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MHTGR DESIGN AND DEVELOPMENT STATUS

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MHTGR DESIGN AND DEVELOPMENT STATUS

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Abstract

The Modular High-Temperature Gas-Cooled Reactor (MHTGR) is an advanced power plant concept which has been under design definition since 1984. The design utilizes basic high-temperature gas-cooled reactor features of ceramic fuel, helium coolant and a graphite moderator which have been under development for 30 years. The geometric arrangement of the reactor vessels, the core and the heat removal components has been selected to exploit the inherent characteristics associated with high temperature materials. The design utilizes passively safe features which provide a higher margin of safety and investment protection than current generation reactors. The design has been evaluated to be economically attractive relative to modern coal fired plants. The design and development program is a cooperative effort by the U.S. government, the utilities and the nuclear industry.

1. Introduction

The development of earlier HTGR plants had proceeded on a trend toward very large monolithic designs during the 1970s and early 1980s. In about 1984 there was a recognition by the U.S. participants within industry, the Department of Energy and the Congress that the changes in the environment for nuclear power, including the financial, electrical demand pattern and public interests, pointed toward a reevaluation of the programs for development of improved reactor designs. An evaluation by the joint industry/government participants led to a focusing of the development of the gas-cooled reactor toward a smaller MHTGR power plant with emphasis on passive safety, reliability and competitive economics (Ref. 1).

A design team of General Atomics, Bechtel National Inc., Combustion Engineering and Stone & Webster Engineering Co. is now focused on the development of the preliminary design that will meet these challenging demands. Base Technology support is being provided by the Oak Ridge National Laboratory. The program is under the sponsorship of the U.S. DOE and in cooperation with utility users represented by Gas-Cooled Reactor Associates (GCRA). This paper provides a status of the MHTGR design and development.

2. System Requirements

The plant has been designed on the basis of top level requirements by the utility/user, through GCRA, and by Nuclear Regulatory Commission (NRC) regulatory criteria applicable to all reactor types. The regulatory requirements specific to the MTHGR have been developed as direct, quantifiable statements defining acceptable consequences or risks to the public for normal operation, transients, design basis events, and other very low probability events. The requirements for safety and investment risk have had strong effects on the plant arrangement and the design of components (Ref. 2).

The Top-Level Regulator Criteria provide the principal definition of plant safety (Ref. 3). The safety design philosophy selected for the MHTGR has been to control radionuclide releases through their retention at the source, within the coated fuel particles themselves, even under accident conditions. This concept places minimal reliance upon active design features or operator action.

The safety philosophy was made possible principally by improvements in the gas-cooled reactor coated particle fuel technology. The retention of radionuclide within the coated fuel particles replaces reliance upon such secondary barriers as the primary coolant boundary or a containment structure.

3. Design Description

The typical MHTGR plant includes an arrangement of four identical modular reactor units located in a single reactor building. The plant is divided into two major areas: a Nuclear Island (NI) containing the four reactor modules and an energy conversion area (ECA) containing two turbine generators. Each of the four modules produces a thermal output of 350 MW(t). All modules are headered to feed two turbine generators of 300 MW(e) each, operating in parallel.

Each reactor module is housed in adjacent, but separate, reinforced concrete structures located below grade and under a common roof structure. The below-grade location provides significant design benefits by reducing the seismic amplifications typical of above-grade structures and by providing confinement.

Almost all components and systems of each module, which are required to meet regulatory requirements, are independent of other modules and are localized within the individual concrete structures. These include plant protection and decay heat removal systems.

The overall reactor configuration is shown in Fig. 1. The reactor components are contained within three steel vessels: a reactor vessel, a steam generator vessel, and a connecting cross vessel. The reactor vessel is approximately the same size as that of a large boiling water reactor and contains the core, reflector, and associated supports. A shutdown heat exchanger and a shutdown cooling circulator are mounted on the bottom of the reactor vessel. Top mounted penentrations house

