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INTERNATIONAL CO-OPERATION IN DEVELOPING THE GT-MHR

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Abstract

High Temperature Gas-Cooled Reactor (HTGR) technology and its development during the last 30 years has led to the design, construction, and operation of five graphite-moderated helium-cooled reactors with gas outlet temperatures up to 950°C and power levels up to 330 MWe. Design and licensing activities of even larger units (up to 1200 MWe) were well advanced in the U.S. when dropping electricity demand led to cancellation of these commercial units.

The experience from these early plants and related design and development activities provided a solid technology base when gas-cooled reactor development shifted towards smaller, passively safe designs. Although operating experience and past developments are still applicable, the push for safer, highly efficient and economical units, and the need for special applications, has added new requirements that demand and justify further R&D and opens the door for broad international cooperation in the further development of base technologies for HTGR applications.

In the fall of 1995, driven by budget constraints and anti-nuclear sentiments, the US government decided to discontinue financial support of the Gas Turbine-Modular Helium Reactor (GT-MHR). At that time, significant work was underway with participation of several vendors with specialized expertise in various aspects of the GT-MHR. Fortunately, the US government provided for documenting the design and development status through an orderly close-out program. Concurrent elimination of government restrictions opened the door for broader international cooperation.

Discussion between General Atomics and the Russian Ministry of Atomic Energy (MINATOM), in the summer of 1994, led to an agreement on a jointly funded design and development program for the GT-MHR. The program is initially focused on the burning of weapons plutonium that becomes available from dismantled nuclear weapons. The long term goal is to utilize the same design for commercial applications - using uranium fuel. This program took advantage of existing technologies and facilities in the US and Russia, but right from the beginning left the door open for broader international cooperation. Accordingly, in January 1996, FRAMATOME has joined the ongoing effort. Discussions are underway with other international entities to join this program.

The program is proceeding well. Several Russian laboratories/design organizations are participating with GA and FRAMATOME. Significant improvements in the power conversion system design are a clear example of the benefit of the cooperative effort.

Further work needs to be done to confirm fuel and components prior to full deployment, etc., providing ample opportunities for international cooperation in many areas.

INTRODUCTION

The Gas Turbine - Modular Helium Reactor (GT-MHR) is an advanced High Temperature Gas-cooled Reactor (HTGR) being developed in an international cooperative program involving General Atomics (GA), the Russian Federation (RF) Ministry of Atomic Energy (MINATOM), and FRAMATOME. The overall goal of the cooperative program is to first develop the GT-MHR for the disposition of surplus weapons plutonium in the RF and then to offer GT-MHR plants fueled with uranium to the international market for electricity generation.

The first step in this cooperative program was an agreement between GA and MINATOM to complete the GT-MHR conceptual design. FRAMATOME subsequently joined the conceptual design program. Other international organizations are actively being pursued for participation in the conceptual design program and are expected to join shortly.

Very satisfactory process has been made to-date. Good technical work is being performed on the conceptual design, international interest in the program is growing, and US restrictions imposed on GA regarding cooperation with RF on nuclear reactor technology have been lifted. Prospects look good that the conceptual design results will be positive and the program will move on into detail design and technology development activities leading to prototype deployment. These activities will broaden the opportunities for international participation.

Although the design work is proceeding on the basis of using weapons plutonium fuel, the project forms an excellent basis for worldwide commercial deployment of GT-MHR plants. A plutonium fueled plant will demonstrate the design and performance. A commercial plant can then be deployed based on the prototype design but fueled with uranium without need for any significant design changes.

BACKGROUND

HTGRs are characterized by a graphite moderator, helium coolant and coated particle fuel. The graphite moderator and coated particle fuel provide an all ceramic core which allows for the generation of high temperature heat energy for electricity generation at high thermal conversion efficiencies and for process heat applications. Helium coolant is the best single phase, inert fluid available for transport of high temperature heat energy from the graphite core.

The five HTGR plants built and operated to-date have validated the basic HTGR design and performance characteristics. The key characteristics which these plants have proven include:

- The ability of coated particle fuel to reliably retain fission products to very high temperatures (up to about 1600°C) and the production of coated particles in commercial quantities that meet the quality requirements necessary for high temperature retention of fission products.

- The inherent high heat capacity characteristics of HTGR graphite moderated reactor cores that provide long times for corrective measures to mitigate upset conditions without challenging safety limits.

