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Tuning Approaches for DLN Combustor Performance and Reliability

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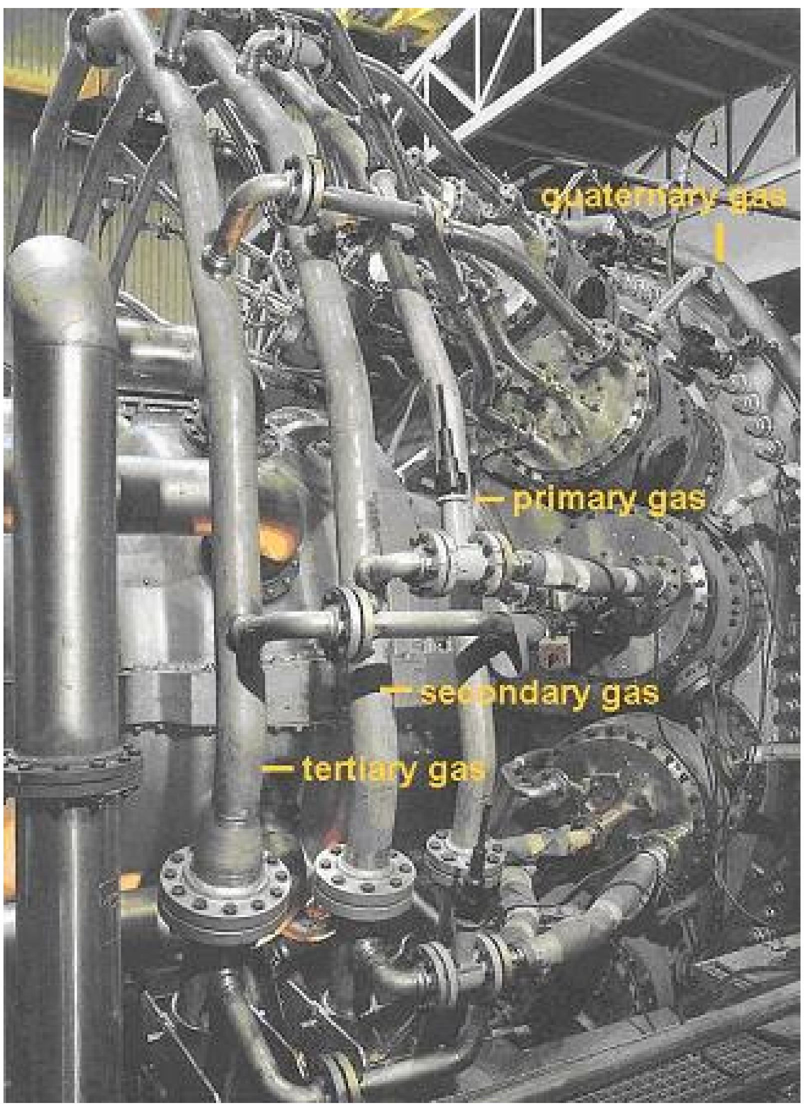

Tuning Approaches for DLN Combustor Performance and Reliability

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Technical Update, March 2005

EPRI Project Manager

L. Angello

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REPORT SUMMARY

Background
Dry low NO_x (DLN) technology eliminated the need for water or steam injection in gas-fired combustion turbines (CTs) by operating at lean fuel conditions. However, DLN burners are susceptible to dynamic pressure fluctuations in the combustion chamber. Severe hardware damage in the combustion chamber structure and potentially in the turbine can occur depending on the frequency and amplitude of these pressure fluctuations and if they are not quickly reduced. Stable combustion in gas turbines is critical to guarantee the turbine's reliability, availability and to attain maximum component endurance. Development of protective systems was necessary to ensure fast response to the onset of combustion dynamics. The protective systems compare some features of the pressure pulsations with pre-determined settings to trigger either a load shedding or trip the unit according to the severity of the fluctuations. These settings are typically excessive and conservative to ensure safe operation and may result in unnecessary interference by the protective system and disruption of efficient operation. Therefore, the determination of settings that activate alarms, induce load shedding or cause complete trip is very critical to the economical operation of the gas turbine. Automated control system would be much more effective in responding to combustion dynamics and minimize the occurrence of such events. Thus, operators often need to remain proactive in preventing onset of excessive pressure oscillations and combustion-induced vibrations and flame instabilities. The phenomenon of combustion instability has afflicted a wide range of ultra low-NO_x combustion systems. Today, combustion instability is viewed as the major challenge facing the CT industry.

Objectives
The primary objective of this report is to describe the combustion tuning techniques employed for utility gas turbines to mitigate the adverse effects of combustion dynamics. With the increased deployment of combustion dynamics monitoring instrumentation, owners/operators of utility gas turbines can be proactive in tuning the combustion to maximize engine reliability, extend inspection intervals and the life of critical component parts while also meeting today's stringent NO_x emissions regulations. This report is the second in a series on the subject of dynamics monitoring and combustor tuning for enhanced operational flexibility and for minimizing onset of acoustic vibrations (humming) and combustion instabilities.

Approach
For this project, EPRI consulted with experts in combustion dynamics; reviewed the publications on; a) commercial and novel monitoring instrumentation and methods, and b) reported experience on diagnostics of combustion instabilities and application of tuning techniques; visited selected plants for a survey of OEM and self-implemented monitoring equipment and instrumentation; and undertook a long-term collection and analysis project for pressure dynamics data on a GE FA Class machine to highlight statistical analysis techniques that can define the pressure dynamic signatures of combustors which define "safe" operating regimes of modern ultra low-NO_x machines.

Results

Combustion dynamics tend to increase as combustion conditions become leaner. Although combustion dynamics are engine model and DLN design-specific; the narrow tolerances required for ultra low NO_x combustion require that all DLN systems to be tuned on a periodic basis. Combustion dynamics monitoring systems (CDMS) are used in tandem with emissions data from continuous emission monitors (CEMs) and engine supervisory data to identify onset of combustion dynamics and pinpoint combustors needing adjustment or repair. Excessive pressure amplitudes in selected frequency bands, each characteristic of specific engine class and DLN design, can point to specific fuel distribution adjustments that, though minor, can prevent damaging vibrations and safeguard continuous operation. Combustion tuning is particularly important following replacement of key burner parts, especially refurbished parts which must often be subjected to calibration testing to ensure compliance with design specifications and matched with other combustors in the engine. Combustor designs that have the capability for stable diffusion pilot flames, as a fraction of the overall fuel dedicated to fully premixed combustion, tend to provide improved combustion stabilization. Also, combustors that have multi-gas fuel systems, such as GE DLN 2.0 and 2.6 designs, provide greater flexibility for combustor adjustments during periods of increased dynamic oscillations. The wealth of information possible with CDMS data provides the potential for greater and more precise interpretation of combustion conditions and the development of active controls and online diagnostics for optimum engine performance and reliability.

EPRI Perspective

OEMs and independent developers of DLN combustors have made and continue to make significant strides toward greater suppression of NO_x formation. The need for dynamics monitoring and combustion tuning is increasingly accepted as a condition for operation of DLNs with single digit NO_x emissions. CDMS provide key data on the integrity of high temperature equipment and can point to specific actions needed to neutralize potentially damaging dynamic oscillations. Automated combustor tuning also promises to be an important avenue future research for managing combustion dynamics and reducing inspection and maintenance costs.

Keywords

Gas Turbines

Dry Low NO_x Combustors

Combustion Instabilities

Combustion Dynamics

Combustion Tuning

Pressure Transducers

Combustion Monitoring

ABSTRACT

The phenomenon of combustion dynamics (CD) is accepted as one of the most important operational challenges facing the gas turbine industry today. Modern DLN combustors must operate within tight tolerances of fuel/air ratio, fuel/air mixing and heat release rate in order to deliver single digit NO_x performance with combustion stability and design power output. Changes in ambient temperature, humidity, and fuel composition can lead to the onset of combustion instabilities, pressure pulsations, and resonant acoustics, also referred to as humming. Large pressure pulsations can cause degradation and catastrophic failure of hot section components and loss of peak power production. Without immediate operator's intervention and periodic combustion tuning, dynamics in lean premix low NO_x combustors can result in emergency shutdown with significant lengthier and costlier repair down times. In response to these operational risks, many new combustion turbines (CTs) come equipped with piezoelectric pressure transducers to monitor dynamics in each combustor. In regions subject to broader changes in ambient conditions, the monitoring retrofit of some low NO_x CTs has been advocated. Combustion Dynamics Monitoring Systems (CDMS), available from OEMs and independents, can provide evidence of the impending and unsafe pressure fluctuations as well as online diagnostics for preventive maintenance. The frequency and pressure amplitude signals from these CDMS coupled with engine emissions and supervisory data provide a wealth of information on the health of low-NO_x combustors. EPRI has undertaken a program to document the equipment and methods for monitoring and controlling the onset of combustion dynamics and to map the operating regime for stable combustion in modern DLN combustors. This is the second in a series of reports on the subject. The first report was released in March 2004, *TR-1005036, Guidelines for Combustor Dynamic Pressure Monitoring*, which describes available dynamics monitoring and data analyses approaches. This second report presents combustion tuning practices and guidelines implemented in response to the onset of combustion-induced dynamic instabilities and CT noise. Follow-on reports will focus on analyzing long term data to provide more specific operating guidelines that are applicable to the development of active controls and are consistent with anticipating, preventing, and effectively responding to dynamic instabilities.

ACKNOWLEDGEMENTS

This project was the result of multiple technical inputs from key individuals. EPRI would like to acknowledge the following individuals and their organizations:

a) Glenn Baker and John Brooks of Control Center who provided general industry practices on CDMS and combustion tuning and information on their SpectraMon™ system

b) Adriaan J.L. Verhage of KEMA contracted by EPRI analyze long-term dynamics data from a 9FA DLN 2.0 and identify controlling variables

c) Dr. Ephraim J. Gutmark of Gutmark Research Associates (GRA) who reported experiences with modern combustors and tuning approaches principally on GE 7FA class and Alstom and Siemens/Westinghouse units

d) Mike Dwyer and Dan Turley of Portland Gas and Electric (PGE) Company who hosted EPRI to demonstrate in-house procedures implemented to monitor and avert damaging combustion dynamics in a 7FA machine

e) David Saad of Progress Energy for his technical insight and experience in CDMS operation and combustion tuning

f) Mike Hoy of TVA who provided technical data on protocols for DLN-1.

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1 INTRODUCTION

Over the past two decades, the CT industry has introduced major innovations in dry low-NO_x (DLN) combustion technologies into modern utility power turbines to achieve significant reductions in NO_x emissions. Although the federal EPA requirement for utility CTs is at 25 ppm (by volume dry, corrected to 15% O_2), several State and local regulations such as those California, Texas, and other states with current ozone attainment schedules, impose much more stringent NO_x emission limits. These State and local regulations often require low “single digit” NO_x emissions for gas firing, based on the capability of modern lean-premix combustors with 9-ppm performance, often coupled with selective catalytic reduction (SCR) for compliance with even lower NO_x emissions, e.g., 3-5 ppm.

The design of combustors for sub-25 ppm NO_x emissions, and especially 9-ppm emissions, relies on the lean premix technology operating at low equivalence ratio (fuel/air), which lowers peak flame temperature (where Thermal NO_x is formed) and reduces the residence time at peak temperature (Snyder et al. 1993). Premixing is achieved by injecting the fuel into the compressed airflow downstream from the compressor before entering the combustor. Usually, fuel and air mixture before enter the flame zone via a swirling device that also provides part of the flame stabilization mechanism. The flame is stabilized partially by the aerodynamic recirculation zone produced by the vortex breakdown of the swirling flow and partially by recirculation regions downstream of the sudden expansion at the combustion inlet (dump plane).

Greater Thermal NO_x suppression is achieved by lowering the equivalence ratio of the combustible mixture. However, as this occurs, the flame becomes less stable and CO emissions can increase dramatically, indicating incomplete combustion. The regime of combustion instability is reached as the flame speed in the mixture is reduced excessively in relation to the inlet velocity. This condition is normally referred to as Lean Blowoff Limit (LBO). LBO is often preceded by axial and trans-axial pressure pulsations that result form complex interactions between turbulence, mixing and jet velocities. These instabilities-induced pressure pulsations can resonate with the combustor enclosure producing the notorious humming experienced in some CTs, which in turn can further amplify the instability effect and cause severe hardware damage.

This section provides a brief summary of the mechanisms of combustion dynamics and potential damage if left unattended. EPRI’s first report on dynamic monitoring (TR-1005036) and several references in Appendix A provide added detail on the onset of combustion dynamics and impacts on the operation and design of modern DLNs.

Combustion Dynamics

Combustion instabilities, sometimes referred to as pulsations, humming (low frequency), screech (high frequency) or dynamics are considered to be the one of the major problems that the gas-turbine industry faces today (Lieuwen and Zinn 2000). Rapid oscillations in the rate of heat release can occur when the premixed combustion charge approaches its flammability limit (the point when stable combustion is no longer self-sustaining. Figure 1-1 shows the flammability limits of a premixed methane/air charge with self-ignition (Joos et al. 1996). The lean blow out (LBO) typically corresponds to an equivalence ratio of 0.5 and is only weakly dependent on pressure. In lean premixed systems, the fuel concentration is low (corresponding to the left side of the chart). Therefore, as equivalence ratios are lowered in the quest for greater NO_x reduction, the potential for lean blowoff and onset of combustion dynamics increases. As the temperature is increased the flammability range widens, and at a sufficiently high temperature, self-ignition of fuel occurs. Thus, when the combustion air temperature is lowered, say with a drop in ambient temperature, the mixture becomes less flammable and more likely to become unstable, especially at low equivalence ratios.

Ignition time also increases exponentially as shown in Figure 1-2. At extremely low equivalence ratio, even small changes in air or fuel flows can induce a sequence of rapid changes in ignition time, affecting the heat release rate as indicated by the mathematical relationship.

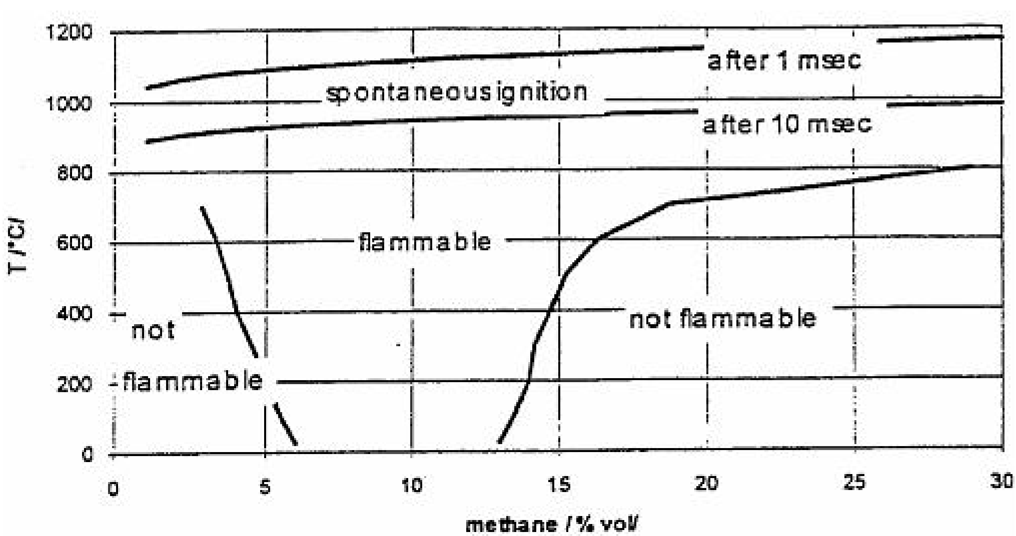
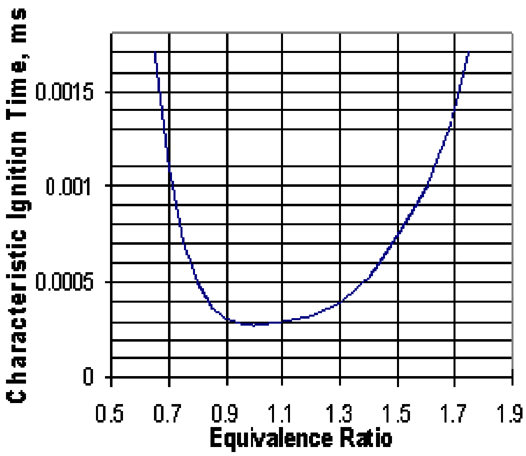


Figure 1-1
Flammability Limits and Self-Ignition at 15 Bars and Stoichiometric F/A Ratio with Methane

Externally induced pressure pulsation can also initiate or add to pressure fluctuations in the combustion chamber. For example, oscillations in fuel delivery pressure to the combustor will create heat release fluctuations, which can translate to further changes in fuel supply pressure at the nozzle. Additionally, small changes in natural gas composition will also affect fuel kinetics and heating value with a resultant change in heat release rate and flame temperature. Unsteady heat release from the combustion process can cause large amplitude pressure pulsations in the combustor (Keller 1995).

