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GAS REACTOR INTERNATIONAL COOPERATIVE PROGRAM INTERIM REPORT

HTR Multiplex Market Assessment

By
G. Garth Leeth
Charles F. Meyer

September 1978

Work Performed Under Contract No. EN-77-C-02-4057

General Electric Company
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HTR MULTIPLEX MARKET ASSESSMENT

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ABSTRACT

The HTR Multiplex utilizes the HTR as an energy source to produce multiple forms of energy. A specific type of multiplex utilizing a high temperature chemical heat pipe (CHP) is examined in this study. Forecasts of the U.S. electric energy markets and industrial heat markets are developed for the 1995-2010 time period. Costs of multiplexes in these markets are compared to costs of the conventional forecast mix of electric generation systems and to costs of fluidized bed combustors in the industrial heat market. The comparisons are by National Electric Reliability Council (NERC) region.

In general, multiplex energy costs for both electricity and industrial heat are lower in those regions expected to install large fractions of oil fired electric generation.

The major finding of the study is that a large potential U.S. market exists for the HTR Multiplex in two segments of the electric and industrial heat markets. It is concluded that the HTR Multiplex can provide peaking and mid-range electricity plus industrial heat for one and two-shift operations at costs approximately 50 percent lower than available alternatives. This market is estimated to be at least 300 GW_t (about 7 quads per year) in the 1995 to 2010 time period.

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SECTION 1
SUMMARY

1.1 BACKGROUND

HTR NOT COMPETITIVE IN ELECTRIC MARKET

During the past decade, many market and commercialization studies of graphite-moderated, gas-cooled high-temperature reactors (HTRs) have been performed. Previous General Electric market studies have arrived at the following conclusions with respect to HTR economics in the U.S.:

- As an electric generator the HTR (either steam cycle or direct cycle) is marginally competitive with LWRs.

HTR MARGINALLY COMPETITIVE IN INDUSTRIAL HEAT MARKET

- In the industrial heat market, the HTR is marginally competitive with coal-derived heat in that portion of market consisting of one- and two-shift operations.

HTR MULTIPLEX PROPOSED

Utilization of the HTR to produce both electricity and one, or more, forms of transportable, storable energy has been suggested. A General Electric commercialization study of such an "HTR Multiplex" indicated that costs of the products from such a system appeared less than the costs for separately produced products.

The purpose of this study is to provide additional insight into and understanding of the potential role of the HTR in future global energy systems. Specific objectives are to:

HTR MULTIPLEX MARKET ASSESSMENT NEEDED

- Obtain a preliminary estimate of the U.S. market for HTR Multiplexes
- Determine whether additional, more detailed studies are desirable
- Outline these further studies, if justified.

1.2 METHODOLOGY

ELECTRIC SYSTEM FORECASTS OBTAINED

Regional forecasts of additions to the U.S. electric energy system were obtained from the General Electric Company's Electric Utility System Engineering Department (EUSED). These forecasts are by National Electric Reliability Council (NERC) region.

INDUSTRIAL HEAT FORECASTS DEVELOPED

The U.S. industrial heat energy demand forecasts were obtained from Corporate Consulting Services of the General Electric Company. These forecasts are basically an update and revision of previous studies. In order to obtain industrial energy use by NERC region, 1972 Census of Manufactures data was used and forecast energy additions (1995 to 2010) were calculated.

HTR MULTIPLEXES SYNTHESIZED

Various HTR Multiplexes were designed to satisfy the regional energy demands in the following way:

- Installed direct electric capacity at the central plant sufficient to satisfy the nuclear energy demands.
- Installed indirect electric capacity at the central plant sufficient to satisfy the oil energy demands.

- Installation of syngas production and pipeline delivery capacity to satisfy the industrial heat demand.

Synthesis of the HTR Multiplexes assumed that all in-plant and pipeline transmission pumping requirements were electric and accounted for from central station production.

1.3 MARKET ASSESSMENT

CONVENTIONAL VERSUS MULTIPLEX COSTS COMPARED

Costs for both the conventional electric systems and the HTR Multiplex systems were calculated. The conventional electric system costs (annual) were then subtracted from the HTR Multiplex system costs and the difference allotted to the industrial heat produced by the Multiplex.

INDUSTRIAL HEAT COSTS COMPUTED

Resulting industrial heat costs were compared to heat costs produced by fluidized bed combustor (FBC) systems.

HTR MULTIPLEX ECONOMICALLY SUPERIOR IN SOME REGIONS

On a regional basis, HTR Multiplex heat costs compared to FBC heat costs are:

- Close in Region MAAC
- Approximately equal in Region SERC – Coal
- Significantly lower in Region SERC – Oil
- Greatly less in Region PSW.

HTR MULTIPLEX MARKET ABOUT 300 GW_T

It is concluded that the 1995-2010 Multiplex market amounts to about 300 GW_t. This is based on the following:

- The HTR Multiplex produces high temperature (1000°F) steam at much lower costs (approximately 50 percent) than the available alternatives considered in this evaluation – for two specific markets:

- Industrial heat for one- and two-shift operations
- Heat for peaking and mid-range steam turbines producing electricity.

- The sum of these two markets amounts to about 300 GW_t in the 1995-2010 time period.

In addition to the economic advantages in the market segments identified above, the HTR Multiplex has features that can have major impacts in market penetration.

HTR MULTIPLEX HAS REDUCED AIR AND THERMAL POLLUTION

Steam produced from a methanator, with no combustion, causes no air pollution. If replacing fossil-fired heat sources, the result will be reduced air pollution. If satisfying new requirements, emission offset requirements will be avoided — quite possibly making the difference between being able to construct new industrial plants and not being able to do so.

Among other stigmas, LWR plants have become known as major sources of thermal pollution, which complicates further their already very formidable siting problems. HTR Multiplexes would produce from one-half to one-fifth the thermal pollution of LWRs.

HTR MULTIPLEX IS POTENTIAL THERMAL BREEDER

At this stage in the growth of nuclear energy, it seems clear that all new systems should be "fuel extenders" — either high converters or, preferably, breeders. The conversion ratio for the current design pebble bed reactors (PBRs) can be pushed to nearly 1.0. Studies have indicated that conversion ratios of 1.07 are attainable with more complex fuel element and fuel handling designs.

HTR MULTIPLEX HAS SAFETY ADVANTAGES

For LOCA situations, the low power density of the HTR and high-temperature capability of graphite result in long time-to-release of fission products: 1000 times greater than LWRs (typically one day versus one minute). The PBR has some additional inherent safety features because of continuous online refueling and fuel element design.

For commercial size PBRs, a fast discharge system (FDS) has been proposed which would provide walkaway-safe shutdown of the entire plant. The FDS would rapidly remove all fuel from the core by allowing the fuel balls to flow downward into a subterranean, water-cooled annulus designed to be inherently safe from a nuclear criticality standpoint and able to contain all afterheat without boiling.

The HTR uses a prestressed structure for the reactor vessel which also encloses the steam generators and reformers. Such vessels cannot fail in a manner which results in missile fragments. This burst protection feature may be an important advantage of the HTR over the LWR.

1.4 CONCLUSIONS AND RECOMMENDATIONS

LARGE POTENTIAL U.S. MARKET FOR HTR MULTIPLEX

A large potential U.S. market for the HTR Multiplex exists. This market consists of two segments: (1) Industrial heat for one-shift and two-shift operations and (2) Peaking and mid-range electric power generation.

HEAT ENERGY COSTS FROM MULTIPLEX 50% LOWER THAN COMPETITORS

It is estimated that about 300 GW_t will be needed to satisfy these two market segments during the 1995-2010 time period. The HTR Multiplex can satisfy this energy market at costs approximately 50 percent below those of coal-fired FBC systems. This conclusion is essentially independent of the accuracy of the cost input data.

HTR MULTIPLEX MARKET AT LEAST 300 GW_T

In addition to the market for syngas delivered energy identified above, it is concluded that a significant additional market exists for the HTR Multiplex in base-load electric energy production. This latter market requires about 300 GW_t in the 1995 to 2010 time period. In summary, the potential U.S. market for the HTR Multiplex in the 1995 to 2010 time period is at least 300 GW_t and may be several times this size.

STUDIES LEADING TO HTR MULTIPLEX IMPLEMENTATION RECOMMENDED

It is recommended that future studies of the HTR Multiplex be concentrated on:

- Selecting a preferred site for the first commercial HTR Multiplex.
- Developing the corresponding criteria and specifications for the total system.
- Outlining a preferred development program through the commercialization phase.

PHASE 2 STUDY OUTLINED

An outline of a Phase 2 study to implement the above recommendations has been completed.

SECTION 2
INTRODUCTION

2.1 BACKGROUND

It is expected that the reader of this document is familiar with the major features of graphite-moderated gas-cooled high-temperature nuclear reactors (HTRs) and the concept of the HTR Multiplex. For those who are not, Section 3 provides some background and descriptive material on these subjects.

The HTR is of international interest as a heat source for electrical energy production and for industrial process heat. Until late 1975, the HTR appeared to be a near-commercial reality in the United States. At that time General Atomic decided to cancel several contracts and no longer offer a gas-cooled reactor to electric utilities. Since then, HTR development has continued at a slow pace. A 300-MW_e HTGR (prismatic core) demonstration plant (Ft. St. Vrain) is currently operating in the U.S. and a similar size PBR (pebble bed core) is scheduled to begin operation in Germany in 1981.

In the U.S., HTR development has been slow because no clear commercial application exists. The HTR development in the FRG has been somewhat more vigorous because high temperature nuclear heat systems are estimated to have lower heat costs than current fossil fueled heat systems in that country.

During the past decade, many market and commercialization studies of the HTR have been performed. Most of these have evaluated the competitiveness of the HTR as a source of heat for generating electricity. Some have looked at the market for industrial process heat. Previous General Electric market studies have arrived at the following conclusions with respect to HTR economics in the U.S.:

- As an electric generator the HTR (either steam cycle or direct cycle) is marginally competitive with LWRs.
- In the industrial heat market, the HTR is marginally competitive with coal-derived heat in that portion of the market consisting of one- and two-shift operations.

Utilization of the HTR to produce both electricity and one, or more, forms of transportable, storable energy has been suggested. A General Electric commercialization study of such an "HTR Multiplex" indicated that costs of the products from such a system appeared less than the costs for separately produced products. However, a study analyzing the U.S. market for such a *joint* product system has not been performed.

2.2 STUDY OBJECTIVES AND SCOPE

The purpose of this study is to provide additional insight into and understanding of the potential role of the HTR in future global energy systems. Specific objectives are to:

- Obtain a preliminary estimate of the U.S. market for HTR Multiplexes
- Determine whether additional, more detailed studies are desirable
- Outline these further studies, if justified.

The scope of this study is limited to consideration of the markets in the U.S. in the 1995 to 2010 time period for electricity and industrial process steam. Both products are produced from an HTR Multiplex incorporating a chemical heat pipe (CHP) system.

SECTION 3
THE HTR MULTIPLEX

3.1 BACKGROUND

3.1.1 Energy Goals

National priorities in the United States and abroad stress the importance of:

- Reducing dependence on oil imports by shifting from natural gas and oil to coal and nuclear fuel
- Increasing the efficiency of thermal power plants
- Cogeneration of electricity and heat to conserve energy.

HTR plants can do much to help achieve these energy goals — *if* HTR plants are commercialized. Substantial and relatively high-risk investments will be required to bring commercial HTR plants on line. The time period before payback on investment could begin is at least 15 years. A very convincing case must be made for HTR plants before they will be perceived as commercially competitive with coal-fired and light-water reactor (LWR) plants, and attract large private-sector investment.

Government subsidies might be postulated which would make development, construction, and operation of HTR plants commercially attractive. Indeed, some government support — financial and institutional — appears to be inescapable, because of very large development costs and various institutional hurdles. But governmental underwriting of construction and operation costs cannot, realistically, motivate widespread commercialization nearly as well as can a profitable market.

3.1.2 The HTR as a Heat Source

The temperature of the high-temperature gas-cooled reactor is high only by comparison to the light-water reactor. Other utility fuels —

coal, gas, oil — burn at temperatures in the order of 3000°F.* The exit temperature of the helium coolant of the two principal HTR types, the HTGR and the PBR, is 1600°F and 1740°F respectively. (HTGR is an acronym for the prism-type gas-cooled reactor of the Gulf General Atomic Company; PBR is an acronym for the pebble-bed gas-cooled reactor of German design.) The comparable LWR temperature is 550°F.

