Electrify Europe, Vienna Austria 2018,

Increasing Reliability, Availability, Maintainability and Flexibility of Advanced Class Gas Turbines by incorporating state-of-the-Art Automation and Data Analytics

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Abstract:

The penetration of renewable power around the world has increased the focus on reliable gas turbines to ensure smooth power transition between the different generating sources and maintain grid stability. The reliability of newly designed power generation equipment is highly dependent on their original design, but it can be complemented by the development and implementation of digital enhancements.

Strategic Power Systems (SPS) is a world class data gathering and analysis company that collects and processes operational data from several thousand gas turbines across the globe. The data is directly collected from numerous operating companies participating in the ORAP program and it is used to calculate Reliability, Availability and Maintainability (RAM) statistics of each participating plant and the corresponding fleets. Their stringent analysis imposes mathematical & statistical requirements such as minimum statistical population size, continuity of the data, inclusion of every unit of the population, etc. The ORAP fleet includes Mitsubishi Hitachi Power Systems (MHPS) Advanced Class Gas Turbines (ACGT). SPS assessment of the MHPS fleet started in 2009 and has consistently shown superior 5 year moving average reliability values in excess of 99%.

This paper describes the fundamental design criteria enabling MHPS ACGTs exhibit the best Advanced Class GT RAM statistics and introduces several state-of-the-art automation and analytics enhancements that will further increase the reliability and flexibility of the current advanced gas turbines.

Introduction

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MHPS pioneered the use of steam cooling exactly two decades ago (1997) and has also led the use of the highest Turbine Inlet Temperature (TiT) during the past two decades. This paper describes four fundamental reasons that have helped MHPS ACGTs have consistently the best Advanced Class GT RAM statistics despite the elevated TiT:

1) Application of a rigorous and conservative design approach while being the leader in TiT
2) The use of a robust Rotor Cooling Air Cooling approach that allows operation at high TiT and high efficiencies without the need for single crystal (SX) components or Super Alloy turbine discs
3) The well-established "Under-one-roof" approach for hot gas path components repair and manufacturing resulting in tighter quality control of these key components
4) Application of short term validation at MHPS "T-point" in-house verification plant followed by long term validation for extended periods of time.

Strategic Power System (SPS) is a well-known, independent company that, among others, collects Reliability, Availability and Maintainability (RAM) data of gas turbines in operation worldwide. SPS gathers detailed operational data directly from the owners of numerous generating assets through the use of their Operational Reliability Analysis Program (ORAP).

Table 1 below shows SPS's RAM data for large frame industrial gas turbines and includes continuous RAM data spanning a 5-year period without exclusion of any type. All RAM metrics in the table clearly reveal superior M501G statistics compared to other advanced Gas Turbines as well as the legacy F-class designs.

Period	Apr 2012 – Mar 2017		
Category	Advanced Technology	M501G	"F" Class
Number of Units	31	24	663
Reliability*	98.37%	99.26%	97.71%
Availability*	91.23%	92.32%	91.01%
Forced Outage Factor**	1.03%	0.37%	0.91%
Unscheduled Maintenance Outage Factor**	0.40%	0.32%	0.60%
MTBF** (hours)	3,955	5,368	2,311
MTTR** (hours)	28.33	18.64	19.29
Frame	7H/9H W501G M501G/M701G		GT24/26, 6F/FA, 7F/FA, 9F/FA, 7FB/9FB W501F, V84.3, V64.3A, V84.3A, V94.3A M501F/M701F

* - Values based on "Simple Cycle Plant" = GT + Gen. + Controls + Direct Ancillaries + Station Equip.
** - Values based on "Gas Turbine only"

 May 2017

Table 1. M501G RAM comparison of legacy F and Advanced Class Fleets

The center (yellow) column of Table 1 represents twenty-four M501G units (roughly one third of the M501G fleet) and allows the following comparisons:

A) Reliability of the M501G Fleet vs. Advanced Technology GT:

99.26% vs 98.37%

The Advanced Technology GT column (left) in Table 1 consists of five different advanced class gas turbine frames (shown at the bottom of the second column) and includes the 24 MHPS' G Class units. In other words, twenty-four of thirty-one Advanced Technology GTs are M501G. This comparison reveals that the RAM data of the seven additional units manufactured by other OEMs is significantly lower than the corresponding numbers of the M501G fleet, thereby decreasing the total Advanced Technology GT reliability and availability averages.

