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HELIUM TURBOMACHINE DESIGN FOR GT-MHR POWER PLANT

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ABSTRACT

The power conversion system in the gas turbine modular helium reactor (GT-MHR) power plant is based on a highly recuperated closed Brayton cycle. The major component in the direct cycle system is a helium closed-cycle gas turbine rated at 286 MW(e). The rotating group consists of an intercooled helium turbocompressor coupled to a synchronous generator. The vertical rotating assembly is installed in a steel vessel, together with the other major components (i.e., recuperator, precooler, intercooler, and connecting ducts and support structures). The rotor is supported on an active magnetic bearing system. The turbine operates directly on the reactor helium coolant, and with a temperature of 850°C (1562°F) the plant efficiency is over 47%. This paper addresses the design and development planning of the helium turbomachine, and emphasizes that with the utilization of proven technology, this second generation nuclear power plant could be in service in the first decade of the 21st century.

1. INTRODUCTION

The gas turbine modular helium reactor (GT-MHR) is a second generation meltdown-proof nuclear power plant that is under development and planned to be operational early in the next century. The power conversion system is based on a direct Brayton cycle, with intercooling and a high degree of recuperation. With a turbine inlet temperature of 850°C (1562°F) the plant efficiency is over 47%, and this is based on using technology from the gas turbine and aerospace industries.

The complete power conversion system, including the closed-cycle helium gas turbine, generator, recuperator, intercooler, and interconnecting ducts is integrated in a steel vessel. The key component in the system is a vertical turbomachine set which consists of a low and high pressure compressor (separated to facilitate intercooling), a turbine, and submerged generator. The single shaft 286 MW(e), 3600 rpm, rotating assembly is supported on active magnetic bearings. While the properties of helium influence the gas flow path geometries, the aerodynamic and structural design procedures used are similar to conventional air-breathing aeroengine gas turbine practice. The high specific power associated with helium operation, together with the high gas pressure in the closed helium loop, results in a machine size that is physically smaller than industrial and aeroderivative gas turbines currently in utility service.

The design and operation of systems with helium as the working fluid is well understood, and a brief section is included with some background information related to helium turbomachinery. Following a brief description of the power conversion system this paper is focused on the aerodynamic, mechanical, and electrical design studies to establish a turbomachine configuration that is compatible with integration in the power conversion vessel. The key to the design of the high efficiency turbomachinery in the GT-MHR plant is the technology available from the gas turbine industry, both industrial and aeroderivative units, and this point is emphasized.

2. BACKGROUND ON HELIUM TURBOMACHINERY

Helium is an ideal working fluid for a nuclear gas turbine because it does not become radioactive and has excellent heat transfer properties. A substantial data base exists regarding an understanding of how the unique properties of helium will be addressed in the design and operation of the rotating machinery.

In the 1970s, two helium facilities were built and operated in Germany, and the roles that they played in the European studies of a nuclear gas turbine plant in that era have been discussed previously (Noack, 1975) and, thus, are only briefly mentioned here. The Oberhausen II 50 MW(e) helium turbine plant had a coke oven gas-fired heater to give a turbine inlet temperature of 750°C (1382°F). In addition, to providing electrical power and district heating to the city of Oberhausen in Germany, data were recorded on the dynamics of the overall plant and on the long-term behavior of specific components. The selection of a relatively low system pressure for this power plant yielded a larger volumetric flow of the helium working fluid, and accordingly the actual rotor size (Fig. 1) is comparable in size to a plant rated at over 200 MW(e). The tip diameter of the turbine last stage is 1525 mm (60 in.).

A high temperature test facility (HHV) was also operated in Germany (at KFA in Julich). The helium turbomachine consisted of two turbine stages [45 MW(e)] and an eight stage compressor [90 MW(e)], with the power difference being supplied by a 45 MW(e) synchronous motor. With compression heat the facility was operated up to a temperature of 850°C (1562°F). The combination of turbine and compressor and the thermodynamic conditions in the closed loop results in a turbomachine rotor (Fig. 1) with dimensions representative of a helium turbine of approximately 300 MW(e) output. The tip diameter of the turbine last stage at 1829 mm (72 in.) is very similar to the GT-MHR turbine with a maximum diameter of 1783 mm (70.2 in.).

Tests performed in the above two facilities confirmed the feasibility of helium turbomachinery of the size required in the GT-MHR. It is also germane to mention that the design of helium turbomachinery is well understood (Hurst, 1970; Endres, 1970; Haselbacher, 1974, 1978; and McDonald, 1980;). Another important technology base is that of the gas circulators operated in helium cooled reactors (IAEA, 1988). Data gained from many years of operation, particularly related to materials considerations in a reactor environment, together with handling and decontamination of rotating machinery, will be utilized in the GT-MHR program.

3. GT-MHR POWER CONVERSION SYSTEM

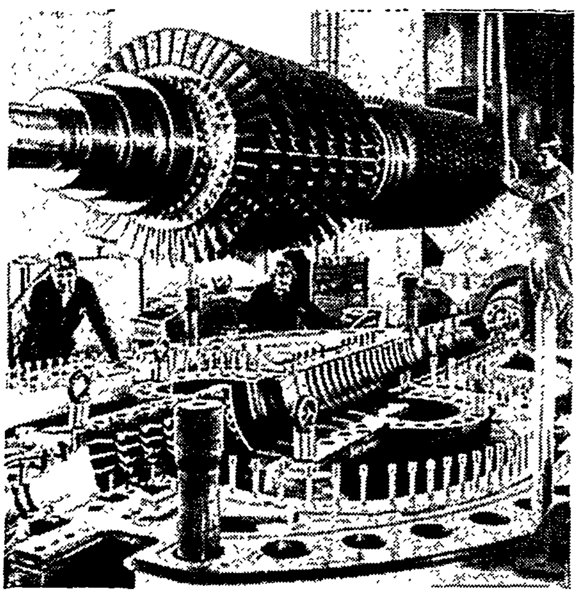
3.1. Plant Configuration

Since the power plant concept has been described previously (Simon, 1993) only a summary will be given here. The physical arrangement of a single module is shown in Fig. 2. The plant, which could consist of a multiplicity of modules, is installed in a below-grade silo, this providing a secure sabotage/damage resistant facility. The primary system components are contained within three steel vessels: a reactor vessel, a power conversion vessel, and a connecting vessel. Salient features of the plant are given in Table 1. Details of the reactor system have been described previously (Baxter, 1994) and the nuclear design draws heavily on the five helium cooled nuclear power plants that have operated in the U.S. and Europe (Melese, 1984). The power conversion system is briefly described in the following section.