3.1.3 Chemical Heat Pipe

Studies of the HTR as a source of process heat have identified the chemical heat pipe (CHP) concept, using steam-methane reactions as a preferred approach. Thermal energy from the nuclear reactor is converted into chemical energy. The resulting chemical substance (a mixture of gases) is pumped through pipelines, for distances up to 300 miles. There, the chemical energy is reconverted to heat to produce steam at temperatures up to about 1100°F. The CHP concept is diagrammed in Figure 3-1.

The steam-methane reactions are

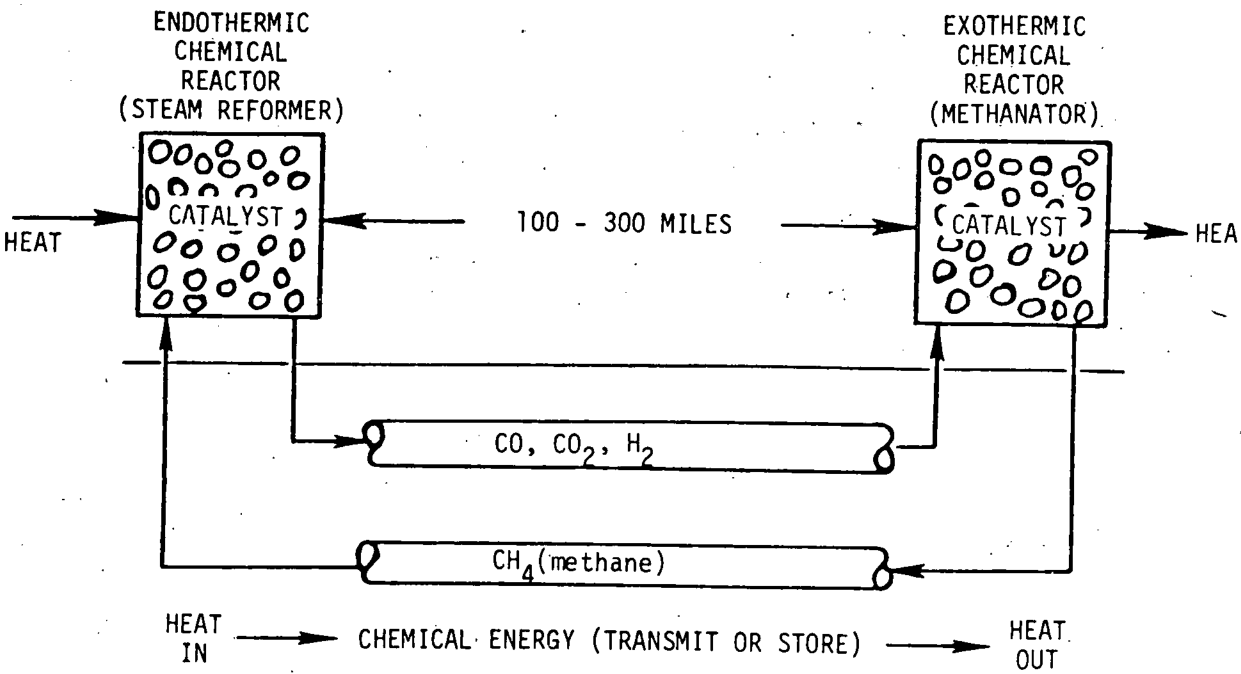
$$CH_4 + H_2O \underset{\text{exothermic}}{\overset{\text{endothermic}}{\rightleftharpoons}} CO + 3H_2$$

$$CH_4 + 2H_2O \underset{\text{exothermic}}{\overset{\text{endothermic}}{\rightleftharpoons}} CO_2 + 4H_2$$

The reactions at the HTR plant steam reformer are those from left to right. At the methanators in industrial plants, the reactions are from right to left. The steam-reformer reaction kinetics and equilibrium characteristics are such that heat must be supplied at peak temperatures in the range of 1600°F to 1800°F.

The technology for the steam-methane reactions is well established; the pipeline energy density is adequate; the chemicals are noncorrosive; the catalyst cost is reasonable; the reaction kinetics are fast; and the

*It is recognized that stoichiometric temperatures are higher than 3000°F.



Source: GE-ESTD, 1976.

Figure 3-1. Chemical heat pipe concept.

cost of methane (CH_4) is low. The methane from the methanator may be returned to the central plant reformer (closed cycle as shown in Figure 3-1) or, if a supply of methane is available at the central plant, it may be burned or used as a feedstock (open cycle).

A substantial volume of storage for gases flowing in both directions is provided by the pipelines; pressure changes ("pipeline packing") generally can smooth load changes for about a one-day period. If additional storage is required, tanks, caverns, or porous underground formations may be used. These would be located at HTR plants, in load areas, and along pipelines, to maintain pipeline flow at as high a level as possible (high capacity factor). This is analogous to the pipeline-management practice of gas companies who charge underground reservoirs with natural gas in the summer months to be withdrawn during the winter.

3.1.4 Electric Power Generation at HTR Plants

The maximum throttle (inlet) temperature usable for today's conventional steam turbogenerators is little more than 1000°F, because of materials limitations. The 3000°F fireside temperature in a fossil-fueled boiler, and the 1600-1740°F primary loop in an HTR steam generator, can provide steam superheat and reheat. Steam conditions ranging from 2400 psi/950°F/1000°F to 3500/1000/1000 are feasible, with plant efficiencies of 38 to 41 percent. An advanced steam cycle might increase the efficiency to 44 percent.

The LWR, operating at substantially lower temperature and pressure than HTR and fossil plants, can achieve a plant efficiency of only about 33 percent.

With the HTGR (1600°F), direct-cycle helium turbines might achieve 36 percent plant efficiency. With the PBR (1740°F), the direct-cycle efficiency might reach 42 percent. Adding an ammonia bottoming cycle could increase these efficiencies by 7 or 8 points.

Since the maximum plant efficiency that can be foreseen is not more than 50 percent, it follows that 50 percent or more of the nuclear heat must be discharged as waste from a single-product HTR electric power plant.

In general, an LWR plant produces electric energy at slightly lower costs than a fossil-fired plant. The higher capital costs and lower plant efficiency of the LWR are more than compensated for by a lower fuel cost. Due primarily to lower power density in the reactor core, HTR capital costs are estimated to be 20 to 30 percent higher than LWR capital costs for the same thermal power. Thus, although the higher exit temperature of the HTR coolant should enable the HTR to achieve greater electrical conversion efficiency than the LWR, the electric power generation costs for the two types of plant are expected to be roughly equivalent. This being the case, it is difficult to justify the development costs that would be required to bring HTR electric power plants on line (GE-ESPD, 1976 and 1977).

3.1.5 Industrial Process Heat from HTR Plants

A basic assumption in this study is that industry will not be colocated with nuclear plants. Exceptions might be an industrial plant large enough to utilize all heat from a large reactor — coal gasification, steel making, and water splitting are possible examples. "Agro-industrial complexes" or other agglomerations of consumers of electricity and heat, which require sizeable numbers of operating personnel, are not seen as suitable neighbors for a nuclear plant. To create an industrial market for nuclear heat requires that a suitable energy form (other than electricity) be supplied from remotely-sited HTR plants to industry located in urban and other areas.

A second assumption is that the energy form which carried nuclear heat to industry must be storable. Very few industrial processes require a continuous, large, and constant amount of heat. Storage will be necessary, to smooth heat-load changes, for two basic reasons: the HTR plant has high capital cost but burns cheap fuel, therefore must operate at as close to maximum rating for as much of the time as possible for economic reasons. It is also undesirable to load-follow with a large nuclear reactor (or a boiler of equivalent thermal capacity) because of thermal stresses induced by changing load.

The combination of the HTR and CHP appears to be a way of serving industrial heat markets with nuclear heat in a realistic and evolutionary manner. However, previous studies (ESPD, 1976 and 1977) have indicated that costs of industrial heat from such a system can marginally compete with coal-derived heat only in that portion of the U.S. market characterized by one- or two-shift operations.

3.2 DESCRIPTION

Since HTR development did not appear justified on the basis of producing electricity alone or industrial heat alone, the concept of an HTR producing both electricity and one or more storable energy forms evolved. To distinguish such a multiple-output energy-conversion plant from total-energy or cogeneration plants which produce electricity and heat, and from nuplexes where the nuclear plant and large users of its electric and thermal energy output are colocated, the term "HTR Multiplex" is used.

The HTR Multiplex, and how its implementation might proceed, were first described in a recent report by the General Electric Company on its study of commercialization of the gas-cooled reactor (GE-ESTD, 1977). The material presented here is an expansion and extension of the earlier study, addressing the question of marketability.

Prior to the study of commercialization of the gas-cooled reactor which culminated in report COO-4957-3 in December 1977 (GE-ESTD, 1977), General Electric evaluated gas-cooled reactor development and defined an advanced reactor that would be the best backup for the LMFBR, competitive in the electric utility market, and the only practical way of applying nuclear power to the industrial sector. The configuration included electric generation with either a helium or steam turbine, the Chemical Heat Pipe to transmit heat to industry, and Chemical Energy Storage (GE-ESTD, 1976). This configuration differs from the HTR Multiplex only in its omission of production of steam or hot water for low-temperature industrial process heat and district heating. The components described below are essentially identical to those described in the 1976 report.

3.2.1 Pebble-Bed Reactor (PBR)

A 3000 MW_t PBR and its graphite reflector assembly would be contained in a cylindrical prestressed concrete pressure vessel about 40 meters in diameter and 30 meters high. The core would consist of a fixed bed of spherical graphite balls, 60 mm in diameter, which contain the fuel. Fuel balls would be added continuously at the top and removed at the bottom, after a residence time of approximately two years. The OTTO (once-through-then-out) online refueling system is expected to provide a 90-percent PBR availability factor. (Shutdowns for refueling typically cause a 12 percent loss in LWR capacity factor.) It also would permit mixing fuel balls of various types, and changing the mix from time to time. Fully remote fuel handling would allow the use of U-233 or other radioactive fuels. A novel fast-fuel discharge system would provide for emergency dispersal of the pebble bed fuel elements into a noncritical, static heat sink in event of a loss of coolant accident. Other inherent and engineering safety features make the PBR a basically stable, tractable system in which operational and emergency events cause only slow, easily-controlled effects. As an example, the AVR research reactor can be, and has been, shut down by simply shutting off the coolant flow rather than by operating the control rods.

3.2.2 Steam Generators and Steam Reformers

Within the prestressed concrete reactor vessel (PCRV) would be housed steam generators, steam reformers, core auxiliary cooling loops, and electrically-driven coolant circulators.

Steam-reformer and steam-generator modules are similar in construction and appearance. They would be cylindrical vessels about 26 meters high and 4.3 meters in diameter. The modules are designed for individual replacement and the mix of steam reformers and generators is flexible because of their modularity. Internally, heat exchange between the reactor coolant and the fluid being heated would take place in a number of concentric tubes; between the helium coolant in the primary loops and the steam or syngas being heated is a buffer layer of helium. If any leakage of primary helium occurs, it would enter the buffer rather than the fluid being heated.

Steam generators are state-of-the-art and require no development to speak of. Extensive experience with steam reformers is available from fossil-fired plants but not from gas-cooled reactors; however, work at KFA in the Federal Republic of Germany, using a high-temperature helium test loop, has provided a considerable amount of design data.

3.2.3 Steam Turbogenerators

Conventional, thoroughly proven, reliable energy-conversion components are available for electric generation. The steam generator operated from the reactor coolant exit (1740°F), steam superheat and reheat can provide steam conditions ranging from 2400 psi/950°F/1000°F to 3500/1000/1000 with plant efficiency in the range of 38 to 41 percent.

If operated to bottom the steam reformers, after they utilize the steam down to a temperature of about 1100°F, the steam generators would not produce steam and electricity at this high a plant efficiency, but the overall plant efficiency — for producing both syngas and electricity — would be in the order of 40 to 80 percent, depending on the relative amounts of syngas and electricity produced.

3.2.4 Hot Water or Steam Recovery

The thermodynamic and environmental advantages of capturing the reject heat from steam turbines and (with some sacrifice in electric generation capacity) producing industrial process steam or hot water for district heating have been mentioned. The components needed for this process are already in wide use, although in sizes smaller than would be needed for a large central station. Design work would be needed, but no development.

