Performance and Reliability Improvements for Heavy-Duty Gas Turbines

J.R. Johnston
GE Power Systems
Schenectady, NY
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Abstract

Many significant advances in technology have been applied to new unit production. These advanced technology improvements can be applied to field units to achieve increased performance, useful life and reliability. Additionally, many development programs have been specifically developed for application to existing operating units.

Several types of improvements are now available for compressors, combustion systems and hot-gas-path turbine parts. This paper provides a summary of uprate programs available for all models of GE heavy-duty gas turbines with special emphasis on new programs for MS6001, MS7001 and MS9001 (both E and F class models). Complete tabulations of performance improvement, material changes and maintenance interval extensions are included. All uprates that involve changes in firing temperature and/or airflow will have some impact on emissions. Tabulations of original gas turbine emission levels and uprated turbine emission levels are included for reference. Advanced technology uprate packages are available to upgrade almost all of the 6,000 GE-design heavy-duty gas turbines.

Introduction

Turbine uprate packages have been introduced because of continued strong user interest in extending intervals between maintenance, improving efficiency and increasing output. Figure 1 lists the main items the customer and GE must consider when evaluating a unit for one of the advanced technology uprate options. This paper covers new uprates that have been successfully developed specifically for field unit application and new uprates that are available as a result of using engineered components that were developed for current new-unit production. Figure 2 lists uprates covered in this paper. Figure 3 shows the growth in scope and numbers of advanced technology uprates supplied per year. To date there are over 400 firing temperature uprates for field units involving every

- Performance Improvements (Output/Heat Rate)
- Maintenance/Inspection Interval Extensions
- Availability/Reliability Improvements
- Emissions Impact/Regulatory Agencies
- Life Extension
- Thorough Review of Gas Turbine Components and Accessories Systems for Compatibility
- Thorough Review of Load Equipment and Accessories for Compatibility

New Unit Technology/Components

Figure 1. Uprate considerations
frame size. The most common time to consider an uprate is during the first or second major overhaul when the unit has been in operation 10 years or more.

Every owner of GE heavy-duty gas turbines should evaluate the overall economics of the various uprate programs. In most cases, the economic evaluation will justify one of the available uprate packages at the next major overhaul.

Information on specific uprate packages or components is available in the Gas Turbine Sourcebook. Reference codes (such as FT2C for

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<td>All</td>
<td>Firing Temperature Increase to Full Rating</td>
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**Figure 2.** Gas turbine uprates

**Figure 3.** Gas turbine advanced technology uprate shipments through 1999
an MS5002 Advanced Technology Uprate) have been added to this text and to many of the figures and tables. The Sourcebook is an automated system available to all GE offices for quick reference on all uprate options listed in the GER and for all other package options available for heavy-duty gas turbines. Soon all of the uprate options as well as those for emissions, fuels, reliability improvement and controls upgrades will be accessible directly by customers on the GE/WEB Optimizer program.

GE engineers and/or customers have written many papers that document the evaluation and implementation process for the more significant uprates. Figure 4 lists the most recent ASME papers that document results of these successful uprate projects.

GE design heavy duty gas turbines. Figure 5 summarizes these development programs with a matrix that shows which program applies to each frame size. We leverage each new program across the entire product line to make each of these programs available to all customers.

Approximately 20% of the inlet air to the axial flow compressor gets lost to the thermal cycle due to losses associated with cooling hot gas path parts or losses due to large clearances. Most uprates on gas turbines typically are achieved by higher airflow or higher firing temperatures. Recently a significant effort has been applied to reducing airflow losses from cooling air and improved seals. The majority of development in the past few years has been directed to reducing these airflow losses. Most of the recent development programs are focused in this area.

**High-Pressure Packing Brush Seals (FS2V)**

Figure 6 shows the original labyrinth seal design between the compressor discharge casing...
“inner barrel” and compressor aft stub shaft. This seal restricts compressor discharge air from leaking into the forward wheel space area. This seal is designed with a nominal clearance of 40 mils to allow for thermal growth differentials and rotor movement during high vibration events.

In practice, most operating units have clearances significantly higher (20 to 60 mils) than nominal. This increased labyrinth seal clearance results in considerable unit performance loss. For a MS7001E unit, a rub of 20 mils on the labyrinth seal teeth equates to at least 1.0% loss in unit performance.

To increase unit performance and to reduce the rate of performance degradation due to wear on labyrinth seal teeth, a new wire brush seal design has been developed. Figure 6 details the wire brush seal. Since the wire brush seal is flexible and will bend (not wear) on contact
with the compressor aft shaft, a closer clearance can be allowed for the initial installation. This provides an increase in output.

Also, since the wire brush seal will “bounce back” to its original configuration after a “rub,” there will be substantially less performance degradation over time than for the original labyrinth seal. Performance improvement is typically about 1% output and 0.5% heat rate. Figure 6 shows a typical HPP brush seal.

**#2 Bearing Brush Seals (FS2X)**

The airflow that passes through the High Pressure Packing (HPP) pressurizes the inner wheel space of the turbine. For units with a middle bearing, a significant amount of this air will leak through the #2 bearing outer seals and vent to atmosphere. This represents a significant performance loss. As a follow-on to the successful HPP brush seal program, a brush seal has also been designed to improve the inner stage packing seal. This seal is now available for all single shaft designs and provides a performance improvement of approximately 1% output and 0.5% heat rate. A cross-section of a stage 2 nozzle with a brush seal is shown in Figure 8.

**Stage 2 Nozzle Inner Diaphragm Brush Seal**

There is a large gap between the stage 2 nozzle inner diaphragm and the stage 1-2 wheel spacer to prevent any contact due to rotor vibration, thermal transients or nozzle deflection. Unfortunately this gap is a substantial leak path. As a continuation of the successful HPP and #2 bearing brush seal programs, a brush seal has been designed to improve the inner stage packing seal. This seal is now available for all single shaft designs and provides a performance improvement of approximately 1% output and 0.5% heat rate. A cross-section of a stage 2 nozzle with a brush seal is shown in Figure 8.

**Stage 2 and 3 Shroud Honeycomb Seal (FS2T/FS2U)**

To avoid bucket tip rub, the clearances between the bucket tip and the stationary shroud blocks have always been about 100 mils. This large clearance allows a significant amount of hot gas
to flow over the bucket tip, resulting in significant performance loss. To address this issue, a honeycomb seal insert (see Figure 9) was designed to be inserted between the labyrinth seal teeth in the stage 2 and 3 shroud blocks. The honeycomb material is softer than the shroud and bucket material, which makes it sacrificial in nature for this application. The bucket tip shroud labyrinth seals are designed to cut a groove into the honeycomb material. The tight clearance between the bucket tip and the honeycomb shroud seals provide a performance improvement up to 0.6% in both output and heat rate. To make sure we effectively cut a groove into the honeycomb material we also design a “cutter tooth” on the leading edge of the bucket shroud tip labyrinth seals (see Figure 10).

**Figure 8.** Stage 2 nozzle with a brush seal

**Figure 9.** Honeycomb seal insert

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*Honeycomb Shroud Blocks*

- **Honeycomb Shrouds**
  - Reduces Leakage
  - Greater Rub Tolerance
- **Requires Buckets with Cutter Teeth**
**Stage #1 Shroud Cloth Seals (FS2Y)**

Leakage of compressor discharge air past the shroud block segments is one of the most critical areas for performance loss. The original pumpkin-tooth style design with an interlocking spline seal is a good seal, but is fairly inefficient. The new design has a flat-face shroud block with a cloth seal that inserts into grooves in both adjacent shroud blocks. *Figure 11* compares the improved design versus the original pumpkin-tooth design. *Figure 12* compares the original bar type spline seal versus the upgraded cloth seal.

