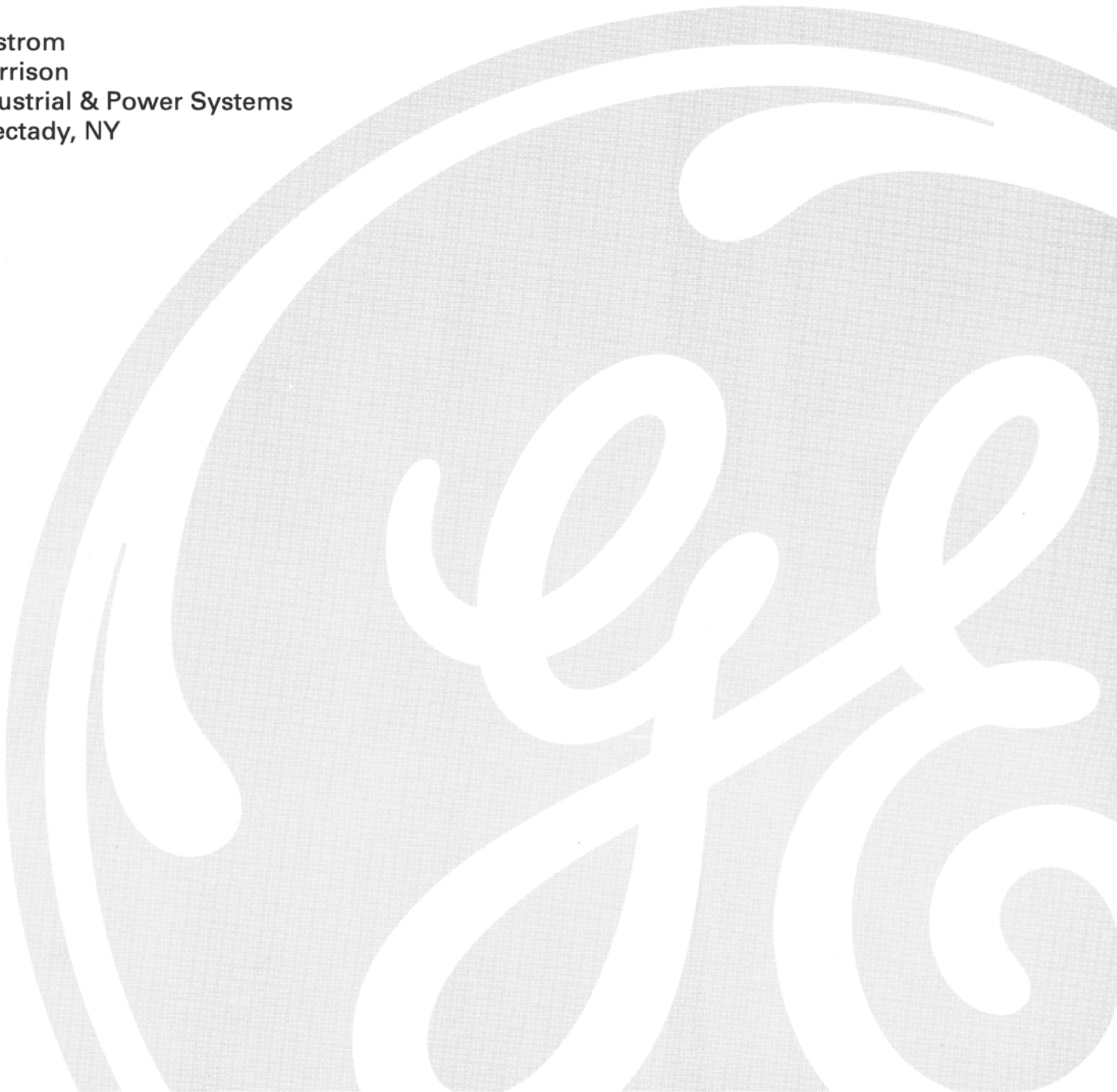




***GE Power Generation***

# **Gas Turbines for Mechanical Drive Applications**

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# GAS TURBINES FOR MECHANICAL DRIVE APPLICATIONS

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## ABSTRACT

Economies of scale and improved levels of reliability have recently led to GE's larger gas turbines being favored for selected mechanical drive applications. Four MS6001B gas turbines have been contracted for oil field gas re-injection service and several major LNG plants are being proposed or on order with MS6001B and/or MS7001EA refrigeration compressor drivers. However, the change from generator drive application to mechanical drive brings new considerations such as variable speed operation, starting method, torsional and lateral acceptability, continuous service reliability and more.

This paper will discuss the key MS6001B and MS7001EA mechanical drive special considerations and provide basic system design guidance. It will answer the majority of "first round" technical questions posed by project developers seeking to use gas turbines as mechanical drivers in the 40,000 to 100,000 hp (30,000 to 75,000 kW) range. It will also provide "first round" data for lower power Frame 5 gas turbine applications in the mechanical drive marketplace.

## INTRODUCTION

Large gas-turbine prime movers have been serving base-load power generation applications with significant success for more than a dozen years. Reliability performance has improved dramatically. Now the process industries are beginning to take advantage of economies of scale to employ the large gas turbines for selected mechanical-drive applications. Figure 1 illustrates how the MS6001B, the LM6000, and the MS7001EA raise the mechanical drives family high-end output power from something less than 40,000 hp (30,000 kW) to over 100,000 hp (75,000 kW) per machine. At the same time, the fuel efficiency is improved by 10% to 25%. Two other frequently-used evaluation criteria – dollars per horsepower and horsepower per square-foot of footprint – are also improved. The economic incentive is clear.

This paper will focus on the MS6001B and MS7001EA gas turbines where extensive engineering reviews have already been performed to support specific mechanical drive proposals and orders. An MS7001EA during factory assembly is

shown in Figure 2. The LM6000 is a new aeroderivative machine that has recently completed an extensive prototype development factory testing program to confirm its mechanical drive operating envelope. The LM6000 will be described in a separate document.

