

ROUTING SLIP

TO Lcdr. Adams.

- | | |
|---|---|
| <input type="checkbox"/> PER OUR CONVERSATION | <input type="checkbox"/> PER YOUR REQUEST |
| <input type="checkbox"/> FOR YOUR INFORMATION | <input type="checkbox"/> FOR HANDLING |
| <input type="checkbox"/> FOR YOUR APPROVAL | <input type="checkbox"/> FOR CIRCULATION |
| <input type="checkbox"/> FOR YOUR SIGNATURE | <input type="checkbox"/> FOR YOUR FILE |
| <input type="checkbox"/> FOR YOUR COMMENTS | <input type="checkbox"/> PLEASE SEE ME |
| <input type="checkbox"/> PASS TO: | <input type="checkbox"/> PLEASE RETURN |

- I share your views.
- After publication of this paper I had a personal letter of reprimand from Adm. McKeel of Naval Propulsion - - - even suggesting an alternative to the PWR is not acceptable.
- I wish you well, but with the above mindset, you may well be wasting your time!

Regards.

Colin H. [Signature]

DATE

1/30/92



The Society shall not be responsible for statements or opinions advanced in papers or in discussion at meetings of the Society or of its Divisions or Sections, or printed in its publications. Discussion is printed only if the paper is published in an ASME Journal. Papers are available from ASME for fifteen months after the meeting.
Printed in USA.

Closed-Cycle Gas Turbine Potential for Submarine Propulsion

COLIN F. McDONALD
GA Technologies Inc.
San Diego, California 92138

ABSTRACT

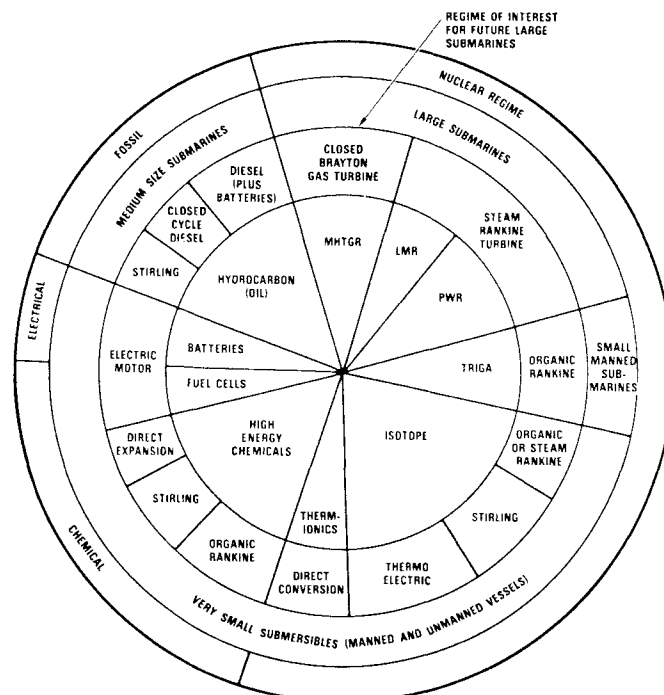
Based on existing technology it is projected that the coupling of a helium closed-cycle gas turbine (CCGT) with a High-Temperature Gas-Cooled Reactor (HTGR) for marine propulsion could realize a power plant specific weight of around 12 kg/kW(e) (20 lb/hp). New and emerging technologies would offer even further performance advantages for future submarines that would see service in the early decades of the 21st century. This paper includes the "enabling technologies" for advanced submarine propulsion, which include the following: (1) high-quality fuel and small passively safe reactor; (2) high-performance turbomachinery embodying magnetic bearings; (3) compact heat exchangers; (4) advanced high-temperature composite materials; (5) computer-controlled automated engine room; (6) compact high-efficiency superconducting generator, motor, and energy storage system; and (7) the possibility of a propellerless electromagnetic thruster. It is projected that the coupling of a gas-cooled reactor with a helium gas turbine could offer substantial performance improvement and weight reduction potential over variants studied heretofore.

1. INTRODUCTION

The focus in this paper is on the utilization of an advanced power conversion system to meet the projected requirements for submarines that would see service in the early decades of the 21st century. The author is intimately familiar with both the HTGR and CCGT systems and, for submarine technology, has taken advantage of only technical material that is readily obtainable in the open literature, the foremost sources (1-6) being well-known to those in the field. The choice of energy sources includes fossil, electrical, chemical, and nuclear. A simple portrayal of prime-mover options is shown in Fig. 1. Systems involving small power levels have been addressed previously (7-12) and are not covered in this paper.

On January 17, 1955, the USS Nautilus made her historic signal "under way on nuclear power," and a new era was born. In the over three decades since then, the power requirements for large submarines have been

satisfied by the pressurized water reactor (PWR) coupled with a Rankine steam turbine system. Such power plants have operated very successfully, demonstrated high levels of safety and reliability, and are projected to be utilized in the foreseeable future.



NOTE: PIE DIAGRAM IS ILLUSTRATIVE ONLY, PROPORTIONS ARE NOT NECESSARILY REPRESENTATIVE.
1-326(6)

Fig. 1. Energy source - prime mover alternatives for submersible systems

In projecting requirements for 20, 30, or even 40 years ahead the reactor options are foreseen to be limited to (1) continued use of the PWR, (2) advanced

HTGR, or (3) liquid metal-cooled system. This paper highlights the merits of the gas-cooled reactor for future submarine propulsion.

Both the HTGR (13,14) and the CCGT (15,16) are well-known and understood, and as will be discussed in following sections, extensive studies have been performed of their coupling for terrestrial power systems. Reportedly (4), a lightweight fast-neutron nuclear gas turbine was proposed for the 1957-1958 U.S. Skate class submarine, but a conventional PWR was finally selected based on lack of technology readiness and extended time for development of the gas-cooled reactor plant. Today, three decades later, the situation is quite different, since gas-cooled reactors have operated for many millions of hours in commercial power stations, and CCGTs (fossil-fired) in Europe have accumulated about a million hours of service life.

The primary motivation for this paper is to put forward the idea that the nuclear gas turbine may well be an attractive submarine propulsion system of the future. Base technologies for both the reactor and gas turbine are well-established, (sufficient to support a near-team project) and substantial performance potential and propulsion system size and weight reduction could be realized with the adoption of new and emerging technologies.

2. NUCLEAR MARINE PROPULSION BACKGROUND

Marine propulsion systems for both military and merchant marine applications underwent a significant transition early in this century with a change from coal to oil firing. The various prime movers, including steam turbines, diesel engines, and more recently, gas turbines have been thoroughly documented (17). From the mid-1940s on, the merits of nuclear propulsion have been recognized, particularly for submarines, and a decade of intense development led to the USS Nautilus entering service. To date primary emphasis has been placed on development of the PWR for submarine propulsion.

Merchant vessels utilizing the PWR and steam turbine power conversion systems were constructed and operated by the United States, USSR, Japan, and Germany. The early promise of operating cost savings was not realized, since merchant ship economics are sensitive to the price of oil fuel. In addition, limited harbor access on the major world trade routes hampered their logistics. With the exception of icebreakers, the first generation of nuclear-powered merchant ships were not successful.

While the PWR is the dominant marine reactor type, limited studies were conducted in the late 1950s, using gas-cooled reactors, but with steam turbines they showed no significant advantage (18-20). Around 1960 an extensive program of design and development was undertaken for a (20,000 hp) power plant based on a compact high-temperature gas-cooled reactor and closed-cycle gas turbine (21,22). The program involved a cooperative effort between the Maritime Administration and the U.S. Atomic Energy Commission to establish a power plant for an oil tanker. Substantial development work was done, particularly on the helium turbomachinery, but the program was eventually discontinued, based on two factors: (1) questionable economics, again affected by very low oil price; and (2) lack of a strong technology base for this type of reactor and prime mover. Perhaps one of the most important findings from this program was that the compactness of the system (reactor and prime mover) showed a savings of more than one-third in space compared with a PWR (23). This advantage was based on technology of the late 1950s and an even greater reduction in size can be projected based on today's technology.

With successful demonstration of the initial HTGR plants (i.e., Dragon, Peach Bottom 1, and AVR) and a seemingly established market for large commercial HTGR plants, there was some renewed interest in the 1970s in nuclear gas turbines. The studies led to the conclusion that for large machines a considerable development effort was necessary, and that it should be classed as a long-term advanced technology HTGR option (24). In the same time frame, many studies were performed on CCGTs for marine propulsion (25-34). This latter reference, while not performed for submarine propulsion, but rather for a surface effects ship, bears relevance since it indicated in studies performed in 1975 that the nuclear gas turbine had the potential for a specific weight (reactor, shielding, and power conversion machinery) of less than 9 Kg/Kwe (15 lb/hp). With the hiatus in gas-cooled reactor deployment, and indeed in all new nuclear plants since the mid-1970s, the CCGT-related studies have essentially laid dormant.

The Modular HTGR (MHTGR), with its inherently passive safety characteristics, has rekindled interest in gas-cooled reactors. Work is currently focused on a steam cycle MHTGR for electrical power generation (35). This plant could be deployed in the near term (i.e., mid-1990s) and can be regarded as state-of-the-art in terms of design, technology, and utilization of code-approved materials (36). Simply stated, there is not a major need for further fundamental research and development.

With gas-cooled reactor technology well established following the operation of five HTGRs (37) and current worldwide interest focused on much smaller plants [90 to 140 MW(e) module rating], it is felt opportune to revisit the nuclear gas turbine for marine propulsion, again recognizing that this plant must be viewed as an advanced variant, which has the capability to exploit the very-high-temperature capability of the MHTGR (38).

For naval application, there will always be a mix of power plants to meet specific requirements. To obviate fuel logistic problems, large strategic vessels such as aircraft carriers and cruisers are well-suited to nuclear power. For smaller vessels (e.g., destroyers), it is likely that advanced fuel-efficient oil-burning gas turbines, based on a regenerative and intercooled cycle, will be utilized in the future (39,40).

