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COLIN F. McDONALD and CHARLES R. BOLAND

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ABSTRACT

Combining the modern and proven power conversion system of the closed-cycle gas turbine (CCGT) with an advanced high-temperature gas-cooled reactor (HTGR) results in a power plant well suited to projected utility needs into the 21st century. The gas turbine HTGR (HTGR-GT) power plant benefits are consistent with national energy goals, and the high power conversion efficiency potential satisfies increasingly important resource conservation demands. Established technology bases for the HTGR-GT are outlined, together with the extensive design and development program necessary to commercialize the nuclear CCGT plant for utility service in the 1990s. This paper outlines the most recent design studies by General Atomic for a dry-cooled commercial plant of 800 to 1200 MW(e) power, based on both non-intercooled and intercooled cycles, and discusses various primary system aspects. Details are given of the reactor turbine system (RTS) and on integrating the major power conversion components in the prestressed concrete reactor vessel.

INTRODUCTION

The advantages of the gas turbine high-temperature gas-cooled reactor exemplified many times in recent years (1-4), consist of the following: (1) plant simplification, (2) improved economics, and (3) siting flexibility. An extensive design and development program for the HTGR-GT components is necessary to commercialize the plant for utility service in the last decade of this century. This paper discusses design aspects of the HTGR-GT plant in its present conceptual design stage and outlines the established technology bases for this new power plant concept. The existence of operating experience from both gas-cooled reactors and closed-cycle gas turbine (CCGT) power conversion systems makes the HTGR-GT plant a potential commercial reality for the late 1990s.

In the current period of energy consciousness, the utility companies are reviewing their nuclear capacity, including the important element of power plant rating. This paper reports on studies based on differing plant variants in the 800 to 1200 MW(e) range. The multiloop power conversion system affords flexibility toward future utility needs and increases plant availability, since operation can be sustained with a loop shut down. Design studies for both non-intercooled and intercooled cycles are underway to maximize plant cost efficiency and resource conservation.

The excellent cogeneration capabilities of the HTGR-GT plant, made possible by the sensible heat rejection of the CCGT, have been well documented (5-7). However, it is the siting flexibility of dry-cooled plants (covered in this report) that has attracted utility attention both in the U.S. and

Europe. Dry cooling relieves plant location from being tied to rivers and bodies of water that may well have already reached their assigned thermal effluent capacity. The HTGR-GT plant also takes advantage of limited cooling water via wet/dry cooling. For the sites with cooling water in the next century, it is projected that bottoming cycle cogeneration will be available as an option to the utility owner.

Compliance with nonproliferation guidelines and changing and more demanding safety considerations have had increasingly important impact on nuclear power plant design. The HTGR-GT plant is adaptable to high-, medium-, and low-enrichment fuel cycles. . This paper outlines power plant studies based on the medium-enriched uranium (MEU) fuel cycle, which are thus in compliance with the current U.S. nonproliferation goals. A conservative design approach has been emphasized for the multiloop plant concept to provide for maximum safety and durability. The HTGR is an inherently safe reactor type by virtue of its graphite-moderated core, single-phase working fluid, and containment of all the nuclear equipment in a prestressed concrete reactor vessel (PCRV).

This paper reports only part of the rapidly increasing international efforts to combine the gas turbine and nuclear energy within the next two decades. The extraordinary role of the HTGR-GT in meeting international energy goals is significant. The studies reported in this paper represent an important step towards the selection of an optimized HTGR-GT plant configuration for the U.S. commercial marketplace.

BACKGROUND OF HTGR-GT PLANT STUDIES

As HTGR-GT plant design studies have progressed (since initiation in 1972), the thermodynamic cycle and plant configuration have evolved from investigations of the best means to satisfy the various performance, economic, safety, and operational goals. Many papers have been published in the open literature in the last seven years; a summary of the design evolution is given in Ref. (8). During this period, external assessments of the HTGR-GT plant have been

carried out by the government and by specialist consulting companies. From the technical and economic standpoints, these reviews have been favorable, as exemplified by the most recent assessment done by NUS Corporation under contract from Electric Power Research Institute (EPRI) (9).

An extensive program of design, development, and testing on the nuclear gas turbine plant is necessary to achieve performance and structural integrity and to qualify the equipment for nuclear power generation. This program is a main part of an international cooperative program currently underway. A dialogue has been in effect for several years between the U.S. program (General Atomic) and the European High Temperature Helium Turbine (HHT Project) partners. This effort intensified in 1977-78 relative to the definition of a European-sited demonstration plant. Such a demonstration plant is considered an attractive approach to creating the necessary technical base from which follow-on commercial plants could be engineered with a high degree of commonality for both 60 Hz United States and 50 Hz European power systems.
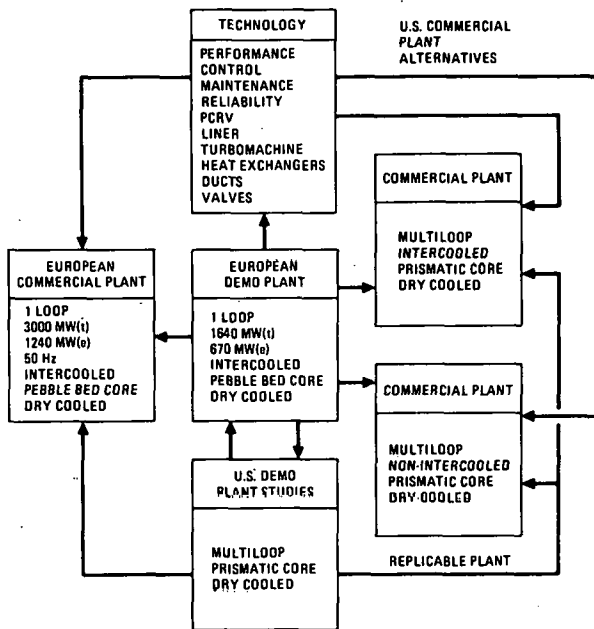

Fig.1 Demonstration-commercial plant relationships

Figure 1 presents qualitatively the relations between the U.S. plant studies, the European (HHT) demonstration project, and possible U.S. and European follow-on commercial plants. Initial details of the HHT demonstration plant concept have been discussed previously (10). The main features of the demonstration plant will be finalized in late 1979, and an extensive international effort will be initiated to meet the goal of demonstration plant operation by about 1990. It is recognized that complete design convergence between the U.S. and European plant variants is not possible because of (1) the fundamental frequency difference, (2) differing codes and standards, and (3) different safety and licensing criteria. It is further recognized, however, that commonality in the main features of the plants, together with a strong technology exchange effort, would be a

move in the direction of minimizing overall cost and lowering development risks, by utilizing worldwide technology.

Work on the HTGR-GT plant over the last few years has been supported by the U.S. Department of Energy and a group of electrical utilities, with participation by industrial companies. A key element in the formulation of a new power plant concept is participation by utility organizations right from the onset, and indeed, such a rapport has been in existence on the HTGR-GT program since 1972. With the formation of the Gas Cooled Reactor Associates (GCRA), the utility inputs to plant design are now more formalized. With regular meetings of the GCRA Technical Advisory Committee (TAC), the utility directives can be factored into the plant design on an on-going basis right from the conceptual design stage.

Until recently, work in the U.S. at General Atomic had been directed towards the design, performance, and economic assessment of a HTGR-GT plant in the 1200-MW(e) class with capability of being adapted to both smaller and larger units. A 1200-MW(e) reference plant established in 1977-78, based on a non-intercooled cycle and embodying three power conversion loops (PCLs), has been described previously (11).

Over the last few years, plant layout studies have been done for a wide range of power levels. These studies have consisted essentially of varying the number of PCLs, sizing the major components, evaluating the impact of component orientation on PCRV diameter, computing plant efficiency, and estimating costs (capital and power generating costs). The range of plants studied in a conceptual manner and the impact on PCRV diameter (which is regarded as a major capital cost indicator) are shown on Fig. 2.

