continues for distances as great as 200 miles.

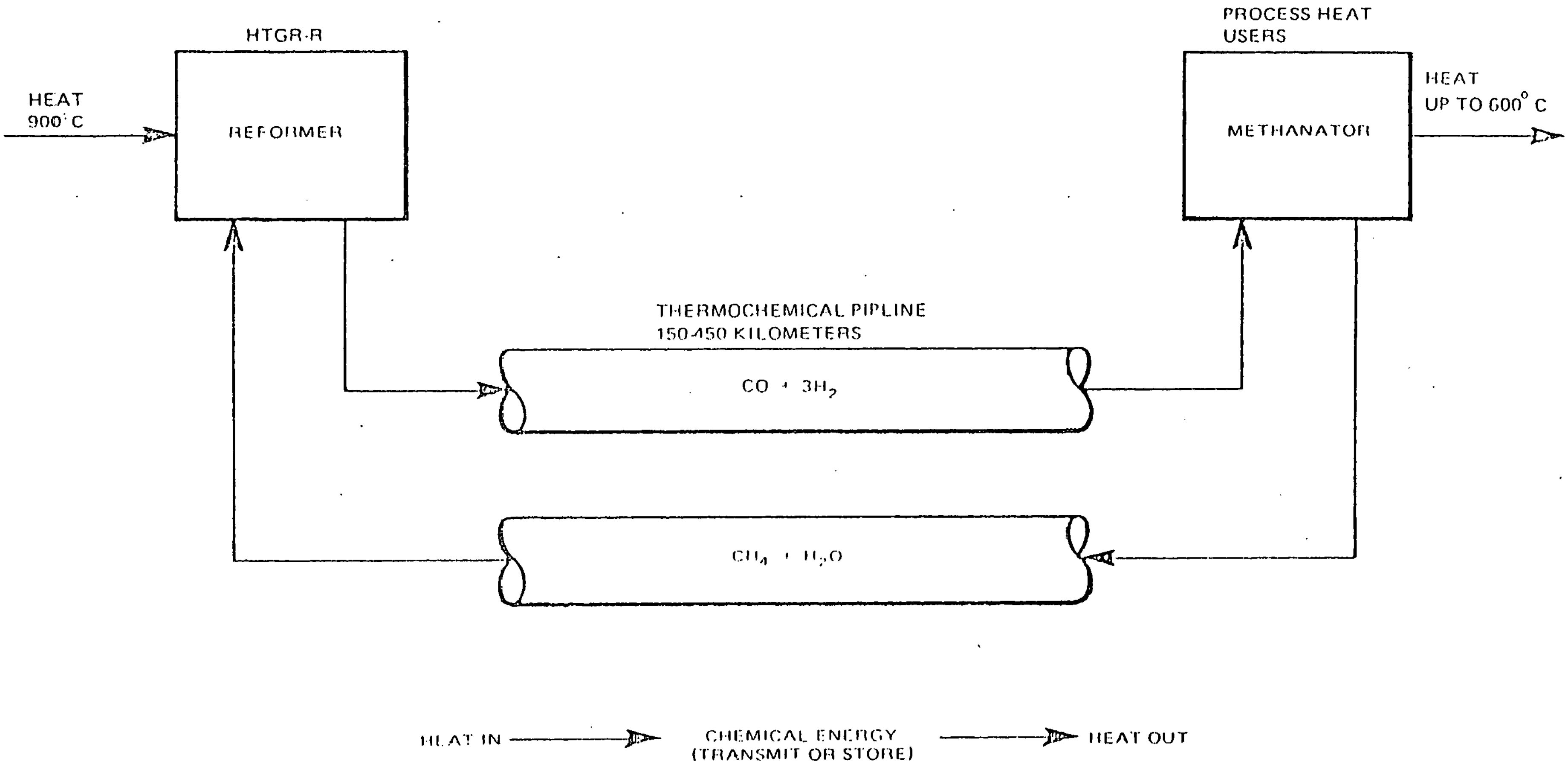

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Figure 3 Thermochemical Pipeline Concept

The reforming version of the HTGR is a developmental advanced system and major tradeoffs must be made to select the optimal HTGR-R plant design. Principal changes under consideration are between high or low reactor core outlet temperatures and between direct and indirect cycle reactor plant configurations.