3.2.5 Pipelines and Storage

CHP syngas from the steam reformers (a mixture of hydrogen, carbon monoxide, and carbon dioxide) could carry a substantial amount of energy away from the central plant or plants, in pipelines. Sizes up to perhaps one meter diameter are envisioned. If the CHP cycle is closed, methane pipelines, somewhat smaller in size than those for syngas, would return methane to the reformers. Storage facilities — tanks, underground porous formations, or caverns — would be required for the syngas and the methane.

If the cycle is open and methane is not returned, a pipeline would be required to import the methane (natural gas) from its source rather than to return it from methanators. Storage for the methane probably would be required, to improve the capacity factor of the pipeline.

If steam is produced, only short-term storage is feasible — perhaps a few hours of supply. Hot water might be stored in larger quantity and for longer periods of time than steam. Mined caverns could contain substantial amounts of water at reasonable cost for periods of at least a few days. If aquifer storage proves feasible, hot water in very large amounts could be stored for months, and withdrawn to meet seasonal demands. This would make production and sale of hot water particularly attractive.

3.2.6 Methanators and Associated Generation of Electricity

At industrial sites, where methanators would be located, steam at 1000-1100°F would be available for industrial process use; for generating mid-range and peaking electricity; or for both. Steam, hot water, or both could be produced by the turbogenerators for local industrial use and for space and tap-water heating.

The concept of shifting generation of mid-range and peaking electricity from central plants to dispersed locations close to load centers is particularly attractive. Among the benefits are a reduction in electric transmission capacity; encouraging in-plant industrial cogeneration of power and heat, which would displace use of oil and gas to fuel boilers and mitigate air pollution; and the possibility of reducing the utility's problem of raising financial capital by encouraging industrial ownership of in-plant electric generation and cogeneration facilities.

The inherent storage capacity of CHP pipelines, through "packing," and the ease of adding supplemental storage capacity to the CHP system if needed, make possible the use of nuclear energy to drive intermittent loads. In effect, the CHP storage fulfills the function ordinarily met by storing fuel oil for mid-range and peaking generation.

3.3 ENERGY FORMS FROM THE HTR MULTIPLEX

On thermodynamic ground, reasons can be developed for generating electricity at the HTR Multiplex with cycles such as a helium turbine with ammonia turbine bottoming, to attain 44 to 49 percent thermal efficiency; or to use the 1740°F helium from the reactor for production of syngas, with the reformers discharging steam at 1100°F to be used by steam turbogenerators. Based on a return temperature of 660°F from steam generators to the reactor, the latter approach leads to the conclusion that 58 percent of the reactor heat would be delivered to steam reformers (CHP output) and 42 percent would be used for generating steam (GE-ESTD, 1976, Appendix B). The plant efficiency would be roughly 65 percent for this mix, after allowance for losses and parasitic power requirements. (Production of steam or hot water would increase the plant efficiency.)

Varying the mix of syngas and electric output from the HTR Multiplex turns out to have far less effect on plant economics than on plant efficiency. Assuming electric-only output from a 3000 MW_t reactor, the net output after allowance for losses would be about 1120 MW_e. With no credit for production of hot water or steam, the plant-plus-transmission efficiency would be about 37 percent. The other extreme is syngas-only output. The net heat output (at the methanators) for syngas only would be 2470 MW_t, the plant-plus-transmission efficiency would be about 82 percent.

Over the range of output mixes from zero syngas to zero electricity, fuel cost would not vary; 3000 MW_t is the reactor output for all cases. The capital cost would vary by only 5 percent over the entire range of output mixes: the cost of the reactor is dominant, and the costs of various mixes of turbines, steam generators, and steam reformers are not very different. (Electric output is assumed to come from steam generators and steam turbines, not from yet-to-be-developed helium turbines with ammonia bottoming.) When the capital and fuel costs are added, the variation in total annual costs over the range from zero syngas to zero electricity is only about 4 percent.

It follows that the choice of energy form outputs from the HTR Multiplex can be made rather freely, in evaluating the competitiveness of the HTR energy output forms with alternative energy sources. Initially, perhaps the HTR Multiplex configuration will favor electric generation because there is a ready market for electric power. At worst, for electric-only output, the plant-plus-transmission efficiency of 37 percent is 5 to 6 points higher than is attainable with LWR plants. As industrial heat markets are penetrated, new HTR Multiplexes would be more oriented toward syngas and other heat-transmission energy forms, with consequent improvement in overall thermodynamic efficiency and savings in national consumption of various fuels.

3.4 IMPLEMENTATION SCENARIO

The description of the HTR Multiplex in Sections 3.2 and 3.3 is brief and engineering-oriented. As an additional aid to understanding the novel and beneficial features of the HTR Multiplex concept, an implementation scenario is described. Such a "first-plant" implementation scenario helps to recognize and discard irrational expectations, to visualize what may be expected and should be programmed, and to estimate the time required for an HTR Multiplex to be in operation. In its December 1977 *Commercialization* report (GE-ESTD, 1977), General Electric presented such a scenario and time sequence for a lead plant. It is reproduced in what follows, with changes in organization and language to make it consistent with the present report and improve its clarity.

Construction of an illustrative implementation scenario is based on the following guidelines:

- A national energy program must consider the most appropriate mix of all developed and developing technologies.
- Development programs to meet the nation's future energy needs must be evolutionary in nature, thus permitting an orderly and reasonable transition from the conventional to the new, and avoiding abrupt, unrealistic, or inefficient demands on society.
- The exact future role of the HTR Multiplex is not currently definable because the market for its products is not yet defined.

Based on the above, an illustrative implementation scenario was developed. It is described in Table 3-1 and Figure 3-2. This illustrative scenario is both flexible and evolutionary. Its key feature is an implementation sequence which is capable of producing different energy forms through development and incorporation of different modules. Actual module requirements will depend upon future market and institutional developments.

Table 3-1. Illustrative energy forms, power levels, and energy use for an HTR Multiplex system implementation scenario.

Phase	Nuclear Heat	Electricity: Base Load	Electricity: Mid Range*	Electricity: Peaking†	Steam	Hot Water	Waste
1	Derated 50%: 1500 MW_{th}	450 MW_e (30%)‡					1050 MW_{th} (70%)
2	Derated 40%: 1800 MW_{th}	450 MW_e (25%)		450 MW_e (5%)			1260 MW_{th} (70%)
3	3000 MW_{th}	450 MW_e (15%)	900 MW_e (12%)	450 MW_e (3%)	600 MW_{th} (20%)	240 MW_{th} (8%)	2360 MW_{th} (42%)
4	3000 MW_{th}	450 MW_e (15%)	900 MW_e (12%)	450 MW_e (3%)	600 MW_{th} (20%)	1290 MW_{th} (43%)	210 MW_{th} (7%)

*Typical mid-range capacity factors are 0.3 to 0.5 (eg 360 MW_e average load).

†Typical peaking capacity factors are 0.15 to 0.25 (eg 90 MW_e average load).

‡Figures in parentheses show fraction of total nuclear thermal energy used or wasted.

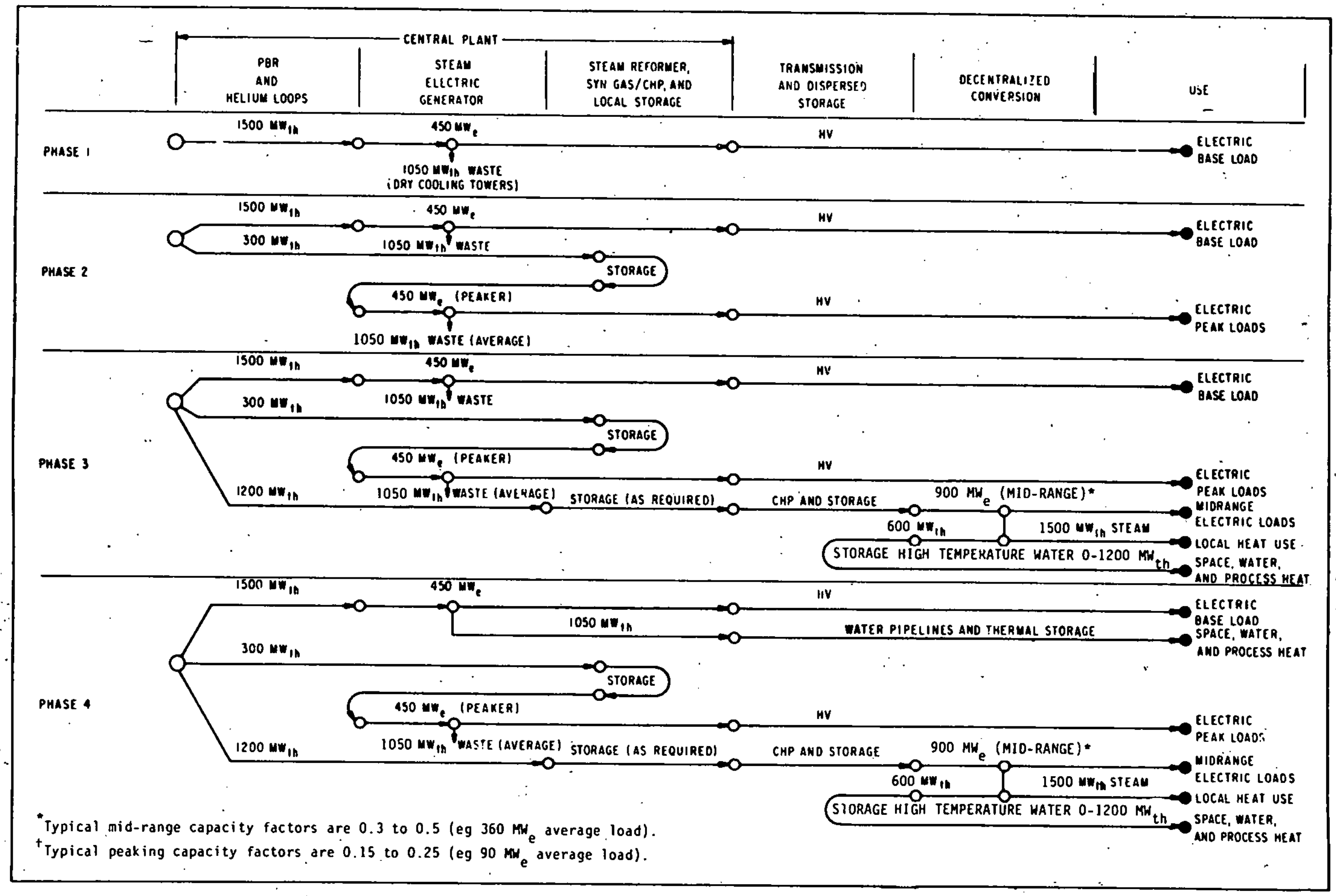


Figure 3-2. Schematic diagram illustrating energy forms and power levels in HTR Multiplex system.

3.4.1 Phase 1: Derated Reactor Operation, Steam-Cycle Electric Generation

Phase 1 assumes 50 percent derating — operation at 1500 MW thermal. This heat output will be conveyed via helium cooling loops to steam generators. A conventional (1000-1100°F inlet) steam turbine drives a 450 MW electric generator. Steam is discharged from the turbine at a high enough temperature, 350°F, to permit condensing in a relatively low-cost dry cooling tower. Reject heat amounts to 1050 MW thermal, for an assumed cycle efficiency of 30 percent. Only one energy form is produced, electricity, which can readily be connected to an existing electric grid and sold.

3.4.2 Phase 2: Add High-Temperature Steam Output for Local Use

After successful operation of the reactor at reduced power level is achieved, the initial test of CHP steam reformers is undertaken. The steam reformer configuration envisioned is the double-containment (duplex) type. A heat rating of 300 MW_t is assumed.

The purpose of Phase 2 is to demonstrate CHP components without the necessity for pipeline transmission. The syngas produced by the steam reformer is stored in underground tanks or caverns at the central plant, as is the methane return from the methanator(s) also installed at the central plant.

The CHP components are used to provide steam for 450 MW_e of electric generating capacity for peaking duty. Although rated at the same total capacity as the base-load generator, the peaking generator(s) operate at a much lower capacity factor. Peak-load power ordinarily would be generated by gas- or oil-fired combustion or steam turbines, for which the fuel is easily storable. The HTR Multiplex approach displaces oil with nuclear heat and fuel storage with CHP storage. With only 300 MW_t of continuous nuclear heat input, 1500 MW_t of steam and 450 MW_e of electricity can be produced. Methanator capacity of 1500 MW_t is required.

