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ADVANCEMENTS IN H CLASS GAS TURBINES FOR COMBINED CYCLE POWER PLANTS FOR HIGH EFFICIENCY, ENHANCED OPERATIONAL CAPABILITY AND BROAD FUEL FLEXIBILITY

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ABSTRACT

The power generation industry faces significant changes: growth in natural gas supply, downward pressure on emissions, retirement of coal assets and continuing expansion of renewables. Gas turbine combined cycle technology continues to advance, offering increasing efficiency and lower lifecycle electricity costs. Advanced combined cycle plants offer improved operating flexibility with faster start times, increased ramp rates and broad fuel flexibility while maintaining high levels of reliability and availability.

GE has developed HA gas turbine products in both 50 Hz and 60 Hz configurations capable of achieving over 62% on a combined cycle, net-efficiency basis at ISO conditions. The 7HA serves 60 Hz regions and 9HA serves 50 Hz regions. The 7/9HA gas turbines share architecture and technology features to maximize performance and accumulate shared experience while minimizing risk. The HA products represent the best of the F and original H-class products. Steam cooling and cooled cooling-air systems from the original H design were eliminated enabling improved operational flexibility, simplified installation and ease of maintenance.

The HA gas turbines have been rigorously tested over their entire operating and fuel range in GE's state of the art test facility in Greenville, SC. Isolating the test stand from the grid provides multiple benefits: 1) both 50 and 60 Hz units can be validated, 2) ability to vary speed and load simultaneously during testing, 3) complete compressor mapping, and 4) realistic testing of grid code compliance.

The first 9HA.01 entered commercial operation at the Électricité de France (EDF) Bouchain power plant on June 17, 2016. The first 7HA.01's and 7HA.02's are shipping in 2016 to power stations in Nagoya City, Japan and two sites in Texas, USA.

1. INTRODUCTION

The European Union Renewable Energy Directive (The European Parliament and the Council of the European Union, 2009) established an overall policy for the production and promotion of energy from renewable sources. It requires the EU to fulfil at least 20% of total energy needs with renewables by 2020. As of June 15, 2015, 26% of the EU's power is generated from renewables (The European Parliament and the Council of the European Union, 2015) exceeding the 2009 objective. The growth of renewable energy sources is, of course, highly beneficial to the environment but introduces intermittency into grid management. Significant reserve margin must be in place to compensate for the potential interruption of renewable sources such as low wind speeds affecting wind generation or low sunlight negating solar generation. Intermittency of renewables demands that complementary sources of power generation must exist. Grid operators need efficient and operationally flexible solutions to navigate the fluctuating energy landscape. These attributes must be combined with state-of-the art reliability, availability, and maintainability (RAM) to ensure steady and predictable operation and revenue generation. These dynamics are increasing the demand for high-efficiency, operationally-flexible, robust gas turbine combined cycle power plants that achieve cost effective conversion of natural gas to electricity.

Gas turbine technology level is commonly identified by letter designation. This paper will define H-class as architectures with firing temperatures greater than 1,430°C. It is important to specifically define the firing temperature, as variation exists in its meaning among gas turbine manufacturers. Here, firing temperature is the conventional T4 or turbine first stage bucket inlet temperature. The reference plane is directly downstream of stage one nozzle (S1N) cooling and represents peak working temperature in the Brayton cycle. H-class builds upon the architecture, manufacturing, and operating experience gained by E and F class systems, with associated firing temperatures and dates of introduction as shown in Figure 1.

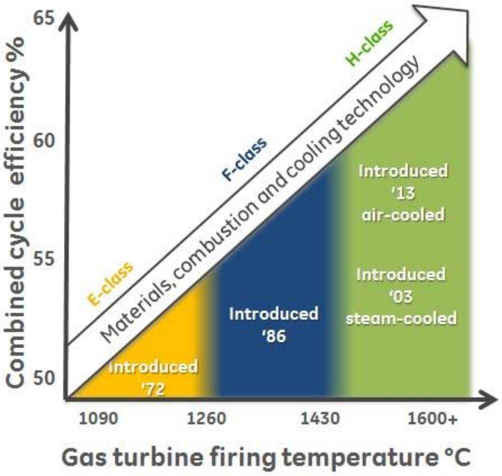


Figure 1. GE Gas turbine E, F and H class progression

2. H-CLASS HERITAGE

Development of GE's H-class technology began in the early 1990's leading to the first commercial operation (COD) in 2003. This original H-class gas turbine pioneered many new features, including the 4-stage, steam-cooled turbine section and 4 stages of variable guide vanes at the compressor inlet. Development and engineering of the first H-class gas turbines are summarized by Matta, Mercer and Tuthill (2000). A total of six original H-class gas turbines were manufactured with each entering commercial operation as shown in Figure 2. This first 9H is operating at Baglan Bay in Wales, UK. The other 9H's are operating at the TEPCO Futtsu station near Tokyo, Japan, with COD's from 2008 through 2010. Two 7H's are in operation at Inland Empire in California, USA with COD's in 2008 and 2010. As of publication of this manuscript, these units have accumulated over 255,000 hours of operation.