3. SUBMARINE PROPULSION SYSTEM REQUIREMENTS

Propulsion requirements are very dependent on the submarine type and mission, and in particular, whether the submarine is in the attack class or used as a platform for ballistic missiles. In this paper, only generic requirements are discussed, since an actual design concept is not being addressed. Since the power conversion system is fully integrated in the hull, the system as a whole must be considered in submarine design (41). Existing PWR propulsion systems are well-understood (42-51), and many of their requirements will be retained, but new requirements will be introduced to ensure that submarines in the 21st century will remain combative. The major generic requirements as highlighted on Table 1 fall into the category of the "four S's," namely: safety, speed, stealth, and strategy. A fifth "S" (surprise) could be added, and it is this one that may well be dominant in ensuring combat success.

4. CLOSED BRAYTON CYCLE PERFORMANCE

The basic thermodynamic cycle is shown in Fig. 2. There are many variants of this that involve intercooling between the compressor stages and reheat between

the turbines. The simplest variant based on utilization of a recuperative heat exchanger was selected for this application, since it yields an acceptable efficiency and minimizes the amount of equipment required in the engine room.

TABLE 1
GENERIC REQUIREMENTS FOR SUBMARINE PROPULSION SYSTEM

SAFETY	<ul style="list-style-type: none"> • PASSIVE REACTOR SYSTEM GIVING INHERENT SAFETY • ISOLATABLE REACTOR SYSTEM • CLEAN CIRCUIT • LOW EXPOSURE TO CREW • STABLE, SINGLE-PHASE WORKING FLUIDS • SECURE IN EVENT OF FLOODING/SINKING • USE OF DEMONSTRATED AND PROVEN TECHNOLOGY • MINIMUM SYSTEM PRESSURE • ABILITY TO WITHSTAND HIGH SHOCK LOADING • RUGGED CONSTRUCTION TO WITHSTAND BATTLE DAMAGE • LOW RAD WASTE FOR DISPOSAL
SPEED	<ul style="list-style-type: none"> • COMPACT SYSTEM WITH LOW SPECIFIC WEIGHT, Kg/kW^(a) • HIGH HEAT-TO-POWER CONVERSION EFFICIENCY • GOOD PART POWER EFFICIENCY • RESPONSIVE TO RAPID LOAD CHANGE • PERFORMANCE POTENTIAL GROWTH • USE OF PROVEN TECHNOLOGY
STEALTH	<ul style="list-style-type: none"> • LOW NOISE LEVEL WITH MAGNETICALLY SUSPENDED TURBOMACHINE ROTOR • NO GEARBOX OR MECHANICAL DRIVE TRAIN • LOW THERMAL SIGNATURE (SENSIBLE AS OPPOSED TO LATENT HEAT REJECTION FROM POWER CYCLE) • PASSIVE AUXILIARY POWER (ELECTROMAGNETIC THRUSTER FOR SILENT RUNNING)
STRATEGIC (SIMPLICITY, CONSTRUCTION, OPERATIONS, ECONOMICS)	<ul style="list-style-type: none"> • SYSTEM FULLY INTEGRATED IN HULL • MINIMUM AMOUNT OF EQUIPMENT • LIFE OF AT LEAST 30 YEARS • LONG FUEL CYCLE (ONE REFUELING IN LIFE OF SUBMARINE) • HIGHLY AUTOMATED (MINIMUM CREW) • HIGH RELIABILITY • MAINTENANCE CAPABILITY • PROVISION REDUNDANCY IN POWER CONVERSION SYSTEM • SYSTEM BE OPERATIONAL DURING ATTITUDE CHANGE (SHOULD NOT DICTATE VESSEL ANGLE LIMITATIONS) • COST-EFFECTIVE SYSTEM

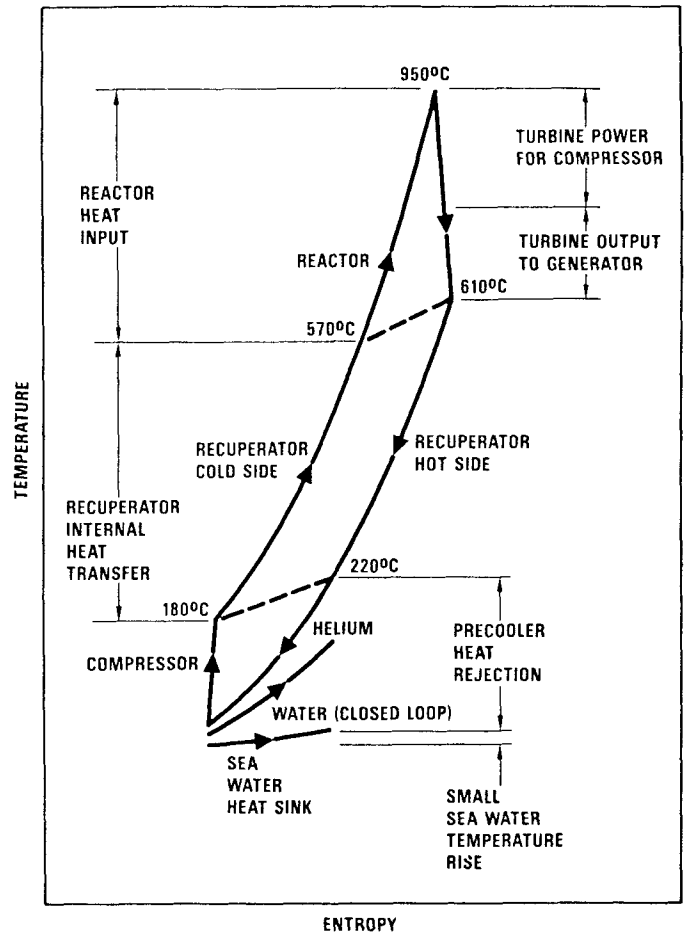
(a) TARGET VALUE FOR PROPOSED STUDY WOULD BE ON THE ORDER OF 9-12 Kg/kW^(a) (15-20 LB/HP) FOR THE COMPLETE POWER PLANT.

I-326(11)

The recuperator is a key component for achieving high cycle efficiency as well as a major contributor to the flexibility of design. Reactor thermal energy is used to heat the high-pressure gaseous working fluid to the maximum cycle temperature. The high-pressure gas is expanded through the turbine to produce useful shaft power and drive the compressor. The turbine discharge gas is cooled, first in the recuperator and then in the precooler before entering the compressor. The low-pressure gas is compressed to the highest cycle pressure in the compressor prior to being heated in the recuperator and thence entering the reactor, completing the closed loop.

The direct Brayton cycle utilizes the same single-phase gaseous working fluid for cooling the reactor and producing power in the prime mover. The choice of gas (and, in particular, its molecular weight) has a strong influence on the system design, and extensive studies have evaluated helium, neon, krypton, helium-xenon, nitrogen, and argon. The most recent study (52) confirms that for multimegawatt terrestrial machines, helium offers an attractive solution, since the system is very heat-transfer intensive. This selection is compatible with the use of proven HTGR technology, although it is recognized that additional power plant weight savings for nonterrestrial applications may be realized with higher molecular weight gas mixtures.

Closed-cycle gas turbine optimization procedures are well-understood (53), and while many parameters



I-326(5)

Fig. 2. Thermodynamic cycle for recuperated helium CCGT

influence the cycle efficiency, the two major ones are turbine inlet temperature and recuperator effectiveness. A representative performance array for the direct Brayton cycle is shown on Fig. 3. In developing this performance array (54), the component efficiency values used reflect advancements which are projected in coming decades, and these are discussed in the section covering enabling technologies. Since CCGT performance potential is one of the major themes of this paper, Fig. 3 represents one of the focal points. Since some of the assumptions necessary to develop this array are design/layout-related (e.g., system pressure loss, bypass leakages, cooling flows, etc.), the efficiency levels must be regarded as somewhat optimistic.

Three operating regimes are identified in Fig. 3 and, as shown on Table 2, these reflect differing technology status. The lowest efficiency regime is based on what could be possible in the near term, particularly as regards reactor technology, since it is based on a core outlet temperature of 785°C (1445°F) as demonstrated in the FSV plant which utilizes prismatic fuel elements. Two cycle efficiency levels are identified on Table 2; namely, an optimistic value of 38% and a more conservative 33%, assuming a reduction of five percentage points from the optimistic estimate. Based on the selection of two reactor cores rated at 75 MW(t) each (this value was selected for illustrative purposes and will be discussed in the following section), the power output range (for the above spread in efficiency)

can be rounded off to say 50,000 to 60,000 hp. The assumed on-vessel power load of 10 MW(e) is arbitrary, but it recognizes that considerable power is needed for vessel operation, weapons systems, the electrolyzers and chemical air scrubbers that provide oxygen and remove carbon dioxide, and the air conditioning system.

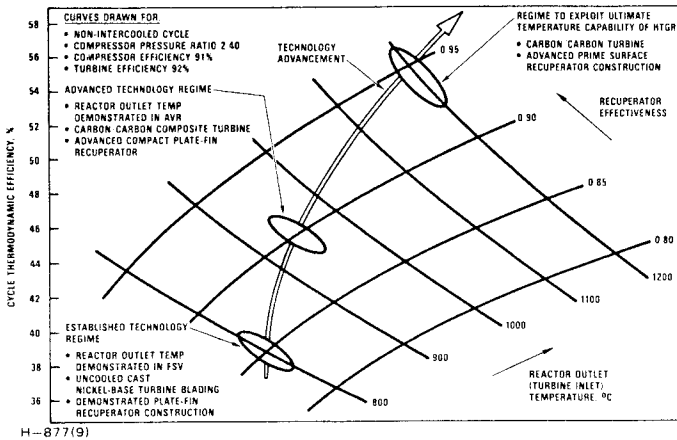


Fig. 3. Performance array for direct cycle nuclear gas turbine plant

The advanced technology regime reflects a reactor outlet temperature of 950°C (1742°F) as demonstrated in the German AVR reactor, which has a pebble bed core. Based on the same rationalization as mentioned above, the efficiency spread is 40% to 45%, and the power output range can be rounded off to say 70,000 to 80,000 hp.

