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ENABLING TECHNOLOGIES FOR NUCLEAR GAS TURBINE (GT-MHR) POWER CONVERSION SYSTEM

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ABSTRACT

Since the onset of gas-cooled reactor work, almost half a century ago, the potential for direct coupling of a nuclear heat source with a gas turbine power conversion system was recognized, however, the technologies for the realization of this were not available, and the plants operated to date have used Rankine steam turbine power conversion systems. In the early 1990s, technology transfer from the gas turbine and aerospace industries, now make possible the introduction of the gas turbine modular helium reactor (GT-MHR) for utility power generation within the next decade. In this paper the enabling technologies for the helium gas turbine power conversion system are discussed, and these include the turbomachinery, magnetic bearings, compact heat exchangers, and helium system operating experience. Utilizing proven technology, the first GT-MHR plant would operate with an efficiency of 47%, and by exploiting its full potential this could perhaps reach as high as 60% early in the next century.

1. INTRODUCTION

Since the nuclear gas turbine was first discussed in 1945 (Keller, 1945), engineering studies have been periodically undertaken in the coupling of a gas-cooled reactor with a helium closed-cycle gas turbine. Comprehensive design and development efforts were undertaken, both in the U.S. and Germany, in the mid to late 1970s, and it was concluded then, that the current state of technology was inadequate to support the deployment of a nuclear gas turbine project (McDonald and Peinado, 1982).

In the last decade, studies of the helium cooled reactor have focused on plants that are safer, smaller, simpler, and with improved economics. A considerable effort has been expended to establish a modular high temperature gas-cooled reactor (MHTGR) with a steam turbine power conversion system, with an efficiency of 38%. In this same decade the following have occurred: (1) continued hiatus in the U.S. nuclear industry, (2) repeal of the National Fuel Act to permit use of natural gas for power generation, and (3) large advancements in gas turbine technology. The result of these is, that in the next two decades, it is likely that gas turbines will become the dominant prime-mover for utility power generation in the U.S. Natural gas burning combined cycle gas turbine plants, with a capital cost on the order of $600/KW(e), are in service today with demonstrated efficiencies of 55%, and this will increase to over 58% for large machines soon to enter service (Farmer, 1993). It is projected that advanced industrial gas turbines, rated up to 300 MW(e), will operate at over 60% efficiency before the end of this century.

In light of the changing power generation market, a reassessment of the nuclear Brayton cycle in 1992 revealed that technology advancements in many areas, particularly from the gas turbine and aerospace industries, would now make the GT-MHR a reality, and offer much improved economics over the steam cycle variant. Such a power plant with an efficiency of around 47%, will have attractive economics for utility power generation shortly after the year 2000.

This paper addresses the key enabling technologies for the GT-MHR helium gas turbine power conversion system and includes the following: (1) turbomachinery technology transfer from aircraft and industrial gas turbines, (2) magnetic bearings, (3) compact high effectiveness plate-fin recuperators, and (4) experience from operating helium systems, this including circulators in nuclear plants (with submerged electrical drives), and the 50 MW(e) Oberhausen II helium turbine plant.

In the design of the GT-MHR power conversion system advantage will be taken of these proven technologies, and it will be based on the use of existing analytical methods, materials, and fabrication procedures. Following a significant penetration of the utility power generation market place, the successful operating experience with the state-of-the-art GT-MHR, together with advanced 21st century technologies (primarily to facilitate higher temperature operation), will permit the full potential of the nuclear gas turbine to be exploited, namely an efficiency perhaps as high as 60%.

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2. GAS-COOLED REACTOR EVOLUTION

The evolution of helium cooled reactors is shown in Fig. 1, and this is complemented by more than 50 carbon dioxide cooled reactors built and operated in the U.K. In the 1960s, four experimental facilities were constructed and operated, namely Dragon (U.K.), AVR (Germany), and Peach Bottom I and UHTREX (USA). Data from these plants were used to facilitate the deployment of two commercial plants in the 1970s, namely Fort St. Vrain and THTR.

Of the above, the most germane in terms of the gas turbine is the AVR plant in Germany which operated for over 21 years, and between 1974 and 1988, a helium outlet temperature of 950°C (1742°F) had been maintained on a long-term basis with low contamination of the circuit. In terms of temperature potential for the MHR it is of interest to note that the UHTREX reactor operated with a reactor outlet temperature of 1315°C (2400°F).

The next gas-cooled reactor being constructed is the 30 MW(t) HTTR in Japan which is expected to be operational in the late 1990s. This reactor has been designed for service up to 950°C (Saito, 1991), and will pave the way for advanced MHTGRs to meet energy needs that will emerge early in the 21st century (McDonald, 1993). Based on the utilization of proven technology, the initial GT-MHR plant could be in operation before the year 2005, and be replicated for utility service shortly after.

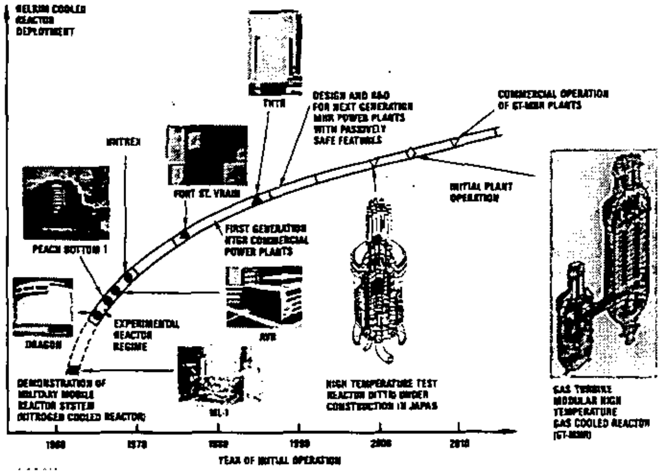

Fig. 1. Helium Cooled Reactor Evolution

3. GT-MHR PLANT CONCEPT

The GT-MHR plant configuration has as its genesis the steam cycle MHR that has evolved over the last 10 years (Bramblett, 1991). The gas turbine plant configuration, which is currently in the conceptual design stage, is shown on Fig. 2. Since the plant design concept has been described previously (Simon, Zgliczynski, 1993 and Neylan 1994), only a brief summary is included here.