From the mechanical drive work done to date, and to support the the first orders for 7 MS6001B and 3 MS7001EA gas turbines, the following areas were found to be of principal interest when considering a mechanical drive application and distinguishing it from generator drives:

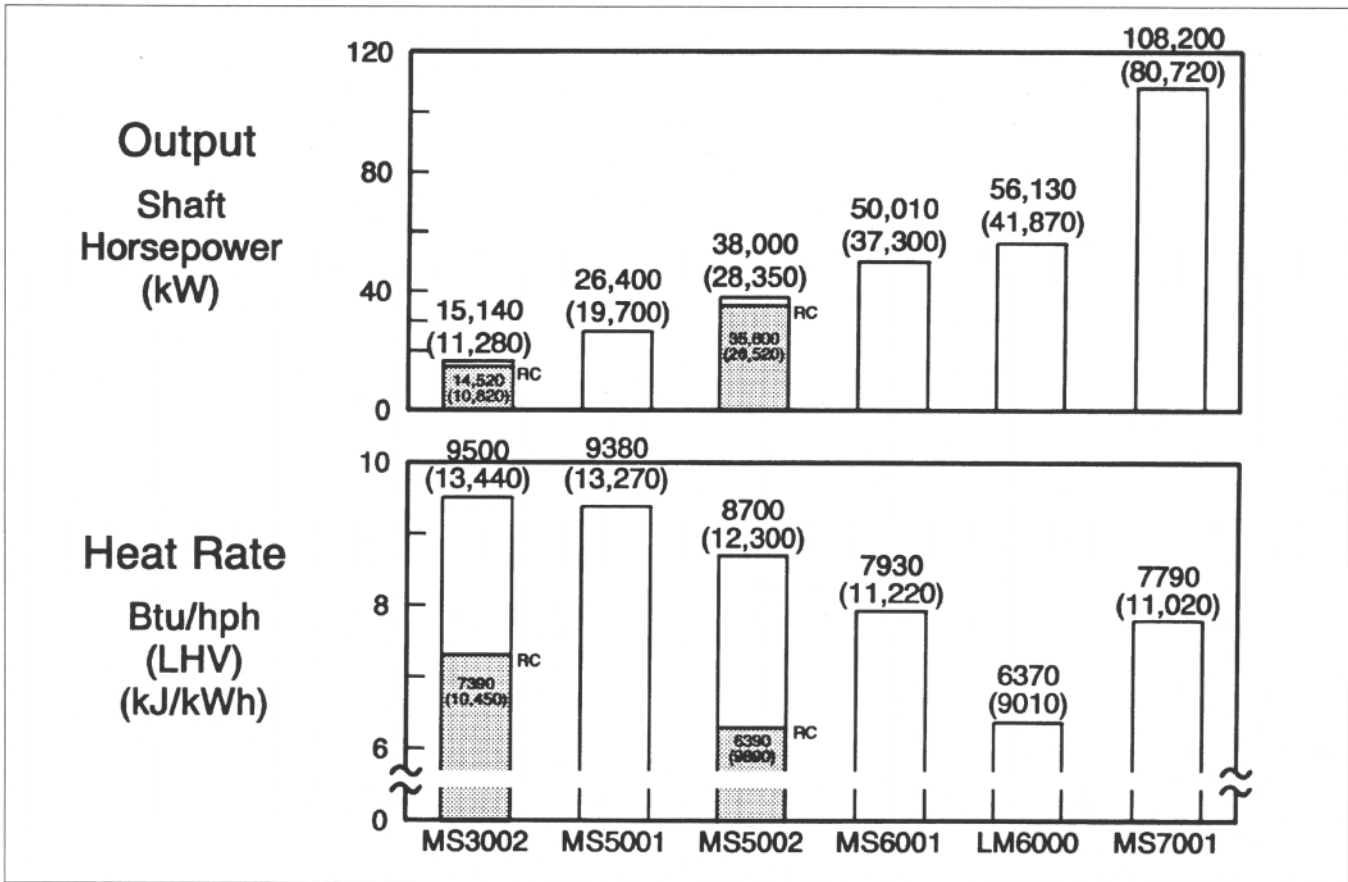
- Continuous Speed Range
- Power and Performance Ratings
- Load Coupling Selection
- Unit Starting Methods and Requirements
- Accessory Systems - General
- Reliability and Durability

While this paper concentrates on the mechanical drive application differences, it should be noted that most of these differences are in the application and not in the actual hardware. The flange-to-flange gas turbine (engine) is exactly the same, as are the majority of accessory support systems.

## SPEED RANGE

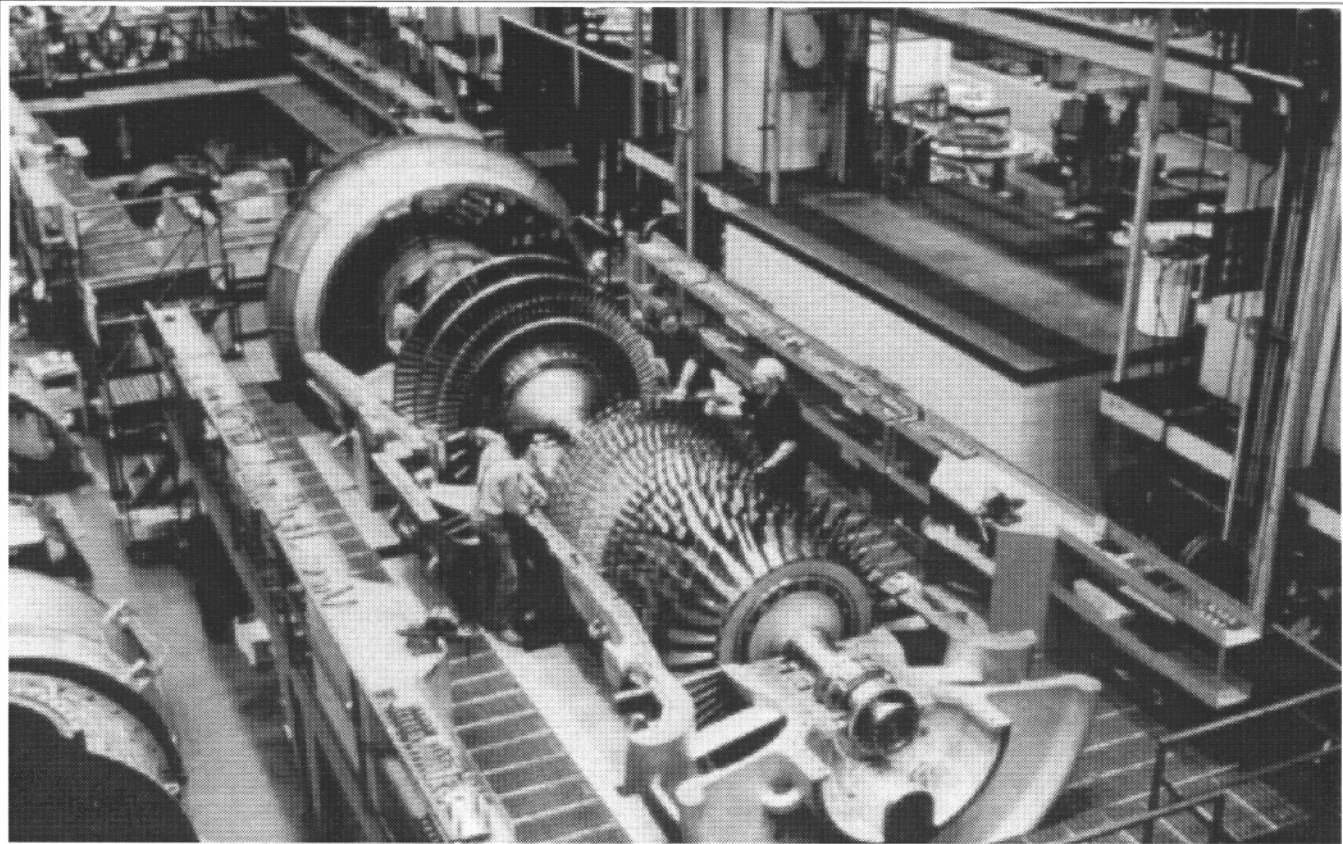
The first notable difference between mechanical drive and generator-drive applications is the need to operate on a continuous basis over a variable speed range. GE's design engineers have analyzed this issue and determined the continuous operation speed ranges for the MS6001B and MS7001EA gas turbines as indicated in Table 1.