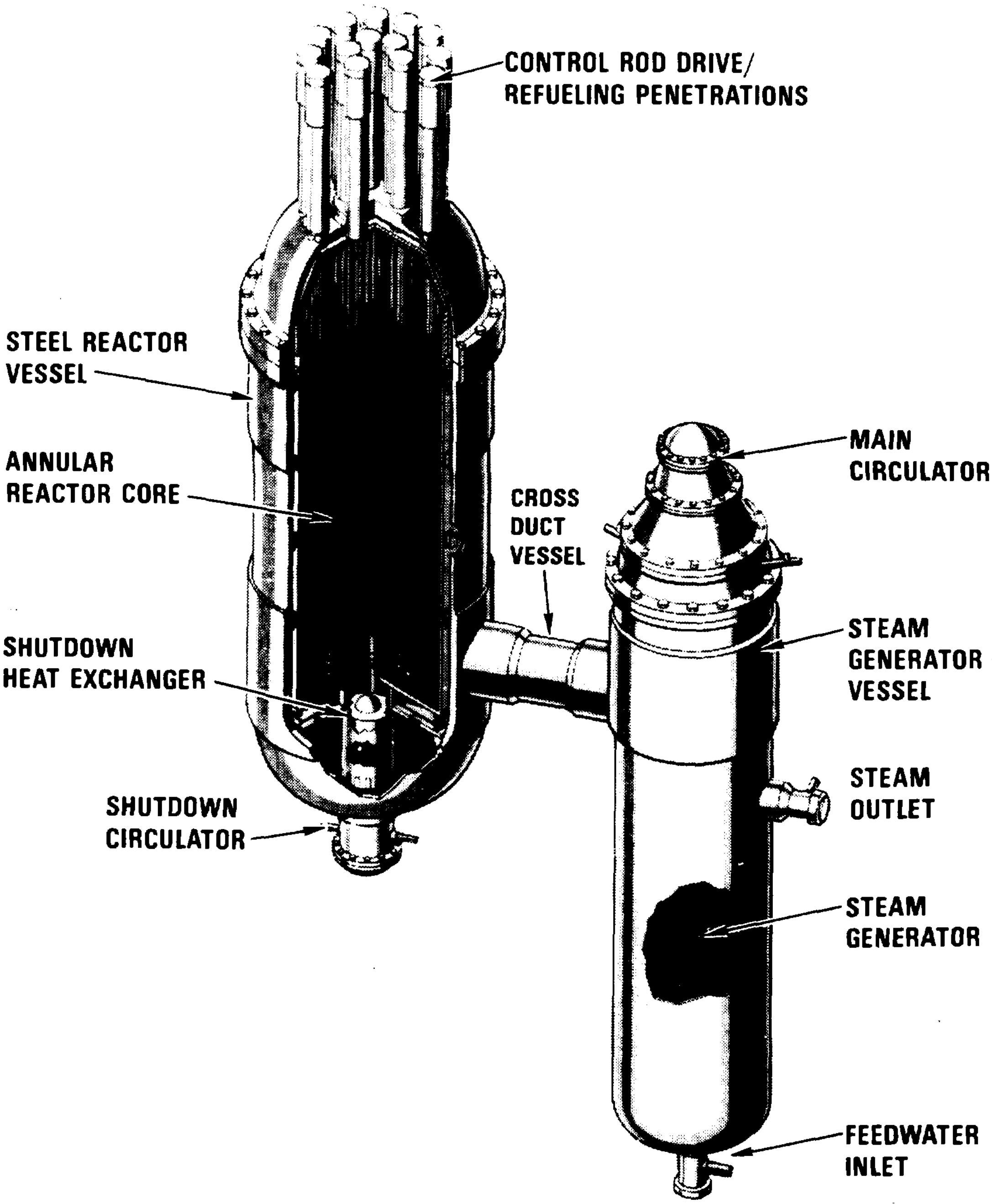

FIG. 1. 350 MWt Modular high temperature gas reactor

- The advantages of helium as a nuclear reactor coolant. Safety issues are simplified by the coolant being single phase; corrosion products are eliminated by the coolant being inert.

- The acceptability of two different fuel configurations, pebble and prismatic.

- The adequacy of the technology data base for the design, analysis, construction, and operation of HTGR reactors.

This HTGR technology data base was developed in the 1960s and 1970s in support of the deployment of large central station power plants. A construction permit had been issued in the US for the first of these plants. However, before large HTGR power plants could be deployed in the US, the oil embargo in the mid 1970s occurred and extensive energy conservation measures were undertaken reducing the electricity demand growth rate. As a consequence, the need for new large central station power plants contracted.

All of the large HTGR plants on order in the US (10 units) were canceled, along with the cancellation of more than 100 LWR plants. The LWR plants under construction were delayed causing capital costs to escalate. Then, in 1979, the Three Mile Island accident occurred which led to wide spread public fear of nuclear power and costly backfits to the existing LWR plants. The financial liabilities, the public's fear of nuclear, and the lack of need for new base load capacity combined to halt new nuclear plant orders in the US.

In the early 1980s, evaluations of the reasons for the dearth of new nuclear plant orders led to the conclusion that smaller, simpler nuclear power plants with inherent safety characteristics were needed for public acceptance. The Modular High Temperature Gas Reactor (MHTGR) was conceived to meet this need, Figure 1. The MHTGR employed a steam cycle power conversion system in common with the prior large HTGR plants.

The MHTGR design had unparalleled safety (meltdown proof), was considerably simpler because of the absence of the need for complex safety systems (completely passive decay heat removal system), and at 350 MWt/135 MWe per module was much smaller than the 1000+ MWe nuclear plant size common in that era. Furthermore, the design maintained fuel temperatures below 1600°C using completely passive means to retain fission products within the coated particle fuel. This provided substantial additional simplifications; the need for secondary containment was eliminated as were the needs for emergency plans for sheltering and evacuation of the public. There was, however, increased importance for the coated particle fuel to meet high quality standards.