Reductions in ambient temperatures also lowers fuel/air ratio and heat release rate affecting combustion stability at already low equivalence ratios. In fact, significant dynamics in selected combustors has occurred during large reductions in ambient temperatures bringing fuel equivalence ratios to the zone of instabilities. These are then exacerbated by pressure pulsations in the chamber, which affect the flow of fuel.



$$\left\{\begin{array}{l}\text{Rate of}\\\text{Heat}\\\text{Release}\end{array}\right\} \propto \left\{\begin{array}{l}\text{Reaction}\\\text{Rate}\end{array}\right\} \propto 1/\tau_{chem}$$

Figure 1-2
Exponential Dependence of Ignition Time on Equivalence Ratio

Our review of the literature and experience to date on combustion dynamics has revealed several causes that are attributed to the onset of equipment-damaging dynamics and resonant acoustics. Among the more frequent causes of combustion dynamics reported over the past two decades are:

- Unstable early designs DLN combustors having severe dynamics flaws
- Variations in manufacturing tolerances of key combustor components for new and refurbished parts
- Progressive degradation of key combustor components resulting in variations among combustors
- Ambient conditions, principally ambient temperature and humidity affecting all or selected combustors
- Improper combustion tuning without considerations to some of the factors described above
- Fuel quality variations

There are three approaches available in dealing with the onset of combustion dynamics. The first is to optimize the combustor and nozzle design to increase flame stability limits. Understanding the driving mechanisms of combustion instabilities is essential for incorporating into the design stages of the gas-turbine engine passive or active control methods that eliminate or mitigate their effects. For example, passive control methods could include changing the combustor, burner or flame holder geometry, modifying the air or fuel injection and distribution pattern, or implementing acoustic damping liners, baffles, and resonators (Schadow and Gutmark 1992). For example, OEMs and other independent combustor vendors and researchers have incorporated various nozzle design techniques to provide the most stable injection by segmenting the total fuel and air entering the combustor in strategically located geometries, which often adjust with turbine load, as the total heat input changes. (Putnam 1971, Candel 1992, Kailasanath, and Gutmark 1998).

The second and third approaches rely on CDMS technology to monitor pressure pulsations in each chamber. In a passive control system, the CDMS is used for online diagnostics to alert the operator to excessive pulsations. This is by far the most popular approach used today. In an active control system, which is advocated by some OEMs, CDMS signals and engine supervisory data are sent to control centers, which use available expertise and historical data on dynamics signatures to pinpoint problems and corrective actions. These are either communicated to the plants for implementation or controls are activated remotely without operator intervention.

More recently, active control technology was developed for suppression of combustion dynamics. Active control is usually achieved with a feedback control loop that includes processing of a signal provided by a sensor that is monitoring the heat release by the flame or the pressure oscillations in the combustor. The processed signal is fed back to an actuator that modulates the air or fuel flows (Candel 1992, McManus et al. 1993). While various active control methods were demonstrated successfully in laboratory environment and were even attempted in large-scale gas turbine rigs, many unresolved problems still remain before they can become a reliable practical solution to thermo-acoustic phenomena. Current monitoring systems often rely on passive controls with combustion tuning implemented during periods of anticipated increased susceptibility to combustion dynamics or following changes to combustor hardware.

Impact of Combustion Pulsations

Combustion instabilities deteriorate the engine performance and reliability, and increase the frequency of required service. Combustion instability can cause flashback, flame blowout due to an increase in the LBO limit mixture ratio, starting problems, damage to combustor hardware, switchover problems, High Cycle Fatigue (HCF) of hot gas path components, and Foreign Object Damage (FOD) to turbine components. In the worst case, system failure can occur due to extensive structural damage and loss of control. Because of increased awareness of the sources and effects of combustion dynamics (CD), many of the early catastrophic failures experienced with early DLN designs have been largely reduced in intensity and frequency. In fact, considerable effort has been invested by gas-turbine companies, academia, and government agencies to study the mechanisms that drive these instabilities, identifying the conditions under which they occur, and developing practical approaches for their monitoring and control, either passively or actively.

Figure 1-3 illustrates damage to one of the five nozzles of a DLN-2.0 combustor that resulted from flashback episode following periods of combustion humming. The damage to the pilot nozzles caused fuel to leak from the side of the nozzle. The presence of the added diffusion flames during the fully premixed operating mode of the DLN 2.0 was detected by an increase in NO_x emissions. The DLN-2.0 combustor is a GE interim combustor design that has lower combustion stability at NO_x levels below 15 ppm compared to the more modern GE technology used in DLN-2.6. The higher susceptibility of the DLN-2.0 to combustion dynamics at low NO_x is due in part to its fully premix operation mode at full load. In comparison, more stable GE DLNs operate in a partial premix mode with a controlled flow pilot diffusion flame for greater combustion stability.

Figure 1-3
Nozzle Tip Burnout due to Flashback

The damage from combustion dynamics can easily extend to other high-temperature components. Figure 1-4 illustrates the damage on a cracked liner, the result of transaxial low frequency (<200 Hz) vibrations.

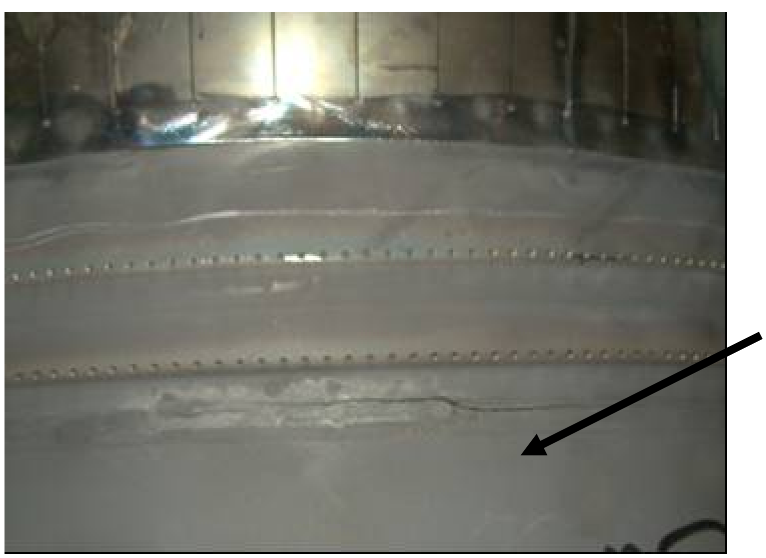


Figure 1-4

Combustor Liner Damage due to Vibration Stress

Some engines have been more susceptible to CD-induced damage than others. In some cases, the damage can be severe. The location of the initial failure is often dependent on the resonant characteristics of the particular hardware. For example S/W 501F engines have suffered numerous cases of transition piece failures. Also, early versions of Alstom GT24 EV burners have caused severe instabilities and equipment damage in some installations. Once CD-induced damage occurs to combustors and transition pieces, the resulting debris will create havoc to turbine blades. Figures 1-5 and 1-6 illustrate the varying degrees of severe vibration damage to early designs of transition pieces and damage to first and second stage blades of an affected S/W 501F engine. Recent modifications introduced by the OEM and other vendors to S/W Premix Combustor (SWPC) and 501F transition pieces and EV burner designs in GT-24 sequential firing have significantly improved the performance and reliability in these engines.

Figure 1-5
Complete Failure of Transition Piece and Evidence of Excessive Metal Temperature

Figure 1-6
First and Second Stage Blade Damage from CD-Induced Failure of S/W 501F Transition Pieces

2 MONITORING AND ANALYSIS OF COMBUSTION DYNAMICS DATA

Because of potential cost impact and other maintenance needs of CD-induced vibrations, all modern DLN-equipped GE, Alstom, and S/W gas turbines come equipped for ready mounting of CD sensors for intermittent measurement and burner tuning. OEMs perform tuning in the commission stage and after a major overhaul. For these intermittent tuning requirements, a permanent monitoring system may not be required. However, most OEMs also offer remote monitoring, diagnostic and tuning of modern combustors with the permanent installation of a monitoring system. In most large GE, S/W and Alstom gas turbines, on-line dynamic pressure transducers are employed to generate an alarm if acoustic amplitudes exceed a preset limit, thus preventing damage to structural components.

Online combustion diagnostic is the most important capability of CDMS technology. From a combination of gas turbine data and CD data, skilled operators can identify serious malfunctioning of the burners and prevent substantial damage of the combustion chamber. For example, the distribution of the exhaust temperatures will change when a particular part of the combustion section deviates from normal behavior. It is even possible to extract from the temperature distribution which combustor or burner section is faulty. Sudden changes in NO_x concentration, coupled with changes in CD frequencies and amplitudes even if they are small, can also be ascribed to combustion chamber problems. The methods of the mentioned companies are often limited to Fast Fourier Transform (FFT) analysis and detection of acoustical levels within prescribed frequency bands. In some cases also trend graphs are generated to predict degradation of components, usually applied to rotors and bearings.

This section briefly summarizes the current CDMS equipment and practices and provides an insight into the value of online monitoring of CD data for engine diagnostic and for operational optimization. EPRI's report "Guidelines for Combustion Dynamic Pressure Monitoring", Product ID 1005036, March 2004 provides a more in-depth review of the information presented in this section.

CD DATA MONITORING

The approach used in monitoring pressure amplitudes and frequencies of dynamic oscillations in each combustor is essentially the same among all OEMs. Piezoelectric pressure transducers sensors resistant to high temperatures are installed near the combustor liner. The closer the transducer is to the liner, the more sensitive is the signal to small changes in combustion-induced dynamic pressures. Transfer tubes can also be used to transmit the pressure waves to the sensors located further away from the combustor so to prevent the sensors from excessive temperatures. The location of diagnostic sensors is generally the most practical position in the given technical system, though not always the optimal position to measure a particular quantity of the combustion process. In GE Frame FA gas turbines, for example, a tube behind a 10 mm hole in the liner conveys the sound towards the sensor, offering adequate information about the major acoustical oscillations.

Table 2-1 lists commercial vendors of electronic systems that process, record, and analyze CD data for online or intermittent diagnostic and analysis. KEMA products Flamebeat™ and MagicCorr™ are tools developed for operators and consultants to display and analyze gas turbine combustion data. Other companies that provide software for combustion diagnosis are GE Bently Nevada, Power Systems Manufacturing (PSM), Control Center, and Alta Solutions, all from the USA. Siemens uses combustion monitoring to operate their Automatic Injection Control-system on annular gas turbines. Both Siemens and Alstom have acoustical or vibrational controlled safeguards on their gas turbines that generate trips if the integrity of components is jeopardized. GE has a tuning system that operates with a dynamic pressure sensor to each of the combustors of the GE gas turbines.

Most CDMS consist of installing:

1. Transfer tubes and sensors
2. Purge and acoustic dampening coil boxes
3. Signal processing instrumentation cart
4. Computer and software

Figures 2-1, 2-2 and 2-3 illustrate the typical monitoring arrangement supplied by GE and some independent installers servicing GE equipment. Figure 2-4 illustrates the installation of a low-and high-temperature pressure transducer sensor directly on the combustor for greater sensitivity in the signal. Figures 2-5 and 2-6 illustrate the sensor installation on 501F SWPC combustor, including installation of thermocouples for flashback detection. In this installation, the thermocouples are placed 180 ^{o}F apart. Although these thermocouples are sufficient to monitor all 8 fuel nozzles of the 501F DLN, coupled with low frequency CD data, an increase in temperature relative to compressor discharge, can provide an early warning of damaging flashback. Note that for 501F engines, the signal transfer tubing accesses the combustor liner through the top hat and a waveguide extends to the liner. In all CDMS applications, a purge system and a signal dampening system to remove background noise are necessary. Figure 2-7 illustrates the GE purge box and acoustic dampening coil box directly below.

Installing the purge boxes requires connecting to a 300 psig nitrogen supply; up to 9 ft length “jumpers” of ¼ copper tubing; a multi-conductor data cable and a power connection for the box heater. The jumpers make a connection between the pressure transducers and 150 ft dampening coils located in the purge box and the permanent ¼ inch stainless steel tubing connected to each of the combustor cans. The supply pressure for the purge nitrogen is based on the fact that the permanent tubing see 250 psi compressor discharge pressure. The purge nitrogen removes condensed moisture prior to sample reading. Since liquid accumulation inside the wave guides is unpredictable, it is always highly recommended by the OEMs and independents to periodically purge the system with compressed nitrogen. A PCB that requires purging will normally produce a lower dynamics signal. PCBs can also go bad. In one case there is a gradual loss of sensitivity where the signal continues to degrade. The other mode of transducer failure is the intermittent shorting. The latter can be easily identified by spikes on the oscilloscope as sudden changes in DC level. Manufacturers can readily provide plots of transducers with good response and those with reduced sensitivity for ease of comparison and problem identification.

Table 2-1
Partial List of Major Commercial Vendors of Combustion Dynamics Data Monitoring Equipment and Diagnostic Services

Vendor	System and Equipment Trade Name	Principal Applications
General Electric	Semi-Continuous Monitoring Systems	Onsite and remote DLN CD monitoring, diagnostic, and tuning services
Siemens	Active Control System (ACS)™	Continuous CD monitoring and diagnostic system with onsite tuning and control capabilities
KEMA	Flamebeat™ and MagicCorr™	CD monitoring, tuning and data management and diagnostic
Power Systems Manufacturers (PSM)	Dynamic/Combustion Acquisition System (DDAQ)™	CD monitoring, tuning, diagnostic and data management coupled with Calpine remote sensing capabilities
Control Center	Uses Alta Solution SpectralMon™ Instrumentation	CD monitoring, tuning, diagnostic and onsite/remote data management. Principally serving S/W and GE equipment
Alta Solutions	AS-250 SpectralMon™	I/O Hardware and computer used by Control Center in SpectraMon™ electronic panels coupled with sensor alarm.