TABLE 2
NUCLEAR GAS TURBINE PERFORMANCE

TECHNOLOGY STATUS	POSSIBLE NEAR-TERM		ADVANCED	
REACTOR OUTLET TEMP, °C (°F)	785 (1445)		950 (1742)	
TEMPERATURE BASIS	DEMONSTRATED IN FSV		DEMONSTRATED IN AVR	
TURBINE BLADE MATERIAL	UNCOOLED CAST NICKEL-BASE ALLOY		COOLED NICKEL-BASE ALLOY OR CARBON-CARBON COMPOSITE	
HOT GAS DUCTS	METALLIC		CARBON-CARBON	
ISOLATION VALVE TECHNOLOGY	PEACH BOTTOM 1 HTGR		VALVE DEVELOPMENT IN SUPPORT OF PROCESS HEAT HTR	
RECUPERATOR TECHNOLOGY	EXISTING PLATE-FIN TYPE (EFFECTIVENESS 0.85)		ADVANCED COMPACT PLATE-FIN (EFFECTIVENESS 0.90)	
PRECOOLER TECHNOLOGY	SPIRALLY FLUTED TUBE		ADVANCED ENHANCED SURFACE	
REACTOR THERMAL RATING, MW(t)	75(a)		75(a)	
NUMBER OF REACTORS	2(a)		2(a)	
TOTAL THERMAL RATING, MW(t)	150		150	
CYCLE EFFICIENCY BASIS		OPTIMISTIC LESS FIVE PERCENTAGE POINTS		OPTIMISTIC LESS FIVE PERCENTAGE POINTS
	OPTIMISTIC		OPTIMISTIC	
CYCLE EFFICIENCY, % ^(b)	38	33	45	40
TOTAL POWER RATING, MW(e)	57	49.5	67.5	60
ASSUMED VESSEL POWER, MW(e) ^(c)	10	10	10	10
POWER OUTPUT, MW(e)	47	39.5	57.5	50
SHAFT POWER, HP	63,000	53,000	77,000	67,000

(a) ASSUMED FOR ILLUSTRATIVE PURPOSES ONLY

(b) CYCLE THERMODYNAMIC EFFICIENCY ESTIMATES FROM FIGURE 3.

(c) ARBITRARY VALUE RECOGNIZING THE NEED FOR CONSIDERABLE ON-BOARD POWER.

1-326(10)

The upper regime represents what can perhaps be described as the ultimate potential of the HTGR if a reactor outlet temperature of 1200°C (2192°F) could be realized (55). Formidable technology advancements in many areas would be necessary to give efficiency values in the mid-50s, and they are considered beyond the scope of this paper. It should be pointed out that the lowest value of efficiency given in Table 2 for the nuclear gas turbine is significantly higher than the mid-20s value generally attributable to the PWR with a low-temperature steam Rankine system.

The thermodynamic cycle of Fig. 2 illustrates two factors particularly germane to submarine propulsion. At the turbine exhaust in the CCGT cycle, the working fluid pressure is typically two orders of magnitude higher than that for a steam turbine. Although the maximum cycle pressures are comparable, the gas turbine optimally operates at small expansion ratios, about 2 to 3:1, whereas, the steam turbine utilizes high ratios, typically 2500:1. Since turbine exhaust volume flow largely governs the size of the machinery and associated piping, the CCGT is a very compact prime mover.

The second advantage concerns the heat rejection. In the CCGT cycle, sensible heat is rejected over a range of temperatures, Fig. 2, as opposed to the latent heat transfer of a condensing vapor at a single, relatively low temperature in the Rankine cycle. This yields a significant reduction in the size of the heat rejection heat exchanger.

For the submarine application, two separate loops would be utilized to reject the heat, as shown thermodynamically in Fig. 2. The intermediate loop would be clean water, pressurized to suppress boiling and thus allow operation at elevated temperatures. This reduces the required flowrate and lowers the associated pumping loss. The ultimate sink is seawater and a large flowrate would be utilized to ensure an acceptable thermal signature.

5. KEY DESIGN DECISIONS

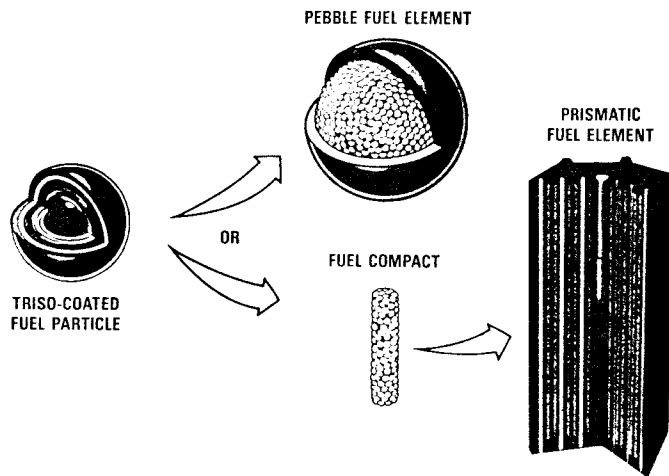
To define an optimum configuration for installation in the submarine hull, studies of major features and parameters are necessary. The following topics must be addressed before key design decisions can be made: (1) core power density, (2) fuel element geometry, (3) number of reactors, (4) number of power conversion loops, (5) degree of integration between the reactor and prime mover, and (6) drive type (mechanical electrical). Comprehensive studies involving the above variables have not been performed, but technical considerations are addressed in the following sections.

6. HIGH-TEMPERATURE REACTOR CONSIDERATIONS

The fuel particles are in the form of dense microspheres coated with layers of pyrocarbon and silicon carbide. The coatings are applied by chemical vapor deposition in a fluidized bed. A crucial element of the MHTGR safety concept is the containment system, which places primary emphasis on retention of fission products in the fuel (56). The ability of the fuel particles to retain fission products is well understood, and the integrity is ensured to temperature levels of over 2000°C (3632°F).

The coated fuel particles can be utilized in a variety of forms: (1) based on terrestrial HTGR plants, the particles can be intimately blended and bonded together by a refractory carbonaceous binder into fuel compacts. The fuel elements (Fig. 4) could be either in the form of prismatic blocks as used in the U.S. (57) or pebbles as used in Germany (58); (2) very compact fuel elements as demonstrated in the

NERVA (Nuclear Engine for Rocket Vehical Application) program (59); or (3) ultra-high power density particle bed reactors being investigated for space power applications (60).



H-557(1)

Fig. 4. Coated fuel particle for prismatic, pebble, or particle bed reactor

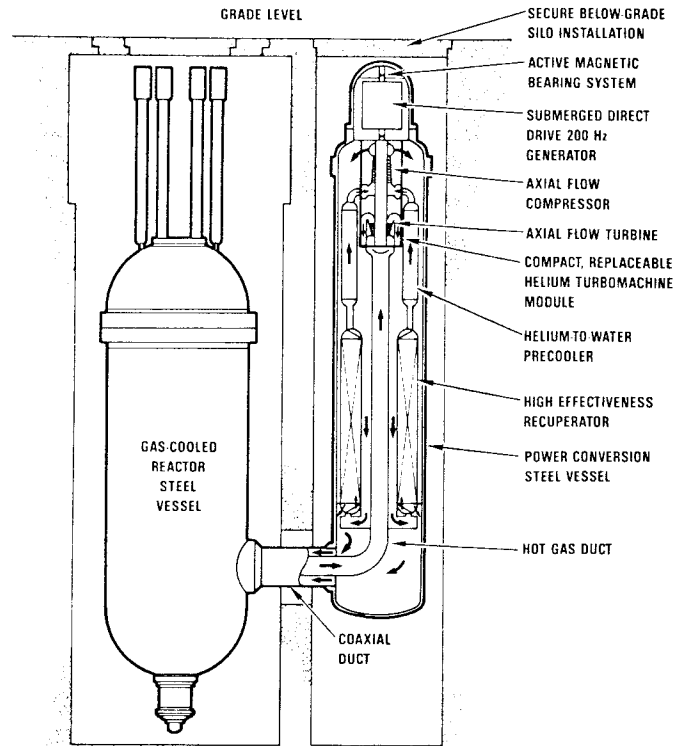
The selection of the most optimum reactor core-type requires intensive study; important factors would include shock-loading capability, potential for very high temperature operation, and fuel cycle considerations. An advantage of the prismatic core is that it is based on U.S. technology and has been successfully demonstrated in the FSV plant. An advantage of the German pebble bed reactor is that it has already demonstrated 950°C (1742°F) operation in the AVR experimental HTR (61). An additional advantage of the PBR may be the ability to refuel the core without breaching the hull.

The selection of core power density is a major design consideration since it propagates beyond the core envelope to determine the vessel size, and hence facilitation in the hull. For terrestrial HTGR applications (where volume and weight minimization are not dominant factors) there has been no big incentive to utilize high core power densities, and the two HTGRs operated in the United States with enriched fuel in fact had very modest values, namely Peach Bottom 1 (8.3 watts/cm³). In the standard MHTGR design (36), the requirement for passive decay heat rejection had a strong influence on the power density and rating of the core. For the 350 MW(t) MHTGR reactor a core power density of 5.9 watts/cm³ was selected. For nuclear space power applications (62, 63), where minimum system volume and weight are paramount, much higher levels of power density (substantially in excess of 100 watts/cm³) are being considered. For future submarine propulsion systems where power levels of up to, or perhaps in excess of 75 MW(e) (100,000 hp) are required, the selection of core power density will be strongly influenced by the ability to integrate the reactor vessel in the hull envelope.