The peaking generator(s), like the base-load generator, discharge steam at 350°F to be condensed in a 1050 MW_t cooling tower. The average electric power generated is 90 MW_e and the average thermal discharge is 210 MW_t.

A number of variations of the Phase 2 configuration are possible and some would appear to make better economic sense than the one described. However, an objective of the lead plant must be kept in mind: to demonstrate CHP components without having to install transmission lines and make arrangements for remote siting. In subsequent plants, better uses would be found at the central plant for the CHP syngas and its storability, in addition to transmitting it to remote sites. For example, the base-load generator might be oversized with respect to the reactor, and used for some load-following while the reactor operates always at constant heat output.

3.4.3 Phase 3: Add Transmission and Remote Use of CHP Syngas

Transmission pipelines are installed to carry the syngas to industrial plants. The reactor is brought to full 3000 MW_t rated output and 1200 MW_t of additional helium loops and steam reformers are activated.

If pipeline packing does not provide sufficient storage, syngas can be stored at the power plant, along the transmission pipelines, at the industrial plant(s), or any combination of these. Storage maximizes reliability, and minimizes cost because pipelines can be operated at high capacity factor.

An important use of syngas is to produce steam for electrical generation. In the case chosen for this illustrative scenario, the generator is a mid-range unit rather than a peaker. Its capacity factor is about 0.4, or twice that of the peaker. Operating from 1200 MW_t of continuous reactor output, the mid-range unit is rated at 900 MW_e. At a cycle efficiency of 0.3, it produces 1500 MW_t of industrial process steam and 600 MW_t of hot water at about 350°F. At CF = 0.4, the average outputs are 360 MW_e, 600 MW_t of steam, and 240 MW_t of hot water. The total of these averages equals the 1200 MW_t from the reactor. (Losses in the steam reformer, pipelines, storage, and methanator have been neglected, as before, because these losses are relatively small for purposes of this scenario.)

The electricity is assumed to be generated principally in response to electric-utility system demands for mid-range power. On this basis, the byproduct steam is available and most of it must be used when the electric system calls for power generation; such large amounts of steam cannot be stored economically. For the byproduct hot water, aquifer storage is postulated. About 30 wells, each capable of receiving and producing 700 gallons of water per minute (one million gallons per day), will be required (Meyer, Hausz, et al, 1976). The mix of steam and hot water can be different than that chosen for illustration; it might even be varied as electricity is produced, if adequate size condensers and valving are provided. Or, electricity may be defined as the byproduct, and the turbogenerator dispatched on the basis of steam requirements, as is often the case for in-plant industrial cogeneration of power and steam.

Note from Table 3-1 that the overall system efficiency (neglecting the losses mentioned earlier) has increased from 30 percent in Phase 1 to 58 percent in Phase 3, due to utilization of reject heat from the 900 MW_e mid-range generator.

An obvious variation of the Phase 3 configuration would be to allocate a portion of the methanator output directly to industrial process use. However, on the basis that much of the high temperature steam in industry is used for direct drive or electrical generation, the example chosen seems reasonable. (Steam-turbine direct drive application can typically be converted to electric drive.) Another variation of interest would be the use for combustion of methane from the CHP system. This would improve the economics of the overall system. However, analysis of such an open-loop system is beyond the scope of this study and is deferred to a later effort.

3.4.4 Phase 4: Add Transmission and Remote Use of Hot Water from Central Plant

Phase 4 differs from Phase 3 only in the addition of facilities to capture and use for district heating (including low-temperature industrial process heat) the 1050 MW_t of reject heat from the base-load 450 MW_e electric generation at the central plant.

The outlet temperature of the turbine is 350°F; this is a very suitable temperature for transmission via an insulated dual-pipeline loop (sendout and return), as has been demonstrated extensively in Europe. The possibility of using electric-utility steam turbines as a source of hot water for a proposed district-heating system in Minneapolis and St. Paul is currently being investigated by Northern States Power, the Department of Energy, the Minnesota Energy Agency, several other agencies, and a number of contractors (including TEMPO).

Capture and use of the waste heat from the peaker — also 1050 MW_t — is not postulated because it would impose severe peaks upon the hot-water transmission system, or require more than 50 Heat Storage Wells to buffer the peaks. As noted under Phase 5, the preferred location for peakers is at industrial and other load centers, when commercial HTR Multiplex plants are built.

Table 3-1 shows the overall system efficiency to be 93 percent for Phase 4, due to utilization of the 1050 MW_t waste from the base-load station. Clearly, losses that have been so far neglected would become significant at this point. Roughly, the 7-percent waste shown in Table 3-1 might increase to as much as 15 to 20 percent if all losses were taken into account. To do so would require a considerably more detailed analysis than undertaken here, but European experience with systems not enjoying all the energy-conserving advantages of the HTR Multiplex shows 80 percent system thermal efficiency. A comparison with current thermal power-plant efficiencies of well under 40 percent encourages further exploration of HTR Multiplex possibilities.

3.4.5 Phase 5: Commercial Systems

Not included in Table 3-1 or Figure 3-2 is Phase 5 — the culmination of successful completion of Phases 1 through 4. Phase 5 is the commercial operation of a number of HTR Multiplexes in various energy markets. These plants would utilize features demonstrated during the lead plant sequence, optimized for energy markets located at particular sites. Various commercial versions can be foreseen; the output energy forms would be tailored to the specific plant site. One version might produce only electricity and gasify coal. Another version might produce electricity, CHP for industry, and hot water for district heating. It is anticipated that both mid-range and peaking electricity will usually be generated from syngas transmitted to industrial and other load centers. These will reduce electric transmission capacity requirements substantially, and minimize (perhaps eliminate) the need for cooling towers in the total system.

3.5 CONSTRUCTION TIME ESTIMATES FOR THE FIRST HTR MULTIPLEX

3.5.1 Phase 1: Derated Reactor Operation, Steam-Cycle Electric Generation

From time of start of construction, assuming effective steps are taken to minimize delays in permits and licensing, a reasonable estimate for the time lapse before Phase 1 is on line is five years. The actual time could be from four to ten years, depending not only on time required for permits and licensing but also on uncertainties involved in the initial design. If all the necessary development work has been accomplished by the time the Phase 1 design must be frozen and construction drawings prepared, the Phase 1 design can include provisions for all of the future additions. In particular, if steam reformer design and development is complete and has been demonstrated to be adequate, one or more reformers to be used during later phases can be incorporated into initial construction. If not, provision must be made for incorporating them into the plant at a later time. Uncertainties will slow the design, complicate licensing, lengthen construction time, and increase costs.

3.5.2 Phase 2: All High-Temperature Steam Output for Local Use

Implementation of the Phase 2 configuration will be greatly expedited, for reasons just discussed, if the steam reformers have been built into the reactor structure during initial construction and the necessary additional cooling capacity is available. The external equipment required for Phase 2 — the storage facilities for syngas and methane, the methanator, and the peaking generator(s) — can be built during Phase 1 operation. Under these conditions, Phase 2 operation could commence as soon as justified by the successful operation of the Phase 1 configuration. Obviously, if permits and licensing for Phase 2 are not at hand, or if problems severe enough to require rebuilding or extensive modification of major components are encountered, initiating the Phase 2 operation and demonstration would be delayed accordingly.

If the steam reformers have not been built into the reactor structure during the initial construction of the plant, there will be some delay between completion of Phase 1 and initiation of Phase 2 operation. The reactor will have to be taken out of service and installation of the reformer(s) accomplished. Installation time will be minimized by incorporating in the initial construction the necessary cavities, connections, and valving to permit rapid addition of the reformer modules. It is estimated that such an installation could be accomplished within a three-month period. Another three to nine months will be needed to test the reformers and bring them on line, assuming minimum regulatory delays.

An assumption to be recalled at this point is that all electricity generated by the lead plant can be delivered to an existing electric transmission system. A strong point in the suggested scenario is the economical combination of base-load and peak-load generating capacity which can be made available to an electric utility system.

One year of operation of the steam reformer and other CHP components at the lead-plant site should be adequate to demonstrate this key portion of the HTR Multiplex.

3.5.3 Phase 3: Add Transmission and Remote Use of CHP Syngas

A key factor in implementing Phase 3 is the arrangements that have been made for delivering syngas to a customer. A critical question is the financial risk involved and who assumes it. To minimize financial risk for all parties, the argument might be made that final commitments for the syngas transmission pipeline should be deferred until successful operation of the prototype plant, during Phase 2, has been demonstrated. This presumably is not acceptable because several years could elapse after completion of Phase 2 before the pipeline is completed. If conversion from oil and gas to nuclear fuel is to be expedited as a national priority, some risk must be taken. Further, the location of the lead plant will be chosen in large part on the basis of proximity to customers for syngas; although analysis shows the syngas can be economically transmitted for up to 200 miles; both the capital and operating costs quickly become very substantial. Thus, it is postulated that all the components for producing syngas have been demonstrated (only the steam reformer has not, at this time), the risk has been found acceptable, and it has been possible to make necessary contractual arrangements before plant construction and to install the needed pipeline during Phase 2.

Six to twelve months should be allowed (again assuming minimal regulatory delays) for working out problems in bringing the plant to full thermal output, activating the additional reformers and the methanator(s), and mating the methanator output to a steam turbine and its associated steam and hot-water delivery systems. From the time that reliable operation is underway, one year of demonstration should be adequate.

3.5.4 Phase 4: Add Transmission and Remote Use of Hot Water from Central Plant

The timing of Phase 4 is not critical. There is no question that hot water can be produced at the plant, and transmitted via pipeline to customers. However, since cooling towers will already be installed, the motivation for selling hot water is primarily to demonstrate the overall plant thermal efficiency that is achievable if waste heat is utilized. The economics of delivering and selling thermal energy via hot-water pipelines will be the determining factor in timing. The hot-water pipeline could be constructed during Phases 2 and 3.

3.5.5 Total Time Required for Lead Plant

The lead plant time requirement from start of construction to full operational output is estimated to be from 7 to 12 years. Assuming that

Phase 1 (Derated Reactor-Steam Cycle Electric Generation) is complete and the plant is online five years after construction startup, the total elapsed time through Phase 3 operation could be 8 to 9 years after construction startup. Phase 4 could also be complete within this time span depending upon motivation.

3.5.6 Phase 5: Commercial Systems

Depending upon the degree of success realized with the lead plant, additional plants could be built in parallel, at perhaps two-year intervals after the lead plant.

SECTION 4
U.S. ENERGY DEMANDS

4.1 ELECTRIC ENERGY

Forecasts of additions to the U.S. electric energy system were obtained from the General Electric Company's Electric Utility System Engineering Department (EUSED). These forecasts are by National Electric Reliability Council (NERC) region — see Figure 4-1 and Table 4-1. Table 4-2 summarizes the electric energy growth rates on which the forecasts are based and Table 4-3 describes the forecast additions by plant type for various time periods.

Table 4-1. NERC regions and geography.