The cloth-seal design seals both radial and axial flow and provides a flexible seal to allow for individual shroud block misalignment. This improved seal design restricts the higher pressure, compressor discharge air from leaking into the hot gas path. As a result, it provides a performance improvement of up to 0.7% in output and 0.5% in heat rate.

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**First Stage Shroud Cloth Seals**

- New Material and Improved Sealing
- Improved Performance (Pending Audit)

*Figure 11.* “Pumpkin-tooth” design vs. new shroud seal design
**New Intersegment Seal Design**

![Diagram of seal designs](image)

**Stage 1 Shroud Abridable Coating (ES20)**

Clearance between the stage 1 bucket and the stage 1 shroud block is a critical factor because it allows combustion air to leak over the tip of the stage 1 bucket, which causes significant performance loss.

A large clearance typically is required to account for conditions that can result in significant bucket rub:

- Casing out-of-roundness
- Misalignment of the rotor
- Shroud block misalignment

The abraidable coating is intended to account for all of these items and to provide an absolute reduction in hot running clearances. The abraidable seal is a 40-mil thick coating in the inner diameter of the stage 1 shroud blocks. The intention is to have the bucket tips rub into the abraidable coating during the first few startups to mold a round gas path, regardless of casing roundness, shroud misalignment, rotor misalignment or bucket tip rubs (on used buckets). The expectation on an installed turbine is a minimum performance improvement of 0.4% output and 0.3% heat rate. *Figure 13* depicts a typical abraidable coating on a Stage 1 shroud.

This combination of cloth-seal replacement shroud blocks and abraidable coating should provide impressive performance improvements in excess of 1.1% output and 0.8% in heat rate.

**MS9171E Single-Piece Stage 1 Shroud**

The initial design for the MS9171E (2055F) design incorporated a two-piece, Stage 1 shroud. This was necessary to achieve acceptable parts life with the original A&SI 310 stainless steel material. The more recent HR120 material is a more crack resistant alloy and is better able to withstand the higher firing temperature. Thus we can now provide a single-piece stage 1 shroud block. The cooling and sealing air changes associated with the 2-piece shroud design resulted in a performance loss of 0.9% to output and 0.4% heat rate. Thus for all MS9171E (2055F) units we can provide the new HR120 single-piece shroud to recover this performance loss (*see Figure 14*).

**Reduced Camber, High Flow Inlet Guide Vanes**

Improvements in Inlet Guide Vane (IGV) material and airfoil design have also increased airflow. *Figure 15* details performance increases available by applying the latest IGV designs to...
older units. The new IGVs are directly interchangeable with the original IGVs in complete sets. However, in many cases new control curves and/or inlet guide vane settings are required to achieve optimal performance. Additionally, the new reduced camber IGVs are made from GTD 450, a stronger and more corrosion-resistant stainless steel.

As part of the modification kit for GTD 450 IGVs, a set of tight clearance, self-lubricating IGV bushings are also supplied.

**GTD222 Stage 2 Nozzle Material (FS1P)**

The new GTD222 high-nickel based alloy was developed in response to the need for an improved creep-resistant alloy for stages 2 and 3 for the MS6/7/9 higher firing temperature designs. The improvement in creep resistance was so great that we were able to reduce the cooling air for the stage 2 nozzle. Figure 16
Figure 17 shows a comparison of creep deflection between the original FSX414 material and the new GTD222 material. Figure 18 shows the performance improvements for MS 6/7/9 units.

**Lean Head End (LHE) Combustion Liners (FR1B)**

The original design of louvered combustion liners for MS3/5 units had relatively high NOₓ levels. More recent developments in combustion liner technology enable the use of leaner head end/lower NOₓ designs. NOₓ reductions of up to 30% can be achieved by applying the newer LHE technology. Figure 19 shows a comparison of the original liner versus the LHE liner. In areas where emission regulations allow it, all uprates to an advance technology uprate package can be done when applying the LHE liner to actually get an uprate with lower emissions. Figure 20 shows an overall 20% reduction in...
NO\textsubscript{x} emissions when applying an advance technology uprate for a MS5001P unit.

**MS5432D Advance Technology Uprate (FT2T)**

Due to the strong customer interest in uprates for the MS5382C, the MS5432D was introduced. For the MS5002D we combined the highly successful MS5002C hot gas path with the MS6001B axial flow compressor as shown in Figure 21. This new design has been successfully applied for both uprates of field units as well as for new unit production to provide approximately a 13% power increase.

**MS3162K Advance Technology Uprate (FT1W)**

Due to strong customer interest in uprates for the MS3152J, MS3216K is being introduced. This design improvement applies modern advanced airfoil design technology to the MS3002 axial flow compressor. This uprate
requires new compressor wheels and blades but retains the original compressor casings. The increase in output is 8.0% and the improvement in heat rate is 7.0%. Figure 22 shows a cross section of a MS3002 unit to highlight the parts that are affected by this advanced technology uprate.

**MS7001F/FA PG 9001F/FA Uprate Packages**

There have been numerous uprates/upgrades involved in the 7F/9F product line over the past several years. In most cases the latest upgraded buckets, nozzles and shrouds can be applied to all of the older production F/FA units. Additionally, if these design improvements are applied in selected packages, significant performance improvements will result. Figure 23 shows specific performance improvements that can be achieved by applying selected component kits to the older production 7/9 F/FA models.

**Massive Steam Injection for MS 7001E**

GE has offered steam injection for power augmentation for 40 years on all of our production machines. Figure 71 shows the relative output/efficiency improvements with up to 5.0% steam injection (as a percentage of airflow). Considerable design effort was applied in 1999 to develop a 9% steam injection option for the MS7001E &EA models. It was determined that by applying the current production advance technology hot gas path parts we can achieve 29.0% in output without any loss in parts life. Figure 24 lists various parameters involved in applying the 9.0% steam injection option.

**Conventional Uprates Applying New Unit Advance Technology**

**MS3002 Advanced Technology Uprate Package - Models A through G (FT1A)**

The MS3002 gas turbine was introduced in 1950. Various design changes in combustion and turbine hot-gas-path design were developed over the years, as the unit was uprated from the MS3002A through the MS3002F and G models. Figure 25 lists the performance characteristics for the various models. This unit has been used for many pipeline, process and generator-drive applications. An advanced technology uprate package was developed because of continued strong customer interest in reduced mainte-
nance cycles, improved efficiency and increased output. Figure 26 details the MS3002 advanced technology package. Figure 27 details predicted improvements in thermal efficiency and output for the advanced technology parts package for regenerative cycle units.

Considerable fuel savings are realized with improvements in thermal efficiency to 33.0% for the regenerative cycle. Regenerative cycle units can be uprated to over 10,620 HP at ISO conditions with greater than 33.0% thermal efficiency, regardless of original unit configuration. Most simple-cycle units can be uprated to 11,590 HP at ISO conditions. Figure 28 details expected reductions in maintenance intervals.

As maintenance inspections for hot-gas path are extended to 48,000 hours, considerable reductions in planned outages and associated main-
Tenance costs are realized. Figure 29 is a cross-section detailing existing components that are replaced with advanced technology components. Performance tests on all units completed to date show actual performance improvements in excess of those shown in Figure 27.

MS3002 Uprate to 3/2F Configuration (FT1U)

Earlier MS3002 Models A through E and G can be uprated with MS3002F combustion and hot-gas-path parts for significant improvements in output, heat rate and expected parts life.