B) Reliability of the M501G Fleet vs. F Class GT:

99.26% vs 97.71%

The second comparison is even more revealing and statistically significant. It shows that the M501G fleet has significantly better RAM statistics compared to the F-class fleet, despite the fact that the M501G features higher turbine inlet temperatures and higher compressor pressure ratio. Moreover, most of the units in the M501G SPS sample population apply steam cooling.

Progressive, rigorous and conservative application of new technology

The high fuel prices in Asian countries have driven Japanese power generation equipment suppliers to design and provide the highest efficiency possible to their clients. Higher temperatures are an effective way to increase efficiency and power output but represent one of the biggest challenges for gas turbine designers due to the potential effect on parts durability.

MHPS has led the TiT designs for more than two decades and has motivated the company to proudly disclose temperature parameters that are commonly considered highly confidential in the industry. This effort has been applied following a conservative and progressive approach described in Figure 1 below.

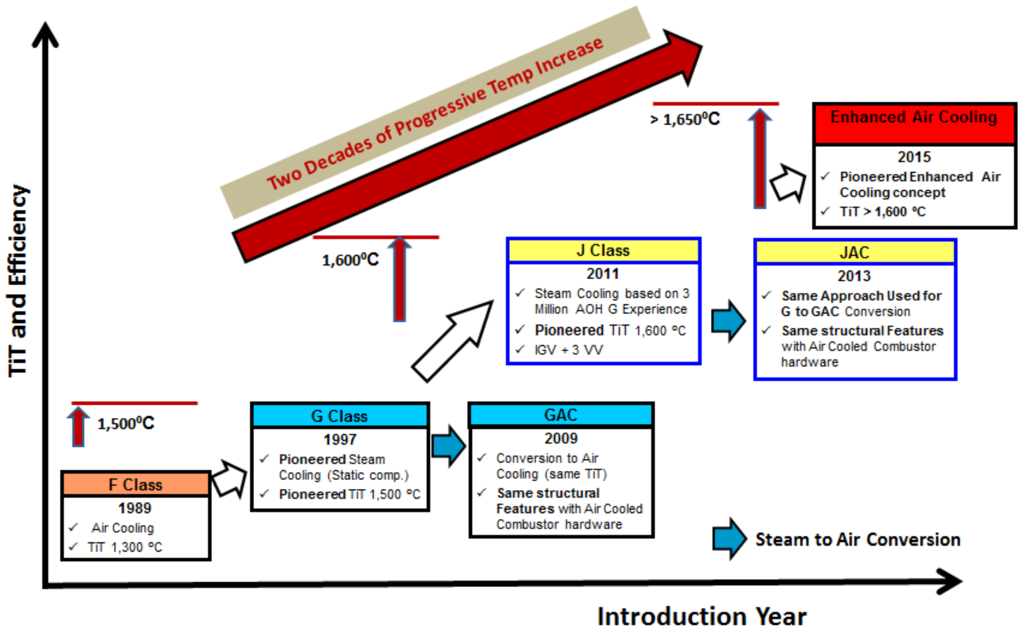

Figure 1. Progressive introduction of Technology

The figure shows the chronological evolution since the F class gas turbines, through two iteration of highly reliable steam cooled GTs and air cooling counterparts (G to GAC and J to JAC) discussed in References 3 and 8.

Robust Rotor Cooling Air Cooling Approach

MHPS started using cooling of the rotor cooling air during the cooperation with Westinghouse in the early 1960's. The approach has been progressively expanded to other components such as Row 2 Vanes and Row 4 Blades. Figure 2 shows a typical isometric representation of MHPS Advanced Class GT enclosure and external auxiliaries. The added coolers are enclosed inside the red oval figures. These auxiliaries require added initial cost and construction activities, but their use allows operation at the highest temperature in the market without the use of expensive components manufactured out of single crystal structures or high nickel content turbine discs.