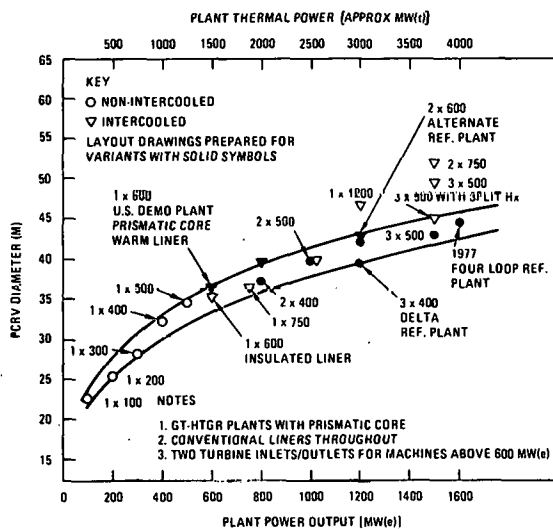Fig.2 Impact of HTGR-GT plant power rating on PCRV diameter

Inputs from TAC indicate a trend away from the larger plants envisioned a few years ago for operation towards the end of this century. Studies are now aimed at plants in the range of 800 to 1200 MW(e), and this paper outlines configurations in this range based on both non-intercooled and intercooled cycles and with differing numbers of PCLs.
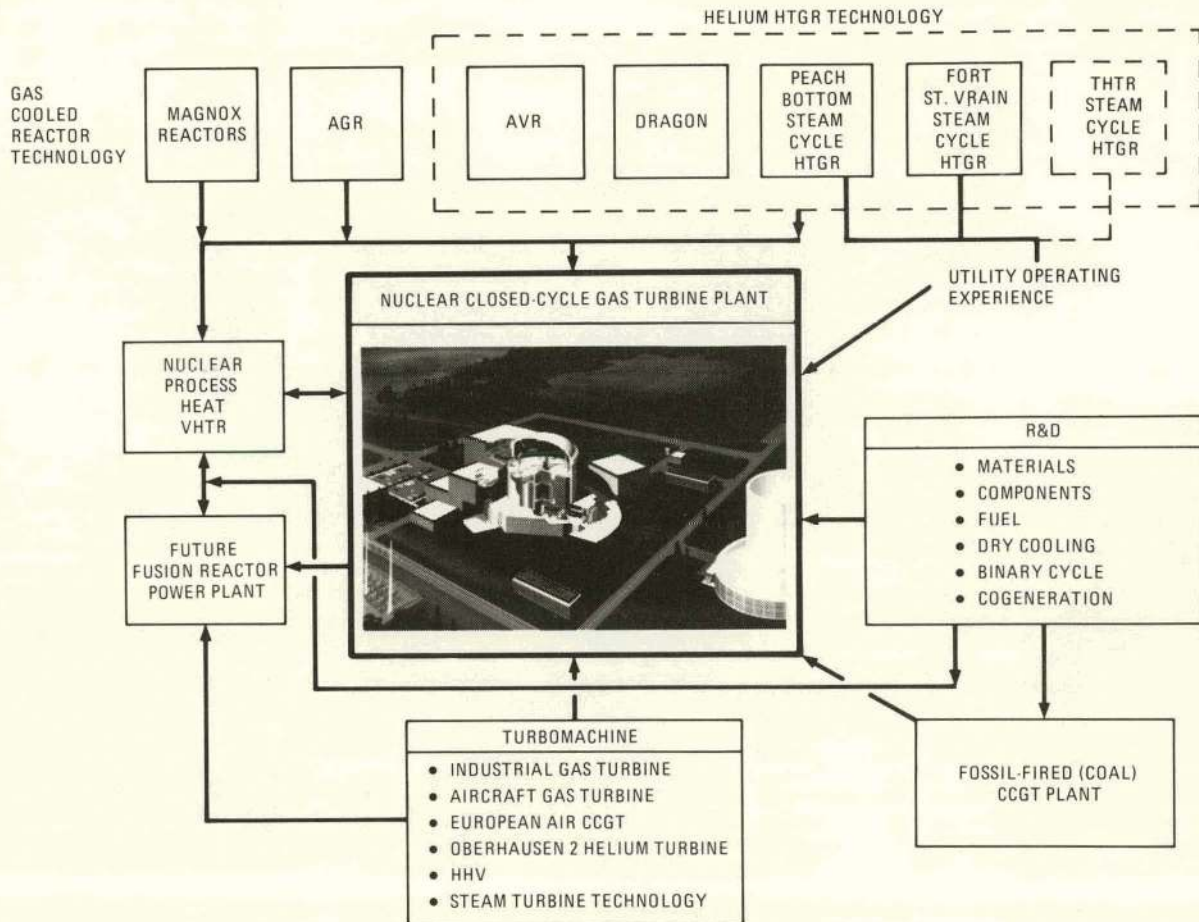
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Fig.3 Technology bases for HTGR-GT plant

TECHNOLOGY BASES FOR HTGR-GT PLANT

The technology resources from which the HTGR-GT plant can draw are formidable and are briefly outlined in this section. The necessary technologies stem from several sources, as shown in Fig. 3, and when combined, form the bases from which a successful nuclear gas turbine plant can be designed, developed, and introduced into utility service with a high degree of confidence that the performance, economic, safety, and reliability goals will be realized.

From the reactor standpoint, there is extensive operating experience for gas-cooled reactors, and in particular, for the helium-cooled high temperature reactor. Valuable pioneering experience from the experimental high temperature reactors in the United Kingdom (Dragon Project), in the U.S. (UHTREX), and in the Federal Republic of Germany (AVR) formed the basis for the first HTGRs entering commercial service: the Peach Bottom and Fort St. Vrain reactors in the U.S. and (in the near future) the THTR plant in Germany. These HTGRs, while based on a steam-cycle power conversion system, provide valuable utility operating experience input to the HTGR-GT program.

While the CCGT is not well known in the U.S., it has demonstrated very high fuel utilization efficien-

cies and a high degree of reliability in the various European plants. Since operation of the pioneer plant in 1939, the 40 years of experience have substantiated the claim that this prime-mover technology is well established (12). With the helium turbomachine itself being the singularly most important PCL component from the development standpoint, the applicability of established technologies from (1) European CCGT plants, (2) helium test facilities, (3) HTGR components and steam-cycle plant operating experience, and (4) advanced open-cycle industrial gas turbines are recognized. The industrial technology bases from which the turbomachine can benefit are shown on Fig. 4, which illustrates existing hardware. The emphasis here relates to the available comprehensive world-wide resources, which if utilized on an international cooperative basis, will make near-term introduction of the nuclear gas-turbine plant a reality.

An important helium turbine plant is the fossil-fired 50 MW(e) Oberhausen 2 unit which was built by Energieversorgung Oberhausen AG (EVO) in the Federal Republic of Germany. Many reports and papers have been written describing the EVO plant construction and operation (13-15). In addition to providing electrical power [50 MW(e)] and district heating [54 MW(t)], the tests carried out on the EVO plant are

HELIUM CIRCULATOR FOR FORT ST. VRAIN HTGR

- HELIUM TURBOMACHINE OPERATING EXPERIENCE IN NUCLEAR ENVIRONMENT

100 MWe ADVANCED OPEN-CYCLE INDUSTRIAL GAS TURBINE

- ANALYTICAL AND DESIGN METHODOLOGY
- AERODYNAMIC TECHNOLOGY
- STRUCTURAL DATA
- BEARING DATA
- MANUFACTURING EXPERIENCE
- CONDITION MONITORING

SUB-COMPONENT TEST RIGS

- HELIUM COMPRESSOR
- HELIUM TURBINE
- BEARINGS
- SEALS
- AUXILIARY SYSTEMS

HIGH TEMPERATURE HELIUM MATERIALS TEST RIG

- MATERIALS RESEARCH • TURBINE BLADING EVALUATION

HELIUM TURBOMACHINE FOR CLOSED-CYCLE NUCLEAR GAS TURBINE POWER PLANT

SEAL TEST RIG

- TESTING OF SHAFT SEALS FOR HELIUM NUCLEAR GAS TURBINE

OBERHAUSEN 1 13.75 MWe AIR CCGT PLANT

- OPERATING EXPERIENCE • RELIABILITY
- CONTROL • MAINTENANCE

OBERHAUSEN 2 50 MWe HELIUM TURBINE PLANT

- HELIUM EXPERIENCE • CONTROL
- PERFORMANCE • MAINTENANCE

HIGH TEMPERATURE HELIUM TEST FACILITY (HHV)