Economic evaluations indicated that a reference four module MHTGR plant using 350 MWt/135 MWe modules had power generation cost projections which were non-competitive with equivalent sized coal and LWR plants. A larger MHTGR module design was then developed rated at 450 MWt/175 MWe per module retaining the same safety and simplification features. The reference four module plant using this module size had projected generation costs essentially equivalent to comparably sized coal plants and large LWR plants. However, the technology for highly efficient combined cycle natural gas fired plants became the low cost new generation alternative. Being equivalent in cost to coal and LWR plants was judged to be an insufficient basis for committing the financial resources necessary to design and construct a first MHTGR plant, and mature plants would not be competitive with new, more efficient combined cycle plants.

The message to us was clear. To be competitive, the thermal efficiency of nuclear power had to be markedly improved to compete with modern high efficiency fossil plants. HTGR technology has always held the promise for electricity generation at high thermal efficiency by means of a closed direct Brayton cycle and fortuitously, technological developments during the past decade provided the key elements to realize this promise. These key elements are as follows:

- The HTGR reactor size had been reduced in developing the passively safe module design. At the same time, the size of industrial gas turbines had increased. The technology was now available for a single turbomachine to accommodate the heat energy from a single HTGR module.

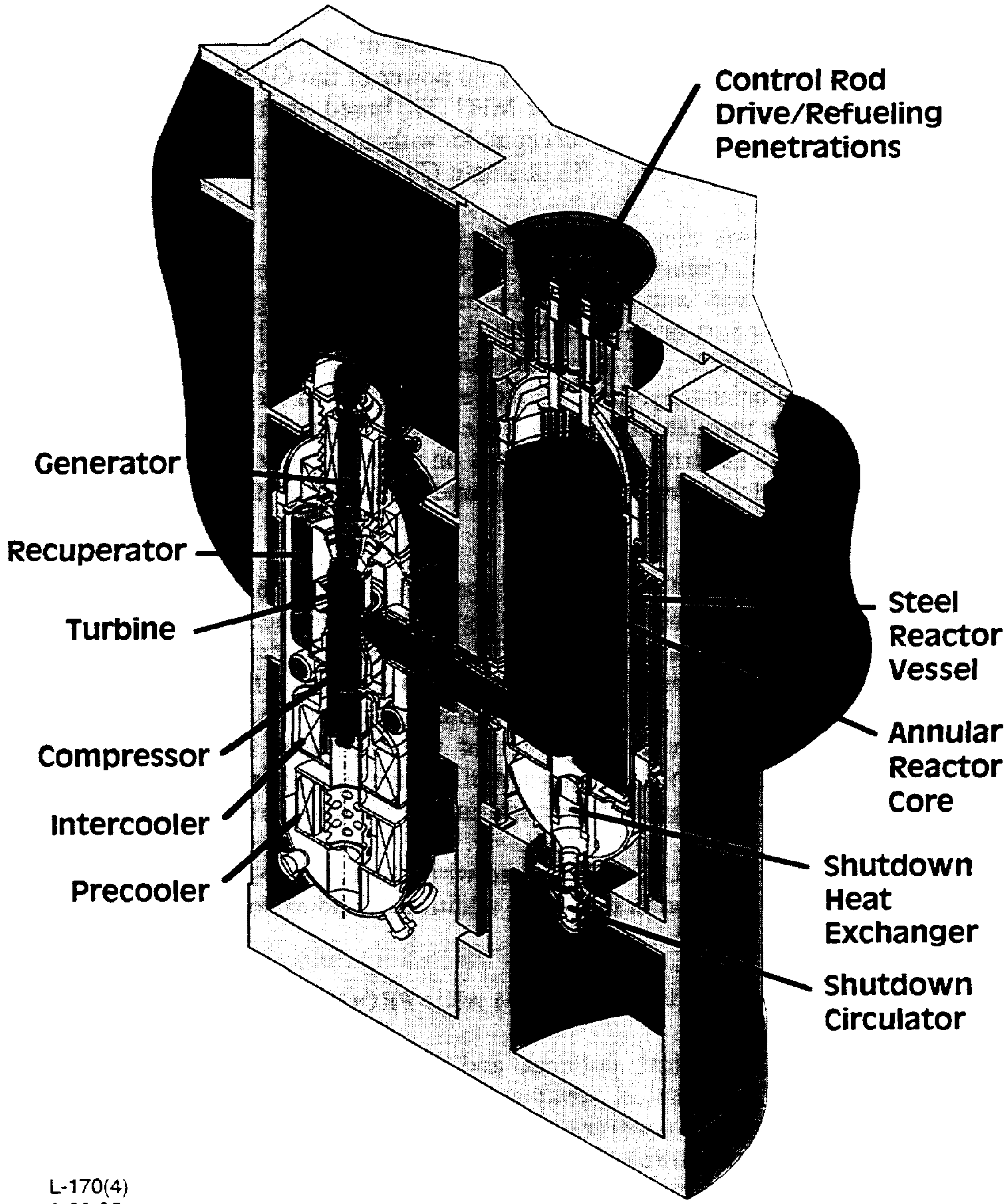

FIG. 2. 600 MWt Gas turbine modular helium reactor

- Highly effective compact plate-fin recuperators had been developed. Recuperator size and capital equipment cost are key economic considerations. Highly effective plate-fin recuperators are much smaller than equivalent tube and shell heat exchangers and provide for substantially less complexity and capital cost.