The plant is based on a highly recuperatured and intercooled Brayton cycle with a net plant efficiency of over 47% (with a reactor outlet temperature of 850°C), which with a core thermal rating of 600 MW(t) could give a module output approaching 300 MW(e). The GT-MHR module arrangement consists of two vertical, juxta-positioned steel vessels with a connecting concentric crossduct vessel as shown in Fig. 2. The reactor vessel contains the annular reactor core, which consists of an assemblage of prismatic fuel elements, and this provides the thermal energy to directly drive a helium turbine that is an integral part of the reactor coolant circuit.

Since this paper addresses the enabling technologies for the power conversion system, it is germane to focus attention on the internals of the power conversion system as shown in Fig. 3. The power conversion vessel, made from modified 9Cr alloy steel is approximately 7 m (23 ft) in diameter and 22 m (72 ft) long, contains the entire power conversion system.

The major component, installed on the center line of the vessel is the vertical single-shaft helium turbomachine which drives the generator. The gas turbine which consists of two compressor sections (separated to facilitate intercooling) and the turbine, is supported from a structure in the plane of the main vessel flange. This structure separates the reactor coolant helium from the clean helium within the generator cavity. The major advantage of the submerged generator is that it obviates the need for a shaft penetrating the primary system boundary. While yet to be optimized, the rotational speed is less than 5000 rpm, and the output of the nonsynchronous generator is coupled to a solid state variable frequency power converter which can provide power at 60 or 50 Hz to the grid. One of the key technologies making the nuclear gas turbine viable is the use of active magnetic bearings, since this eliminates one of the earlier concerns, namely lubricant ingress. The current rotor design is suspended on three journal

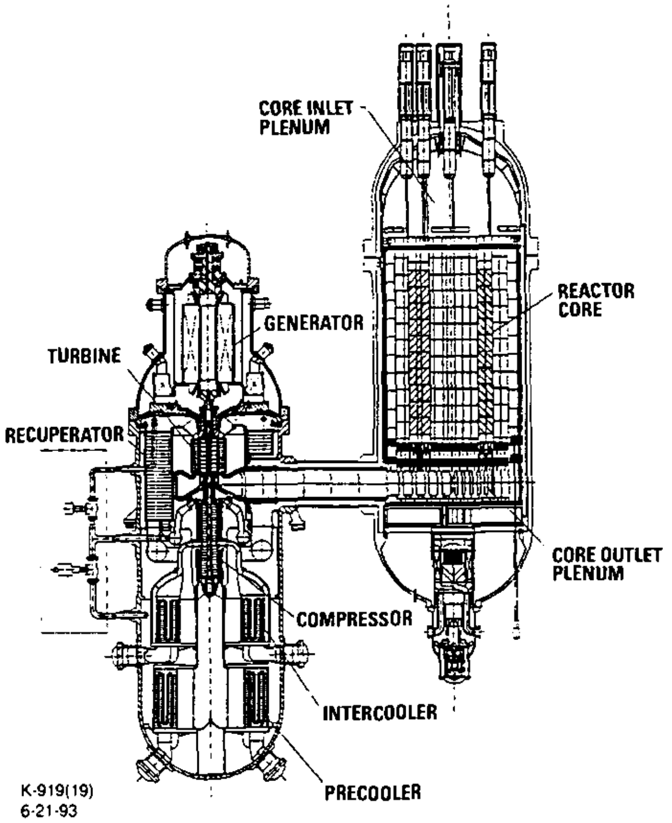

Fig. 2. GT-MHR Plant Arrangement

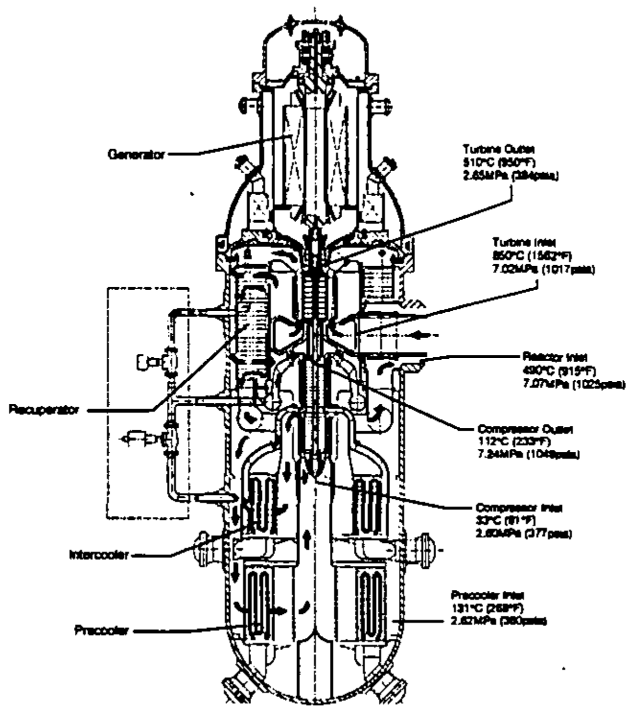

Fig. 3. GT-MHR Power Conversion Vessel Assembly

bearings, and the thrust bearing is installed at the top of the rotating assembly for ease of access.