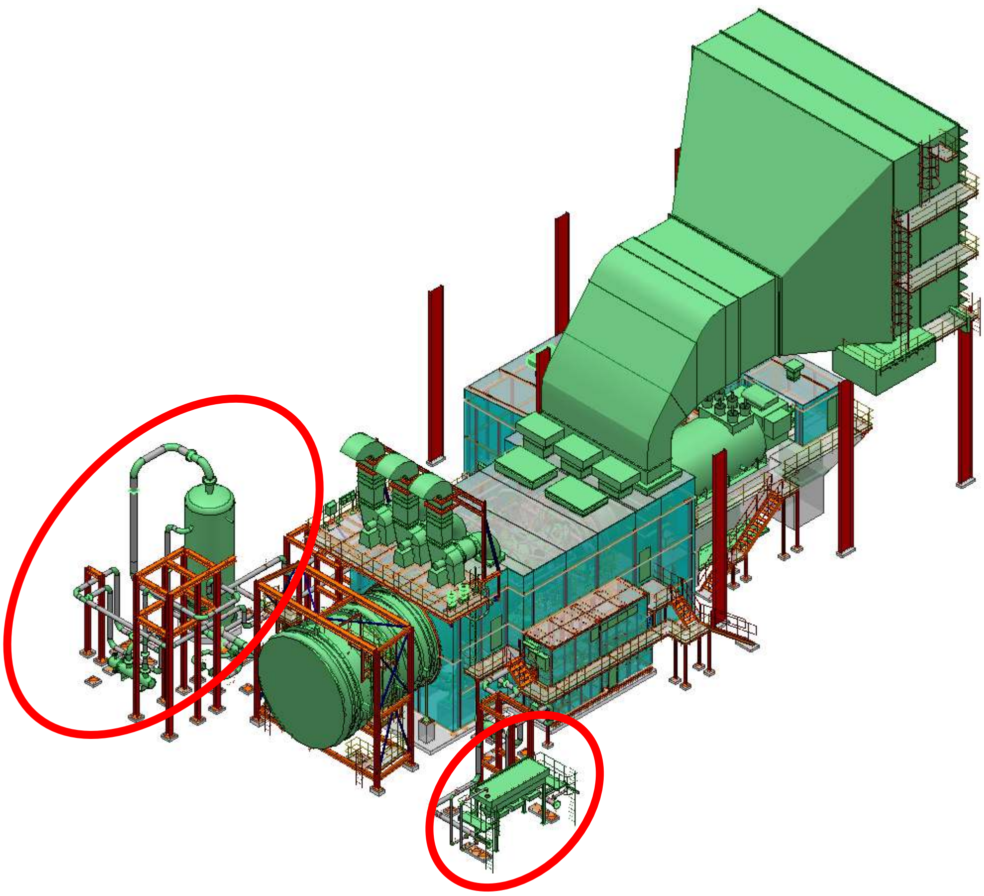

Figure 2. MHPS Cooling Air Approach

High nickel discs can be applied for their higher creep tolerance to higher discs metal temperatures resulting from using hot cooling air, however, this material is well known to experience disc cracking and even liberation as stated item 9 of Table 2 below (reference 2).

A	Technical & design
1	Insufficient design clearance between rotor and stator blading in the compressor resulting in rubbing and detachment of material causing significant damage to components downstream.
2	Compressor first row blade distress, with downstream DOD
3	Material erosion of initial compressor stages associated with fogging or water injection, scale deposits on blading as well as mechanical blade failures due to airflow stalling or surging.
4	Gas turbine compressor contamination due to poor evaporative cooler design
5	Compressor diaphragm hook-fit wear and failure
6	Flame instabilities within the burner area of the combustion chamber leading to vibration and subsequent component cracking.
7	Flashbacks moving the burner flame front from its intended location impinging on components not designed for high temperatures and damage due to melting and detachment.
8	Gas turbine loss of stage 1 blades due to root seal pin locking up to change the resonant frequency
9	Cracking/liberation of first stage turbine disc
10	Failure and detachment of thermal barriers and insufficient blade cooling leading to thermal related damage associated with increased firing temperatures.
11	Gas turbine loss of latter stage vanes due to vane movement/erosion/liberation

http://www.imia.com/wp-content/uploads/2013/05/IMIA-WGP-64-Combustion-Turbines-FINALa.pdf

<u>Table 2</u>. International Association of Engineering Insurance recurrent Large Claim Experience

The manufacturing of high Ni content discs involves slow machining to avoid surface imperfections that can result in systemic failures as described in Reference 5.