The speed range of the MS6001B is bounded on the high end by encroachment limits on first-stage compressor blading resonance conditions and at the low end by third-stage turbine bucket resonance conditions. The MS7001EA upper end limit is determined by the stress-temperature-design life criteria for the turbine section buckets, while the lower-end limit is determined by compressor stall margin. Compressor stall margin considerations also preclude continuous operation on either machine at any lower speed points. While the available speed range is not as wide as with GE's smaller two-shaft machines or the MS5001R, it is applicable for certain select compressor drive applications such as refrigeration processes.



GT21796B

Figure 1. Gas turbine comparisons - mechanical drive performance at ISO conditions with gas fuel



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Figure 2. MS7001EA During factory assembly

**Table 1**  
**ALLOWABLE CONTINUOUS**  
**SPEED RANGES**

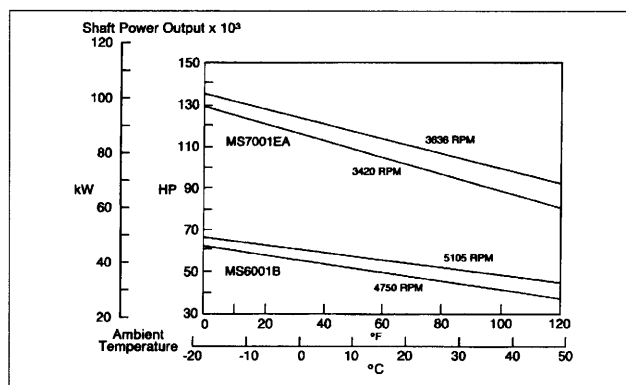
	Speed (rpm)	
	MS6001B	MS7001EA
Maximum Continuous Speed	5105	3636
Nominal Rated Speed	4860	3460
Minimum Continuous Speed	4750	3420

**POWER AND PERFORMANCE**  
**RATINGS**

Gas-turbine ratings are traditionally established with a single operating point at ISO ambient conditions. For mechanical drive units that operating point includes zero inlet and exhaust losses and allows that the maximum continuous speed is at least 105% of nominal rated speed. Table 2 presents the current mechanical-drive ISO ratings.

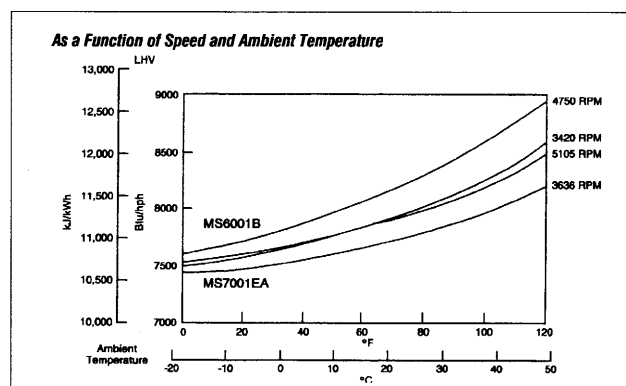
Single-point ratings permit standardized comparisons of different machines but are not nearly as useful as the families of curves that show how output capability and heat rate vary over the normal operating range of ambient temperature, turbine speed, and load level. Figure 3 illustrates the output power capability of the MS6001B and MS7001EA machines as a function of ambient temperature and speed. As would be expected, the higher ends of the speed ranges offer the higher power levels.

Fuel efficiency is measured as heat rate and varies according to the operating conditions. Figure 4 shows how heat rate varies with ambient temperature and shaft speed for the machines operating at maximum capability. Note that both the MS6001B and the MS7001EA show improving heat rate with decreasing ambient temperature.



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**Figure 3. Mechanical drive output power capability as a function of speed and ambient temperature**



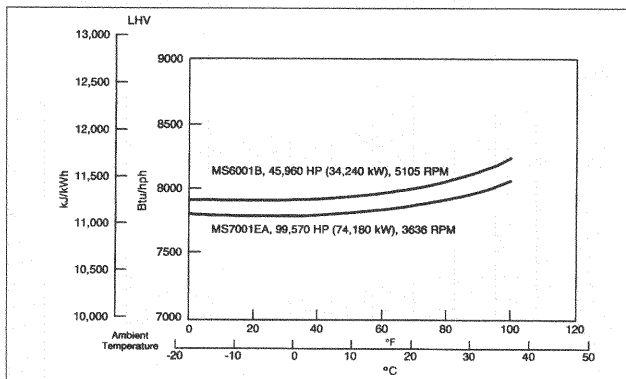
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**Figure 4. Mechanical drive heat rate at maximum capability as a function of speed and ambient temperature**

The MS7001EA is slightly more fuel-efficient than the MS6001B. For both machines, the effect of operating speed on heat rate is greater at the higher ambient temperatures.