US-DOE MHTGR PROGRAM

350 MW(t) MODULAR HTGR ISOMETRIC

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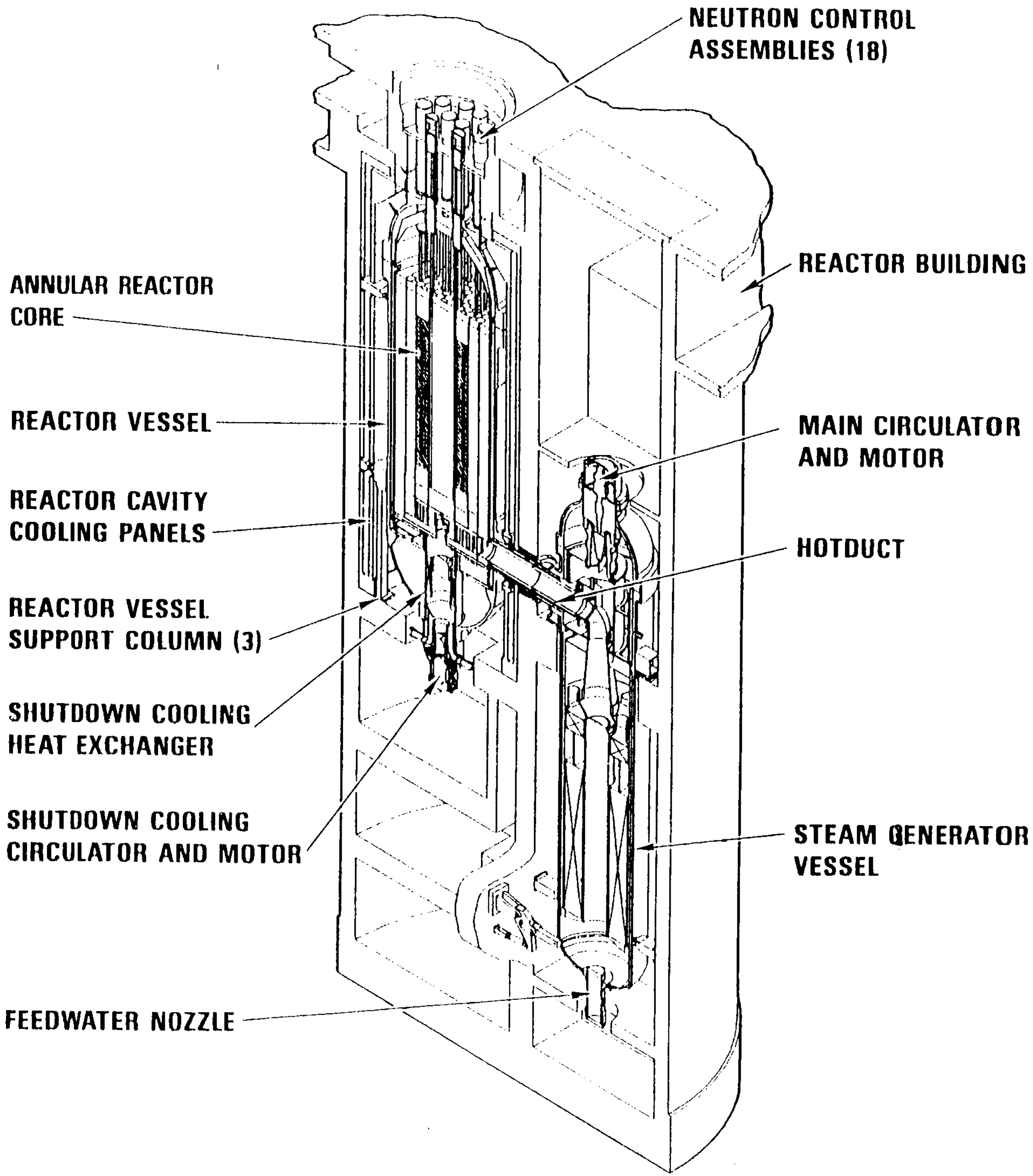

FIGURE 1

the control rod drive mechanisms and the hoppers containing boron carbide pellets for reserve shutdown. The penetrations are also used as access for refueling and inspection.

The heat transfer during power operation or normal core decay heat removal operation is accomplished by helium which is heated as it flows down through the core. It is collected in a plenum below the core and flows through a coaxial hot duct inside the cross vessel to a once-through helical bundle steam generator.

After flowing downward over the steam generator tubes, the cool helium flows upward in an annulus between the steam generator vessel and a shroud leading to the main circulator inlet.