Experience and knowledge gained from operation and maintenance of these plants have been applied to enable an evolutionary approach for a new set of H-class products, designated the 7HA and 9HA. These products and their associated design and validation strategy were detailed by Vandervort et al. (2015). The 7/9HA gas turbine hot gas path is entirely air-cooled, facilitated by advances in turbine cooling, sealing, materials, and coatings. The "H" signifies H-class firing temperature with the addition of "A" denoting air-cooling.

3. 7/9HA GAS TURBINE ARCHITECTURE EVOLUTION

The 7HA and 9HA gas turbines were developed with an evolutionary approach combining experience from the original H-class architectures plus field experience from F-glass gas turbines. The 7HA and 9HA are speed and geometric scales with factors of .083 (versus 9HA) and 1.2 (versus 7HA), respectively. The 7HA serves the 60 Hz market while the 9HA serves the 50 Hz market. Scaling based upon this approach has been routinely applied for industrial gas turbines, including the 7/9E's and 6/7/9F's offered by GE Power. The methodology is described by Gebhardt (2000).


UK – 1 X 9H

First Fire	COD	Fired Hours*
Nov. 2002	Aug. 2003	63,140

Futtsu 4 – 3 X 9H

First Fire	COD	Fired Hours*
Nov. 2007	July 2008	47,203
Apr. 2009	Dec. 2009	45,842
Apr. 2010	Dec. 2010	41,113

Inland Empire – 2 X 7H

First Fire	COD	Fired Hours*
May 2008	Aug. 2008	36,630
July 2008	May 2010	21,868

* As of June 2016

Total	255,796

Figure 2. GE H-Class power plant experience

The 7/9HA compressor is a direct scale from the 7F.05, developed as an enhancement for the original 7F gas turbines. The 7F.05 generates 241MW in simple cycle at ISO conditions. A total of 21 7F.05 units have entered commercial operation as of June 2016, accumulating over 70,000 operating units and 1,500 starts. 71 orders have been received for the 7F.05 with an additional 18 'technology selections'.

The 7/9HA uses the DLN 2.6+ combustor, with DLN as an acronym for Dry-Low NOx. Evolutionary enhancements are introduced and will be described in section 3.2. The DLN 2.6+ combustor combines the best features of GE's DLN systems and was introduced over 10 years ago on the 9F gas turbine.

The 7/9HA turbine has four-stages and operates at the same pressure ratio as the original 7/9H gas turbines. The hot gas path architecture benefits from extensive F and H class fleet experience, and by leveraging technology from GE's Aviation (Aircraft Engines) business.

Heritage of the 7/9HA gas turbines is shown by Figure 3.

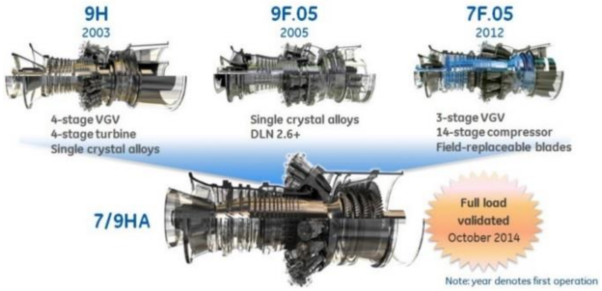


Figure 3. 7/9HA gas turbine evolution

The 7/9HA family of gas turbines offers two output sizes for both 7HA and 9HA. The 7HA.01 and 9HA.01 were developed first, with the 7HA.02 and 9HA.02 directly following. The ".02's" are flow scales of the ".01's". The process of flow scaling can be summarized by increasing compressor inlet and turbine exit annulus areas to accommodate higher air flow with resultant increase in power output. Pressure ratio is increased to maintain aerodynamic flow function in the mid-to-later compressor and first and second turbine stages. Thus, the machine midsection flow-path is unchanged between the two architectures. Both compressor and turbine outer diameters are unchanged for the .02's versus the .01's. Margin had been provided in the original ".01" products to enable increased inlet and exhaust annulus without change to flange-to-flange outer dimensions. The overall length increases by about one meter for both the 7HA.02 and 9HA.02.