Urating with 3/2F combustion and hot-gas-path parts will provide 9,400 HP NEMA rating in regenerative cycle and 9,700 HP NEMA rating in simple-cycle operation. For example, an MS3002A unit rated at 5,000 HP could be uprated to 9,400 HP in regenerative configuration by upgrading with MS3002F hot gas path components. For performance changes for...
other models, refer to Figure 25. Both ratings also include the high flow 81° IGVs. The MS3002F components are much more readily available than earlier production parts, which makes it possible to achieve considerable benefits in parts availability and parts standardization. In upgrading the combustion system for older vintage MS3002 units, the MS3002F or MS3002F combustion systems could be used. The MS3002F combustion system has the added advantage of being easily converted to a Dry Low NOx (DLN) combustion system if also required.

This uprate requires converting to the MS3002F Stage 1 and 2 shrouds, nozzles, wheels and buckets, and either the MS3002F or MS3002F combustion system. All MS3002F hot-gas-path components can be retrofitted into the existing
turbine shell with some modifications. Figure 30 details individual component upgrades for use in applications where a complete “A” to “F” uprate may not be required.

**MS3002 H and J Advanced Technology Uprate Package (FTID)**

A modernization and uprate program developed for the MS3002 H and J units based on similar design improvements has been introduced on other units in the GE heavy-duty product line. This program involves uprating the turbine to 1,700 F/966 C from the present 1,730 F/943 C firing temperature. Figure 25 lists the original performance for these units. Figure 31 details the design improvements for the MS3002 H and J advanced technology uprate program. The key ingredient required for the MS3002J advanced technology uprate is the directionally solidified GTF 111 Stage 1 bucket. All of the components in this package are necessary to enable the uprate and will provide improvements in output of 3.7% and heat rate of 0.3%.
In addition to the performance improvement, considerable extension of recommended inspection intervals can be realized. Figure 28 compares recommended maintenance intervals for the original design components and the advanced technology components when used in complete uprate packages. The significant differences are an extension of combustion inspection intervals from 8,000 hours to 12,000 hours and elimination of the recommended hot-gas-path inspection, which was at 24,000 hours.

Figure 29. MS3002 modernization and uprate program

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<td>Stage 1 Wheel/Bucket</td>
<td>- Solid One Piece 3/2F Forged A286 Wheel Replaces Composite Wheel. Stage 1 3/2F Bucket Is Made from U500 Material And Has an Integrated Coverplate</td>
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<td>Stage 2 Wheel/Bucket</td>
<td>- Solid One Piece 3/2F Forged A286 Wheel Replaces Composite Wheel. 3/2F Wheel Can Run at 6000 RPM vs. 5000 RPM for Composite Wheels. Stage 2 Bucket Will Be 3/2F Bucket Made of U500 Material.</td>
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Figure 30. MS3002F component design improvements

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<td>- Swirl Cooled Cross Fire Tubes</td>
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<td>- Hard Facing on Cross Fire Tube Ends</td>
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<td>- Thick Wall Transition Pieces with Floating Seals</td>
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<tr>
<td>FS1U</td>
<td>- Stainless Steel Exhaust Diffuser (High Ambient Temp. Applications Only)</td>
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</tbody>
</table>

Figure 31. MS3002H and J advanced technology uprate
As maintenance intervals for hot-gas-path parts are extended to 48,000 hours, considerable reductions of planned outages and associated maintenance costs are realized. Nine sets of MS3002J advanced technology uprate parts have been installed. MS3002J units shipped prior to 1978 would get an additional 2.2% output increase by using the latest design inlet guide vanes (see Figure 15). High ambient temperature MS3002J units will also need to change the exhaust diffuser material to a high temperature stainless steel design. Figure 43 shows the relative performance improvement for an MS5002A unit by increasing the exhaust temperature limit to 1050 F/566 C. Similar performance improvements will be achieved for MS3002J units by using the higher temperature stainless steel exhaust diffuser material (see figure 39).

**MS3162K Advance Technology Uprate (FT1W)**

To address strong customer interest in improved thermal efficiency and increased output, the new MS3162K was recently introduced. The primary design change is in the axial flow compressor with an improved aerodynamic blading design. The overall increase in performance.

---

**Figure 32. MS3162K advanced technology uprate definition**

- Complete Aerodynamic Redesign of Compressor Blades
- Parallel Combustion System
- Combustion Liner and Transition Piece Redesign
- Reduced Area Stage One Nozzle
- Stage One Shroud Seals
- Increased Capacity Thrust Bearing
- High Pressure Packing Brush Seal
- #2 Bearing Brush Seal
- Combustion Wrapper Redesign
- Compressor Anti-Surge Valve

**Figure 33. MS3002J uprate summary**

<table>
<thead>
<tr>
<th></th>
<th>Output</th>
<th>Heat Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Flow IGV’s (Pre 1978)</td>
<td>+2.20%</td>
<td>-0.50%</td>
</tr>
<tr>
<td>MS3152J Adv Tech Uprate</td>
<td>+3.70%</td>
<td>-0.30%</td>
</tr>
<tr>
<td>Stage 2 Shroud Honeycomb Seal</td>
<td>+0.40%</td>
<td>-0.40%</td>
</tr>
<tr>
<td>HPP Brush Seal</td>
<td>+0.70%</td>
<td>-0.50%</td>
</tr>
<tr>
<td>Stage 1 Shroud Cloth Seal</td>
<td>+0.50%</td>
<td>-0.50%</td>
</tr>
<tr>
<td>MS3162K Adv Tech Uprate</td>
<td>+8.20%</td>
<td>-7.15%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>+15.7%</td>
<td>-9.35%</td>
</tr>
</tbody>
</table>
formance is +8.2% output and –7.15% heat rate. The complete redesigned compressor blading will still fit within the existing 3/2 J compressor casings. Figure 22 is a cross-section of the new MS3162K. A detailed listing of all design changes is shown in Figure 32. A significant visual difference is the change to a parallel reverse flow combustion system.

Figure 33 is a summary of all performance improvements for MS3142J units

**MS5001 Advanced Technology Uprate Package - Models A through P (FT3L and FT3M)**

The MS5001 unit was first introduced in 1957. Various design changes in combustion and turbine hot-gas-path design have been made over the years, as the unit was uprated from the MS5001A to the current MS5001P model. Figure 34 lists the original performance characteristics of the various models. This unit has been used for both mechanical- and generator-drive applications.

The initial advanced technology uprate package was designed to apply to models L through P only. This uprate package is intended to improve efficiency and output and to extend maintenance intervals. Figure 35 details the MS5001 parts package for models A through P. Figure 28 details expected extensions in maintenance intervals. As maintenance inspections for hot-gas-path are extended to 48,000 hours, considerable reductions of planned outages and associated maintenance costs are realized. Estimated output and heat rate improvements for MS5001 advanced technology uprates are shown in Figure 36 for models MS5001 L through P.

Incremental output and heat rate improvements can be as high as 31.1% and 9.1%, respectively. Load equipment capability must be carefully reviewed for each application to determine if it is adequate for the uprate or if a similar uprate is required. Several units with advanced technology parts have had more than 50,000 operating hours since the uprate. To determine the best possible uprate program for each customer, it is usually necessary to do a thorough review of all available uprates and to review the capabilities of all associated load equipment.