The main circulator is a submerged electric motor driven single stage axial compressor with active magnetic bearings. The helium is discharged from the circulator and flows through the annulus of the cross vessel and hot duct and then upward to the top plenum over the core.

In order to meet availability and maintenance requirements, a separate shutdown cooling system is provided as a backup to the primary heat transport system. The heat removal systems allow hands-on plant maintenance to begin within 24 hr after plant shutdown.

A reactor cavity cooling system (RCCS) is located in the below grade concrete structure external to the reactor vessel to remove plant residual heat. This system is totally passive and provides the alternative safety related heat sink if the forced cooling systems are inoperative. The heat is transferred by means of conduction, convection and radiation from the core to the RCCS. This system has no controls, valves, circulating fans, or other active components. The RCCS is the only safety related heat removal system utilized by the MHTGR.

The reactor core and the surrounding graphite neutron reflectors are supported on a steel core support plate at the lower end of the reactor vessel. A horizontal cross-section of the reactor core and vessel internals is shown in Figure 2.

The reactor core primarily contains graphite fuel blocks that are hexagonal in cross section. (Ref. 4). The fuel (Fig. 3) is in the form of coated particles of low enriched fissile uranium oxycarbide and fertile thorium oxide. The fuel particles are bonded together in fuel rods which are contained in sealed vertical holes in the fuel blocks. These fuel blocks are stacked in columns to make up an annular shaped core. Unfueled graphite blocks form the center of annulus, and surround the active core to form the reflector. Key reactor core design parameters are shown in Table 1. The annular shape of the core has been selected to enhance the heat removal capabilities in the event of a loss of all forced cooling.

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350 MW(t) MODULAR REACTOR CORE CROSS SECTION