- The technology for large magnetic bearings had been developed. The use of oil lubricated bearings for the turbomachine with the reactor coolant directly driving the turbine was problematic with regard to the potential coolant contamination by the oil. The availability of magnetic bearings eliminates this potential problem.

The product of integrating these technologies into a closed Brayton cycle power conversion system coupled to a modular HTGR reactor is the Gas Turbine - Modular Helium Reactor (GT-MHR), Figure 2. The rated power of the GT-MHR was increased to 600 MWt, from 450 MWt used in the prior MHTGR, based on further evaluations which showed the higher power level was acceptable without increasing the module vessel diameter. With a net efficiency of 47.7%, a single GT-MHR module produces 286 MWe.

The GT-MHR was formally selected in 1993 as the reference concept for development by the US gas reactor program for commercial deployment. However, driven by budget constraints and anti-nuclear sentiments, the US government decided to discontinue financial support of the GT-MHR starting in the fall of 1995. At that time, significant work was underway with participation of several industrial companies and national laboratories. Fortunately, the US government provided for documenting the design and development status through an orderly close out program. The documentation is now essentially complete. US government restrictions on providing other countries access to the documentation were also eliminated which opens the door for broad international cooperation.

Concurrent with the 1993 selection of the GT-MHR as the reference concept for development in the US, GA and MINATOM signed a memorandum of understanding for cooperating on the development of the GT-MHR for commercial deployment. Subsequently, in early 1994, MINATOM proposed that the cooperative program focus on development of the GT-MHR for disposition of weapons plutonium. In the summer of 1994, GA and MINATOM agreed to initiate development of the GT-MHR for weapons plutonium disposition, and to jointly fund the preparation of the conceptual design, with the long term goal of utilizing the same design fueled with uranium for commercial deployment.

In January 1996 FRAMATOME joined with GA and MINATOM as a participant in the cooperative program and is providing additional funding to support the GT-MHR conceptual design work in Russia.

GA/MINATOM COOPERATIVE PROGRAM AND PROGRESS

There are many technical, political, and economic advantages of the GT-MHR cooperative program. The technical advantages include the GT-MHR system advantages (melt-down proof safety, high generation efficiency, high plutonium destruction) and the program advantages realized from reciprocal technology transfer covering a broad spectrum of scientific, engineering, materials and manufacturing know-how. The political advantages include fulfillment of joint plutonium destruction proliferation objectives, economic support for Russian institutes and industries, and development of an environmentally clean, pollution free energy source. The economic advantages include reduced development costs and a nuclear plant design for commercial deployment having low electricity generation cost.

The GT-MHR cooperative program addresses both US and Russian requirements including safety and regulatory requirements, performance and economic requirements, and operational requirements. The requirements include top level design criteria and specific design codes and standards. This approach is being used to enhance the prospect that a uranium fueled design can be readily deployed in markets throughout the world.

The GT-MHR conceptual design work is being directed by a joint steering committee composed of representatives from MINATOM, OKBM, KI, GA, and FRAMATOME. The steering committee provides oversight of project activities and establishes guidelines for conducting the work. It is responsible for establishing the overall direction and strategy of the program.

Unrestricted existing information on the US sponsored GT-MHR design has been made available to the program and this information is serving as a relatively mature starting point for the cooperative conceptual design effort. A major achievement to-date has been significantly improved power conversion component conceptual designs with major contributions from the OKBM designers, Figure 3. The current GT-MHR power conversion configuration now incorporates both US and Russian technology and is a clear demonstration of the cooperative program advantages.

A goal of the current program is to evolve it into a broad based international cooperative program and efforts are underway to foster participation of other international industrial organizations and/or governments. Several organizations in major nations with nuclear power capability have expressed interest in becoming involved with the program. Discussions are ongoing to determine appropriate terms and conditions under which they might participate. A broad based international cooperative program reduces the up-front financial burden on any one country and is considered by many international leaders to be the best way available today to develop a modern nuclear power system for commercial deployment in the world market.

Following completion of the conceptual design, scheduled for October 1997, the broad based international cooperative program would be responsible for carrying out the detailed design and development activities.

PLANNED GT-MHR DEVELOPMENT ACTIVITIES

The GT-MHR concept is based on taking advantage of existing technology to the maximum practical extent (e.g., the core is designed to use the same prismatic fuel proven in the Fort St. Vrain demonstration plant). No new technology has to be developed because the needed technologies have essentially been demonstrated elsewhere. The GT-MHR concept does, however, incorporate new features for addressing new requirements which require additional development. Principle among these features are passive decay heat removal, plutonium fuel, and use of a closed Brayton cycle power conversion system. The development activities planned for these new features are described here organized into the development tests for the reactor system and the development tests for the power conversion system.

GT-MHR Reactor System Development Tests

The development tests planned for the GT-MHR reactor system, Figure 4, include fuel tests, tests of the reactor cavity cooling system, and design verification tests of key reactor sub-systems and components. These tests are briefly described in the following.

Fuel Tests are planned to qualify TRISO-coated plutonium particle fuel for GT-MHR performance parameters and to provide data for validation of fuel performance models including fission gas release and plate-out. To supply fuel for these tests, current fuel manufacturing equipment and procedures will be adapted for processing weapons-grade plutonium into GT-MHR fuel.