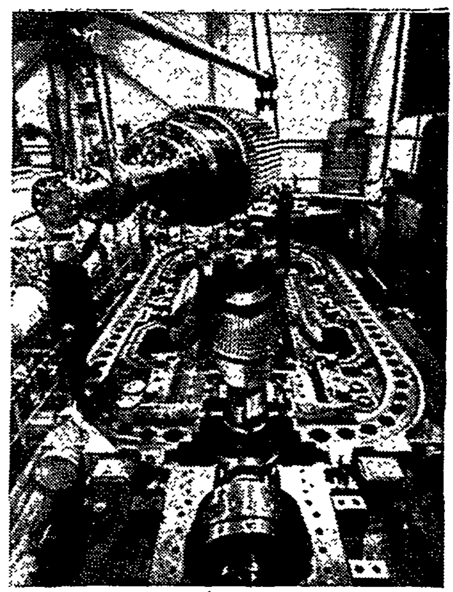
3.2. Power Conversion System

Details of the power conversion system have been discussed previously (McDonald, 1994a) and only a summary will be given here. The power conversion vessel (Fig. 3) contains the helium turbomachine, generator, and the heat exchangers. The major component, installed on the center line of the vessel is the vertical single-shaft helium turbomachine which drives the generator, and the remaining sections of this paper are focused on this component.

There are three major heat exchangers installed in the power conversion vessel and they provide an important role in the



HIGH PRESSURE ROTOR FROM
OBERHAUSEN II HELIUM GAS TURBINE



ROTOR FROM HHV
TEST FACILITY

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FIG. 1. CLOSED-CYCLE GAS TURBINE HELIUM TURBOMACHINERY

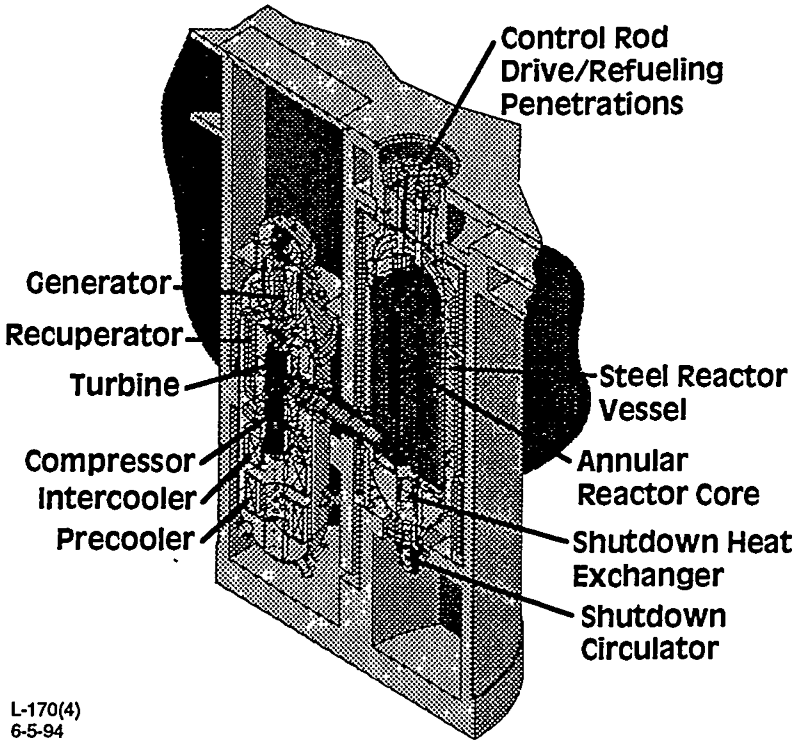

FIG. 2. GT-MHR POWER PLANT CONFIGURATION

TABLE 1
SALIENT FEATURES OF GT-MHR POWER 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 DESIGN GOAL, MWt	600
	MODULE POWER OUTPUT, MWe	286
	NET EFFICIENCY, %	47.7
THERMAL DATA	THERMAL CYCLE	RECUPERATED/INTERCOOLED
	TURBINE INLET TEMPERATURE, °C (°F)	850 (1562)
	TURBINE INLET PRESSURE, MPa (psia)	7.02 (1016)
	COMPRESSOR PRESSURE RATIO	2.86
	COMPRESSOR EFFICIENCY, %	89.9/88.2
	TURBINE EFFICIENCY, %	93.1
	RECUPERATOR EFFECTIVENESS	0.95
	SYSTEM PRESSURE LOSS ($\Delta P/P$), %	7
COMPONENT DESIGN FEATURES	TURBOMACHINE	SINGLE-SHAFT ROTOR
	COMPRESSOR TYPE (STAGES)	MULTISTAGE AXIAL FLOW (14/19)
	TURBINE TYPE (STAGES)	MULTISTAGE AXIAL FLOW (11)
	GENERATOR TYPE	SYNCHRONOUS
	BEARING TYPE	ACTIVE MAGNETIC BEARINGS
	RECUPERATOR TYPE	COMPACT PLATE-FIN MODULES (6)
	PRECOOLER/INTERCOOLER TYPE	FINNED TUBE HELICAL BUNDLE
	PRESSURE VESSEL(s)	VERTICAL STEEL VESSELS
PLANT STATUS	DESIGN STATUS	CONCEPTUAL
	TECHNOLOGY STATUS	STATE-OF-THE-ART
	DEPLOYMENT	AFTER YEAR 2000

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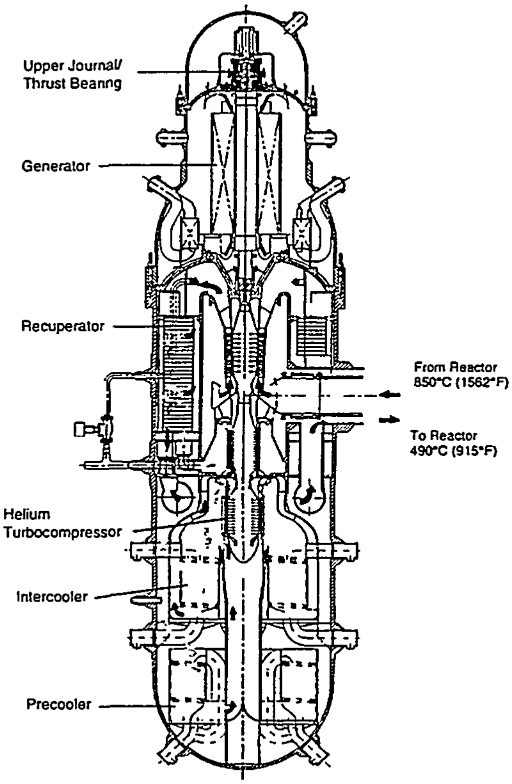

