GE Power

HA GAS TURBINE

Validation of the HA Gas Turbine Platform

HA GAS TURBINE

Validation of the HA Gas Turbine Platform

GE's heavy duty gas turbine systems are built on years of innovation and backed by proven, reliable technology. Since the 1940's, GE has been developing and testing aircraft engines and gas turbines—evolving two industries and creating new platforms to concurrently enhance performance and reliability.

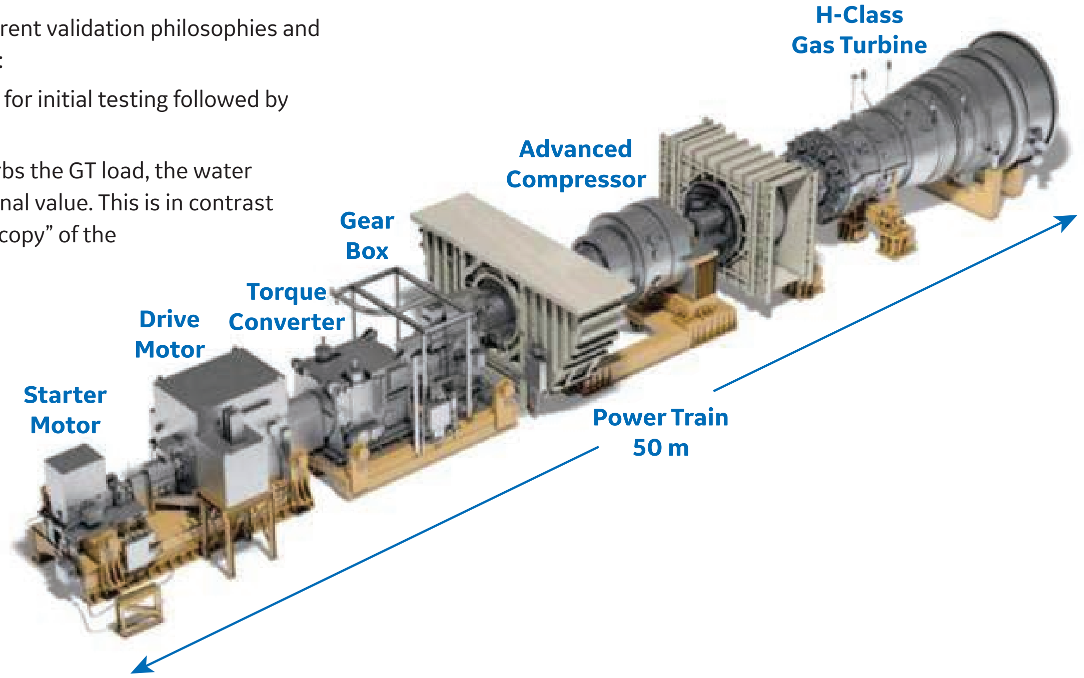
World's Most Comprehensive Validation Capability

In 2008, GE developed the world's largest and most comprehensive full-speed, full-load (FSFL) gas turbine test facility located in Greenville, South Carolina, USA. The objective of this significant achievement is to be able to support, prove, and accept the accuracy of the technical parameters of our gas turbine fleet. Therefore, this off-grid, world-class, $200 million facility provides full-scale validation of 50 and 60 Hertz gas turbine systems. Here, GE performs comprehensive off-grid testing with superior load response and full over/under frequency testing capability beyond the typical grid-connected installations. The range of operating conditions and data obtained from the gas turbine and its systems exceeds the bandwidth of the entire F-class installed fleet operating data, and is equivalent to multiple units running over 8000 hours with full instrumentation.

