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GE Power Systems

The F Technology Experience Story

Eric Gebhardt
GE Power Systems
Atlanta, GA

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Introduction

Prior to 1987, the largest gas turbines (both 50 Hz and 60 Hz) operated at firing temperatures in the neighborhood of 2012°F(1100°C). Combined Cycle plants were operating at efficiencies upwards of 45%. Reliability/Availabilty had begun to reflect the maturing of the gas turbine in base load service, with fleet availability between 85% and 95% depending on turbine model and manufacturer.

In June 1987, GE introduced a new generation of gas turbine – the MS7001F. The introduction of the MS7001F was driven by the demand for higher efficiency plants with lower emissions and lower cost (per KW/Hr). When the MS7001F was first introduced projections were made that the unit would obtain 200 MW and 50% efficiency in a Combined Cycle Duty Application.

Since that time the numbers of GE "F" Technology units in the world has grown to 146 that were in operation at the end of 1999. It is estimated that there will be 239 in operation by the end of 2000 *(See Figure 1)*.

History

Gas turbines were first used for power generation in the 1950s, and were used almost exclusively for peaking duty. For this mode of service, designs were required which featured low specific cost and good starting reliability.

Through the 1960s and early 1970s, continuing advances in gas-turbine efficiency, reliability, and availability facilitated a wider range of applications for gas turbines. As operating hours increased, fuel cost assumed greater significance in optimizing machine design. The importance of this factor grew dramatically with the rapid rise in fuel prices following the oil crises of the 1970s.

As operating (fuel) cost became more important in gas-turbine economics, technology development was focused on improving efficiency, primarily through increasing firing temperature. In 1981 the MS7001F program began, planners realized that the larger gas turbine size would mean lower power plant specific cost, and a higher firing temperature would result in higher combined cycle efficiency.

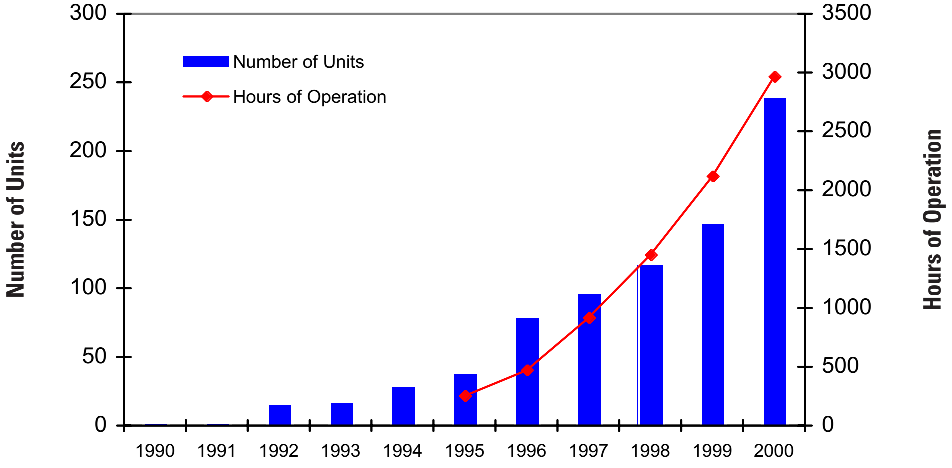

Figure 1. Cumulative number of units and hours in operation each year. 2000 values are estimated based on sales and units in manufacturing.

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In order to achieve the higher firing temperatures many changes would be required to the unit to ensure no adverse affects on maintenance intervals. Key technologies had been developed which would allow for this new design. These included new compressor airfoil designs which would allow for a higher inlet mass flow, as well as new methods for large superalloy castings which would allow for more efficient cooling of the buckets and nozzles. The one major factor against significant advancement was the power generation industry was in downturn. GE made the decision to continue with the design despite the status of the industry at the time.

Design

Prevailing economic factors resulted in the decision to introduce the first "F" machine configured to serve the 60 Hz market (MS7001F), then follow with a 50 Hz product (MS9001F), and finally flowing the technology to a size demanded by industrial cogeneration and district heating (MS6001F). The MS7001F (60 Hz) and MS9001F (50 Hz) programs were integrated and had overlapping development cycles which were closely followed by the MS6001F (which would be gear driven at 50 Hz or 60 Hz) *(See Figure 2)*.

