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Very-High-Temperature Reactors for Future Use*

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Abstract

Very-High-Temperature Reactors (VHTRs) show promise for economic generation of electricity and of high-temperature process heat. The key is the development of high-temperature materials which permit gas turbine VHTRs to generate electricity economically, at reactor coolant temperatures which can be used for fossil fuel conversion processes.

KEY WORDS: (Gas Turbine Nuclear Reactors) (Process Heat Nuclear Reactors) (High-Temperature Materials) (Fossil Fuel Conversion Processes) (Nuclear Power) (Inherently Safe Reactors)

1. Introduction

The future potential of very-high-temperature reactors (VHTRs) for process heat applications and also electricity generation has been known for some time, and design concepts of such VHTRs have been developed (ref. 1). VHTRs have generally been considered to apply initially to high-temperature process heat systems, followed by gas turbine units generating electricity. Prior to about 1984, VHTRs were generally identified with high power level units (>1000 MW[th]) utilizing prestressed concrete reactor vessels as the primary containment; these were extensions/modifications of the High-Temperature Gas-Cooled Reactor (HTGR) designs for steam cycle units generating electricity.

The steam cycle HTGRs were developed to provide economic nuclear power in large units (~1160 MW[e]) having high thermal efficiency and fuel conversion ratios in the 0.8 to 0.85 range. High operating temperatures and high thermal efficiencies are achieved by using an all-ceramic core. Initially, HTGRs used graphite moderator impregnated with uranium oxide fuel. In order to reduce the fission product release from the core and limit radioactivity in the coolant circuit, coated particle fuels were developed. The first HTGR coated particles utilized pyrolytic carbon coatings which are effective for fission gas retention but are not impervious to metallic fission product release. Subsequently, silicon carbide coatings were added between two pyrolytic carbon coatings to improve retention of all fission products within the coated particle.

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The emphasis was on reducing the radioactivity of fission products depositing on components (such as steam generators) to reduce maintenance and operating problems. High-quality fuel was not required since a secondary containment building was planned, therefore acceptable fuel contamination fractions in the graphite and defective fuel fractions were in the range of 10^{-2} to 10^{-3}.

Interest in HTGRs decreased after the mid 1970s due to the slowdown in the U.S. economy, the reduced power requirements, and less need for conservation in uranium use. At the same time, the disenchantment with nuclear power (which was highlighted in particular by the Three Mile Island accident, and more recently by the Chernobyl accident) led to increasing requirements relative to the assurance of nuclear safety. As a result, utilities encountered economic difficulties and cash flow problems because of the high cost of building and retrofitting nuclear power plants to meet more stringent safety requirements. The above, along with the increased costs for providing additional power, led utilities to forecast a decrease in the size of future nuclear power plants from a nominal 1000 MW level to 500 MW or less. In addition, and particularly as a result of the Chernobyl accident, increased emphasis was placed on developing systems which have a high degree of inherent safety.

During the above time period, operation of an experimental HTGR reactor in Juelich, Federal Republic of Germany, along with associated development of improved HTGR coated particle fuel, demonstrated that high-quality coated particles having a very low defective fraction as well as a very low fuel contamination level outside the coatings were practical (fractions of about 10^{-5}). The combination of very-high-quality fuel (which retains essentially all fission products at temperatures of 1600 to 1700°C), the need for a relatively low power unit (which permits to relatively low maximum fuel temperatures [~1600°C] under accident conditions), and emphasis on achieving a high degree of inherent safety resulted in the Modular High-Temperature Gas-Cooled Reactor (MHTGR) (ref. 2).

The features of the MHTGR are as follows:

1. The negative temperature coefficient of reactivity inherent in this system assures that the reactor will shut itself down if temperatures in the core exceed normal operating levels. This action is inherent and does not depend upon action by the plant operators or automatic insertion of mechanical control rods or any other plant protection system.

2. The design core power level and core power density are set at levels such that afterheat production cannot cause excessive fuel temperatures even when only passive cooling systems are in use. In addition to the normal systems for cooling the reactor core, the present MHTGR design has a passive natural-circulation "chimney" built into the design to remove heat from the pressure vessel wall. This "chimney" provides adequate cooling for the core even if the helium coolant were lost from the reactor system and the normal cooling systems failed. Further, even if the natural circulation heat removal system were lost, the design is configured so that conduction of heat to the surrounding earth would provide an ultimate, inherent cooling path sufficient to cool the reactor core and protect the public from the release of fission products.