**Table 2**  
**MECHANICAL DRIVE ISO RATINGS**

	MS6001B	MS7001EA
Output Power, hp (kW)	50,010 (37,310)	108,210 (80,720)
Nominal (Rated) Speed (rpm)	4,860	3,460
Heat Rate (Btu/HP-hour) (LHV) (kJ/kWh)	7,930 (11,220)	7,790 (11,020)
Heat Consumption (x10 <sup>6</sup> Btu/hour) (kJ/hr)	396.6 (418.4)	842.9 (889.3)
Exhaust Temperature °F (°C)	1022 (550)	1001 (538)
Conditions:		
Ambient Temperature °F (°C)	59 (15)	
Barometric Pressure psia (bar)	14.7 (1.013)	
Fuel	Natural Gas	
Inlet Air Pressure Loss (in H <sub>2</sub> O) (mm H <sub>2</sub> O)	0.0	
Exhaust Pressure Loss (in H <sub>2</sub> O) (mm H <sub>2</sub> O)	0.0	



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**Figure 5. Mechanical drive heat rate at constant load**

Figure 5 shows how heat rate is affected by ambient temperature when operating at constant load level. The improvement in heat rate due to lower ambient temperatures more than compensates for the fact that the machines are operating at part-load conditions. In the constant load mode of operation (typical of many mechanical drive applications) the gas turbines operate the majority of time below their full capability, without penalty on fuel economy and with a parts-lives/maintenance advantage due to reduced firing temperatures and stress levels.

## LOAD COUPLING SELECTION

The coupling between the gas turbine and the driven equipment must meet several requirements; obviously it must continuously transmit the required full-load torque and comfortably withstand the transient peak torques associated with upset conditions. But it may also be required to transmit or isolate thrust loads; it must accommodate alignment shifts due to thermal growths; and it must complement the torsional and lateral rotor dynamics of the full equipment line-up (referred to as the train). GE has close working relationships with three leading manufacturers of dry-diaphragm couplings and for both the MS6001B and the MS7001EA there are fully acceptable couplings available for all mechanical-drive applications reviewed to date. In fact, the standard load coupling currently furnished with the MS6001B generator drive is a dry-diaphragm-type flexible coupling. Figure 6 shows a large dry-diaphragm coupling approximately 106 inches (269 cm) long by 28.4 inches (72 cm) diameter rated for 99,200 hp (74,000 kW) at 3600 rpm with 1.5 service factor.

In Table 3, the thermal growth data at the gas-turbine output flange is provided to assist rotat-



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**Figure 6. Flexible load coupling rated 99,200 hp (74,000 kW), 3,600 rpm (Photo courtesy of Lucas Aerospace Power Transmission Corporation)**

**Table 3**  
**THERMAL GROWTHS AT GAS TURBINE OUTPUT FLANGE**

	Direction (Toward)	Magnitude inches (mm)	
		MS6001B	MS7001EA
<u>Axial Growths</u>			
Startup			
Expected	Turbine	0.121 (3.07)	0.225 (5.72)
Worst Case	Turbine	0.132 (3.35)	0.242 (6.15)
Steady State Full Load	Load	0.081 (2.06)	0.073 (1.85)
Shutdown			
Expected	Load	0.149 (3.78)	0.193 (4.80)
Worst Case	Load	0.235 (5.97)	0.329 (8.36)
<u>Radial Growths</u>			
Vertical	Up	0.095 (2.41)	0.118 (3.00)
Horizontal	-	nil	nil

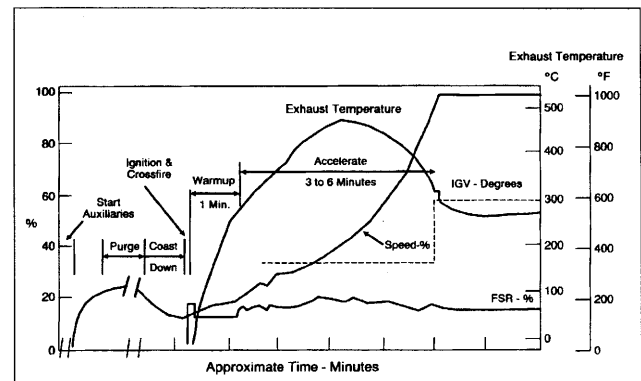
ing machinery designers in their preliminary planning. The coupling in Figure 6 is also continuously rated for a simultaneous misalignment consisting of an axial deflection of +/- 0.485 in. (12.3 mm), a parallel offset 0.468 inches (11.9 mm) and an angular offset of 0.310 degrees. It would more than accommodate the MS7001EA in most train arrangements.

The MS6001B and MS7001EA gas turbines were originally designed as generator drivers wherein the gas turbine thrust bearing is often the only thrust bearing in the generator drive train and thrust loading from the generator is relatively small. These gas-turbine thrust bearings can clearly support the thrust loading imposed by a flexible-diaphragm-type load coupling but cannot necessarily support the unassisted thrusts of all compressor trains. The three MS6001B and three MS7001EA gas turbines on order for refrigeration compressor drivers for the Malaysian LNG plant, plus the four MS6001B gas reinjection drivers, will all utilize flexible load couplings. However, in a different but thoroughly studied MS7001EA case, a balance-piston arrangement on the axial-flow load compressor (stage one) followed by a flexible coupling to the second stage compressor led to a train design wherein a rigid gas-turbine load coupling became the preferred arrangement. Full torsional and lateral studies were performed to confirm the acceptability of the rotor dynamics of that train.

## UNIT STARTING REQUIREMENTS

Figure 7 illustrates the normal starting sequence of the gas turbine. After the acces-

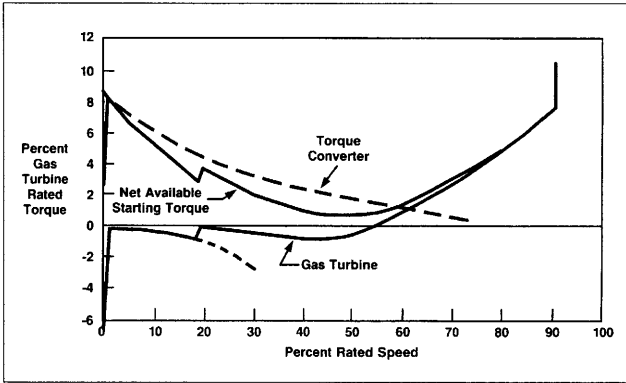
sories systems are activated, the gas turbine is brought to crank speed for three to six minutes while unfired to allow fresh air to purge through the inlet and exhaust systems. Purging time depends on the equipment configuration and local operating practices and has the purpose of removing any possibly explosive gas-air mixtures from the system. Then the gas turbine is allowed to coast down to optimal firing speed, the starting device (typically a motor and torque converter) is re-activated, the igniters are activated, fuel is admitted to the combustion chambers, flame is confirmed and a one-minute warm-up period is observed. The fuel flow is then increased on a programmed basis while the gas turbine and train accelerate to 92% of rated speed. At that point the compressor bleed valves are opened, the inlet guide vanes are opened to the normal operating range and the gas turbine is ready to accept load at a rate up to about 50% per minute. This point is referred to later in this paper as the "empowerment point."