There are three heat exchangers installed in the power conversion vessel, and they provide an important role in the realization of high efficiency. The heat exchangers in the Brayton cycle are far less demanding in terms of operating temperature than in the Rankine cycle since they are installed in the system after the prime-mover, but they do have demanding requirements in terms of compactness for installation within the vessel. The role of the recuperator is to utilize thermal energy from the turbine exhaust to preheat the high pressure compressor discharge helium before it enters the reactor, thus contributing to efficiency enhancement. The recuperator utilizes a high surface compactness plate-fin type of geometry to meet the 95% effectiveness requirement. In the current design, six recuperator modules are used. The precooler and intercooler are low temperature, radial flow, water cooled, heat exchangers. The reject heat from the cycle is removed in the precooler. The major role of both of these units is to provide low helium inlet temperature to the compressors, and this is important since the power absorbed by the compressors is directly proportional to the absolute inlet temperature. These heat exchangers, utilizing finned-tube geometries and a cross-counterflow configuration, operate in a very quiescent environment. An important aspect of these Brayton cycle heat exchangers if that water ingress to the helium circuit (in the event of a tube leak) is obviated since the helium is at a higher pressure than the water.

The aforementioned components are interconnected by a series of ducts to give the required gas-flow paths. The geometries for these ducts must be carefully established as the plant design advances, to minimize pressure loss and ensure good velocity distributions into the turbomachinery bladed sections and heat exchangers. In a similar manner detailed attention must be given to the structural support of the components to accommodate differential thermal expansion and to facilitate ease of installation and removal.

Salient features of the plant are given in Table 1, these representing data at the current conceptual design stage. Work in progress will confirm the configuration, reactor power, and power equipment design parameters for the pioneer plant. It should be pointed out that, in the computation of the 47% net plant efficiency, state-of-the-art component performance was assumed. In looking to the future, perhaps two decades beyond initial introduction of the GT-MHR, considerable "pushing of the envelope" can be projected. By increasing the reactor outlet temperature, factoring in evolutionary advancements in turbomachinery and heat exchangers, and evaluating the practicality of more advanced thermodynamic cycles (e.g., two stages of intercooling, combined cycles, etc.), the potential exists for an efficiency of over 60% (McDonald and Etzel, 1994).

TABLE I
SALIENT FEATURES OF GT-MHR PLANT

PLANT DATA	PLANT TYPE	NUCLEAR GAS TURBINE
	CONSTRUCTION TYPE	MODULAR
	REACTOR TYPE	MHR
	CORE GEOMETRY	ANNULAR CORE
	FUEL ELEMENT TYPE	PRISMATIC BLOCK
	POWER CONVERSION SYSTEM	DIRECT CYCLE HELIUM GAS TURBINE
	CORE THERMAL RATING, MWt	600
	MODULE POWER OUTPUT, MWe	286
	NET EFFICIENCY, %	47.6
THERMAL DATA	THERMODYNAMIC CYCLE	RECUPERATED/INTERCOOLED
	TURBINE INLET TEMPERATURE, °C(°F)	850 (1562)
	TURBINE INLET PRESSURE, MPa (PSIA)	7.0 (1017)
	COMPRESSOR PRESSURE RATIO	2.8
	COMPRESSOR EFFICIENCY, %	90
	TURBINE EFFICIENCY, %	92
	RECUPERATOR EFFECTIVENESS	0.95
	SYSTEM PRESSURE LOSS (ΔP/P) %	6
COMPONENT DESIGN FEATURES	TURBOMACHINE	SINGLE-SHAFT ROTOR
	COMPRESSOR TYPE (STAGES)	MULTISTAGE AXIAL FLOW (11/15)
	TURBINE TYPE (STAGES)	MULTISTAGE AXIAL FLOW (9)
	GENERATOR TYPE	ASYNCHRONOUS 50/60 Hz
	BEARING TYPE	ACTIVE MAGNETIC BEARINGS
	RECUPERATOR TYPE	COMPACT PLATE-FIN MODULES
	PRECOOLER/INTERCOOLER TYPE	RADIAL FLOW STRAIGHT TUBE
	PRESSURE VESSEL(S)	VERTICAL JUXTAPOSITIONED STEEL VESSELS
PLANT STATUS	DESIGN STATUS	CONCEPTUAL
	TECHNOLOGY STATUS	STATE-OF-THE-ART
	DEPLOYMENT	2003-2005

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4. ENABLING TECHNOLOGIES FOR POWER CONVERSION SYSTEM

4.1. Helium Turbomachinery

While the properties of helium influence the gas flow geometries (as will be discussed below) it is important to note that the aerodynamic and structural design procedures used are identical to conventional air-breathing gas turbine practice. To the nonspecialist, gas turbines with a rating on the order of 300 MW(e), as outlined in this paper, may seem large compared with open cycle units, but in point of fact the high degree of pressurization associated with the closed cycle system results in machine sizes that are physically smaller than industrial and aeroderivative gas turbines in utility service, and since the enthalpy drop in the turbine is many times greater than air, very high specific power can be realized. After many years of experience, the design of helium turbomachinery today is well understood (McDonald, 1981; Haselbacher, 1974; and Ponomarev-Stepnoi, 1981).