Fuel supply capability and fuel nozzle sizing are increased to accommodate the corresponding increased flow needed to maintain constant firing temperature.

Table 1 provides output for simple-cycle and combined-cycle configurations of the HA products. These performance values are shown on a net basis at ISO with boundary conditions per the Gas Turbine World (2015) standard. SS is an abbreviation for 1x1, single-shaft configuration.

	Gas Turbine Output (MW)*	SS Combined Cycle Output (MW)*	Combined Cycle Efficiency *
7HA.01	280	419	61.8%
7HA.02	346	509	62.0%
9HA.01	429	643	62.6%
9HA.02	519	774	62.7%

*Net, ISO, Gas Turbine World (2015)

Table 1. 7/9HA Product offerings

Provisions have been made in the architecture to enable future growth for this product set. For example, the 7HA.02 and 9HA.02 platforms offer 'line-of-sight' for growth to greater than 600 and 860 MW (respectively) CC net output and over 63% net combined cycle efficiency. In parallel, field experience combined with advances in critical gas turbine technologies will enable extension of maintenance intervals and component lives to reduce life cycle costs.

3.1. 7/9HA COMPRESSOR

The 7/9HA compressor is a direct evolution from the 7F.05 gas turbine as previously stated. The 7F.05 compressor has a 14-stage architecture with inlet guide vanes followed by three stages of variable guide vanes. There are two extraction points for supply of cooling air to the hot gas path. This compressor incorporates the latest aerodynamic and durability enhancements. Features include 3-D aerodynamics, field replaceable blades and application of 'super-finishing' or coating of blades. These elements combine to provide high efficiency, wide operability, minimal degradation, optimal reliability and maintainability. The 7F.05 compressor was the first product validated in the GE's new Full Speed Full Load (FSFL) test facility. Operability, aerodynamic performance, surge margin and reliability of the compressor were shown to meet or exceed requirements. The 9HA.01 compressor is shown by Figure 4.

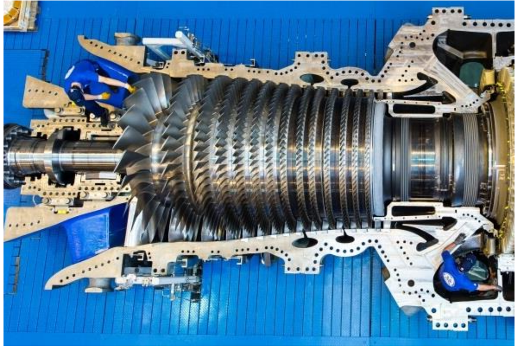


Figure 4. 7/9HA Gas turbine compressor

3.2. 7/9HA COMBUSTOR

The 7/9HA gas turbines have been designed to operate with lower than 25/15 ppm NOx/CO from below 30 to 100 percent load. This level of performance at H-class firing temperatures is possible as a result of investment in combustion technology and testing capability coupled with millions of hours of experience with DLN combustion. Even lower emissions can be guaranteed for both 7HA and 9HA via reduction in firing temperature or inclusion of exhaust Selective Catalytic Reduction (SCR).

The 9HA.01 gas turbine was introduced with proven DLN 2.6+ combustion technology that has run reliably for over 2.4 million fired hours across more than 100 9F.03 and 9F.05 gas turbines. It represents the continued advancement of the DLN 2.6+ combustion system for performance, operability, fuels capability, reliability and low emissions. This system employs multiple fuel circuits supplying 6 fuel nozzles with five arranged circumferentially around a center nozzle. The operational strategy uses fuel staging to achieve low emissions with robust maneuverability.

The 7HA.01 and 7HA.02 gas turbines incorporate combustion improvements enabling further reduction in emissions levels and improved turndown capability. The quaternary circuit used on earlier versions of the DLN 2.6+ combustion system has been repurposed to directly inject fuel into the combustion reaction zone. This new "Axial Fuel Staging" (AFS) system enables lower NOx emissions with improved turndown. It also reduces thermal loading that combines with advanced materials and coatings to deliver state-of-the-art durability. The 7HA combustor is shown in Figure 5 along with a photograph of the flame from full-scale laboratory testing.

9HA.01 and 9HA.02 gas turbines with shipment dates from mid-2017 and onward can incorporate an evolutionary improvement to the premixing fuel nozzles, in addition to AFS. The 5 around 1 fuel nozzles can be replaced by an equivalent number of arrays with smaller, tubular premixers. Each tube is individually supplied with gaseous fuel via standard end cover circuitry. Fuel supply valves and piping are unchanged from the original system to enable application of the existing control and operational strategies. The tubular premixers achieve higher mixing efficiency enabling lower NOx at high firing temperatures. Figure 6 shows this new premixing configuration. This combustor is designated DLN 2.6e.