3. The high degree of inherent safety of the MHTGR nuclear island permits the balance-of-plant (BOP) to be built to conventional fossil fuel plant standards, cutting down on the unit cost of construction. By far the largest cost of present nuclear power plants is associated with the BOP, and this cost is high because much of the BOP has to be built to nuclear quality assurance standards. With the above MHTGR features, the unit BOP costs for

MHTGRs can be reduced, compensating for increases due to power-level economic-scaling factors. Factory production of the relatively small components for many MHTGRs also permits mass-production economics to apply.

Overall, the above features result in an MHTGR of low unit power level (140 MW[e]) which can be utilized in plants containing several units (or modules) to accommodate power generation needs, and which utilizes natural phenomena and inherent safety features to retain fission products within the reactor system under postulated events which have extremely low probabilities of occurring. Fig. 1 gives a schematic of the primary system of an MHTGR, indicating the various component features. Fig. 2 shows how several MHTGR units or modules can be arranged in a plant to produce the desired total power output.

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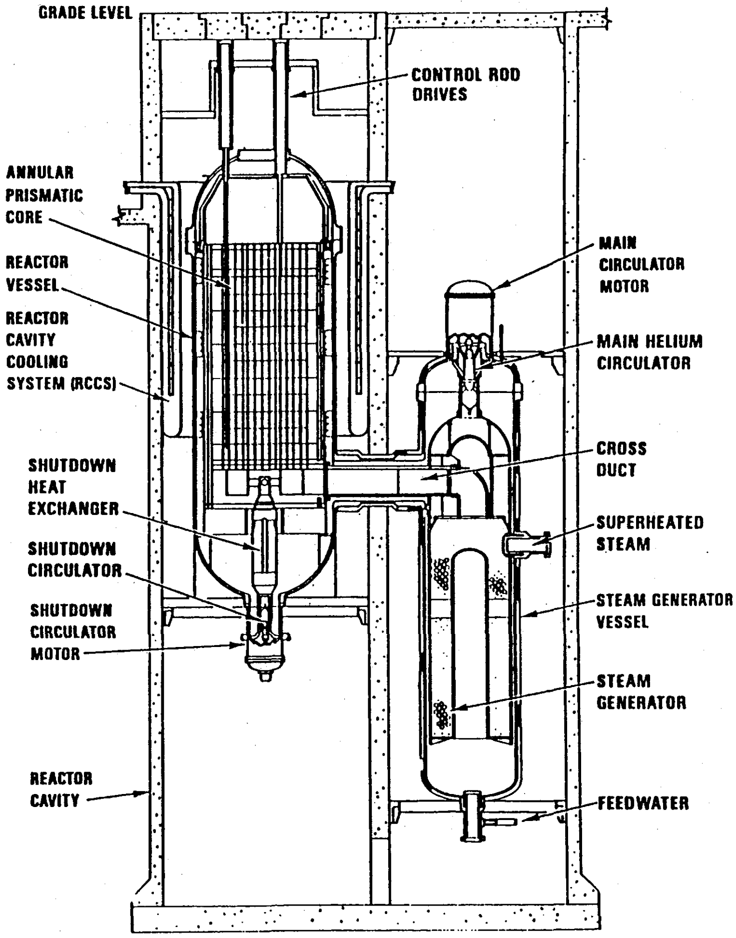

Fig. 1 350 MW(th) modular HTGR unit

The development of MHTGRs gives new meaning to the potential of VHTRs. Modular concepts of relatively low power per unit are particularly appropriate for early application of VHTRs to both electricity generation and to high-temperature process heat applications. For example, gas turbines are more readily developed for low power than for high-power units, and the market for high-temperature process heat applications will be initially small and distributed. In addition, the high inherent safety of modular units permits VHTRs to be sited close to their application, improving economic performance. Modular units also permit high plant availability to be attained. Consequently, modular systems are advantageous for VHTRs.