<u>"Under-one-roof" hot gas path components repair and manufacturing approach</u>

Hot gas path components deficiencies are a well known cause of unscheduled outages with a potential for catastrophic damage. The integrity of these components imposes manufacturing and refurbishment under tight quality control that must not be compromised by cost cutting efforts. MHPS applies the "under-one-roof" approach where either new casting or used parts to be refurbished are handled entirely within MHPS facilities. This also ensures full control of timely delivery to new or existing projects where delays have a big impact on the availability of the plants. The picture in Figure 3 below shows MHPS facility in Orlando Florida, which mimics Takasago's "under-one-roof" approach.

Figure 3. **MHPS Orlando "Under-one-roof" facility**

Short and long term validation at MHPS

Validation of new technology involves a long process that starts with R&D testing of individual components, combustion tests using atmospheric and high pressure test rigs, testing of scaled down compressors and many other individual tests. The next step involves operation of the gas turbine at different RPMs to confirm compressor surge margins, smooth operation without frequency excitations and other important operational stability. Finally, operation under sustained long term load conditions will confirm if the individual components can sustain the demanding conditions that can result in failures that don't occur within a few hundred hours. These include low cycle fatigue which is commonly related to start/stops during long term operation.

In MHPS case, the first stage takes place at Takasago R&D center co-located in the GT Factory premise. The last two stages, short and long term validation are conducted at the T-Point Validation plant shown in Figure 4. The short term validation is conducted prior to closing the breaker and it is followed by sustained operation in compliance with the local utility that buys the power generated.

Figure 4. **MHPS Validation Power Station**

This validation plant was built in the mid-90s and has operated since 1997, generating in excess of 21,800 GW-hr.

One of the advantages of this approach, as compared to a shop test, is the construction of the plant following MHPS standard plant design. The picture in Figure 5 shows the standard enclosure, which is typically not used during shop tests. It allows confirming the effect of external cooling on the unit and the instrumentation inside.

Figure 5. Validation Plant Standard Enclosure

The use of standard plant design includes coupling the GT flexible rotor to the more rigid standard generator rotor and exciter. The plant follows MHPS standard plant bearing count (five as shown in Figure 6), bearing span, stiffness and damping used in future plants running with the same GT. This is useful to determine any rotor-dynamic issues, vibrations, and frequency response which are highly influenced by the generator rotor high torsional inertia. All these points cannot be accurately evaluated when connecting equipment different from the standard power generation plant.

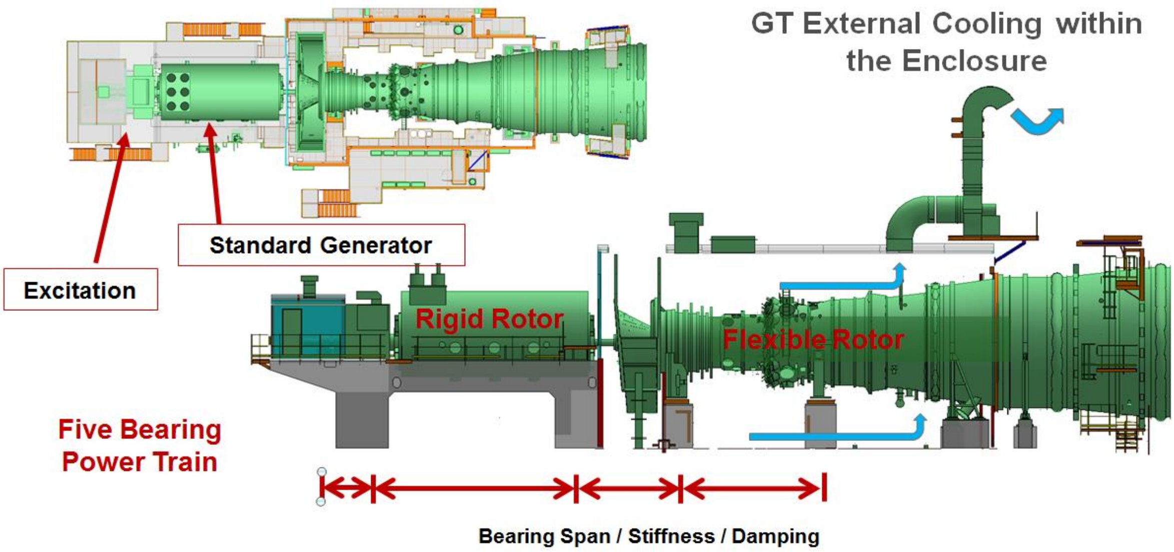

Figure 6. MHPS Validation Approach (Standard Equipment)

One added benefit of the long term validation applied at T-Point is the evaluation of the durability of the hot gas path parts in order to establish realistic intervals between inspections. Figure 7 shows the use of initially short intervals and their extension based on thorough inspection of the parts during long term validation. This approach renders a realistic pro-forma evaluation of the ROI of a future projects, that otherwise, will confront lost revenue by shorter than estimated continuous operation capabilities of the gas turbine.