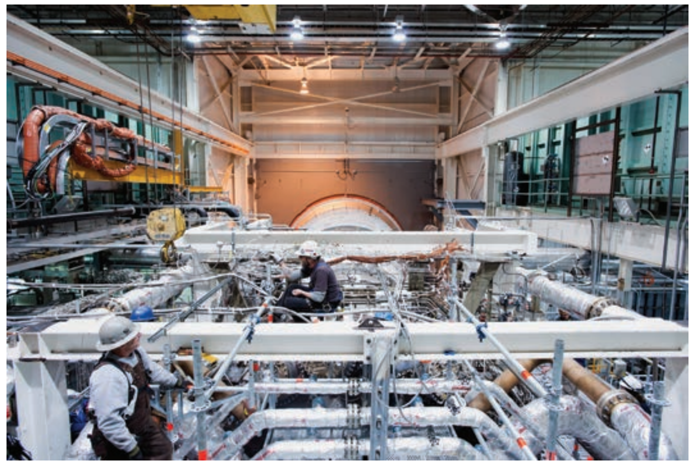
During validation, over 6,000 sensors and instruments collect data on all components of the gas turbine through all aspects of operation. This amounts to capturing more than 8,000 data streams continuously during testing. It includes: capabilities at different load profiles; ambient ranges; over/under-frequency; and transient load changes on both gas and liquid fuels. This world class facility and comprehensive testing approach are a unique way to recognize the acceptance of GE gas turbines to global requirements for grid code response and operability features.

Other OEMs have somewhat different validation philosophies and facilities with inherent limitations:

1) A water brake as a load source for initial testing followed by a grid connected test project.
   a) While the water brake absorbs the GT load, the water brake itself offers no additional value. This is in contrast to GE's approach of using a "copy" of the GT compressor as the load absorbing device. Therefore, the compressor is also a test article providing a more rigorous validation of the compressor.
   b) Water brakes have challenges with respect to precise control of load. This means that there is uncertainty in the performance of the gas turbine as there is uncertainty in the load being applied.
   c) Water brakes are often restricted from getting to full load levels. This means that the gas turbine cannot always be run to full load conditions.
   d) After water brake tests are complete, additional testing is done in the field to more thoroughly validate the gas turbine design. Test learnings in the field that require hardware changes could significantly impact the commercial operation of the launch unit.
2) A dedicated, grid connected test facility with extensive hours at less than full load.
   a) Being grid connected restricts testing at the facility to 60 Hz platforms. Any 50 Hz platforms require extensive grid connected testing in the field during the launch project.
   b) Being grid connected requires that the gas turbine must be run at 3600 rpm. This means that any design robustness issues that are sensitive to running speed cannot be identified. In addition, varying running speed is a surrogate for varying ambient temperature. Running at fixed speed means that only the actual ambient conditions at the site can be tested.
   c) Operation at part load limits the ability to understand the platform boundaries, leaving the possibility that future applications of the platform may experience operating conditions well beyond what has evaluated in the test facility.



In 2012, GE's 7F.05 gas turbine was validated in the FSFL test facility with this robust approach. The test results impressed customers and industry partners, who subsequently committed to this technology with over 65 units sold prior to the first 7F.05 in the field entering into commercial operation in 2014. Successful commercial operation then took place on both gas and light crude fuels at multiple sites around the world, confirming the robustness of GE's comprehensive testing methodology.



The 7F.05 fleet in commercial operation has grown to 36 units with over 162,000 fired hours of operation and over 3,200 fired starts as of April 2017. The fleet leader has operated approximately 13,100 hours, or roughly 55% of the first Hot Gas Path Inspection (HGPI) interval for this unit. Fleet reliability and availability levels of 99.54% and 98.64% demonstrate the success of the validation strategy: rigorous testing to take the platform beyond normal operating boundaries, evaluation of data to learn where to make improvements, and validation of the improvements.

Number of Units	Number of Unit-Years	Reliability	Availability	Total Operating Hours
4	5.78	99.64%	98.68%	50,616

Note: Values shown are Simple Cycle Plant scope, or SCP (GT+GEN+SC BOP).

Introduced in 2012, the 7F.05 Heavy Duty Gas Turbine was the first GE gas turbine to complete both the compressor validation testing (2011) and Full Speed Full Load (FSFL) testing (2012) at the test facility in Greenville, SC. Since that testing was successfully completed, more than seventy (70+) units have been ordered making the 7F.05 the fastest growing gas turbine fleet in the last decade. The rapid adoption of the technology improvements and orders growth is directly correlated to the demonstration of the engine's capability. The validation testing provided the learning and the confidence in the technology for the rapid deployment of the fleet. The 7F.05 core architecture is a technology evolution of the largest fleet of gas turbines in the world. Because of this evolution, and the rigorous validation testing, the 7F.05 is expected to continue to out-perform the 7F fleet statistic data found in third party reports such as ORAP®. According to the published ORAP® report for the last 12 months (January to December 2016) the 7F fleet has industry leading reliability of 98.33% and availability of 91.95%.