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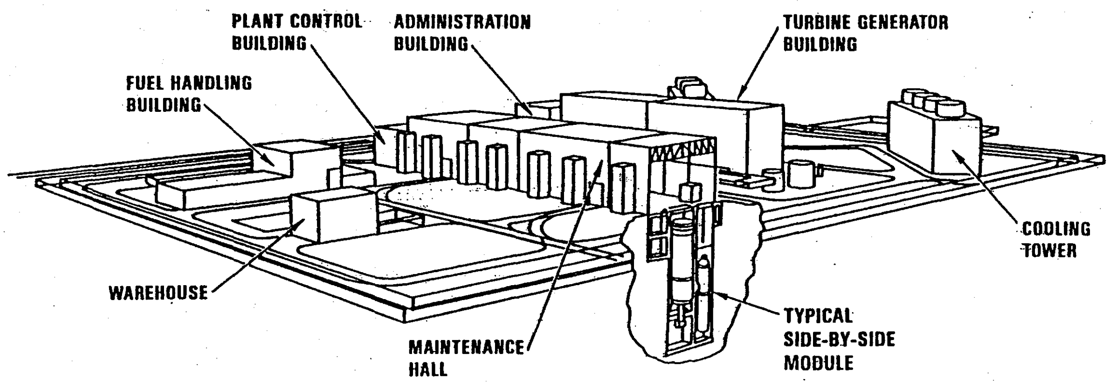

Fig. 2 Modular HTGR plant (4-units)

2. The Role of Very-High-Temperature Reactors

It is generally recognized that there are limited world resources of petroleum and natural gas such that based on projected world population growth and projected per capita energy use, oil and gas will provide only a relatively short-term energy source for generating large amounts of power. While oil and gas will be available to a limited extent for a long time, the cost of such fuels will increase so that large-scale economical use will probably be limited in several decades. It is also generally recognized there are large quantities of coal resources, such that coal could provide world energy requirements for several centuries. The growing use of coal as an energy resource can lead to significant increases of CO_2 and other contaminants in the atmosphere; such increases could lead to undesirable climatic changes in the world's environment (ref. 3). Nuclear energy and solar energy, however, are energy sources which are environmentally benign. Solar energy, because of its dilute nature, will be difficult to harvest economically in large quantities for electricity production. Nuclear power, on the other hand, is publicly perceived as having safety and waste disposal problems, even though those risks are very low compared with risks society generally accepts. The perceived safety problems have led to uncertainty in licensing and operating requirements for nuclear plants, resulting in economic uncertainties.

The MHTGR has inherent safety features unprecedented in power reactor design, and could provide the means for acceptance of nuclear power on a wide-scale basis. In the longer term there will be a need to convert coal to methane, methanol, or synthesis gas to provide a long-term hydrocarbon source for transportation and chemicals. If nuclear energy were used in the coal conversion process, much less CO_2 would be generated than if coal were used for providing process energy. Independent of CO_2 generation, nuclear energy has the potential of making coal conversion processes more economic. Process Heat (PH) VHTRs can provide the energy for coal conversion processes. One such process is the hydrogenation of coal, with the hydrogen being produced by steam reforming of the methane produced in coal hydrogenation. A schematic of a PH-VHTR used for the steam reforming of methane is shown in Fig. 3; in this illustration, an indirect cycle is indicated, with the intermediate heat exchanger being used to transfer energy to a reformer.