The heart of the "F Technology" came from the First stage compressor aerodynamic design, higher temperature capable materials and more sophisticated hot gas path component cooling circuit.

MS7001F

From the beginning, the MS7001F development program contained an extensive series of tests. These were grouped into three phases: (*See Figure 2*)

- First were component and technology validation tests. These tests included combustor operation, bucket and compressor blade vibration tests, heat transfer coefficient measurement and many others.
- Second was the factory test under load with test points at full firing temperature. An axial flow compressor was used for the factory-loaded tests.

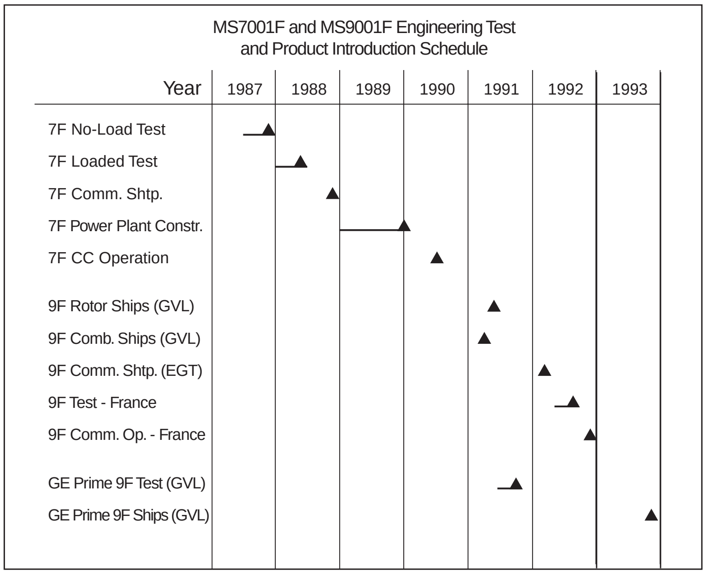

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Figure 2. Schedule of key milestones

- Third in the series was the field test, where full flow and full temperature could be simultaneously achieved.

Additional changes were also decided on to support drive in industry for increased Reliability and Availability. These changes were:

- Dedicated accessory base skids that were arranged for easy access and powered by individual electric motors. This design was to minimize downtime associated with all types of maintenance.
- Axial exhaust was designed to reduce the losses between the gas turbine exit and the heat recovery steam generator (HRSG).
- Cold end generator drive configuration.
- Two bearing design was adopted similar to steam turbines and MS6001B/MS5001 gas turbines.

MS9001F

The MS9001F was introduced in 1989 and was designed using aerodynamic scaling from the MS7001F. Fundamental component configurations can be based on this scaling technique. However, some phenomena are known not to scale. Their effects were investigated by the same thorough analysis used in the preceding design, and the necessary adjustments were made.

Initially there were two MS9001F units built practically simultaneously. A unit with minimal instrumentation was operated at no load in the Greenville factory, and a fully instrumented unit was assembled in the Belfort factory. The instrumented unit later underwent fully-loaded testing in simple-cycle operation.

The Greenville test confirmed the predicted compressor performance, efficiency, and operational functionality.

During disassembly following the Greenville test, slight cracking was observed on four compressor vanes. Analysis was performed and a resolution was implemented prior to the unit being placed in operation.

The heavily instrumented unit from Belfort experienced dynamic excitation on stages 14, 15 and 16 stators during startup and acceleration from cold conditions. Although a modified start-up procedure eliminated the condition, changes were made in blade profiles to completely eliminate the possibility of vibration problems on future units. All blades put in service were of the modified design.