Dual fuel capability is available with No. 2 distillate as standard backup fuel. The unit can start on either gaseous or liquid fuel and can transfer under load. The combustion system can achieve 25/15 ppm NOx/CO on liquid fuel with water injection for NOx abatement.

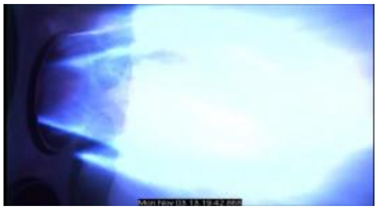


Figure 5. 7HA GT combustor (left) and flame image from combustion laboratory testing (right)

Figure 6. Enhanced premixing section for 9HA combustor

3.3. 7/9HA TURBINE

The turbine for the 7/9HA is very similar to the proven, original H-class 4-stage gas turbine (7/9H) with exception of simplification by eliminating steam cooling, cooled cooling air and the associated equipment. Metals chosen for the 7/9HA are proven alloys with over 50 million hours of operation on F and H-class gas turbines. Turbine cooling was enhanced based upon combination of this experience coupled and use of state-of-the-art analytical methods. The inner and outer turbine shell takes advantage of passive measures to accommodate thermal expansion for optimization of clearances.

Abradable and honeycomb shrouds and shorter shank buckets were carried forward from the original H-class gas turbine. Near flow path seals for enhanced nozzle sealing were leveraged from GE's Aviation technologies.

Development benefited from use of Computational Fluid Dynamics (CFD), and component testing, aided by partnerships with multiple Universities, National Laboratories and GE's Global Research Center. The turbine section and corresponding velocity field as generated by CFD are shown in Figure 7. Highly resolved wake and boundary layer effects are shown in the diagram. Understanding of the corresponding physics is important to optimization of the turbine aerodynamic and cooling architectures.

Figure 7. 7/9HA Turbine (left) and velocity field from computational fluid dynamics (right)

4. FSFL VALIDATION OF THE 7/9HA GAS TURBINES

In 2008, GE developed the world's largest and most comprehensive full-speed, full-load (FSFL) gas turbine test facility in Greenville, South Carolina, USA. This off-grid, world-class facility provides full-scale, full load validation of 50 and 60 hertz gas turbine systems. The first usage of this facility was for the previously-mentioned 7F.05 compressor in 2011 followed by the 7F.05 gas turbine in 2012. 7F.05 power plants in both the USA and Saudi Arabia have achieved commercial operation (COD), earlier than would have been possible without the facility.

The facility was subsequently used for validation of the 9HA.01 and 7HA.01 gas turbines. The 9HA.01 is pictured in the facility by Figure 8. The combustion systems are centered in the viewing region with the compressor to the left and turbine to the right.

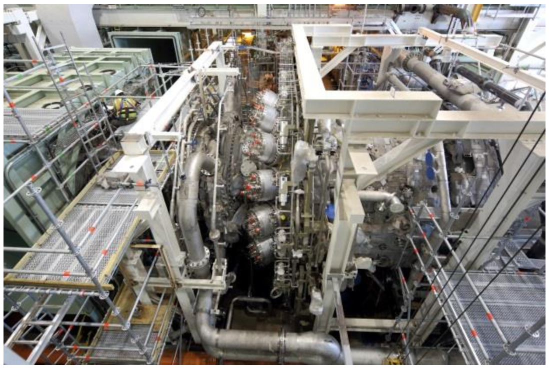


Figure 8. Photograph of 9HA.01 in FSFL facility

Overall plan for validation of the HA gas turbines is shown by Figure 9. Currently, the 7HA.02 gas turbine is installed in the test bed with preparations in progress for validation later this year. Figure 10 shows the 7HA.02

entering the test stand. The 9HA.02 will be validated in this facility in 2018.

Figure 9. 7/9HA Product FSFL validation plan

Figure 10. 7HA.02 Entering FSFL validation facility

The FSFL facility was developed to enable operation independent of the grid. Key elements of the FSFL train are the gas turbine, a load compressor, and starting means. The facility was developed to allow for the load compressor to utilize a full scale production version of the actual gas turbine compressor, to provide the most relevant validation. Typically the turbine section of a large, industrial gas turbine generates approximately twice the power needed to drive the gas turbine compressor with the remainder driving the generator for conversion to electrical power.