As the next advanced gas turbine platforms evolved, GE has validated several platforms at the full load, full speed validation facility:

- 9HA validation took place from October 2014 to March 2015
- 7HA.01 validation took place from October 2015 to February 2016
- 7HA.02 validation took place from September 2016 to May 2017.

Extensive mapping of all systems and controls was performed: 90-110% speed, ignition to 155% load, and ambient temperature equivalents from -37°C to 85°C (-35°F to 185°F). This testing was observed by many customers and industry partners, such as Insurers, Investors, and EPC's

Selected capabilities for the 9HA and their proven results are shown in the table below:

9HA.01 Performance Criteria	Validated Capability
Turbine Output	>401 MW
Turbine Net Heat Rate (LHV)	<8,612 KJ/kWh <8,162 BTU/kWh
Exhaust Energy	>2,011 MM kJ/hr >1,906 MM BTU/hr
Turndown in Emissions Guarantee	30% of Baseload
Sudden Load Step (GT)	+/-20%
Block Load Rejection	Base to 55% Load
NOx Emissions at 15% O2	<25 ppm
Gas Variation (Modified Wobbe Index)	Up to +/-15% (Rich to Lean Gas Fuel)
Full Plant Load	<30 Minutes
Turning Gear to FSNL	<11 Minutes
FSNL to FSFL	<12 Minutes

These not only demonstrate gas turbine systems and control capabilities, but also confirm the design methods and tools, along with the growth potential of the HA platform.

HA GAS TURBINE

Validation of the HA Gas Turbine Platform

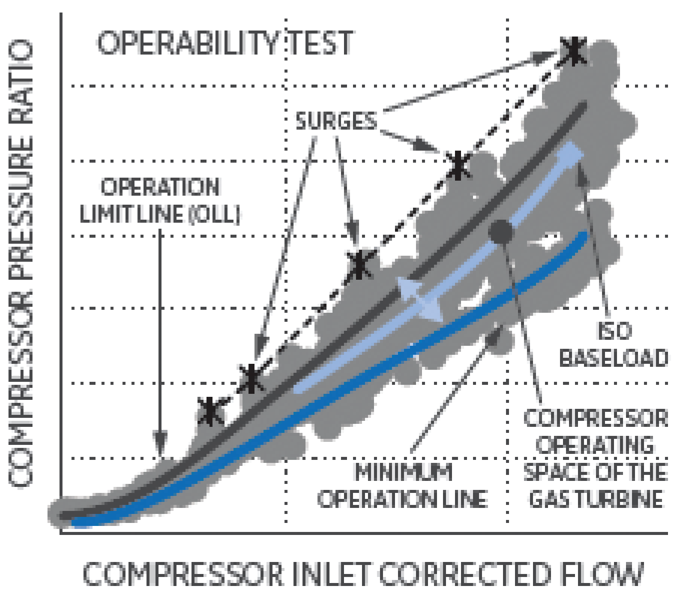
Wide Compressor Operability Demonstrated

The 7F.05 compressor (validated in 2011) is the basis of the 7/9HA compressor, updated with a cooling flow extraction for the third stage of the turbine. Compressor aeromechanics were proven through:

- Strain-gauges and light probes
- HCF drivers and responses for speed, load, ambient temperature, and frequency variation
- Loaded +/-10% speed sweeps performed across IGV/Load range; providing data relative to part-load, frequency and operation variation
- Multiple start-ups, shutdowns and induced trips evaluated
- Surge line defined based on actual controlled forced surge maneuvers