Since reforming activity decreases below 600°C and the rate of reforming increases with elevated temperature, there is an incentive to use a higher core outlet temperature to achieve better plant performance. However, the higher temperatures usually require more expensive materials and additional technology development. The selection of the direct or indirect steam reforming configuration depends upon economical and safety/licensing considerations. For the indirect cycle (IDC) configuration, an intermediate heat exchanger (IHX) is located within the prestressed concrete reactor vessel (PCRV) and secondary helium is piped to the reformers and the steam generators located outside the containment building. The direct cycle (DC) configuration eliminates the secondary helium loops with both the reformers and steam generators located within the PCRV. The two plant design configurations and two temperature options of 950°C and 850°C result in four reactor plant cycles for comparative evaluation. However, only the 950°C DC and 850°C IDC configurations are being evaluated in the current program. The relative performance of the other two reactor plant cycles (950°C IDC and 850°C DC) will be inferred from the results of the study.

The heat cycles, key process equipment, system configuration and overall heat balance have been defined for comparison of the major plant characteristics and cycle efficiencies of the two reactor systems being studied. System economics, reliability, performance and operability/controllability are design criteria used to optimize system design conditions. Parametric studies have been performed to define the principal plant parameters. The balance of plant (BOP) design has evolved in several stages resulting in the selection of a thermally-driven heat cycle and the incorporation of contact condenser/evaporator heat exchangers.

A layout of the HTGR direct cycle reformer plant configuration is shown in Figure 4. This passive system was found to be less costly and more reliable than the turbocompressor heat cycle considered as an alternative for the BOP system. The contact condenser/evaporator replaces the mix-feed-evaporator as the key process equipment