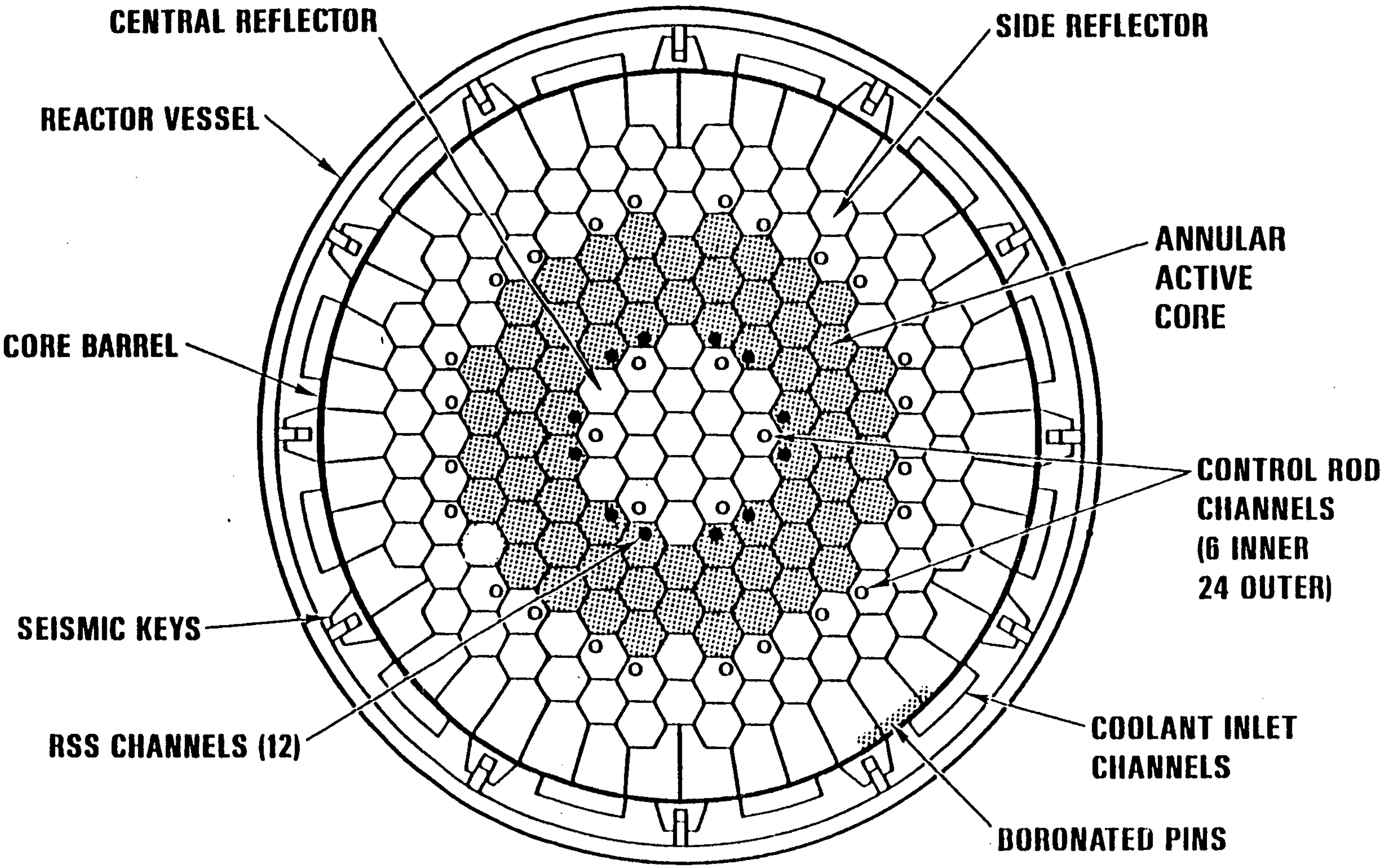

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FIGURE 2

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FUEL COMPONENTS

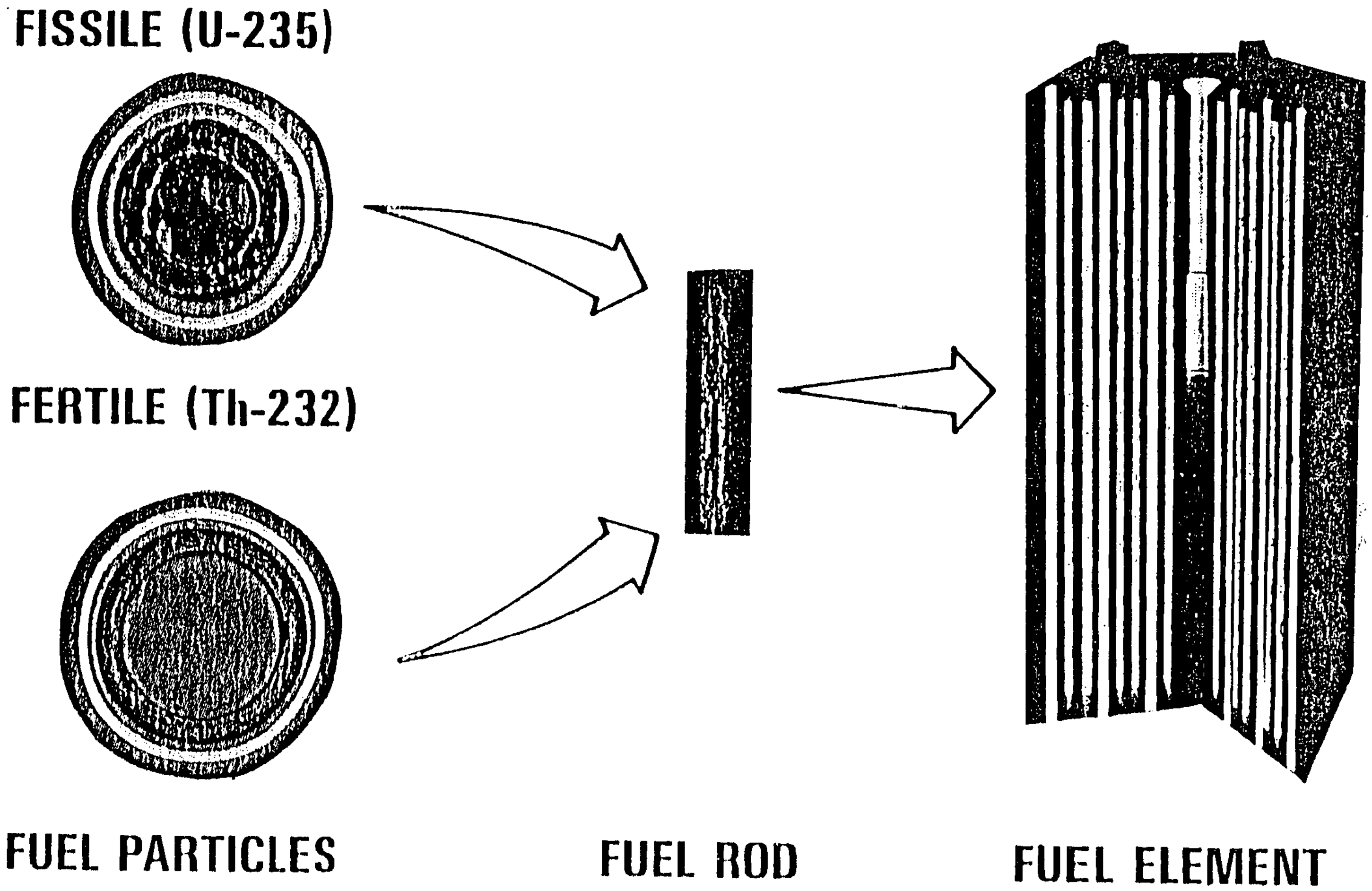

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FIGURE 3

TABLE 1
REACTOR SYSTEM DESIGN PARAMETERS

ITEM	VALUE
CORE THERMAL POWER	350 MW
CORE POWER DENSITY	5.9 w/cm^3
ANNULAR CORE DIAMETERS:	
OUTER	3.5 m
INNER	1.6 m
CORE HEIGHT	7.9 m
NUMBER OF COLUMNS IN ACTIVE CORE	66
NUMBER OF FUEL ELEMENTS PER COLUMN	10
NUMBER OF CONTROL RODS	30
NUMBER OF RESERVE SHUTDOWN COLUMNS	12

The MHTGR utilizes a once-through fuel cycle; that is, it does not rely on recycling of spent fuel. Each module is refueled once every 20 months. The refueling is accomplished with reactor shutdown and depressurized, utilizing a refueling machine accessing the fuel elements through the appropriate control rod penetrations in the top of the reactor vessel. The spent fuel is transported to the spent fuel storage pool for temporary storage before shipping to final storage offsite.

Thermal energy from the four reactor modules is delivered to two steam turbine generators to produce 538 MW(e) net, of electric power. The turbine plant is similar to a modern fossil-fired plant except that the MHTGR plant utilizes a nonreheat steam cycle. A mechanical draft cooling tower rejects the condenser heat load to the atmosphere. Key plant performance parameters are summarized in Table 2.

Table 2
Plant Performance Parameters

Thermal Power	1400 MW(t)
Electrical Output	588 MW(e) Gross; 538 MW(e) Net