FIG. 3. GT-MHR POWER CONVERSION
VESSEL ASSEMBLY

realization of high efficiency (McDonald, 1994b). The recuperator utilizes a high surface compactness plate-fin type of geometry to meet the 95% effectiveness requirement. The precooler and intercooler are low temperature finned-tube, helical bundle, helium-to-water heat exchangers that remove the reject heat from the thermodynamic cycle. An additional helium-to-water heat exchanger is installed in the upper portion of the vessel to remove electrical reject heat from the generator, exciter, and magnetic bearings.

The turbomachine and the heat exchangers are connected by a series of ducts to give the required gas-flow paths. Detailed attention must be given to the structural support of the components, together with the sealing system to accommodate differential thermal expansion, and to facilitate ease of installation and removal of the components.

3.3. Performance

The base case parameters were selected based on the utilization of existing technology. The value of reactor outlet (i.e., turbine inlet) temperature of 850°C (1562°F) was selected on the basis of the following: (1) modest extension from that demonstrated in the Fort St. Vrain plant, (2) use of existing types of fuel and fuel coatings (with the necessary fuel quality for direct cycle service being available consistent with the program schedule), and (3) utilize uncooled turbine blades of existing nickel-base alloys. The recuperator, with an effectiveness of 95% is an extension of existing plate-fin technology used in industrial gas turbines.

A performance array for the base case conditions showing the influence of compressor pressure ratio and recuperator effectiveness on net plant efficiency is given in Fig. 4. The initial estimate of plant efficiency is 47.7% with a pressure ratio of 2.86. The pressure ratio is slightly higher than optimum, this being selected to keep the steel reactor vessel temperature within limits (i.e., a higher value of turbine expansion ratio lowers the gas temperature at the turbine exit).

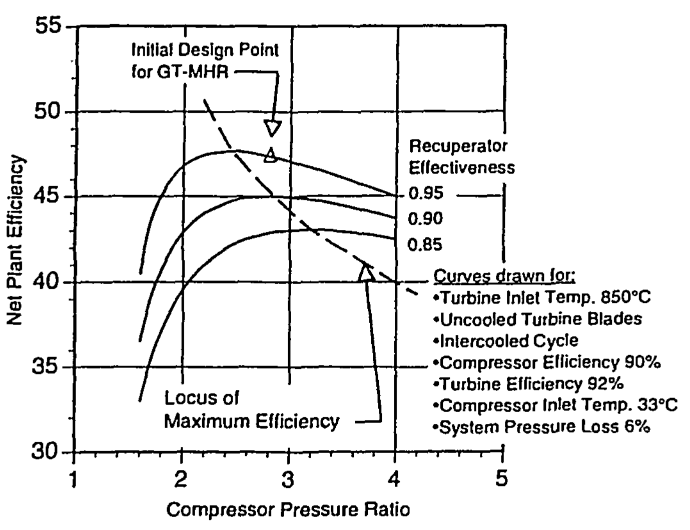

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FIG. 4. INFLUENCE OF KEY CYCLE PARAMETERS ON PERFORMANCE

The shape of the curve is such that if the expected value of recuperator effectiveness is not realized (or degraded as a result of leakage) there would be no significant loss of plant performance. As will be discussed in detail in the next section, the optimum pressure ratio in a highly recuperated closed Brayton cycle has a low value, so that the number of compressor and turbine stages can be kept to a manageable number for the low molecular weight helium working fluid.

4. TURBOGENERATOR DESIGN

4.1. Requirements

The requirements are multifaceted, and are shown in a very summary form in Table 2. As the program advances, detailed requirements will be developed and will form the basis for the turbogenerator design and fabrication specifications.

The aerothermal requirements were finalized based on an on-going dialogue between systems analysts and the turbomachine designer. Since the turbomachine is integrated in the power conversion vessel, it cannot be designed in an isolated manner and many of the requirements (particularly regarding assurance of the many interfaces) involves close working relationships between the major component designers. Further discussion on the requirements will be included in the following sections covering the actual machine design.

TABLE 2
HELIUM TURBOMACHINE REQUIREMENTS

Aerothermal	Helium Mass Flow Rate, kg/sec (lb/sec)	320 (705)
	Compressor(s) Inlet Temperature, °C (°F)	26 (79)
	LP Compressor Inlet Pressure, MPa (psia)	2.6 (373)
	Compressor Pressure Ratio	2.86
	Turbine Inlet Pressure, MPa (psia)	7.02 (1016)
	Turbine Inlet Temperature, °C (°F)	850 (1562)
	Compressor Efficiency, %	90
	Turbine Efficiency, %	92
Mechanical	Machine Orientation	Vertical Assembly
	Rotor Configuration	Single-Shaft
	Configuration	Facilitate Single Stage of Intercooling and Recuperation
	Generator Drive	From Turbine End
	Bearing System	Active Magnetic Bearings
	Catcher Bearings	Anti-Friction Bearings
	Turbine Blades	Uncooled
	Machine Integrity	Fragment Containment in Casing in Event of Disc Failure
	Materials Limitations	No Alloys Containing Cobalt
Operational	Rotational Speed, rpm	3600
	Machine Life, Years	40 (60 being considered)
	Power Regulation	Inventory Control
	Removal/Refurbishment Frequency, Years	7
	Removal/Replacement Time, Days	10
	Operating Environment	MHR Primary Loop Chemistry
Electrical	Generator Type	Synchronous
	Generator Efficiency, %	99
	Orientation	Vertical
	Operating Environment	Submerged in Helium
	Generator Cooling	Helium (Dedicated System)
	Generator Cavity Environment	Free From Radioactivity
	Maximum Cavity Temperature, °C (°F)	50 (122)
	Generator Installation	Design for Ease of Removal with Turbomachine In-Situ
	Exciter Type/Installation	Brushless/Submerged

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4.2. Rotational Speed Considerations

An initial decision was made regarding the selection of a single or split shaft arrangement. While the ease of changing the power turbine to meet 60 and 50 Hz requirements favored the split-shaft arrangement, the following considerations overrode this advantage and led to the selection of a single-shaft machine: (1) reduced number of bearings, (2) ease of machine removal/replacement, (3) ability to control turbine overspeed in the event of load loss, and (4) generator can be used in a motor mode to start machine (a separate motor may be required on the high pressure spool of a split shaft machine).