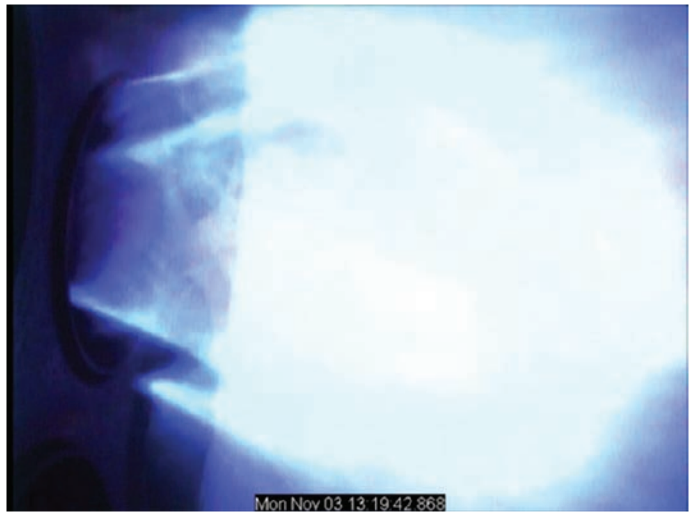
A key compressor measure, the Operation Limit Line (OLL) is defined to maintain margin to surge. Results shown below illustrate the wide operating range relative to tested limits of the HA compressor, which far exceed what could be run during on-grid validation.

9HA Compressor – Test Stand

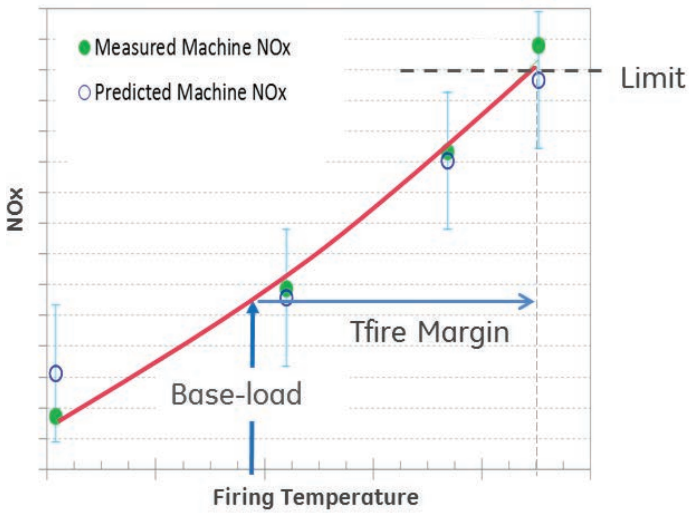


Wide Gas Combustion Capability Validated

The HA combustion system is based on the DLN 2.6+, which has over 2.9 million hours of experience, with simplified fuel staging and enhanced liquid fuel system architecture. Validation results demonstrate reliable ignition, cross-fire, acceleration, and loading on both gas and liquid fuels. Below is the HA DLN 2.6+ combustion system as viewed from the side, showing how the lean, premixed flame is structured and stabilized.

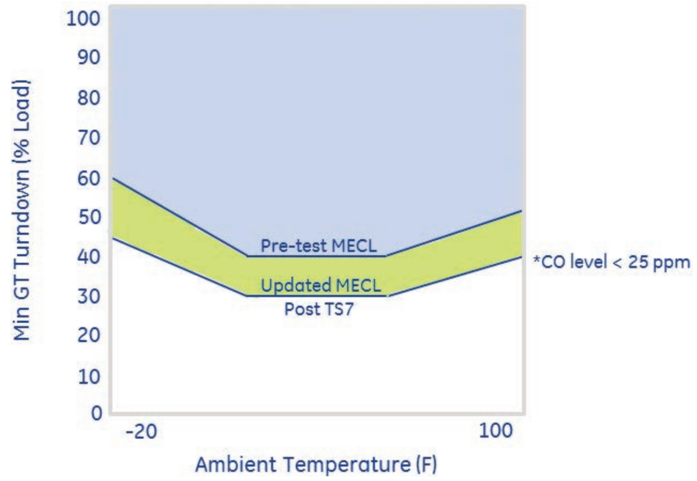


A wide range of fuel gas modified Wobbe index (MWI – the relative measure of the energy injected to the combustor at a fixed pressure ratio) has been achieved, which signifies the ability of the HA gas turbine to operate on both lean and rich fuels. A plot of the measured gas turbine NOx levels as validated ensures emissions are below allowable limits and support continued firing temperature increases for improved heat rate.