Net Efficiency	38.4%
Steam Conditions	538°C (1000°F)/16.6 MPa (2400 psig)
Core Exit Helium Temperature	687°C (1268°F)
Cold Helium Temperature	259°C (498°F)

4. Design Status

The MHTGR design is based on 30 years of reactor experience with the carbon dioxide-cooled Magnox and Advanced Gas-Cooled Reactor (AGR) developed in the United Kingdom; the 15 MW(e) Arbeitsgemeinshaft Versuch Reaktor (AVR) development plant and the 300 MW(e) Thorium Hochtemperatur Reaktor (THTR) demonstration plant developed in Germany; the 40 MW(e) Peach Bottom I developed in this country by General Atomics (GA); and the 330 MW(e) Fort St. Vrain (FSV) demonstration plant, also a GA project. The FSV, AVR, and THTR facilities have provided invaluable confirmation and demonstration of specific and generic HTGR design and operating characteristics. A significant design achievement was the submittal of a Preliminary Safety Information Document to the NRC in October 1986. Detailed presentations have been made to the NRC in support of their in-depth review. A statement of licensability of the design is expected later in 1988 from the NRC.

A conceptual plant design was completed in July 1987. All systems and major components were configured, sized, and arranged. The design of the systems and system components selected for this plant are within the state-of-the-art. Only limited technology development is needed to complete the final design. A supportive technology program has been planned to confirm and validate the data for completing the design (Ref. 5).