NERC Region	Map Region (Figure 4-1)
NPCC	NPCC
MAAC	MAAC
ECAR	ECAR
SERC - Oil SERC - Coal	SERC
WNL	MAIN + MARCA
WSC	ERCOT + SPP
PNW PSW	WSCC

The time period of interest for this evaluation is 1995-2000. This is based on the assumption that the development schedule of the HTR Multiplex would be about as described in Section 3. In other words: (1) Design, development, and prototype construction from 1979 to 1990, (2) Prototype operation beginning in 1990, and (3) Commercial operation

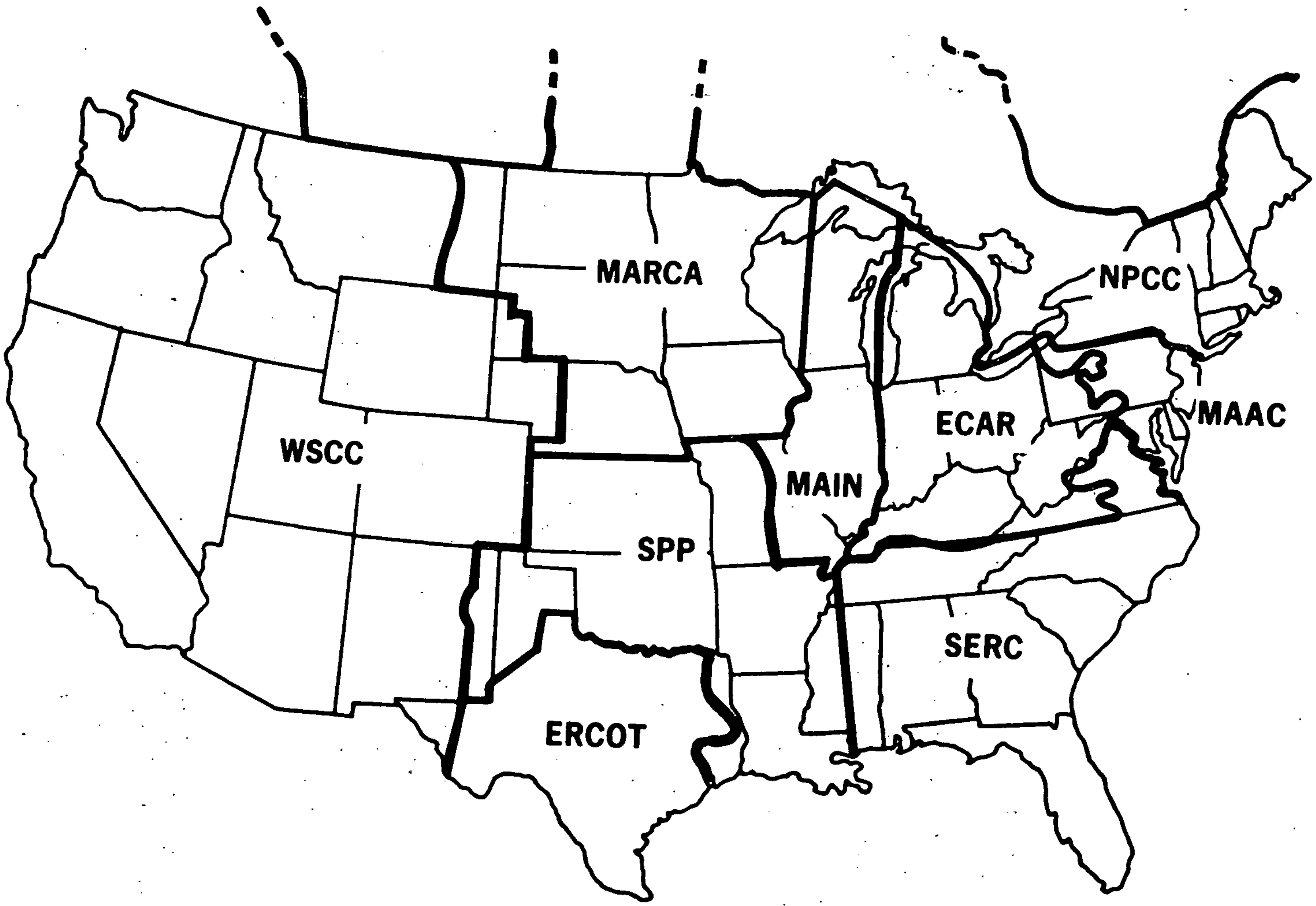


Figure 4-1. Regional Reliability Councils of the National Electric Reliability Council.

Table 4-2. Average peak load growth, percent.

Region	1976-80	1980-85	1985-90	1990-95
NPCC	3.3	3.3	3.1	2.8
ECAR	5.5	5.6	5.1	4.8
MAAC	4.3	3.6	3.2	2.8
WNC	5.0	5.0	4.3	3.9
WSC	7.0	5.9	5.1	4.8
SERC — OIL	6.6	5.6	5.5	5.0
SERC — COAL	6.3	5.5	5.3	4.8
PNW	5.3	4.9	4.1	3.8
PSW	5.3	4.9	4.1	3.8
Nation	5.1	4.9	4.5	3.8

starting in 1995. For this study the 1976-1995 additions (shown in Table 4-3) were assumed to apply for the 1995-2010 time period. This corresponds to an average growth rate of about 3 percent during this latter period and further assumes the plant mix would remain the same for each region.

Annual electric energy production by plant type for the year 2010 from the cumulative additions was calculated by using the capacity factors given in Table 4-4. The results are summarized in Table 4-5.

4.2 INDUSTRIAL HEAT ENERGY

The U.S. industrial heat energy demand forecasts were obtained from the Corporate Consulting Services of the General Electric Company. These forecasts are basically an update and revision of previous studies.

Industrial energy growth rates for the period 1954 to 1971 are shown in Table 4-6.

Future industrial energy growth rates will be affected by many factors:

- Reduced population growth rate will tend to reduce energy growth rate
- Energy availability and cost will result in conservation measures and reduced energy growth rates

Table 4-3. National economic mix cumulative additions by type.

Additions (GW)	Nuclear	Fossil	GT	STAG	Hydro	Total
1976-1990						
NPCC	11	5	3	1	1	
MAAC	11	6	5	1	0	
ECAR	31	31	13	0	1	
SERC — OIL	13	5	1	6	4	
SERC — COAL	46	22	7	0	5	
WNC	10	28	15	0	0	
WSC	33	42	13	2	0	
PNW	12	10	4	1	8	
PSW	14	15	3	11	5	
Nation	181	165	64	22	24	456
1976-1995						
NPCC	21	5	4	1	2	
MAAC	19	7	7	2	0	
ECAR	51	52	17	0	1	
SERC — OIL	23	6	1	11	5	
SERC — COAL	79	29	10	0	7	
WNC	15	44	20	0	0	
WSC	66	46	21	4	0	
PNW	18	13	6	1	10	
PSW	20	23	3	19	6	
Nation	312	226	89	38	31	696
1991-1995						
NPCC	10	0	1	0	1	
MAAC	8	1	2	1	0	
ECAR	20	20	4	0	0	
SERC — OIL	10	1	0	5	1	
SERC — COAL	33	7	3	0	2	
WNC	5	16	5	0	0	
WSC	33	4	8	2	0	
PNW	6	3	2	0	2	
PSW	6	8	0	8	1	
Nation	131	60	25	16	7	239

Table 4-4. 1995 capacity factors, percent.

Region	Nuclear	Fossil Coal	Gas Turbine	Comb. Cycle	Fossil Oil	Natural Gas
NPCC	69	72	14	30	46	--
MAAC	63	56	23	45	45	--
ECAR	68	57	25	34	33	31
SERC — OIL	68	77	16	54	50	68
SERC — COAL	69	54	29	45	29	53
WNC	70	58	18	37	33	32
WSC	68	67	11	23	48	29
PNW	64	66	5	28	29	20
PSW	66	53	9	66	59	13
Nation	67	67	18	59	47	28

Table 4-5. Electric energy production from cumulative additions (1995-2010).

Region	Annual Energy in 2010 ($kWh_e \times 10^{11}$) Nuclear	Coal	GT	STAG
NPCC	1.27	0.32	0.05	0.03
MAAC	1.05	0.34	0.14	0.08
ECAR	3.04	2.60	0.37	--
SERC — OIL	1.39	0.41	0.01	0.52
SERC — COAL	4.63	1.37	0.25	--
WNC	0.92	2.24	0.33	--
WSC	3.93	2.70	0.20	0.08
PNW	1.01	0.75	0.03	0.02
PSW	0.81	1.07	0.02	0.64
Total	18.05	11.80	1.40	1.37

Table 4-6. Industrial energy growth.

Time Period	Growth Rate (%)
1954-1958	1.57
1958-1962	4.30
1962-1967	3.45
1967-1971	2.37
1954-1971	2.95

- Shifts in product demand among industries of different energy intensities will affect total energy growth rate
- Feedstock availability will result in the use of new feedstocks, new processes, and a shift in energy intensity patterns.

Overall, it is probable that the industrial energy growth rate will reduce significantly, particularly during the next decade or so. If the U.S. is successful in reaching a self-sufficient energy basis late in this century, it is possible that energy growth rates will again increase in the latter part of the 1971 to 2010 era. For the purpose of establishing HTR Multiplex applications in 2010, the growth rate of 2.95 percent in the era 1954 to 1971 was reduced to 1.79 percent for the period 1971 to 2010. This growth rate results in a 2010 energy use that is double that of 1971.

To obtain information about the geographical distribution of energy use, the 32 largest energy-using Standard Metropolitan Statistical Areas (SMSAs) were analyzed. These areas use about 50 percent of the total U.S. industrial energy use. The results are summarized in Table 4-7. Based on the above, a forecast of total U.S. industrial energy requirements was developed and is summarized in Table 4-8.

The potential market considered for HTR Multiplex applications is the sum of: installations to provide the increase in energy requirements; and installations to replace other types of systems, which have reached end of life. Assuming a 30-year lifecycle on these older systems, one-sixth of the installed capacity at the beginning of a 5-year period would be replaced during that period. On this basis, the forecast energy market in the 1995-2010 era is summarized in Table 4-9.

In order to obtain industrial energy use by NERC region, 1972 Census of Manufactures data was used. The resulting energy geographical distribution was assumed to remain constant through 2010. Using the ratios obtained, the forecast energy additions (1995 to 2010) were calculated and are shown in Table 4-10.

Table 4-7. Energy use by SMSA.

Standard Metropolitan Area	1971 kWh x 10^9 Purchased Fuel Use
New York City and Northeast New Jersey	101.1
Chicago and Northwest Indiana	162.7
Detroit	63.7
New Orleans	32.1
Houston	204.3
Philadelphia	73.3
Los Angeles — Long Beach	60.0
St. Louis	36.4
Pittsburgh	98.6
Cleveland	42.5
Toledo	19.3
Akron	17.9
Milwaukee	16.5
Boston	14.4
Louisville	15.3
Beaumont — Port Arthur — Orange	100.0
Cincinnati	16.4
Buffalo	24.7
Baltimore	27.4
San Francisco — Oakland	40.2
Allentown — Bethlehem — Easton	16.4
Birmingham	24.5
Kansas City	15.2
San Bernardino — Riverside — Ontario	16.2
Youngstown	21.7
Galveston — Texas City	47.3
Lake Charles	44.8
Baton Rouge	38.4
Canton	14.4
Corpus Christie	37.2
Huntington — Ashland, WV	17.4
Charleston, WV	16.0
TOTAL	1476.3

Table 4-8. Total energy (kWh x 10^9).

	1971	1995	2000	2005	2010
32 Sampled Areas	1822	2791	3051	3334	3644
168 Other Areas	785	1203	1314	1437	1570
Other Manufacturing	1510	2313	2528	2763	3020
All Manufacturing Industry	4117	6307	6893	7534	8234

Table 4-9. Industrial energy market (1995-2010).

	New Market, kWh x 10^9			
	1995-2000	2000-2005	2005-2010	1995-2010
32 Sampled Areas	260	283	310	853
168 Other Areas	111	123	133	367
Other Manufacturing	215	235	257	707
All Manufacturing Industry	586	641	7-0	1927
	Replacement Market, kWh x 10^9			
	1995-2000	2000-2005	2005-2010	1995-2010
32 Sampled Areas	465	509	556	1530
168 Other Areas	201	219	240	660
Other Manufacturing	386	421	461	1268
All Manufacturing Industry	1052	1149	1257	3458
TOTALS	1638	1790	3247	5385

Table 4-10. Industrial energy demand (2010).

Region	Energy (kWh x 10^9)
NPCC	285
MAAC	504
ECAR	2081
SERC — OIL	202
SERC — COAL	462
WNC	418
WSC	1025
PNW	114
PSW	294
TOTAL	5385

SECTION 5
COST DATA

5.1 CONVENTIONAL ELECTRIC SYSTEM

Cost input data for the conventional electric system components and fuels was obtained from the EUSED of the General Electric Company. These costs are summarized in Tables 5-1, 5-2, and 5-3. Note that all costs are in 1985 dollars.

Table 5-1. Plant costs ($\$/kW_e$).