In GE's FSFL facility the load compressor absorbs the power normally transmitted to the grid by the generator. This unique arrangement allows the gas turbine to be operated at full load conditions without having to be connected to the grid. Instrumentation of the load compressor also enables doubling the amount of compressor validation data. The load compressor can be operated at different points on the map versus the actual gas turbine compressor. Further, the load compressor can be operated under conditions of higher duress than would be prudent for the complete gas turbine. The FSFL train is shown in Figure 11.

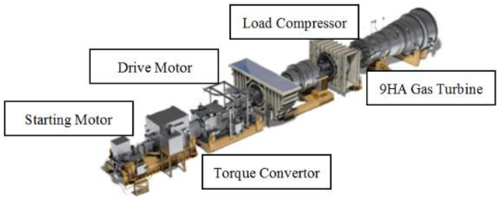
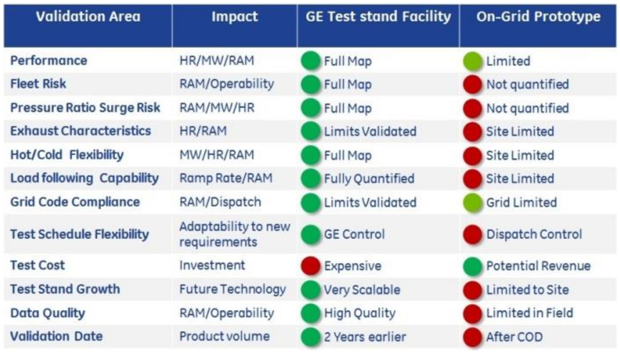


Figure 11. FSFL Test facility shaft-line showing compressor validation rig and 9HA gas turbine

Comprehensive testing can be performed with an operating envelope larger than the variances a fleet of turbines can experience in the field. This level of testing validation of the gas turbine and its systems is comparable to a gas turbine operating well beyond 8,000 hours connected to a grid. The basis for this statement is the wide range of conditions that can be tested. Freedom from the grid connection enables the use of speed as a variable. This includes capabilities at different load profiles, equivalent ambient ranges, and over-/under-frequency as well as transient load changes on both gas and liquid fuels. The facility and approach allows validation of the full gas turbine to global requirements for grid code operability and stability. These points are summarized in Table 2.



Validation Area	Impact	GE Test stand Facility	On-Grid Prototype
Performance	HR/MW/RAM	🟢 Full Map	🟢 Limited
Fleet Risk	RAM/Operability	🟢 Full Map	🔴 Not quantified
Pressure Ratio Surge Risk	RAM/MW/HR	🟢 Full Map	🔴 Not quantified
Exhaust Characteristics	HR/RAM	🟢 Limits Validated	🔴 Site Limited
Hot/Cold Flexibility	MW/HR/RAM	🟢 Full Map	🔴 Site Limited
Load following Capability	Ramp Rate/RAM	🟢 Fully Quantified	🔴 Site Limited
Grid Code Compliance	RAM/Dispatch	🟢 Limits Validated	🟢 Grid Limited
Test Schedule Flexibility	Adaptability to new requirements	🟢 GE Control	🔴 Dispatch Control
Test Cost	Investment	🔴 Expensive	🟢 Potential Revenue
Test Stand Growth	Future Technology	🟢 Very Scalable	🔴 Limited to Site
Data Quality	RAM/Operability	🟢 High Quality	🔴 Limited in Field
Validation Date	Product volume	🟢 2 Years earlier	🔴 After COD

Table 2. Benefits of off-grid, FSFL facility vs on-grid prototype

Nearly 6,000 sensors and instruments collect data on all aspects of operation and components of the gas turbine during validation. This amounts to more than 8,000 data streams captured continuously during testing. Gas turbine performance is mapped over a broader operating envelope, than would be expected in a fleet of gas turbines connected to the grid. Isolation from the grid facilitates off-speed (90%-110% speed) operation over a range of equivalent loaded conditions. Variable speed also enables testing at ambient temperature equivalent to a range from -37°C to 50°C. Compressor flow and pressure capability can be measured under both steady-state and transient conditions. In contrast to the operating range of the fleet of more than 530 units, the tests conducted in the FSFL test facility characterized the new compressor over a much larger operating space as summarized in Figure 12.

This approach is recognized as providing product validation superior to a unit connected to the grid for 8,000 hours of operation, and is a key aspect of the commitments of insurability secured from major insurers.