The current focus is on the preliminary design. This phase will be completed with the production of a Preliminary Standard Safety Analysis Report (PSSAR) and a request for a Preliminary Design Approval (PDA) from the NRC. A Final Design Approval (FDA) from the NRC is expected following the completion of the final design and the submittal of a Final Standard Safety Analysis Report (FSSAR).

The FDA will enable the potential electric utility/user to proceed with assurance that the plant will not be subject to licensing delays and review during construction. The issuance of the FDA and successful operation of the first plant will facilitate the certification of a standardized MHTGR design by rule making which is the ultimate licensing goal of the program.

5. Economic Assessment

The total costs for generating electricity in an MHTGR plant have been evaluated by the Gas-Cooled Reactor Associates and the Oak Ridge National Laboratory (Ref. 6). The costs were developed in general conformance with the Department of Energy (DOE) Cost Estimate Guidelines for Advanced Nuclear Power Technologies (Ref. 7)

Plant capital costs for reference MHTGR plants were developed by General Atomics, Bechtel National and Combustion Engineering on a detail account level for a first-of-a-kind (FOAK) plant, a replica plant conforming to the certified design and an equilibrium nth-of-a-kind (NOAK) plant conforming to the certified design.

Fuel cycle costs were developed by General Atomics based on detailed fuel depletion analyses, fuel fabrication cost estimates and reference DOE costs for uranium, separative work and spent fuel disposal.

The MHTGR equilibrium plant costs have been evaluated in comparison with comparably sized coal plants. The reference coal plants were single unit 400 MWe and 600 MWe designs from the Technical Assessment Guide of the Electric Power Research Institute (Ref. 8).

From the GCRA/ORNL evaluation, the comparison of capital costs for an equilibrium plant is summarized in Table 3.

Costs have been developed to design, construct, operate and maintain reference MHTGR power plants, and a comparison of the costs has been made with those for competing coal plants (Ref. 6). The costs were developed in general conformance with the Department of Energy (DOE) cost estimating guidelines for advanced nuclear technologies.

Table 3
Plant Capital Cost Comparison

Component	($/KWe) 400MWe Coal	 600MWe Coal	 540MWe MHTGR
Direct and Indirect Capital	1450	1200	1550
Contingency and Funds during Construction	530	450	590
TOTAL COST	1980	1650	2140

The results show the MHTGR capital cost to be somewhat higher, but competitive with an equivalent size coal plant on a $/kWe basis.

The inherent characteristics of the MHTGR provide the basis for offsetting the traditional scaling law for nuclear power plants costs. Plant simplification and reduction in active safety and major investment risk protection systems result in reduced cost. The separated construction of the nuclear portion and the balance of plant permits the use of conventional rather than nuclear standards for the majority of field construction.