The next decision involved the selection of the rotational speed, the initial assumption being to select a high rotational speed to minimize the size of the rotor, and to use an external frequency converter. An initial layout with a rotational speed of 5200 rpm gave an acceptable envelope, but was determined not acceptable from the rotor dynamics stability standpoint. A design with a rotational speed of 4473 rpm was found to have acceptable critical speeds, and this machine will be mentioned later.

At this point in the design an assessment was made of the frequency converter, with the following findings: (1) very high cost [higher on a $/KW(e) basis than the turbomachine), (2) loss of 1.5% points in efficiency (compared with a direct drive), (3) very large installation, and (4) reliability concerns. This assessment led to the selection of a more cost-effective system with a rotational speed of 3600 rpm, synchronous generator, and power regulation by a combination of by-pass and gas inventory control. This machine is discussed in the following sections.

The issue of meeting the 60/50 Hz requirement is being further studied. A possible candidate involves a hybrid machine (say 3300 rpm), with a common gas flow path, number of stages, and identical external interfaces, but with the compressor(s) and turbine blading customized for either 3600 or 3000 rpm operation.

4.3. Helium Turbomachine Design

An overall view of the vertical rotating assembly is given in Fig. 5. Various aspects of the machine design including aerodynamic, mechanical, and electrical are covered in the following sections.

4.3.1. Compressor Aerodynamic Design.

Since axial compressor aerothermodynamic design techniques have been well documented, it is not the intent to describe detailed analyses in this paper, but rather to outline how the fluid properties of helium influence the flow path geometries, and to emphasize that the gas dynamic procedures used are essentially identical to conventional air-breathing gas turbine practice.

The choice of working fluid affects the turbocompressor primarily in two ways: (1) the number of stages for the attainment of the required pressure ratio and high efficiency, and (2) the machine size for a high pressure closed system. 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. As mentioned

286 MWe HELIUM TURBOMACHINE

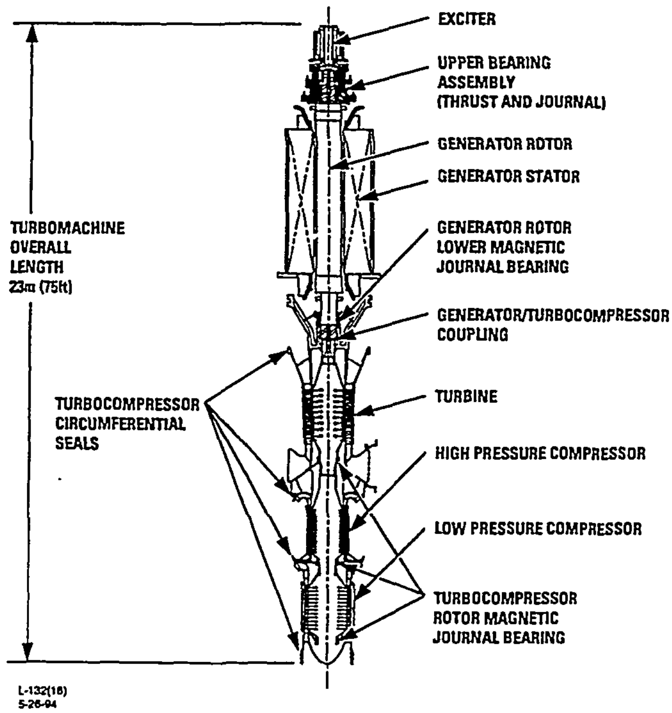

FIG. 5. OVERALL VIEW OF VERTICAL TURBOMACHINE

previously (Section 3.3) the low pressure ratio in a highly recuperated closed Brayton cycle results in a number of compressor stages that is comparable with existing air-breathing gas turbines and this is illustrated in Table 3.

Substitution 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. For the selected machine configuration (i.e., single shaft with synchronous generator) the compressor rotational speed is, of course, fixed at 3600 rpm. The size of the machine is thus dictated by the choice of blade speed, there being an incentive to use the highest values 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.

For the specified thermodynamic conditions compressor design solutions were established by General Electric Aircraft Engines using their FLOWPATH code, and preliminary results for the 3600 rpm machine are given in Table 4. Helium compressors for closed cycle gas turbines are characterized by small blade heights, high hub-to-tip ratios, and low aspect ratios. An important parameter is the rear stage hub-to-tip ratio, and an accepted upper limit for high efficiency compressors is about 0.90. With high pressure helium, the blade heights are small and end-wall losses become significant; thus, careful mechanical design is necessary to minimize tip clearance effects. While the end-wall effects have an adverse effect on efficiency, four factors that will partially offset this are: (1) very high Reynolds numbers (5×10^6), (2) very low

TABLE 3
TURBOMACHINE SALIENT FEATURES

System	Nuclear Gas Turbine	Power Generation Unit (for Comparison) Heavy Duty Industrial GT	Aeroderivative Gas Turbine
Plant	GT-MHR	MS9001F (GE)	LM6000 (GE)
Power, MWe	286	226	42
Working Fluid	Helium	Air	Air
Thermodynamic Cycle	Recuperated and intercooled	Simple cycle	Simple cycle
Turbine Inlet Temp., °C (°F)	850 (1562)	1288 (2350)	1243 (2270)
Compressor Pressure Ratio	2.8	15	30
Mass Flow Rate, kg/sec (lb/sec)	320 (705)	613 (1351)	123 (271)
Specific Power, kWe/kg/sec	895	370	340
Compressor			
Number of Stages	14 LP + 19 HP	18	5 LP + 14 HP
Max. Tip Diameter, mm (in.)	1683 (66)	2515 (99)	1372/737 (54/29)
Turbine			
Number of Stages	11	3	2 HP + 5 LP
Max. Tip Diameter, mm (in.)	1778 (70)	3251 (128)	889/1321 (35/52)
Tip Speed, m/sec (ft/sec)	335 (1100)	510 (1674)	476/249 (1562/817)
Blade Cooling	Uncooled	Cooled	Cooled
Rotational Speed, rpm	3600	3000 (50 Hz)	10,225/3600
Shaft Arrangement	Single shaft	Single shaft	Twin shaft
Bearing Type	Active magnetic	Oil lubricated	Oil lubricated
Number of Journal Bearings	4	2	6
Machine Orientation	Vertical	Horizontal	Horizontal
Overall Length, m (ft)	13 (42)	14.5 (47.5)	4.5 (15)
Overall Diameter, m (ft)	2.75 (9)	4.8 (15.7)	2.5 (8.2)
Overall Turbine Weight, kg (tons)	*45,000 (50)*	*300,000 (330)*	*5600 (6.2)*
Generator			
Installation	Submerged	External	External
Type	Synchronous	Synchronous	Synchronous
Cooling	Helium cooled	Hydrogen cooled	Hydrogen cooled
Year Plant Entering Service	After year 2000	1991	1992