Reactor Cavity Cooling System (RCCS) Tests are planned to provide design data and verify integrated performance. The tests include determining the effective conductivity of the graphite core, buoyancy-induced fluid mixing in the enclosures along the core, and emissivities of metal surfaces including the RCCS panels, reactor vessel and metallic reactor internals. Final verification of the RCCS design is planned by an integrated RCCS systems test using a scale model of the reactor metallic internals and reactor vessel.

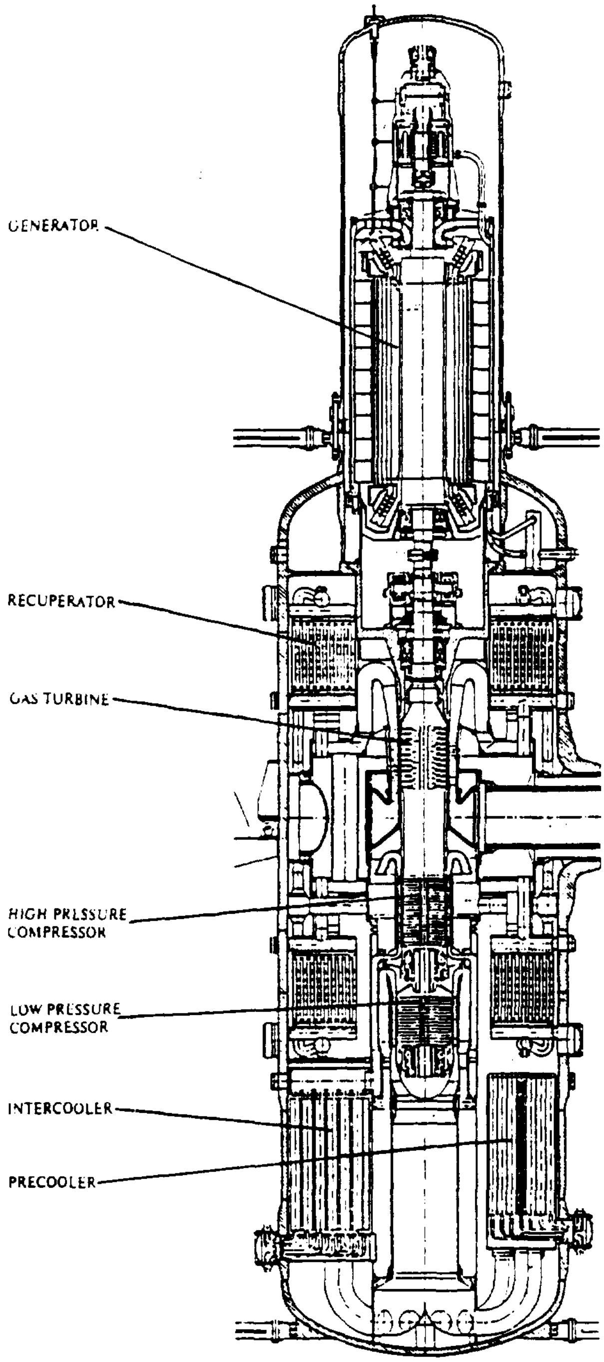

FIG. 3. GT-MHR power conversion system incorporates US and RF technology

Design Verification Tests are planned to verify the design and performance of the of the principle reactor sub-systems and components which include the following:

- The Reactor Internals and Hot Duct
- Fuel Handling System
- Neutron Control System
- Reactor Service Equipment
- Shutdown Cooling System

GT-MHR Power Conversion System Development Tests

The development tests planned for the Power Conversion System (PCS), Figure 5, include design verification tests of the key sub-systems and components and performance testing of a full-scale integrated power conversion system using a fossil-fired heat source. These tests are briefly described in the following.

Design Verification Tests are planned to verify the design and performance of the of the principle PCS sub-systems and components which include the following:

- Generator Tests
- Turbocompressor Tests
- Magnetic Bearing Tests
- Seals Tests
- Recuperator Tests
- Precooler/Intercooler Tests

PCS Integrated Tests are planned using the first GT-MHR power conversion module and will be performed in two phases using a fossil energy heat source:

- Phase I, Steady State Simulation - This phase will be done in two steps: Step 1 will reproduce full helium temperatures distribution at part pressure, and Step 2 will be full helium pressures distribution at part temperature.