Table 4
Comparison of Busbar Costs

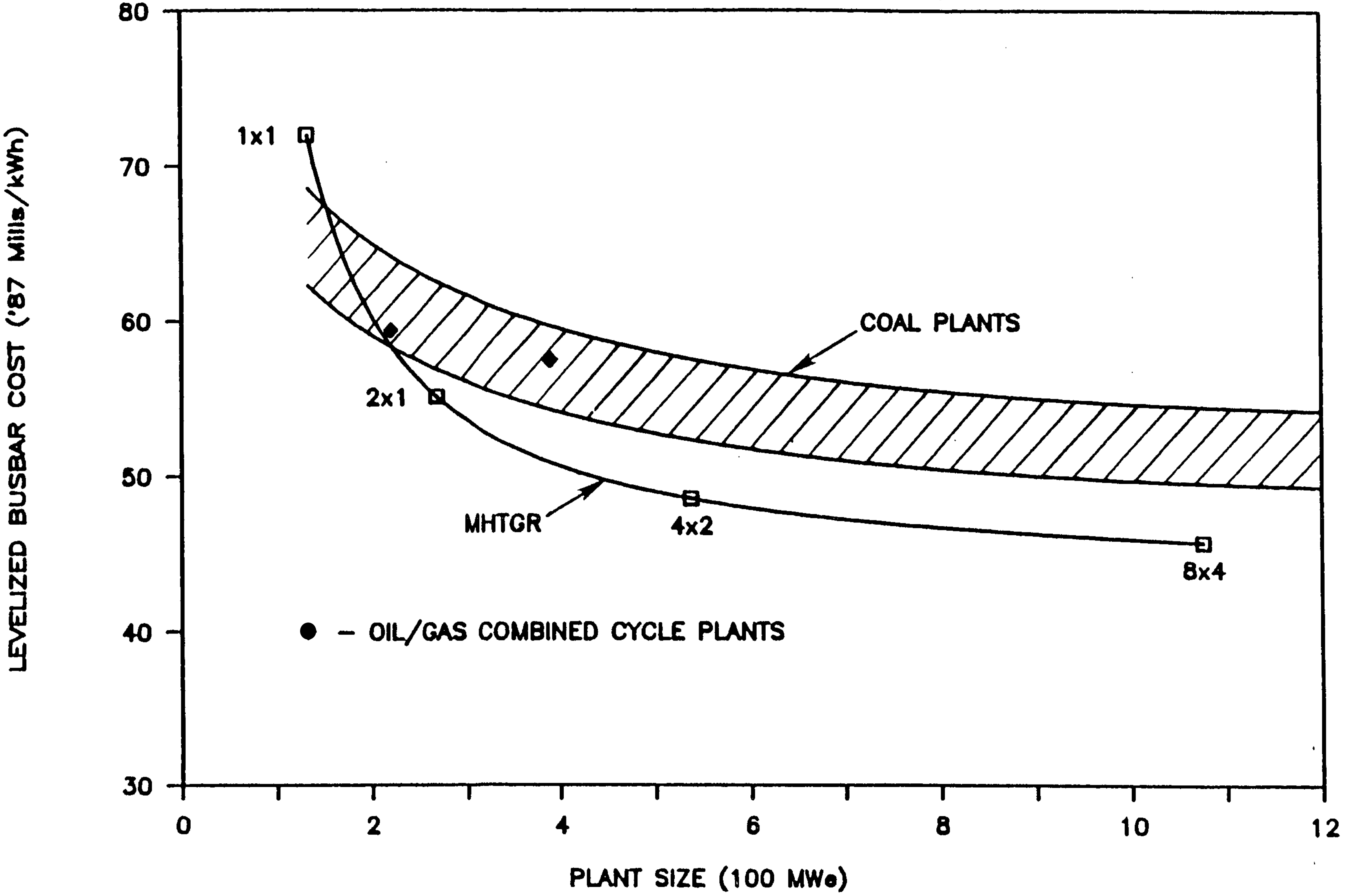
Component	(Mill/KWh) 400MWe Coal	 600MWe Coal	 540MWe MHTGR
Capital	27	22	28
Fuel Cycle	25	25	11
Operation, Maintenance and Decommissioning	8	6	9
TOTAL BUSBAR COSTS	60	53	48

A comparison of the reference MHTGR equilibrium plant 30-year levelized busbar costs with those for the single unit coal plants is given in Table 4. The MHTGR fuel cost component is considerably less than those for the coal plants. The MHTGR O&M costs and decommissioning are slightly greater than the coal plants. The busbar costs have been evaluated by LaBar and Bowers as a function of plant size. This projection is shown in Fig. 4. The net result is an estimated MHTGR busbar cost that is 10% to 20% less than those for the coal plants.

FIGURE 4

EQUILIBRIUM PLANT POWER COST PROJECTION

(2010 STARTUP, 80% CAPACITY FACTOR)



COAL COST: $1.75/MBTU IN '87$ WITH 1% REAL ESCALATION

OIL/GAS COST: $3.00/MBTU IN '87$ WITH 2% REAL ESCALATION 1990 – ON

6. Conclusions

A second generation nuclear power system MHTGR has been designed to meet utility and regulatory requirements. The MHTGR responds to concerns of the public, the government, the utilities, and industry about nuclear safety, economic risk, and investment protection.

Based on technology developed and demonstrated in the United States, the United Kingdom and West Germany, this system makes use of the refractory-coated nuclear fuel, helium gas as an inert coolant, and graphite as a stable core structural material.

Public safety and protection of the plant investment is provided by inherent and passive features. The high-performance MHTGR provides flexibility in power output and siting, competitive energy costs, and can serve diverse energy needs both domestically and internationally.

7. Acknowledgement

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