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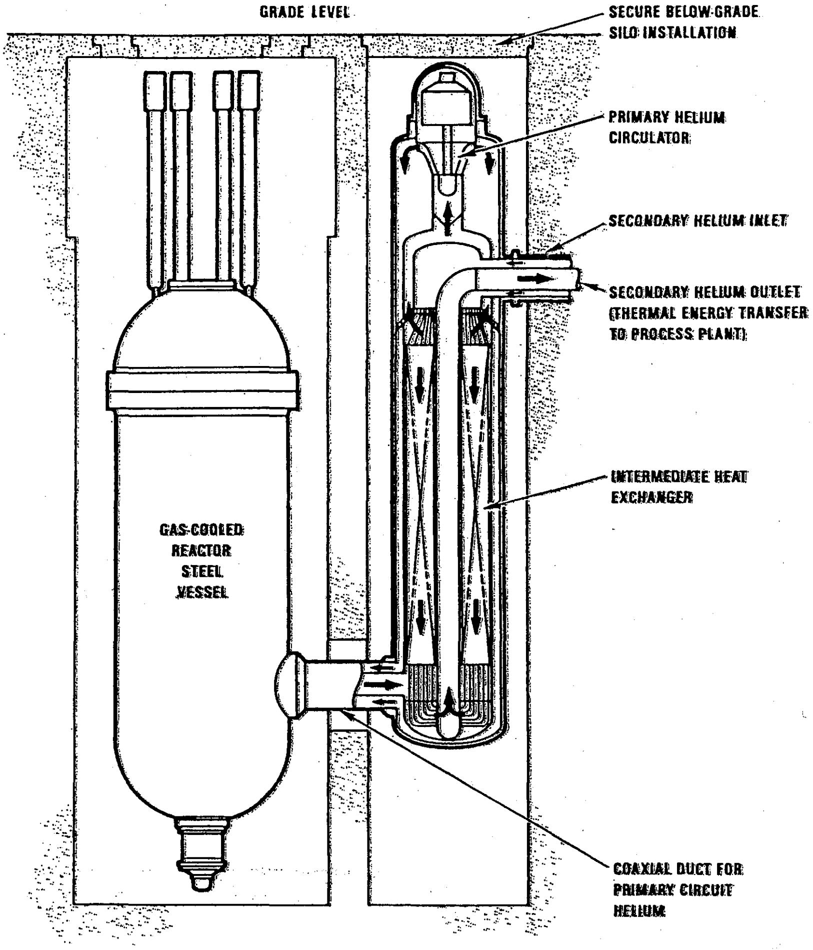

Fig. 3 Process heat very-high-temperature reactor (PH-VHTR) plant concept

The phase-in of high-temperature processes for converting coal to convenience fuels will be gradual, and it is estimated that the amount of energy for obtaining 5 million barrels of oil equivalent per day from coal would require ~150 GW(th) (refs. 4 and 5). Eventually, as coal becomes the dominant source of hydrocarbons, the high-temperature process heat market will become much larger, and control of the CO_2 source term will become more important.

In summary, the following conditions relating to energy use appear on the horizon: (1) decreased ability to rely on oil and natural gas; (2) increased use of coal; (3) increased emphasis on technology to convert coal to forms useful in the transportation sector; (4) increased use of coal conversion processes to produce synthesis gas; and (5) increased emphasis on development of environmentally benign energy sources for use in the industrial sector. Nuclear process heat has a large potential role to play in the above changes in energy use practice. In order for that role to be applied, low-cost process heat energy has to be produced, as discussed below.

3. Strategy for VHTR Implementation

In order for modular VHTRs to generate low-cost high-temperature process heat, these plants will also need to generate electricity. This is possible with Gas Turbine (GT) VHTRs. Gas turbines can efficiently use the temperatures associated with high-temperature processes and generate electricity at high thermal efficiency. The market for electricity is much larger than for high-temperature process heat, particularly during the early stages of VHTR application. Developing GT-VHTRs at an early date results in a unit which can be applied to a present market. A schematic of a GT-VHTR is illustrated in Fig. 4; as shown, it is similar in concept to the MHTGR. The efficiency of the GT-VHTR increases as the gas turbine inlet temperature increases, and permits a GT-VHTR to produce very-high-temperature coolant which can also be used for process heat applications; a plant can then have a number of modules with GT-VHTRs and PH-VHTRs working in tandem. Economics would be further improved if GT-VHTRs could operate at such temperatures that the exit gas from the gas turbine could be used for process heat, reducing the cost of process energy to very low levels. As outlined above, the key to economic application of nuclear process heat is to first develop the GT-VHTR for electricity production; the PH-VHTR would be a subsequent application.