Region	Nuclear	Coal with Scrub	Coal with 50 Percent Scrub	STAG	GT	Oil-Steam
NPCC	1265	1045	NA	545	270	743
MAAC	1208	998	NA	520	257	709
ECAR	1208	998	NA	520	257	709
SERC – OIL	1035	855	NA	446	221	608
SERC – COAL	1035	855	NA	446	221	608
WNC	1208	998	898	520	257	709
WSC	1035	855	770	446	221	608
PNW	1093	903	812	470	233	641
PSW	1093	903	812	470	233	641
National Average	1150	950	855	495	245	675

5.2 HTR MULTIPLEX SYSTEM

Since the Multiplex is not a commercial system, obtaining realistic cost data consistent with the costs for the conventional electric system components was difficult. The two major uncertainties relate to the nuclear system and the syngas producing components. Costs for the nuclear system were based on data received from the General Electric Company Energy Systems Program Department. Costs for the syngas system elements were taken from information developed by the General Electric

Table 5-2. Plant O&M costs (1985 $), $/kW/yr.

Region	Nuclear	Coal with Scrub	GT	STAG
NPCC	21.5	26.7	1.2	3.7
MAAC	21.5	24.5	1.2	3.7
ECAR	21.5	22.3	1.2	3.7
SERC — OIL	21.5	22.3	1.2	3.7
SERC — COAL	21.5	22.3	1.2	3.7
WNC	21.5	22.3	1.2	3.7
WSC	21.5	22.3	1.2	3.7
PNW	21.5	22.3	1.2	3.7
PSW	21.5	22.3	1.2	3.7
National	21.5	22.3	1.2	3.7

Table 5-3. Fuel costs* ($/10^6 Btu).

Region	Reload Nuclear	Coal	Distillate
NPCC	1.77	4.26	8.28
MAAC	1.77	3.85	8.04
ECAR	1.77	3.30	8.31
SERC — OIL	1.77	4.15	7.91
SERC — COAL	1.77	3.52	7.91
WNC	1.77	2.89	7.60
WSC	1.77	1.78	8.21
PNW	1.77	1.48	8.24
PSW	1.77	1.41	8.24
National	1.77	3.30	8.08

*Fuel costs all 30-year levelized values.

Company Corporate Research and Development (COO-2676-1). The nuclear plant costs were also compared to EPRI cost estimates as a further check on validity. This comparison is summarized in Table 5-4.

Table 5-4. Nuclear plant cost comparison (national average costs).

Reactor Type	$/kW$_e$ (1976 $) EPRI Estimates	$/kW$_e$ (1976 $) GE Estimates	$/kW$_e$ (1985 $) GE Estimates
LWR	765	769	1150
HTR	--	935	1400

Note that the ratio of investment costs (HTR to LWR for all-electric plants) is about 1.22. This is consistent with previous ESPD estimates and is intuitively reassuring since HTR core power densities are an order of magnitude lower than LWRs. Table 5-5 summarizes the national average costs developed for the HTR Multiplex and used in this evaluation. These costs are also in 1985 dollars and were assumed to have the same regional variation as the LWRs in the conventional electric system. Note that the items listed in Table 5-5 are not the conventional component breakdown (eg "nuclear plant" is not a nuclear steam supply system). The items of Table 5-5 were specifically chosen for convenience in synthesizing HTR Multiplex systems as described in Section 6.

Table 5-5. HTR Multiplex costs (1985 $) (national average values).

Item	Cost
Nuclear Plant	$330/kW$_t$
Steam Generator	$ 68/kW$_t$
Turbine Generator (Central Plant)	$315/kW$_e$
Turbine Generator (CHP Plant)	$245/kW$_e$
Steam Reformers	$105/kW$_t$
Methanators	$ 45/kW$_t$
Pipeline	$105/kW$_t$ - 100 miles
Storage	$ 70/kW$_t$ - day

The two turbine generator plant costs listed in Table 5-5 relate to two different types of steam turbine systems used in the HTR Multiplex. Central plant steam turbines are single-unit, highly efficient (~40 percent) machines operating as base load devices. Turbines for the CHP plant are small, multiple units, with lower efficiency (~30 percent), and operating as peakers or mid-range devices.

Multiplex fuel costs were assumed to be identical to those of the LWR (Table 5-3) and O&M costs were the same fraction of investment costs as the LWRs.

5.3 FLUIDIZED BED COMBUSTORS

Fluidized bed combustors (FBC) appear to have costs similar to conventional stokers using low sulfur coal and lower than those using high sulfur coal where all systems meet emission requirements. The fluidized bed combustors were therefore selected as the industrial heat source for comparison with the HTR Multiplex. Cost data for FBC were based on a recent EXXON study (NTIS PB-264 528). Table 5-6 gives the investment costs for FBC systems in 1985 dollars.

Table 5-6. FBC investment costs.

Region	Cost ($/kW$_t$)
NPCC	375
MAAC	350
ECAR	350
SERC — OIL	300
SERC — COAL	300
WNC	350
WSC	300
PNW	315
PSW	315
National	325

The fuel costs used for the FBC systems are those in Table 5-3 and the O&M costs were assumed to be the same fraction of investment costs as the coal systems described in Table 5-2.

SECTION 6
HTR MULTIPLEX MARKET ASSESSMENT

6.1 METHODOLOGY

The procedure used to obtain a preliminary assessment of the potential market for the HTR Multiplex consisted of the following steps:

1. Describe a conventional electric system using input data from Section 4.
2. Synthesize HTR Multiplexes that satisfy the same electric requirements (energy and power) as the conventional system and also supply industrial heat.
3. Cost both the conventional and HTR Multiplex systems using information from Section 5.
4. Subtract the annual conventional electric systems costs from the Multiplex systems costs.
5. Allot the system cost differences obtained in Step 4 to the industrial heat produced and compute the specific cost of industrial heat for each Multiplex.
6. Calculate the specific cost of industrial heat from fluidized bed combustor (FBC) systems using cost data from Table 5-6.
7. Compare the industrial heat specific costs for the Multiplex and the FBC systems.
8. Estimate the potential market for the HTR Multiplex. Describe the limitations and expected validity of the results and any general conclusions that can be reached from the analyses.

Since all of the systems considered in this assessment are added in the same time frame (a fairly short period) and the majority of the costs is for similar systems (nuclear), a present-worth analysis was not used. A fixed charge rate of 0.165 was used for all systems. This slightly favors the FBC systems since they would normally be purchased under industrial, not utility, financing conditions. To summarize, the costing methodology used constant 1985 dollars and the same fixed charge rates for all systems considered and is believed to result in accurate *comparable* costs.

6.2 SYSTEMS REQUIREMENTS

The nuclear- and oil-burning plants described in Table 4-3 were selected as a realistic comparison set for the Multiplex. In other words, the coal- and hydro-plant additions were ignored and the combination of nuclear, gas turbine, and STAG plants were the only additions considered. This resulted in a conventional electric system production shown in the first two columns of Table 6-1. The HTR Multiplex was also required to supply 50 percent of the industrial heat requirements as given in Table 4-9. These values are listed in the last column of Table 6-1. Typical industrial heat requirements consist of 36 percent for high temperature heat (above 1100°F) and about 6 percent for seasonal heat (space heating). This eliminates 42 percent of the total heat market from Multiplex considerations. Accordingly, the value of 50 percent was selected as being a realistic fraction of the market that could be served. The ratio (oil to nuclear) shown in column 3 of Table 6-1 is included as a useful characterization of the conventional electric energy system. To summarize, Table 6-1 describes the electric energy production requirements for the year 2010 for both the conventional electric system additions and the HTR Multiplex plus the additional industrial heat requirements for the Multiplex.

6.3 HTR MULTIPLEX SYNTHESIS

The various HTR Multiplexes were designed to satisfy the annual energy requirements of Table 6-1 in the following way:

- Installed direct electric capacity at the central plant sufficient to satisfy the nuclear energy demands.
- Installed indirect electric capacity at the central plant sufficient to satisfy the oil energy demands. This is accomplished through syngas production and storage and with utilization of peaking mid-range steam turbines. Note that the sum of the

Table 6-1. Annual energy production, 2010 (from 1995-2010 additions).

Region	Electricity ($kWh_e \times 10^{11}$) Nuclear	Oil	Ratio	Industrial Heat ($kWh_t \times 10^{11}$)
NPCC	1.27	0.07	0.055	1.43
MAAC	1.05	0.22	0.210	2.52
ECAR	3.04	0.37	0.122	10.41
SERC – Oil	1.39	0.53	0.381	1.01
SERC – Coal	4.63	0.25	0.054	2.31
WNC	0.92	0.33	0.359	2.09
WSC	3.93	0.28	0.071	5.13
PNW	1.01	0.05	0.050	0.57
PSW	0.81	0.66	0.815	1.47
Totals	18.05	2.76		26.94

direct and indirect electric capacities equals the installed capacity of the conventional electric system.

- Installation of syngas production and pipeline delivery capacity to satisfy the industrial heat demand.

Synthesis of the HTR Multiplexes assumed that all in-plant and pipeline transmission pumping requirements were electric and accounted for from central station production. In other words, the central plant direct electric production was sized to account for these "losses." Figure 6-1 was used to calculate the central plant electric generation since it is primarily a function of the heat-to-electric energy ratio of the Multiplex. An iteration of this step was not performed but would be desirable in a detailed analysis. The resulting calculated electric power capacities are given in Table 6-2. Values in parentheses under the Multiplex are the actual installed capacities – accounts for pumping losses. The sum of the direct and indirect values equals the conventional electric capacities for each region.

Additional thermal capacity was included in the Multiplex to satisfy the industrial heat demands of Table 6-1 assuming a 0.95 conversion efficiency – nuclear heat to syngas. The resulting HTR Multiplex capacities are shown in Table 6-3, broken down into the three categories described above.

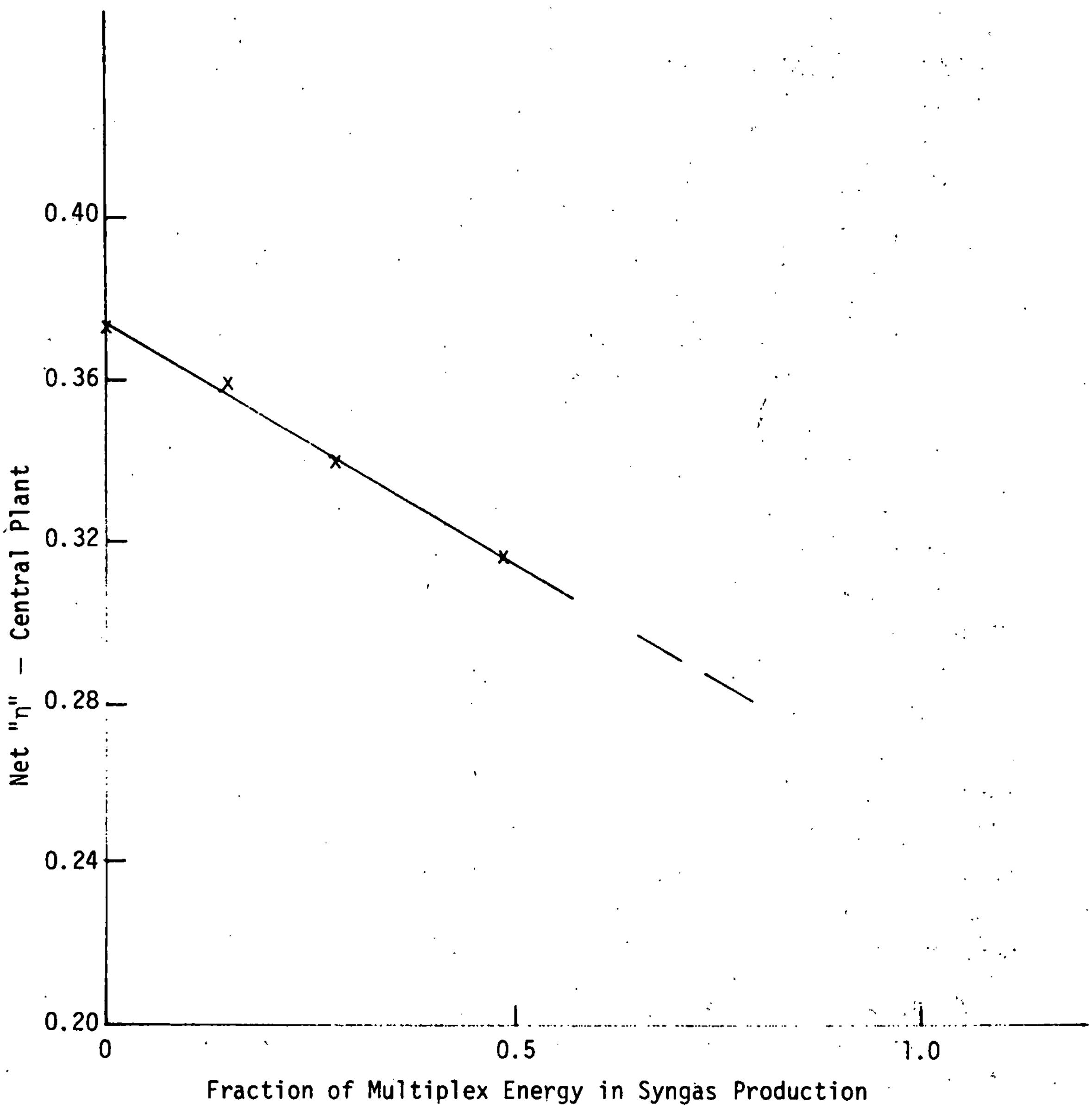


Figure 6-1. Electric power pumping losses versus syngas production ratio.