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TABLE 4
PRELIMINARY AEROTHERMAL DATA FOR 286 MW(e) HELIUM TURBOCOMPRESSOR

	LOW PRESSURE COMPRESSOR	HIGH PRESSURE COMPRESSOR	TURBINE
ROTATIONAL SPEED, RPM	3600	3600	3600
NUMBER OF STAGES	14	19	11
EFFICIENCY ACROSS BLADING, %	89.9 (POLYTROPIC)	88.2 (POLYTROPIC)	93.1 (ADIABATIC)
INLET AND EXIT LOSSES ($\Delta P/P$), %			
• INLET LOSS	0.10	0.20	0.10
• DIFFUSER LOSS	0.55	0.55	0.55
• DUMP LOSS	0.15	0.15	0.15
GAS FLOW PATH DATA			
• FIRST STAGE			
– TIP DIAMETER, MM (IN.)	1584 (66.3)	1372 (54.0)	1707 (67.2)
– HUB DIAMETER, MM (IN.)	1466 (57.7)	1242 (48.9)	1367 (53.8)
– BLADE HEIGHT, MM (IN.)	109 (4.3)	65 (2.55)	170 (6.7)
– HUB/TIP RATIO	0.87	0.906	0.80
– TIP SPEED, M/SEC (FT/SEC)	317 (1041)	258 (848)	322 (1056)
• LAST STAGE			
– TIP DIAMETER, MM (IN.)	1661 (65.4)	1372 (54.0)	1783 (70.2)
– HUB DIAMETER, MM (IN.)	1466 (57.7)	1242 (48.9)	1367 (53.8)
– BLADE HEIGHT, MM (IN.)	97.5 (3.85)	65 (2.55)	208 (8.2)
– HUB/TIP RATIO	0.88	0.906	0.77
– TIP SPEED, M/SEC (FT/SEC)	313 (1027)	258 (848)	336 (1103)
• ROTOR BLADED LENGTH, MM (IN.)	1735 (68.3)	1760 (69.3)	2032 (80.3)

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Mach number (<0.40), (3) close blade tip clearance for a machine not exposed to severe thermal transients, and (4) retention of clean oxide-free blade surfaces in the inert helium environment. The initial compressor design solutions given in Table 4 have high values of polytropic efficiency, acceptable gas dynamic loading factors, and at this early stage of design have surge margins of over 20%.

4.3.2. Turbine Aerodynamic Design.

The properties of helium affect the turbine in very much the same way as they influence the compressor. That is to say for a given expansion ratio, the total number of stages for a helium turbine will be much greater than for an air-breathing gas turbine. Because it is desirable to have as high a blade speed as possible in order to reduce the number of stages to a minimum, the most critical stress conditions are those of the first stage since the rotor blade temperature is at the maximum value.

The turbine blade centrifugal stress (for a given blade geometry) is proportional to the rpm^2 x annulus area, and for a single shaft, 60 Hz machine, one degree of freedom is lost to the designer. From Table 4, it can be seen that an 11 stage turbine with very high adiabatic efficiency was established. With tip speeds conservative by modern gas turbine practice (Table 3), the helium turbine is characterized by small blade heights. In fact, the diameter of the rear stage of the turbine is substantially smaller than a near equivalent power rated air-breathing industrial gas turbine (Fig. 6). The smaller size is attributable to the very high specific power, since the enthalpy drop in the helium gas turbine is much greater than that in an open-cycle gas turbine.

With a turbine inlet temperature of 850°C (1562°F), turbine blade cooling is not necessary, and the turbine blades can be fabricated from an existing nickel-base alloy. A conservative ground rule established for the turbomachine is that stress levels in the major subcomponents be commensurate with a plant operating life of 40 years. To meet this requirement, cooling of the turbine discs is necessary, and a preliminary analysis showed that the life goal can be met with a purge flow of 1.1% (bled from the high pressure compressor).

4.3.3. Turbocompressor Mechanical Design

4.3.3.1. Rotor Assembly

The machine has been designed with the high pressure gas in the center of the assembly and this not only minimizes the number of seals, but provides a near balanced thrust condition during full power operation. With separation of the low and high pressure compressors (to facilitate intercooling), and with the mid plane turbine inlet duct, the single shaft machine is characterized by a long slender rotor. A lightweight and rigid rotor construction, resembling aeroengine practice, was chosen to minimize weight and ease critical speed concerns. The turbocompressor assembly is shown in Fig. 7. This particular design being the aforementioned 4473 rpm variant, but the overall features are the same for the 3600 rpm design.