The key to the design of high efficiency helium turbomachinery is the technology available from the gas turbine industry, both industrial and aeroderivative units. Details of a pre-conceptual design of the helium turbine are compared with existing machines in Table 2. For comparative purposes, two General Electric gas turbines are included: (1) the MS9001F (Brandt, 1990) shown in Fig. 4 is a heavy industrial gas turbine that is in operation with a rating of 226 MW(e) and (2) the LM6000 (Casper, 1993) shown in Fig. 5 which is derived from the CF6-80C2 commercial aircraft engine and is rated at 42 MW(e). State-of-the-art technology from these engines is directly applicable to the design of the helium turbomachine, particularly in the areas of design methodology, performance, materials, and fabrication methods. Design of the helium turbomachine for the GT-MHR by General Electric Aircraft Engines is currently in progress.

TABLE 2
TURBOMACHINE FEATURE COMPARISON

APPLICATION	NUCLEAR GAS TURBINE	FOSSIL-FIRED HELIUM CLOSED-CYCLE GAS TURBINE	POWER GENERATION	
			HEAVY DUTY INDUSTRIAL GT	AERODERIVATIVE GAS TURBINE
PLANT DESIGNATION	GT-MHR	OBERHAUSEN II	MS9001F (GE)	LM6000 (GE)
POWER, MW(e)	~300	50	226	42
WORKING FLUID	HELIUM	HELIUM	AIR	AIR
THERMODYNAMIC CYCLE	RECUPERATED & INTERCOOLED	RECUPERATED & INTERCOOLED	SIMPLE CYCLE	SIMPLE CYCLE
TURBINE INLET TEMP, °C (°F)	850 (1562)	750 (1382)	1288 (2350)	1243 (2270)
COMPRESSOR PRESSURE RATIO	2.8	2.7	15	30
MASS FLOW RATE KG/SEC (LB/SEC)	320 (705)	85 (187)	613 (1351)	123 (271)
COMPRESSOR NUMBER OF STAGES MAX. TIP DIAMETER, MM (IN.)	 11 LP + 15 HP 1245 (49)	 10 LP + 15 HP —	 18 2515 (99)	 5 LP + 14 HP 1372/737 (54/29)
TURBINE NUMBER OF STAGES MAX. TIP DIAMETER, MM (IN.) BLADE COOLING/MATERIAL	 9 1500 (59) UNCOOLED/NICKEL BASE ALLOY	 11 LP + 7 HP — UNCOOLED/NICKEL BASE ALLOY	 3 3251 (128) COOLED/GTD-111	 2 LP + 5 HP 1321/889 (52/35) COOLED/NICKEL BASE ALLOY
ROTATIONAL SPEED, RPM	3000	5500/3000	3000 (50 Hz)	3600
SHAFT ARRANGEMENT	SINGLE SHAFT	TWIN/GEARED	SINGLE SHAFT	TWIN SHAFT
MACHINE ORIENTATION	VERTICAL	HORIZONTAL	HORIZONTAL	HORIZONTAL
BEARING TYPE	ACTIVE MAGNETIC BEARINGS	OIL LUBRICATED	OIL LUBRICATED	OIL LUBRICATED
YEAR ENTERING SERVICE	~2005	1974	1991	1992

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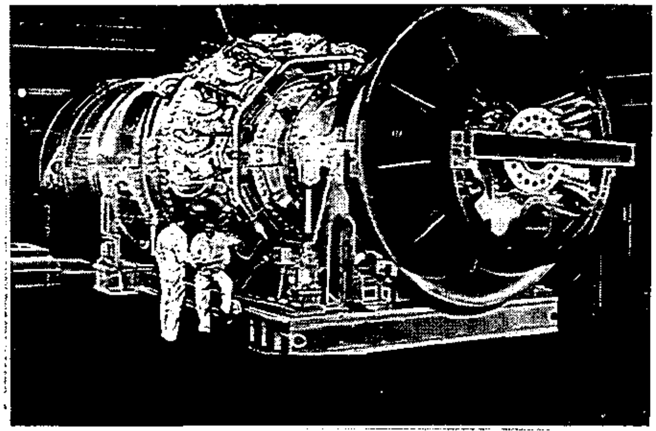

Fig. 4. MS9001F Industrial Gas Turbine (Courtesy General Electric Company)

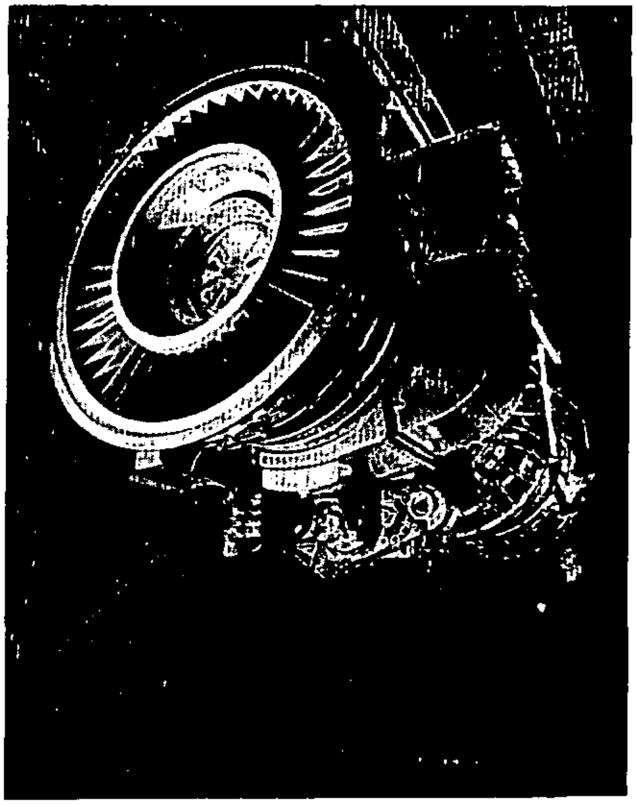

Fig. 5. LM6000 Aeroderivative Gas Turbine (Courtesy General Electric Company)

Since the choice of working fluid affects the turbomachinery, it is germane to briefly discuss the impact of using helium. The specific heat of helium is five times that of air, and since the stage temperature rise varies inversely as the specific heat (for a given limiting blade speed), it follows that the temperature rise available per stage when running with helium will be only one-fifth that of air, and this of course, results in more stages being required for a helium compressor. It is fortunate that in a highly recuperated helium closed Brayton cycle the optimum pressure ratio is low (i.e., 2.8) and, in fact, the number of compressor and turbine stages are comparable with air-breathing gas turbines.