Figure 2-8 illustrates the electronic data acquisition system and charge converter that are part of the process instrumentation cart. A computer provides the FFT analytical software and data display and analysis capability, including alarm setting. The instrumentation cart connects the cables from the purge boxes and supplies standard 120- or 220-v 60-Hz power. The CDMS signal is calibrated by sending a known AC signal at 100 Hz into the system and checking the reported voltage and frequency. In most cases, GE does not install permanent combustion dynamics monitoring systems on the GT they sell. However, as overhaul intervals are extended, GE considers a two phases approach:

Phase 1: Remote tuning on return from combustion inspections

Phase 2: Engine mounted system that allows continuous monitoring and even remote tuning

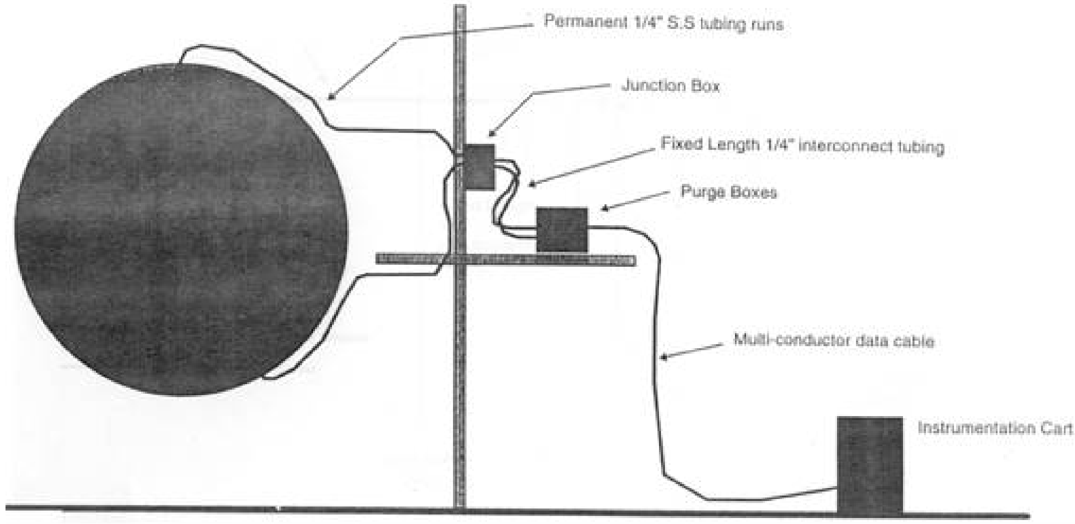


Figure 2-1
GE's Layout of Combustion Dynamics Measurement System (CDMS)

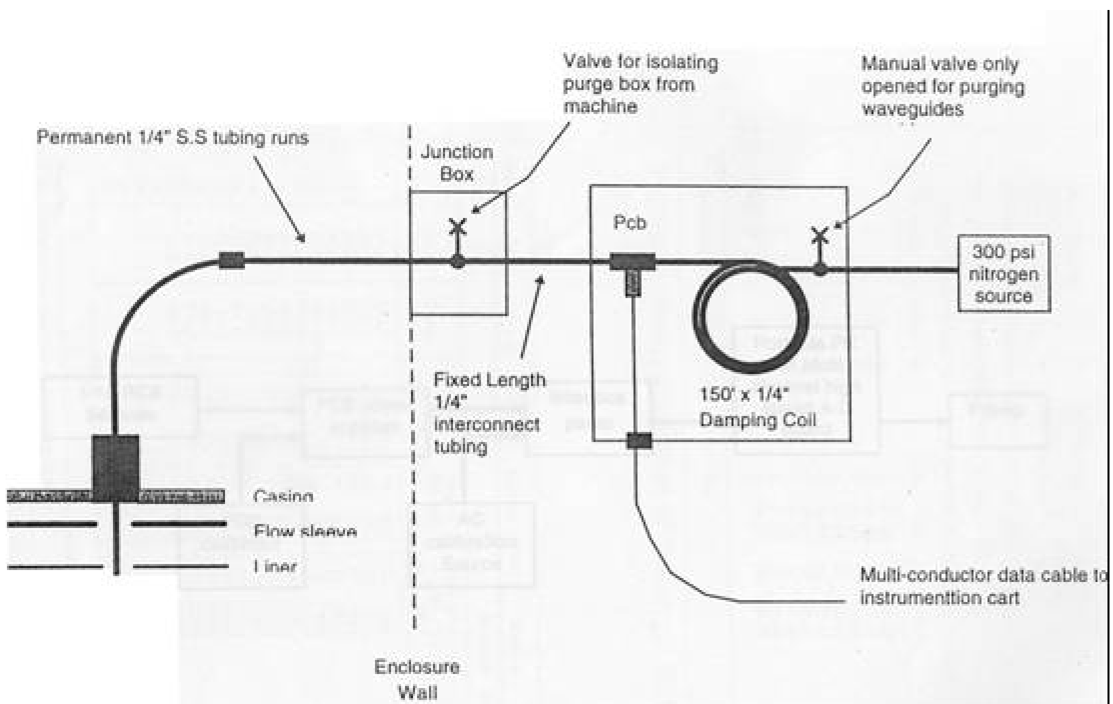


Figure 2-2
Schematic of PCB Sensor and Waveguide – GE Installations

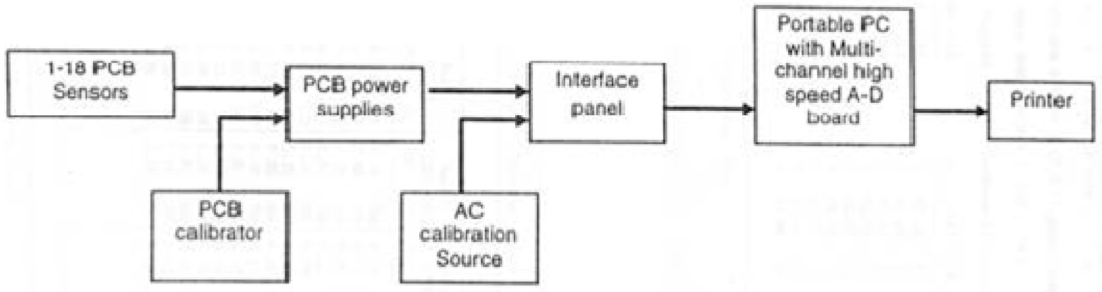


Figure 2-3
Schematic Instrumentation Cart (GE CDMS System)

Figure 2-4
Installation of Transfer Tube for Low-Temperature Sensor (on the left) and Installation of a High-Temperature Sensor on GE Combustors

Some systems provide storage of a long-term dynamics data. These data can be used as an equipment-specific signature of the combustion characteristics of present hardware. In this way a large database of CD spectra is created that can be used to develop long-term trends for the benefit of identifying slow equipment degradation prior to reaching the alarm stage. Several articles about combustion monitoring, and damage prediction, applied to commercial gas turbines are given by (Anderson, 2000), (Verhage and Stevens, 1998), (Verhage, Jansen, and Stevens, 1999), (Verhage, Jansen, and Spiele, 2000), (Verhage, 2002).

Figure 2-5
CD Sensor Installation on 501F

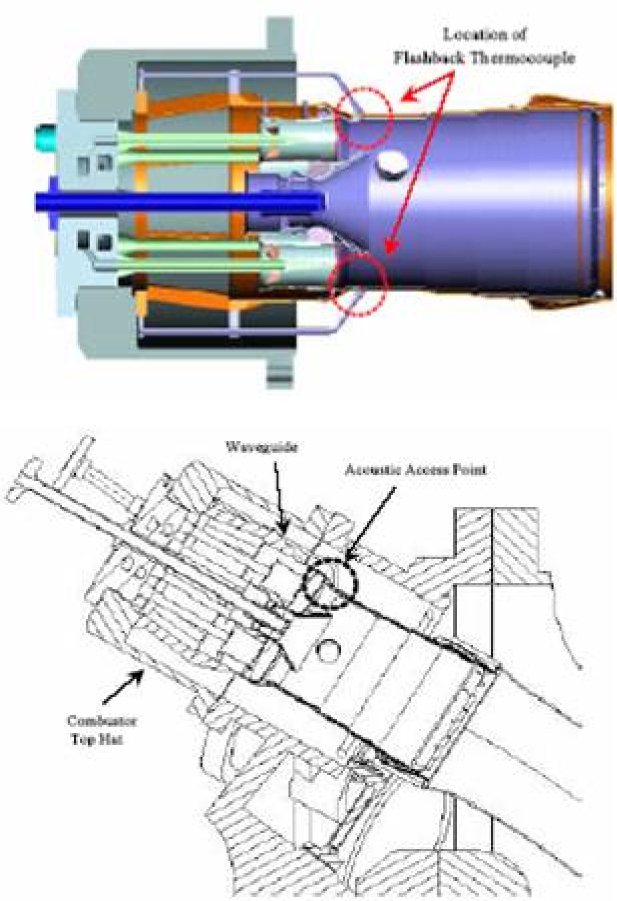
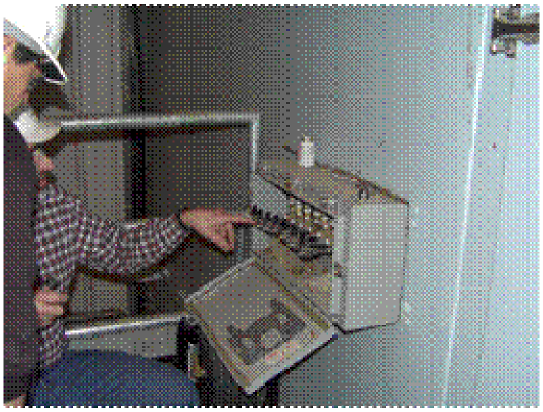


Figure 2-6
Location of Acoustic Sensor Waveguide and Flashback Thermocouples (Sewell, 2004)



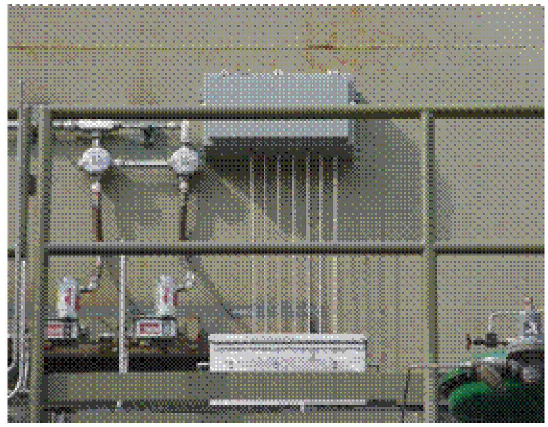
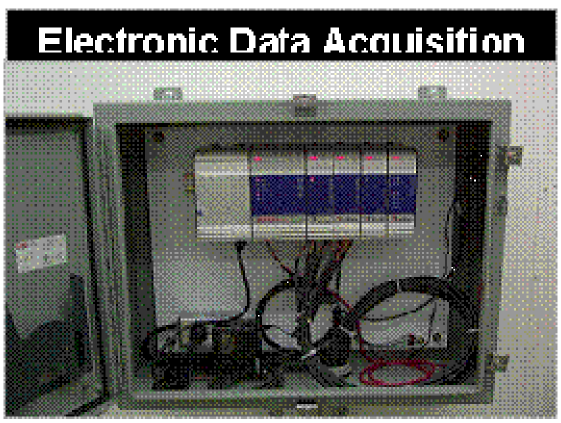


Figure 2-7
Purge Box and Acoustic Dampening Coil Box – GE Installations



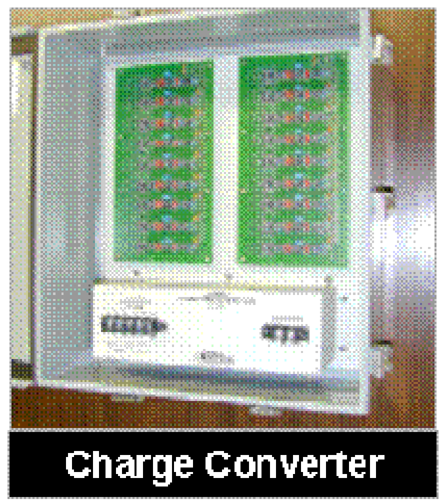


Figure 2-8
Key Elements of Electronic Data Cart in CDMS Applications

Signal Processing and Display

Pressure oscillations occur at discreet frequencies that are associated with the natural acoustic properties of the surrounding enclosure. Once the acoustic signature is profiled, it is then possible to monitor changes in the pressure amplitudes in the frequency ranges that are characteristic of a given combustor design. This can lead to effective monitoring, online diagnostic, and combustion tuning techniques, some of which are currently implemented in modern CTs.

Figure 2-9 illustrates typical combustion dynamic signatures of major fleets from GE, Siemens, Alstom and Mitsubishi. The data plots pressure amplitudes versus oscillation frequencies. For example, the recommended frequency ranges for monitoring CD changes in the 7FA DLN-2.0 combustors are:

- 110-130 Hz
- 150-180 Hz, and
- 2500 Hz

For the 9FA DLN-2.0, the frequency ranges where dynamics pressures show the greatest increase due to combustion instabilities are:

- 150-170 Hz
- 190-220 Hz
- and 2350 Hz

For Siemens/Westinghouse Power Corp (SWPC) 501F DLN, the dominant frequency is around 125 to 140 Hz. On that basis, monitoring is established for selected frequency bands. Alarm limits are set for these bands to indicate excessive pressure amplitudes, as illustrated in the Mitsubishi chart. For example, for 7FA DLN-2.0 the three bands are: <140 Hz, 140-500 Hz, and >2500 Hz, where monitoring particular combustion instabilities are manifested by pressure increases at these specified frequency ranges.

The data display is done in different formats for each of the main CDMS equipment suppliers, although in each case the formats can generally be adjusted and changed over time if required. This is especially the case when an in-depth analysis of the data is attempted, often requiring a comparison of several data sets from the data historian coupled with selected engine supervisory data.

Figure 2-10 illustrates the bar chart that often accompanies the GE CDMS data display for DLN combustors. This display is often the most useful view to rapidly assess the variation in dynamics amongst all the combustors as well as which combustor exceeds the set alarm limits. Figure 2-11 illustrates a similar bar-chart utilized by KEMA FlameBeat™. Another typical CDMS data display shows pressure amplitude versus frequency for each of the scanned combustors. The main use of this display is to assess the qualitative similarity of the noise spectrums in all chambers, though the information can also point to pressure peaks that exceed selected alarm limits. Figure 2-12 illustrates the display of Fast Fourier Transform (FFT) data from the KEMA FlameBeat™ and MagicCorr™ display on the 18 combustors of a GE 9FA DLN-2.0 engine.

As shown, the alarm levels are set in the lower frequency bands where flame instabilities produce the highest pressure pulsations.

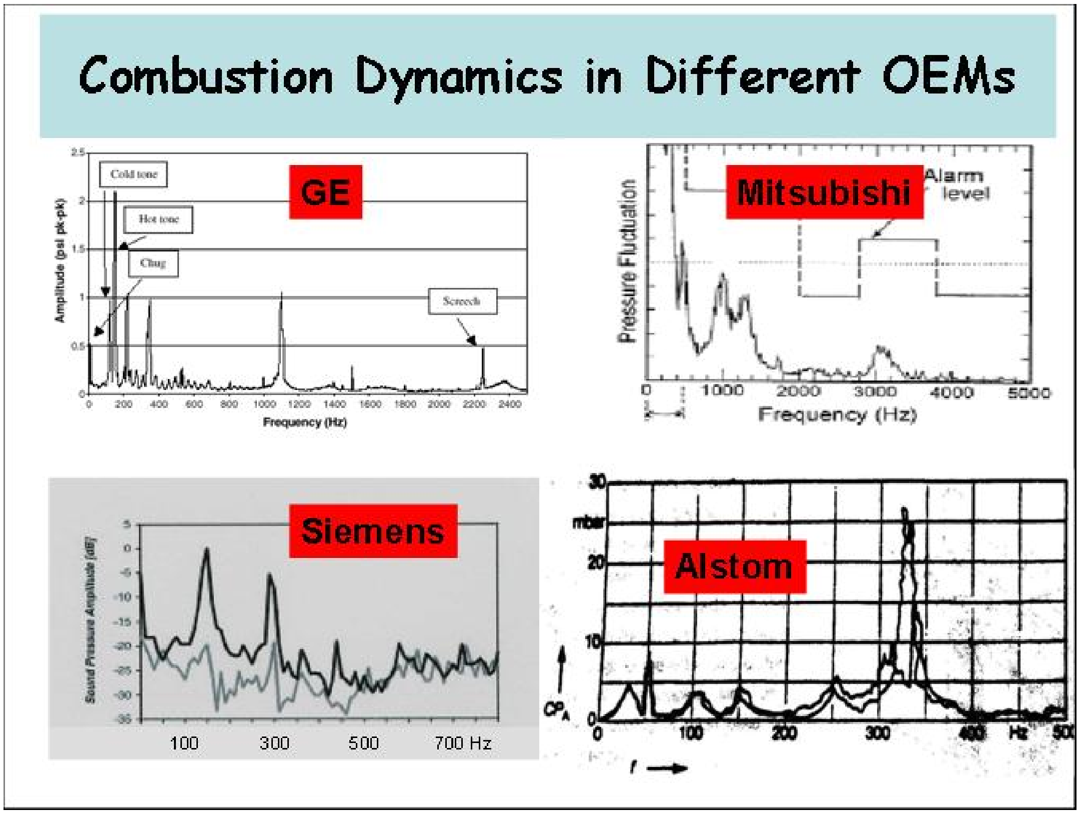
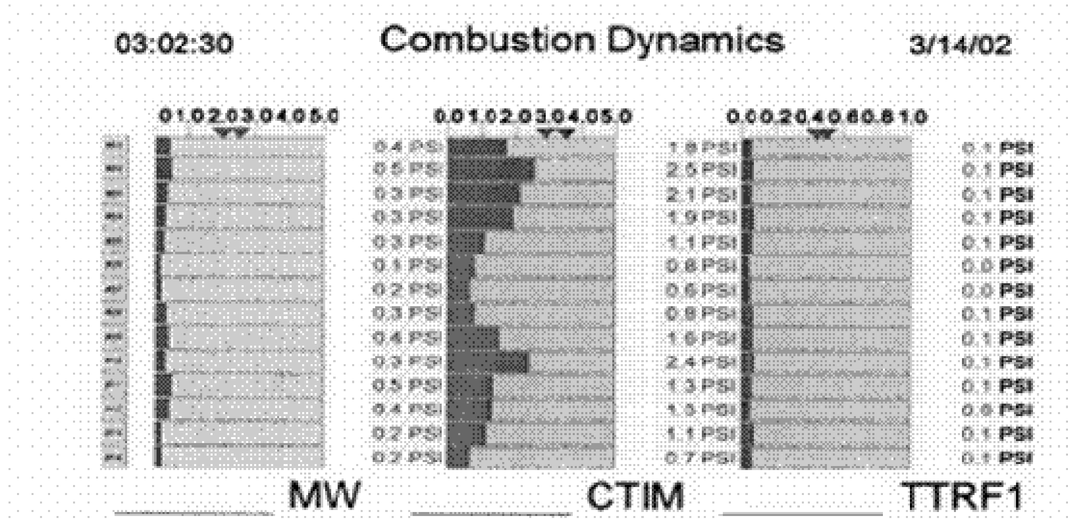