- AERODYNAMICS
- TRANSIENTS
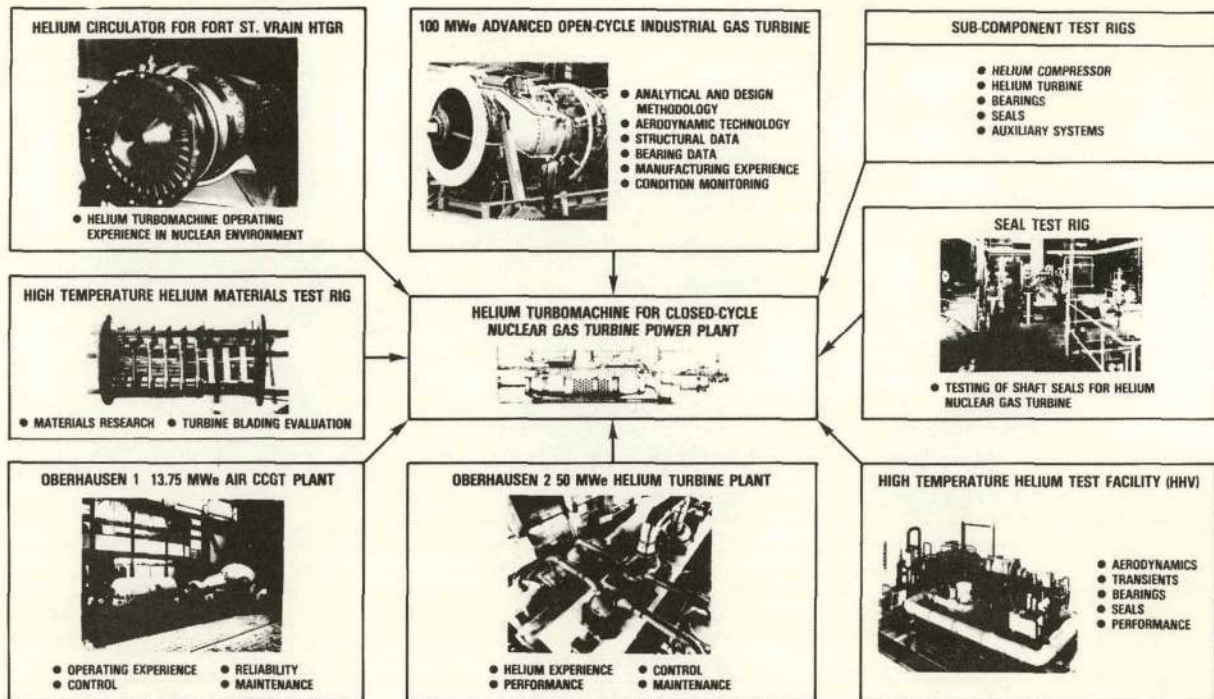- BEARINGS
- SEALS
- PERFORMANCE

Fig.4 Technology bases for nuclear closed-cycle helium turbomachine

intended to supply information (for the nuclear gas-turbine program) on the dynamics of the overall plant and on the long-term behavior of specific components. Another important plant is the high temperature helium test facility (HHV) at the Kernforschungsanlage (KFA) in Julich. The operation of this helium test plant represents a central test within the European HHT project. By this program, essential characteristics of the turbomachine are to be verified. Furthermore, this plant serves for tests of prototype components for the HHT demonstration plant. A full account is given in Ref. (16) of the roles of the EVO plant and HHV test facility in the development of the European HHT project.

Emphasis of the formidable technology bases for the HTGR-GT plant has been made in this section of the paper, because this adds credibility to the claim that a new power plant type such as the HTGR-GT, while now only in the conceptual design stage, could become a commercial reality for utility service by the year 2000.

THERMODYNAMIC CYCLE(S) AND PERFORMANCE

A detailed account of the systems-related studies leading to the selection of an optimized set of cycle parameters is reported in a separate paper (17), so only a brief summary of the impact these have on plant layout and design will be covered here. In the HTGR-GT plant studies done over the last few years by General Atomic, there has been a strong motivation to use the non-intercooled cycle for the following reasons: (1) plant simplicity in both turbomachine and primary system and (2) high reject temperature for economical dry cooling and optional bottoming cycle. In Europe, on the other hand, the intercooled cycle has always been favored because

(1) it has higher efficiency, (2) the reject water temperature is well suited to district heating, and (3) there is a carry-over from the European fossil-fired CCGT plants, which have all been intercooled.

In any compression process involving a multi-stage system, cooling between the stages reduces the compression work, and in the case of the CCGT, the plant efficiency is increased by virtue of the higher net turbine output. On a purely thermodynamic basis, an increase of about 3 percentage points can be computed for the intercooled cycle. When the additional pressure losses in the intercooler and in the more complex ducting arrangement are taken into account, the gain in efficiency is reduced to about 2 percentage points. Nevertheless, such a gain over the 40-year operating life of the plant has significant economic implications, and hence, the current study of plant designs is based on both intercooled and non-intercooled cycles. Some of the major factors involved in the issue of intercooling versus non-intercooling are outlined on Table 1.

As mentioned previously, efforts are underway for both plant variants to select the cycle parameters for minimum power generating cost. For the purpose of component sizing and plant configuration layout studies, it was necessary to establish early comparative cycle data. The tentative values used are shown on Table 2, and these data are felt to be very representative for design purposes. The key differences between the two cycles are shown on the loop diagram for the non-intercooled plant (Fig. 5) and on the flowpath diagram for the intercooled variant (Fig. 6).

An important parameter influencing the efficiency of the closed-cycle plant is the turbine inlet temperature. For the power plant studies outlined in this paper, a turbine inlet temperature of 850°C has been assumed. This temperature is modest

TABLE 1
MAJOR FACTORS RELATING TO THE ISSUE OF INTERCOOLING

Non-intercooled Plant
1. Simpler turbomachine (shorter rotor, less duct connections)
2. Simpler gas flow paths and primary system layout
3. Less complex system implies improved availability and reliability
4. High reject temperature well suited for cogeneration (i.e., binary cycle, process steam, district heating, etc.)
5. Reduced plant construction time (simpler PCRV)
6. Reduced complexity and risk

Intercooled Plant
1. Increased cycle thermodynamic efficiency
2. Reduced helium mass flow rate (i.e., smaller components)
3. Source of cooler high-pressure gas available for cavity liner cooling
4. Reduced core inlet gas temperature
5. Possible use of additional water-to-helium heat exchanger (intercooler) for decay heat removal
6. Heat rejection split between two water-to-helium exchangers (precooler and intercooler) results in smaller unit assemblies
7. Utilization of European experience from the small fossil-fired CCGTs
8. Water outlet temperature well suited for district heating
9. Additional maintenance requirements
10. Increased plant capital cost
11. Additional potential source of water ingress to primary system

TABLE 2
HTGR-GT CYCLE DATA USED IN PLANT CONFIGURATION COMPARISON STUDIES

| Thermodynamic Cycle	Non-intercooled	Intercooled
Heat rejection mode	Dry-cooled	Dry-cooled
Turbine inlet temp, °C	850	850
Ambient air temp, °C	15	15
Compressor inlet temp, °C	26.7	26.7
Max system pressure, MPa	7.93	7.93
Compressor pressure ratio	2.50	3.0 (1.73/1.73)
System pressure loss ($\Delta P/P$), %	~9	~11
Compressor flow kg/s/MW(t)	0.57	0.50
Recuperator effectiveness	0.90	0.90
Compressor efficiency, %	89.8	90.8 LP, 90.2 HP
Turbine efficiency, %	91.8	92.2
Precooler water outlet temp, °C	132	87
Intercooler water outlet temp, °C	--	66
Cycle efficiency, %	~40.0	~42.0
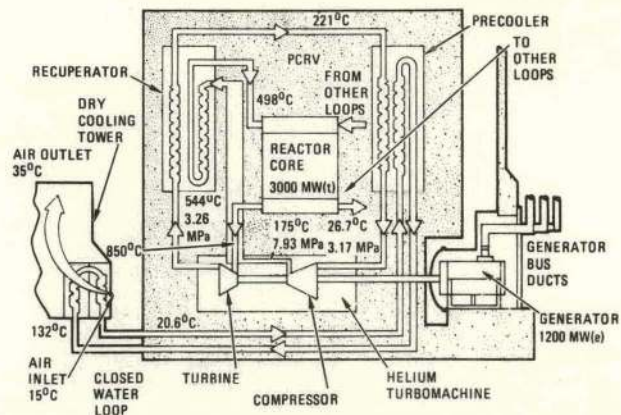
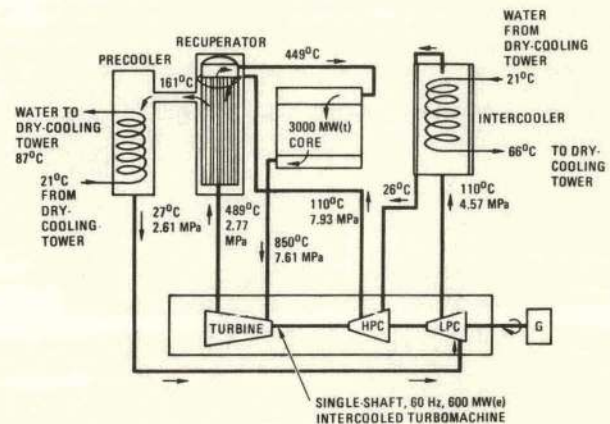Fig.5 Loop cycle diagram for non-intercooled dry-cooled HTGR-GT power plant

Fig.6 Flow path diagram for two-loop intercooled HTGR-GT plant

compared to that for most industrial gas turbine practice (18); it is below the level where turbine blade cooling is necessary, and it facilitates utilization of an existing nickel-base alloy which is used extensively in industrial gas turbines. The impact of turbine inlet temperature, together with other important parameters, is shown on Fig. 7 for a non-intercooled cycle. Projected operating regimes for various CCGT plant applications are shown on this plot. It is clear from Fig. 7 that the CCGT offers significant potential for high levels of plant efficiency when dry cooled.