The two compressor assemblies are of welded construction, and the turbine discs are bolted together. The weight of the turbocomprssor rotor is 9075 kg (10 tons), and the overall machine "cartridge" weighs on the order of 45,400 kg

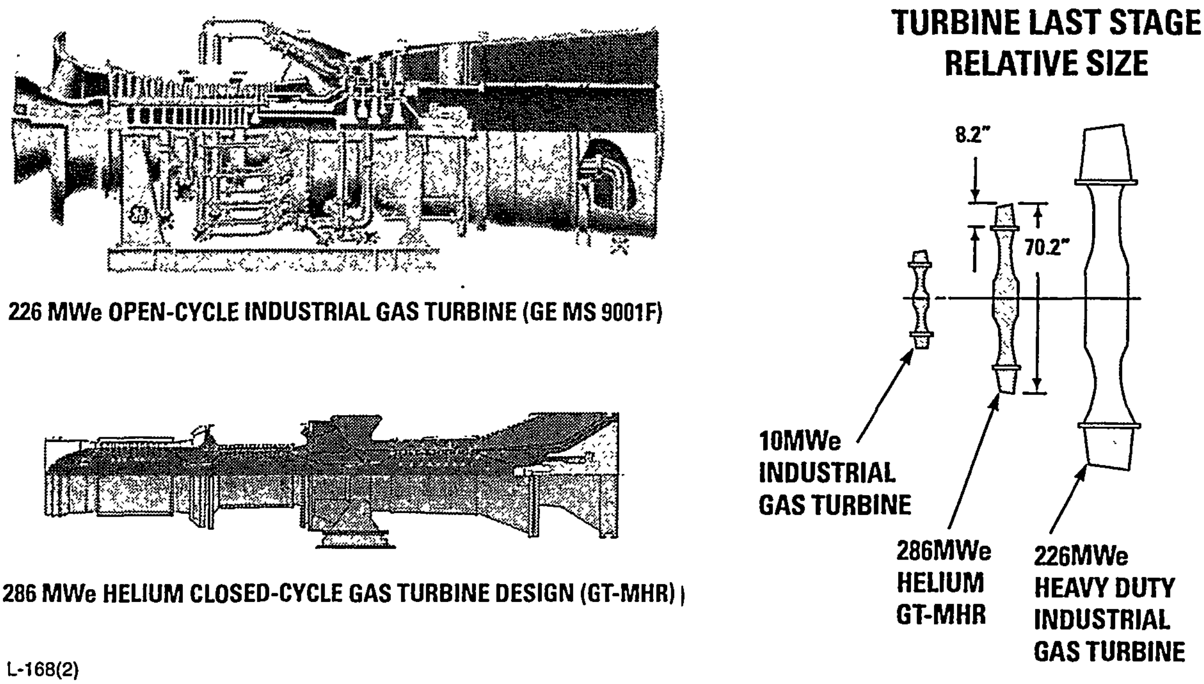

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FIG. 6. COMPARATIVE SIZES AIR AND HELIUM GAS TURBINES

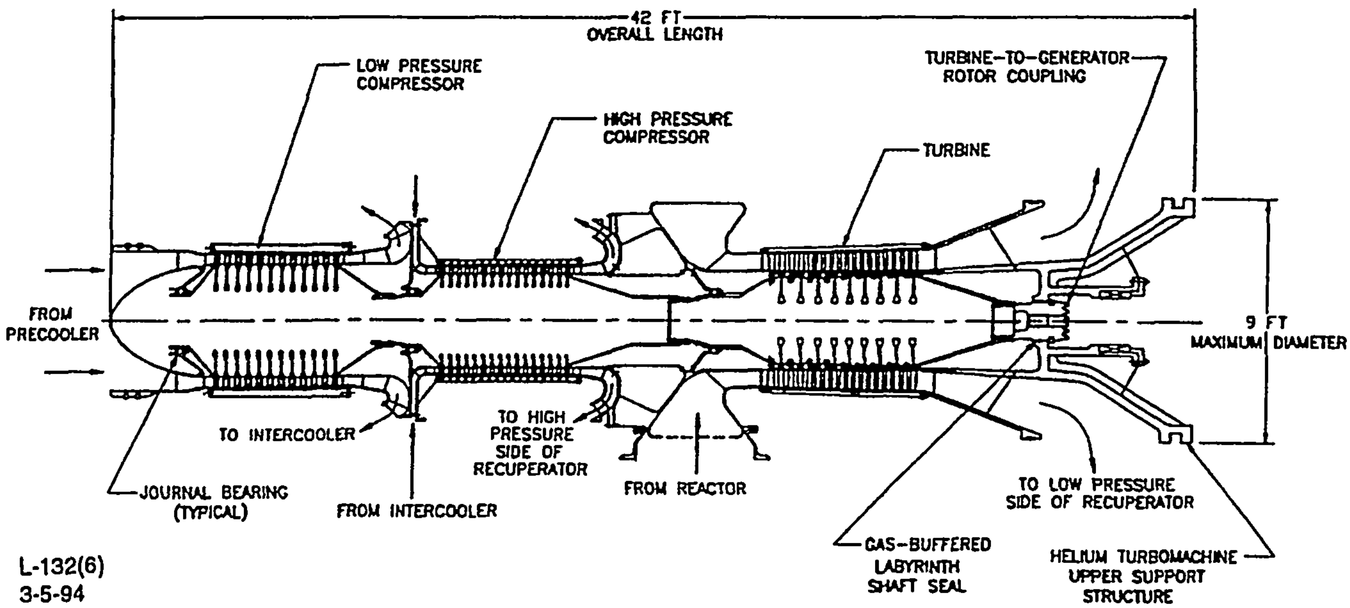

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FIG. 7. HELIUM TURBOCOMPRESSOR LAYOUT

50 tons). Burst shields are incorporated in the machine structure around the compressor(s) and turbine. These have been designed, such that in the event of a rotor failure, the disc and blade fragments will be contained within the machine casing. The turbocompressor static structure is supported from the semi-elliptical plate located in a plane below the generator (see Fig. 3). The rotating assembly is supported from the thrust bearing which is located above the generator.

4.3.3.2. Bearings. The entire rotor (weighing 50 tons), including the generator, is supported by an active bearing system. For the 4473 rpm machine design (Fig. 7) the initial modeling of the rotating assembly was based on the utilization of a five journal bearing system. This arrangement confirmed the rotor stability, with operation at the design point being between the second and third critical speeds, with adequate margin. A similar analysis is underway for the 3600 rpm machine, and means to reduce the number of bearings are being investigated.

The magnetic bearing system incorporates considerable redundancy, the primary bearings being backed-up by a second set of bearings powered by an uninterruptible power source. Mechanical antifriction catcher bearings are also incorporated to prevent rotor damage in the unlikely event that both magnetic fields are lost.

While the rotor is heavier than in applications to date, the thrust bearing unit loads and peripheral velocities are bounded by operating experience. In recent years there has been substantial use of magnetic bearings in industrial applications (Dussaux, 1990). Today, over eight million hours of operating time has been accumulated on active magnetic bearings. Over 150 large turbomachines (e.g., gas compressors, turbines, turboexpanders) have run for more than 1.5 million hours, and the GT-MHR machine will take advantage of this technology base.

