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ECONOMIC CHARACTERISTICS OF A SMALLER, SIMPLER REACTOR*

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ABSTRACT

Reduced load growth and heightened concern with economic risk has led to an expressed utility preference for smaller capacity additions (Reference 1). The Modular High Temperature Reactor (MHTGR) plant has been developed as a small, simple plant that has limited financial risk and is economically competitive with comparatively sized coal plants. Competitive economics is achieved by the simplifications made possible in a small MHTGR, reduction in the quantity of nuclear grade construction and design standardization and certification. Assessments show the MHTGR plant to have an economic advantage over coal plants for plant sizes from 270 MWe to 1080 MWe. Financial risk is limited by small unit sizes and short lead times that allow incremental deployment. Evaluations show the MHTGR incremental deployment capability to reduce negative cash flows by almost a factor of 2 relative to that required by a single large nuclear plant.

INTRODUCTION

The deployment of new electric generating facilities in the 1960's and 1970's with capacities in the range of 1000 MWe, or greater, was compatible with historical and then-projected load growth rates. Unfortunately, the overall impact of the Arab oil embargo and the ensuing conservation ethic resulted in significantly lower growth rates. Moreover, the time required to design, license and construct large nuclear plants far exceeded the originally projected schedules. The schedule extensions coupled with a period of high interest rates has resulted in several financial disasters. And, even some relatively successful projects are faced with prudency hearings and potential disallowances and/or multi-year phase-in of capital costs into the rate base.

Today the electric load growth rate in the U.S. is in the vicinity of 2 to 3%/yr. as compared to about 7%/yr. in the early part of the last decade. For most electric utility systems in the U.S., today's smaller load growth dictates the need for smaller capacity additions to avoid the possibility of large excess generation capacity. Moreover, uncertainties in the load growth rate dictates the need for plants with shorter lead and construction times.

The challenge faced by such smaller nuclear plants is: Can they have less financial risk and be economically competitive in spite of the projected diseconomy of scale? The approach to achieving competitive economics and lower financial risk in a small high temperature gas-cooled reactor plant and an assessment of the resultant economics and financial risk is presented here.

A SMALLER, SIMPLER REACTOR PLANT

The Modular High Temperature Gas-Cooled Reactor (MHTGR) has been designed as a small reactor plant that is projected to be economically competitive and have limited financial risk. A summary description of the reference MHTGR plant is provided in the MHTGR Conceptual Design Summary Report (Reference 2). The reference MHTGR plant consists of four 350 MW(t) reactor modules and two turbine generators (4x2) which produce a net output of approximately 540 MWe. Only those design characteristics and plant features that play a major role in making possible the achievement of competitive economics and limited financial risk will be addressed here.

Simplification Through Passive Safety

Fundamental to the achievement of competitive economics and limiting financial risk is simplicity. Enhanced simplicity in the MHTGR is achieved through the minimization of often complex, engineered safety systems. Fundamental to the MHTGRs enhanced simplicity is a total passive safety concept made possible through the use of:

- Refractory coated particle fuel capable of retaining fission products at very high temperatures.
- Graphite moderator which remains stable to very high temperatures and has a high heat capacity.

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- Helium coolant which is inert, non-corrosive, and remains as a gas under all operating conditions.
- Strong negative temperature coefficient that shuts down the nuclear reaction without reliance on control material insertion to the core.

Design features introduced to provide passive safety include limiting the MHTGR core size and power density such that the fuel particle coatings retain the fission products to an acceptable degree under all circumstances. Decay heat is removed through the passive mechanisms of conduction, radiation and natural convection. Collectively, these features result in benign response characteristics which simplify operation and provide for long times (days) for operator actions to prevent equipment damage. As a consequence of the passive features incorporated in the MHTGR design, there is no need for complex engineered safety systems or operator actions to assure safety and the long response time available for investment protection actions limits financial risk.