Further review of the advanced technology uprate package resulted in a design to apply the uprate to older vintage MS5001A through

---

### Table: Performance History of MS5001 Units

<table>
<thead>
<tr>
<th>Model</th>
<th>Ship Dates</th>
<th>kW (NEMA) (1)</th>
<th>Firing Temp (F/C)</th>
<th>Air Flow (10^5 lbs/hr)</th>
<th>Exhaust Temp (F/C)</th>
<th>Heat Rate (Btu/lb)</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1957-61</td>
<td>10,750</td>
<td>1500/816</td>
<td>662/300</td>
<td>840/449</td>
<td>15,810</td>
<td>21.6</td>
</tr>
<tr>
<td>C</td>
<td>1961-64</td>
<td>10,750</td>
<td>1500/816</td>
<td>662/300</td>
<td>835/446</td>
<td>15,810</td>
<td>21.6</td>
</tr>
<tr>
<td>D</td>
<td>1961-63</td>
<td>10,750</td>
<td>1500/816</td>
<td>662/300</td>
<td>835/446</td>
<td>15,810</td>
<td>21.6</td>
</tr>
<tr>
<td>E</td>
<td>1963</td>
<td>11,500</td>
<td>1500/816</td>
<td>695/315</td>
<td>830/443</td>
<td>15,780</td>
<td>21.6</td>
</tr>
<tr>
<td>G</td>
<td>1963-64</td>
<td>12,000</td>
<td>1500/816</td>
<td>695/315</td>
<td>830/443</td>
<td>15,780</td>
<td>21.6</td>
</tr>
<tr>
<td>H</td>
<td>1964</td>
<td>12,500</td>
<td>1500/816</td>
<td>695/315</td>
<td>820/438</td>
<td>14,430</td>
<td>23.6</td>
</tr>
<tr>
<td>K</td>
<td>1965</td>
<td>12,500</td>
<td>1500/816</td>
<td>695/315</td>
<td>820/438</td>
<td>14,430</td>
<td>23.6</td>
</tr>
<tr>
<td>L</td>
<td>1966-67</td>
<td>14,000</td>
<td>1600/871</td>
<td>702/318</td>
<td>895/479</td>
<td>14,440</td>
<td>23.6</td>
</tr>
<tr>
<td>LA</td>
<td>1967-60</td>
<td>15,250</td>
<td>1650/899</td>
<td>707/322</td>
<td>930/499</td>
<td>14,190</td>
<td>24.1</td>
</tr>
<tr>
<td>M</td>
<td>1969-70</td>
<td>16,100</td>
<td>1700/927</td>
<td>716/325</td>
<td>965/518</td>
<td>14,050</td>
<td>24.3</td>
</tr>
<tr>
<td>R</td>
<td>1970-87</td>
<td>19,400</td>
<td>1720/938</td>
<td>767/346</td>
<td>955/513</td>
<td>13,260</td>
<td>25.8</td>
</tr>
<tr>
<td>R-N/T</td>
<td>1987-</td>
<td>20,500</td>
<td>1755/957</td>
<td>767/348</td>
<td>970/521</td>
<td>12,780</td>
<td>26.8</td>
</tr>
<tr>
<td>N</td>
<td>1970-72</td>
<td>24,600</td>
<td>1730/943</td>
<td>928/421</td>
<td>988/481</td>
<td>12,190</td>
<td>28.0</td>
</tr>
<tr>
<td>P</td>
<td>1972-78</td>
<td>24,600</td>
<td>1730/943</td>
<td>938/425</td>
<td>904/494</td>
<td>12,140</td>
<td>28.1</td>
</tr>
<tr>
<td>P-N/T</td>
<td>1978-86</td>
<td>23,350</td>
<td>1730/943</td>
<td>968/439</td>
<td>901/483</td>
<td>12,020</td>
<td>28.4</td>
</tr>
<tr>
<td>P-N/T</td>
<td>1987-</td>
<td>26,820</td>
<td>1765/963</td>
<td>961/445</td>
<td>905/485</td>
<td>11,860</td>
<td>28.7</td>
</tr>
</tbody>
</table>

(1) In early 1970s, Rating Standards Were Changed From NEMA (1000 ft/300m Altitude and 80°F/27°C) to ISO (Sea Level and 59°F/16°C) Conditions. To Convert From NEMA to ISO Rating for Approximate Comparison, Multiply NEMA Rating by 1.12. Includes 0/0 Inches H2O Inlet/Exhaust Pressure Drops. All Ratings Based on Natural Gas Fuel.
MS5001 K models. This basically involved a new turbine casing in addition to the advanced technology package. Figure 34 shows original performance for models A through K. The maximum uprating by applying the advanced technology package is the MS5001 R advanced technology rating, also shown in Figure 34. Actual percentage improvement for this performance uprate can vary depending on original unit configurations.

Figure 36. MS5001 models L through P advanced technology uprate package

Compressor Upgrades - MS5001 Models A through M and R (FT3F) and MS5002A (FT2E)

In 1970, the basic MS5001 compressor was uprated by adding a zero stage to increase airflow by approximately 28% and output by 36%. Previous 5001 models A through M and the more recent 5001R models can all be uprated to the 5001 N/P compressor design by adding a

---

Table: Incremental % Gains

<table>
<thead>
<tr>
<th>Drive</th>
<th>Incremental % Gains</th>
<th>Exhaust Temp. Increase °F/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>5001L</td>
<td>Generator 31.1 9.1</td>
<td>86/48</td>
</tr>
<tr>
<td>5001L</td>
<td>Mechanical 25.9 7.2</td>
<td>77/43</td>
</tr>
<tr>
<td>5001LA</td>
<td>Generator 20.3 7.5</td>
<td>51/28</td>
</tr>
<tr>
<td>5001LA</td>
<td>Mechanical 17.7 7.2</td>
<td>52/29</td>
</tr>
<tr>
<td>5001M</td>
<td>Generator 14.0 6.5</td>
<td>16/9</td>
</tr>
<tr>
<td>5001M</td>
<td>Mechanical 12.3 7.1</td>
<td>19/11</td>
</tr>
<tr>
<td>5001R</td>
<td>Generator 6.0 2.9</td>
<td>16/9</td>
</tr>
<tr>
<td>5001R</td>
<td>Mechanical 5.7 2.7</td>
<td>15/8</td>
</tr>
<tr>
<td>5001N</td>
<td>Generator 6.0 3.3</td>
<td>10/6</td>
</tr>
<tr>
<td>5001P</td>
<td>Generator 6.0 3.3</td>
<td>10/6</td>
</tr>
</tbody>
</table>
Performance and Reliability Improvements for Heavy-Duty Gas Turbines

zero stage. This can be accomplished by changing the compressor bellmouth forward and aft compressor casings and stages 1, 2, 3 and 10 compressor wheels and blades, adding a zero stage and adding variable inlet guide vanes.

It is also recommended to change the remaining stages of compressor blading because of the age of blades and the increased loading on them, resulting from increased airflow and pressure ratio. For 5001 models A through M, this modification would have to be done in conjunction with a hot-gas-path uprate to a 5001R model configuration to accommodate the increased airflow. MS5001R units can be uprated without combustion or flange-to-flange changes.

Sixteen compressor uprates have been shipped to date. The typical MS5001 shaft speed range for mechanical-drive application is 80% to 105% of 4,860 rpm for the lower airflow 16-stage compressor MS5001 A through M and R units. The higher airflow 17-stage MS5001N/P compressor has a more limited speed range of 90% to 105% of 5,100 rpm. Thus, with this modification, some speed range flexibility loss comes with the airflow/output increase. Figure 34 shows airflow for all 5001 models.

An uprate of 36% is possible at site rating conditions of 40 F/4 C at 5,100 rpm with only a compressor uprate. An uprate of 42% is possible with compressor and advanced technology turbine uprate. Figure 37 shows an MS5001 16-stage compressor and an MS5001 17-stage compressor to demonstrate the differences in length and configuration between 16- and 17-stage compressor MS5001 units. Similarly, the MS5002A compressor can be uprated to the MS5002B configuration by adding a zero compressor stage to provide full MS5002B performance, as is shown in Figure 41.

**MS5001 Speed Increase to 5,355 RPM (FP4E)**

Most mechanical-drive MS5001 units were rated at 4,860 rpm at the 100% speed point. This allowed for the 5% over-speed requirement most mechanical-drive customers require for operational process variations.