4.3.3.3. Seals. As will be mentioned in the following section, there is a requirement to keep the generator cavity free from radioactive contamination. A dynamic shaft seal is incorporated between the turbine and the generator. This shaft labyrinth seal is supplied with purified helium and the buffer flow is split in two directions, some clean helium entering both the generator and turbine cavities. The capacity of this system will be sized to cover the full spectrum of plant operation conditions, including startup, shutdown, and transients.

The major helium turbocompressor components are is being designed for the 40-year plant life, with scheduled removal at 7 year intervals for inspection and maintenance as required. The removal frequency was based on the experience from circulators in the gas-cooled plants in the UK which are refurbished every 8 years. The 7-year value for the GT-MHR machine is in concert with the refueling schedule. To minimize plant downtime, a spare machine 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. The turbomachine assembly has several interfaces with static structures/components within the power conversion vessel. Circumferential static seals are necessary at these interfaces. These seals must be engineered to meet the following: (1) minimum leakage, (2) accommodate nonuniformities between the machine and its mating parts, and (3) accommodate differential expansion and thermal distortions. Initial design work has shown that the requirements (in terms of size, temperature, pressure differential) are bounded by gas turbine industry experience, namely segmented piston ring types (retained by springs). It is recognized, however, that a significant engineering effort must be expended on the design and development of these seals since the performance of the closed cycle gas turbine is sensitive to seal leakage.

In closing comments on this section covering the turbocompressor design, there is a need to mention that the key to the design of high efficiency helium turbomachinery is the technology available from the gas turbine industry. This includes both aeroderivatives, as exemplified by the LM 6000 (Casper, 1993), and large industrial engines such as the MS9001F (Brandt, 1990), and details of these are given in Table 3. 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.

4.4. Electrical Generator Design

The major requirements for the generator are given in Table 2. The rating of the generator is within the range of units in production for gas and steam turbine plants. To minimize development requirements, a major goal was to use conventional generator technology to the maximum extent possible, recognizing the two major differences, namely: (1) vertical installation and (2) operation in a helium environment. The major reason for having a submerged generator is that it obviates having a shaft penetrating the primary pressure boundary.

The basic generator is a two-pole synchronous unit rated at 325 MVA. A brushless exciter system with a shaft mounted exciter alternator and shaft mounted diode rectifiers is the most suitable arrangement for supplying and controlling the dc field current in the generator rotor. A view of the submerged generator is given in Fig. 8. Based on existing units, initial studies have shown that the following changes would have to

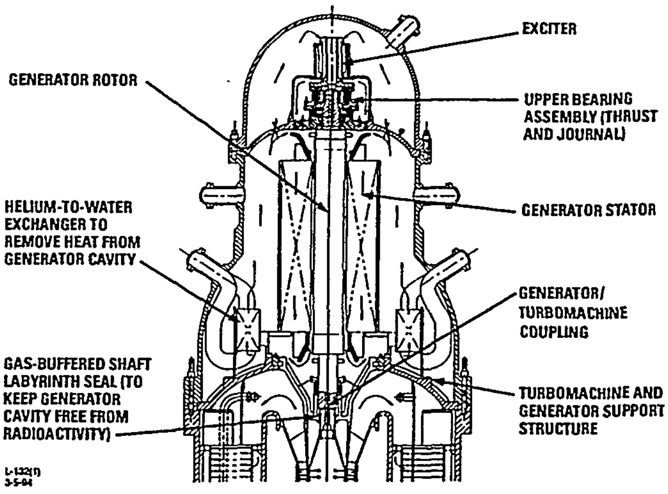

FIG. 8. SUBMERGED GENERATOR INSTALLATION

be accommodated for the GT-MHR application: (1) modifications to the stator frame and internal structures for the vertical installation, (2) stator and gap cooling with helium (instead of hydrogen or air) can be realized. The generator efficiency has been estimated at 98.7%.

An axial flow fan is mounted on the rotor and this circulates helium within the generator cavity. Heat is removed from the electrical equipment (i.e., generator, exciter, upper magnetic bearing) by means of two (100% redundant) helium-to-water heat exchangers installed in the generator cavity. Operational experience from submerged electric motor circulator drives in the AVR and THTR plants has shown acceptable performance and reliability for operation in a helium environment. For the much larger GT-MHR generator, with its selected winding insulation system, some development effort is necessary. While it is known that helium (at high and low pressure) has adequate dielectric strength and heat removal capabilities (although with higher fan and windage losses) tests will be performed to confirm the insulation performance, and integrity of the windings (particularly during out gassing associated with a postulated depressurization event).

The generator must be lifted prior to removal and replacement of the helium turbocompressor which is a scheduled maintenance activity. To facilitate this the curvic coupling between the generator and turbocompressor rotors must be remotely activated. A solution to this (for which further engineering work is necessary to define the design) is to incorporate a center tie bolt in the generator. All of the electrical penetrations are located in the closure wall surrounding the generator cavity. Major penetrations include: (1) electrical power out, (2) power supply for the magnetic bearings, (3) water lines for the coolers, (4) instrumentation, and (5) diagnostic systems.

5. DEVELOPMENT APPROACH

Currently, engineering efforts are being focused on confirming the conceptual design. As more detailed analysisand design are undertaken for the turbomachine, and its integration in the steel vessel, development requirements are also being formulated. This will lead to a comprehensive technology development program. Since the gas turbine plant is an evolution of the steam cycle HTGR, some of the technology from both component tests and actual plant operation will be either directly applicable or can be readily extrapolated. There are, however, new components in the GT-MHR (such as the turbomachine) that must be assessed in terms of risk reduction before they operate in a nuclear environment. In addition there is the integration complexity associated with having the entire power conversion system installed in the reactor circuit.

While the development plan is currently being formulated, there are essentially three major elements to consider prior to operation of the power conversion system with a nuclear heat source, namely: (1) subcomponent tests, (2) an integrated test with a nonnuclear test source, and (3) testing of the system in the plant prior to installing the nuclear fuel, using compression heat, perhaps supplemented by an external source to elevate the system temperature. While not comprehensive at this stage, some of the testing considerations for the rotating machinery are highlighted in Table 5 and discussed below.