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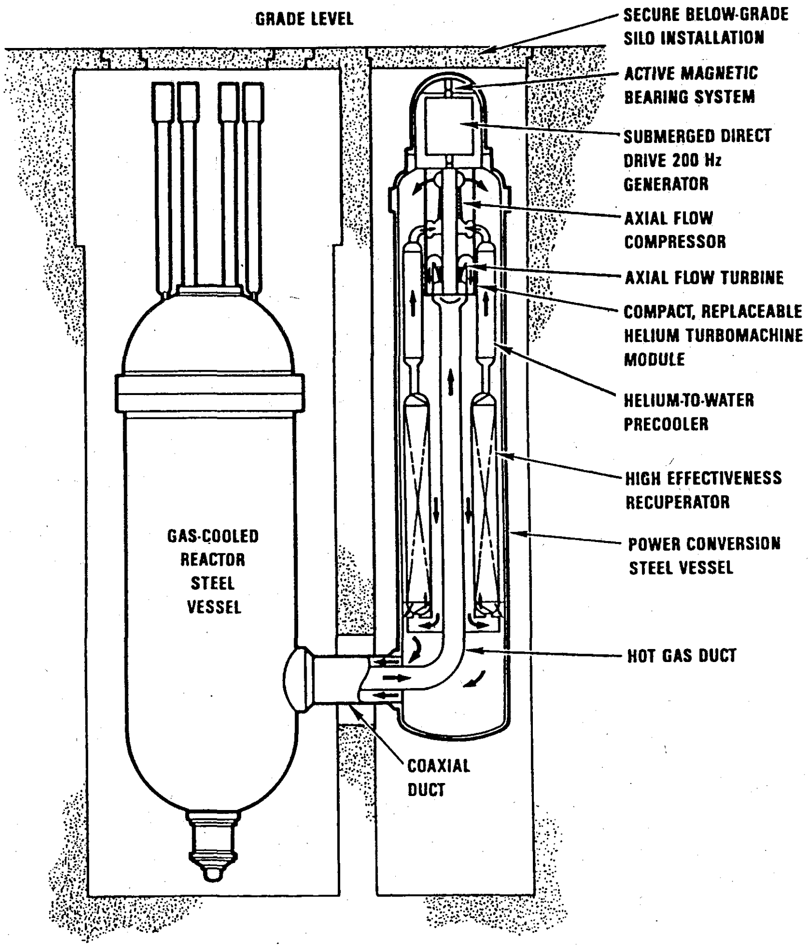

Fig. 4 Gas turbine very-high-temperature reactor (GT-VHTR) plant concept

Based on the above, the deployment strategy for VHTRs would be that shown in Fig. 5. Present-day MHTGRs would be used for electricity generation using the steam cycle; such units would continue to be built in accordance with market need. The development of GT-VHTRs would follow, with increasing efficiencies being obtained with increasing time as VHTR outlet gas temperatures increased. PH-VHTRs would follow GT-VHTRs in time, with increasing application as process heat costs are decreased.

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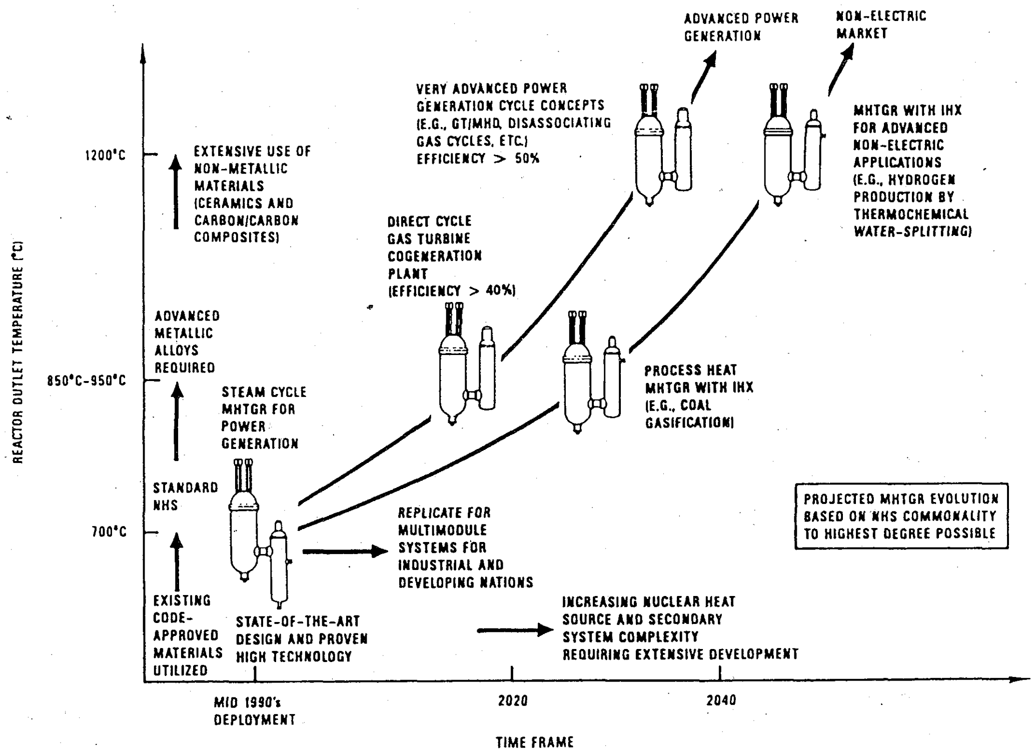