Design Enhancements

The most significant impact which test data had on the appearance of the “F” family of gas turbines was the choice of a rotor designed with IN706 material rather than the lower-strength, M152. The design team recognized that ductility of M152 could be reduced by exposure to the environments of a turbine with high pressure ratio and high gas path temperature. As the effect of exposure of iron-based wheel alloys to turbine environments was more fully understood, the decision was made to increase the robustness of the rotor by applying a material far less sensitive to exposure to high temperature. So the rotor was redesigned with lighter, yet stronger, wheels and spacers. In the process, the total depth of bolt holes in the rotor was reduced, hence the multiple-bolt construction, much like the MS5001 turbine rotor, in place of the through-bolting used on the MS7001E and similar machines.

The outcome of the testing of the machines resulted in tuning of other portions of the design. These changes would result in better overall life of the units. The first rotating blade of the compressor (stage zero) was re-tuned to raise a natural frequency. Blade clearances were adjusted to reduce the level of rubbing during transients. The solidity of compressor stator stage 17 was increased to eliminate a high vibratory stress due to flow separation under some operating conditions.

In order to ensure that the units would meet life predictions temperatures were measured to confirm calculations. Data from the testing confirmed the calculations that were performed and thus verified our parts life estimates that were made early in the design.

MS6001FA

Conceptual design of an MS6001F gear driven version began in 1991. The objective was to bring the benefits of “F” technology to the market segment traditionally served by the MS5001 and the MS6001B. An output in the range of 60 MW to 70 MW would represent a proportional increase in output beyond the MS6001B similar to the increase of the MS6001B relative to the MS5001. Since the MS6001FA was to be a gear-driven machine, the grid frequency of the application was irrelevant in selecting scale factor. The MS6001FA is a 2/3 scale of the MS7001FA. The design program began in 1993 and the first unit was assembled in late 1995.

Emissions

Due to environmental concerns with the exhaust of the heavy duty gas turbine emissions criteria commonly specify a maximum concentration of NO_x in the exhaust. During the “F” programs, a parallel program delivered low-emission combustors for the GE product line. The goal was to develop single-digit NO_x capability for all gas turbine products. Interim steps resulted in systems capable of 42 ppm and 25 ppm. The F technology, because of high specific output, brings an additional benefit to the environment. Because of the higher specific output of high firing temperature machines, less NO_x and CO are emitted per unit of power produced for the same exhaust concentrations. Because of the increased efficiency, less fuel is required for a given level of power production; hence, F technology machines emit less CO_2. *Figure 3* illustrates the benefits of F technology given fixed emission standards.

Operational Issues

After more than five years of essentially trouble-free service and more than 150,000 fleet operating hours, a number of GE F class gas turbines experienced compressor or turbine rotor distress beginning in mid-1994. Ultimately, most of the operating units were affected to some extent by these issues. Root cause was identified, resolutions were designed and implemented throughout the fleet in a manner designed to minimize the unavailablity to the operators.

The issues encountered during this period did impact customers’ operations, but these observations are important in assessing the implications to advancing technology:

- “F” Technology Fundamentals were not root cause of issues. “F” Technology Fundamentals include high firing temperature and associated high temperature materials, advanced cooling or high mass flow compressor stages.
- Issues were associated with features and processes applied to single machines or a limited population. Turbine Rotor flexibility had fleet-wide implications.