Reduced Nuclear Grade Construction

The second principle used in the development of the MHTGR design to achieve competitive economics and to limit financial risk is reduced nuclear grade construction costs achieved by segregation of the safety systems to one area and minimization of nuclear grade site construction activities. All components, systems and structures that are required for the control of radionuclides are contained on the Nuclear Island (NI) (reactors, reactor building, spent fuel storage, etc.). To minimize nuclear grade site construction activities on the NI, components and systems are modularized and factory fabricated. Aside from construction of structures, most of the nuclear grade site construction activities are associated with the interconnection of the modules. The cost savings and risk reduction potential of modularization and factory fabrication in the MHTGR plant is covered in a companion paper to this conference (Reference 3).

The balance of the plant is physically separated from the NI in the Energy Conversion Area (ECA) (turbine generators, maintenance shops, etc.). All ECA construction activities can be performed in accordance with high quality fossil plant standards thereby eliminating nuclear grade construction costs on a major fraction of the plant. This approach improves productivity, reduces schedules and reduces field erection costs.

Standardization

The third principle applied to achieve good economics and to limit financial risk is standardization. The MHTGR plant configuration is ideally suited for standardization of the NI and design certification by the Nuclear Regulatory Commission (NRC) of all safety related components, systems and structures within the NI. After certification, it is expected that the NRC licensing review of a follow-on plant would be limited in scope to site specific issues. The licensing process and associated schedules would be predictable, resulting in significant reductions in engineering costs and plant lead time.

Standardization also leads to good economics for small unit sizes as the result of the economy of multiplicity. When several units are required to fulfill a given requirement, serial production practices can be employed. When serial production methods are used, the cost per unit and construction time per unit decreases due to learning. Also, when more than one unit is produced, more efficient production methods can be justified. Taken together, these effects lead to the realization of the economy of multiplicity.

Summary of Approach

In the past, competitive nuclear power was driven heavily by the perceived economies of scale. Fundamental to the MHTGR concept is a departure from reliance on the economy of scale in favor of the economies of simplicity, reduced nuclear grade construction and standardization. Simplification is accomplished in the MHTGR by using a small reactor that requires fewer safety related systems. Reduced nuclear grade construction cost is made possible by establishing a physically separated NI and by modularization of systems for factory fabrication. Standardization (and certification) of the design reduces engineering costs and makes possible the economies of multiplicity in replicating incremental power units.

Financial risk in the MHTGR is limited by inherent slow response characteristics to operational events, small plant size by short construction period and design standardization and certification. The slow design response characteristics provide time to take actions for protection of the investment. The small plant size and short construction period limits the initial capital requirements. Design standardization and certification result in predictable costs and schedules.

ECONOMIC ASSESSMENT

MHTGR Costs

To allow an assessment of MHTGR economics, 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. The costs were developed in general conformance with the Department of Energy (DOE) cost estimating guidelines for advanced nuclear technologies (Reference 4) using the Energy Economic Data Base (EEDB) Program code of accounts.

Plant capital costs for reference MHTGR plants were developed 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. Costs were developed by General Atomics and Combustion Engineering for the reactor plant equipment and by General Electric for the plant control systems. Costs for most of the other equipment, field labor, and field material necessary to construct the NI were developed by Bechtel. Costs for all the equipment, field labor, and field material necessary to construct the ECA were developed by Stone & Webster, as well as a few of the systems and buildings within the NI. Gas Cooled Reactor Associates (GCRA) developed the owner's cost, integrated the cost estimates and performed the cost assessments.

An assessment of operations and maintenance (O&M) requirements was developed for the reference MHTGR plant by a GCRA chaired HTGR Program task force familiar with nuclear generating plant O&M requirements and the MHTGR design. The O&M requirements were translated into costs by the Oak Ridge National Laboratory (ORNL) using methods derived from techniques developed for estimating light water reactor and coal plant O&M costs. The O&M costs include the expenses for onsite staff, maintenance materials and supplies, offsite technical support, nuclear regulatory fees, insurance premiums and administrative and general costs.

Fuel cycle costs were developed by General Atomics based on their fuel fabrication cost estimates and reference DOE parameters for uranium and separative work costs (Reference 4).

No detailed evaluation has been performed to-date for assessing the decommissioning cost of a MHTGR plant. A cost of $130/kWe has been assumed for the current cost projection based upon accepted "rule-of-thumb" decommissioning costs (Reference 4) for other types of nuclear generating plants. This allowance is thought to be conservative for the MHTGR considering the small number of systems requiring decontamination.