PLANT CONFIGURATION STUDIES

Three-Loop, 1200-MW(e) Non-Intercooled Plant Concept
As previously mentioned, this 1200-MW(e) plant variant has received the most design attention in recent years, and in terms of performance and cost, forms the base case for comparison with other plant concepts. An isometric view given on Fig. 8 shows the major elements of the power conversion system integrated inside the PCRV. The compact nature of the installation is shown on the plan view of the PCRV (Fig. 9). An obvious goal in all plant design and layout studies is the minimization of the PCRV
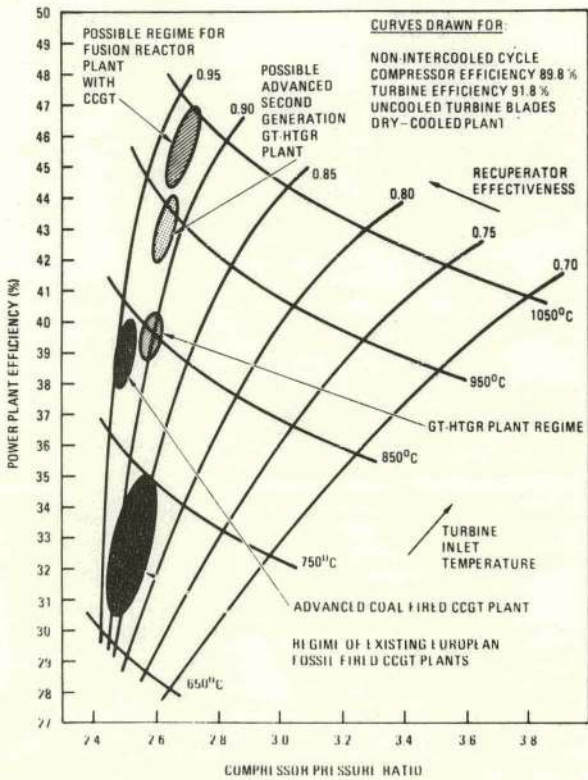
Fig. 7 Representative cycle parameter array for non-intercooled HTGR-GT plant

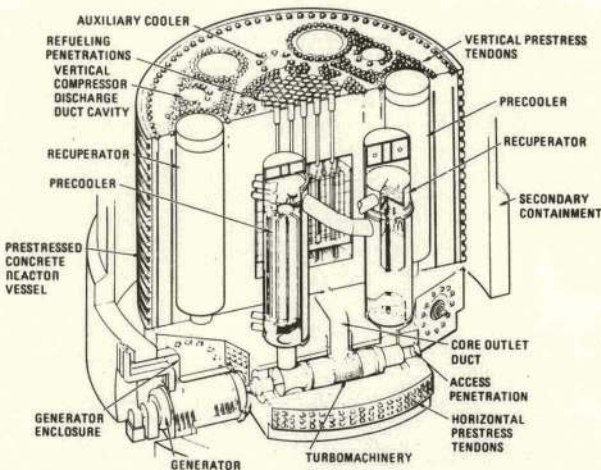Fig.9 PCRV plan view for 3 x 400-MW(e) non-intercooled HTGR-GT plant

Fig. 8 Integrated HTGR-GT plant based on 3 PCLs and non-intercooled cycle

diameter because of its economic impact. The arrangement shown on Fig. 9 has the following main features: (1) centralized core cavity, (2) delta orientation of the three turbomachines, and (3) recuperator and precooler positioned over the turbomachine cavity. This arrangement represents a very good utilization of space within the reactor vessel, and in fact, satisfies the economic goal of PCRV diameter minimization.
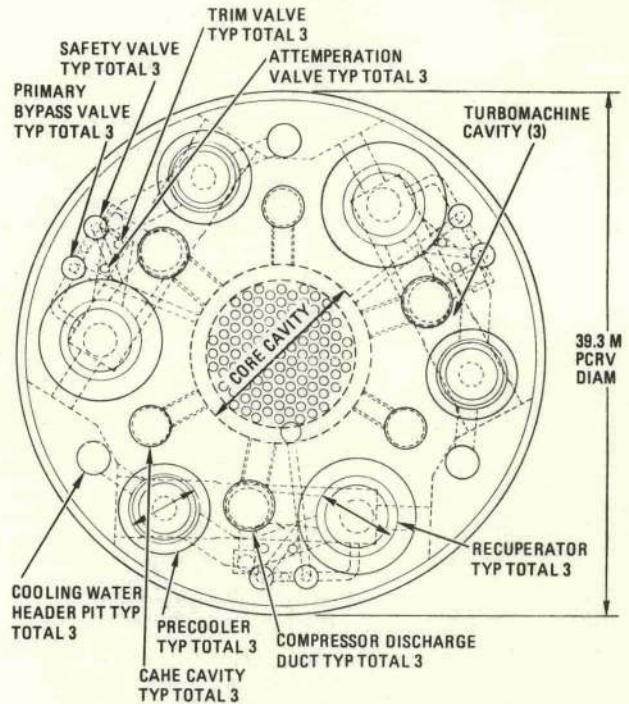
The delta orientation of the PCLs, as shown on Fig. 9, is well suited to the non-intercooled cycle. Incorporation of intercoolers is not attractive in this three-loop arrangement, since they must be positioned radially outwards from the turbomachine cavity, and this results in an unacceptably large increase in PCRV diameter. As will be outlined in the following sections, evaluation of the intercooled cycle is being done for two-loop plant variants.

Two-Loop, 1200-MW(e) Intercooled Plant Concepts

The motivations for the study of a two-loop plant included the following: (1) potential capital cost reduction, (2) flexibility in power range, (3) adaptability to intercooling, (4) maximization of technical interchange between U.S. and European programs, and (5) simplified turbomachine maintenance. Accordingly, studies in the last year have involved the conceptual design and layout of two-loop plant variants based on both intercooled and non-intercooled cycles.

A representative layout of a two-loop intercooled plant is shown on the PCRV plan view given on Fig. 10. While studies have been performed for PCL ratings of 400, 500, and 600 MW(e), the main features of the plant are essentially the same, and the view shown on Fig. 10 for a 2 x 600 MW(e) concept can be considered representative. Again, as in previous studies, efforts were expended to minimize the diameter of the PCRV, and this was achieved by a combination of the following: (1) offsetting the core cavity, (2) chordal positioning of the two horizontal turbomachine cavities, (3) positioning the recuperator and precooler over the turbomachine cavity, and (4) establishing simplified gas flow paths within the primary system. Layout studies led to the positioning of the two intercoolers and three decay heat removal systems,
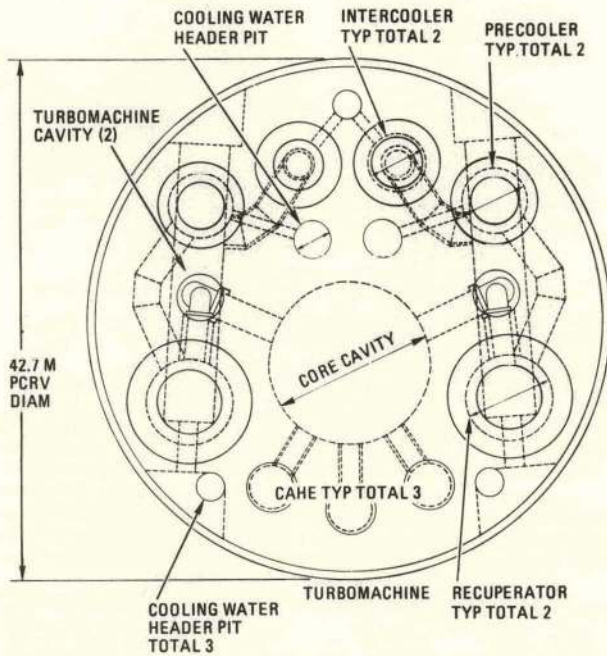
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Fig. 10 PCRV plan view for 2 x 600-MW(e) intercooled HTGR-GT plant

Fig. 11 View through PCL for two-loop HTGR-GT plant

as shown on Fig. 10, to give an acceptable arrangement from the standpoints of gas flow paths and PCRV structural considerations. It is recognized that with more in-depth studies the positioning of the major components within the vessel (and the angle of the turbomachine cavities) may change; however, the general arrangement shown on Fig. 10 is regarded as the optimum for a two-loop intercooled plant. The elevation view through the PCRV on Fig. 11 shows the simple gas flow paths between the turbomachine and the heat exchangers (it should be noted that the intercooler is not shown in this particular sectional view). The gas flow paths to and from the reactor core cavity are shown on Fig. 12. Also shown on this figure is a section through the core auxiliary cooling system (CACS), and the gas flow paths to and from the core cavity and in the heat exchanger and circulator can be clearly seen.