**Figure 7. Typical gas turbine starting characteristics**

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When a single-shaft generator-drive gas turbine goes through the start-up cycle it has the tremendous benefit of merely driving an unloaded generator. The generator main circuit breaker is open and the friction, windage and inertia of the two-pole generator rotor are relatively low. Therefore, as illustrated by Figure 8, a modestly-sized starting motor (or other starting means) can bring the gas turbine to the self-sustaining speed of about 60 percent and then a very slight net available torque from the gas turbine takes over and continues to accelerate the set to the empowerment point of about 92% speed. The net available torque always exceeds the load torque imposed by the generator.

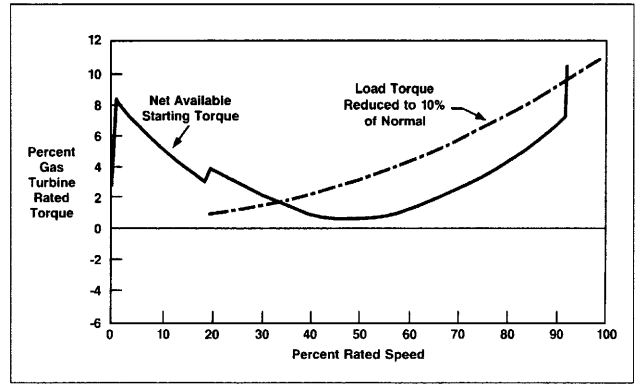


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Figure 8. Typical gas-turbine starting torque characteristics

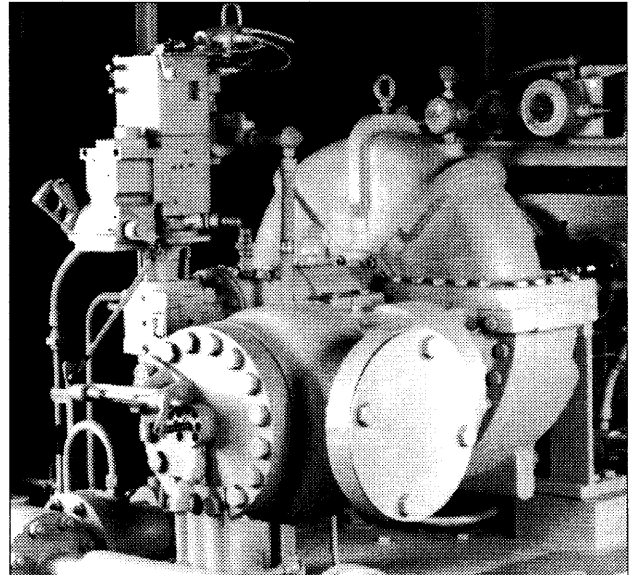
With a single-shaft gas-turbine mechanical drive, there is the need to significantly unload the driven equipment during the start-up process and at the same time provide much greater starting assistance in order to get to the 92% (speed) empowerment point. Figure 9 illustrates how the net available torque, between 30% and 92% speed, from the standard gas-turbine starting system (motor and torque converter) is inadequate to overcome the load torque from a typical load compressor that is already unloaded to 10% of normal torque.

To remedy this shortfall, the oil field MS6001B compressor drive application utilizes a 2800-hp (2100-kW) expansion turbine (Figure 10) as the starting means while the process compressor torque levels are reduced more than 90% by closing the suction(s) and venting the discharge(s). Figure 11 illustrates this starting torque situation. The saw-tooth torque characteristic of the expansion turbine is the result of a stepped throttle control for deliberate torque limiting. Sufficient torque is available to accelerate the train. Alternatively, a separate or supplementary starting means, such as an electric motor or expansion turbine, can be included in



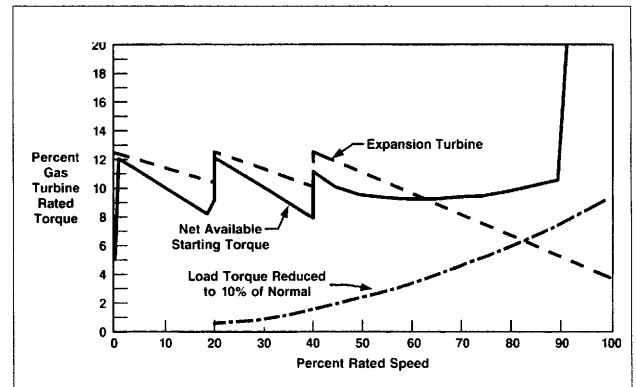
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Figure 9. Gas-turbine starting torque situation (to show inadequacy of standard motor-starting means for mechanical-drive applications)



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Figure 10. 2800-hp (2100-kW) expansion turbine used for starting oilfield compressor drive



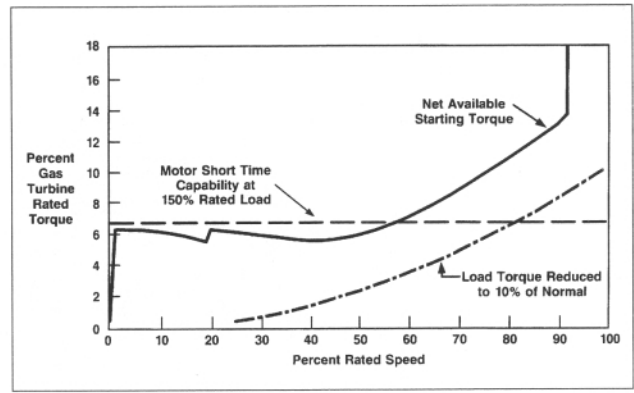
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Figure 11. MS6001B starting-torque characteristics with 2800-hp (2100-kW) expansion turbine for starting

the drive train to provide the necessary system starting torque. The three MS6001B and the three MS7001EA compressor drivers for the Malaysian LNG plant use steam turbines within the train as the primary train starting means.

The normal MS7001EA starting device is an 800 hp (600 kW) electric motor driving at 50% overload (short-time) through a torque converter and accessories gear-box to the gas turbine. GE does not have any larger starting means available for application at the front end of the MS7001EA that could provide torque assistance in the 30% to 92% speed range. A supplemental starting device would have to be placed at the load equipment end of the train. Supplementary starting means including steam turbines and a 5,000 hp (3,750 kW) adjustable speed motor drive have been proposed for use with the MS7001EA mechanical drives. These additional or supplementary starting means can also be used as booster drives on the train.