Table 6-2. Installed electric capacities, GW_e (1995-2010).

Region	Nuclear	GT	STAG	Multiplex Direct		Multiplex Indirect
NPCC	21	4	1	(21.07)	18.12	7.88
MAAC	19	7	2	(18.49)	14.98	13.02
ECAR	51	17	0	(56.33)	43.38	24.62
SERC — Oil	23	1	11	(23.33)	19.83	15.17
SERC — Coal	79	10	0	(75.08)	66.07	22.93
WNC	15	20	0	(17.05)	13.13	21.87
WSC	66	21	4	(65.98)	56.08	34.92
PNW	18	6	1	(16.56)	14.41	10.59
PSW	14	3	11	(14.99)	11.54	16.46
National	306	89	30	308.87	257.54	167.46
Totals		425				425

Table 6-3. Installed Multiplex capacities, GW_t (1995-2010).

Region	Nuclear	Oil	Heat	Total
NPCC	52.68	3.58	21.41	77.67
MAAC	46.23	10.47	37.78	94.98
ECAR	140.80	17.70	156.50	315.00
SERC — Oil	58.32	25.40	15.17	98.89
SERC — Coal	187.70	12.08	34.62	234.40
WNC	42.63	15.79	31.32	89.74
WSC	164.94	13.46	76.98	255.38
PNW	41.41	2.42	8.56	52.39
PSW	37.47	12.37	22.08	71.92
Totals	772.18	113.27	404.42	1289.87

6.4 SYSTEMS COST COMPARISON

Costs for the various systems described in Tables 6-1, 6-2, and 6-3 were calculated using the cost information from Section 4. The FBC system specific heat costs were also calculated using data previously described. Results are summarized in Table 6-4.

It is worth noting that the cost of an HTR Multiplex is relatively independent of the electricity-to-syngas production ratio (Leeth, 1978). This is due to the fact that the combination of steam reformers, pipe-

Table 6-4. Cost summary (1985 $).

	System Costs ($ x 10^9)			Heat Costs ($/$10^6$ Btu)		
					FBC	
Region	Conventional Electric	Multiplex	Difference	Multiplex	CF = 0.9	CF = 0.3
NPCC	8.24	12.89	4.65	9.53	7.78	12.94
MAAC	8.46	15.37	6.91	8.03	7.13	11.99
ECAR	21.29	50.80	29.51	8.31	6.44	11.28
SERC — Oil	11.55	13.41	1.85	5.40	7.20	11.48
SERC — Coal	25.98	31.11	5.13	6.51	6.43	10.71
WNC	8.85	14.93	6.08	8.52	5.95	10.81
WSC	23.67	35.10	11.43	6.52	4.31	8.59
PNW	6.28	7.56	1.28	6.59	4.05	8.57
PSW	10.07	9.98	- 0.09	- 0.18	3.97	8.99
Averages				6.62	5.92	10.54

lines, methanators, etc is only slightly more costly than steam generators, steam turbines, and electric generators.

As expected, the cost of industrial heat from the HTR Multiplex falls between the FBC (C.F. = 0.9) and FBC (C.F. = 0.3) on a national average basis. This is consistent with previous studies, but the HTR Multiplex heat costs are much closer to the FBC (C.F. = 0.9) than for a PBR-CHP (no electric energy production) system. The interesting item is the regional variation in HTR Multiplex industrial heat costs as shown in Table 6-4. Note that Multiplex heat costs compared to FBC (C.F. = 0.9) heat costs are:

- Close in Region MAAC
- Approximately equal in Region SERC—Coal
- Significantly lower in Region SERC—Oil
- Greatly less in Region PSW (actually calculated to be negative!).

The above results are not unexpected and can be explained by a careful examination of each regional system. To a first approximation, the ratio of oil-to-nuclear heat is the critical parameter. For example, Region PSW has over 80 percent of its electric energy produced from oil (see Table 6-1). This is expensive electric energy. Table 6-4 merely demonstrates that an HTR Multiplex could produce electricity plus industrial heat at a lower total cost than the conventional electric system (mostly oil) could produce electricity.

6.5 MARKET ASSESSMENT

Based on Table 6-4, one could conclude that an HTR Multiplex market in the 1995-2010 time period exists in Regions SERC—Oil, SERC—Coal, and PSW amounting to about 400 GW_t. However, a more conservative and realistic assessment leads to the conclusion that, as a minimum, the 1995-2010 Multiplex market amounts to about 300 GW_t. This is based on the following:

- The HTR Multiplex produces high temperature (1000°F) steam at much lower costs (approximately 50 percent) than the available alternatives considered in this evaluation — for two specific markets:

- Industrial heat for one- and two-shift operations
- Heat for peaking and mid-range steam turbines producing electricity.

- The sum of these two markets amounts to about 300 GW_t in the 1995-2010 time period.

The above conclusions are easily verified by a careful examination of Table 6-4 and the preceding analyses. They can also be demonstrated by observing that the two markets identified can be characterized as low capacity factor systems. Based on Tables 6-2 and 6-4, the national average cost of a Multiplex is about $590/$kW_t$. The comparable cost for an FBC is about $325/$kW_t$. Thus, for capacity factor ratios of 1.8 or greater, the capital charges for an HTR Multiplex are lower than for an FBC. Since the Multiplex is expected to operate at a C.F. of 0.80 or greater, any FBC operating at a C.F. of 0.45 or less will have greater capital charges. When fuel costs are included (typically much lower for the Multiplex), the cost advantages of the Multiplex over the FBC systems become very large as is demonstrated in Table 6-4.

To summarize, the 1995-2010 U.S. potential market for the HTR Multiplex is at least 300 GW_t. It consists of about 25 percent of the industrial heat market (one- and two-shift operations) and about 15 percent of the electrical market (peaking and mid-range generation). In addition, there appears to be a high probability that the HTR Multiplex could capture a significant fraction of the base load electric market depending on regional economic factors and relative fuel costs.

6.6 DISCUSSION

As noted in Section 6.5 and Table 6-4, the cost advantages of the HTR Multiplex over FBC systems for low capacity factor, high temperature steam markets is of the order of 50 percent. This is such a large margin that the conclusion is valid even though the input cost data may be uncertain by 10 to 15 percent.

Since the HTR all-electric system produces electricity at only a slightly higher cost than LWRs (of the order of 5 percent), it seems probable that the HTR Multiplex will be able to compete in the joint product (heat and electricity) markets in some regions of the U.S. Verification of this will require a more detailed analysis than the present preliminary assessment.

One additional item should be mentioned — that of alternatives to the HTR Multiplex. It is technically possible to construct a Coal Multiplex and obtain the same capacity factor advantages over dispersed-fuel systems as the HTR Multiplex possesses. This possibility should be considered more carefully. However, it appears likely that the Coal Multiplex would be more costly than the HTR Multiplex for the same reasons that coal-electric generation is more costly, in general, than nuclear-electric generation. Since the nuclear system is a smaller fraction of the Multiplex than for a standard electric plant (pipelines, pumps, storage, etc), it is almost certain that a Coal Multiplex would be even less competitive with an HTR Multiplex than a coal-electric system is with a nuclear-electric system.

SECTION 7
ADDITIONAL MULTIPLEX CONSIDERATIONS

In the foregoing market assessment, some aspects of the HTR Multiplex have been mentioned but not discussed in any detail. Other aspects, although important, have not been mentioned. Some of these factors can be of major importance in the development of the HTR Multiplex and should be carefully considered in any thorough market analysis.

7.1 MULTIPLEX CONFIGURATION

The one basic component of the HTR Multiplex is the HTR itself — and even its design and configuration remain to be defined. The other energy-system components chosen to be colocated with the HTR will affect the HTR configuration and be affected by it. A set of optional HTR configurations may prove desirable; conversely, the benefits of standardization may dictate that a basic configuration be chosen.

7.2 CHEMICAL AND INDUSTRIAL PRODUCTS

Various chemical reactions can be driven by heat from HTR Multiplex. The steam-methane reactions and chemical heat pipe have been considered here because they appear broadly applicable to produce industrial steam and draw largely upon well-known technology. Other reactions, perhaps supplementing rather than replacing the steam-methane reactions, should also be evaluated.

Hydrogasification of coal at the HTR Multiplex is a chemical reaction of interest. Methane produced from coal could become the feedstock for the reformer plant, and permit one-way single-pipeline operation of a CHP system, and furnish methane at the methanator output for clean combustion or chemical feedstock.

Another example is thermochemical water splitting. Hydrogen and oxygen are valuable chemicals widely used in industrial processes. If piped to industrial sites and available at attractive prices, they would be used even more widely. Piped to thermal-electric plants, hydrogen and oxygen could be recombined in a combustion process that is absolutely nonpolluting: only steam would be produced, to drive a turbine whose exhaust could be condensed to supply heat to hot water used in district-heating networks. Energy efficiency would be outstanding, for several reasons. The pipeline pressure would make unnecessary at least part of the compressor ordinarily required in a combustion turbine and using perhaps one-third of the shaft work. The H_2-O_2 stoichiometric combustion temperature being very high, water injection would be required — which would increase mass flow. Part of the heat rejected by the combustion/steam turbine and used for district heating might be stored for space heating in cold weather (Hausz, 1972).

Innumerable industrial processes requiring heat in the 1100-1700°F range might be considered for location at an HTR Multiplex. Steelmaking is an example. However, until enough experience and public acceptance have been gained from simpler HTR Multiplex configurations, postulating colocation of industry at the HTR Multiplex does not appear realistic.

7.3 HOT WATER

In connection with chemical plant operations and baseload generation of electricity at the HTR Multiplex there will be a substantial amount of reject heat. This heat will either be expensively wasted by discharging it through cooling towers or into water bodies, or utilized for district heating.

Rejected heat from steam turbines usually is carried away in a fluid at not much over 100°F. Many Btu's are involved but they are thermodynamically unavailable. By sacrificing a small fraction of electric generation — say, 10 percent — the cooling water can be discharged at a sufficiently high temperature, such as 300-350°F, to be salable for space heating, hot tap water, absorption air conditioning, and some process-heat applications. The practice is quite common in Europe, and is being considered more seriously in the United States than was the case before oil became scarce and expensive. This cogeneration approach to district heating is an excellent and usually cost-saving approach to energy conservation and to displacing oil and gas with coal and nuclear fuels.

Transport of hot water via pipeline is quite economical if the amount of heat to be moved is large enough. An analysis by TEMPO in 1976 indicated that a combination of dual-pipeline networks and heat storage in underground aquifer formations, as diagrammed in Figure 7-1, would be economically feasible for transmission distances of 100 miles or more from a central station (Meyer, Hausz, et al, 1976).

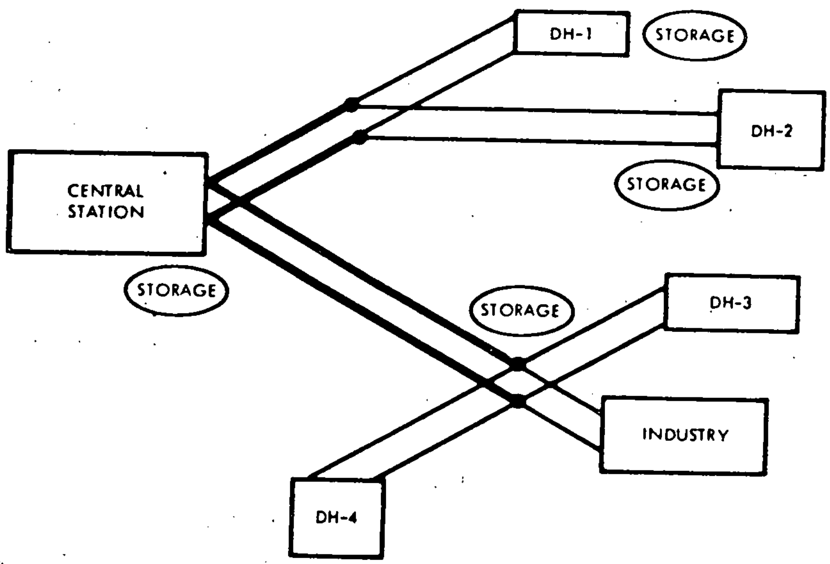


Figure 7-1. Pipeline network to load centers.