Two-Loop Non-Intercooled Plant Concepts

As part of the study to compare the designs, economics, performance, and availability of intercooled versus non-intercooled plants, a layout study was performed to identify the main features of a two-loop non-intercooled plant variant.

A representative layout of a two-loop non-intercooled plant is shown on the PCRV plan view given on Fig. 13. While studies have been performed for PCL ratings of 400, 500, and 600 MW(e), the main features of the plant are essentially the same, and the view shown on Fig. 13 for a 2 x 500 MW(e) concept can be considered representative. Several layout variants were developed for the non-intercooled plant, and the one shown on Fig. 13 has the following characteristics: (1) centralized core cavity, (2) chordal turbomachine cavity orientation, and (3) recuperator and precooler positioned over the turbomachine cavity. The positioning of the three CACS units (in a different orientation from the aforementioned intercooled variant)
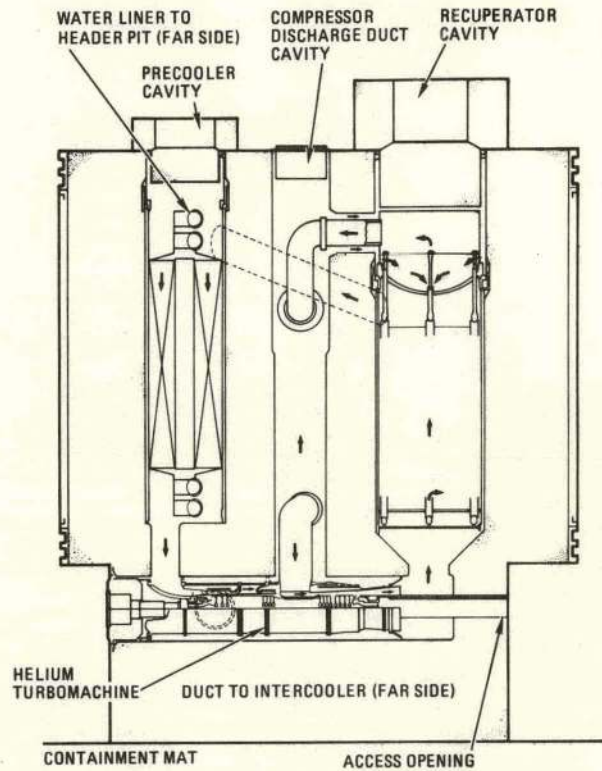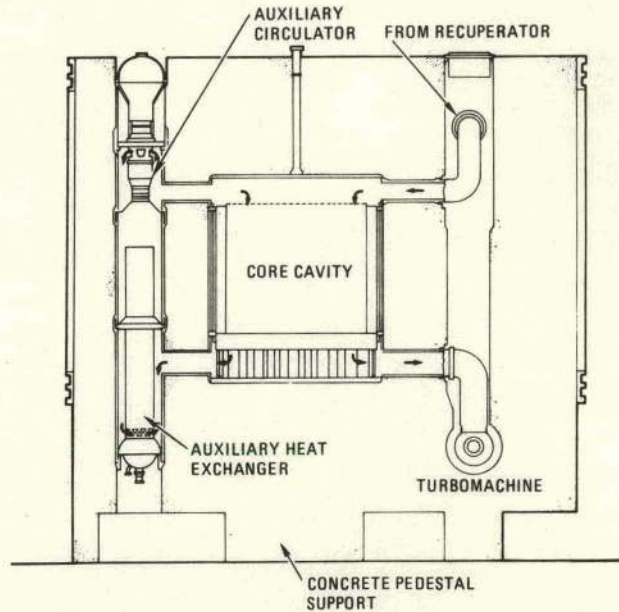

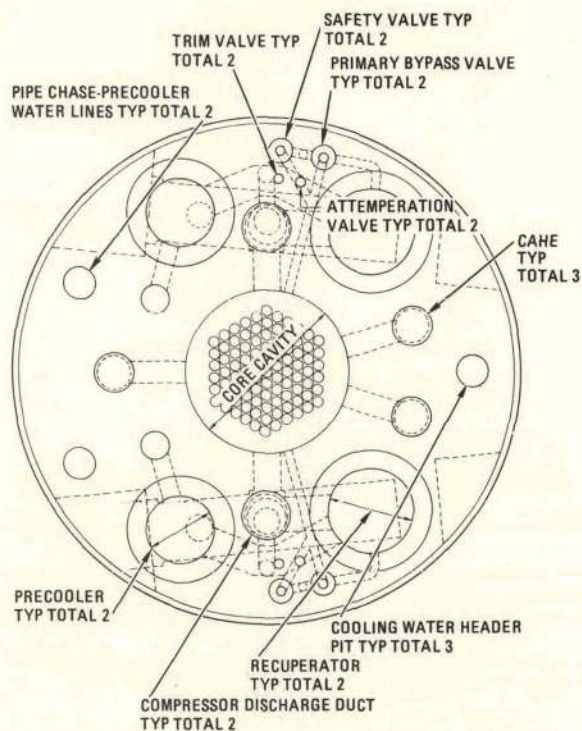Fig. 12 Elevation through PCRV showing core cavity and decay heat removal system

Fig.13 Plan view of PCRV for 2 x 500-MW(e) non-intercooled HTGR-GT plant

is conducive to good gas flow paths, PCRV structural considerations, and minimization of the vessel diameter. The main characteristics of the elevation views through the PCRV (shown previously for the intercooled variant on Figs. 11 and 12) are near identical for the two-loop non-intercooled plant.

Summary of Plant Layout Studies

Two major decisions in the HTGR-GT program will be made in 1979: (1) the power plant rating, and (2) the issue of intercooling versus non-intercooling. As will be mentioned in the following sections, a decision has been made to proceed with a plant embodying two PCLs. The plant layout studies presented in this paper are in support of the overall evaluation that will lead to the selection of a new reference plant concept.

As shown on Fig. 2, design studies have been performed for a wide range of plant variants. However, the most recent work done (and reported in this paper) has centered on (1) two- and three-loop concepts, and (2) PCL ratings of 400, 500, and 600 MW(e). A summary of the salient features of the plant concepts studied is given on Table 3. The main disadvantages of the three-loop plant are (1) inflexibility of power rating [i.e., it is better suited to plants of 1200 MW(e) and higher], (2) not attractive as an intercooled variant (i.e., complex gas flow paths and large PCRV diameter), (3) high capital cost associated with the large number of components, and (4) an operational problem exists in that the generator must be moved before a turbomachine can be replaced.

From Table 3 and the layout concepts presented, it can be observed that the two-loop plant offers a simplified PCRV arrangement and has rating flexibility

in the range of 800 to 1200 MW(e). It is also significant that an intercooler can be embodied without a major impact on PCRV diameter. The motivations for utilization of a two-loop plant layout concept are given on Table 4.

COMPONENT DESIGN CONSIDERATIONS

It is not the purpose of this paper to describe in detail the design considerations for the major components of the HTGR-GT plant, since as noted below, these have been reported previously. However, for an integrated plant, the PCL components cannot be treated as isolated units, and indeed, their design and the resolution of the interconnecting gas flow path geometries must be considered during the establishment of the plant primary system configurations. During the aforementioned primary system design studies, extensive layout work was done to identify the most attractive installation and orientation of the major components. The main PCL components which have a strong influence on the primary system design are the turbomachine and the heat exchangers, and brief descriptions of these are given below.

Helium Turbomachine

The most recent turbomachinery design work for the HTGR-GT power plant has been done by the Power Systems Division and Pratt and Whitney Aircraft Division of United Technologies Corporation (UTC). General Electric and Brown Boveri Company were earlier participants in the HTGR-GT program. Since details of the helium turbomachine have been described previously (18-21), only a very brief summary will be given in this paper.

In support of the plant configuration studies, turbomachine conceptual designs were done for machines in the 400, 500, and 600 MW(e) power classes for both intercooled and non-intercooled types. To span the above power range and to illustrate the difference between the machine types, only the 400 MW(e) (non-intercooled) and 600 MW(e) (intercooled) variants will be addressed in this paper. Details of the 400 and 600 MW(e) turbomachines are shown on Figs. 14 and 15, respectively, and the salient features are summarized on Table 5. As will be discussed below, the two machines embody similar features in many areas. The design and performance predictions for these machines reflect the influence of technology from a demonstrated advanced technology industrial gas turbine in the 70 to 100 MW(e) power size (22).

An extremely simple arrangement consisting of a single-shaft direct-drive arrangement was chosen for both machines. The use of a two bearing rotor, feasibility of which has been confirmed by rotor dynamic analyses to ensure adequate critical speed margin, maintained the smallest number of individual parts and tended to minimize the overall cost of the machine, and to ease inspection and maintenance requirements.