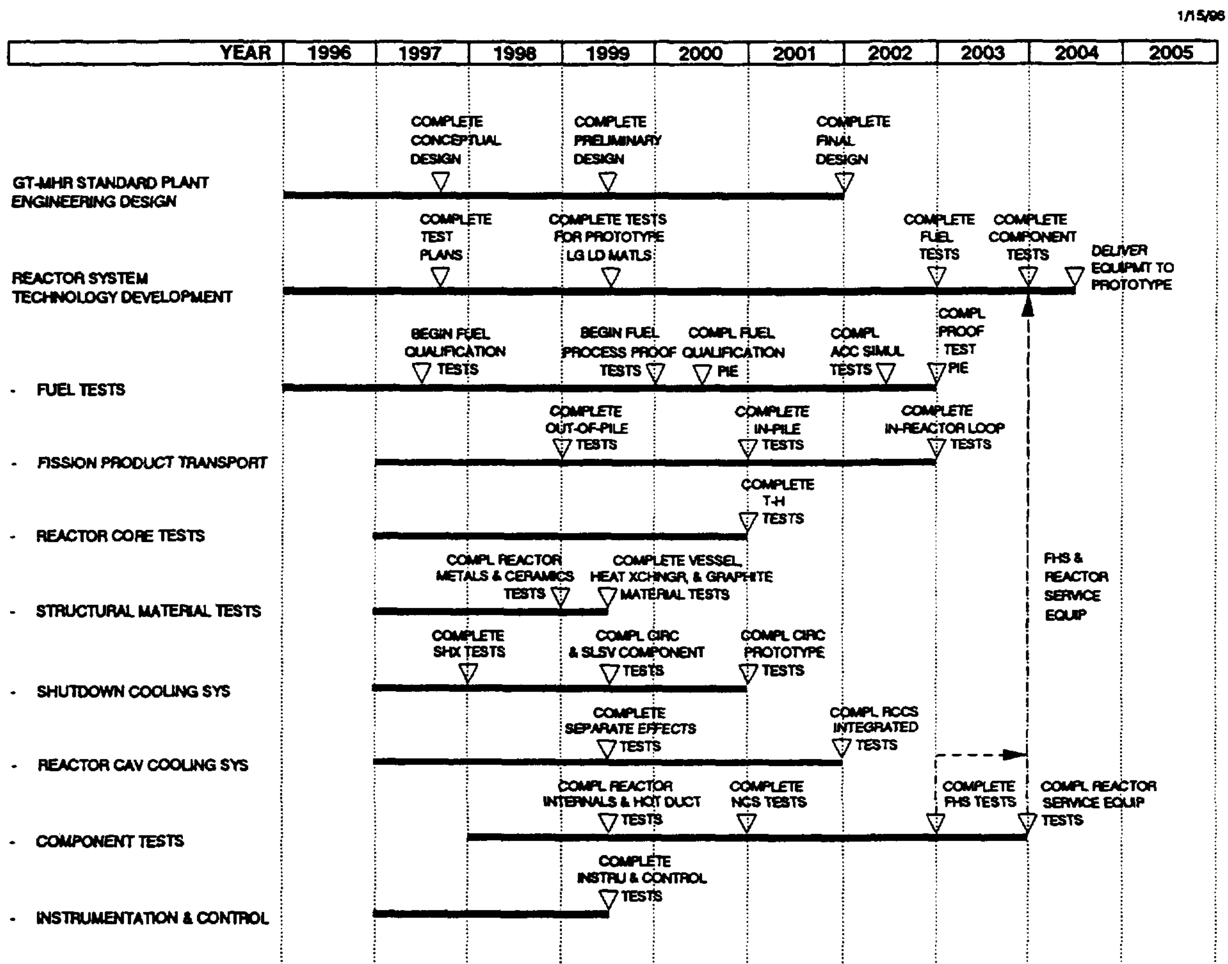

FIG. 4. GT-MHR reactor system summary development schedule

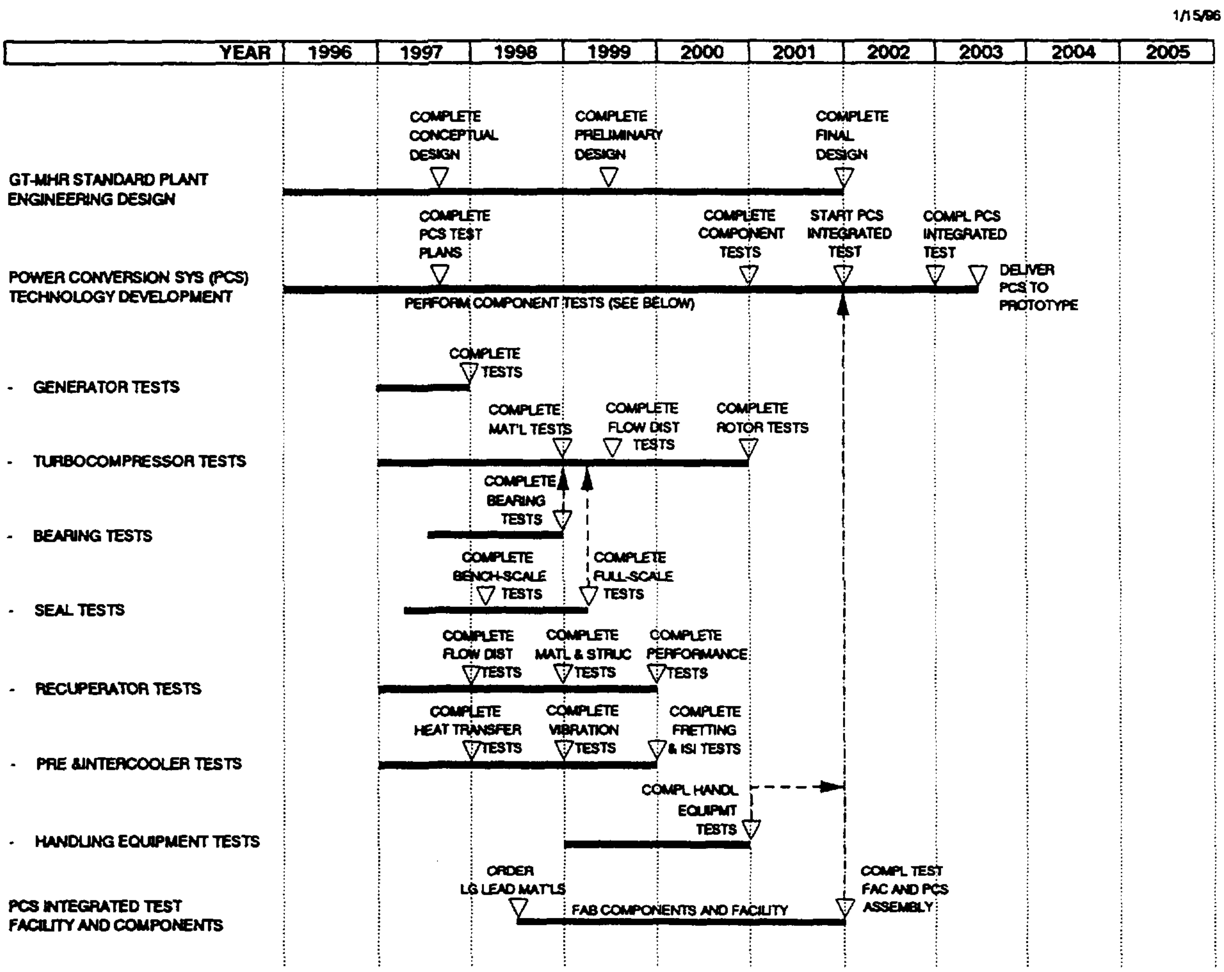

FIG. 5. GT-MHR power conversion system summary development schedule

- Phase II, Key Transient Simulation - Two transients will be run for each plant duty cycle selected according to their severity in producing thermal and pressure loads on the PCS components. One transient will start from a steady state condition in which the helium temperatures distribution has been simulated at part pressure, and the other from a steady state condition in which the helium pressure distribution has been simulated at part temperature.

COMMERCIALIZATION OF THE GT-MHR

In addition to design, development, and licensing activities, the overall program plan for development of the GT-MHR, Figure 6, includes the construction and operation of a prototype module. Performance testing of the prototype will demonstrate all of the GT-MHR systems and their operating characteristics in a fully prototypical plant.

The licensing activities will be pursued in parallel with the detail design and development activities and have the objective that the prototype plant satisfy US, RF, and other applicable international regulatory requirements. The intent is to address the licensing issues which will be directly applicable to follow-on commercial units.

Construction and operation of the prototype module, fueled with weapons plutonium, is the final preparatory step needed for commercialization. The design and development activities, the licensing activities, and the construction and performance of the prototype form the foundation for commercializing the technology. The manufacturing, construction, licensing, and operating experience obtained will provide a firm basis for the information necessary for establishing terms on the part of sellers for commercial offerings and for obtaining required financing on the part of buyers.

The participants in the international cooperative program for development of the GT-MHR will have direct access to the technology. Direct access to the technology will enable the participants, either individually or as partners, to become vendors of GT-MHR commercial plants for the world electric generation market. There is a large market projected for new electric generation capacity in the next century and the projected cost and environmental benefits of the GT-MHR show it has high potential to be highly cost effective and capture a significant share of the world market.

Advanced discussions are now being held with additional potential participants. It is expected that the participant membership will be finalized prior to the initiation of the detail design and development activities planned after completion of the conceptual design in the fall of 1997.