Substiution of helium for air greatly modifies aerodynamic requirements by removing Mach number limitations; the problem then becomes that of trying to induce the highest possible gas velocities that stress-limited blades will allow. The size of the machine is dictated by the choice of blade speed, there being an incentive to use the highest values possible commensurate with stress limits to reduce the number of stages, since the stage loading factor is inversely proportional to the square of the blade speed. In an open cycle gas turbine, the centrifugal blade root stress is dominant and this is proportinnal to the blading annulus area times the square of the speed. In a highly pressurized closed-cycle system, the gas bending stress must also be included and this tends to give blades of increased thickness and longer chordal dimensions. The latter impacts the length of the bladed rotor, and hence the bearing span.

A helium turbomachine tends to be characterized by the following: (1) high hub-to-tip ratio, (2) low aspect ratio, (3) low Mach number (<0.4), (4) high Reynolds number ($>3 \times 10^6$),

(5) very small annulus flare (because of small gas density difference across the blading), and (6) long slender rotor. For the helium turbomachine, high compressor and turbine efficiencies are projected based on a combination of the following: (1) low Mach number, (2) high Reynolds number, (3) clean oxide-free blading surfaces in the closed circuit, and (4) close blade tip clearance for the based loaded plant.

In the case of the turbine, the very modest inlet temperature of 850°C can be accommodated with uncooled blades made from existing nickel-base alloys. The turbine is, of course, free from corrosion effects associated with combustion products. The load change transients in the nuclear plant are mild compared with those in combustion turbines. The helium turbomachine is being designed for a life of 40 years, with scheduled removal at 7 year intervals for inspection and maintenance as required. To minimize plant downtime, a spare turbomachine will be kept at the plant site, and it is projected that the unit could be removed and replaced in a 10 day period. The unit removed would be decontaminated and refurbished for future use.

In closing on this section, it is pertinent to point out that the helium turbomachine is, in fact, less complex than a modern high bypass ratio turbofan engine for commercial airline service. Within the industry, a very high confidence level is expressed for near term deployment of a helium gas turbine.

4.2. Active Magnetic Bearings

In studies of the direct cycle gas turbine done over 15 years ago, the only choice of bearing was an oil lubricated system since the rotor weight was too great for practical gas bearings. Oil bearing systems were very complex (Adams, 1978), and even with redundant gas buffered labyrinth seals, there was always concern about potential oil ingress into the reactor system. Over 5 years ago the potential for the use of magnetic bearings in closed cycle systems was recognized (McDonald, 1988), and in the meantime, there has been substantial use of them in industrial applications (Dussaux, 1990). Today, over 6 million hours of operating time has been accumulated on active magnetic bearings. Over 120 large turbomachines (i.e., gas compressor, gas turbines, turboexpanders, etc.) have run for more than 1.5 million hours, and simply stated, the technology is mature enough for the GT-MHR.

In the GT-MHR turbomachine (Fig. 3) the current layout has a bottom-mounted journal bearing, a midspan journal bearing, and above the generator is a combined journal and thrust bearing. A distinguishing feature compared with the aforementioned applications is the vertical orientation of the rotating assembly. The major impact that this has is on the bearing system relates to the catcher bearing. If the magnetic field is lost (although an unlikely event because of built-in redundancy), the rotor will drop onto catcher bearings. The catcher bearing system must be capable of withstanding multiple drops without incurring damage during the rundown of the machine. An approach to give a "soft drop" capability would utilize a hydrostatic gas catcher bearing supplemented by a self-lubricated sleeve bearing for extreme load conditions and operation at low speed (Storace, 1993).

For a 300 MW(e) helium turbomachine, the rotor weight could be as high as a 40 tons. In the initial design concept, the rotor aerodynamic thrust is upwards and is almost identical in value to the rotor weight. This means that a "rotor drop" onto the thrust catcher bearing at full speed will not be dramatic, nevertheless, the catcher bearing must be designed to take the full rotor weight. While the rotor is heavier than in applications to date, the thrust bearing unit loadings and peripheral velocities are bounded by current operating experience. It is of interest to note, that in support of a helium circulator program, funded by EPRI, a magnetic bearing test program was conducted by James Howden and Company in Scotland. A vertical rotor with a rotational speed of 6000 rpm, and a simulated thrust of over 10 tons was repeatedly dropped onto a dry-lubricated thrust catcher bearing. Over 25 drops were experienced without damage, and valuable data were generated in terms of material selection and bearing geometry for operation in a helium system. It is also of interest to note, that a small [20 KW(e)] helium circulator (Fig. 6) has operated over 15,000 hr trouble-free with magnetic bearings (Henssen, 1985). The significance of this application is that the circulator operated in a high temperature helium test loop with a gas inlet temperature of 950°C, and this necessitated the use of ceramic insulation in the bearing area.