To take advantage of the various advanced technology uprate programs available for these units, it is frequently necessary to drive the load compressor at a higher speed. Considerable mechanical and dynamic analysis was done on the MS5001 rotor design (both 16-stage MS5001R and 17-stage MS5001P) that resulted in a decision to operate MS5001 units as high as 5,355 rpm (105% of 5,100 rpm). To date, 16 MS5001 mechanical-drive units have been uprated to operate as high as 5,355 rpm.

There is a fairly minor rotor bending critical speed at about 5,400 rpm, so operation at 5,355 rpm does not conform to the API requirement

---

*Figure 37. Comparing MS5001R and P*
for a 5% speed margin from all critical speeds. However, no vibrational problems have resulted on the units that have the speed increase.

This successful experience led to allowing generator-drive units to operate at 5,355 rpm. As all MS5001 generator-drive units have load gears, this uprate would require changing out the load gear or replacing all the rotating internal parts. As the turbine will operate at the same torque at the higher speed, the output will increase up to 3% at higher ambient temperature conditions. Figure 38 plots output versus ambient temperature for an MS5001P unit comparing 5,100 rpm versus 5,355 rpm speed.

The airflow is already so high at lower ambients that the compressor/turbine efficiency is near optimum. The higher airflow associated with the speed increase results in efficiency that offsets the output increase due to speed. Thus, there is no performance advantage at lower ambients, as shown in Figure 38.

**Exhaust Frame and Diffuser Upgrade (FS1W)**

Many older upgrade MS5001 and MS5002 units are already near their exhaust temperature control limit due to materials in the exhaust diffuser. By re-skinning the exhaust frame and diffuser with higher temperature material, we can go to a much higher limit at 1050 F. This is necessary in many cases to realize the Advance Technology Uprate that is shown later in Figure 43.

**MS5001P Uprate Summary**

**MS5002 Advanced Technology Package - Models A and B (FT2C)**

The MS5002B gas turbine was introduced in 1970. Various minor design changes have been made to reach the 35,000 HP ISO rating. Because of the interest expressed by many customers, a development program was undertaken to increase the MS5002B rating to 38,000 HP (ISO). This rating has been applied to current production units as an MS5002C. This advanced technology package can be applied to all existing MS5002A and B units. Figure 41 shows a comparison of MS5002 ratings for both
Performance and Reliability Improvements for Heavy-Duty Gas Turbines

Advanced Tech Update (FT3M) Output +6.0% Heat Rate -1.0%
GTD 450 IGV’s (Pre 1978/post 1978) (FT3B/FT3C) Output +3.9%/1.9% Heat Rate -0.2%/0.5%
86° IGV’s Output +0.2% Heat Rate +0.1%
High Pressure Pkg Brush Seals (FS2V) Output +0.6% Heat Rate -0.4%
Stage 2 Shroud Honeycomb Seals (FS2T) Output +0.4% Heat Rate -0.4%
5355 RPM Turbine Speed (FT3X) Output +3.0% (at High Ambients)
Stage 1 Shroud Cloth Seals (FS2Y) Output +0.5% Heat Rate -0.5%
Inner Stage Brush Seal (FS2Z) Output +1.0% Heat Rate -0.5%
S1S Abradable Coating Seals (FS2O) Output +0.4% Heat Rate -0.3%
Total Output +16.0/14.0% Heat Rate -3.2/-3.5%

Figure 40. MS5001P uprate summary

ISO Rating

<table>
<thead>
<tr>
<th>Ship Dates</th>
<th>Output hp (kW)</th>
<th>Heat Rate** (Btu/hp-hr/ (kJ/kWh))</th>
<th>Firing Temp F/C</th>
<th>Air Flow (lbm/h)</th>
<th>Exhaust Temp (F/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC</td>
<td>RC</td>
<td>RC</td>
<td>RC</td>
<td>RC</td>
<td>RC</td>
</tr>
<tr>
<td>MS526A</td>
<td>1970-Present</td>
<td>25,200/ 26,250/ 7,390/ 9,780/ 1,705/ 1,690/ 773/ 773/ 987/ 638</td>
<td>597/338/ 975/ 951</td>
<td>351/351/ 521/324</td>
<td>504/499</td>
</tr>
<tr>
<td>MS532B</td>
<td>1975-1977</td>
<td>31,050/ 32,550/ 7,480/ 9,240/ 1,710/ 1,700/ 923/ 923/ 932/ 660</td>
<td>932/927/ 419/419</td>
<td>408/420/ 506/499</td>
<td>531/524</td>
</tr>
<tr>
<td>MS533B</td>
<td>1975-1977</td>
<td>32,000/ 33,550/ 7,180/ 8,950/ 1,710/ 1,700/ 932/ 927</td>
<td>932/927/ 419/419</td>
<td>408/420/ 506/499</td>
<td>531/524</td>
</tr>
<tr>
<td>MS5352B</td>
<td>1978-Present</td>
<td>32,000/ 33,550/ 7,070/ 8,830/ 1,710/ 1,700/ 932/ 927</td>
<td>932/927/ 419/419</td>
<td>408/420/ 506/499</td>
<td>531/524</td>
</tr>
<tr>
<td>MS53352C</td>
<td>Present</td>
<td>35,600/ 38,000/ 6,990/ 8,700/ 1,770/ 1,770/ 966/ 966</td>
<td>966/966/ 434/445</td>
<td>434/445/ 521/516</td>
<td>516</td>
</tr>
<tr>
<td>MS543D</td>
<td>July 1997</td>
<td>42,600/ - 8,700/ - 1,807/ - 1,113/ - 950/</td>
<td>450/450/ 510</td>
<td>510</td>
<td></td>
</tr>
</tbody>
</table>

Includes 0/0 Inches H2O Inlet/Exhaust Pressure Drops Base Load Operation on Natural Gas Fuel
*First Number Is Turbine Exhaust; Second Is Regenerator Stack
**Heat Rates are Lower Heating Value. To Convert to % Thermal Efficiency, Divide 2547 Btu/hp-hr by Heat Rate (Btu/hp-hr) and Multiply 100

Figure 41. MS5002 performance history

original and uprated configurations. Figure 42 is a listing of the MS5002 advanced technology package. This uprating package has been sold for over 70 MS5002B units, uprating their output to meet changing operational conditions. This advanced technology package also results in considerable maintenance savings due to fewer inspections, as shown in Figure 28. The MS5002 Advanced Technology Uprate Program can also be applied to earlier MS5002A units.

Due to the increase in firing temperature, it is also necessary to change the MS5002A stage 2 buckets to the MS5002B standard design, as shown in Figure 42. To maximize output at higher ambients, it will usually also be desirable to change to a higher temperature stainless steel for the exhaust diffuser. Figure 43 shows the difference in output for an MS5002A
advance technology uprate with the standard 1000 F/538 C exhaust temperature limit versus the additional output possible at higher ambient temperatures with a 1050 F/566 C exhaust temperature limit. The latter exhaust temperature limit is possible due to the new high-temperature stainless steel material.

**MS5002 “D” Advanced Technology Uprate (FT2R and FT2S)**

Due to continued strong customer interest in additional uprate capability for the MS5002 unit, an MS5002 uprate to the MS5002D model was developed. This involves replacing the 17-stage MS5002 axial compressor with a 17-stage MS6001 axial flow compressor. Figure 21 depicts the combination of MS6001 and MS5002 technology to produce the MS5002D.

The MS5002D field retrofit program can be offered in two phases: MS6001 compressor upgrade only for about 10% uprate (FS2R) or MS6001 compressor with optimized hot gas path for about 12% uprate (FS2S). The primary design change for the optimized hot gas path is a new Stage 1 nozzle with reduced throat area to provide a higher compressor pressure ratio.

Figure 44 is a tabulation of all of the available uprate programs for a typical MS5002B unit.