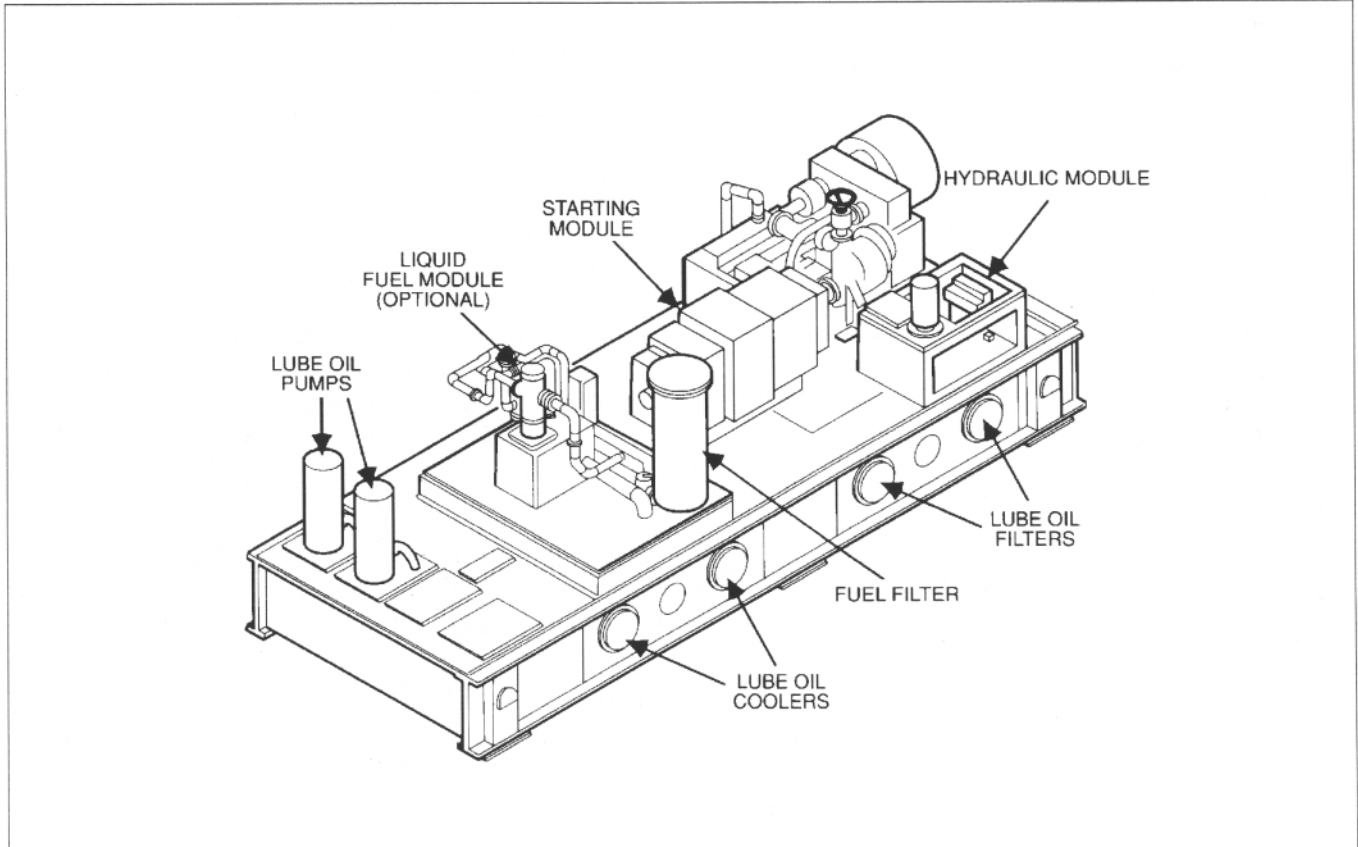
Figure 12 illustrates the starting torque characteristics of an MS7001EA with a 5,000-hp (3,750-kW) (rated) supplementary adjustable-speed starting motor providing the entire starting impetus. The actual torque required from the motor is significantly less than its rated capability during



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**Figure 12. MS7001EA gas-turbine starting-torque characteristics with 5,000-hp (3,750-kW) adjustable speed motor supplement**

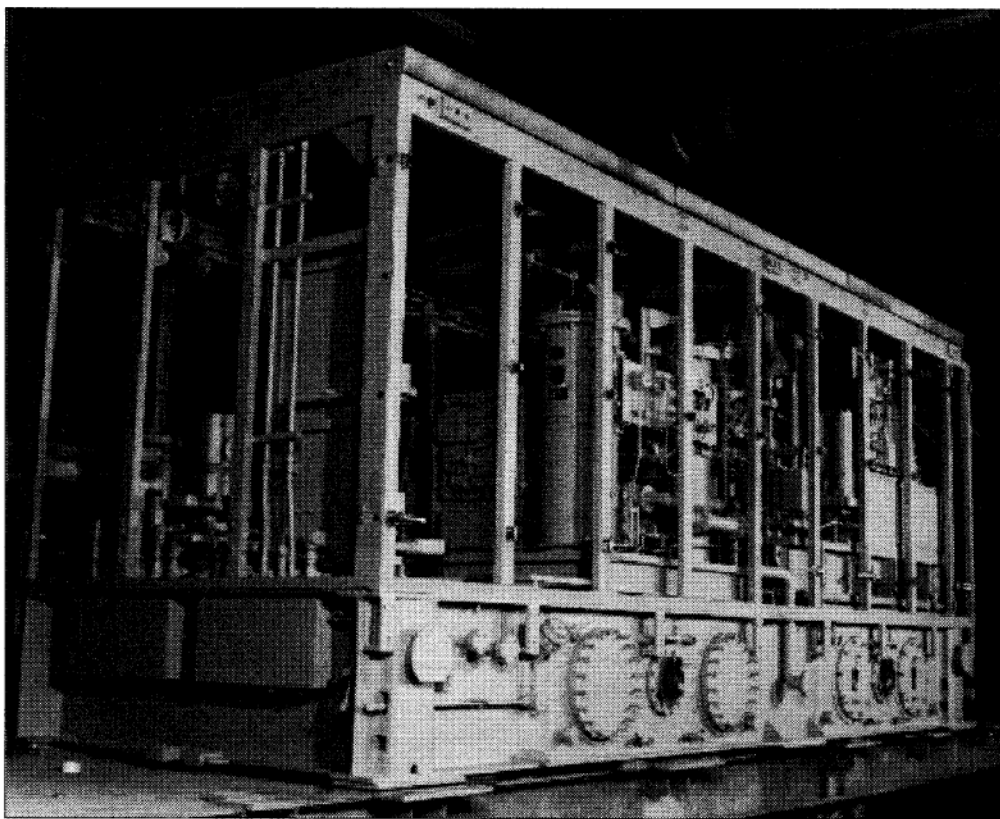
much of the starting period. It is only during the three minutes to accelerate from 60% speed to 90% speed that the motor is pressed into high-load operation. The required torque magnitude will vary among applications according to the particular characteristics of the process compressors and the method and degree of unloading achieved.