7. POWER PLANT MAJOR FEATURES

Little effort has been expended on advanced MHTGR variants such as the gas turbine. A concept definition has been performed on a small nuclear gas turbine for

subterranean application (64). Similarly the performance potential has been identified in a scoping study (54) to explore the feasibility of utilizing the side-by-side steel vessel concept adopted for the steam cycle plant (Fig. 5). Analytical studies have been performed by university staff (MIT) for a small gas turbine plant based on the utilization of a 200 MW(t) pebble bed reactor (65).



H-647(5)

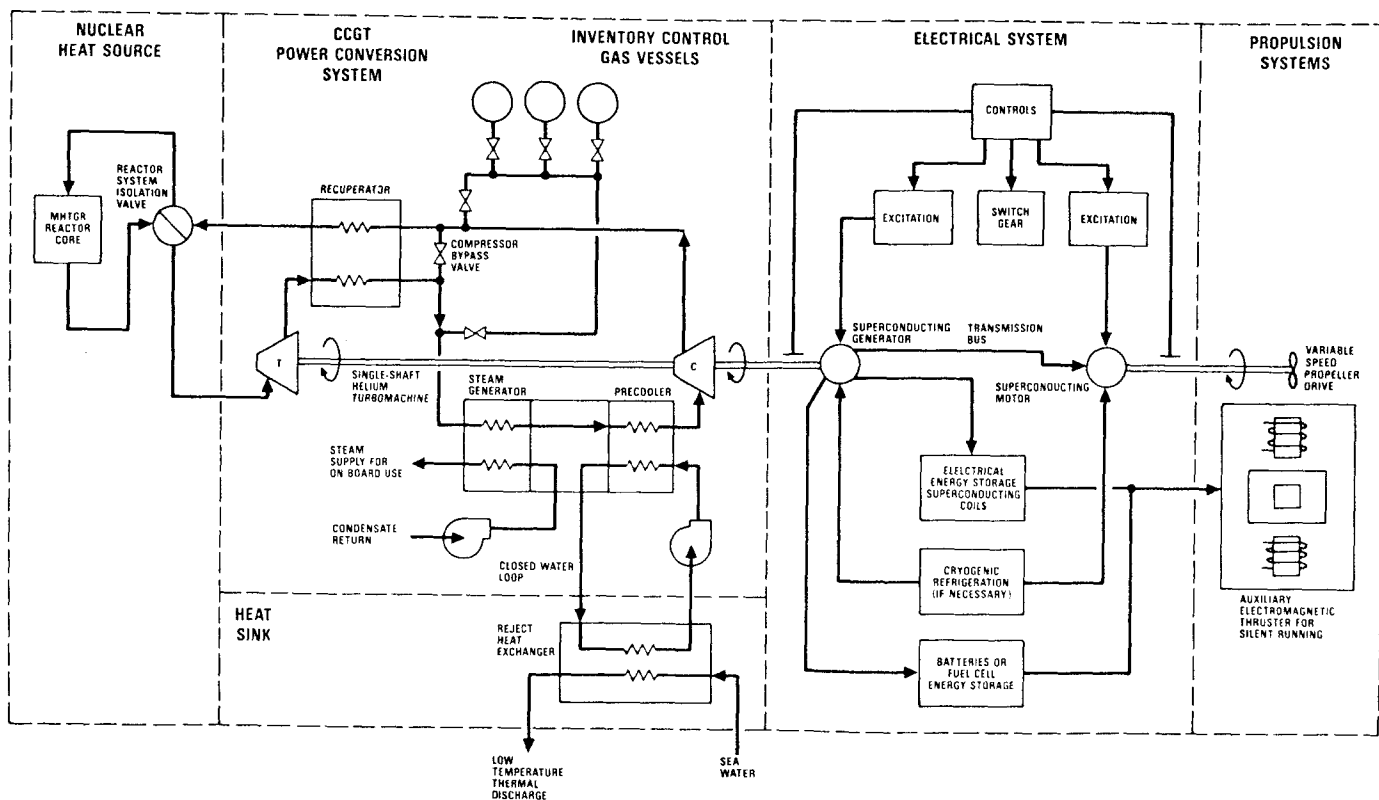
Fig. 5. Advanced high efficiency MHTGR gas turbine plant concept

A schematic of a candidate system is shown on Fig. 6. The major elements are (1) nuclear heat source, (2) gas turbine power conversion system, (3) electrical system, and (4) propulsion system. These are addressed in the following sections.

7.1. Nuclear Heat Source

The cylindrical reactor core could comprise an assemblage of prismatic or pebble fuel elements or a compact particle bed system. In the current MHTGR design, graphite is used for both the moderator and reflector. In the previous marine gas-cooled reactor study (22), beryllium oxide (a more efficient moderator) was used in the core and reflector to give a more compact assembly. The choice of moderator and reflector material would be made early in the reactor design for the submarine propulsion system. Neutron control would be provided by control rods in the reactor core. In addition, an independent reserve shutdown system would be included.

For a projected hull life of at least 30 years (51), the reactor core must be designed with an extended fuel cycle. Knowledge of the vessel power profile over its lifetime would be necessary to define



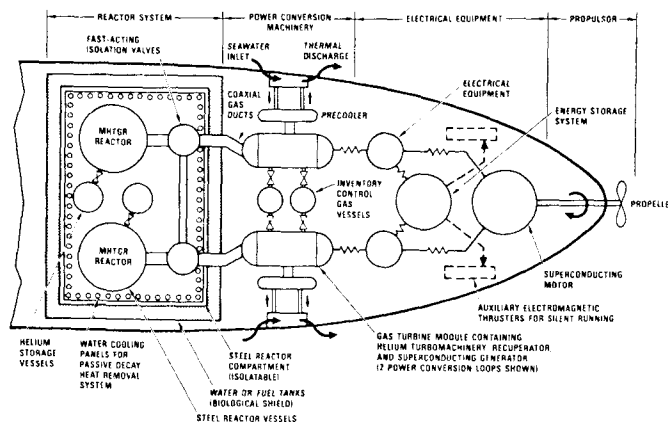
1-326(4)

Fig. 6. Nuclear gas turbine system for submarine propulsion

this, but with an obvious goal of having only one refueling operation during the life of the submarine the fuel cycle would have to be at least 15 years.

The most effective installation of the power conversion system inside the hull is dependent on the key design decisions established from optimization and trade-off studies, two foremost being the number of reactors and power conversion loops. As diagrammatically illustrated in Fig. 7 an arrangement is shown with two reactor vessels and two power conversion loops. In this arrangement the vessels for the reactor and power machinery have been separated. An alternate configuration could have all of the equipment installed in one vessel, and this has been studied in the past (34). In Fig. 7 the two steel vessels would be installed in the reactor compartment. This compartment would be sealed and surrounded by a biological shield, which could be in the form of a water or diesel fuel tank. The inner surface of the compartment would have water-cooled panels that would remove the decay heat should the main loop or reactor shutdown cooling system be unavailable. Man access into the sealed reactor compartment would be possible only after removal of the core.

Also installed in the reactor compartment are the isolation valves, which are open during normal operation but would be closed rapidly during situations (such as repair of battle damage) when the reactor must be isolated. These valves must operate in a high-temperature environment, be fast-acting, and have high reliability. A technology base exists for this component, namely: (1) the coaxial valve used in Peach Bottom 1 and (2) advanced technology valves under development in Germany for high-temperature process heat reactors (66).



1-326(3)

Fig. 7. Nuclear gas turbine propulsion system schematic

7.2. Power Conversion System

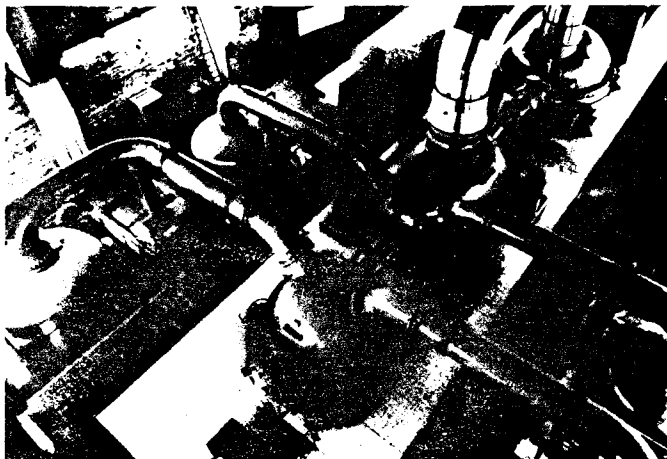
7.2.1. Helium Gas Turbine. The single-shaft helium turbomachine would embody a multistage axial flow compressor and turbine. Helium rotating machinery is well-understood, and many designs have been performed in the past (67). Based on performance optimization and blade stress levels the rotational speed of the turbomachine would likely be on the order of 10,000 to 12,000 rpm. Materials for the turbine blading would be different for the two temperature cases shown on Table 2. At a reactor outlet temperature of 785°C

(1445°F), the blades would be uncooled and made from an existing nickel-base cast alloy (e.g., IN 100). For a temperature of 950°C (1742°F) and above, carbon-carbon composites would be used, and intensive development efforts are under way on this material for advanced gas turbines (68,69).

Undoubtedly, the most significant recent technology advancement that makes the CCGT an attractive prime mover is in the tribology field. For this application the turbomachine rotor would be suspended on active magnetic bearings. This type of bearing has been proven in industrial machinery (70-72) and offers major advantages in closed-cycle systems (73), including the obviation of lubricant ingress, freedom from maintenance, and a very high degree of reliability. The principle is quite basic, namely, that by using a stationary electromagnet (stator) and a rotating ferrous material (included in the rotor), the shaft is levitated in a magnetic field while maintaining an accurate position under varying loads and speeds. It is the introduction of an electronic control system, for real-time sensing and positioning of the shaft displacement, that has made the active magnetic bearing system a reality in the last decade. A catcher bearing system (antifriction, dry-lubricated ball bearing type) would be incorporated to prevent mechanical contact between the rotor and stationary parts in the very unlikely event that both primary and secondary magnet energizing sources are lost.