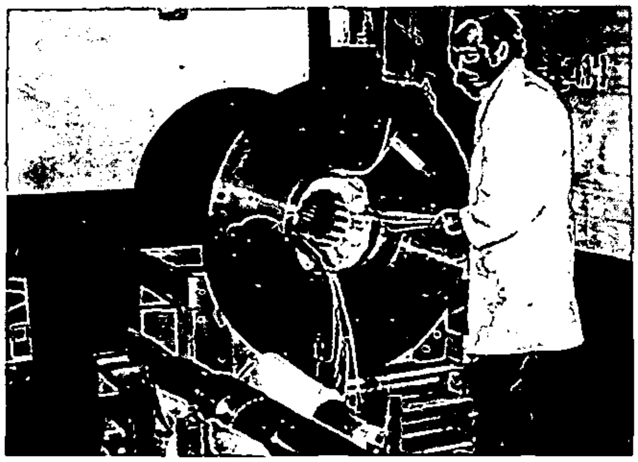

Fig. 6. Helium Circulator with Magnetic Bearings (Courtesy HRB, Germany)

Clearly, the GT-MHR can take advantage of the aforementioned technology, but testing of the full size bearings must be undertaken prior to the fabrication of the first turbomachine. Design verification of both the journal and thrust bearings will be an important task early in the program. Since the turbomachine is not directly synchronized with the grid (but rather a frequency converter is used), an inherent part of the control system will be to vary the speed. This means that rotor dynamic stability must be assumed over a wide speed range, and this must be verified to get a good understanding of the critical speeds.

4.3. Compact Plate-Fin Recuperator

Perhaps the key technology that facilitates the high efficiency of the GT-MHR plant is the utilization of a compact recuperator. In early direct cycle gas turbine studies, the state-of-the-art recuperator technology permitted only the use of tubular geometries, and with their low compactness, the effectiveness was limited to less than 90% because of volume limitations within the vessel (McDonald, 1977). Since then, very significant advancements have been made in gas turbine recuperator technology (McDonald, 1990a, b). It is the compact plate-fin type of recuperator (Kretzinger, 1985), that permits utilization of higher effectiveness values, with attendant gains in plant efficiency and operating economies.

The GT-MHR plant design embodies six recuperator modules, of about the same size as used in current regenerative industrial gas turbine engines (Fig. 7). A comparison of the GT-MHR recuperator design with other applications is given in Table 3. Operating in a clean, closed helium circuit, very small hydraulic diameter passages can be used, with resultant surface compactness values on the order of three times that in open cycle gas turbine recuperators. Operating in the laminar flow regime, but with highly offset surfaces, very high heat transfer coefficients can be realized by virtue of the surface geometry, high system pressure and the high thermal conductivity of helium. With the very high unit thermal density (i.e., 17 MW/m^3), an effectiveness of 95%, together with a low pressure loss, can be achieved with a six module recuperator that is readily integrated in the power conversion system (Fig. 3).

Existing recuperator technology established by Allied-Signal Aerospace Company is directly applicable to the GT-MHR. Over 60 recuperated industrial gas turbines have accumulated over 3 million hours of service. The operating environment for these units, in terms of transients and thermal shock is more severe than those that will be experienced in the GT-MHR. The recuperator gas inlet temperature of 510°C (950°F) is modest compared with other applications (e.g., vehicular gas turbine units) and 316 stainless steel can be used. Direct technology transfer to the GT-MHR will include: (1) heat transfer analytical methodology, (2) mechanical design, (3) structural analysis, (4) fabrication, and (5) development testing.

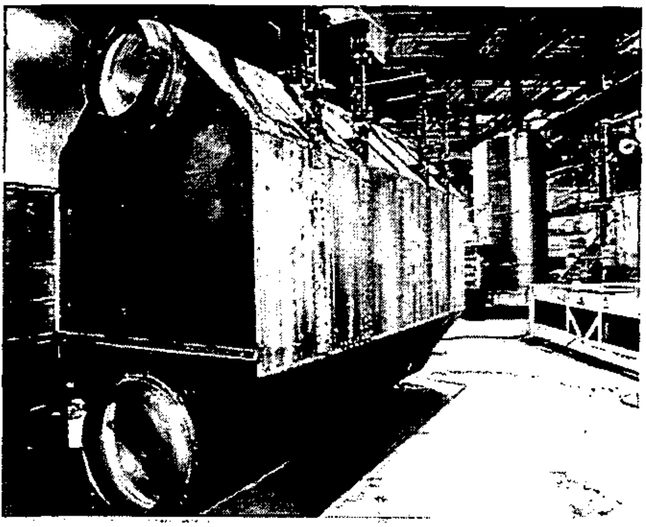

Fig. 7. Compact Plate-Fin Recuperator Module (Courtesy Allied-Signal Aerospace Company)

TABLE 3
RECUPERATOR FEATURE COMPARISON

APPLICATION	NUCLEAR GAS TURBINE	FOSSIL-FIRED HELIUM CLOSED-CYCLE GAS TURBINE	REPRESENTATIVE/ RECUPERATED INDUSTRIAL GAS TURBINES
PLANT DESIGNATION	GT-MHR	OBERHAUSEN II	
WORKING FLUIDS	HELIUM/HELIUM	HELIUM/HELIUM	AIR/GAS
GAS TURBINE RATING, MW(e)	~300	50	10-60
RECUPERATOR TYPE	PLATE-FIN	TUBE AND SHELL	PLATE-FIN
SURFACE GEOMETRY	COMPACT OFFSET FINS	PLAIN TUBES	COMPACT OFFSET FINS
FLOW CONFIGURATION	COUNTERFLOW	CROSS COUNTERFLOW	COUNTERFLOW
TYPE OF CONSTRUCTION	BRAZED ASSEMBLY	WELDED	BRAZED ASSEMBLY
RECUPERATOR ASSEMBLY	MODULAR	MONOLITHIC	MODULAR
NUMBER OF RECUPERATOR CORES	6	1	2 TO 8
MASS FLOW, KG/SEC (LB/SEC)	320 (705)	85 (187)	45–240 (100–530)
HOT GAS INLET TEMP., °C (°F)	510 (950)	460 (860)	510–575 (950–1065)
INTERNAL PRESSURE DIFFERENTIAL, MPa (PSI)	4.6 (664)	1.8 (255)	0.9 (130)
EFFECTIVENESS	0.95	0.80	0.80 TO 0.88
OVERALL PRESSURE LOSS, %	2.8	2.8	3.5 TO 4.0
MATERIAL	316 ST. ST.	MEDIUM CARBON STEEL	409 ST. ST
COUNTERFLOW SURFACE DENSITY, M^2/M^3 (FT^2/FT^3)	1906 (581)	130 (40)	624 (190)
THERMAL DENSITY, MW/M^3	17	2	1
SERVICE LIFE, YEARS	40	30	UP TO 40
YEAR ENTERING SERVICE	~2005	1974	1979(a)