Figure 2-9
Combustion Dynamics Spectra in CTs from Different OEMs



	Vrms	.5 Hz to 140 Hz		140 Hz to 500 Hz		500 Hz to 2500 Hz	
Can #1	0.23	0.42PSI	115.19 Hz	1.76PSI	176.90 Hz	0.06PSI	596.50 Hz
Can #2	[illegible]	0.46PSI	113.13 Hz	2.56PSI	176.90 Hz	0.06PSI	530.70 Hz
Can #3	0.70	0.34PSI	113.13 Hz	2.13PSI	176.90 Hz	0.05PSI	524.53 Hz
Can #4	0.66	0.29PSI	112.11 Hz	1.94PSI	176.90 Hz	0.07PSI	1135.45 Hz
Can #5	0.58	0.26PSI	7.20 Hz	1.07PSI	176.90 Hz	0.06PSI	543.04 Hz
Can #6	0.53	0.15PSI	113.13 Hz	0.79PSI	176.90 Hz	0.04PSI	1146.77 Hz
Can #7	0.46	0.17PSI	109.02 Hz	0.65PSI	176.90 Hz	0.05PSI	1131.34 Hz
Can #8	0.64	0.33PSI	109.02 Hz	0.79PSI	174.84 Hz	0.06PSI	556.41 Hz
Can #9	0.80	0.39PSI	109.02 Hz	1.55PSI	174.84 Hz	0.06PSI	539.96 Hz
Can #10	0.94	0.31PSI	112.11 Hz	2.39PSI	174.84 Hz	0.08PSI	525.56 Hz
Can #11	0.83	0.47PSI	112.11 Hz	1.33PSI	174.84 Hz	0.06PSI	1134.43 Hz
Can #12	0.81	0.40PSI	112.11 Hz	1.30PSI	174.84 Hz	0.05PSI	559.50 Hz
Can #13	0.72	0.19PSI	96.74 Hz	1.13PSI	174.84 Hz	0.08PSI	568.76 Hz
Can #14	0.51	0.20PSI	115.19 Hz	0.66PSI	176.90 Hz	0.06PSI	583.15 Hz
Peak		0.47PSI		2.56PSI		0.08PSI	
Average		0.31PSI		1.44PSI		0.06PSI	

Figure 2-10
CD Bar-Type Display from GE-CDMS – 7EA DLN-2.0

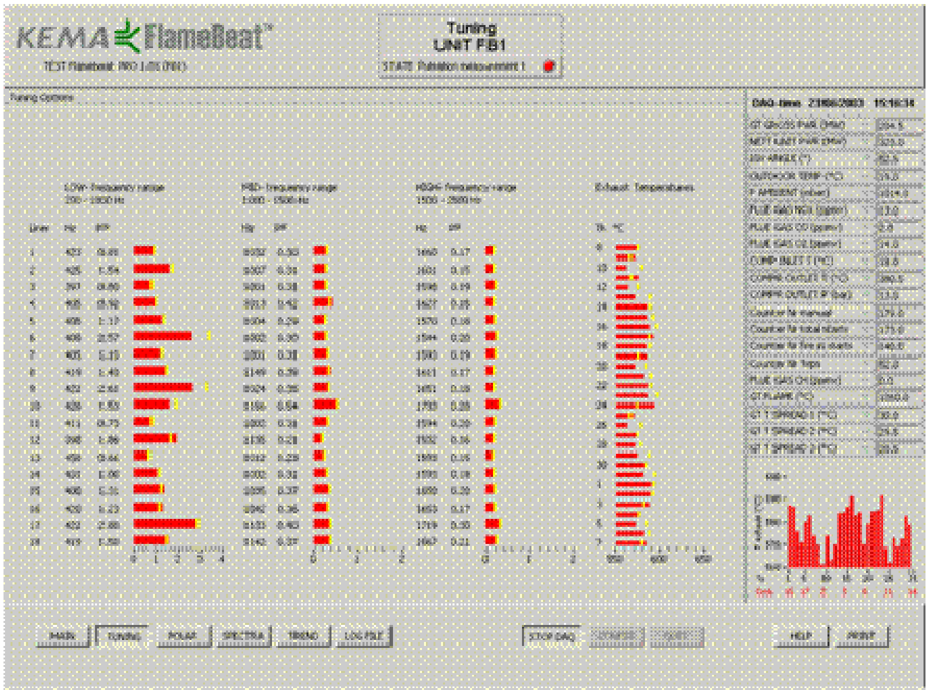


Figure 2-11
Tuning Screen with Maximum Amplitudes in Three Adjustable Frequency Bands, Together with Turbine Exhaust Temperature Distribution

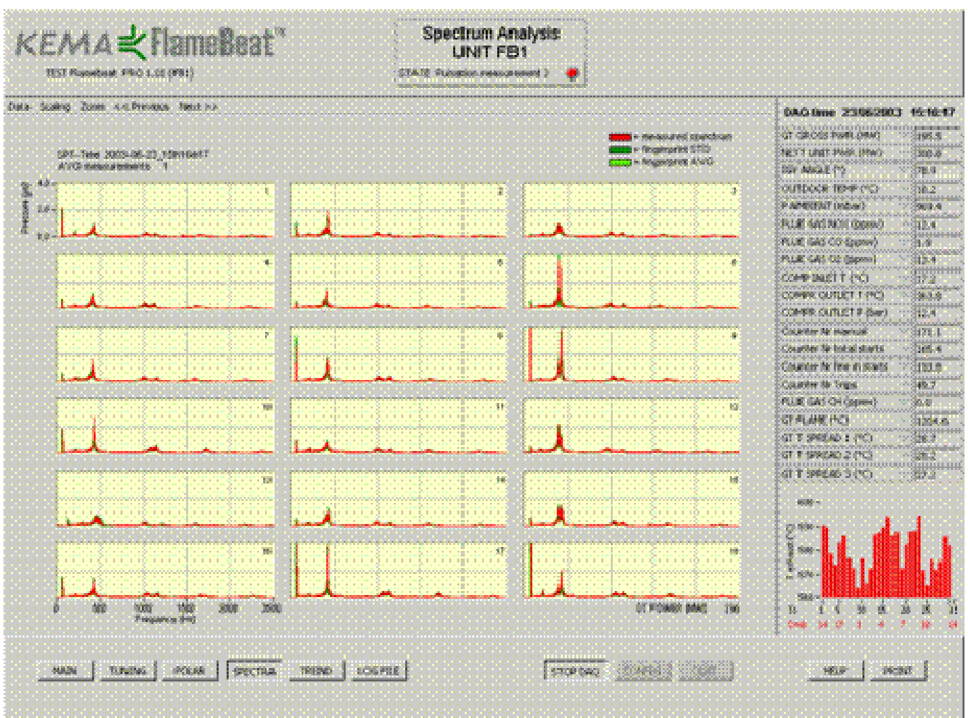


Figure 2-12
FFT Dynamic Spectra of 18 Combustion Chambers of the GE MS 9001FA Gas Turbine, Recorded with FlameBeat™

The key benefit of CDMS is the ability to set alarm levels where the operator can be alerted to the potential problems before they grow into hardware damage events. Based on input from the OEMs, alarm levels on CD pressure amplitudes are set and monitored for each combustor. Figures 2-13 through 2-16 illustrate alarm displays in different CDMS equipment.

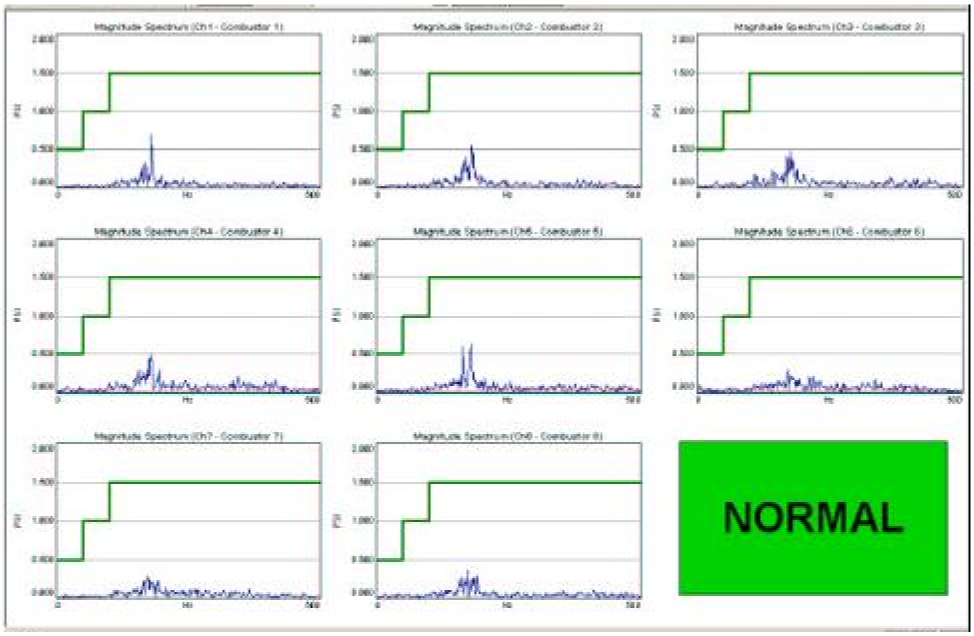


Figure 2-13
Three Alarm Levels Set for CD Frequency Ranges Affecting SW 501F DLN Combustors

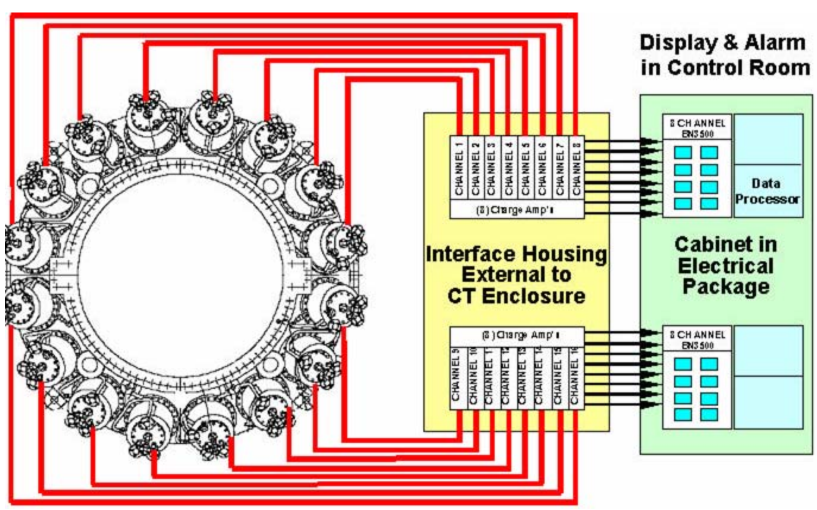


Figure 2-14
Siemens/Westinghouse Combustion Dynamics Alarm Display

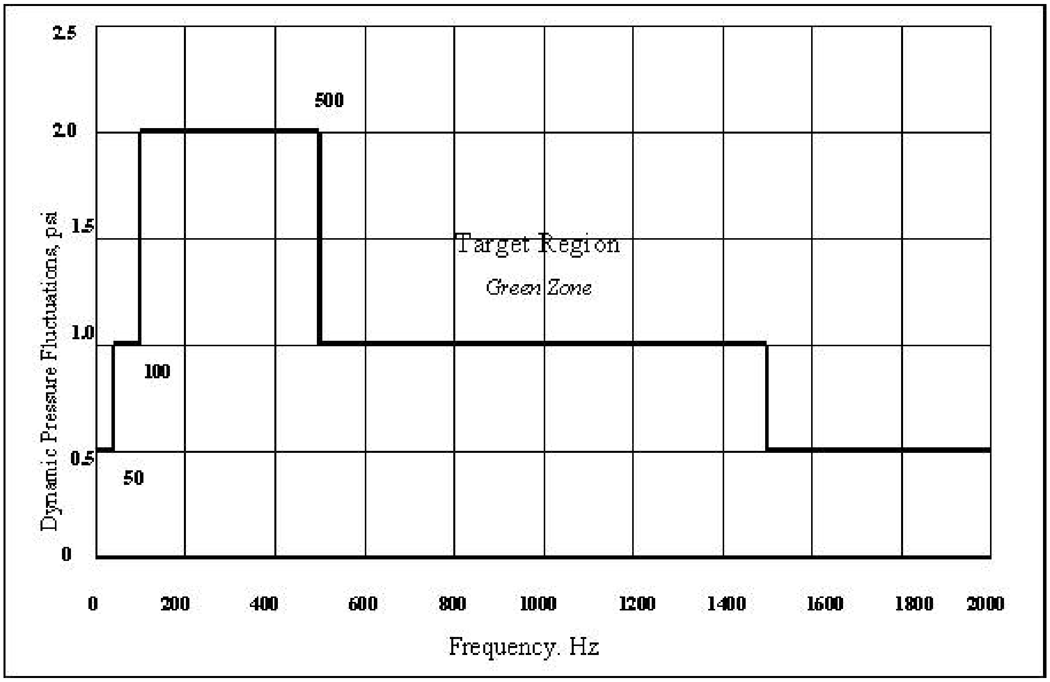


Figure 2-15
Siemens/Westinghouse Combustion Dynamics Alarm Limits

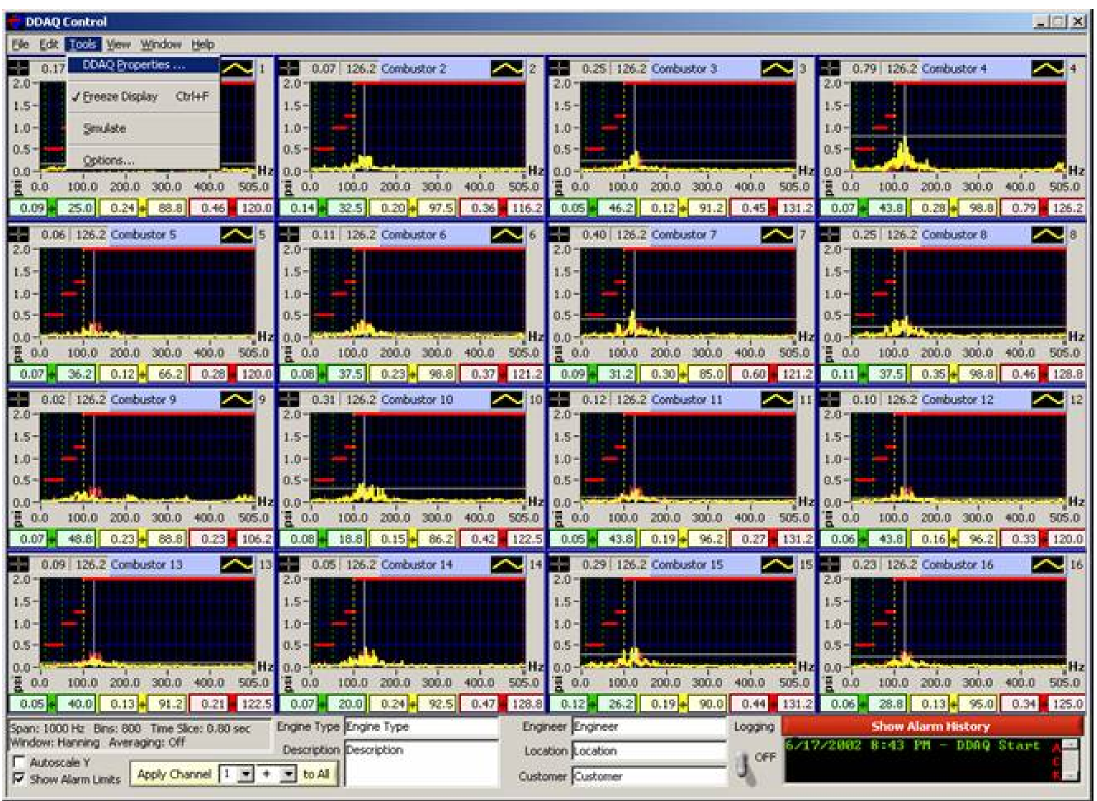


Figure 2-16
Display Screen for Individual Combustor Dynamic Spectra in Relation to Alarm Set Points – PSM DAAQ Display

ONLINE DIAGNOSTICS

The degree of analyses between these systems is varied, ranging from simply alerting the operator with an alarm when pressure pulsations in any one of the combustors exceed set points (as in the case of instrumentation from Alta Solutions) or, in some cases, to more sophisticated data evaluation that permits greater pinpointing capability of potential hardware distress. The latter integrates CD data with key data from the engine digital control system (DCS) with the intent to display and analyze parameters that describe the condition of the installation, its performance, and the risk of failure of components.