An important technology base for the deployment of large helium CCGT systems is the 50 MW(e) Oberhausen II helium turbine plant (Fig. 8) operational in Germany (74). This helium gas turbine operates with an inlet temperature of 750°C (1382°F) and is based on a coke-oven gas-fired heat source. Clearly, as a utility power plant it was not designed for minimum weight or compactness, but it has demonstrated the practicality of a large closed-cycle helium system.

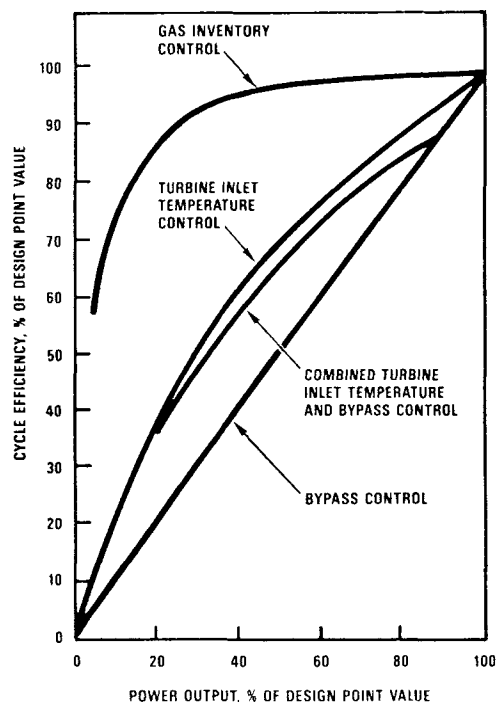
A major goal in the design of the turbomachinery will be to minimize circuit noise, and three factors are important: (1) acoustic considerations in the design of the blading, this involving a good understanding of all the blade-passing frequencies; (2) sound attenuation of the casings and ducts; and perhaps the most important of all, (3) the use of a magnetically levitated rotor with no bearing contact.



H-877(18)

Fig. 8. 50 MW(e) Oberhausen Helium Gas Turbine Plant operational in the Federal Republic of Germany (by courtesy EVO)

7.2.2. Gas Inventory Control System. An inherent attractive characteristic of the CCGT is the ability to control power output by regulating the reactor system pressure. At constant rotational speed and constant temperature at the turbine and compressor inlets, the power rating is directly proportional to the gas inventory; hence, mass flow rate can be varied over a wide range, and this control means has been extensively used in the European CCGT plants (75). Power variation by inventory control could be an important factor for submarine propulsion, since it permits very rapid change in plant output, depending on the power-demand profile of the system, and enables high efficiencies to be realized at plant-load operating conditions as illustrated on Fig. 9. The vessels necessary for the inventory control system (Figs. 6 and 7) would also be used as part of the gas storage system.



H-741(10)

Fig. 9. CCGT power level regulation by gas inventory control

7.2.3. Heat Exchangers. As shown on Fig. 6, there are two heat exchangers in the CCGT cycle: (1) helium-to-helium recuperator and (2) helium-to-water precooler; the latter unit having two sections as will be discussed below. Both of these heat exchangers have single-phase fluids so that flow stability is ensured. In a similar manner to that shown on Fig. 5, the recuperator would be integrated in the turbomachine vessel; but to relieve equipment congestion and give improved access, the precooler would likely be installed in its own steel vessel.

For submarine propulsion, equipment size and weight minimization is of the essence, and very compact heat exchangers are mandatory. In the last decade, very significant advances have been made in recuperator technology for industrial gas turbines. Compact plate-fin recuperators have demonstrated high performance and have proven integrity (76).

The precooler assembly is used to dissipate the reject heat from the power conversion cycle. The heat exchanger is split into two sections: (1) extraction of useful thermal energy in the form of steam for on-board use and (2) heat rejection to the ultimate seawater heat exchanger. The water pressure level in the precooler loop is modest and regulated to suppress boiling. As shown on Fig. 2, the latent heat rejection characteristic of the Brayton cycle facilitates a significant temperature rise on the water side with attendant low water flow, and this manifests itself in lower pumping power and hence reduced pump noise compared with Rankine steam plant.

A major goal in the design of the precooler will be to minimize its size and weight. Candidate surface geometries include finned-tubes, dimpled tubes, and use of turbulators or roughened surfaces. A particularly attractive fluted-tube geometry has been developed which offers the advantage of heat transfer enhancement on both helium and water sides. This unique geometry has an attractive heat transfer-to-friction relationship (77) and seems well-suited for the precooler.

7.3. Electrical System

Elimination of the noisy reduction gears associated with mechanical drive systems is an obvious goal for improved stealth submarines of the future. An electrical drive system is proposed as shown on Fig. 6, and while the nuclear gas turbine is not necessarily tied to superconducting machinery, it is surely prudent to include it for vessels that will be operational in the early decades of the 21st century.

Superconducting electric propulsion systems have for long been a goal for marine propulsion (78), but it is recent materials developments (79-81) that will now make them a reality. While much work remains to be done to identify the most optimum ceramic superconductor material, geometries, and configurations to practically accommodate very high current density, the goals of high-efficiency superconducting generators and motors in much reduced size should be realizable in the foreseeable future. It is proposed to utilize a direct drive superconducting generator with the unit integrated in the gas turbine module in a manner similar to that shown on Fig. 5. The major advantage of this arrangement is that it eliminates a drive shaft penetrating the steel vessel.

7.4. Propulsion

While actually beyond the scope of this paper, it is felt that technology for advanced propulsors will be available in the same time frame as a nuclear gas turbine. The obvious goal of having a quiet, propellerless system has been discussed previously (2). Again, the recent breakthrough in superconducting materials could make this a reality in the form of electromagnetic or magnetohydrodynamic propulsion (82,83).

Electromagnetic pumps have been used extensively in liquid metal reactors (84). The advantage of this type of electromagnetic pump are numerous and include (1) no shaft seal and hence it can be totally sealed, (2) no moving parts, (3) no free surface requirement (e.g., a sump), thus it can be conveniently located in piping or duct systems. Electromagnetic pumps utilize the "motor" principle in that a conducting fluid carrying a current in a magnetic field experiences a force that motivates the fluid. Experience to date has been predominantly for liquid metal systems and the relatively high electrical conductivity of sodium and NaK make them most amenable to pumping by electromagnetic means.

Seawater has an electrical conductivity about six orders of magnitude less than liquid metal, but could be pumped by electromagnetic means. The performance of

this type of pump is affected adversely by entrained gas in the liquid, this being due to the increased resistance that results from the presence of gas bubbles. For operation in the ocean (or river deltas), such a pump would be affected by changes in salinity. Much work remains to be done to establish an electromagnetic system capable of accommodating many tens of megawatts.

A possible start would be to use a small electromagnetic thruster for silent running (and for under the ice operation), again taking advantage of projected advancements in the superconductor field. As shown on Fig. 6, the auxiliary electromagnetic thruster draws power from electrical energy storage superconducting coils, supplemented by the batteries as necessary. Studies are required to establish the practicality of such an approach. The energy stored in an electromagnetic system is proportional to the product of electrical inductance and current squared. The ideal electric storage system has extremely high current levels; hence, the attractiveness of high-current density superconductors.

The attractiveness of having a practical and silent system, with no drive shaft penetrating the hull and with no moving parts (made possible by emerging superconducting technology) that in the simplest terms sucks seawater in one end and expels it at the other end to propel a submarine forward, will surely foster considerable development in coming decades.

7.5. Operation and Maintenance

The structural integrity of the fuel is such that the fuel particles themselves will retain the fission products for the full spectrum of postulated events. It should be noted, however, that there are many additional barriers between the fuel kernel and the engine room equipment, and these are illustrated simply on Fig. 10. The performance of the highly enriched fuel in the FSV HTGR has been excellent, the primary circuit is very clean, and personnel exposures have been exceptionally low. The low FSV exposure levels are anticipated to remain better than an order of magnitude below those of the U.S. light-water reactors (85). Even higher fuel quality standards are being sought for the MHTGR. A manned engine room will be possible, but there are obvious benefits from minimizing the vessel crew complement, and this extends to the power plant.

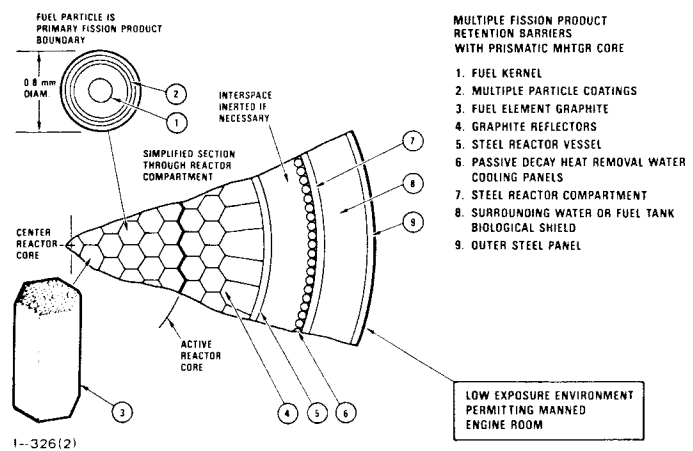


Fig. 10. Very low exposure to engine room crew with MHTGR plant

In the time frame envisioned for introduction of the nuclear gas turbine, automated on-line diagnostic systems for condition monitoring will permit automated computer control of the propulsion system, perhaps obviating the need for a manned engine room.

With a direct gas turbine system the reactor coolant is also the prime mover working fluid, and while the primary circuit is projected to be very clean, the components will become radioactive, and this impacts maintenance procedures. The power plant is of modular construction and, if problems arise, modules would be replaced. Maintenance is clearly a topic that warrants detailed study, and this would take advantage of previous work done in this area (86).