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**Figure 13. Standard accessories base arrangement**





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**Figure 14. Gas turbine accessories base for MS6001B and MS7001EA**

## ACCESSORY SYSTEMS

For the most part, the accessory systems that support the normal generator-drive gas turbine will be used to support the mechanical drive. If explosion-proofing is a requirement it can be met. Both the MS6001B and the MS7001EA now utilize the same accessory base design (Figures 13 and 14) which is available for either 50Hz or 60Hz electrical power. It offers redundant lube-oil coolers and redundant lube-oil filters which are normally requested on mechanical-drive applications.

On generator drives and smaller mechanical drives, GE practice has been to supply the lubrication oil to the load equipment from the single gas-turbine lube-oil system. Compressor seal air systems have generally been kept separate. On the larger mechanical-drive trains with moderate oil-flow requirements, this may still be possible. Table 4 describes lube-oil availability from the systems utilizing the largest gear pumps that can be fitted to the gas turbine's accessory gear box. Lube-oil temperature is conservatively held to 140°F (60°C) based on external cooling-water systems

**Table 4  
GAS TURBINE LUBE OIL SYSTEM PARAMETERS**

		<u>MS6001B</u>	<u>MS7001EA</u>
Main Lube Oil Pump Capacity (min. speed with 15% margin)	gpm (m <sup>3</sup> /h)	586 (133)	595 (135)
Gas Turbine Oil Flow Reqmts. (including GT accessories)	gpm (m <sup>3</sup> /h)	115 (26)	254 (58)
Lube Oil Flow Available to Load	gpm (m <sup>3</sup> /h)	471 (107)	341 (77)
Lube Oil Pressure (nominal)	psig (kg/cm <sup>2</sup> )	100 (7.0)	90 (6.3)
Lube oil Temperature			
Nominal	°F (°C)	130 (54)	130 (54)
Maximum	°F (°C)	140 (60)	140 (60)

and the frequent industrial customer requirement for such low temperatures. The gas turbines will however operate comfortably with lube oil temperatures up to 160°F (71°C), which is the common maximum temperature for packaged generator drives.

The gas-turbine control system employed across the GE product line is the SPEEDTRONIC Mark V which features triple-redundant micro-processors and redundant sensors for extremely high reliability. This system has full flexibility to coordinate with the sequencing and control requirements of the load equipment/process including precise speed control of the train, start-up coordination, incorporation of surge controllers, etc.

## RELIABILITY AND DURABILITY

Mechanical-drive process applications are usually characterized by extremely long run periods and low tolerance for unplanned outages. In short, these applications require extremely high reliability and durability.

GE design engineers have especially focused on reliability since the early 1970s with a continuum of special programs and projects. Two of the most significant activities were the establishment of a comprehensive field data collection system known as ORAP (Operational Reliability Analysis Program) in 1976 and a high-reliability design program sponsored by EPRI (Electric Power Research Institute) and begun in 1982. The ORAP system collects field operational data from participating customers on an events-logging basis. Every event that changes the operating status is logged to the nearest tenth of an hour and nearly every failure event is tagged with a component responsibility code and a failure mode code. ORAP is currently tracking 32 MS6001B and 153 MS7001 units (of which 54 are either model E or EA). Total gas-turbine history in ORAP is over 3,200 unit-years. Not only does this system provide a good measurement of actual reliability performance but it provides excellent feedback to the design engineers on problem areas for improvement. From the ORAP data base one can trace, in Figure 15, the Forced Outage Factor of the gas turbines and their supporting controls and accessories systems. Generator failure events are not included.

The EPRI high-reliability design program first observed that about 65% of the forced-outage events and 35% of the forced outage hours were attributable to the controls and accessories systems. A 40 man-year effort was then launched to maximize the reliability of the controls and

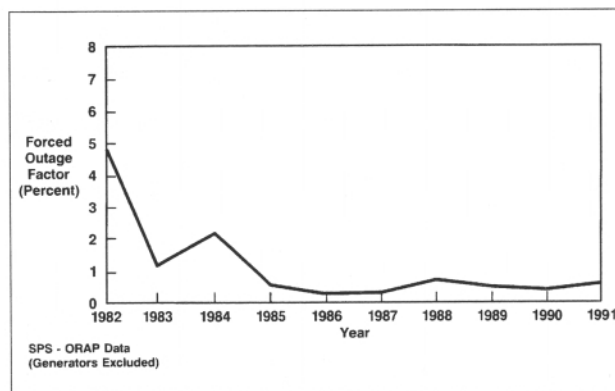


Figure 15. MS7001E/EA gas turbine reliability in terms of Forced Outage Factor

accessories systems. The identified improvements (over 60) served as the basis for MS7001F system design and were also applied across the product line as applicable. For example, the change from Speedtronic MkII to MkIV alone accounted for a major block of improvement, reducing failure rate by 356 events per million fired hours and forced outage factor by 0.44%.

One parameter shaping the EPRI program was mission time, or run time. The 3,000-hour run-time basis used in the program placed particular emphasis on the importance of redundancy throughout the controls and accessories systems. The net result is that, for the current production MS6001B and the MS7001EA gas turbines, a fleet average MTBF above 6,000 hours is expected together with a Forced Outage Factor of less than one percent.

Durability denotes long continuous run times without forced or planned shutdowns; one to two years is a reasonable expectation with clean fuel and clean inlet air. The normal gas-turbine inspection program has a baseline interval of 8,000 hours between planned inspections. But in recognition of the needs of mechanical-drive applications, the MS5002 gas turbine has long had a baseline interval of 12,000 hours and there are some combustion system options for the MS6001B and MS7001EA such that they too can start out with a 12,000 hour inspection interval. Considering a service profile of very few starts, steady load, and probably gas fuel, it is likely that the results from the first combustion inspections will suggest extension of the intervals to 16,000 hours, or about two years of service. Stringent air emissions requirements can, however, require heavy steam injection or water injection programs that will reduce inspections.