Costs for the following variants of equilibrium plants were derived from the costs for the reference 4x2 plant to assess the cost impact of reactor multiplicity (or plant output) at one site:

- One reactor/one turbine (1x1) - ~135 MWe
- Two reactor/one turbine (2x1) - ~270 MWe
- Eight reactor/four turbine 2(4x2) - ~1080 MWe

Coal Plant Costs

The MHTGR equilibrium plant costs have been evaluated in comparison with comparably sized coal plants. Capital costs for single unit 400 MWe and 600 MWe pulverized coal fired (PCF) plants were obtained from the EEDB program (Reference 4). The EEDB cost models for these plants were based on the plants having precipitators, wet limestone scrubbers and natural draft wet cooling towers. The single unit 400 MWe and 600 MWe plant results were also used to develop costs for two unit 800 MWe and 1200 MWe plants.

Coal plant capital cost data were also obtained from the Electric Power Research Institute (EPRI) (Reference 5) for 200 MWe, 500 MWe and 2x500 MWe PCF plants. The EPRI coal plants were of the same type as those from the EEDB program.

Coal plant O&M costs were provided along with the capital costs obtained from the EEDB program. A representative U.S. coal cost of $1.75/MBTU (1987$ with 1% real escalation up to and through the economic life of the plant) was used for determining the fuel cost component of the busbar cost based upon projected coal cost data for various regions of the U.S.

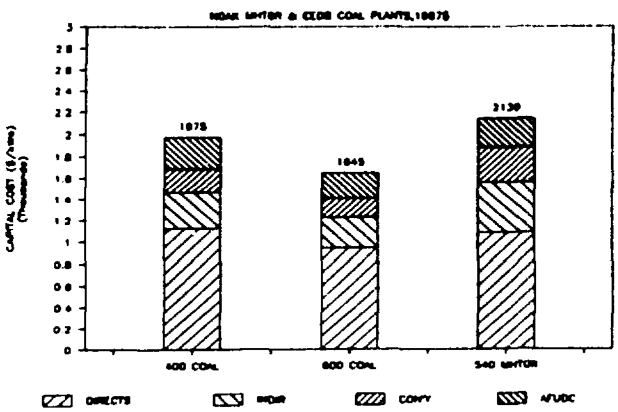


Figure 1--Capital Cost Comparison

Comparison of Capital Costs

A graphical comparison of the capital costs, on a $/kWe basis, of the reference MHTGR equilibrium plant and the single unit coal plants is provided in Figure 1. As illustrated in this figure, the direct costs are fairly comparable. Contingency percentages are about 20% for the MHTGR versus 15% for the coal plants. The interest during construction costs, also termed allowance for funds used during construction (AFUDC), for the reference equilibrium MHTGR plant are approximately equivalent to those for the coal plants. The results show the MHTGR capital cost to be in the economically competitive range with an equivalent size coal plant on a $/kWe basis.

Comparison of Busbar Generating Costs

A comparison of the reference MHTGR equilibrium plant 30 year levelized busbar costs with those for the single unit coal plants is given in Figure 2. The capital cost components stem from the costs discussed in the preceding section. The MHTGR fuel cost component is considerably less than those for the coal plants. The MHTGR O&M costs are slightly greater than the coal plants. The net result is an estimated MHTGR busbar cost that is less than those for the coal plants.

A comparison of the 30 year levelized MHTGR equilibrium plant and coal plant generating costs vs. plant size is shown on Figure 3. The single unit coal plant busbar cost data points have been overlaid with a band which indicates an estimate of the range of single unit plant busbar costs. Three data points based on the coal plant capital costs from EPRI are also included on Figure 3. The EPRI data were used to help establish the single unit band range. The two-unit coal plant busbar cost data points plotted on Figure 3 indicate the trend in busbar costs for multi-unit plants. The MHTGR equilibrium plant data points have been connected by a single trend line.