5.1. Subcomponent Tests

Subcomponent tests will be undertaken to provide data that would be factored into the system final design to give a high degree of confidence that the first unit will operate well and meet requirements. These tests would be conducted early in the

TABLE 5
TURBOMACHINE DEVELOPMENT/TESTING SUMMARY

COMPONENT	TEST ACTIVITY	SUBCOMPONENT TEST	INTEGRATED TEST[a]	INSTALLATION IN PLANT: NON NUCLEAR[b]	INSTALLATION IN PLANT: NUCLEAR OPERATION
TURBOMACHINE	MATERIALS (PLATEOUT EFFECT ON TURBINE BLADES)	X			
	MATERIALS (OXIDE COATINGS)	X			
	MAGNETIC BEARINGS (JOURNAL & THRUST)	X			
	CATCHER BEARINGS	X			
	ROTOR DYNAMIC STABILITY	X			
	SEALS (LEAKAGE & INTEGRITY)	X			
	FLOW DISTRIBUTION (INLET & OUTLET DUCTS)	X			
	PERFORMANCE VERIFICATION		X (PARTIAL)	X (PARTIAL)	X
	INTERFACE RESOLUTION	X (MOCKUPS)	X		
GENERATOR	INSULATION (PERFORMANCE IN HELIUM)	X			
	INSULATION INTEGRITY (BLOWDOWN)	X			
	EXCITER (PERFORMANCE IN HELIUM)	X			
	PERFORMANCE		X (PARTIAL)	X (PARTIAL)	X
	INTERFACE RESOLUTION	X (MOCKUP)	X		
OVERALL TURBOGENERATOR DESIGN VERIFICATION	DIFFERENTIAL THERMAL EXPANSION		X (PARTIAL)	X (PARTIAL)	X
	SEALS INTEGRITY/LEAKAGE		X (PARTIAL)		X
	PERFORMANCE VERIFICATION		X (PARTIAL)		X
	INSTRUMENTATION/DIAGNOSTICS		X (PARTIAL)		X
	INTERFACE ASSURANCE		X		
	REMOVAL/REPLACEMENT		X	X	X

(a)PROTOTYPICAL POWER CONVERSION SYSTEM TESTED WITH FOSSIL-FIRED HEAT SOURCE (AT FULL TURBINE INLET TEMPERATURE AND SPEED BUT AT REDUCED PRESSURE).
(b)HOT FLOW TEST PRIOR TO INSTALLATION OF NUCLEAR FUEL

program. Most of these tests will be done in existing facilities or modifications to existing test rigs/facilities.

5.2. Integrated Test

Because of the complex nature of the integrated system within the confines of the steel vessel, consideration is being given to a design verification test of the complete power conversion system using a nonnuclear heat source prior to reactor operation. With 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) partial performance verification; (3) seal bypass/leak flow quantification and integrity assurance; (4) flow distribution measurement; (5) differential thermal expansion measurement; (6) calibration of control, instrumentation, and diagnostic systems; (7) signature characterization (e.g., acoustics); (8) verification of remote handling equipment for turbomachine removal and replacement; and (9) operator training.

Various options for the nonnuclear test facility are currently being evaluated. A major goal would be to operate the helium turbomachine at full speed and at the design value of turbine inlet temperature [850°C (1562°F)]. The test will be done at part load conditions, with the selection of system pressure to be determined from the aforementioned evaluation.

The above development approaches currently being evaluated have different perspectives regarding risk reduction and, of course, cost, but they do share the same goal, namely that they be consistent with a schedule that would facilitate operation of a revenue-bearing GT-MHR plant before the year 2005.

6. GT-MHR DEPLOYMENT

An inherent part of the project planning is the evaluation of development and testing approaches, particularly regarding the integrated test. Decisions in this area are necessary prior to the preparation of detailed project schedules. For the purpose of this paper it is meaningful to put into perspective the time frame for the power conversion system design and development. The schedule shown in Fig. 9 is tentative and is included only to show the approximate time frame for the major activities and their relationships.

As mentioned previously, subcomponent testing would be completed in the early phase of the program, with data generated for inclusion in the final design of the power conversion system. Long-lead procurement, particularly for the steel pressure vessel must be undertaken early in the program. While detailed planning is still underway the tentative schedule shows nuclear operation of the plant in a period of 10 years.

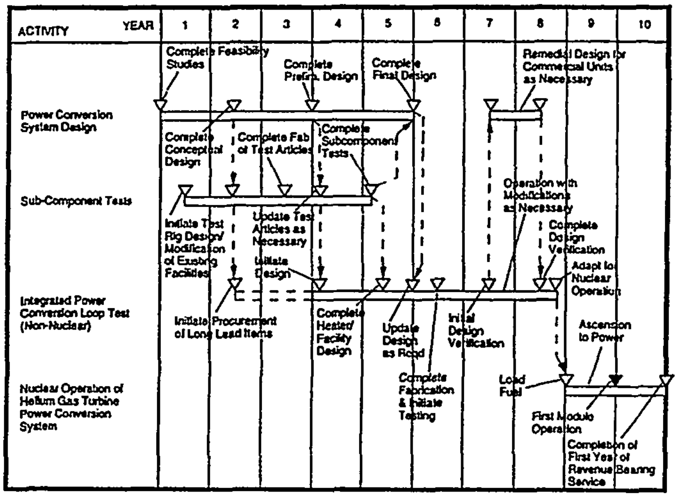

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FIG. 9. GT-MHR POWER CONVERSION SYSTEM SCHEDULE

7. CLOSING REMARKS

The technology for a near-term plant with a turbine inlet temperature of 850°C (1562°F) has a sound basis in the U.S. (McDonald, 1994c) in terms of turbomachine design/performance or materials advancements.

The helium turbomachine is in an early stage of design but sufficient work has been done to confirm the following: (1) performance goals realized, (2) overall machine assembly integration in the power conversion system vessel, (3) machine design based on proven gas turbine technology, and (4) development requirements tentatively defined.

The following key areas have been identified for in-depth analysis/design of the 3600 rpm reference machine configuration: (1) number of bearings (rotor stability verification), (2) active magnetic bearing system, (3) hybrid design for 60/50 Hz operation, (4) seal design for minimum leakage, (5) differential thermal expansion, and (6) clarification of interfaces with other components.

Development approaches are being formulated to minimize risk in the most cost-effective manner. It has been recognized right from the onset of the program that a thorough program of development and testing for design verification must be adhered to.

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 GT-MHR since it can perhaps be regarded as the ultimate turbine "green technology."

8. ACKNOWLEDGMENTS

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