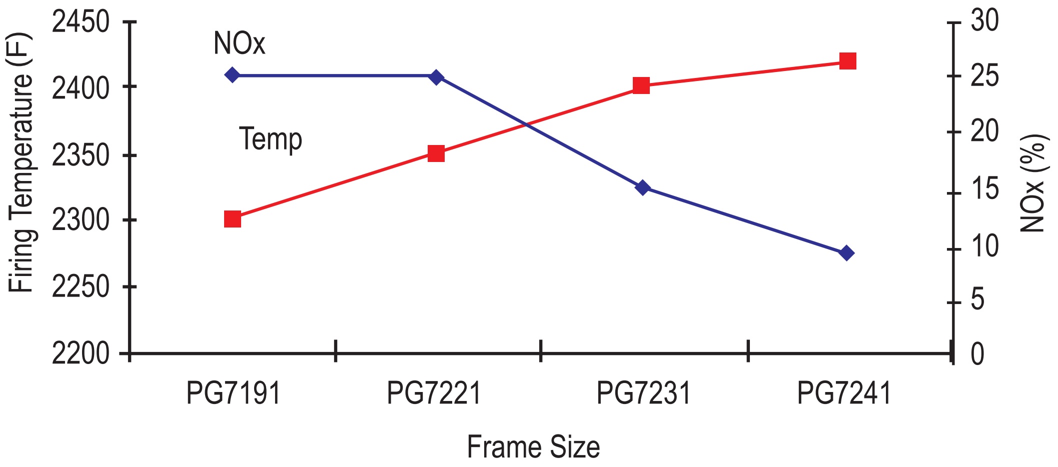

Figure 3. Emissions versus firing temperature

- The components that were affected were limited to a few internal rotor components.
- Because of the efforts made to advance the reliability of gas turbines, particularly in the controls and diagnostics, in most cases, the problems were detected before any damage occurred.
- Resolutions for all of the issues that were encountered have been implemented and have been completely successful.

Compressor Issues and Resolution

Tie Bolts

Several early production MS9001F units experienced cracking of compressor rotor through bolts. All cracked compressor bolts were traced to one particular supplier. Root cause was determined to be vendor methods for production of the bolts, which were outside of GE's specifications. No MS7001F units were not affected nor were any of the US built MS9001F units.

Compressor rotor bolts were standardized in the methods of production and the vendor in question was disqualified. Bolts tensioning procedures were also revised to reduce mean stress level variation. Standardization and control of bolt and nut details realize similar improvements in stress level.

Continued reliable operation of the units assembled with the now-standard parts and procedures in both MS7001F and MS9001F sizes validates the design.

15th Stage Wheel Cracking

During disassembly of the units to replace compressor through bolts a crack was found on the 15th stage wheel web area where the rotor blades were staked in place.

The RCA for web cracking discovered that there were two factors that caused this. One was the thickness of the material and second was the procedure used to stake the blades in place.

Dovetail area distress and the effect of dovetail proc-essing on blade dynamics resulted in thickening of the rim area and standardized staking practice on future units. No substantive changes in the basic compressor design were required. Configuration details and assembly practices of the current production units increase the rotor's robustness.

17th Stage Fillet Cracking

Early in 1997 a unit was removed from service due to vibrations which were beyond balance abilities. Shortly thereafter another unit was removed with similar characteristics. After many weeks and rigorous analysis it was found that the cause of the vibrations was a crack in the fillet region of the 17th stage of the compressor.

The RCA showed two key contributing factors. First factor was unit specific operational parameters had led to cracking in this area. Second factor was impact damage that was caused during assembly of the compressor rotors.

Maintenance factors for startup, operations and shutdown were implemented. The steam turbine industry recognized this fact in the 1950 to 1970 time frame when the growth of the industry led to larger steam turbines. This is also true of gas turbines, as the size of the unit increases there is a larger requirement for maintenance factors.

Disassembly procedures were reviewed and revised with additional precautions to be taken to ensure there was no impact between the windage nut on the compressor through bolts and fillet radius of the 17th stage. *(See figure 4)*.

Turbine Rotor Issues

Turbine 2-3 Spacer

The design of all early turbine rotors contained features which caused sufficient rubbing between the 2-3 spacer rim and the 3rd stage wheel seal land to cause portions of the land to break away. In some instances, rotor balance was affected.

The same rolling motion caused flexing of the 2-3 spacer. During the cooldown cycle on some units, the spacer cooled sufficiently faster than the mating wheels to cause the rabbet fit to become disengaged. The stresses in the web of the 2-3 spacer were high enough in this condition to cause cracking, and this cracking was observed in a few rotors removed from service.

Rim distress is avoided by cutting back the aft flange of the 2-3 spacer. This has been done on several units already operating. Along with this change, the operating conditions leading to light rabbet loads are eliminated by lowering the rotor fast cool down cranking speed.