Compressor aeromechanics are validated through use of strain-gauges and light probes applied along the flow-path. High cycle fatigue (HCF) drivers and response predictions are validated across the speed, load, ambient

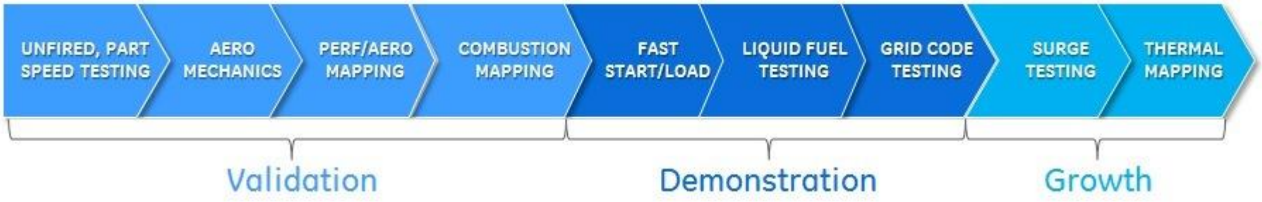


Figure 13. Standard Full Speed, Full Load validation plan

temperature, and operating pressure range. Loaded speed sweeps greater than +/-10% provide parametric sensitivities to frequency and operating condition variation, and validate the speed range a gas turbine would be expected to operate in the field. Modulation of the variable inlet guide vanes plus operation of back-pressure valves on the load compressor offers means to complete verification of the entire compressor map. The performance of multiple startups, shutdowns, and trips facilitates validation and verification of expected transient behavior.

The compressor surge lines are established based on actual surges. Surge margin is quantified by intentionally maneuvering the load compressor into a surge condition and monitoring the response. Multiple surge events are performed for each platform. Typically, this would not be possible on a gas turbine connected to the grid and provides additional verification of the system capability. Gas turbine transient events including grid events, fast and peaking starts, fuel transfers, and load rejections are performed under highly monitored conditions. These results also provided valuable feedback on the fidelity of analytical methods.

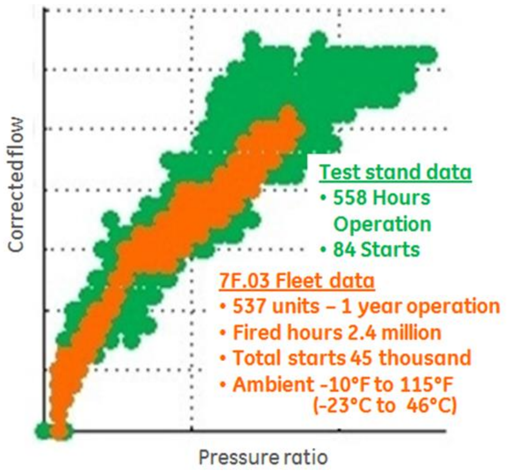


Figure 12. Full Speed, Full Load validation

The standard FSFL validation test plan and schedule are shown in Figure 13. The program is portioned into three sections: validation, demonstration, and growth. As noted, FSFL tests have been completed for the 9HA.01 and 7HA.01.

Validation includes extensive testing to provide measurements to support comparison with analytical predictions to validate the methods. For 9HA.01 and 7HA.01, agreement was excellent over the range of collected points. Several minor design modifications were made to the configuration as a result of the findings. The ability to immediately address and re-measure to validate effectiveness verifies benefit of the FSFL facility.

The demonstration phase built upon the off-grid capabilities for exercising the full operational capability. A large, heavy-duty gas turbine and, generally, associated combined cycle cannot be easily exercised without significant effort to maintain grid stability. The 9HA.01 and 7HA.01 gas turbines under test were rapidly loaded and unloaded at rates in excess of 15 percent per minute. Load rejections to equivalent breaker open conditions were performed from multiple operating points including base load.

Liquid fuel performance and operability were verified on the 9HA.01, including transfer capability. NOx levels on liquid fuel of lower than 25 ppm corrected to 15% O2 were demonstrated. Water injection is necessary to achieve this level of performance.

The growth phase of testing applies an even more extensive means of collecting hot gas path temperature information to understand the uprate potential for the platform over time. Significant testing was dedicated to exploring the growth capability of the HA gas turbine technology for future upgrades. Aeromechanic and aerothermal data are collected for operations up to 115 percent of rated output and firing temperatures over 55°C higher than the nominal baseload operation. Testing also includes varying the cooling supply to the hot gas path components to understand impacts on component temperatures and life capabilities. Owners and operators expect opportunity to increase output and efficiency by upgrading equipment over the life of a power plant. This expectation is well-evidenced by the history of both E-and-F-class gas turbine platforms. The overall results from the 9HA.01 and 7HA.01 programs are shown in Table 3.