All major engine OEMs, such as GE, Siemens, and Alstom provide both onsite and remote CD data monitoring and analysis support for rapid response capability to today's tight combustion tolerances. The remote capability for GE is located at the GE Monitoring and Diagnostics Center in Atlanta. Data collected in this center is used for example for performance monitoring. Data from 15 on-engine sensors is taken from the on-site monitoring system and is run through a data base to be validated and calculate performance. The process at the center is mostly manual. Data collected every four hours from each site (mostly from F class engines) is visually compared against previous record. Abnormalities are forwarded to specialists for manual analysis. The collected data and analysis is used by GE to improve reliability and performance. North American Energy Services, NRG Energy, FPL Power Generation, and EPON operate continuous dynamics monitoring on their engines.

To interpret the spectral data correctly, simultaneously measured gas turbine parameters are often merged with the spectra. Selected parameters are extracted from the dynamic pressure spectra such as the amplitude averaged over the full spectrum, and the position and amplitude of the major peaks. As shown in the previous figures, it is important to measure only selected frequency ranges, where combustion-induced pressure pulsations occur within a given combustor design. This leads to an important data reduction, whilst retaining the major information of the state of the combustion system. The trend data are the combined time arrays of gas turbine data and these extracted spectral parameters. The trend data can be used to timely predict degradation and damage.

Diagnostics monitoring for combustion dynamics on large commercial gas turbines for power generation, if present at all, is generally restricted to acoustical measurements and flame detection. This direct information of the combustion process should be complemented with data from the gas turbine, such as the computed firing temperature, exhaust temperatures, NO_x emission, and load, to confirm the presence of unsafe combustion conditions and to help identify corrective actions.

Permanent combustion monitoring allows operators a regular view of the status of the hot path of the gas turbine. They can use the available controls to minimize combustion dynamics and to avoid trips due to flame loss, initiated by the flame detector. Such controls are de-icing, pilot flame adjustment, load shedding, re-tuning of gas valves, inlet guide vane adjustment within the allowable limits, air- and gas pre-heating. Archived dynamic pressure data can also be used to develop. At a minimum, the operator requires software with alarm indicators when parameters derived from the combustion dynamics are subject to sudden changes.

Advanced analysis with help of the complete data bank of spectral- and gas turbine parameters requires correlation tools. In this way the influence of ambient temperature, pressure, humidity, compressor cleaning, de-icing, etcetera, on the combustion dynamics can be mapped. Analysis performed on data acquired during a 300 days period show that the amplitude of the acoustical emission from flames increases linearly with load, and decreases with ambient temperature. It also reveals fault conditions when the acoustic impedance in a particular combustor changes with time. The distribution of the exhaust temperature, coupled to spectral data, provides an extra check for operator to make a decision for inspection.

Directly measured combustion data offer the possibility to make maps of combustion behavior under normal operating conditions. On-line monitoring of direct combustion data and merged gas turbine parameters allows operators to detect damage and degradation in an early stage. Knowledge gained in this way helps to prevent trips, and (consequential) turbine damage caused by breakage of components. It also reduces overhaul time as the state of the components can be assessed during the running period, allowing the timely ordering of replacement parts. For example, over 13,000 hours of inspection interval on a DLN2 dual fuel engine was achieved by on-line dynamics monitoring and regular tuning. Combustion monitoring with merged turbine data is therefore highly recommended and has been generally adopted by all major gas turbine manufacturers.

Figure 2-17 illustrates one of the features of the CD data analysis capability. In this case, the CD spectra of one combustor taken at two different times are compared with the intent to identify any trends in the acoustic signature of the combustor and the properties of the flame. Selection of two comparable signatures are based on matching load as well as ambient conditions and other fuel factors that are known to have an influence on the spectra and amplitude of pressure oscillations. In this example, the amplitude of pressure pulsations at a specific frequency may reveal some important changes in the combustion process and hardware.

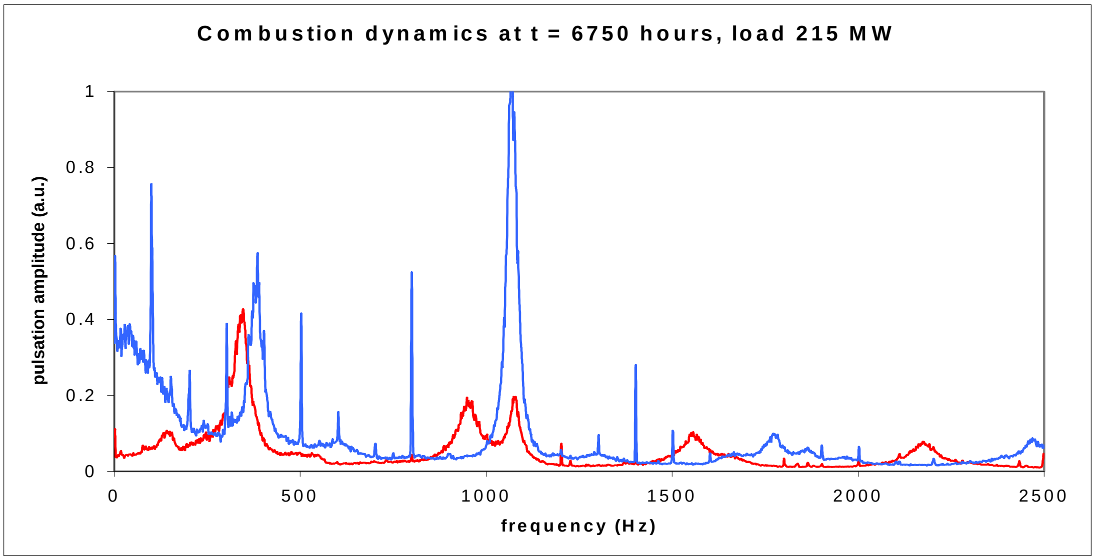


Figure 2-17
Same-Condition Comparison of Pressure Dynamics Spectra in the Same Combustor Recorded at a Specified Interval

Broad correlations of pressure pulsations versus key engine operating parameter may be limited in revealing the level of detail necessary for in depth diagnostics, but can offer general trends. For example, Figure 2-18 illustrates a correlation attempted between sum of peak amplitudes measured over the spectral frequency of interest recorded during changes in ambient temperature. Although there is some apparent variation in the data especially at lower ambient temperatures, this type of analysis can reveal the degree of change anticipated as conditions vary for the operation of the gas turbine. Thus, changes in pressure amplitudes that go beyond those accepted as within safe operating practices can be set as additional triggers for evaluation and further analysis. This type of analytical support can then be more readily incorporated into the operation of the gas turbine to provide general guidelines as to under which operating conditions more detailed supervision and diagnostic may be necessary.

The gas turbine data are usually not sufficient to pinpoint the type of damage, nor do they provide enough information to decide whether the unit should be inspected straight away, or that deferment of the stop to the next weekend is allowed. A deviation in the distribution of the exhaust temperatures, together with a small step in NO_x emission may indicate a damaged burner or burner group, a crack in the combustion chamber, a local stagnation in the gas supply, or the extreme sensitivity of a burner section to atmospheric changes. This ambiguity is the reason why equipment manufacturers use the direct method of acoustical measurements of combustion dynamics in the commissioning and tuning stages. Together with the gas turbine parameters they gain a rapid insight into the combustion process and adjust the different combustors and burner groups to minimize both the acoustical emission from the flames and their NO_x-production. It is therefore recommended to leave the direct combustion diagnostics on the gas turbine after commissioning and tuning, and use it as a permanent tool for combustion monitoring.

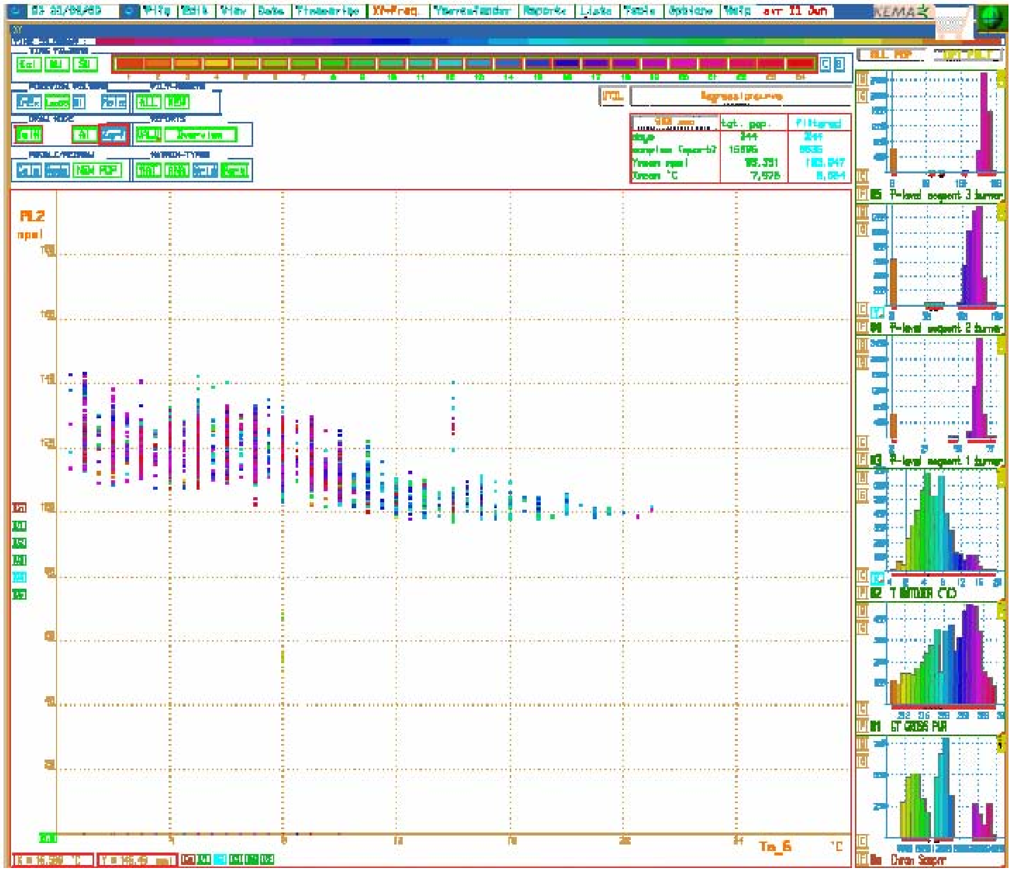


Figure 2-18
Analysis of CD Pressure Amplitudes with Changes in Ambient Temperature at Constant Engine Load

The following two sections provide two examples of CD diagnostic capability that led to the implementation of corrective actions and combustor tuning preventing potential hardware damage and safeguarding operation.

Combustion Diagnostics Worksheet

It is clear that the availability of CDMS technology in modern DLN-equipped engines provides invaluable data for online tuning and hardware diagnostics. The Combustion Diagnostic Worksheet in Table 2-2 contains a matrix of hardware faults or failures with manifested changes in three performance monitoring areas, namely CDMS, engine supervisory data, and continuous emission monitoring (CEM) system. The following fault parameters are included:

- Off-calibration fuel nozzle
- Eroded or burned fuel nozzle
- Clogged fuel nozzle
- Obstructed air passages
- Clogged air filter
- Compressor fouling
- Cracked combustion liner
- Cracked transition piece
- Crossfire tube failure

Only combustion-related faults are considered in the matrix. The number and corresponding shading in the matrix highlight the most likely impact of each fault on the combustion dynamics frequency signature and tne engine emissions. Thus a heavily shaded number "3" indicates that pressure amplitudes will likely change in selected frequency range and changes in either NOx or CO are also most likely and can be used as a confirmation that engine may have the hardware failure indicated. In the case of engine supervisory data, the numbering system also addresses the relative severity of the recorded impact. Thus a number "3" indicates that if a noticeable change is recorded, then an action is highly recommended.

All the fault condition parameters have one thing in common in that they all affect the local air/fuel ratio to all or selected fuel nozzles. Thus if refurbished parts are not properly calibrated, then some nozzles will be more apt to initiate combustion instabilities which can aggravate over time and ultimately result in failure. Whether the fuel or air flows are affected by failed nozzles or obstructed or reduced compressor discharge conditions, then these conditions can lead to the onset of dynamics in one or more combustors. Even failures of combustor liners or transition pieces can bypass sufficient air away from the nozzles to cause a localized fuel rich condition with can be manifested in increases in NOx emissions. The hardware damage is sufficient to cause changes in combustion signature in both frequency and amplitude of sound.

The following sections present some sample cases of combustion diagnostics done with the aide of CDMS technology coupled with other available engine performance data.

Table 2-2.

Combustion Diagnostic Worksheet – Combustion Related Operational Faults.

Faults	Dynamic Spectra Signature				Engine Supervisory Data					CEM
	Low Hz Press. Spike(1)	Med. Hz Press. Spike(2)	Hi Hz. Press. Spike(3)	Hz Shift	Flashback Thermo-couple	Exhaust Temp. Spread	Inlet Press. Drop	Hot Exhaust Temp.	Cold Exhaust Temp.	Changes in NOx and CO
Off-calibration Fuel Nozzle	2	1								2
Eroded/Burned Fuel Nozzle	3				3	2				3
Clogged Fuel Nozzle		1	2	1		1	1`			1
Obstructed Air Passage	2	1						2		2
Clogged Air Filter	2	1						2		2
Compressor Fouling	2	1						2		1
Cracked Combustor Liner		2	1	3		1			3	
Cracked Transition Piece		1	3			3				3
Crossfire Tube Failure		2	1			1			3	

(1) Low frequency tone humming - <50 Hz for SW501F DLN and <140 Hz for GE 7FA DLN
(2) Med frequency: 50-100 Hz for SW501F DLN and 140 to 250 Hz for GE 7FA DLN
(3) High frequency: 100-250 Hz for SW501F DLN and 250-2500 Hz for GE 7FA DLN

Note: Ambient temperature can affect the affect low to medium frequency spikes
Changes in load tend to shift frequency, so always compare spectral signature at same engine load and ambient temperature

GE DLN 2.0 Combustor Diagnostics

Table 2-2 lists the dynamics response of DLN2.0 in a 9FA engine as supplied by the OEM. The potential causes and impacts, of increased dynamics if left unattended, are also included. At different operating conditions (as outlined in Table 2-3) different tones of high amplitudes appear in the pressure spectrum (Figure 2-20). The tones frequencies range from 10-20 Hz chug to >2200 Hz screech. Amplitude can reach over 2 psi peak to peak levels. The different tones appear during different regimes of the run-up of power.

The different modes of operation of the DLN2.0 system are as follows:

1. Primary Mode: 4 diffusion burners
2. Lean-Lean Mode: 4 diffusion burners + tertiary burner
3. Piloted Premix Mode: 4 diffusion burners and 5 premix burners (4 secondary and one tertiary)
4. Full Premix Mode: 5 premix burners (4 secondary and one tertiary)

The 100-135 Hz mode appears during mode 4 when all 5 burners have even fuel split at base load and the ambient temperature is high (these tones have highest amplitude in the summer). Reduced ambient temperature from 22 C to 6 C cuts the amplitude of the fundamental cold mode by 50% but increases its first harmonic indicated in Figure 2-20.