Current production spacers are of a new design that prevents the rim engagement, the disengagement of the rabbet, and high flexing stress. The issue has not occurred in units with the

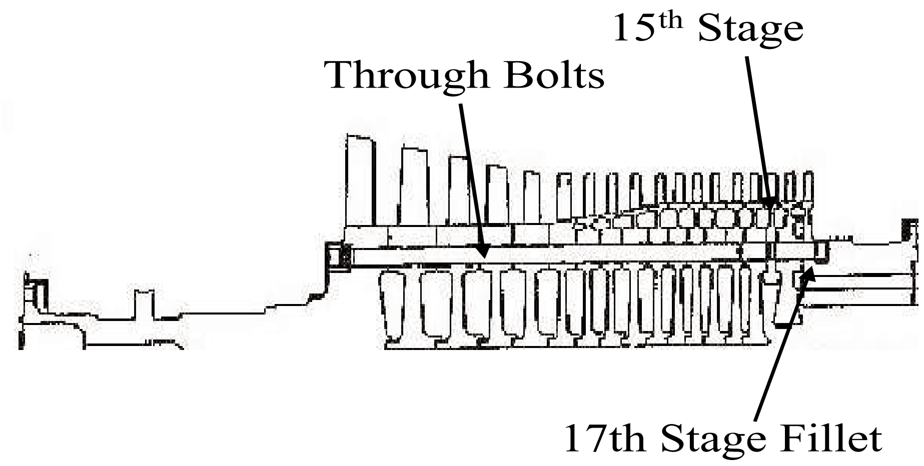

Figure 4. Cross section of compressor rotor showing locations of components

new spacer, or in units with field modifications and cooldown cycle modifications.

Third Stage Subassembly Bolts

Two MS9001F and three MS7001F units experienced cracking of the forward end of the third stage subassembly bolts. Root cause analysis was performed and it was found that under certain operating conditions combined with low elongations on the bolts that the bolts would relax causing high cycle fatigue. Conclusion of the RCA was to revise the elongation process to reduce variability and to change the bolts to a different material to increase margin to event. *(See figure 5)*.

Availability

At the beginning of the "F" Program, GE and an industry advisory board set product availability goals which were higher than had yet attained by any gas turbine. As can be seen in *Figure 6*, availability of the "F" units has followed the mature proven units.

Uprates

Gas turbine designers are obliged to pursue opportunities for improving efficiency, reliability, and maintenance cost, in such ways as to not invalidate the experience base. This experience base, from whatever gas turbine product it comes, can benefit multiple product lines. *Figure 7* shows the incremental evolution of the E class machine. As the E class matured, a decision was made to introduce the F class machines—the 7F and its scaled versions, the 9F and the 6F. Many factors drove this decision, but once the F machines were introduced, technology advancement or operating experience on the F product line has helped drive further evolution on the older E class machines, albeit in more gradual steps.

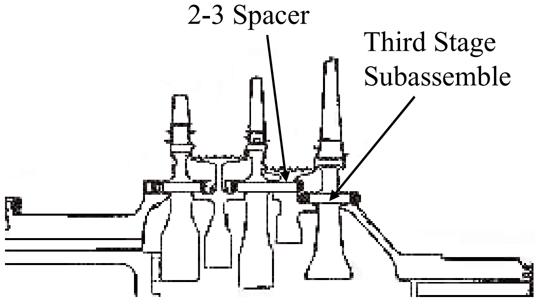

Figure 5. Cross section view of the turbine rotor showing affected components

Design improvements for the "F" product line are made incrementally, and based on proven materials, extensive laboratory or engine testing, and operating experience. When the "F" technology was announced, uprate potential was projected. Immediately upon completion of the prototype testing at the Greenville factory, these uprates began. One of the projections made was that the combined cycle efficiency would be increased from the 50% cited in the introduction paper, to 55%. The 55% level was achieved in 1994 with the testing a MS7001F unit in combined-cycle mode.

Uprates continue, as the technology becomes available and as experience on the high temperature components of the "F" fleet remains favorable. *Table 1* shows the evolution of the MS7001F machine. Each uprate has been achieved without reducing inspection intervals below those established by the original design. The first uprate of the MS7001F simply took advantage of the better than expected performance observed in testing. Firing-temperature upgrades involved modifications to component cooling and pressure ratio.