Validation criteria	**9HA.01 capability**	**7HA.01 capability**
Turbine output	> 429 MW	> 280 MW
Turndown in emissions	< 30% BL	< 20% BL

guarantee		
Grid stability	+/- 3%	
Gas variation (Modified Wobbe Index)	+/- 15%	
	(lean-to-rich natural gas & LNG)	
NOx emissions at 15% O2	< 25 ppm	

Table 3. Summary of Capabilities from 9HA.01 and 7HA.01 FSFL Testing

5. OPERATIONAL AND FUEL FLEXIBILITY

Operational flexibility has become a necessary attribute for gas turbine combined cycles. Operational Flexibility is defined as the capability of a power plant to robustly maneuver to accommodate a wide range of power generation needs. This includes robust startup, rapid loading, prompt entry into emissions compliance, high ramp rates, deep turndown, grid code compliance, fuel flexibility, and overall eases of control. Fuel flexibility is a very broad term and has recently been detailed by Jones, Goldmeer and Moneti (2011) and Goldmeer (2015).

The 7/9HA gas turbines build upon aircraft engine technology to increase ramp rates while preserving efficiency for both base and part load operation. Achieving operational flexibility requires attention during development, utilization of field experience from operating plants, and utilization of a modern control system. By combining these elements, the HA products are capable of the following:

- Full plant load in less than 30 minutes from turning gear.
- Ramping capability in emissions compliance of greater than 15 percent load per minute.
- Deep turndown in excess of 30% of baseload output.
- Fuel flexibility with the capability to operate on both gaseous and liquid fuels. A wide range of gaseous fuels can be used, including rich natural gas (ethane, propane and butane), shale gas, lean natural gas (containing N2 and/or CO2 as inserts) and Liquefied Natural Gas (LNG).
- Fuel transfer from gas to liquid
- Return transfer from liquid to gas

Gas turbine combined cycles offer significantly better ramping or load following characteristics than other forms of large scale generation such as coal-fired boilers or nuclear plants. Deep turndown or ability to maintain emissions compliance to low loads combined with state-of-the-art DLN combustors enables the plant to meet strict emission limits during frequent transient operations. The 'Rapid Response', combined-cycle system was developed to provide the plant operating flexibility needed for immediate dispatch or load following services, as detailed by Smith (2013). Overall startup time is minimized by utilization of purge credit where traces of fuel from previous operation are flushed from the system by 'cranking' of the gas turbine following shutdown.

Plant controls are provided by GE's Mark VIe platform, developed specifically for power generation. The system can scale across applications ranging from gas turbine to plant-level control and protections. As with the accessories, the control system is modular to provide extended life and allow for future technology upgrades. The Mark VIe is a key element of GE's new Digital Power Plant as introduced by Reitenbach (2015).

6. PLANT CONSTRUCTABILITY, INSTALLATION AND MAINTAINABILITY

Gas turbine accessories for the HA gas turbines have been engineered according to the principal of 'Prime Packaging'. The gas turbine compartment and accessories have been modularized to achieve optimal constructability, facilitate installation, and simplify maintenance. Modules house piping, valves, electronics, lighting, instrument air lines, walkways and ladders. The modules can be completely fabricated and assembled in manufacturing areas where labor productivity and quality are optimal. Installation of the gas turbine and accessories is typically on the critical path for construction and commissioning of a power plant. Use of modularized accessories will reduce this portion of the commissioning process by at least 25 percent, enabling a faster commissioning and return on capital investment. Similarly, maintenance outage time is reduced by an equivalent amount enabling higher power plant availability. These modules are stacked on site in a building block manner around the gas turbine. The concept is shown summarized by Figure 14.