The results on Figure 3 show that the MHTGR has promise of having an economic advantage versus coal over the range from 270 MWe for the basic 2x1 plant to 1080 MWe for the 8x4 plant. The reference 4x2 plant compares quite favorably with equivalent single unit coal plants. For coal plants sized beyond 500-600 MWe, the conventional practice is to utilize multi-units. Relative to the multi-unit coal plants, the MHTGR retains an economic advantage.

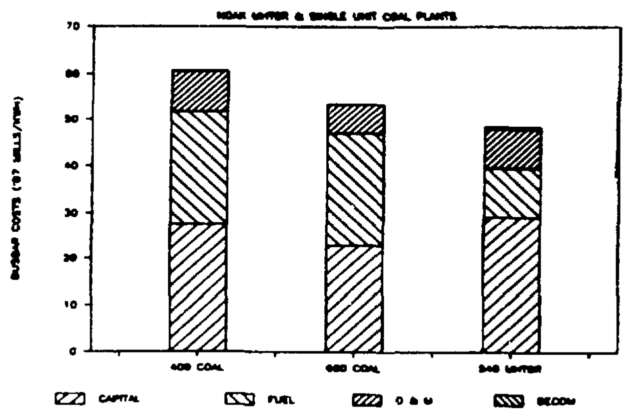


Figure 2--Comparison of Busbar Costs

Cash Flow Requirements

The MHTGR is designed for short lead times, short construction periods and small incremental commitments. The MHTGR may be deployed in 135-270 MWe increments which can be committed on a time frame that minimizes the planning horizon and provides a good fit to expected and actual load growth. A typical large 1100 MWe nuclear plant may be constructed over a six year period with capital commitments beginning 9 to 10 years prior to planned commercial operation. The same size MHTGR station may be built in four 270 MWe increments over an eleven year period with increments going into commercial operation every 2 years for six years.

Figure 4 illustrates current dollar cash flows for deploying a single unit 1100 MWe nuclear plant in 2005 and four 270 MWe MHTGR units biannually in 2002, 2004, 2006, and 2008. Consistent financial parameters are applied for both projects and reflect the nominal cost of money and a 5% inflation rate. The peak annual cash flows for the MHTGR project are 500 million less than the single large plant and the peak cumulative project cash flow is $2.5 billion lower. Further, the MHTGR project gradually adds $4.5 billion to the utility's rate base over seven years whereas the single large plant would add $5.8 billion in one year. An alternative, four year phase-in for the single large plant was also examined to avoid "rate shock." Of course, any consideration of phasing-in capital costs into the rate base has a negative impact on the project cash flows. Overall, the MHTGR project requires less external financing, reduces rate shock, offers greater planning flexibility and the potential for a better match to projected load growth.

Financial Risk Considerations

Excessive capital exposure is limited in a MHTGR plant by predictable costs and schedules resulting from design standardization and certification and because the MHTGR may be deployed in small increments. Increased flexibility is also achieved by being able to make decisions on individual power commitments in increments of 133 or 270 MWe. These decisions can also be made with greater certainty due to the shorter lead time of the small MHTGR power units.

Investment risk due to operational events is essentially eliminated by the inherently benign response characteristics of the MHTGR. The slow response characteristics have been demonstrated in operating high temperature gas-cooled reactors and allow tens of hours for decisions to be made for operator actions to prevent equipment damage.

Finally, to further assure that the financial risk is minimal, the MHTGR design has been developed to satisfy the utility/user requirement (Reference 6) that there be no need for emergency planning to evacuate and shelter the public. This is satisfied by requiring that the NRC and Environmental Protection Agency (EPA) criteria for protection of the public be met at and beyond the plant Exclusion Area Boundary (EAB), (i.e., the Emergency Planning Zone boundary is made coincident with the EAB). As a result, siting should be eased and allowed to proceed with enhanced political and public acceptance.