The aforementioned major features of a nuclear gas turbine propulsion system are summarized on Table 3. As mentioned above there are many variants to the basic configuration that could be considered.

TABLE 3
MAJOR FEATURES OF ADVANCED NUCLEAR GAS
TURBINE SYSTEM FOR SUBMARINE PROPULSION

NUCLEAR SYSTEM	REACTOR TYPE NUMBER OF REACTORS REACTOR THERMAL RATING, MW(t) DECAY HEAT REMOVAL SYSTEM LIFE, YEARS	MHTGR 1 OR 2 75 (SELECTED FOR ILLUSTRATIVE PURPOSES) DEDICATED SYSTEM 30 (MINIMUM)
REACTOR CORE	REACTOR COOLANT FUEL PARTICLES FUEL ELEMENT GEOMETRY POWER DENSITY, W cm ³ ENRICHMENT FUEL CYCLE, YEARS REACTOR ORIENTATION	HELIUM HTGR CERAMIC COATED PRISMATIC BLOCK, PEBBLE OR PARTICLE BED REACTOR TO BE DETERMINED HIGH ENRICHED FUEL 15-11 (REFUELING IN VESSEL LIFETIME) VERTICAL
CLOSED CYCLE GAS TURBINE	THERMODYNAMIC CYCLE NUMBER OF MODULES POWER CONVERSION SYSTEM ORIENTATION TURBOMACHINE TYPE ROTATIONAL SPEED, RPM LOAD CONTROL TURBINE INLET TEMP, °C (°F) PRESSURE RATIO TURBINE BLADING TURBOMACHINE BEARINGS THERMODYNAMIC CYCLE EFFICIENCY	REGENERATIVE, NON-INTERCOOLED 1 OR 2 HORIZONTAL AXIAL FLOW, SINGLE SHAFT 10,000 TO 12,000 INVENTORY CONTROL UP TO 950 (1742) 2 TO 2.6 CARBON-CARBON COMPOSITE ACTIVE MAGNETIC BEARINGS APPROX 45% (AT 900°C)
HEAT EXCHANGERS	HELIUM-TO-HELIUM REGENERATOR HELIUM-TO-WATER PRECOOLER	COMPACT PLATE-FIN UNIT WITH HIGH EFFECTIVENESS ENHANCED FLUTED TUBES
DRIVE SYSTEM	GENERATOR MOTOR DRIVE PROPULSOR ENERGY STORAGE SYSTEM AUXILIARY DRIVE	HIGH-SPEED, COMPACT SUPERCONDUCTING GENERATOR COMPACT, VARIABLE SPEED SUPERCONDUCTING MOTOR SINGLE PROPULSOR SUPERCONDUCTING MAGNETIC COILS ELECTROMAGNETIC PROPULSOR FOR SILENT RUNNING
PLANT STATUS	DESIGN STATUS TECHNOLOGY STATUS TECHNOLOGY BASES PROPULSION SYSTEM DEPLOYMENT	EMBRYONIC IDEAS STAGE) ADVANCED TECHNOLOGY • 5 HTGRs BUILT AND OPERATED • INDUSTRIAL AND AEROSPACE CCTs • ADVANCED TECHNOLOGY TRANSFER FROM DEFENSE PROGRAMS • EARLY DECADES OF 21st CENTURY

1-326(9)

8. SAFETY CONSIDERATIONS

For the proposed nuclear gas turbine for submarine propulsion, the paramount design consideration will be the safety of the crew, and this will be dominant in establishing the major power plant features, consistent with satisfying the other major requirements. Safety analysis will cover all modes of operation: (1) normal power production, (2) postulated abnormal events, (3) influence of battle damage, (4) in-port operation, and (5) the ultimate accident case involving vessel flooding and sinking.

The excellent safety characteristics of the MHTGR are well-known and tend to be dominated by the inherent characteristics of the coolant, core materials, and these have been reported previously (87).

9. TECHNOLOGY READINESS/DEVELOPMENT

9.1. Design Development

The feasibility/practicality of the system will be

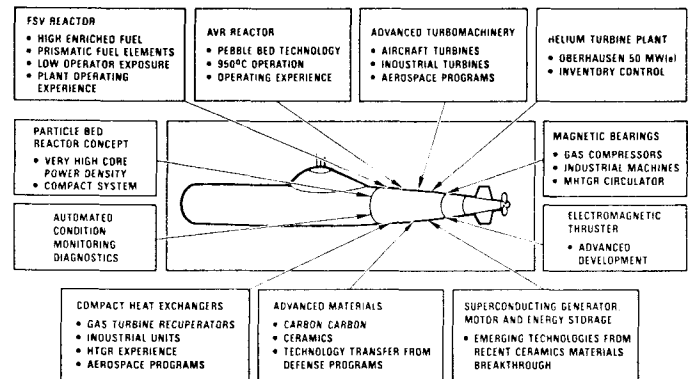
dependent on the results of in-depth engineering analysis and design studies in the following areas:

1. Selection of most optimum core power density reactor core geometry and identification of the reactor system.
2. Integration of the steel vessel(s) in the reactor compartment.
3. Identification of the cooling system.
4. Primary system gas flow path development.
5. Sizing of major components and engine room equipment layout.
6. Performance assessment.
7. Equipment weight and volume identification.
8. Plant control system definition.
9. Safety analyses encompassing all aspects of the above.

9.2. Enabling Technologies

The three operating regimes identified on Fig. 3 reflect different levels of technology readiness. A gas turbine plant could be designed today (with attractive levels of specific weight and efficiency) based on tried and proven technology. The nuclear gas turbine has the potential for very high efficiency and developments are necessary (particularly in the materials area) to take advantage of the very high temperature capability of the HTGR. Technology advancements must also be factored into the systems design to identify more compact and lightweight components.

The enabling technologies necessary to make the advanced nuclear gas turbine a reality are multifaceted, and some of them are identified on Fig. 11. It should be pointed out that many of these technologies are already in progress for advanced defense systems, and technology transfer would benefit the proposed gas turbine concept. Many of these developments will reach maturity by the end of this century, and the necessary data will be available for the design of future submarine propulsion systems.



1-326(11)

Fig. 11. Enabling technologies for advanced nuclear gas turbine submarine propulsion system

10. SUMMARY

In the last three decades the PWR with a steam turbine power conversion system has proved to be a safe and reliable power plant for marine propulsion but it has perhaps reached its zenith in terms of performance potential and specific weight, which can be approximated as being on the order of 60 Kg/Kwe (100 lb/hp) as reported in the literature (3,34). As shown on Fig. 1, the other options for large submarine propulsion are liquid metal or gas-cooled reactors. Both offer the

potential for substantial increase in power output per unit of weight or volume.

Worldwide interest has intensified recently in gas-cooled reactors with the conception of the MHTGR which, in a smaller size than studied previously, offers significant advancements in safety, construction, and economics, not heretofore seen in this type of power plant. The helium gas-cooled reactor offers unique flexibility for diverse applications including meeting the requirements of various space power, terrestrial, subterranean, and undersea systems (88). Until the ultimate goal of direct energy conversion becomes a reality, some form of thermal prime mover is needed for submarine propulsion, and the nuclear gas turbine must be viewed as an attractive candidate for deployment early in the 21st century.

The utilization of the nuclear gas turbine is not directly tied to the use of superconducting electrical equipment, but this coupling has been featured in a prudent manner for a futuristic power plant. The recent breakthrough in superconducting metal oxide ceramic materials will surely lead to very compact electrical equipment. It may well be the key to the ultimate goal of having a silent propellerless submarine propulsion system, and the compact high-efficiency nuclear gas turbine could provide the electrical power supply for an electromagnetic thruster, free from moving parts to give hitherto unachievable levels of stealth.

This publication is essentially viewed as an introductory paper on the topic of nuclear gas turbine propulsion; accordingly, a specific design has not been presented, the theme being rather one of emphasizing performance potential. The requirements (Table 1) put forward are generic in nature, and the adequacy of a system should be matched against these. The projected advantages of the nuclear gas turbine are highlighted on Table 4. It is concluded that the proposed system is attractive in terms of satisfying the four basic "S" requirements; namely, safety, speed, stealth, and strategy, and may well provide the all-important fifth "S" (surprise).

There has always been strong interest by the technical community in submarines and their propulsion systems, but it is rare that such enthusiasm extends to the general public. However, a recent publication (89) has clearly done this.