These include improved clearance and leakage control achieved with the help of honeycomb seals - which have been used now for years in the MS9001E and MS7001EA machines. *Figure 8*

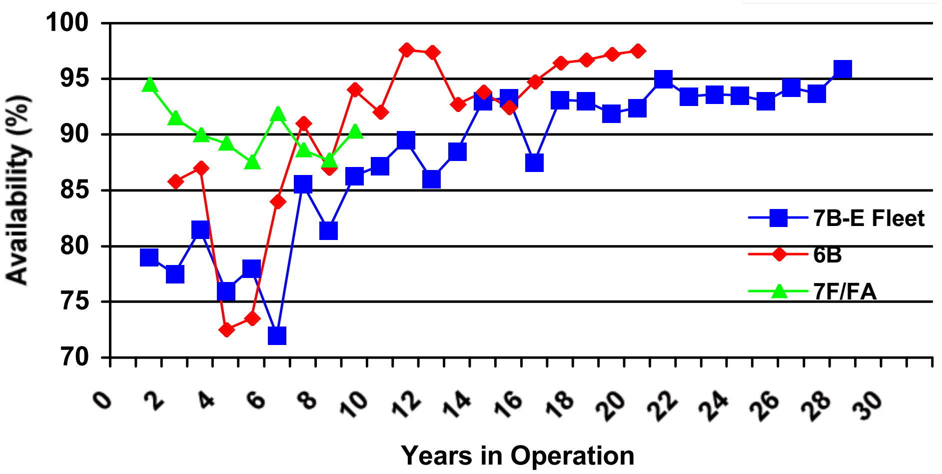

Figure 6. "F" Technology following proven technology

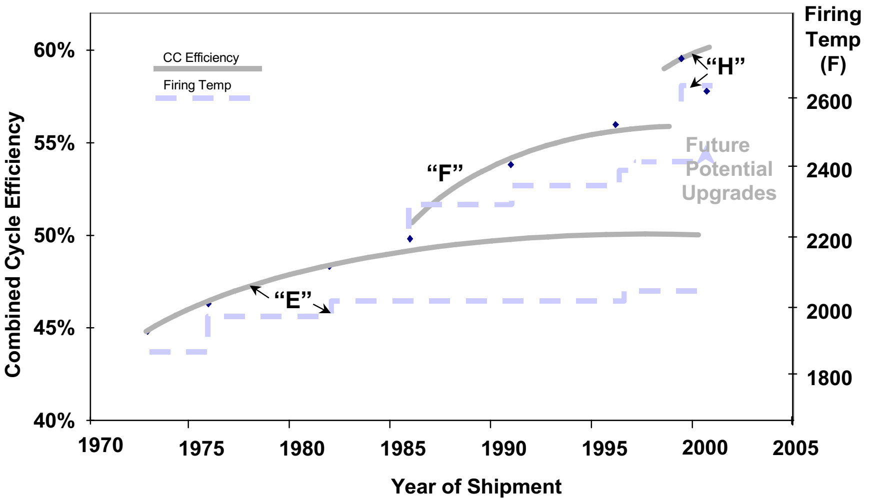

Figure 7. Incremental evolutions of "E" and "F" technology

shows the evolution of the PG7231FA to the PG7241FA, illustrating the incremental enhancements that were incorporated recently into the 7F product line.

Future Evolution of the F/FA

As GE looks forward to the next steps in the continued evolution of the F/FA product line, a range of factors is being considered. The continuing improvement in F reliability and growing experience base; the development and testing of H and other technologies; and, a recent F compressor mapping test are all key factors that will be carefully weighed.