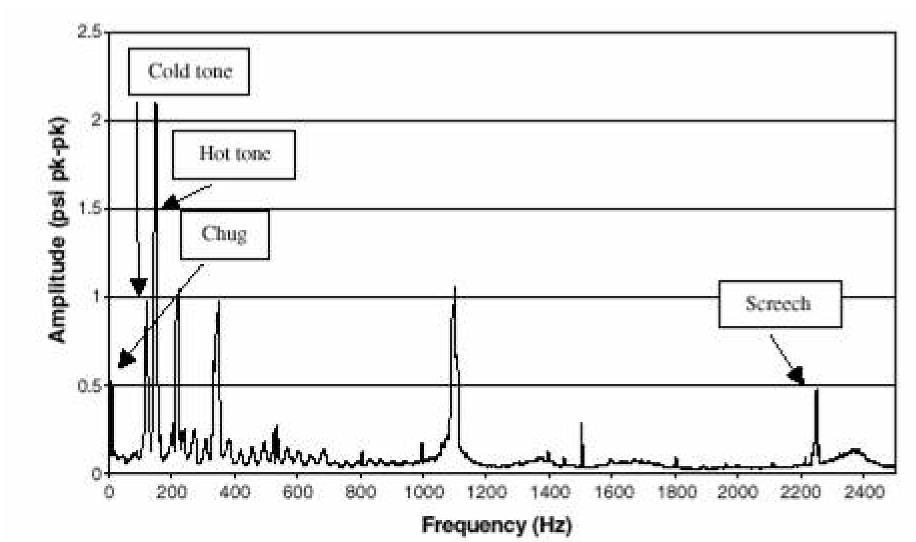


Figure 2-19
Pressure Pulsations Spectra at Different Operating Conditions

The 140-180 Hz tone appears when the fuel split to the secondary burners increases during part load conditions (the minimum stable generation –MSG load) and the ambient temperatures are low. These tones are more sensitive to variations in ambient temperature. Reducing the ambient temperature from 22 C to 6 C can result in an order-of-magnitude increase in the amplitude of the hot tone as illustrated in Figure 2-21. The screech mode (and its sub-harmonic frequency) appears during part load with even fuel split. The very low frequency chug mode appears near Lean Blow Out (LBO) conditions when the secondary fuel system is reduced. It is usually accompanied by low NO_x and very high CO. Maximum allowed level of the different tones is shown in Table 2-4.

Table 2-3
The Dynamic Response of GE DLN2-9FA Combustion System

Table 1. The dynamic response of the GE DLN2 9FA combustion system.

	Frequency (Hz)	Exciting conditions	Impact
Cold tone	100–135	Even fuel split between secondaries and tertiary, high ambient temperatures	Hardware damage
Hot tone	140–180	Grows with increasing secondary split. Most prevalent at part load conditions on the IGV temperature control curve. Will increase with reducing ambient temperatures	Initial damage to cross fire tubes a precursor to further hardware damage
Screech	2500+	Typically occurs at part load operation when approaching an even gas split. Can normally be driven through. Is indicative of existing component damage	Screech is very destructive and levels of 1 psi pk–pk will cause high cycle fatigue, which can quickly crack welds and lead to component hardware failure
Chug	10–20	Indicative of a lean combustor. May be accompanied by low levels of NO_x and high levels of CO. Tends to occur at part load operation as supply to secondary fuel system is reduced.	An indication that unit is running too lean and about to flame out on one or more secondary burners

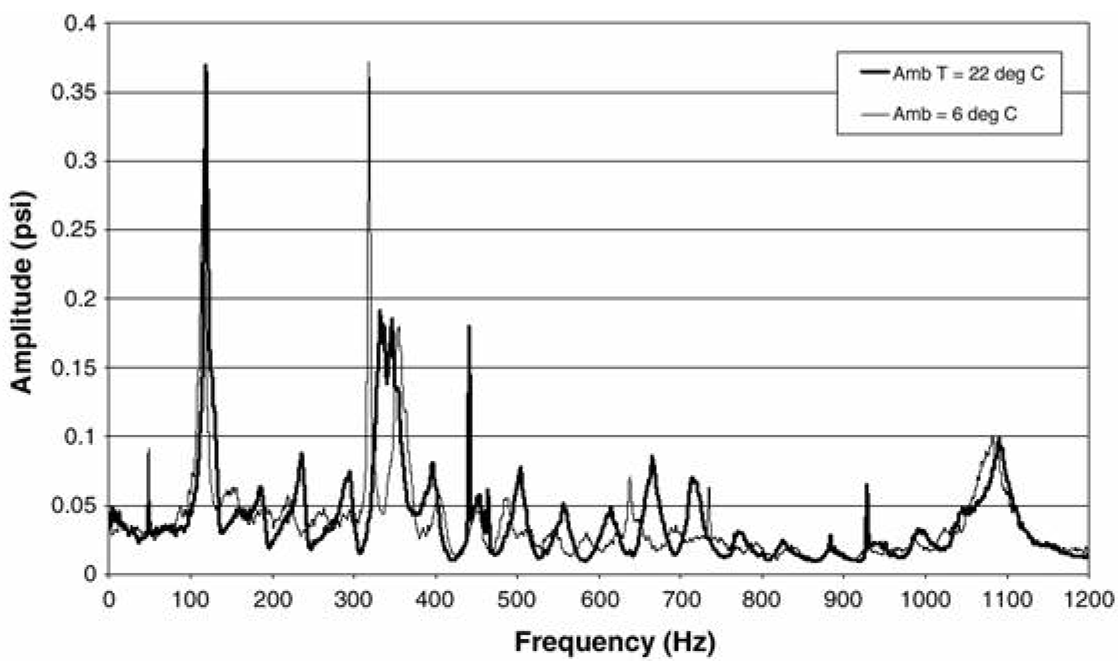


Figure 2-20
Effect of Ambient Temperature on the Cold Tones

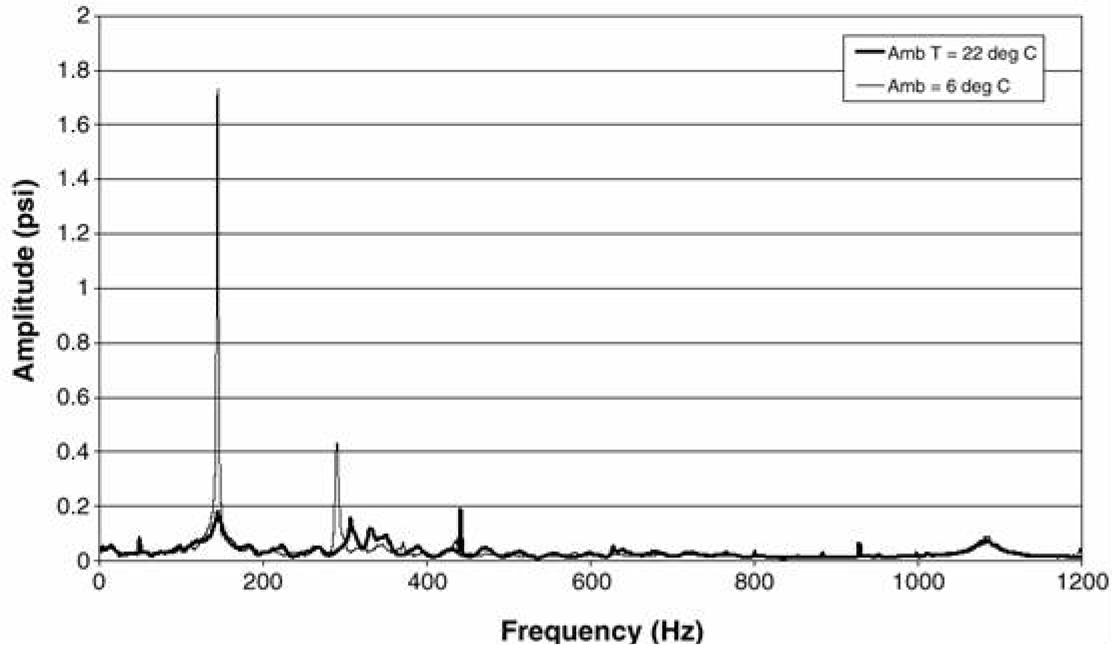


Figure 2-21
Effect of Ambient Temperature on the Hot Tones

Table 2-4
Tuning Limits, as Set by the Engine OEM

	Frequency (Hz)	Expected level (psi pk–pk)	Maximum acceptable level (psi pk–pk)
Cold tone	100–135	<0.5	1 (2.0 at part load)
Hot tone	140–180	<2	2.5 (3.0 at part load)
Screech	2500+	<0.3	0.3
Chug	10–20	<2	2

Frequency spectra are calculated at a rate of 100 per 5 minutes intervals for each one of the 18 cans, and are then averaged to reduce noise. The pressure fluctuations spectra are split to the frequency bands of interest and the following parameters are recorded: peak frequency and its amplitude, and band power. The spectra are compared with the baseline spectra to determine any deviation. Any peak higher than 4 psi will trigger an alarm.

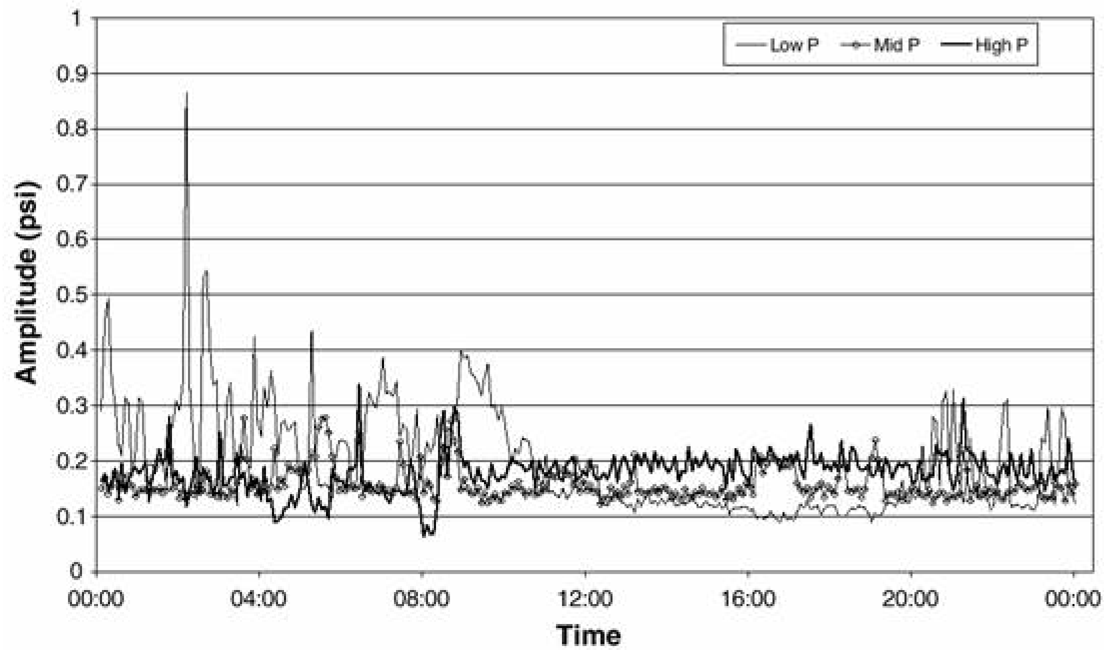


Figure 2-22
Pressure Traces in Three Different Frequency Bands

The amplitudes of the pressure fluctuations at three different frequency bands are shown in Figure 2-22. Both low and medium bands are the most sensitive to ambient conditions and their amplitudes are higher between 8 p.m. and 10 a.m. The spectra of the pressure dynamics change as a function of load and therefore the baseline spectra are measured over a range of loads. The variation with ambient conditions and fuel composition are also accounted for in the analysis software.

Damage in the combustor such as liner cracks will result in changes in frequency and its amplitude. A crack in the liner will cause compressor air to enter the combustor changing the temperature distribution and therefore the speed of sound and the frequency. It will also change the amount of air going through the burner and therefore will changes the amplitude of the pressure pulsations (usually will increase it). Cracks will also be detected by thermocouples distributed in the exhaust duct of the turbine. These thermocouples can be mapped to a certain combustor and help pinpoint the location of the damaged combustor as indicated in Figure 2-23. Additionally, emissions will be affected by cracks and will be indicated in the measurements of NO_x, CO, and O_2 that are performed in parallel (Figure 2-24).

Changing load may cause a switch in the unstable mode from cold to hot even at a constant ambient temperature. Figure 2-25 shows that as the load is reduced from base load to MSG the dominant mode shifts from cold to hot tone.