Aerothermodynamic analysis showed that for both the 400 and 600 MW(e) machines a single turbine inlet duct (from the reactor) could be utilized, and the pressure losses and flow inlet geometry to the turbine bladed section were satisfactory. In the plant layout studies, it was found that a key element (from the standpoint of effective PCRV volume utilization) is the embodiment of a turbomachine with a single turbine inlet duct. For machine sizes above 700 MW(e), studies have shown the need for two turbine inlet ducts; for a plant embodying two such gas turbines, the gas flow paths are unduly complex, and the PCRV diameter is excessive.

TABLE 3
COMPARISON OF HTGR-GT PLANT CONCEPTUAL DESIGNS

Loop Rating, (MW(e))	400		500	600	400
Thermodynamic cycle	Non-intercooled	Intercooled	Non-intercooled	Intercooled	Non-intercooled
No. of loops	2	2	2	2	3
Plant output, MW(e)	800	800	1000	1200	1200
Plant efficiency, %	~40.0	~42.0	~40.0	~42.0	~40.0
Core rating, MW(t)	2000	1905	2500	2860	3000
Plant type	Power conversion system integrated in PCRV				
Heat rejection	Dry-cooled				
Liner type	Conventional, insulated, and water-cooled				
Core type	HTGR prismatic fuel elements				
Fuel type	MEU				
Fuel cycle, yr	3				
Core power density, W/cm^3	6.8				
Core position	Offset	Offset	Central	Offset	Central
Turbomachine position	Chordal	Chordal	Chordal	Chordal	Delta
No. of recuperators	2	2	2	2	3
No. of intercoolers	--	2	--	2	--
No. of precoolers	2	2	2	2	3
No. of major cavities	12	14	12	14	16
PCRV diam, m	37.2	39.6	39.6	42.7	39.3
PCRV height, m	35.4	35.4	35.4	35.4	35.4
No. of CACS units	3	3	3	3	3
Design status	Conceptual	Conceptual	Conceptual	Conceptual	Conceptual

TABLE 4
MOTIVATING FACTORS FOR A TWO-LOOP COMMERCIAL PLANT CONFIGURATION

1. Efficient PCRV design of small diameter strongly impacts cost.
2. Simplified vessel (tendon layout eased in bottom head).
3. Intercooling can be utilized with no major impact on PCRV size.
4. Non-intercooled efficiency of 40%, and intercooled value of 42% possible.
5. Simplified gas flow paths within PCRV (pressure loss ≠ 12%).
6. Ease of maintenance, since generator does not have to be moved to replace the turbomachine.
7. Spare machine approach by utility group/organization ensures high plant availability.
8. Plant operation on one loop considered possible (impact on availability and heat supply).
9. Flexibility in power range advantage for different utilities.
10. Growth potential possible from conservatively designed power conversion equipment.
11. Main loop cool-down perhaps eased by duplication of turbomachines.
12. Commercial plant can be replicated from the first-of-a-kind plant.
13. No scaling from demo to commercial plant necessary.
14. Reduced development risk and cost.
15. Simplified electrical system since all of the high voltage connections are at one end of the plant.

The 400-MW(e) non-intercooled machine (Fig. 14) has 18 compressor stages and eight turbine stages. In the 600-MW(e) machine (Fig. 15), intercooling necessitates splitting the compressor into 2 eight-stage sections, and a high-efficiency nine-stage turbine is utilized. For both machines, the rotors are of welded construction. Welded rotors have a long successful history in Europe for both gas and steam turbines. The stress levels in the turbine blades are commensurate with a life of 280,000 h (i.e., 40 years at 80% capacity factor). For the turbine inlet temperature of 850°C, blade cooling is not necessary, and an existing-nickel-base alloy (IN-100), which has been used extensively in open-cycle industrial gas turbines, was selected for the turbine blading.

The casing diameter for both machines is 4.0 m, but of course, the higher helium mass flow rate for the 600-MW(e) machine results in an increased annulus flow area and larger blade heights, as shown on Table 5. The overall lengths of the 400-MW(e) (non-intercooled) and 600-MW(e) (intercooled) machines are 11.3 m and 15.8 m, respectively. Since the turbomachine is installed inside the reactor vessel, rotor burst protection is incorporated in the machine design in the form of containment rings around the compressor and turbine rotor bladed sections.

Man-access provisions are provided in the PCRV for inspection and limited maintenance work on the journal bearings, which are of the multiple, tilting pad, oil-lubricated type. The spaces in which the bearings are located are isolated from the main cycle working fluid by shielding (purge gas from the plant helium storage system is used to give an acceptable radiological environment for man-access). The drive to the generator is from the compressor end of the turbomachine, and the thrust bearing is located external to the PCRV to facilitate inspection and maintenance and to limit the number of oil-systems in the primary system to a minimum. Diagnostic condition monitoring, in-situ inspection, and maintenance features are designed into the turbomachine system (23).

For a single-shaft helium turbomachine (with a rotational speed of 3600 rpm) in the power range of
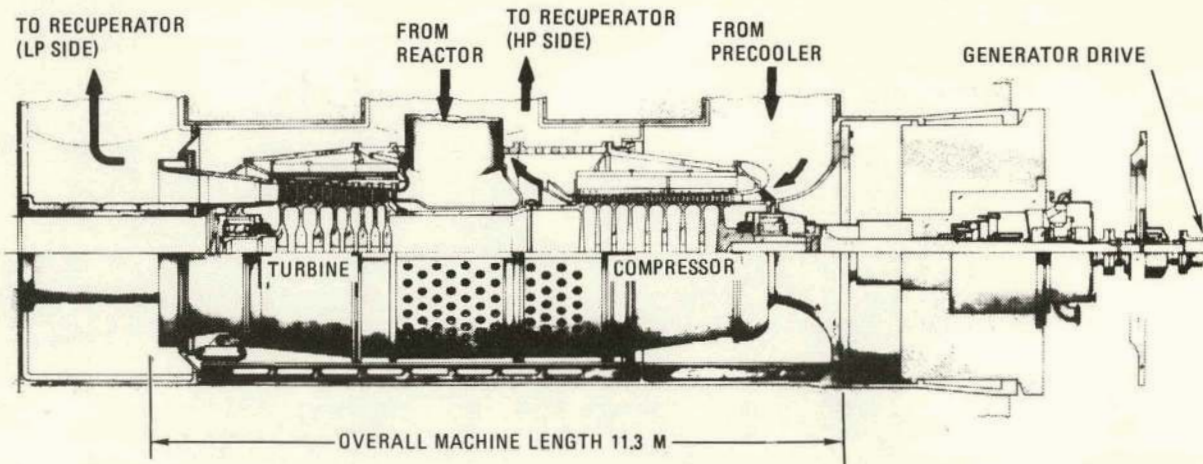
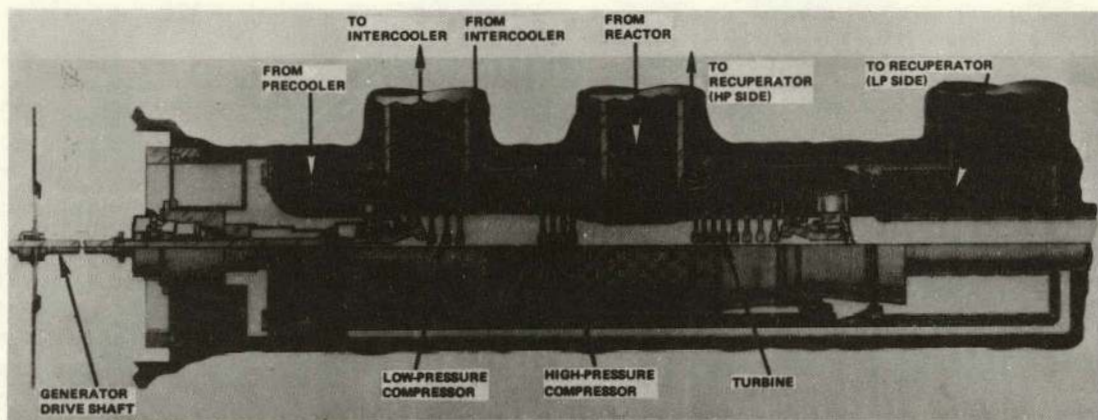Fig.14 400-MW(e) non-intercooled turbomachine for HTGR-GT plant

Fig.15 600-MW(e) intercooled turbomachine for HTGR-GT plant

400 to 600 MW(e), the rotating section is compact and is substantially smaller than an equivalent air-breathing machine because of the high degree of pressurization (particularly at the turbine exit) and the high specific power associated with the helium working fluid. The external dimensions of the helium turbomachines discussed in this paper are, in fact, quite similar to those of an existing air-breathing, advanced, open-cycle industrial gas turbine in the 70 to 100 MW(e) range. The fact that the helium turbine (particularly the rotor assembly and casings) is comparable in size with existing machines substantiates the claim that conventional fabrication methods and facilities can be used.