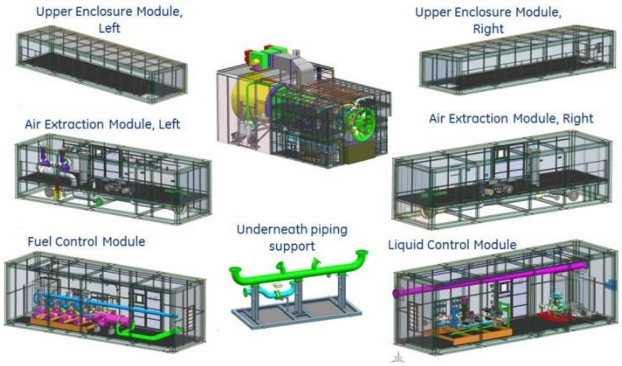


Figure 14. GT accessory modularization

7. 9HA.01 FLEET LEADER AT EDF BOUCHAIN

The first 9HA.01 entered commercial operation on June 17, 2016 at the Électricité de France (EDF) Bouchain plant, located in the Nord Pas-de-Calais region of France. This unit was manufactured at GE's Belfort Gas Turbine Center of Excellence in France. This plant was recognized by Guinness World Records as the world's most efficient combined-cycle power plant, as detailed by Larson (2016). Efficiency of this plant was 62.22% on a net combined cycle basis while producing more than 605 MW of electricity. Operational flexibility of the 9HA.01 gas turbine enables the plant to respond quickly to fluctuations in grid demand, providing opportunity for increasing usage of renewable energy in France. Approximately 1,000 hours of operation have been accumulated as of July 2016. The power plant is shown by Figure 15.

Figure 15. EDF Bouchain Power Plant

8. 7HA FLEET LEADERS AT NISHI-NAGOYA, EXELON WOLF HOLLOW AND COLORADO BEND

The fleet leaders for the 7HA.01 will be deployed at Chubu Electric Power, Japan. GE and Toshiba were awarded contracts in 2012 to supply and install six 7HA gas turbines for the combined cycle project being built at Chubu Electric's Nishi-Nagoya thermal power plant in Nagoya City, Japan. The 1x1 SS combined cycle plants are each rated at 405 MW and will operate with a 60 Hz world-record of greater than 61% net efficiency. GE began shipping units to Toshiba, the Engineering Prime Contractor (EPC), in February 2016. The first of these units is shown exiting the Greenville, SC manufacturing center as Figure 16. All six gas turbines are expected to be installed and operational by March 2018.

Figure 16. First 7HA.01 shipment to Chubu Nishi-Nagoya

Fleet leaders for the 7HA.02 have been manufactured and transported to Exelon's Wolf Hollow and Colorado Bend stations. Both plants are configured as 2x1 MS with gas turbine output of 330 MW per unit and total plant output of 1,000 MW. Modular construction detailed by Section 6 of this manuscript will enable shorter installation cycles with faster return on investment. Construction of the Exelon Wolf Hollow Power Station is shown by Figure 17. This station will achieve commercial operation in 2017.

Figure 17. Exelon Wolf Hollow 7HA.02 2x1 MS Power Station under construction

9. SUMMARY

The 7/9HA gas turbines achieve greater than 62% combined-cycle efficiency, net, at ISO conditions for the lowest cost of electricity. Economy and efficiency of scale are realized. Both Capital Expenditure (CAPEX) and Operating Expenditure (OPEX) are minimized by this combination of cost-effectiveness and state-of-the-art efficiency. Low OPEX is also enabled by the broad range of fuel flexibility offered for the 7/9HA gas turbines; plant owners can source fuel from the most competitive providers. F-class experience with gaseous fuels ranging from standard natural gas to LNG and rich or lean methane has been built upon to provide a similar capability for the 7/9HA's.

The product family represents a merging of pioneering H technology with greater than 40 million hours of F-class experience. Products serve both the 50 and 60 Hz regions with the 9HA and 7HA, respectively. Both are available in two output sizes for varying block size needs. Speed scaling was applied to develop the 7HA from the 9HA, and flow scaling was applied to increase output by over 15% for the ".02's" versus the .01's.

Turbine architecture has been simplified by elimination of the 7/9H steam cooling and cooled cooling-air. The hot gas path is entirely air cooled, as enabled by advances in turbomachinery technology. Proven materials and coatings are utilized to ensure reliable operation. Development and engineering of the 7/9HA gas turbines has been accelerated by synergy with our Aviation business and Global Research Center. Looking forward, these pipelines of technology development are available to offer continuous improvements over the product life-cycle.

The off-grid, FSFL test facility required major investment, but has been justified by the collection of extensive validation data and learning. Results verified performance and demonstrated capability to achieve operational flexibility and reliable operation over the lifecycle of the power plant.

Attention has been focused on plant constructability and maintainability resulting in the development of a wholly pre-engineered and packaged set of accessories. These advances accelerate construction scheduling and improve maintenance outage productivity.

The first 9HA.01 achieved commercial operation at the Électricité de France (EDF) Bouchain plant. This plant was recognized by Guinness World Records as the world's most efficient combined-cycle power plant. Efficiency of this plant was 62.22% on a net combined cycle basis while producing more than 605 MW of electricity.

The first 7HA.01's will achieve commercial operation by March 2018 at the Nishi-Nagoya power station in Nagoya City, Japan. The first 7HA.02's have been assembled and transported to Exelon's Wolf Hollow and Colorado Bend stations, both in Texas, USA.

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