A 40-year period is not unreasonable (2) when putting forward a new proposal for procurement. It is

TABLE 4
PROJECTED ADVANTAGES OF CLOSED-CYCLE
GAS TURBINE FOR SUBMARINE PROPULSION

INSTALLATION	<ul style="list-style-type: none"> • COMPACT MACHINERY RESULTS IN SPECIFIC WEIGHT AND SPECIFIC VOLUME CONSIDERABLY LESS THAN PWR STEAM CYCLE • POTENTIAL FOR VERY LOW SPECIFIC WEIGHT AND VOLUME USING ADVANCED TECHNOLOGY • MODULAR CONSTRUCTION FACILITATES REPLACEMENT OF MAJOR SYSTEMS • SYSTEM VIEWED AS PRACTICAL FOR LARGE SYSTEMS (UP TO 100,000 HP) • COMPACT HIGH-SPEED TURBOMACHINE COMPATIBLE WITH SUPERCONDUCTING GENERATOR, MOTOR, AND ENERGY STORAGE SYSTEM
PERFORMANCE	<ul style="list-style-type: none"> • HIGH EFFICIENCY POSSIBLE WITH ESTABLISHED TECHNOLOGY • POTENTIAL FOR SIGNIFICANT EFFICIENCY IMPROVEMENT BASED ON VERY HIGH TEMPERATURE TECHNOLOGY UTILIZATION • LOW HEAT SINK TEMPERATURE BENEFICIAL TO BRAYTON CYCLE • HIGH EFFICIENCY REALIZABLE AT PART POWER (INVENTORY CONTROL) • HIGH FUEL BURNUP YIELDS LONG FUEL CYCLE (AT LEAST 15 YEARS BETWEEN REFUELING)
OPERATIONAL CHARACTERISTICS	<ul style="list-style-type: none"> • COST POWER CONVERSION SYSTEM ADAPTABLE TO COUPLING WITH PRISMATIC, PEBBLE OR PARTICLE BED HIGH-TEMPERATURE GAS-COOLED REACTORS • SYSTEM RESPONSIVE TO RAPID POWER CHANGE (INVENTORY CONTROL) • PERFORMANCE UNAFFECTED BY LARGE BOAT ANGLES • TWIN REACTOR/TWO POWER CONVERSION LOOPS OFFERS REDUNDANCY • AUTOMATED, COMPUTER-CONTROLLED ENGINE ROOM (MINIMIZES CREW)
SAFETY	<ul style="list-style-type: none"> • SMALL PASSIVELY SAFE REACTOR CORE • HIGH FUEL PARTICLE INTEGRITY (i.e., CLEAN CIRCUIT) • LOWER SYSTEM PRESSURE THAN PWR • VERY LOW EXPOSURE TO OPERATORS (MULTIPLE BARRIERS) • CORE CAN BE RAPIDLY ISOLATED AND PASSIVELY COOLED • NO NUCLEAR PROBLEMS IN ULTIMATE VESSEL FLOODING ACCIDENT • SOPHISTICATED DIAGNOSTIC SYSTEM
STEALTH (EMISSIONS/SIGNATURES)	<ul style="list-style-type: none"> • LOW MACHINERY NOISE LEVEL (NO GEARBOX) • MAGNETIC SUSPENSION OF TURBINE ROTOR (NO BEARING NOISE) • SENSIBLE RATHER THAN LATENT HEAT REJECTION FROM POWER CYCLE RESULTS IN LOW-TEMPERATURE THERMAL EFFLUENT • PASSIVE AND SILENT AUXILIARY ELECTROMAGNETIC THRUSTER (POSSIBLY BY ENERGY STORAGE SYSTEM)

I-326(7)

suggested that in systems architecture studies under way for submarines needed in the early decades of the 21st century, the nuclear gas turbine propulsion system be included as a candidate.

11. CONCLUSION

11.1. Based on existing and proven HTGR and CCGT technology a near-team direct cycle plant would offer improved performance over existing submarine propulsion systems. It is postulated that a specific weight of 12 kg/kW(e) (20 lb/hp) could be realized.

11.2. Based on the utilization of advanced technologies, many of which are in progress for defense systems, there is a substantial gain in performance and reduction in specific weight to be realized by increasing the reactor outlet temperature. Since machinery power density has been identified as a critical parameter in the size and economics of attack submarines (90), there will be substantial rewards for deployment of advanced technologies.

11.3. Factor into the design in a prudent manner the impact of projected technology breakthrough in the field of high-temperature superconductors as they apply to compact generators, motors, and energy storage systems.

11.4. Studies should be initiated to identify the most optimum submarine power plant configuration based on the coupling of a gas-cooled reactor with a closed-cycle gas turbine prime-mover.

12. ACKNOWLEDGMENTS

The author would like to thank the management of GA Technologies Inc. for permission to publish this paper. The views in this paper are those of the author. The author extends his thanks to Dr. Robert Schleicher of GA for his many valuable comments in reviewing this paper.

13. REFERENCES

1. "Jane's Fighting Ships 1986-1987," Jane's Publishing Company Ltd., London.
2. Moore, J. E., and R. Compton-Hall, "Submarine Warfare Today and Tomorrow," Adler & Adler Publishers Inc., Bethesda, Maryland, 1986.
3. Tyler, P., "Running Critical," Harper & Row Publishers, New York, 1986.
4. Friedman, N., "Submarine Design and Development," Naval Institute Press, Annapolis, 1984.
5. Polmar, N., "Atomic Submarines," D. Van Nostrand Company Inc., Princeton, New Jersey, 1963.
6. Miller, D., and J. Jordan, "Modern Submarine Warfare," Military Press, New York, 1987
7. Sternlicht, B., and J. W. Bjerklie, "Comparison of Dynamic and Static Power Conversion Systems for Undersea Missions," ASME Journal of Engineering for Power, October 1966, pp. 323-333.
8. Mills, C. B., "A Small Nuclear Reactor for Undersea Use," Nuclear Technology, Vol. 10, February 1971, pp. 133-138.
9. Brasier, R. J., and C. B. Mills, "Reactor Power Plant for Undersea Applications," Nuclear Technology, Vol. 22, May 1974, pp. 224-228.
10. Hewitt, J. S., "The Amps 1.5 MW Low-Pressure Compact Reactor," Paper Presented at Seminar on Small and Medium-Sized Nuclear Reactors, August 26-27, 1987, Lausanne, Switzerland.

11. Hewitt, J. S., et al., "SAGA-N: A Nuclear-Powered Submarine Vehicle for Commercial Service," paper presented at Canada Nuclear Society Sixth Annual Conference June 3-4, 1985, Ottawa, Canada.
12. Reader, G. T., et al., "The Stirling Powered Submarine Concept," paper No. 879416, in Proceedings of 22d IECEC, August 1987, Vol. 4, pp. 1897-1901.
13. Agnew, H. M., "Gas-Cooled Nuclear Power Reactors," Scientific American, 244, 6, 1981.
14. Melese, G., and R. Katz, Thermal and Flow Design of Helium-Cooled Reactors, published by The American Nuclear Society, 1984.
15. McDonald, C. F., "Large Closed-Cycle Gas Turbine Plants," Sawyer's Gas Turbine Engineering Handbook, Vol. II, Chapter 8, pp. 8-38, 1985.
16. Pietsch, A., "Closed-Cycle Gas Turbines 50 MW(e) and Smaller," Sawyer's Gas Turbine Engineering Handbook, Vol. II, Chapter 9, pp. 9-1 to 9-24, Turbomachinery International Publications, 1985.
17. Taggart, R., "Marine Propulsion: Principles and Evaluation," Gulf Publishing Company, Houston, Texas, 1969.
18. Brown, T. W. F., "Propulsion of Ships by Steam Turbine Machinery," Nuclear Engineering, April 1958.
19. Hinton, C., and R. V. Moore, "The Nuclear Propulsion of Ships," Nuclear Engineering, January 1958.
20. Richards, J. E., "High-Temperature Reactors for Marine Propulsion," Nuclear Engineering, January 1962.
21. Browne, H. L., "The Maritime Gas-Cooled Reactor Propulsion Plant of the Future," General Dynamics Corporation Publication GA-A1040, November 2, 1959.
22. Resnick, B. T., "Technical Considerations in the Development of a Maritime Gas-Cooled Reactor System," ASME Paper No. 61-GTP-14, 1961.
23. Kramer, A. W., "Nuclear Propulsion for Merchant Ships," U.S. Atomic Energy Commission Publication, 1962.
24. McDonald, C. F., and C. O. Peinado, "The Nuclear Gas Turbine - A Perspective on a Long-Term Advanced Technology HTGR Plant Option," ASME Paper No. 82-GT-289, 1982.
25. Bohm, E., "Nuclear Gas Turbines for Marine Propulsion," paper presented at Nuclear Gas Turbine Colloquium, May 24-25, 1965, Paris, France.
26. Dobler, F. X., and R. A. Rackley, "Closed Gas Turbine Marine Power Systems," Paper No. 759160 in Proceedings of Tenth IECEC August 18-22, 1975, pp. 1065-1070.
27. Fayrweather, D. J., et al., "Advanced Marine Closed Brayton Engines," Paper No. 769030 in Proceedings of Eleventh IECEC, September 12-17, 1976, Vol. 1, pp. 177-183.
28. Kuo, S. C., and H. T. Shu, "Parametric Design Studies of Lightweight Closed-Cycle Gas Turbine Ship Propulsion Systems," Paper No. 77908 in Proceedings of Twelfth IECEC, August 28, 1977, Vol. 1, pp. 166-171.
29. Gathy, B. S., "A Marine Nuclear Power Plant Design Utilizing the Direct Brayton Cycles," ASME Paper No. 70-GT-3, 1970.
30. Parker, G. H., et al., "Feasibility Study for Lightweight Compact Closed-Cycle Brayton System," Paper No. 789442 in Proceedings of Thirteenth IECEC, August 20, 1978, Vol. 1, pp. 272-277.
31. Kuo, S. C., and H. T. Shu, "Alternative Closed-Cycle Gas Turbine System Design Considerations for Ship Propulsion Applications," ASME Paper No. 78-GT-18, 1978.
32. Spurrier, F. R., "A Compact Closed-Cycle Gas Turbine for Marine Propulsion," ASME Paper No. 79-GT-62, 1979.
33. Calvo, R., and R. E. Thompson, "Compact Closed-Cycle Brayton System for Marine Propulsion," ASME Paper No. 80-WA/GT-4, 1980.
34. Thompson, R. E., "Lightweight Nuclear Power Plant Applications of a Very High-Temperature Reactor (VHTR)," Paper No. 759164, in Proceedings of Tenth IECEC August 18-22, 1975, pp. 1089-1097.
35. Dean, R. A., and T. A. Johnston, "Development of the Modular HTGR in the U.S.A.," paper presented at ENC-6 Conference, Geneva, Switzerland, June 1986.
36. Breher, W., et al., "Modular High-Temperature Reactor (MHTGR) Status," Paper No. 879274, in Proceedings of Twenty-Second IECEC, August 10-14, 1987, Vol. 3, pp. 1569-1574.
37. "Status of and Prospects for Gas-Cooled Reactors," International Atomic Energy Agency Technical Report Series No. 235, Vienna, Austria, 1984.
38. McDonald, C. F., "Exploitation of the Very High-Temperature Capability of the MHTGR to Meet National Energy Needs After the Year 2000," Paper No. 869069, in Proceedings of the Twenty-First IECEC, 1986, Vol. 1, pp. 273-280.
39. Fogg, H. E., et al., "The Marine Gas Turbine for the 1990s and Beyond," SAE Paper No. 871378, June 1987.
40. Johnson, G. A., et al., "Intercooling and Regenerating the Modern Marine Gas Turbine Propulsion System," SAE Paper No. 871379, June 1987.
41. Daniel, R. J., "Submarine Design," Naval Forces International Forum for Maritime Power, No. 111, 1987, Vol. VIII, pp. 18-34.
42. Reinertson, J. H., et al., "The Submarine Propulsion Plant - Development and Prospects," Naval Engineers Journal, Vol. 75, No. 2, May 1963, pp. 349-364.
43. Blose, J. F., and J. F. McCartney, "A Method for Synthesis and Selection of Propulsion Plants for Submarines," MEL Research and Development Report 67/64, June 19, 1964.
44. Edwards, J., "A Review of the Status of and Prospects for Nuclear Marine Propulsion," J. Inst. Nuc. Eng., Vol. 3, No. 17, May-June 1976, pp. 55-72.
45. Wignall, M. B., "Can the Navy of a Medium Maritime Power Afford Not to Go Nuclear for Propulsion by the 1990s?" J. Inst. Nuc. Eng., Vol. 21, No. 6, November-December 1980, pp. 167-174.
46. Pocock, R. F., "Nuclear Marine Propulsion - A Brief Historical Survey," *ibid.*, pp. 174-179.
47. Horlick, T., "Submarine Propulsion in the Royal Navy," Proc. Instn. Mech. Engrs., Vol. 196, 1982, pp. 65-79.
48. Horton, C. C., "Submarine Nuclear Power Plants," The Nuclear Engineer, Vol. 25, No. 1, April 1984, pp. 3-5.
49. Battle, N., "PWR Plant Development for Marine Propulsion," *ibid.*, pp. 7-14.
50. Hemond, H. C., "Don't Make It Bigger Please," Naval Engineers Journal, March 1985, pp. 54-57.
51. O'Rourke, R., "The Nuclear-Powered Submarine," Naval Forces International Forum For Maritime Power, No. 1, Vol. VIII, 1986, pp. 84-91.
52. Mason, J. L., et al., "Monatomic Working Gases Versus Air for the Closed Brayton Cycle," ASME Paper No. 85-IGT-60, 1985.
53. Mock, E. A., "Closed-Cycle Gas Turbine Optimization - Procedures and Examples," paper presented at AGARD Lecture Series on Closed-Cycle Gas Turbines, Von Karman Institute, Brussels, Belgium, May 1977.