The aforementioned helium turbomachine design activities have been done in support of the HTGR-GT plant for the U.S. market (60 Hz system); however, it should be pointed out that a formidable effort has also been expended in Europe for the HHT plant (10), and details of the turbomachine for this 50-Hz system have been reported in Refs. (24-26).

Heat Exchangers

While details of the heat exchangers have been discussed previously (27), it is meaningful to discuss them briefly in the context of this paper, since they are large components and have a significant influence on the integrated primary system. The combined effects of size constraint (integration in the PCRV side-wall cavities), in-service inspection (ISI), in-situ repair, and maintenance and fabrication considerations have a significant effect on the choice of surface geometry, flow configuration, and mechanical design.

In the conceptual design phase of the HTGR-GT plant, the thermalhydraulic sizing and analysis of the heat exchangers was performed by General Atomic, and the mechanical design work was done by Combustion Engineering. In support of the plant configuration studies, heat exchanger conceptual designs were done for units with PCL ratings of 400, 500, and 600 MW(e) for both intercooled and non-intercooled types. To span the above power range and to illustrate the major differences between the two cycle types only, the exchangers for the 400-MW(e) (non-intercooled) and 600-MW(e) (intercooled) variants are discussed in this paper. The salient features of the recuperators, precoolers, and intercooler are given on Table 6.

TABLE 5
DETAILS OF HTGR-GT PLANT TURBOMACHINE DESIGNS

Turbomachine Rating, MW(e)	400	600
Machine type	Non-intercooled	Intercooled
Machine arrangement	Single-shaft	Single-shaft
Frequency, Hz	60	60
No. of turbine inlet ducts	1	1
Turbine inlet temp, °C	850	850
Compressor pressure ratio	2.50	3.0 (1.73/1.73)
No. of compressor stages	18	8 + 8
Max compressor tip diam, m	1.83	2.18
Blade height, mm (min/max)	80.0/125.7	76.2/165.1
Compressor adiabatic efficiency (across blading), %	89.8	90.8 LP/90.2 HP
No. of turbine stages	8	9
Max turbine tip diam, m	2.18	2.40
Blade height, mm (min/max)	125.7/297.2	165.1/393.7
Turbine isentropic effic. (across blading), %	91.8	92.2
Blading life, h	280,000	280,000
Blade cooling	No	No
Turbine blade material	Nickel-base alloy, IN-100	
Generator drive end	Compressor	
Rotor burst shield	Yes, integral part of machine structure	
Thrust bearing position	External to PCRV	
No. of journal bearings	2	2
Journal bearing man access	Yes	Yes
Type of rotor construction	Welded rotor	Welded rotor
Machine casing diam, m	4.0	4.0
Machine length, m	11.3	15.8
Machine weight, kg	276,770	317,600
Design technology base	Large industrial open-cycle gas turbines	

The heat exchanger types selected for the HTGR-GT plant conceptual design have a sound technology base, and in this regard can be considered to be conservative. The helium-to-helium recuperator concept (shown on Fig. 16) remains unchanged from that reported previously in Ref. (28), namely, a straight-tube, counterflow arrangement, with an overall assembly made up from a multiplicity of contiguous hexagonal modules. In the case of the helium-to-water exchangers (precooler and intercooler), an extensive study led to a change in concept from the previous straight-tube, counterflow, modular approach (28), to a multipass cross-counterflow helical bundle configuration as typified in Fig. 17. The helical approach has the advantages of higher water velocity, considerably fewer tubes, larger tube diameters, more straightforward headering, and better ISI accessibility than the straight-tube counterflow variant.

The recuperator, precooler, and intercooler assemblies are well integrated in the PCRV, and the interfaces have received attention during the conceptual design phase to ensure the viability of the selected mechanical design approaches. The axial counterflow recuperator (embodying tubes of small diameter) bears a close resemblance to units that have operated trouble-free for over half a million hours in the European fossil-fired CCGT plants. The multipass cross-counterflow helical bundle approach selected for the precooler and intercooler has been used extensively for steam generators in gas-cooled

TABLE 6
DETAILS OF HTGR-GT PLANT HEAT EXCHANGER DESIGNS

| PCL Rating, MW(e)	400 MW(e) Non-intercooled		600 MW(e) Intercooled		
Exchanger	Recuperator	Precooler	Recuperator	Precooler	Intercooler
Exchanger configuration	Counterflow	Multipass cross counterflow	Counterflow	Multipass cross counterflow	
Construction type	Straight tube modular	Helical bundle	Straight tube modular	Helical bundle	
Heat duty/unit, MW(t)	918	581	1253	533	337
LMTD, °C	42.5	30.5	44.3	27.3	19.3
Effectiveness	0.898	0.972	0.898	0.961	0.939
Tubes per exchanger	66,483	827	94,668	1196	1118
Tube o.d., mm	11.1	28.6	11.1	28.6	28.6
Wall thickness, mm	1.1	2.9	0.8	2.9	2.9
Modules per exchanger	83	1	161	1	1
Exchanger diam, m	5.64	4.72	6.8	4.9	4.7
Effective tube length, m	12.2	105	12.8	82.3	76.2
Effective bundle ht, m	12.2	12.5	12.8	13.7	10.97
Exchanger assy. ht, m	20.4	19.8	21.1	21.1	18.3
Exchanger assy. wt, tonnes	726	435	998	490	363
Max metal temp, °C	515	177	465	125	89
Max internal ΔP, MPa	4.62	1.83	5.08	1.3	3.2
Materials	Ferritic 2 1/4 Cr-1 Mo	Low-alloy 1/2 Cr	Ferritic 2 1/4 Cr-1 Mo	Low alloy, 1/2 Cr	
ISI/repair level	Module	Individual tubes	Module	Individual tubes	
Assembly location	Factory/optional	Factory	Factory/optional	Factory	
Transportation mode	Barge	Barge	Barge	Barge	
ASME code class	Section VIII	Section VIII	Section VIII	Section VIII	
Design status	Conceptual				
Technology status	State-of-the-art-technology				

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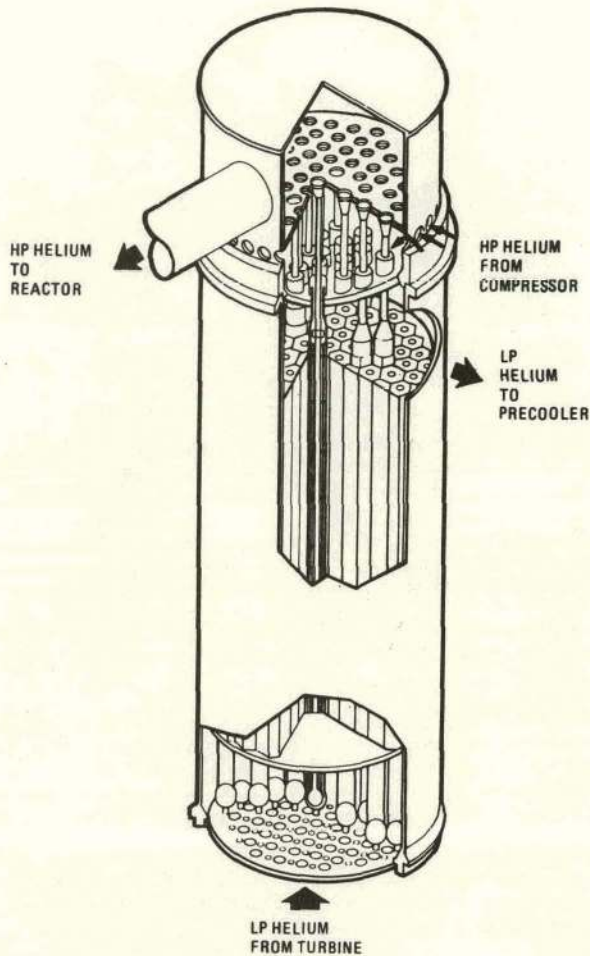
Fig. 16 Straight-tube, modular, counterflow recuper-
ator concept for HTGR plant

reactors. Thus, in adopting the aforementioned con-
servative design approach, it can be stated that the
exchanger design types selected for the HTGR-GT plant
have a proven background in the utility power-
generating industry.

Another obvious issue related to the size and
weight of the heat exchangers is the technology for
handling, transporting, and installing the units in
the reactor vessel. It has been shown (27) that the
heat exchangers for the HTGR-GT are, in fact, no
longer or heavier than units being built for contem-
porary steam plants, and that existing and proven
methods of handling and transportation are indeed
applicable.