Figure 45 is an uprate study for a typical MS5002B unit with options to uprate to an MS5002C or an MS5002D configuration. Also shown is a comparison of standard uprate performance vs. performance with a control curve “tilted” to optimize high ambient temperature output.

**MS6001B Uprates**

Figure 46 provides a history of ratings for all vintages of MS6001 models. Several uprate options are available (see Figure 47) by applying the lat-
est new unit technology. The improved honeycomb shroud seals (FS2T and FS2U) provide improved sealing over the shroud tips on stage 2 and 3 buckets, thus improving output by 0.6% (see Figure 9). The load gear can be replaced to allow the turbine speed to increase to 5,133 rpm (FP4D), as shown in Figure 48. The higher turbine speed will provide approximately 1% higher output. The GTD stage 2 nozzle and inlet guide vane improvements are shown in Figure 18. The sum of these improvements will yield a 9.45% output increase for units built prior to 1987.

**MS6571B Uprate to (FT4L)**

All vintages of MS6001 units can be uprated by 35 F/19 C in firing temperature by applying the MS6001 advanced technology uprate package (see Figure 47). This uprate program began in late 1994 with field testing on a fully instrumented MS6001 unit to provide a detailed aerodynamic and performance map of the existing design. Based on this test data, an uprate program was developed to increase firing temperature by 35 F/19 C. Figure 49 is a summary of all the uprate programs for a MS6001B unit.

Due to concern over bucket life for stages 1 and 2, the metallurgical, mechanical design and cooling circuits were extensively redesigned to provide considerable additional expected parts life and to be suitable for the firing temperature.
The remaining hot gas path parts have been upgraded with the same design changes incorporated in the MS9001E when its firing temperature was increased to 2055 F/1124 C. The performance increase for the firing temperature increase is approximately 3.0%.

**MS7001B Turbine Uprate (FT5X)**

The MS7001B model was introduced in 1970. Design changes in compressor, combustion and
hot-gas-path components were introduced over the years to achieve the present MS7001 EA model. Figure 50 lists a performance uprate history for the MS7001 model. By applying standard current production MS7001EA parts to older MS7001B units, GE can increase output as detailed in the four possible uprate options listed in Figure 51. Figure 52 details individual design improvements for each MS7001EA component involved in the B to E uprate.

The most significant design improvement for each MS7001B and E unit is the stage 1 turbine nozzle. As shown in Figure 50, the E unit has a higher airflow than the B unit, but it has a smaller “throat area” for the stage 1 nozzle. This design provides a significant increase in compressor pressure ratio. When the MS7001EA Stage 1 nozzle is applied to MS7001B units, there is a 6% increase in compressor pressure ratio. Extensive evaluation indicated the increase in pressure ratio was acceptable on MS7001B units. The first application of this uprate was to a utility unit in Alaska. Extensive field testing (completed in August 1988) proved this uprate was a success.
Option 1 involves new reduced camber IGVs and MS7001EA Stage 1 buckets and nozzle. Due to increased efficiency, the actual exhaust temperature decreases for this option.

Option 2 is intended to increase firing temperature as much as possible to keep exhaust temperature at pre-uprate levels. This option would be applicable to heat recovery unit application, where exhaust temperature decreases would be detrimental to combined-cycle efficiency and exhaust temperature increases might not be compatible with the HRSG.

Option 3 is the maximum exhaust temperature with the existing MS7001B exhaust frame and diffuser assembly. This option would increase the MS7001B rating at ISO conditions to approximately 70 MW.

Option 4 involves increasing the firing temperature for an MS7001B unit to the full 2020°F/1104°C MS7001E/EA firing temperature by also changing to the MS7001EA exhaust frame and diffuser assembly. See Figures 57 and 58 for these uprate options.

In addition to the output increases, a significant improvement in maintenance/inspection intervals is achieved by using the higher firing temperature MS7001E parts. Figure 53 details expected extensions in maintenance intervals.
using 7EA hot-gas-path parts. Due to the cost of this uprate, it may be desirable to uprate MS7001B units a few components at a time to take advantage of the individual component design improvements. Each MS7001EA component in Figure 52 can be applied to MS7001B units with only minor modification. A turbine/generator performance comparison will be required in each case to determine load equipment capability to accept the uprating. This may also result in generator and electrical auxiliary modifications.

**MS7001C, E and EA Uprate to 2035 F/1112 C Tf (FT5Y)**

All vintages of MS7001C, E and EA units can be uprated to the latest 7EA firing temperature of 2035 F/1112 C. Figure 54 details all required material changes for each model to uprate to 2035 F/1112 C. Figures 57 and 58 list output and heat rate improvements for increasing firing temperature to 2035 F/1112 C, and for all other performance improvements applicable to MS7001 C, E and EA models.

### Significant Savings in Maintenance Cost

**Figure 53.** Typical MS7001B vs. MS7001E maintenance

<table>
<thead>
<tr>
<th>Inspection Intervals - Hours</th>
<th>7B/9B</th>
<th>7EA/9E</th>
<th>Extendor™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion Liners</td>
<td>3,000</td>
<td>8,000</td>
<td>16,000</td>
</tr>
<tr>
<td>Transition Pieces - Thin Wall</td>
<td>3,000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Transition Pieces - Thick Wall</td>
<td>8,000</td>
<td>8,000</td>
<td>-</td>
</tr>
<tr>
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<td>16,000</td>
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<tr>
<td>Major</td>
<td>48,000</td>
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</tr>
</tbody>
</table>

---

- Improved Stage 1 Nozzle With Chordal Hinge and Improved Sidewall Cooling and Sealing Design
- Directionally Solidified (DS) Stage 1 GTD111 Buckets
- New HR120 Stage 1 Shroud Blocks With Cloth Seals
- GTD222 Stage 2 Nozzle - Reduced Cooling Air Design
- 7EA Stage 2 Scalloped Shroud Bucket - IN738
- GTD222 Stage 3 Nozzle
- 7EA Stage 3 Scalloped Shroud Bucket - U500
- Extendor™ Combustion Wear System
- Thermal Barrier Coated Combustion Liners - Hastelloy-X
- Nimonic Thick Wall Transition Pieces

**Recommended**

- GTD450 Reduced Camber IGVs Set at 86°
- Stage 2/3 Honeycomb Shroud Blocks
- HPP & #2 Bearing Brush Seal
- 1100 F/593 C Exhaust Isotherm Conversion (100 HP Blowers)

**Figure 54.** MS7001E/EA uprate requirements for 2035 F/1112 C firing temperature
MS7001 C, E and EA uprates to 2055°F/1123°C Tf (FT5Q)

All vintages of MS7001C, E and EA units also can be uprated to the latest MS7001EA 7EA firing temperature of 2055°F/1123°C. This involves changing the stage 2 and 3 buckets, stage 1 nozzle and stage 1 shroud to the latest designs detailed in Figure 52. Figure 55 is a diagram of all of the MS7001E 2055F uprate sections. Depending on the turbine vintage, the unit's existing firing temperature and other product improvements that may have already been incorporated, output may be improved from 5% to 19% (see Figure 57). Heat rate can also be improved by over 3% as shown in Figure 58.

- Features & Benefits
  - Increased Output (+4.9 to 18.0%)
  - Decreased Heat Rate (-1.5 to -3.8%)
  - Improved Cooling Features
  - Improved Materials

Figure 55. MS7001E 2055°F uprate

Exhaust Frame Cooling Circuit Modification

Figure 56. MS7E and MS9E exhaust frame diagram
1100 F/593 C Maximum Exhaust Isotherm Limit (FT7G)

The higher firing temperatures currently used on MS6001/7001/9001 units frequently result in reduced operating flexibility and, sometimes, output on higher ambient days. Figure 59 plots exhaust temperature versus ambient temperature for a typical MS7001E unit for different IGV angles.