(a)APPROXIMATELY 60 RECUPERATED GAS TURBINES IN SERVICE WITH AN ACCUMULATED RUNNING TIME OF 3.15 MILLION HOURS

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The closed cycle system operates with a higher recuperator pressure differential than open cycle units, but the value of 4.6 MPa (664 psi) is bounded by existing plate-fin heat exchanger experience. As part of the component development program, a full size recuperator module would be tested to confirm its performance and structural integrity under representative plant conditions. The recuperator is a helium-to-helium heat exchanger, and if leaks develop in service, the only impact will be slight degradation of plant performance. While minor leaks can be tolerated, if the level reaches a point where performance loss is significant, the faulted module will be removed and replaced.

The precooler and intercooler are helium-to-water heat exchangers and they operate in a very benign environment, and in fact, their metal temperatures are less than 121°C (250°F). The technology for these units is commercially available. In both units the water-side is pressurized to suppress boiling and stable operation is assured. Since the helium pressure is greater than the water pressure, the issue of water ingress into the reactor circuit, as a result of a tube failure for example, is obviated.

4.4. Helium System(s) Experience

4.4.1. Rotating Machinery in Gas-Cooled Reactors

Experience gained from the operation of helium circulators in the AVR, THTR, and FSV plants provides another valuable data source for the GT-MHR. The circulators in the AVR and THTR (Fig. 8) plants were horizontal machines with submerged electric motor drives (IAEA, 1988). While the di-electric strength of helium is different from that of air or hydrogen (used in the

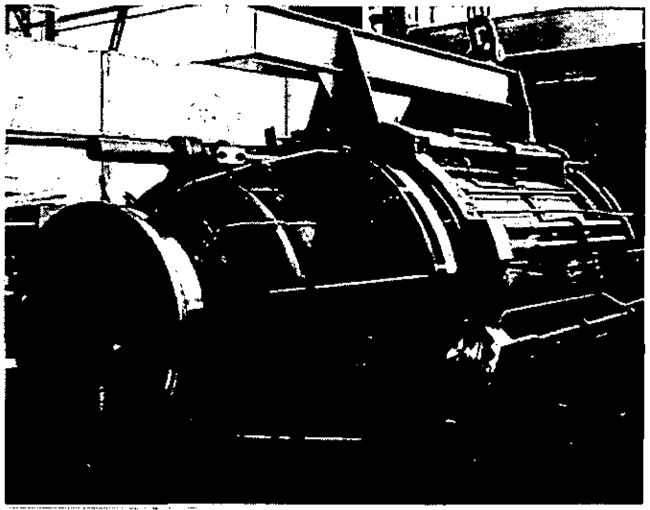

Fig. 8. THTR Plant Helium Circulator (Courtesy HRB, Germany)

cooling of conventional generators), the insulation system in the submerged systems performed well. In the AVR plant, each of the two circulators operated trouble-free for over 130,000 hr during the 24 year plant life. In the THTR plant, the six circulators had accumulated over 100,000 hr of trouble-free operation when the plant was prematurely decommissioned. These German machines have been included in this discussion mainly because of their utilization of submerged electric motor drives. This proven technology will be used for the submerged generator in the GT-MHR plant.

Experience gained from the operation of the vertical axial flow circulators in the FSV plant is also germane (McDonald, 1992). Particularly valuable know-how associated with operating in helium included sealing techniques, which are difficult with a low molecular weight gas, and coatings application to avoid galling and self-welding in mating oxide-free surfaces. Removal and replacement procedures were well established for handling vertical assemblies, particularly the utilization of shielded casks. A circulator was removed from the plant after 60,000 hr service, and with only local water washing of the impeller (shown in Fig. 9), direct hands-on maintenance was undertaken. It is hoped that this will be the case for the helium turbomachine.