Fig. 5 MHTGR/VHTR deployment strategy

4. Technology Advances Required for VHTR Application

The key to the successful development of VHTRs is the development of high-temperature materials which can be utilized in efficient gas turbines and in high-temperature processes. VHTR reactor core materials also have to operate at the higher operating temperatures required for gas-turbine and process-heat systems. In general, such temperatures require an extension of materials technology beyond that which is presently available for steam cycle MHTGRs. Material technology advancements needed to produce VHTR coolant outlet temperatures of ~850°C are generally those associated with materials external to the core itself (850°C average outlet temperature is a lower limit for which gas turbines and the steam reforming of methane might be practical). At the same time, "hot streaking" within the outlet coolant gas will lead to peak metal temperatures of about 900°C for an average outlet gas temperature of 850°C. Emphasis should be on validating the long-term mechanical properties of materials such as Inconel 617 and Hastelloy XR (and their modifications), with determination of their practicality in VHTR systems as a function of temperature. These materials, and others, should be usable for peak temperatures up to ~900°C.

In order to increase VHTR applications, coolant gas temperatures of 950°C and above appear to be required. Materials technology requirements increase significantly at such temperatures. A brief summary of the kinds of material developments which appear needed is given below for various areas.

4.1 Fuel

Fuel in the steam cycle MHTGR is exposed to peak operating temperatures of about 1300°C under normal operation, with average temperatures being about 800°C. Accident scenarios for the MHTGR will cause fuel to rise to ~1600°C, which is still acceptable for primary retention of fission products within the fuel particles. At higher temperatures (>~1800°C), silicon carbide (a key coating material) will deteriorate significantly after relatively long periods of time. Increasing the outlet gas temperature of VHTRs will tend to cause the fuel temperature to increase for the same average core power density, and it may become important to develop improved fuel coatings. Development of an advanced coating design with zirconium carbide replacing the silicon carbide appears advantageous, and could permit VHTR core power densities to be maintained at present MHTGR design levels while retaining the capability of acceptable fission product retention.

4.2 Graphite

The bulk of graphite testing has focused on material properties at temperatures and neutron exposures characteristic of an HTGR having a 750°C outlet temperature. Present information indicates that the performance of the core support and side reflector graphites are adequate for VHTR applications. For core graphite, testing needs to be extended to provide information on irradiation creep behavior and oxidation at the higher temperatures associated with VHTRs.

4.3 Fission Product Behavior

As the core temperature increases in VHTRs, the fission product behavior models already in use for MHTGRs need to be updated for the higher operating temperature conditions. Additional experimentation will be required to provide data for model validation, including tests involving the advanced structural materials required for high operating temperatures. Deposition and reentrainment characteristics of fission products on surfaces will be needed for normal operations and for depressurization conditions, respectively.

4.4 Structural Materials for Components

Extensive testing will be required to develop and qualify structural materials for use in VHTR applications. Long-term (greater than 50,000 h) tests are required to quantify creep behavior, corrosion behavior, and mechanical property behavior, as well as failure criteria. Components for which material development will be required include gas turbines, hot duct material, insulation, reformers, steam generators, recuperators, heat exchangers, and circulators; environments include VHTR helium compositions, synthesis gas, and coal gasification compositions.