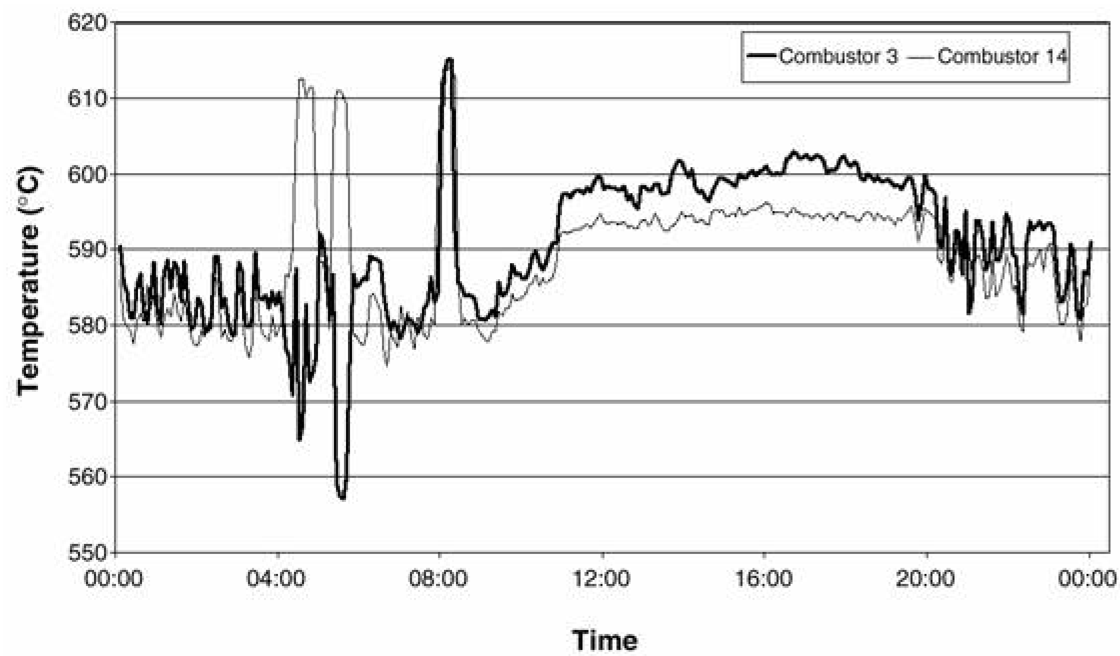


Figure 2-23
Exhaust Gas Temperatures Related to Combustor Cans Number 3 and 14

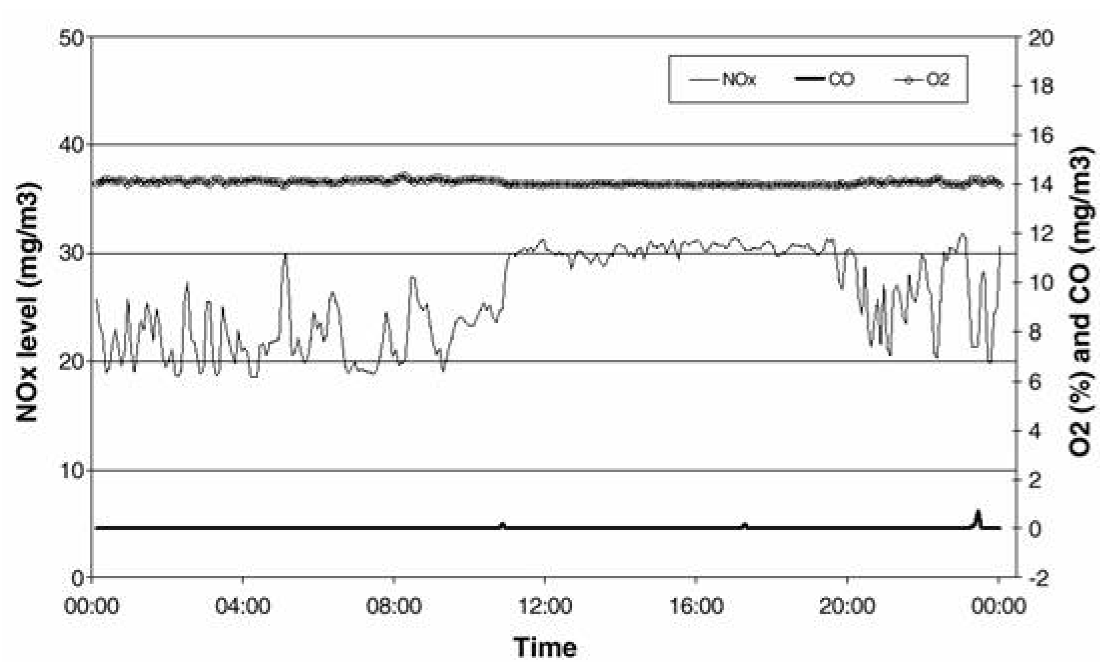


Figure 2-24
Emissions Levels Monitoring During a 24 Hours Period

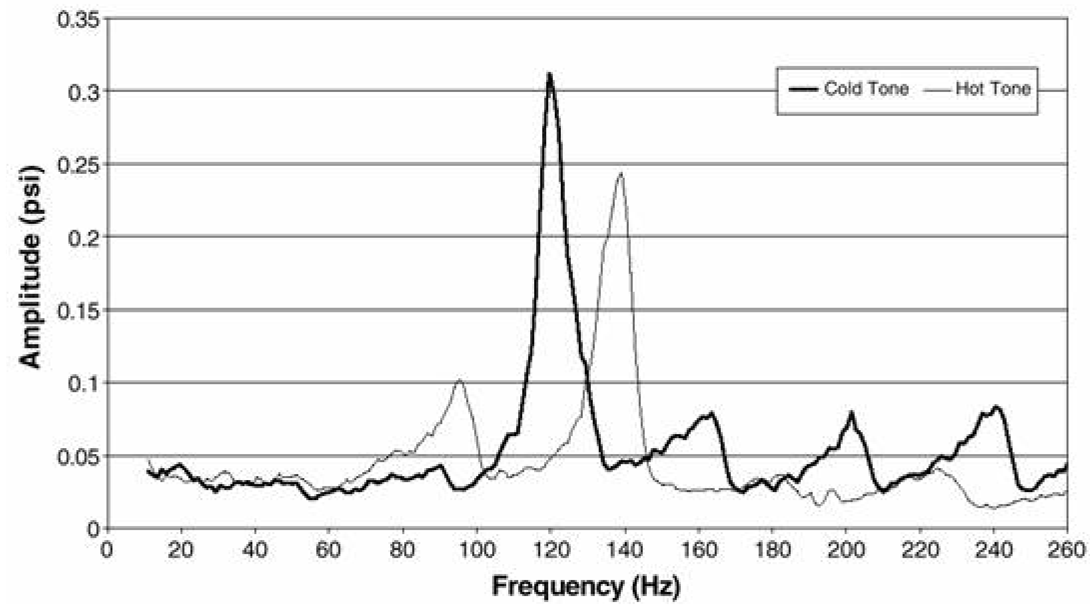


Figure 2-25
Effect of Load on the Pressure Pulsations

The history of the effect of a liner crack growth on the pressure pulsations level and frequency, the NO_x emissions, and exhaust temperature is shown in Figures 2-26 and 2-27 on this engine. The crack started on 12/2 and grew slowly over a period of one week until it finally open up on 12/9. During this week the mid tone amplitude grew gradually from 1.5 psi (peak to peak) to 3 psi and jumped to 10 psi after the catastrophic event. At the same time the frequency which was most of the time around 325 Hz with occasional jumps to 150 Hz, slowly occurred more often at the lower frequency and stabilized at 150 Hz following the final failure. NO_x did not show any indication of changes during the week and stayed at a level of 20 mg/m^3. However, immediately with the occurrence of the final failure it jumped to 180 mg/m^3 and triggered the trip. The exhaust temperature dropped gradually during the week from 618 C to 610 C indicating increased compressor air entering the can through the cracked liner.

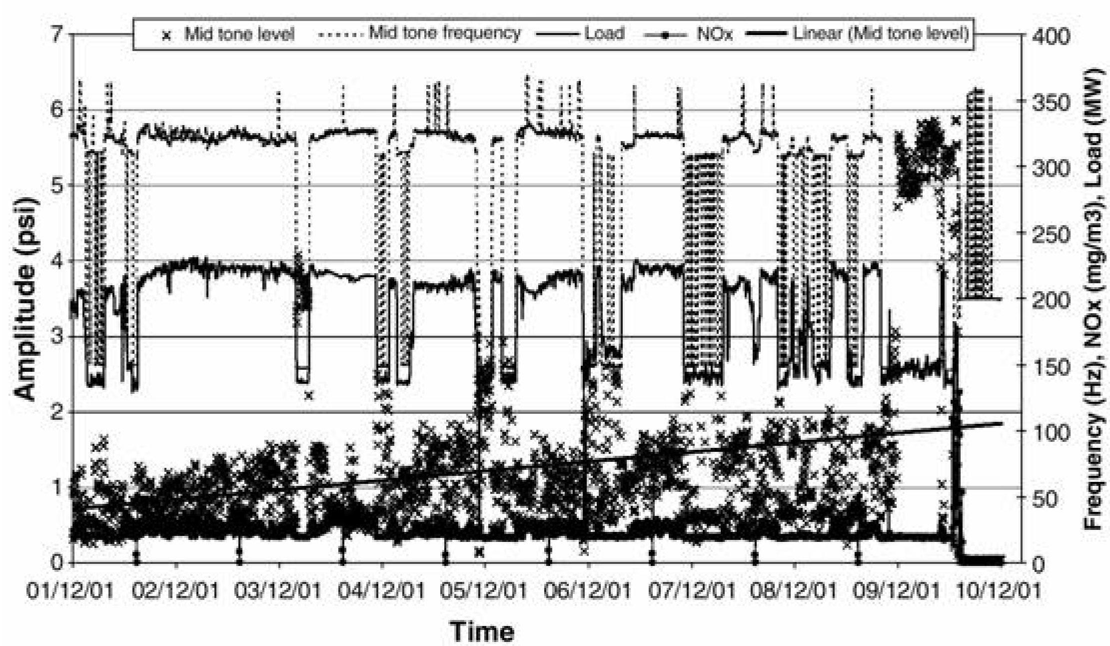


Figure 2-26
Effect of Growing Liner Crack on Pressure Pulsations Frequency and Amplitude, and NO_x Emissions

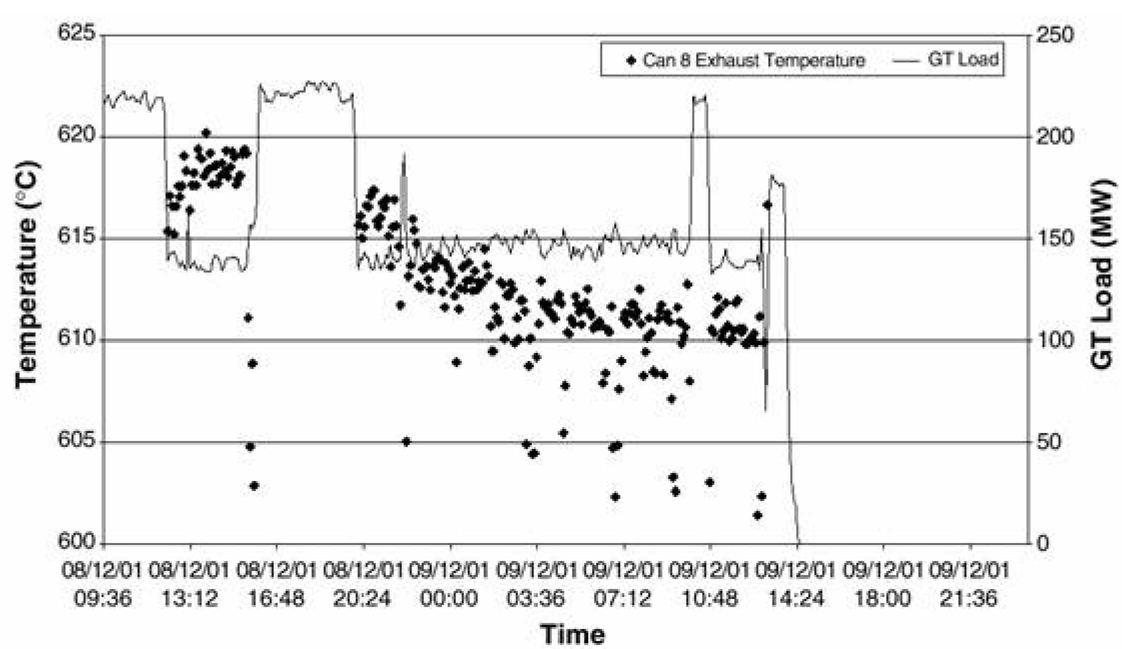


Figure 2-27
Effect of Growing Liner Crack on Exhaust Gas Temperature (Can 8)

SW 501F DLN Combustor

In a series of CD diagnostic cases, J. Sewell (2004) highlighted the capability of continuous CDMS technology in providing and advance warning system for operators. In Figure 2-28, Sewell presents an event when one of the combustors experienced low frequency dynamics (0.837 at 23.75 Hz). The figure shows two separate spectra, one at peak hold and the other a live trace. The peak hold trace is useful in validating the sudden increase above an historical high which would indicate a potential problem in the combustor. In the example, the alarm was triggered because the alarm level at this low frequency was set at 0.5 psi. A quick check of the frequency spectra in all the other combustors showed that the low frequency dynamics was limited to only the combustor at position 8. A reading of the flashback temperature (defined as Tfb = Tc – Ts where Tc is the readout of the thermocouples installed just downstream of the premixers as shown in Figure 2-6 and Ts is the reference compressor discharge temperature) showed that combustor 8 exceeded the 200 F set alarm limit. The increase in low frequency dynamics was consistent with an increase in flashback temperature. A subsequent inspection revealed an obstructed premixer causing a reduction in air flow that resulted in a potentially damage-causing flashback.

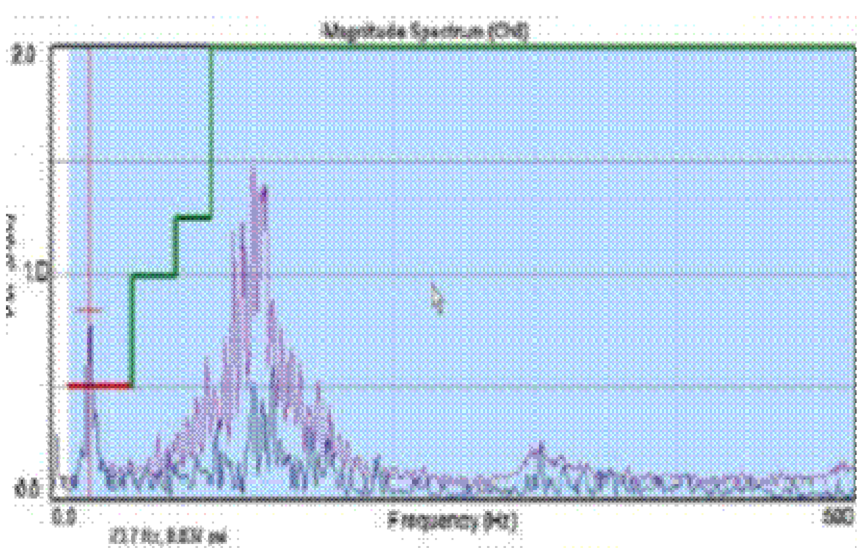


Figure 2-28
Dynamic Spectrum with 23.75 Hz Spike in Alarm, Amplitude is psi (0-PK) – Sewell 2004

Although small variations in spectra are likely to be present from one combustor to another due to variations in attenuations from different length tubing, frequency spectra should generally be similar for all combustors. Thus CDMS data can readily pinpoint combustors that may be in jeopardy for excessive vibration. In continuous CDMS applications, live spectra data coupled with analysis of engine operational data forms a powerful tool for online combustion diagnostics. In another test case illustrated in Figure 2-27, Sewell presents a case where a significant spike of over 2.0 psi occurred at 15.25 Hz, in position 16. This dynamic is typically outside the normal spectra envelope of the 501F DLN. The spike was accompanied by an increase in pressure pulsations in adjacent combustors at positions 1 and 15. Engine supervisory data also revealed an increase in

NO_x emissions and a small increase (below alarm level) in the blade path temperature variance. Boroscope inspection of affected cans revealed a broken pilot in position 16 combustor. It is not unusual that adjacent combustors also show an increase in dynamics because of their proximity to the affected combustor. In this case, repairs prevented a potentially significant damage if left unattended.

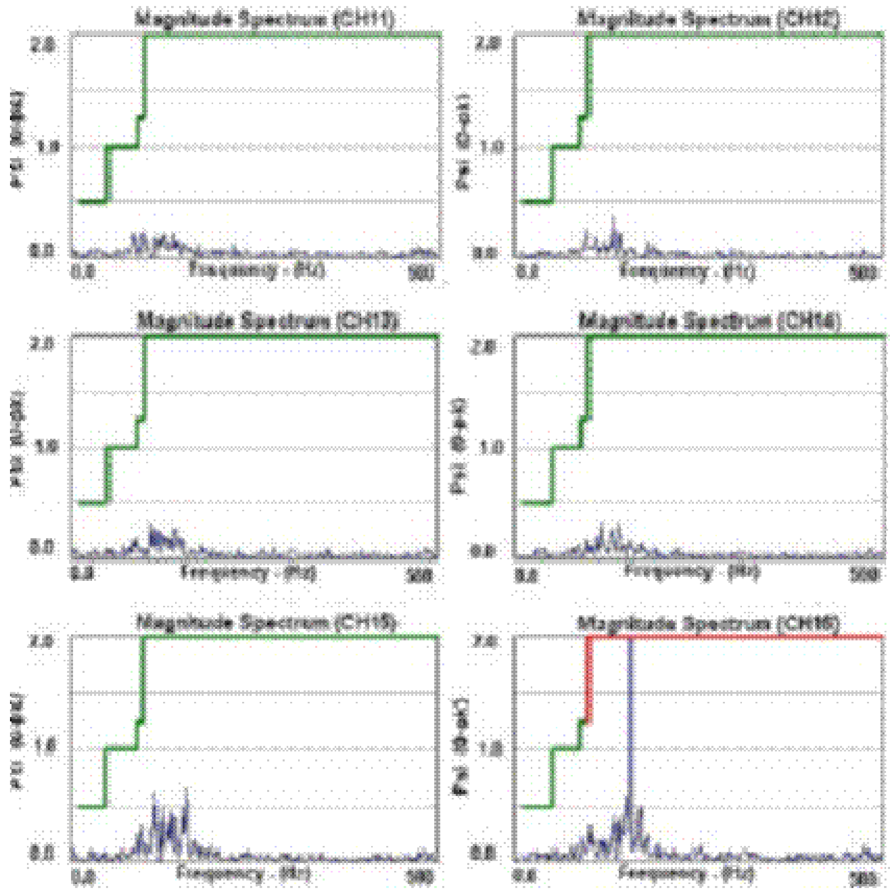


Figure 2-29
Initial Pilot Nozzle Failure Spectrum without Peak Hold

Amplitude in position 16 is above threshold and adjacent combustor is exhibiting same frequency – Sewell 2004. A third test case pointing to the benefits of online continuous CDMS and diagnostics of excessive CD is offered by one of the transition piece failure events that plagued the 501 FD fleet, engines equipped with compressor discharge bypass. In this case, excessive CD was monitored outside the typical range for this type of engine. Figure 2-30 shows spectra data on four combustors with a marked increase in dynamics in combustor 5 at 225 Hz coupled with some increases in adjacent combustors also in the same frequency range. An analysis of the time progression data showed a steady increase in pressure coupled with changes in the temperature spreads. The latter finally forced an engine trip only to reveal a cracked transition piece that allowed compressor air to cool the turbine inlet temperature.