Compressor Capability Offers Further Options

In 1998 a compressor test was run to revalidate the operating surge limit for the F/FA compressor. The results of this test indicated there was significant additional capability in the compressor. *Figure 9* shows how this development

	PG7191(F)	PG7221(FA)	PG7231(FA)	PG7241(FA)
Output	150 MW	159 MW	167.8 MW	171.7 MW
Heat Rate	9880	9500	9380	9360
(LHV) Pressure	BTU/kWh 13.5:1	BTU/kWh 15.1:1	BTU/kWh 14.9:1	BTU/kWh 15.5:1
Ratio Firing Temp.	2300°F	2350°F	2400°F	2420°F
Introduction	1991	1993	1997	1999

Table 1. Evolution from PG7191(F) to PG7241(FA+e)

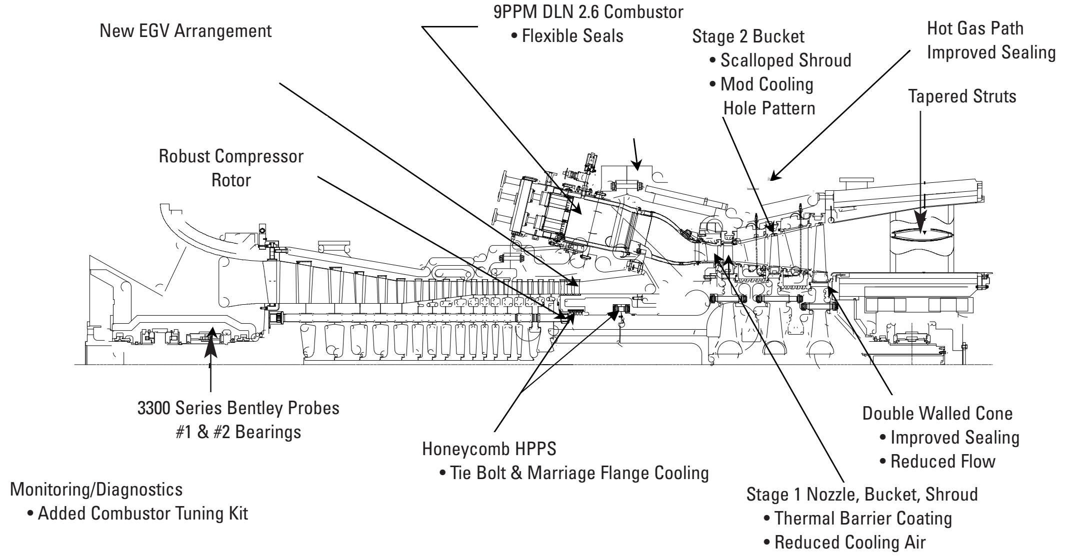

Figure 8. Transition from PG7231 to PG7241 gas turbine illustrates incremental improvement philosophy

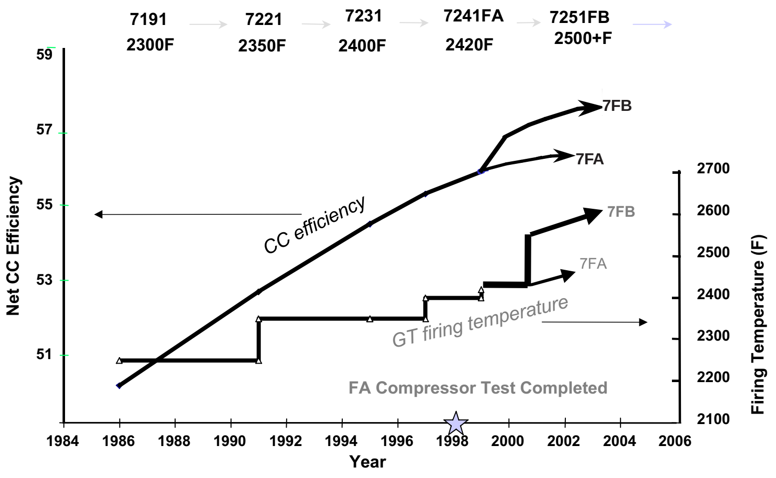

Figure 9. Evolution of the MS7001F

opens up additional options for the next step in "F" evolution – to continue on a gradual incremental change in pressure ratio and temperature or take a more aggressive path and take advantage of the results of the 1998 compressor test. As these options are examined, significant technical tradeoffs must be analyzed.

References

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2. Eldrid, R., Marks, P., "Continuing Evolution of F Technology" Dec 1999.

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