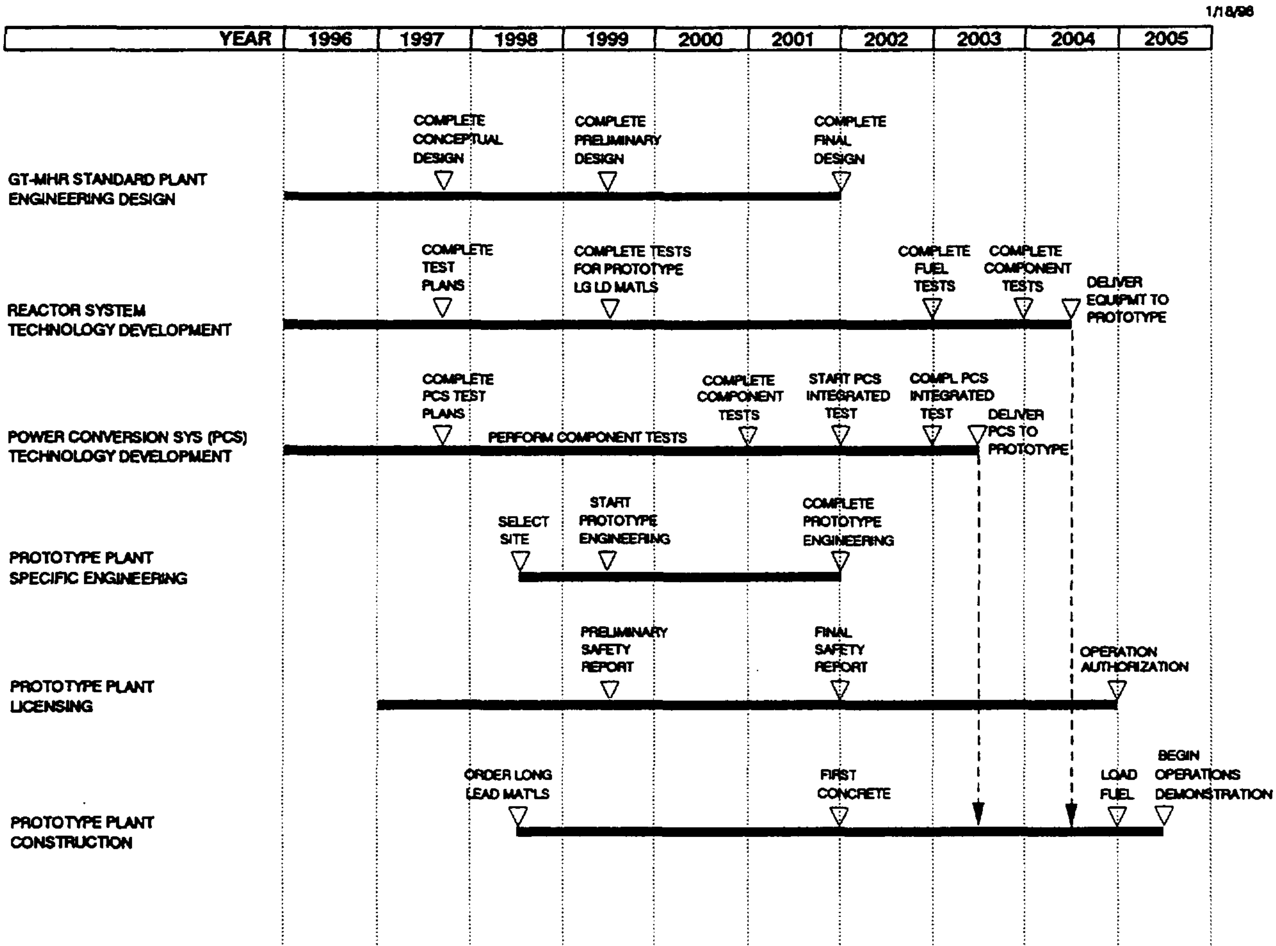

FIG. 6. GT-MHR international program summary schedule

CONCLUSIONS

The key conclusions regarding the GT-MHR background, international cooperative program, development requirements, and commercialization considerations in this paper are as follows:

- Substantial HTGR technology has been developed in support of the five HTGR plants that have been built and operated and in the programs carried out for developing the technology for large central station power plants. The key characteristics of HTGR plants, which include coated particle fuel, graphite moderator, and helium coolant, have been demonstrated.

- Repercussions of the oil embargo in 1973 followed by the Three Mile Island accident in 1979 combined to halt orders for large central station nuclear power plants in the US due to the large financial liabilities, the public's fear of nuclear, and the lack of need for new base load capacity.

- The MHTGR with a power rating of 350 MWt/135 MWe was conceived to meet the perceived need for smaller, simpler nuclear power plants with passive safety characteristics but was concluded to be non-competitive with equivalent sized coal and LWR plants. A larger MHTGR variant with a power rating of 450 MWt/175 MWe was more competitive but was still not competitive with combined cycle plants.

- To be competitive, the thermal efficiency of nuclear power has to be markedly improved to compete with modern high efficiency fossil plants. Technological developments during the last decade on industrial gas turbines, magnetic bearings and highly effective recuperators have made practical the coupling of a modular HTGR with a Brayton cycle power conversion system for the generation of electricity with net thermal efficiencies approaching 50%. The GT-MHR is the product of this coupling.

- Budget constraints and anti-nuclear sentiments have caused the US government to discontinue financial support of the GT-MHR. Fortunately, the US government provided for documenting the design and development status and eliminating restrictions on providing other countries access to the documentation.

- GA and MINATOM have initiated a cooperative program for the development of a conceptual design of the GT-MHR for weapons plutonium disposition with the long term goal of utilizing the same design for commercial deployment using uranium fuel. FRAMATOME has subsequently joined the cooperative program.

- The GT-MHR cooperative program has many technical, political, and economic advantages including the benefits realized from reciprocal technology transfer covering a broad spectrum of scientific, engineering, materials and manufacturing know-how. Design progress to-date clearly demonstrates the advantages of the reciprocal technology transfer.

- A goal of the current program is to evolve it into a broad based international cooperative program and several international organizations have expressed interest in joining. A broad based international cooperative program is considered by many international leaders to be the best way to develop a modern nuclear power system for commercial deployment.

- No new technologies need to be developed for the GT-MHR. The GT-MHR concept does, however, incorporate new features for addressing new requirements which require additional development. Principle among these features are passive decay heat removal, plutonium fuel, and use of a Brayton cycle power conversion system.

- Development tests required for the GT-MHR include fuel tests, tests of the reactor cavity cooling system, design verification tests of key systems and components and performance testing of a full-scale integrated power conversion system using a fossil-fired heat source.

- The GT-MHR deployment program includes construction and operation of a prototype module. Construction and operation of a prototype module is the final step needed for commercialization of the technology.

- The participants in the GT-MHR international cooperative program will have direct access to the technology which will enable them to become vendors of GT-MHR commercial plants for the burgeoning world electric generation market.