SUMMARY CONCLUSIONS

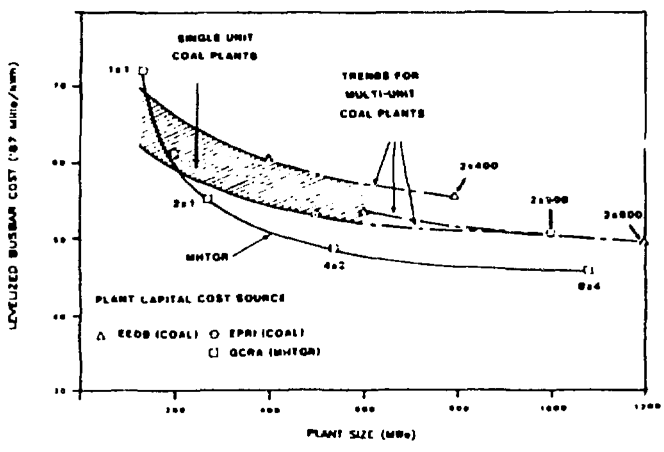
A smaller, simpler MHTGR reactor plant has been evaluated to be economically competitive with comparatively sized coal plants. In terms of busbar generation cost, the reference 540 MWe MHTGR equilibrium plant meets the utility/user goal (Reference 6) of having a 10% economic advantage over equivalent sized coal plants. Constructing two of the reference plant power blocks on the same site for a twice-size plant (1080 MWe) results in a large MHTGR facility which retains an economic advantage over equivalent size multi-unit coal plants.

The competitive economics are primarily the result of:

- passive safety concept simplifications
- separation of nuclear and conventional construction
- limited nuclear grade site construction
- modularization and factory fabrication
- standardization and certification
- economies of multiplicity
- short lead and construction times

The smaller, simpler MHTGR has characteristics for a financial risk profile that is understandable and manageable and within tolerable limits. Reductions in construction, financial, and planning risk are achieved by reducing incremental capital commitments and lead times by matching load growth through modular unit commitment and deployment. In a 1100 MWe

(2010 STARTUP, 80% CAPACITY FACTOR)



COAL COST $1.75/MBTU IN 1978 WITH 1% REAL ESCALATION FOR 2010 STARTUP

Figure 3--Equilibrium Plant Power Cost Projection

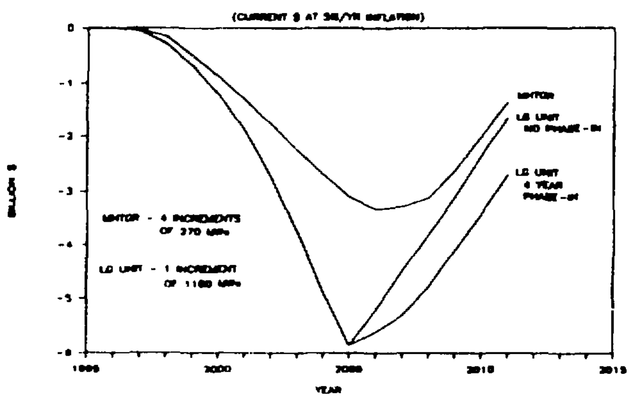


Figure 4--Cumulative Project Cash Flow

facility, the deployment of the MHTGR in four increments of 270 MWe has been evaluated to reduce the total cumulative negative cashflow by over 40% relative to that required to deploy a typical 1100 MWe single unit nuclear power plant. Licensing risk is reduced by providing a greater degree of inherent and passive safety and avoiding the need for off-site emergency planning and sheltering of the public. Standardization and certification of the design by the NRC further reduces the uncertainty associated with constructing, licensing, and operating the MHTGR.

REFERENCES

1. "Summary Report on the Utility/User Questionnaires", Gas-Cooled Reactor Associates, GCRA 86-004, February 1986.
2. "Conceptual Design Summary Report, Reference Modular High-Temperature Gas-Cooled Reactor Plant," DOE-HTGR-87-092 September 1987.
3. Dilling, David A. and Jones, Graham, "The Potential for Modular Construction/Zone Outfitting in the MHTGR", IECEC Conference Proceedings, July 31-August 5, 1988.
4. C.R. Hudson II, "Cost Estimate Guidelines for Advanced Nuclear Power Technologies," ORNL/TM-10071/R1, July 1987.
5. "Technical Assessment Guide", EPRI P-4463-SR, Volume 1, Electricity Supply, December 1986.
6. "Utility/User Requirements for the Reference Modular High Temperature Gas-Cooled Reactor Plant", GCRA 86-002, Rev. 4, January 1988.