Generation and sale of hot water has not been specifically considered in the analysis reported here. The most efficient system for district heating is to employ two or three stages to heat the return water. A nominal return temperature of 150°F would suggest that the turbine exhaust at a temperature somewhat higher than 150°F, into a condenser cooled by the return water. The coolant water would then be heated to its sendout temperature of 300-350°F in heat exchangers that are much like feedwater heaters. Steam extracted from the turbine at appropriate stages would be condensed in these heaters. In this way, the maximum amount of work would be extracted from the steam before it is condensed. The alternative is to exhaust all the steam from the turbine at somewhat above 300-350°F and heat the return water from 150°F to its sendout temperature in one stage.

7.4 TRANSMISSION CORRIDORS

An environmental problem which has come to the fore in relatively recent years is securing rights-of-way for transmission lines. An example of the problem is the armed confrontation between farmers in Minnesota and an electric utility attempting to install transmission. The farmers' very forceful presentation, which carried the day, was that they were not going to yield farmlands for the benefit of city dwellers who needed electricity. Another example of the transmission corridor problem, also in Minnesota, was the April 1978 action of that State's Supreme Court in reversing approval of an electric power line route which would adversely affect a lake and a virgin oak forest. The court reaffirmed the State's policy of "nonproliferation" of power line rights-of-way, and instructed a lower court and the Minnesota Environmental Quality Council to evaluate alternatives which would "harmonize the need for electric power with the equally important goal of environmental protection" (People for Environmental Enlightenment and Responsibility v. Minnesota EQC).

Pipelines encounter their share of objections when rights-of-way are to be obtained, but pipelines at least are unobtrusive when completed. One of the merits of the HTR Multiplex concept is its employment of pipelines to transport a substantial fraction of its energy products. Suggestions have been made which would concentrate thermal power generation capacity into a few geographical locations, rather than permitting construction of plants as close to load centers as possible. The use of pipelines could be a particularly important factor in minimizing the width of transmission corridors in this situation.

7.5 THERMAL POLLUTION

LWR power plants are inherently less efficient energy converters than fossil-fired plants with higher source temperatures. Among other stigmas, LWR plants have become known as major sources of thermal pollution, which complicates further their already very formidable siting problems. HTR Multiplexes are even more efficient than fossil-fired electric plants, which is a useful public-relations aspect.

More significant than electrical generation efficiency, to mitigation of the thermal pollution problem, is that the HTR Multiplex (and other thermal power plants) can be so conceived and configured as to discharge little or no waste heat. As noted earlier, this is made possible by reallocating a small portion of the energy content of the steam supply to heating water rather than making electricity. The hot water is then piped away from the plant to be used for district heating. When the demand for district heat (including essentially uniform year-round use of hot tap water) is enough to utilize all the heat cogenerated by the power plant, no waste heat will be discharged. Cooling water and towers need not be provided.

The HTR Multiplex will usually produce more hot water than can be immediately used in the district heating system during summer months. In this case either cooling water or towers must be available for heat rejection or large scale heat storage must be available. The leading candidate for large scale seasonal heat storage (hot water in aquifers) remains to be demonstrated; but seems relatively sure to be viable in many locales.

In brief, thermal pollution from HTR plants is inherently less than from competitive LWR power plants because of greater energy-conversion efficiency. When hot water is a product of the HTR Multiplex, thermal pollution is further reduced. If seasonal storage for the hot-water product is available, thermal pollution may be completely eliminated.

7.6 AIR POLLUTION

The industrial process heat needs that can be met with steam (and, perhaps, methane) from the CHP system would otherwise be met by burning fossil fuels. Steam produced from a methanator, with no combustion, causes no air pollution. If replacing fossil-fired heat sources, the result will be reduced air pollution. If satisfying new requirements, emission offset requirements will be avoided — quite possibly making the difference between being able to construct new industrial plants and not being able to do so. In nonattainment air-quality areas where emission offset requirements govern, utilization of CHP chemical energy may provide the requisite offset so that an industrial plant can add facilities whose emissions otherwise would not be permitted.

When hot water for district heating is considered as a product of the HTR Multiplex, a consequence is reduction in air pollution from the fossil-fueled commercial and residential boilers and furnaces which the hot water would displace.

7.7 FUEL EXTENSION, BREEDERS, AND PROLIFERATION

7.7.1 Fuel Cycles

Other General Electric studies (GE-ESTD, 1976 and 1977) discuss nuclear fuel cycles in some detail. Aspects such as fuel utilization, fast breeders using plutonium-239 for fuel, and thermal breeders using uranium-233 for fuel are covered. Some of the key points and conclusions are repeated here because they are important factors in considering development of any new nuclear power system.

7.7.2 Fuel Extension and Breeding

At this stage in the growth of nuclear energy, it seems clear that all new systems should be "fuel extenders" — either high converters or, preferably, breeders. The conversion ratio for gas-cooled reactors can be pushed to nearly 1.0 by using the thorium fuel cycle with high heavy-metal content and limiting the core to low burnup. Studies have indicated that conversion ratios of 1.07 are attainable with more complex fuel element and fuel handling designs.

LWRs currently produce plutonium-239 which ultimately is expected to fuel the fast breeders. With appropriate thorium refueling, LWRs could produce uranium-233 for use in thermal breeders. DOE is supporting a program to develop the thorium cycle as a backup to the LMFBR plutonium cycle through a development of the light-water breeder reactor (LWBR).

The pebble-bed reactor appears to be superior to the LWBR because of intrinsic design features such as proven online refueling and inherent nuclear materials characteristics. The online refueling capability allows more uniform (therefore, more complete) fuel burnup to be achieved, as well as easier conversion to fully remote refueling (required with uranium-233), than do either the LWR or the prismatic-fuel gas-cooled reactor.

7.7.3 Proliferation

Nonproliferation features have become an overriding factor in many fuel cycle decisions in the United States. Moratoria on nuclear fuel reprocessing and use of plutonium have been called for. Design and control procedures for fuel reprocessing centers have been devised to minimize proliferation risks. One scenario postulates that fuel shipped from reprocessing centers to outlying reactors would contain low-enriched uranium (less than 20 percent) either in all-uranium fuel (the so-called "denatured" fuel) or mixed with thorium.

Of the four types of fuel cycles usually considered for gas-cooled reactors, two meet the currently applicable nonproliferation criterion of no reprocessing. Reactors operating on these cycles could conceivably be built anywhere in the world with low-proliferation risk, providing the necessary enrichment services are provided by the U.S. or other nuclear-weapon states, and the spent fuel is put in long-term storage. The two cycles are:

- Low-enriched uranium, once-through. Fissile material, U-235 ($\sim$8 percent). Fertile material, U-238 ($\sim$92 percent).
- Low-enriched uranium/thorium, once-through. Fissile material, U-236 ($\sim$8 percent). Fertile material, U-238 (32 percent), Th (60 percent).

Use of these cycles could be unrestricted if no reprocessing capability were available except at controlled centers introduced before 1990.

7.8 SAFETY

7.8.1 Inherent Safety Features of HTRs

For LOCA situations, the low power density of the HTR and high-temperature capability of graphite result in long time-to-release of fission products: 1000 times greater than LWRs (typically one day versus one minute). The German AVR pebble-bed research reactor operated by Kernforschungsanlage (KFA) since 1966 can be and has been shut down by simply turning off the coolant flow rather than operating the control rods.

The PBR has some additional inherent safety features because of continuous online refueling and fuel element design. The continuous refueling results in low fission product inventory and the spherical fuel elements result in low temperature gradients; hence, low thermal stresses. Based on AVR experience, these features result in very low fission product activity in the primary coolant stream.

7.8.2 Engineered Safety Features

Engineered safety features proposed for HTRs include multiply redundant cooling systems, to remove afterheat from the core during any shutdown and from the core and module liners in normal operation, and auxiliary shutdown systems such as feeding boron carbide spheres into the core to provide backup to the control rods and to the negative reactivity-versus-temperature coefficient of the fuel balls.

For commercial size PBRs, KFA has proposed a fast discharge system (FDS) which would provide walkaway-safe shutdown of the entire plant. The FDS would rapidly remove all fuel from the core if fuel temperatures were to exceed some predetermined safe limit, by allowing the fuel balls to flow downward into a subterranean, water-cooled annulus designed to be inherently safe from a nuclear criticality standpoint and able to contain all afterheat without boiling.

In the event that a pressure vessel experiences an accidental increase of pressure which causes structural failure of the vessel, the mode of failure is important. If fragments of the vessel become missiles, they may damage or destroy the structural integrity of the secondary containment and release radionuclides.

LWR reactor vessels and steam generators are welded steel structures, built, in accordance with Sec. III of the ASME Code governing pressure vessels, to withstand up to about 2000 psi. When such vessels fail catastrophically, they usually fragment into missiles.

The HTR uses a prestressed structure for the reactor vessel which also encloses the steam generator or reformers. Either concrete or cast steel blocks are held in compression by steel tendons (cables). Such vessels cannot fail in a manner which results in missile fragments. This burst protection feature may be considered an important advantage of the HTR over the LWR.

SECTION 8
CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

A large potential U.S. market for the HTR Multiplex exists. This market consists of two segments: (1) Industrial heat for one-shift and two-shift operations and (2) Peaking and mid-range electric power generation. It is estimated that about 300 GW_t will be needed to satisfy these two market segments during the 1995-2010 time period. The HTR Multiplex can satisfy this energy market at costs approximately 50 percent below those of coal-fired FBC systems. This conclusion is essentially independent of the accuracy of the cost input data.

In addition to the market for syngas delivered energy identified above, it is concluded that a significant additional market exists for the HTR Multiplex in base-load electric energy production. This latter market requires about 300 GW_t in the 1995 to 2010 time period according to the estimates shown in Table 6-4. However, this potential base-load electric market is much less certain than the syngas market. It is certainly regionally dependent and may even be site-specific.

In summary, the potential U.S. market for the HTR Multiplex in the 1995 to 2010 time period is at least 300 GW_t and may be as much as three times this size.

8.2 RECOMMENDATIONS

It is recommended that future studies of the HTR Multiplex be concentrated on:

- Selecting a preferred site for the first commercial HTR Multiplex.
- Developing the corresponding criteria and specifications for the total system.

- Outlining a preferred development program through the commercialization phase.

Obviously, these studies will need to analyze in considerable detail items such as: Regional and site-specific electric and heat demands, regulatory requirements, institutional problems, environmental and safety issues, technology development, and even political concerns. A brief outline of this suggested Phase 2 study is given in Section 9.

SECTION 9
PHASE 2 STUDY OUTLINE

TASK 1

Forecast U.S. electric energy markets to at least 2010 providing a range (eg high, nominal, low) of estimates. The forecast should be regional and include items such as load centers, distances, plant types and costs, fuel costs, heat rates, and load-duration curve estimates by plant type.

TASK 2

Develop a detailed forecast of U.S. industrial heat markets with upper and lower bound estimates, load centers, distances, temperature requirements, duty cycles, etc. This forecast should be both analogous to and consistent with the electric energy market forecast.

TASK 3

Select a preferred region for implementation of the first HTR Multiplex and, based on this region, develop system specifications and criteria. These should include, to the extent possible, consideration of factors such as regulatory requirements, environmental concerns, enhanced safety features, decommissioning procedures, and fuel reprocessing-waste disposal techniques.

TASK 4

Synthesize a conceptual design for the HTR Multiplex system based on the criteria developed in Task 3.

TASK 5

Outline an implementation plan leading to commercialization of the HTR Multiplex defined in Task 4. This should consider relevant institutional factors, U.S. energy goals, organizational and management procedures, and technology development schedules. Note that Task 4 and Task 5 must be performed in an iterative manner.

SECTION 10

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