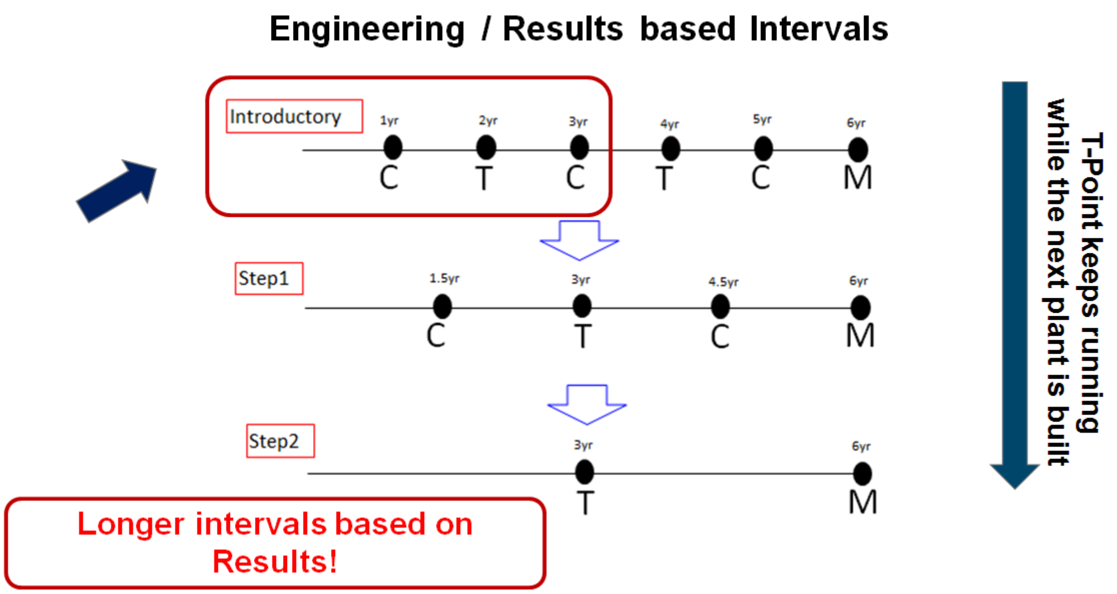

Figure 7. Realistic Inspection Intervals based on MHPS Validation Results

Incorporation of State-of-the-Art Automation and Data Analytics for further increase of Reliability, Availability, Maintainability and Flexibility.

In parallel with the development and validation of the MHPS ACGT, there have been impressive advancements in software and digital hardware technology that have vastly improved data volume manipulation capabilities and calculation speeds. These advanced technologies are driving control automation and smart analytics that have enabled drastic changes in the way power plants are controlled and designed to make them more efficient, clean and flexible. The evolution of competitive power markets and increasing penetration of renewable generation is increasingly demanding that combined cycle plants operate in more challenging duty cycles, with more rapid load changes, lower turndown and more start/stop cycles. This is making the more robust and thoroughly validated MHPS ACGT designs, coupled with digital automation and data analytics, strongly positioned to respond to changing power market dynamics.

Advanced Data Analytics

In the area of data analytics, MHPS has over 20 years of monitoring and diagnostics experience and has a proven track record of improving its customers' RAM through data analysis and support. Despite its success, the data analysis efforts have been manpower intensive as many processes relied on Subject Matter Experts (SMEs) to mine through large amounts of data to validate new control methodologies and to troubleshoot operational issues. Understanding the design and operating characteristics of power plant equipment now allows the application of Machine Learning (ML) and Artificial Intelligence (AI) algorithms. Today, MHPS is deploying digital solutions that help customers address these challenges through advanced data analytics.