Many older units were shipped with a 1020 F/549 C or 1040 F/560 C maximum exhaust temperature limit (isotherm). In many cases, the following resulted:

- Reduction in output on hot days as firing temperature had to be reduced when maximum exhaust temperature was reached
- Inability to operate at lower IGV angles

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on hot days to maximize part load heat rate at part load on heat recovery units

- Reduced turn down ratio on DLN units at all ambients

The increase in maximum exhaust temperature setting to 1100 F/593 C resolves these problems, as shown in Figure 59. Figure 56 shows a cross section of the material changes required to go to 1100 F exhaust temperature limit. The change in maximum exhaust temperature setting generally will require changing the exhaust frame blower to 100 HP blowers. The ability to raise the maximum exhaust temperature setting on existing units must be reviewed thoroughly due to possible impact on other exhaust system components.

**Uprates with “Tilted” Control Curves (FT7I)**

Normally turbine control curves are designed to keep a constant firing temperature across the ambient temperature range of each site. This results in a significant decrease in unit output at higher ambient temperatures. To attempt to partially compensate for this performance loss, we can “tilt” the control curve to “overfire” on hot days and “underfire” on cold days. The formula provides 1.55 additional output on hot days and loses about 20% on cold days. The parts life savings on cold days compensates for the slight parts life decrease on hot days by overfiring. This option is restricted to base load units and to units with the latest advance technology uprate components. See Figure 60 for a typical example of a tilted control curve.

**MS7001F and FA Uprate to the “MS7001FA Uprate” Configuration (FT5L)**

The MS7001F was introduced in 1988 and has been uprated for new unit production to the current “MS7001FA uprate” configuration. Ratings for all vintages of MS7001F units are
listed in Figure 50. Numerous design changes in metallurgy, cooling and coatings have been incorporated into the latest 7FA uprate designs. In each case, the original 7F/FA parts can be upgraded individually, on a spare part basis, to realize the parts reliability advantages of the latest PG7241FA uprate parts. Due to variations in 7F units, it is essential that an individual unit review be made to determine the scope of the uprate kit for each unit. Figure 23 shows the performance gains for earlier 7F vintage units by applying selected kits of PG7241FA parts.

**MS9001B Turbine Uprate (FT6X)**

Many design changes have been incorporated into the MS9001 since its mid-1970s introduction. Figure 61 lists a performance uprate history for the MS9001 model. Current production MS9001E buckets and nozzles (all three stages) can be retrofitted into all earlier production MS9001B units with minor modifications and into existing MS9001E units as direct replacement parts. Substantial improvements in expected parts life will be realized when uprating older MS9001B units with current production MS9001E hot-gas-path parts. Two customers have already purchased several MS9001E components to uprate their MS9001B units.

It is also possible to uprate MS9001B combustion systems to use MS9001E components by changing to the MS9001E type combustion system. This would provide significant improvements in recommended combustion inspection intervals (see Figure 53).

---

**Table:**

<table>
<thead>
<tr>
<th>Model</th>
<th>Ship Dates</th>
<th>ISO Performance* kW</th>
<th>Firing Temp (F/C)</th>
<th>Air Flow (10^6 lbs/hr)</th>
<th>Heat Rate (Btu/kW-hr)</th>
<th>Exhaust Temp. (F/C)</th>
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</thead>
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<tr>
<td>PG9111B</td>
<td>1975-81</td>
<td>85,200</td>
<td>1840/1004</td>
<td>2.736/1.241</td>
<td>10,990/11.592</td>
<td>945/507</td>
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<tr>
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<td>1955/1068</td>
<td>3.155/1.431</td>
<td>10,700/11,286</td>
<td>953/512</td>
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<td>PG9157E</td>
<td>1981-83</td>
<td>109,300</td>
<td>1985/1085</td>
<td>3.183/1.444</td>
<td>10,700/11,286</td>
<td>968/520</td>
</tr>
<tr>
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<td>2055/1124</td>
<td>3.355/1.520</td>
<td>10,620/11,202</td>
<td>1003/539</td>
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<td>4.804/2.179</td>
<td>10,080/10,632</td>
<td>1,082/583</td>
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<td>9,630/10,158</td>
<td>1,097/592</td>
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<td>2420/1327</td>
<td>5.174/2.344</td>
<td>9,295/9,804</td>
<td>1123/623</td>
</tr>
</tbody>
</table>

*Base load distillate fuel, includes 0/0 inches H2O inlet/exhaust pressure drops.

**Figure 61.** MS9001 performance history
Option 3 is the maximum exhaust temperature with the existing MS9001B exhaust frame and diffuser assembly. This option would increase the MS9001B rating at ISO conditions to approximately 93 MW.

Option 4 involves increasing the firing temperature for the MS9001B units to the full 2020 F/1104 C MS9001E firing temperature by also changing to the MS9001E exhaust frame and diffuser assembly. See Figures 65 and 66 for performance improvements for these four uprate options.

**Figure 62. MS9001E uprate requirements for 2020 F/1104 C firing temperature**

**MS9001 Uprate to 2020 F/1104 C (FT6C)**

Earlier models of MS9001E turbines with firing temperatures of 1955 F/1068 C, 1985 F/1085 C or 2000 F/1093 C can be uprated to the MS9161E rating at 2020 F/1104 C. Figure 62 details all required changes and Figure 65 lists improvements in output. Figure 66 lists improvements in heat rate for this uprate as well as for all other performance improvements applicable to earlier MS9001E models.

**Figure 63. MS9001E uprate requirements for 2055 F/1124 C firing temperature**

All components involved in the MS9001 uprate programs are identical to the components used in new unit production. Due to the extensive scope of these uprate programs, it may be desirable to incorporate individual components on a spare/replacement part basis. Figure 64 details all the design improvements on the flange-to-flange components. Performance improvements associated with individual components are included in Figures 65 and 66. GER-3928 has complete details on the MS9001 uprate programs.

**MS9001F Uprate to the MS9001FA Configuration (FT6Z)**

The MS9001F began production in 1993. Ratings for all vintages of MS9001F units are listed in Figure 61. Numerous design changes in metallurgy, cooling and coatings have been incorporated into the latest 9FA designs. In each case the original 9F parts can be upgraded individually, on a spare parts basis, to realize the parts reliability advantages of the latest 9FA parts. Due to variations in 9F units, it is essential that an individual unit review be made to deter-
mine the scope of the uprate kit for each unit. Figure 23 shows the performance gains for earlier 9F and 9FA vintage units by applying selected kits of PG9351FA parts.

**Model Letter Uprates**

In addition to the advanced technology uprates for a given model gas turbine, it is possible to uprate from one model letter to another (i.e., MS5001L to MS5001R). A quick review of the performance history charts in this paper will show the significant differences in firing temperature, airflow and rating among the various models.

- **MS3002** (see Figure 25)
- **MS5001** (see Figure 34)
- **MS5002** (see Figure 41)
- **MS6001** (see Figure 46)
- **MS7001** (see Figure 50)
- **MS9001** (see Figure 61)
In general, model letter uprates can be accomplished with relative ease where firing temperature changes are involved, and less easily accomplished where airflow changes are involved. However, every older unit can be uprated to a higher model letter.

**Absolute Performance Guarantees**

All performance uprates listed in this paper are based on airflow or firing temperature increases that are directly correlated to performance increases, usually expressed as “percentage increases” or “delta increases.” The absolute performance achievable after an uprate can vary due to many variables usually present on older units, such as casing out-of-round, surface finish of non-uprated parts, and clearances. Recognizing that many customers prefer absolute performance guarantees, Figures 67

---

**Figure 66. Frame 9 uprate options: effect on heat rate**

**Figure 67. Absolute performance guarantees for advanced technology generator drive**
and 68 were prepared to show common performance guarantee points for typical advanced technology uprates. All performances listed are based on ISO conditions (59 F/15 C, sea level, 0"/0" inlet/exhaust pressure drops, 60% relative humidity), natural gas fuel and base load, and assume the axial flow compressor is not rebladed. Similar performance can be easily provided for variations on these conditions.