In the 850 - 900°C range, validation work needs to be carried out to assure that materials such as Inconel 617, Hastelloy XR, or other near-commercial materials can indeed operate economically, and that components manufactured out of such materials are reliable. As the temperature of VHTR operation increases to 900 - 950°C, other new alloys require development. Possible alloys may involve aluminides (refs. 6 and 7) which are very strong and oxidation resistant at elevated temperatures. By adding selected "contaminant" materials such as boron and by adjusting the nickel aluminide composition to be near-stoichiometric leads to a ductile material which retains its strength. In developing such an alloy or others, extensive study is needed of alloying behavior, surface and solid state reactions, metal processing factors, materials compatibility, welding and joining technology, physical properties, radiation effects, tensile ductilities, creep resistance, and cold-working capability, as well as long-term behavior under various conditions.

To attain the very high temperatures (>1000°C) that will be needed for VHTRs in the future may require the development of advanced metal matrix composites and advanced structural ceramics which incorporate ceramic fibers, whiskers, and/or particulates to produce composites with improved properties which are fracture resistance, have high strength and high temperature stability, and which provide a combination of excellent mechanical properties, wear resistance, hardness, stiffness, and heat and corrosion resistance. This has to be done in the face of present knowledge that ceramics are notorious for their brittleness and sensitivity to microscopic flaws such as cracks, voids, and impurity inclusions. Further, the methods of fabrication have to be such that the overall process is economical, and the product has to have a consistent level of quality.

5. Conclusions

Very-High-Temperature Reactors (VHTRs) are logical future energy systems which follow from the Modular High-Temperature Gas-Cooled Reactors (MHTGRs) presently being designed and developed for electrical power plants. By operating them at higher outlet gas temperatures, MHTGRs become VHTRs. The key to the application of nuclear process heat will be the ability to generate low-cost energy. Under such circumstances, nuclear process heat can displace fossil fuels as an energy source and contribute to the long-term goals of a cleaner environment and the preservation of fossil fuels for specialty applications such as transportation fuels and chemicals. Beneficial applications are foreseen in the area of coal liquefaction, gasification, and chemicals production. The design temperature of coolant gas exiting present MHTGRs is about 700°C; the outlet gas temperatures of VHTRs need to be at least 850°C, with desirable values being 950 to 1000°C. In the longer term, outlet temperatures of 1100 to 1200°C and higher should be the goal. Initial use of VHTRs would be as electricity producers, using helium gas-turbine units based on the Brayton power cycle. VHTRs would also be used for high-temperature process heat applications such as the steam reforming of methane in the near term and the gasification of coal (either by hydrogenation or by steam gasification) in the longer term. The above applications permit nuclear energy to be used for generating synthesis gas (hydrogen and carbon monoxide) by reacting carbon with steam. In the very long term, VHTRs could be used for the direct thermochemical splitting of water; such application could be important if a hydrogen-based energy economy were developed.

Low-cost energy generation is facilitated by generating electrical energy with Gas-Turbine VHTRs (GT-VHTRs) utilizing the same outlet gas temperature as Process-Heat VHTRs (PH-VHTRs). As a result, GT-VHTRs can work in tandem with PH-VHTRs. Further, the higher the temperature of coolant gas to the turbine, the higher the thermal efficiency for electricity production, tending to reduce the unit cost of energy and extending the process heat market. The modular nature of VHTRs permits process heat plants to have high availabilities when used in tandem with gas turbine plants. The large market for electricity generation permits VHTR plants to consist of many modules and be economic, while supplying the initial needs of the process heat industry. The key technology needs for both GT-VHTRs and PH-VHTRs concern the development of economical materials for use in components operating at very high temperatures. Relative to components external to the core, operating temperatures of 850 to 900°C should be a near-term goal (~10 years), of 950 to 1000°C an intermediate-term goal (~25 years), and of 1100 to 1200°C and higher a long-term goal (~50 years). High-temperature components include fuel and graphite elements, gas turbines, recuperators, reformers, heat exchangers, hot ducts, circulators, and insulation. Environments include VHTR-helium, synthesis-gas, and coal-gasification compositions. Components need to be long lived and economic, and operate reliably under pressure and thermal transient conditions. Successful VHTR development provides a means for wider application of nuclear energy to the benefit of mankind.

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