Turndown Capability Validated

Turndown below 30% GT load in terms of Minimum Emissions Compliant Load (MECL) at 25ppm CO and NOx was demonstrated, and mapping results have been used to improve the fidelity of the combustion emissions models to quantify guarantee-able MECL at extreme ambient temperatures and for customer-specific emissions requirements.



Turbine Aerothermal Capability and Durability Validated

The 4-stage, air cooled hot gas path of the HA is based on over 50 million hours of experience of F and H class gas turbine operation. Proven alloys, thermal coatings and superior cooling schemes are used for the buckets, nozzles and shrouds.

The HA hot gas path and turbine rotor capability and durability are substantiated through extensive monitoring of temperature, pressure, strain and vibration gauges on static and rotating components. Temperatures are also confirmed by using state-of-the-art techniques to understand contours between instrumented thermocouples. Steady state and transient data, along with detailed thermal and structural models are used to verify low cycle fatigue (stress/strain induced), high cycle fatigue (vibration induced), and creep capabilities (strain at time and temperature) of the turbine components and rotor.

Also proven are the performance and operation of the rotor sealing and passive clearance control systems. The turbine rotor after validation testing is shown next.

Robust Architecture

The extensive testing performed on the 9HA (and 2015 testing of the 7HA) recognizes the legitimacy of the gas turbine architecture with regard to short and long term mechanisms. The test plan enabled simulation of high cycle fatigue due to grid events but also low cycle fatigue and creep due to stress and temperature variations. Sensors located at key components confirmed the thermal gradient and stress analyses and their interaction. As such the 9HA architecture demonstrated the expected robustness and was validated from a lifecycle perspective.

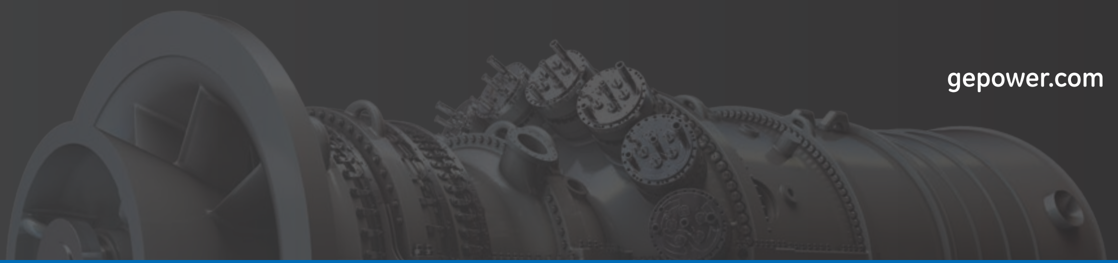
Global Grid Code Capability Demonstrated

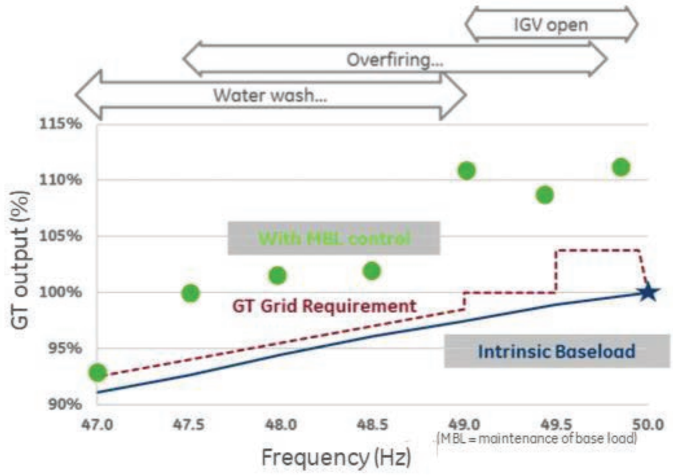
The off-grid validation facility allows unique testing against global grid code requirements through effective full over/under frequency capability. This includes frequency control, load control, and load rejection to house load.