For a long-term program such as the HTGR-GT,
there is an obvious incentive to maintain the com-
petitiveness of the plant by utilizing technology
advancements in a prudent manner. Improvements in
the heat exchangers will be continually sought, such
as the adoption of advanced surface geometries, and
the obvious goals that will be addressed in the
future include (1) increased reliability/
availability, (2) cost reduction, (3) size reduction,
and (4) improved ISI capability and maintenance
approaches.

The aforementioned heat exchanger design acti-

vities have been pursued in support of the HTGR-GT
plant for the U.S. market; however, it should be
pointed out that a formidable effort has also been
expended in Europe for the HHT plant and details of
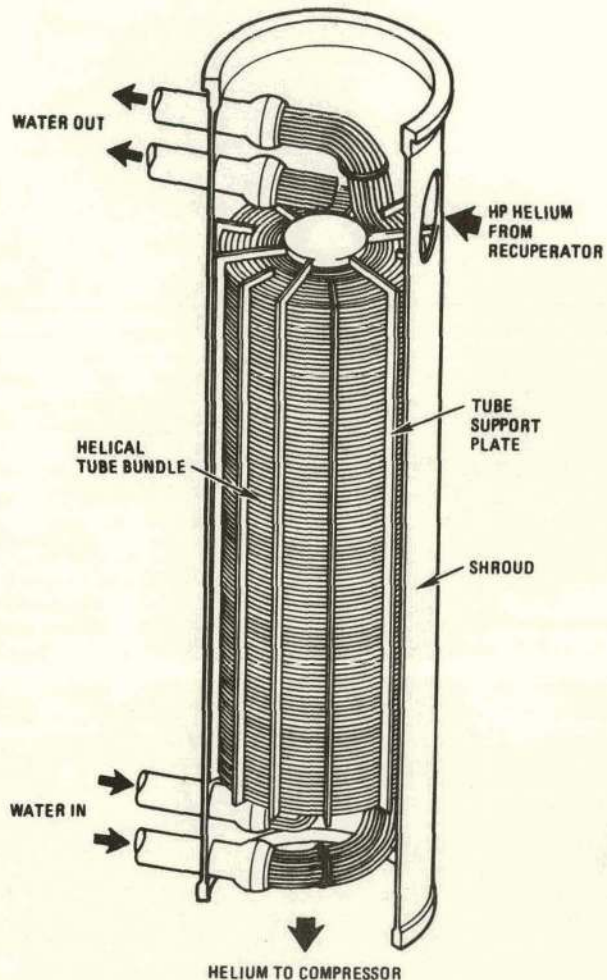these heat exchangers have been reported in Ref.
(29).

Fig. 17 Helical-bundle, cross-counterflow, helium-to-
water heat exchanger concept (precooler and
intercooler) for HTGR-GT plant

BALANCE OF PLANT DESIGN

The main point of this paper has been a discus-
sion of the reactor turbine system (RTS) for differing
power plant concepts. In addition to the RTS, which
is integrated in the reactor vessel, an important task
in the design process is the establishment of the
overall plant configuration, and this essentially in-
volves the design of all the balance of plant equip-
ment and buildings. Since this is a comprehensive
task and the subject of a forthcoming paper, balance
of plant design will only be highlighted in this paper,
but the importance of the task should be noted since
a significant percentage of the overall plant cost
is associated with the balance of plant items. In

addition, many of the plant operational require-
ments, such as service systems, purification trains,
refueling schemes, and on-site maintenance facili-
ties, strongly impact the balance of plant features
and economics.

Details of the overall plant plot plan for the
three-loop non-intercooled plant have been discussed
previously (23), so only the recent work associated
with the two-loop variant will be mentioned here.
As shown on Fig. 18, a reactor containment building
(RCB) encloses the PCRV, and while the configuration
illustrated is in a conceptual stage for the 2 x 600
MW(e) intercooled plant variant, it can be considered
representative for the HTGR-GT plant. The secondary
containment building and the PCRV incorporate safety
features that limit loss of primary coolant and mini-
mize damage in the event of failures in the turbo-
machine, shaft seals, heat exchangers, generator, or
PCRV cavity closures.

A significant change from previous plant con-
ceptual designs involves the utilization of all water-
cooled generators of the type that have been exten-
sively used in Europe for many years. The former
hydrogen-cooled generator involved installation in
local generator cells (which increased the complexity
and cost of the RCB) to prevent the possiblity of a
hydrogen explosion within the containment building in
the event of a gas leakage from the generator inter-
nals. As can be seen from Fig. 18, a simpler concept
is now proposed with the generator located within the
containment building. This eliminates the concern
over a secondary containment rotating seal penetration.
A tentative plant arrangement concept for a two-loop
plant is shown on Fig. 19. This scheme illustrates
the general layout of the various buildings, and in-
depth studies are currently underway by the architect/
engineer to further define the balance of plant facil-
ities to satisfy all of the plant requirements.

SUMMARY

The work reported in this paper is only one part
of the widespread international efforts to combine the
gas turbine and nuclear energy. The benefits of the
HTGR-GT plant are such that the worldwide efforts to
bring it into use should increase rapidly. It is pro-
jected that with a dedicated effort the demonstration
plant could be introduced into commercial utility
service in the late 1990s, and the first commercial
plant (essentially replicated from the demo plant)
could be on-line around the turn of the century.

For the next generation of nuclear power plants,
the dominant criteria in all design endeavors is to
establish unquestionable safety features. The HTGR
with its graphite-moderated core, single-phase gas-
eous working fluid, and integration of the equip-
ment within a PCRV offers unprecedented safety
characteristics. In addition to this vital element,
the prospective advantages of the HTGR-GT to utili-
ties include plant simplification, improved econo-
mics, and siting flexibility.

The work reported in this paper has outlined
design-related studies which are in progress and
directed towards the selection of a commercial plant
reference design. A companion paper (17) has addressed
systems-related studies leading to the selection of
optimized parameters for minimum power generating cost.
As discussed, a decision has been made to proceed with
the design of a two-loop commercial plant configura-
tion. This paper presents design-related studies
which are important to deciding on the definition of
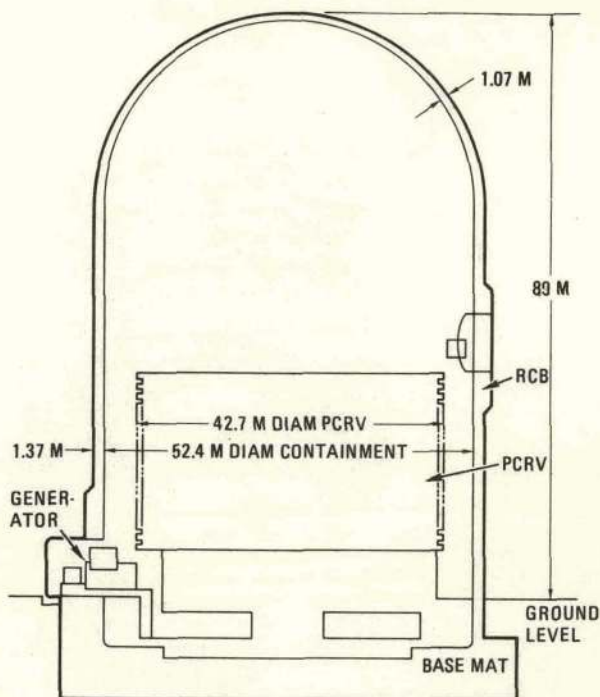two vital HTGR-GT features: (1) rating of the PCLs

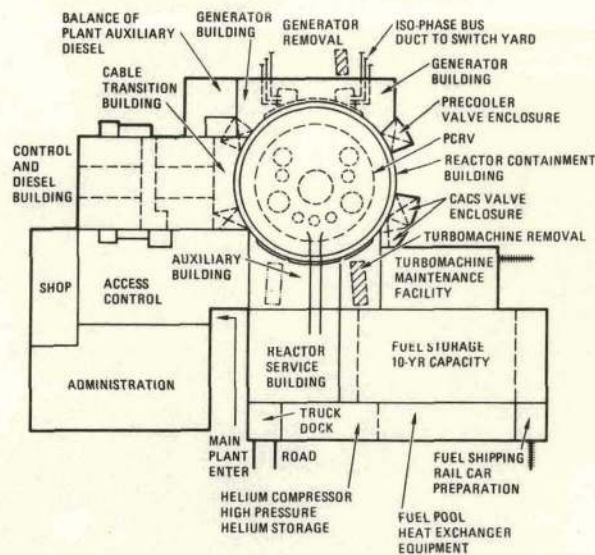Fig.18 Elevation view through RCB for two-loop HTGR-
GT plant

Fig.19 Tentative overall arrangement for two-loop
HTGR-GT power plant

and (2) the choice of intercooled or non-intercooled
cycle. These decisions will be made in 1979, and the
definition of the reference commercial plant concept
will be presented in a future paper.

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