**Table 5  
GE GAS PERFORMANCE CHARACTERISTICS  
MECHANICAL DRIVE UNITS**

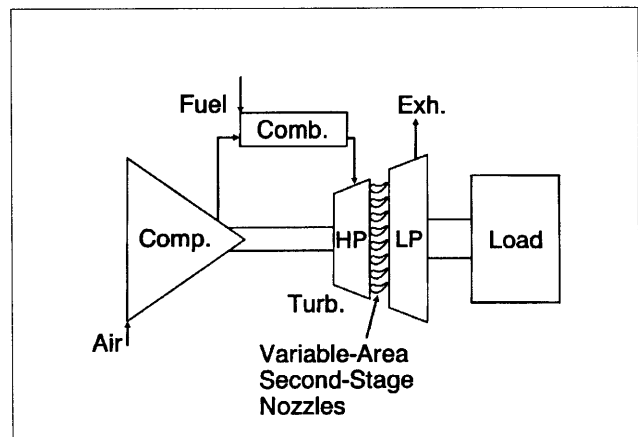
Model	Fuel (G-Gas)	Output		Heat Rate (LHV)		Exhaust Flow		Exhaust Temp.		Output Shaft Speed
		HP	kW	btu/hph	kJ/kWh	lb/h	kg/h	°F	°C	RPM
M3142(J)	G	15140	11290	9500	13440	421600	191230	1008	542	6500
M3142R(J)	G	14520	10830	7390	10450	421600	191230	698	370	6500
M5261(RA)	G	26400	19690	9380	13270	740400	335840	988	531	4860
M5352(B)	G	35000	26100	8830	12490	977900	443570	915	491	4670
M5382(C)	G	38000	28340	8700	12310	993400	450600	960	516	4670
M5352R(C)	G	35600	26550	6990	9890	956200	433720	693	367	4670
M6501(B)	G	50010	37290	7930	11220	1039600	471550	1022	550	4860
M7111(EA)	G	108200	80680	7790	11020	2224700	1009100	1001	538	3460
LM6000(PA)	G	56130	41860	6370	9010	999500	453360	836	447	3600

**15.14 to 108.2 KHP (11.29 to 80.68 KKW), 26.7 to 40% Efficient**

## OTHER GAS TURBINE APPLICATIONS

While the demands of the marketplace are requiring more and more available shaft power for specific industries, the more traditional gas turbine product models remain a very significant part of the product line mix (Table 5). The mechanical drive MS5002B,C family has been an industry standard for over thirty years. The MS5002's predecessor, the MS3002 was placed into service in 1952 with an ISO rating of 4,500 kW. Today's MS5002C generates 38,000 hp (28,350 kW) using the same basic variable second-stage nozzle design as introduced initially.

With the high-energy impulse turbine design used by GE, two turbine stages efficiently convert gas stream available energy into mechanical energy. It is then possible to design a variable second-stage nozzle (Fig. 16) between the high pressure turbine (driving the compressor) and the low pressure turbine (driving the load). When the second-stage nozzle is opened, the

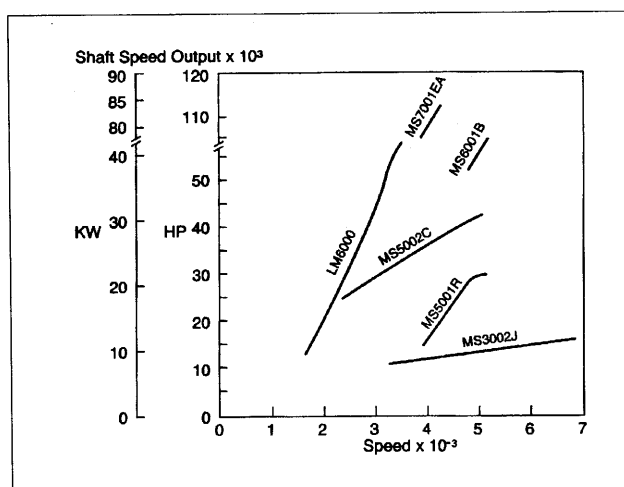


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**Figure 16. Simple-cycle two-shaft turbine.**

back pressure on the high pressure turbine is lowered, resulting in greater energy utilized across the high pressure turbine. The ability to modulate energy between turbine sections of the MS5002B,C has the advantages of:

- Good part-load efficiency for all cycle arrangements



GT23673

**Figure 17. Power and speed range of mechanical drives (ratings at ISO)**

- Better control over speed when load suddenly changes
- Maximum power output over a wide range of ambient temperatures and driven-equipment speeds

The performance of the familiar two-shaft gas turbines has continually been improved with advancements in technology to meet the demands of the marketplace. For example, the directionally-solidified buckets used in the first stage have allowed significantly-higher firing temperatures and extended maintenance intervals. The current plans to introduce NO<sub>x</sub>-abatement capability to the mature two-shaft design enhance its applicability for mechanical power today. Figure 17 shows the relationship between power and speed for various gas turbine designs.

Another of the design enhancement characteristics to the MS5002B,C is the variable inlet guide vane. As more and more mechanical-drive gas turbines are being connected to a heat recovery device, the ability to deliver a constant exhaust temperature over a wide load range becomes very important for plant operation and efficiency. Along the lines of overall plant efficiency, more emphasis is being placed on the ability to burn various process off-gases, typical at very low heating value. Current combustion hardware allows use of fuels as low as 105 Btu/ft<sup>3</sup> (4,133 kJ/NM<sup>3</sup>) and up to 3,000 Btu/ft<sup>3</sup> (118,100 kJ/NM<sup>3</sup>). Such fuel requirements are reviewed on a case-by-case basis.

## SUMMARY

GE's large gas turbines are ready to serve in selected mechanical drive applications. The high reliability demonstrated in power-generation applications combined with the economies of scale in power, fuel efficiency and space utilization provide strong incentive for such consideration. In the case of the MS6001B and MS7001EA, there are basically three areas of technical sensitivity. The first is the need to live with a somewhat narrow continuous operating speed range. The second (and of traditional concern) is to gain assurance of acceptable train rotor dynamics. The third area is the configuring of an acceptable start-up system. The speed range is fixed but in the second and third areas there are multiple acceptable solutions.

This paper has been primarily concerned with the differences between mechanical and generator drives. However, when put in perspective, the actual differences are small. The commonalities (and therefore relevant experience factors) are great! The entire flange-to-flange engines are the same, as are the majority of accessory systems and controls. In fact, the design changes for mechanical drive applications are no greater in scope than the customizing features applied to some generator-drive machines.

While the large single-shaft gas turbines offer significant economies for scale in specific applications, there are certain limitations to their use in all cases. In applications requiring wide speed ranges and flexibility, the somewhat smaller MS5002C still remains the driver of choice. Capability to control exhaust temperature, easier starting requirements and increased output along with NO<sub>x</sub> abatement continue to keep the familiar MS5002C still a turbine of choice in today's world.

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