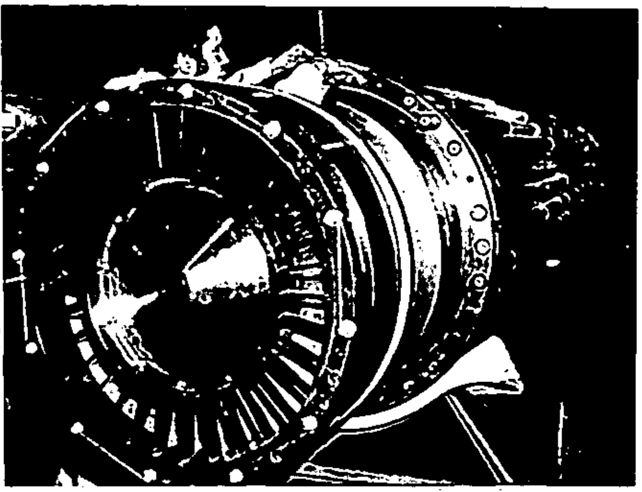

Fig. 9. Fort St. Vrain Plant Helium Circulator

4.4.2. Oberhausen II Helium Turbine Plant

The largest of the European closed-cycle gas turbines was the 50 MW(e) Oberhausen II helium turbine plant that operated in Germany (Zenker, 1988). The coke oven gas-fired plant (Fig. 10) operated for over 30,000 hr with a turbine inlet temperature of 750°C (1382°F). The selection of a relatively low system pressure for this plant (compared with future nuclear systems) yields a larger volumetric flow of the helium working fluid, and accordingly, the actual equipment is comparable in size to a plant rated close to 300 MW(e). The size of the bladed rotor would, in fact, be similar to that needed for the GT-MHR plant (Table 2). Valuable experience gained from operation of this plant could benefit the GT-MHR in the following areas: (1) plant control, (2) component characteristics (over full operating spectrum), (3) transient data, (4) methods to establish helium leak tightness, (5) rotor dynamics, (6) acoustic data, and (7) reliability.

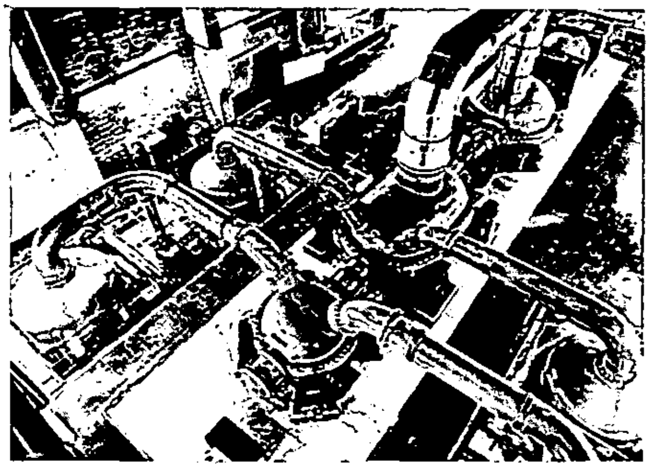

Fig. 10. Oberhausen II Helium Turbine Power Plant (Courtesy EVO, Germany)

4.5. Other Power Conversion System Components

While the major components have been discussed above, there are many other pieces of equipment that are important to the operation of the power conversion system and these include: controls and instrumentation, bypass valves, seals, ducts, condition monitoring equipment, in-service inspection probes, services (electrical and labyrinth seal buffer gas supply), vessel penetration, and all of the handling equipment for remote removal and replacement of the turbomachine and other components. The aforementioned components are installed in the power conversion vessel, and advantage will be taken of light water reactor experience with steel pressure boundary components in the U.S. which covers over 1500-reactor years of successful operation in over 100 operating commercial power plants. All of these items require detailed design, but their fabrication and development are bounded by existing experience in the power generation industry.

5. GT-MHR DEPLOYMENT

The formulation of a detailed deployment plan is currently in progress, and for the power conversion system there are essentially two major elements: (1) subcomponent testing and (2) an integrated test (with a nonnuclear heat source) of the complete power conversion system.

Subcomponent testing would include the following: (1) turbomachine magnetic bearings, (2) seals, (3) performance and life cycle tests of a recuperator module, (4) by-pass valves, and (5) control and instrumentation. Data from these tests would be factored into the system final design with a high degree of confidence that the first unit will operate well and meet the requirements.

Because of the complex nature of the integrated system within the confines of the steel vessel, there is a need for a design verification test of the complete power conversion system using a nonnuclear heat source prior to reactor operation. With initial operation in a clean helium environment, it will be possible to quickly remedy any minor deficiencies if they are identified. The following would be accomplished: (1) interface resolution, (2) performance verification, (3) bypass/leakage flow qualification,

(4) flow distribution measurement, (5) calibration of control and instrumentation system, (6) signature characterization (e.g., acoustics) for condition monitoring system, (7) verification of remote handling equipment for turbomachine removal and replacement, and (8) operator training.

Various options for the nonnuclear test facility are currently being evaluated, but perhaps the most cost-effective method would be to completely simulate the reactor system. The complete power conversion system vessel would be identical to future commercial units, as would be the complete reactor vessel. A temporary heater, either fossil-fired or an electrical unit, would be installed in the reactor vessel. The actual rating of the heater would be related to the system pressure (perhaps 20% of the design value), but a major requirement would be to operate the helium turbomachine at full speed and at the design value of turbine inlet temperature (850°C). Following verification of the system on "clean helium," and resolution of any minor deficiencies identified, the temporary heater would be removed and replaced with the reactor core. Following a short period of monitored nuclear operation, the plant would start commercial service. This deployment approach is consistent with a schedule that would facilitate operation of a revenue-bearing GT-MHR plant before the year 2005.

6. SUMMARY

The GT-MHR will enter utility service at a time when gas turbines (burning natural gas and coal gas) could be the dominant prime-mover in the U.S. These high efficiency plants with high reliability will pave the way for the nuclear gas turbine, since its introduction, as perhaps the ultimate "green technology," is only a matter of resolve. As outlined in this paper, the GT-MHR plant, based on existing and proven technology, will operate with an efficiency of about 47%. With the utilization of advanced technologies, the potential exists for advancement to over 60%.

The major point made in this paper is as follows: the technology for the GT-MHR plant has a sound basis in the U.S., and no breakthroughs are necessary in terms of component design/performance or materials advancements, however, a thorough program of development and testing for design verification must be adhered to.

With a cooperative international program, the GT-MHR could be realized early in the first decade of the 21st century, and meet the needs of the industrialized and newly industrializing nations throughout the next century.

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