Digital Solutions to Improve Reliability, Availability, Maintainability and Flexibility

In reference 6, we have discussed examples of the advancements applied to MHPS Advanced Class Gas Turbine plants for AI-based combustion system self-tuning, increased gas turbine loading ramp rates and faster combined cycle loading. These and other "Digital Solutions" use the knowledge derived from analysis of massive amounts of operational data obtained from the T-Point Validation Plant and the fleet of plants monitored by the three 24 hours/ 7 days a week MHPS Remote Monitoring and Diagnostics Centers regionally located around the world. This detailed knowledge, combined with the latest advancements in digital control systems with adaptive and anticipatory control methodologies allows modern gas turbines to be operated more precisely and less conservatively in the more challenging and flexible operating regimes demanded by today's competitive power markets. A few examples are given below of how these advancements help plant operators achieve more responsive, reliable and economically viable operation in dynamic markets, while maintaining reliability and availability comparable to base-load-operated units.

Self-Tuning System

Mitsubishi Hitachi Power Systems pioneered the development and implementation of Self-tuning Combustion Dynamics systems as described in the 2003 ASME/IGTI paper cited in reference 1. The original self-tuning system was called A-CPFM (Advanced Combustion Pressure Fluctuation Monitoring) and made use of algorithms to manipulate extensive amounts of data in order to provide early detection and protection against hardware distress caused by combustion dynamics. This "expert system" performed fine-tuning adjustments of several combustion parameters as a reaction to pressure oscillations.

The latest MHPS Self-Tuning system is called Second Generation A-CPFM. It takes advantage of the improved computational power developed in the last decade to speed up processing complex algorithms while incorporating a fast response calorimeter to include feedforward control logic to react to fuel composition changes, as described in Figure 8.

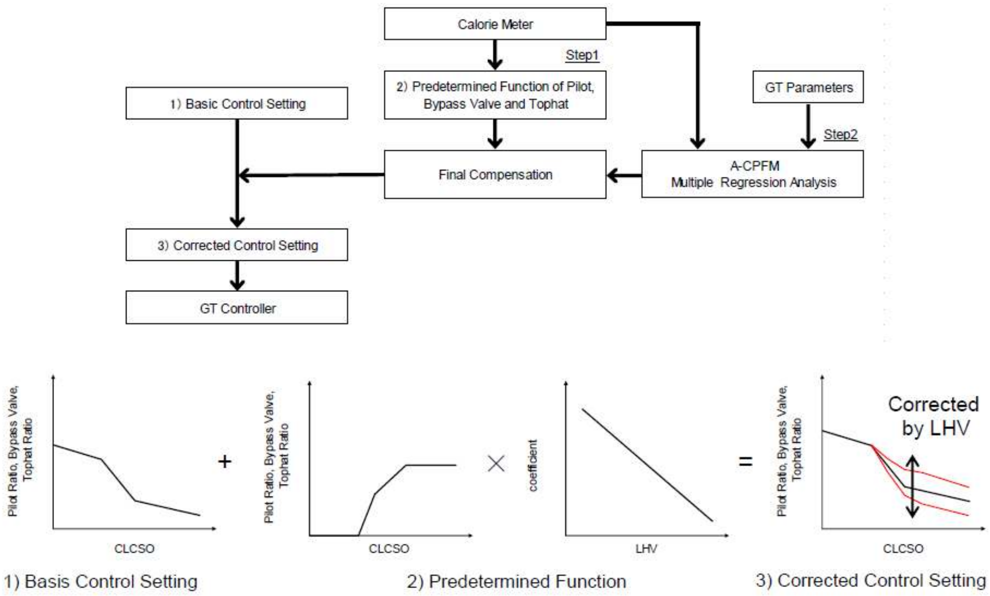

Figure 8 Concept of the improved control method

The application of the latest self-tuning system has improved RAM and flexibility of the gas turbines through fuel and environmental changes that otherwise could have triggered combustion dynamic related load runbacks or trips. It has also helped operation at reduced minimum loads, when the main limitation is related to emissions or combustion dynamics. Table 3 below shows the number of units equipped with the different versions of MHPS self-tuning systems.

GT Model	A-CPFM version	Units	Actual Operating Hours (AOH)	
F	Original	60	3,435,219	6,255,475
	Second Generation	103	2,820,256	
G	Original	3	213,826	2,099,666
	Second Generation	48	1,885,840	
J	Second Generation	17	306,518	
Others	Original	5	291,779	
Second Generation Total		168	5,012,614	
Total		236	8,953,438	

Table 3 Operating experience of A-CPFM system

Increased Turndown and Improved Part Load Efficiency

New digital control strategies are used in gas turbines to allow safe operation at higher exhaust temperatures at partial load. This approach has been implemented with precise control of inlet guide vanes (IGV) to reduce loading rate restrictions and avoid overshoot of firing temperature during transients. The outcome of this strategy was improved combustion stability with reduced emissions at lower turndown loads as shown in Figure 9 and also an improvement in part load combined cycle heat rate as shown in Figure 10.