Frequency response of the 9HA gas turbine is demonstrated by the following:

- Load step changes from -70 MW to +65 MW
- Initial Loads from 50-90%
- All events contained with margin to requirement

Finally, the ability to maintain base load is confirmed through inlet guide vane, firing temperature, and water wash power augmentation.

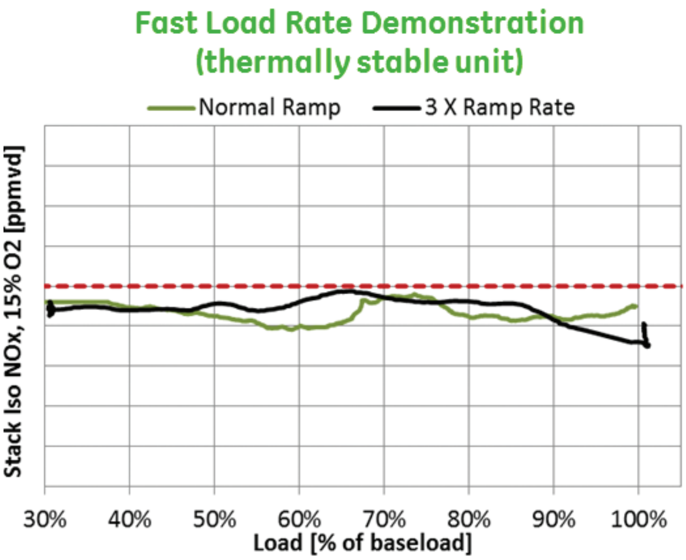




With this, the HA gas turbine is validated at and beyond compliance to the world's most stringent grid code requirements to date. This is significant and unprecedented in the industry, and only possible with GE's full load, variable speed facility that operates off-grid.

Fast Loading Validation

The 9HA gas turbine is subjected to extreme acceleration and loading rates to gather engineering data. GT load rates within emissions compliance above MECL exceeding 60MW per minute have been demonstrated.



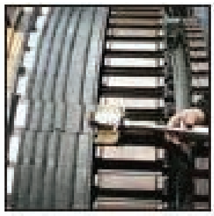
Validation Beyond the Design Envelope for Growth

Significant testing time is dedicated to exploring and determining the growth capability of the HA gas turbine technology for future upgrades. In addition to the compressor operability data collected, aeromechanic and aerothermal data for operating at 115% of rated output and firing temperatures over 55 degrees C (100 degrees F) higher than nominal base-load operation is gathered. Testing also includes varying the cooling supply to the hot gas path components to understand impacts on component temperature and life-cycle capabilities.

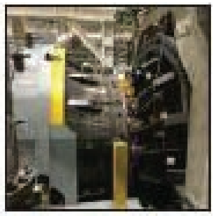
Major Outage Procedures and Tooling Validated

At the completion of the validation testing, a major outage was conducted by GE's Power Generation Services to authenticate field tooling and outage procedures. The turbine inner/outer shell and all combustion and hot gas path parts were removed for engineering evaluation. Parts were reinstalled with the addition of alternative technologies for evaluation to support future systems growth. The outage provided field experience that has been used to train field personnel and prove maintainability and outage durations for the HA fleet.

Flow Sleeve Removal



Rotor Seal Removal Tool



ITS Rollout Tooling

7/9HA Gas Turbine System Validation Summary

Months of validation equals proven results which exceed expectations for performance, operability and emissions. Gas turbine data thus obtained is also fully supportive of plant level combined cycle performance and operability guarantees which depend on exhaust energy to the bottoming cycle. This has been achieved through GE's proactive testing approach coupled with extensive measurement, which is possible only with the world's largest full load, variable speed test facility. Recognized by US Exim, insurers, and owners/bank engineers as evolutionary and proven, the 7/9HA gas turbine is validated over a wide range of ambient conditions, and during real over- and under-frequency events — a first for the industry. Growth capabilities of the complete HA portfolio are reliably established for continued advances in reliably lowering the cost of converting fuel to electricity and heat.

GEA32162A (07/2017)