54. McDonald, C. F., "Performance Potential of a Future Advanced Nuclear Gas Turbine Concept," Proceedings of ASME COGEN-TURBO '87 Symposium, Montreux, Switzerland, September 2-4, 1987, pp. 247-261.
55. Schulten, R., "Problems Already Solved and Those Still Outstanding in Developing High-Temperature Reactors and Processes for Utilizing HTR Heat," paper presented at VGB Conference on High-Temperature Gas-Cooled Reactors, August 1985, Dartmund, Germany.
56. Northup, T. E., et al., "An Assessment of the Modular HTGR Containment System," Paper No. 879276 in Proceedings of Twenty-Second IECEC, August 10-14, 1987, Vol. 3, pp. 1579-1584.
57. Turner, R. F., et al., "Annular Core for Modular High-Temperature Gas-Cooled Reactor (MHTGR)," paper presented at Seminar on Small- and Medium-Sized Nuclear Reactors, Lausanne, Switzerland, August 24-26, 1987.
58. Steinwarz, W., "Modular High-Temperature Reactor Launched," Modern Power Systems, August 1987, pp. 45-53.
59. Pierce, B. L., and R. R. Holman, "NERVA Derivative Reactor/Brayton Power System for Multimegawatt Power Applications," Paper 879364, Proceedings of 22nd IECEC, August 10, 1987, pp. 2045-2048.
60. Powell, J. R., and F. L. Horn, "High Power Density Reactors Based on Direct Cooled Particle Beds," Proceedings of Symposium on Space Nuclear Power System, Albuquerque, New Mexico, January 14, 1985, pp. 319-329.
61. Ivens, G., et al., "Experience Gained With the AVR Experimental Nuclear Power Station," Brown Boveri Review, Vol. 74, No. 1, January 1987, pp. 12-19.
62. Walter, C. E., and J. S. Pearson, "Gas-Cooled Reactor for Space Power Systems," Paper No. 879362, in Proceedings of Twenty-Second IECEC, August 10-14, 1987, Vol. 1, pp. 485-492.
63. Horn, F. L., et al., "The Use of Nuclear Energy for Bimodal Applications in Space," Paper No. 869420, Proceedings of 21st IECEC, August 25-29, 1986, Volume 3, pp. 1849-1853.
64. McDonald, C. F., et al., "Very High-Efficiency Small Nuclear Gas Turbine Power Plant Concept (HTGR-GT/BC) for Special Applications," ASME Paper No. 84-GT-269, 1984.
65. Staudt, J. E., and L. M. Lidsky, "An MGR Brayton-Cycle Power Plant Design," Paper No. 879154, in Proceedings of Twenty-Second IECEC, Vol. 3, pp. 1549-1554.
66. Kruschik, J., "Development of a New Hot Gas Double Axial Valve and Design Concept for a Coaxial Valve," ASME Paper No. 86-GT-31, 1986.
67. McDonald, C. F., and M. J. Smith, "Turbomachinery Design Considerations for the Nuclear MHTGR-GT Power Plant," ASME Journal of Engineering for Power, Vol. 103, No. 1, pp. 65-77, 1981.
68. Denis, L., et al., "Carbon-Carbon Components for Advanced Gas Turbine Engines," ASME Paper No. 81-GT-35, 1981.
69. Fitzer, E., et al., "Carbon Fibers and Their Composites (A Review)," High Temperatures - High Pressures, Vol. 16, pp. 363-392, 1984.
70. Hendrickson, T. A., et al., "Application of Magnetic Bearing Technology for Vibration-Free Rotating Machinery," Naval Engineers Journal, Vol. 99, No. 3, May 1987, pp. 107-111.
71. Brunet, M., "Applications of the Active Magnetic Bearings to Turbomachinery," in Proceedings of 1987 ASME Cogen-Turbo, IGT1, September 1987, Vol. 1, pp. 191-200.
72. Weise, D. A., "Present Industrial Applications of Active Magnetic Bearings," Paper No. 879147 in Proceedings of Twenty-Second IECEC, August 1987, Vol. 2, pp. 775-779.
73. McDonald, C. F., "Active Magnetic Bearings for Gas Turbomachinery in Closed-Cycle Power Plant Systems," paper to be presented at Thirty-Third ASME Gas Turbine Conference, Amsterdam, The Netherlands, June 5-9, 1988.
74. Zenker, P., "The Oberhausen 50 MW(e) Helium Turbine Plant," Combustion, April 1976, pp. 21-28.
75. Frutschi, H. U., "Rapid Positive Load Changes by Gas Injection in Closed Gas Turbine Cycles," ASME Paper No. 78-GT-8, 1978.
76. Kretzinger, K., et al., "Gas Turbine Regenerators," Garrett Air Research Manufacturing Company of California Technical Paper No. 85-22130, Rev. 5, January 1985.
77. Yampolsky, J. S., "Spiral Fluted Tubing for Enhanced Heat Transfer," paper presented at International Seminar on Advancement in Heat Exchangers, August 1981, Dubrovnik, Yugoslavia.
78. McCann, E. F., and C. J. Mole, "Superconducting Electric Propulsion Systems for Advanced Ship Concepts," Naval Engineers Journal, December 1972, pp. 35-45.
79. Bowen, H. K., "Ceramic Superconductors," Ceramic Bulletin, Vol. 66, No. 8, 1987, pp. 1191-1194.
80. Fisher, A., "Superconductor Frenzy," Popular Science, July 1987, pp. 54-58.
81. Heppenheimer, T. A., "Superconducting - The New Billion Dollar Business," High Technology, July 1987, pp. 12-18.
82. "Superconducting Subs: Twice as Deadly, Half the Size," Navy News and Undersea Technology, p. 5, Summer 1987.
83. Brady, D., and J. Edyvane, "Propulsion in the Pod - Fact or Fiction," Submarine Review, April 1986, pp. 16-26.
84. Barnes, A. H., and J. F. Cage, "Electromagnetic Pumps," Liquid Metals Handbook, The Atomic Energy Commission and The Bureau of Ships, Department of the Navy, November 1955, pp. 288-305.
85. Brey, H. L., and H. G. Olson, "Fort St. Vrain Experience," Gas-Cooled Reactors Today, Vol. 1, pp. 35-39, September 1982.
86. McDonald, C. F., and J. A. Paget, "Maintenance Considerations in the Design of the Direct-Cycle Nuclear Gas Turbine Power Plant," ASME Paper No. 79-gt-116, 1979.
87. Silady, F. A., et al., "Safety and Licensing of MHTGR," paper presented at Seminar on Small and Medium-Sized Nuclear Reactors, August 24-26, 1987, Lausanne, Switzerland.
88. McDonald, C. F., "The High-Temperature Gas-Cooled Reactor - A Versatile Nuclear Heat Source for Space, Terrestrial, Subterranean, and Undersea Power Applications," paper to be presented at Twenty-Third IECEC, Denver, Colorado, July 31, 1988.
89. Clancy, T., "The Hunt for Red October," Naval Institute Press, 1984.
90. Chapman, R. M., "Attack Submarine Development - Recent Trends and Projected Needs," U.S. Naval Institute Proceedings, August 1978, pp. 97-102.