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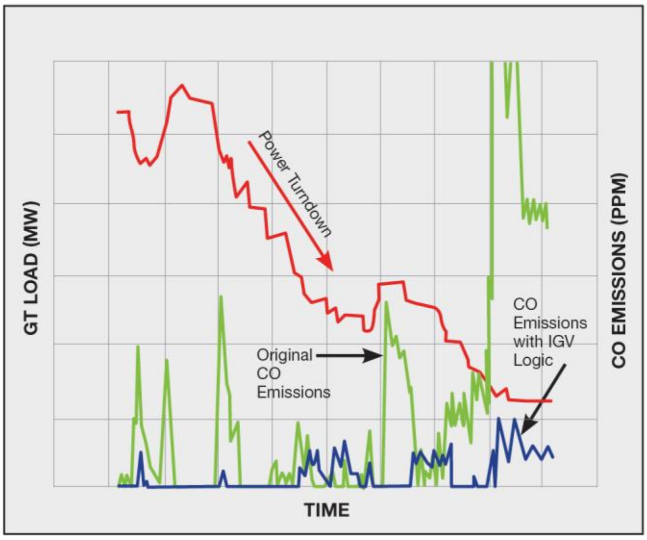

Figure 9: Reduced Emissions and Lower Turndown

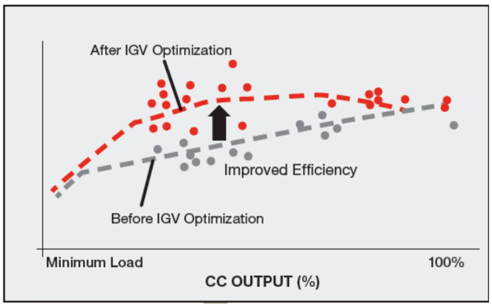

Figure 10: Improved Part Load Efficiency

Peak Power Options

Conventional control strategies restrict operation near base load to avoid firing temperature overshoot, combustion instability and operation in excess of gas turbine nameplate ratings. Today's more sophisticated controls coupled with upgraded monitoring and data analytics can safely allow limited operation beyond the nameplate rating so operators can take advantage of periods of high energy market prices and maximize demonstrated plant capacity that would be usable in emergency situations.

New digital control strategies have been implemented to allow operation in Maximum Air Flow Mode where the inlet guide vanes are fully opened, going beyond the normal maximum efficiency flow rate, resulting in additional output at rated gas turbine firing temperature. An additional Peak Fire Mode has also been implemented which goes beyond the output achievable with the Maximum Air Flow Mode by carefully increasing firing temperature above rated firing temperature.

These and other control strategies are enabled by advanced data analytics. When combined with the robust and validated ACGT designs, MHPS can support its customers' increasingly challenging operating requirements while maintaining the proven levels of RAM traditionally associated with base-load operation.

Summary:

1. MHPS has led the introduction of high TiT for two decades since pioneering the introduction of steam cooling at a TiT of 1,500 °C.

2. The use of external cooling air coolers has allowed the application of high TiTs without the using single crystal hot gas path components or high nickel content turbine discs that are prone to cracking.

3. MHPS gradual introduction of technology including the use of robust cooling air cooling, the use of "under-one-roof" hot gas path manufacturing and refurbishment, and the short and long term validation applied to new or modified gas turbines has resulted in the highest reliability of MHPS advanced gas turbines.

4. Digital technology has been successfully retrofitted to combined cycle plants, including advanced self-tuning combustion dynamics system, reduced steam turbine and combined cycle start-up times and broadened operating range in order to flexibly respond to grid rapid demand changes resulting from renewable penetration.

5. Fast processing and analysis of digital data has enhanced the use of the inlet guide vane (IGV) system to improve combustion stability and attain lower minimum loads in emissions compliance, while improving part load efficiency to improve plant dispatch.

6. Digital analysis of gas turbine operational data has allowed MHPS to increase the gas turbine firing temperature for controlled periods of time without adverse operational effects or excessive component life consumption.

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