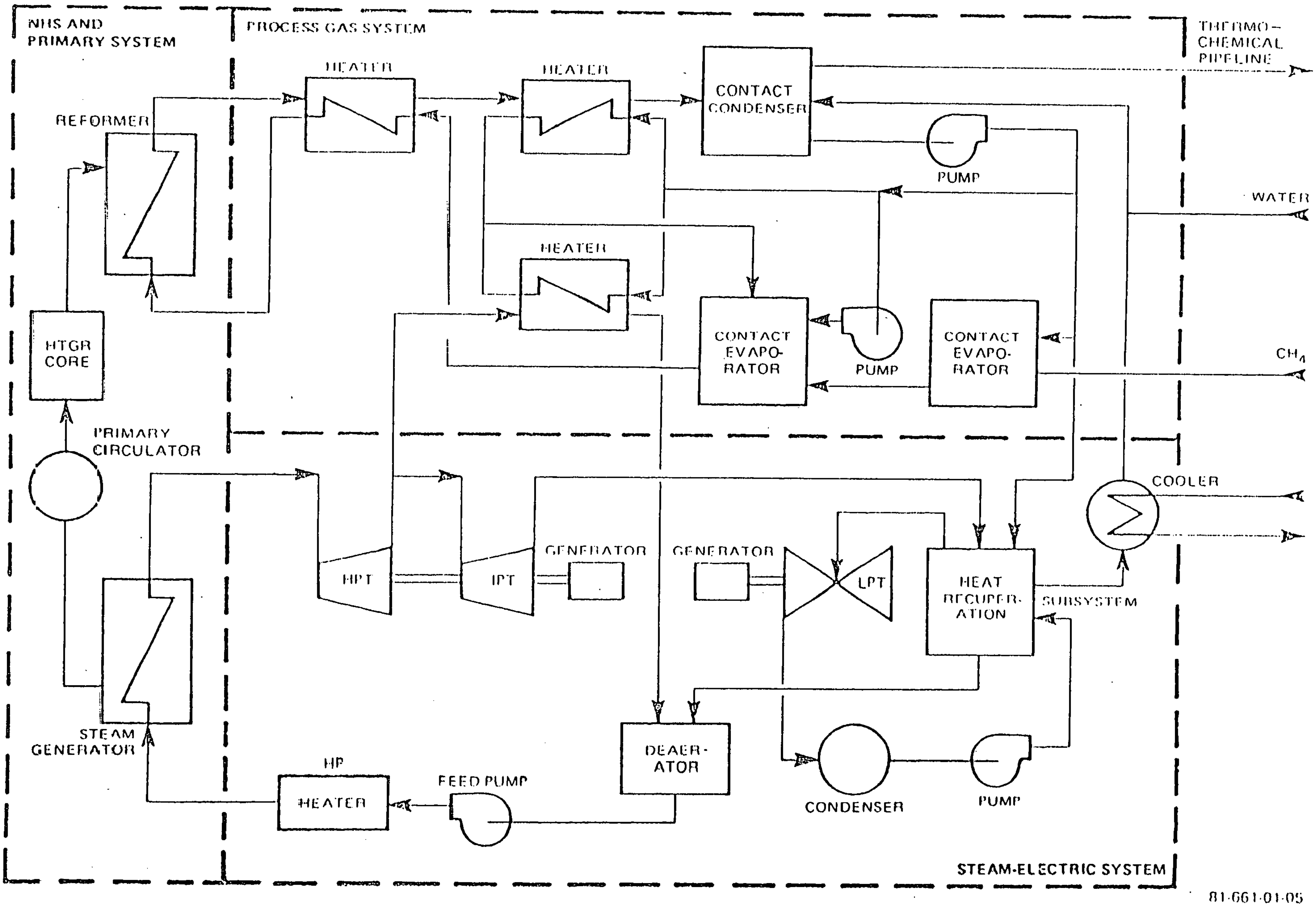

Figure 4 HTGR Direct Cycle Reformer Plant Configuration

for the reformer BOP plant system. The simplicity of the direct contact heat exchanger design will reduce component costs of the key process heat exchange equipment and increase system reliability. As the component configuration for the 950°C DC and 850°C IDC process plant are almost identical, key plant characteristics and operational capabilities for both cycles can be easily compared.

To maximize the cycle efficiency of the HTGR-R plant, four plant features have been incorporated into the design and operation to reduce the overall plant waste heat rejection.

1. Steam is condensed in the contact condenser to conserve the energy and as a source of heat and water supply for the reforming process. The process system operating at higher pressure is designed to allow more waste heat to be recovered into the steam-electric system.

2. The 40 psia pressure is also selected for the LP turbine to maximize the waste heat that could be recovered from the process plant.

3. The low pressure steam reheat arrangement improves the heat rate of the LP turbine.

4. The turbine feedwater is heated with the waste heat from the process system to maximize the gross power output of the steam-electric system.

A summary of the plant performance for the reference 950°C DC and 850°C IDC HTGR-R plants is presented in Table 1. The overall plant efficiency is defined as the sum of the net power output and pipeline thermochemical energy divided by the core power. It is used as a means to compare the relative overall performance of the HTGR-R for different plant design conditions. The overall plant efficiency is about 65% for the reference 950°C DC plant design and 47% for the 850°C IDC Plant. The reformer split referred to in the table is that percentage of the total energy which is input to the reformer.

The current estimate of the relative delivered energy costs via the TCP show an advantage for the 950°C direct cycle plant of approximately 25% over the 850°C

TABLE 1

HTGR REFORMER PLANT PERFORMANCE

Reforming Pressure Reformer Split	850°D IDC 25 Bar 42%	950°C DC 49 Bar 54%
Core Power, MWt	1170	1170
Circulator Power*, MWe	-99.5	-65.6
Reformer System Pumping**, MWe	-3.6	-0.7
Heat Added by Steam System, MWt	+384	+265
Heat Rejected to Steam System, MWt	-352	-232
Pipeline Pumping**, MWe	-73.0	-33.0
Plant Heat Rejection, MWt	-580	-380
Feed Pump Power, MWe	-6.0	-6.7
Auxiliary Load, MWe	-10.0	-8.0
Gross Power Output, MWe	191.8	169.7
Electric Power, MWe 24 Hr/day Net	0	55
Thermal Energy, MWt		
Available 8 hr/day	1635	1995
Available 24 hr/day	545	665
Overall Efficiency, %	47	65

* Circulator Efficiency: Drive = 92%, Control = 96%

** Pumping Efficiency: Drive = 92%, Pumping = 84%

indirect cycle plant. The comparative costs to be documented later include estimated capital and fuel costs, as well as influence of thermal efficiency differences.

Detailed Results of FY 1981 Studies

Documentation of the detailed results of studies conducted with the HTGR-Process Heat system during FY 1981 will be published in a report titled "High Temperature Process Heat - Design and Cost Status Report - FY 1981". This report is due for distribution prior to the end of calendar year 1981 and will contain the specific results of the design tasks and cost estimates discussed in this report.