**Non-Recoverable Performance Degradation**

Since uprate performance increases are based on real airflow and/or firing temperature increases, the performance increases provide real and lasting performance improvements. *Figure 69* is plotted to show the approximate performance increase for a typical MS7001B uprate option III at approximately 48,000 fired hours.
The expected typical non-recoverable performance degradation is plotted for the original configuration as well as for uprate option III. This shows that the performance increase of 15.05% at 48,000 fired hours still returns an expected incremental performance increase of 10.9% at 100,000 fired hours. By comparison, uprates that are based on component refurbishment and/or blade coatings will usually disappear completely in 10,000 to 15,000 fired hours.

Several sealing design improvements listed in this publication are intended to reduce performance degradation between major overhauls:

- Cloth seals for stage 1 shroud blocks
- High-pressure packing brush seals
- No. 2 bearing brush seals
- No. 2 and No. 3 bucket/shroud honeycomb seals
- Abraidable coating for stage 1 shroud blocks

Considerable research and development effort continues in order to develop improved gas path leakage sealing systems that improve output and reduce performance degradation rate on existing units.

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**Power Augmentation Uprates**

For certain applications where power augmentation or supplemental power is needed for certain operating conditions, a variety of power augmentation options are available:

- Evaporative coolers for inlet air (FJ3F)
- Steam injection into compressor discharge (F3JB)
- Water or steam injection into combustor head end (FGIA/FGIB)
- Helper/starter expansion turbines (FJ3E)

Evaporative coolers can result in power increases of up to 14% in hot dry ambients. *Figure 70* shows typical power augmentation for adding an evaporative cooler.

Steam injection for power augmentation can result in power increases of 15% to 18% by injection of up to 5% mass flow (of compressor inlet air) of steam into the compression discharge. *Figure 71* shows typical power augmentation for adding steam injection. A development program is in progress to evaluate increasing the maximum allowable steam injection rate with a goal of 9% by mass flow of air (refer to Application Engineering for details).

---

*Figure 70. Effect on output and heat rate of evaporative cooling over the ambient range*
Water or steam can be injected into the combustor head end using the standard NOx water/steam injection systems. Approximately 2% mass flow is possible, which results in approximately 5% to 6% performance increase. Helper/starting turbines would have to be sized for specific applications.

Considerable application engineering support is required to maximize performance improvement for any of these power augmentation options. In addition, a thorough review of all gas turbine auxiliaries and all load equipment must be made to ensure that they are compatible with the supplemental power output.

**Combustion System Upgrades**

Each of the advanced technology upgrades detailed in this paper includes significant improvements to combustion system components. These combustion system upgrades can also be supplied as individual options for substantial improvements in component life and/or for extension in recommended combustion inspection intervals. *Figure 72* details the more significant combustion system design improvements incorporated into new unit production during the past several years. All these design improvements are available individually or as a package. The Sourcebook codes listed for each option provide an easy reference number for GE field offices to quickly provide detailed information on each option. *Figures 28 and 53* provide details on maintenance interval extensions.

**Extendor™ Program for Increased Combustion Inspection Intervals (FR1V)**

All heavy-duty gas turbines undergo periodic combustion inspections to check for material creep, thermal barrier coating erosion and wear. See *Figures 28 and 53* for standard recommended inspection intervals with conventional and advanced technology parts. *Figure 73* details the new combustion wear-resistant components now known as the Extendor™ system. With the Extendor system, combustion inspection intervals can be extended up to 24,000 hours for base load continuous dry units operating dry on natural...
gas fuel (12,000 hours with water injection using breach load fuel nozzles).

The Extendor system is a combination of:

- Wear-resistant coatings and materials
- Enhanced clearances
- Mechanical design improvements

The Extendor combustion system improvements can be retrofitted into existing combustion hardware during routine maintenance or to new components using the same conversion package. The system is currently available for standard Frame 5, 6, 7 and 9 gas turbine models with slot-cooled combustion liners and Nimonic transition pieces. See Figure 73 for additional details.

**Emission Levels**

In considering an uprate to an existing gas tur-
bine, the impact on emission levels must be considered. Figure 74 lists typical NOx emission levels before and after uprates for many of the uprate programs. Also listed are reduced emission levels with various options available for emission control (water injection, steam injection and Dry Low NOx). Detailed review of site and specific emission levels are provided with each uprate study.

**Low NOx louvered combustion liners – MS5/1, 3/2, 5/2 (FR1B)**

A lean “head end” louvered combustion liner is available for MS3002, MS5001 and MS5002 units. The louvered slot pattern and dilution hole pattern have been changed to provide a much “leaner” combustion system than the standard louvered liner. This results in an approximately 30% reduction in NOx as compared to the standard louvered liner. This uprate compares the original louvered liner design (“N” liner) to the lean head end liner (“P” liner). As shown in Figure 74, the NOx emissions level for a standard MS5001P unit increases about 12% when uprating with advanced technology parts.

When the advanced technology uprate is applied in conjunction with the lean head end louvered P liner, the result is an uprate that results in significantly lower NOx levels (i.e., a 12% increase due to uprate minus 30% for lean head end liner). Figure 20 plots NOx emissions for an advanced technology uprate with and without the P lean head end liner. Dozens of advanced technology uprates have been sold with the lean head end liner without the need to add emissions control equipment. Lean head end liner designs are available for almost all vintages of MS3002, MS5001 and MS5002 units for both regenerative and simple cycle applications for gas fuel only, or for distillate fuel units with atomizing air.

### Summary

GE has an advanced technology uprate package available to uprate almost all of the 7,200 GE design heavy-duty gas turbines, as shown in Figure 71. These advanced technology uprate packages provide significant savings to our customers due to reduced maintenance, improved efficiency and increased output. Changes in emission levels associated with a gas turbine

#### Figure 74. NOx emission levels at 15% O2 (ppmvd)

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<th>Single Shaft Units</th>
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<th>Dry</th>
<th>H2O/Steam Inj</th>
<th>Dry Low NOx</th>
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</thead>
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<tr>
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<td>Gas</td>
<td>Dist (FG1A)</td>
<td>Gas (FG1C)</td>
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<table>
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<th>Two Shaft Units***</th>
<th>Firing Temp.</th>
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<th>H2O/Steam Inj</th>
<th>Dry Low NOx</th>
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<td>S.C</td>
<td>R.C.**</td>
<td>S.C.</td>
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<tr>
<td>MS3002J</td>
<td>1730/943</td>
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<td>211</td>
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</tr>
<tr>
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<tr>
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* 2% Water Injection for Distillate Fuel
** S.C. = Simple Cycle and R.C. = Regenerative Cycle
*** Two-Shaft NOx Levels Are All on Gas Fuel

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**Note:** The tables depict NOx emissions levels at 15% O2 (ppmvd) for various gas turbine models. The emissions levels are categorized by single and two-shaft units, with additional columns for dry and H2O/steam injection conditions. Detailed specifications and corresponding emission levels are provided for each model, illustrating the impact of advanced technology uprates on NOx reduction. The summary highlights the broader implications of these advancements for customers, emphasizing efficiencies and emission reductions. **Figure 74** specifically illustrates NOx levels at 15% O2 for typical uprate programs, setting a baseline for the benefits achieved through advanced technology enhancements.
GE Has an Advanced Technology Uprate Package Available to Uprate Most of the 7,200 GE Design Heavy-Duty Gas Turbines to Improve Performance and Reliability

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