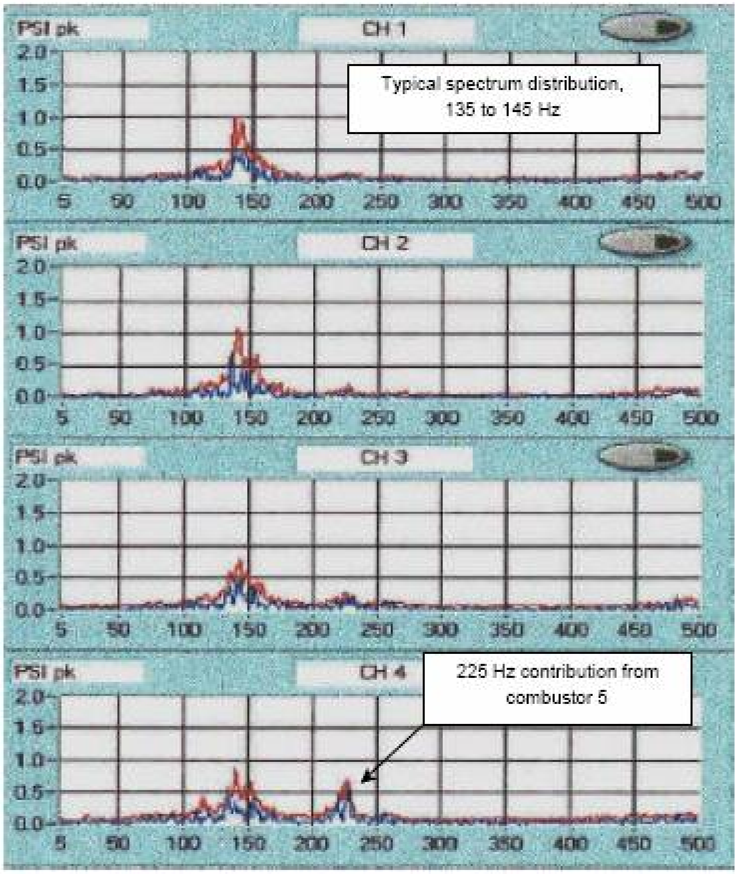


Figure 2-30
Combustors 5 thru 8 Early Indication of Transition Piece Failure (Combustor 5)

Red line is peak hold and blue line is live trace. – Sewell 2003.

Burner Balancing

The onset of equipment-damaging pressure pulsations in a premixed combustor is very sensitive to minute changes in equivalence ratios (air/fuel ratios). We know that changes in ambient temperature and humidity affect the quantity of combustion air to all combustors equally. On the fuel side, small changes in the mass of natural gas to each combustor can also be affected to such an extent that selected combustors can become much more prone to high levels of dynamics. This variability in fuel flows can be caused by nozzle erosion as well as obstructions caused by foreign contaminants in the fuel. These variations can occur among fuel nozzles in each combustor, and from combustor to combustor. The acceptable variability in the flow among fuel nozzles is typically less that 1 percent. This is not too surprising because at the low levels of equivalence ratios necessary for ultra low NO_x performance, even 1 percent change in fuel flow can result in significant changes in equivalence ratio to the extent that other factors can initiate the onset of unacceptable dynamic oscillations due to reduced flame stability.

The practice of burner balancing and flow check calibrations for each fuel nozzle is part of the maintenance process and is not really part of CDMS online diagnostic. However, we have included this section to highlight what may be an important aspect of preventive maintenance that can assist in keeping dynamics from occurring during periods known to be more susceptible to these combustion instabilities, e.g., cold weather conditions. In fact, OEMs and users alike are implementing a rigorous quality program to check that the flow to each nozzle falls within acceptable variance. This is especially the case when selected burners are replaced with refurbished ones are installed alongside a set of older, and perhaps more worn-out burners.

Figure 2-31 illustrates the level of variability that can occur among burners. This example is for a silo combustor. The as-found variability among the premixed burners shows 8.2 percent difference between the highest and lowest fuel flows. Similar variability was found for the pilot. After ultrasonic cleaning the burners have improved flow variability to 3.2 percent maximum. Replacement of orifices in selected burners further improved balancing to 1.4 percent maximum variability, within the OEM manufacturing tolerances. Similar improvement was achieved with pilot nozzles.

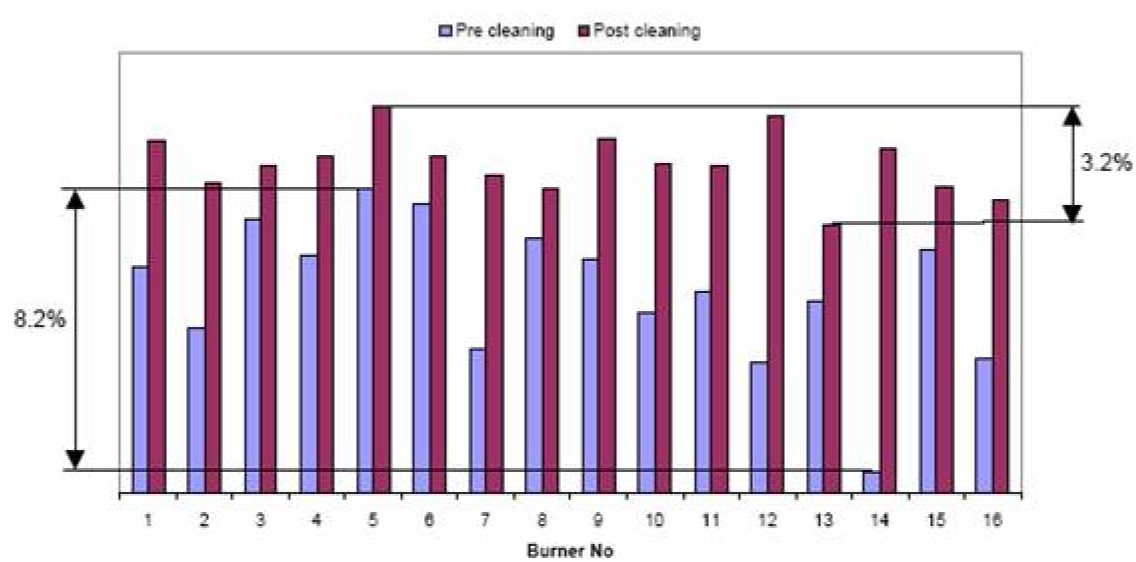


Figure 2-31
Premix Flow Distribution (Pre and Post Cleaning), McKenzie, 2004

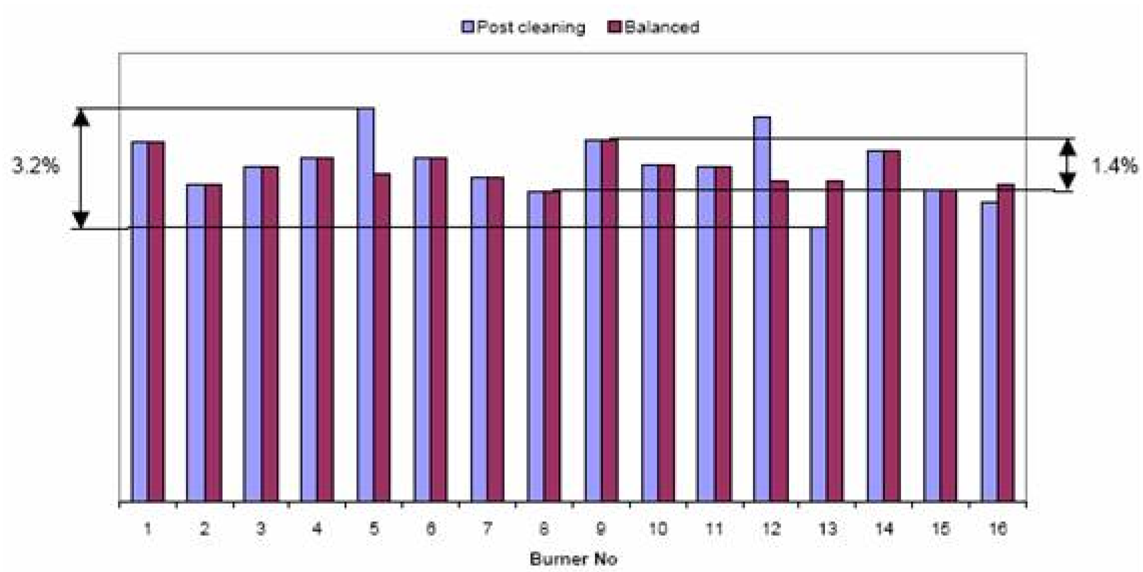


Figure 2-32
Premix Flow Distribution Pre and Post Balancing (Flow Trimmed Burners are 5, 12, 13 and 16)

3 TUNING PRACTICES AND GUIDELINES – GE DLN COMBUSTORS

The previous sections have highlighted the benefit of online continuous CDMS technology and showing how the diagnostic of CD data, along with relevant engine operating data, can be used not only to potentially avoid catastrophic hardware failures but to extend the life and inspection interval. Careful analysis of the CD data can provide an early warning signal that something is wrong. This leads to detailed diagnostic that in principle can minimize impacts on operation and reliability of modern DLN combustors.

Combustion tuning can be viewed principally as either reactive or proactive. Reactive tuning is in response to a CD event as described in the section on monitoring and diagnostic of CD data. This often requires online availability of CDMS, or at a minimum, a routine and frequent monitoring program targeting seasonal and other operating conditions that are more conducive to onset of CD, such as cold ambient condition, peak loads, and immediately following the retrofit of refurbished or new combustion hardware. Proactive tuning infers a more regimented combustion tuning program aimed at avoiding even the onset of CD but also optimizing performance. Though proactive tuning in general is less practiced, it is easy to see that the availability of online CDMS technology coupled with CEMs emissions data and engine supervisory data can readily offer this capability. In fact, OEMs and selected researchers are hard at work to address this capability and develop active controls, and diagnostic software to develop safe engine performance envelopes that minimize CD, and optimize performance of modern utility CTs. These controls can be implemented either locally by the operators, or in a more advanced scenario, implemented remotely via high-speed telecommunication links between the monitored site and the OEM’s centralized service center.

Combustion tuning in CT can also be differentiated among:

- Overall CT tuning
- Multi-can specific tuning
- Single can specific tuning

Each of these approaches depends on the type of event that is likely to affect dynamics. For example, changes in ambient temperature are likely to affect all combustors equally. Thus the combustion tuning associated with cold weather seasons may involve changes to overall fuel splits rather than combustor-specific changes. Replacement of nozzles, liners and other burner parts with refurbished equipment may affect both the air and fuel flows to affected combustors. In fact, it is highly recommended that whenever burner equipment is replaced, the air and fuel flows are carefully checked and calibrated to ensure adequate distribution among all combustors in such a way that selected combustors do not become more susceptible to CD because of minor changes in overall engine conditions or slow degradation of key passages over time. In fact, combustion tuning without first assuring that replacement parts meet the specifications necessary for adequate distribution to each combustor, can actually be counterproductive and detrimental to the performance of the specific combustor. Finally, combustion tuning may be required for a single combustor. This is often the case due to progressive or sudden hardware damage. But it can also point out the need to maintain important design tolerances in manufacturing that have become so critical to the performance of modern DLN combustors.

This section reviews the tuning practices and guidelines for GE DLN combustors. The information was obtained from users and from independent CDMS suppliers and tuners. In some case, the information reflects OEM guidelines and specific procedures. In those instances, the user is directed to the OEM for more detailed information and for direct implementation of recommended protocols.

GE DLN1 COMBUSTOR

The GE DLN-1 illustrated in Figure 3-1 is a two-stage premixed combustor. The combustion system operates in four distinct modes: primary, lean-lean, secondary, and premix. At full load, the standard settings calls for 17 percent of the fuel to flow through the secondary center nozzle that provides a diffusion pilot flame for enhanced combustion stability and 83% through the five primary lean premix nozzles that give this combustor design its ability to reach 9-ppm NO_x emission performance. Recent design modifications of GE’s DLN-1 combustor at both GE and Power Systems Manufacturers LLC (a division of Calpine) have further improved NO_x performance with a combustor capable of 5-ppm emissions and stable combustion. Thus, because of its combustion characteristics, the tuning experience in response to CD induced instability is relatively minor. Furthermore, many DLN1 are installed on peakers which see operation during typically warmer months.

Figure 3-2 illustrates the gas fuel system for the DLN-1 as supplied by GE. In its OEM configuration the Gas Splitter Valve (GSV) sets the split between primary and secondary fuel according to the Speed Ratio and Gas Control valves and engine load. Increasing the amount of fuel to the secondary center nozzle provides a richer diffusion fuel flame in the center thus creating greater overall flame stability. In general, because of its design, the DLN-1 combustor has had very little experience with unacceptable combustion dynamics and CD-caused hardware damage. Although many of the current 7EA fleet equipped with DLN-1 combustors are operating few hours per year as simple cycle peakers, these combustors have had little or no reported CD problems. This is in contrast to their ability to operate reliably with 9 ppm NO_x emissions or lower. Nonetheless, GE has developed a DLN1 tuning protocol that is based on optimizing the primary/secondary gas split by implementing small changes to its preset standard 83/17 percent split. Generally, only minor adjustments have been proven necessary to prevent CD from affecting operation. This is due in part to the inherent stability of this particular combustor design and in part to the primary application of 7EA engines employed in peaking cycle duty, operating during the day when higher ambient temperatures are more favorable to stable combustion.

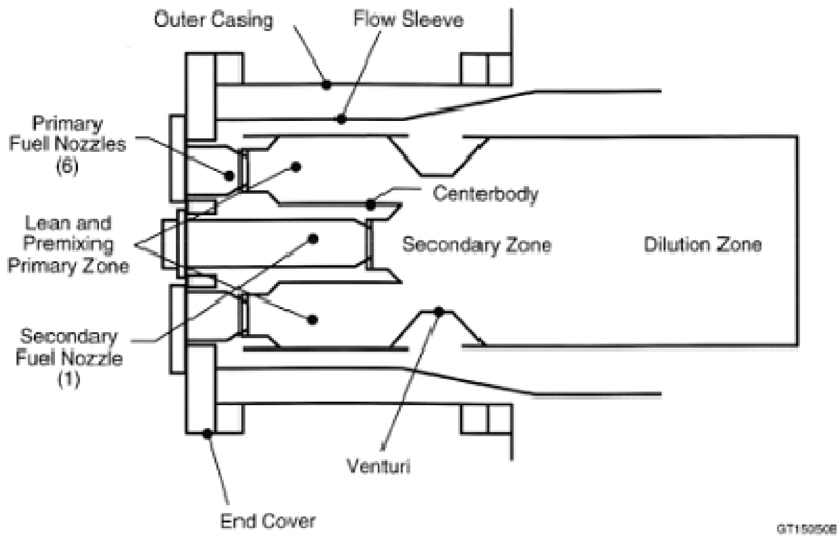


Figure 3-1
Dry Low NO_x Combustor GE 3586G

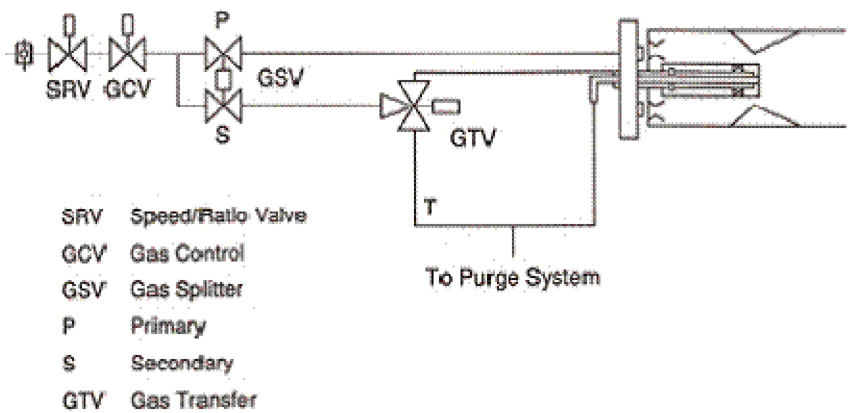


Figure 3-2
Dry low NO_x Gas Fuel System – DLN 1.0 GE 3586G

Figure 3-3 illustrates the DLN1 combustion tuning process map prepared by the OEM. The procedure calls for the CDMS (generally only a portable one has been needed) working in tandem with a calibrated continuous emission monitoring (CEM) system and GE MK5 supervisory data. The procedure calls for setting the full-load fuel split to achieve a 9-ppm or lower NO_x emission performance as illustrated in Table 3-1. Then, using isotherm runs at 1100 F, then either at 1090 or 1110 F to establish acceptable NO_x, CO, and O_2 emissions as well as temperature spreads. The isotherm run sheet is illustrated in Table 3-2.

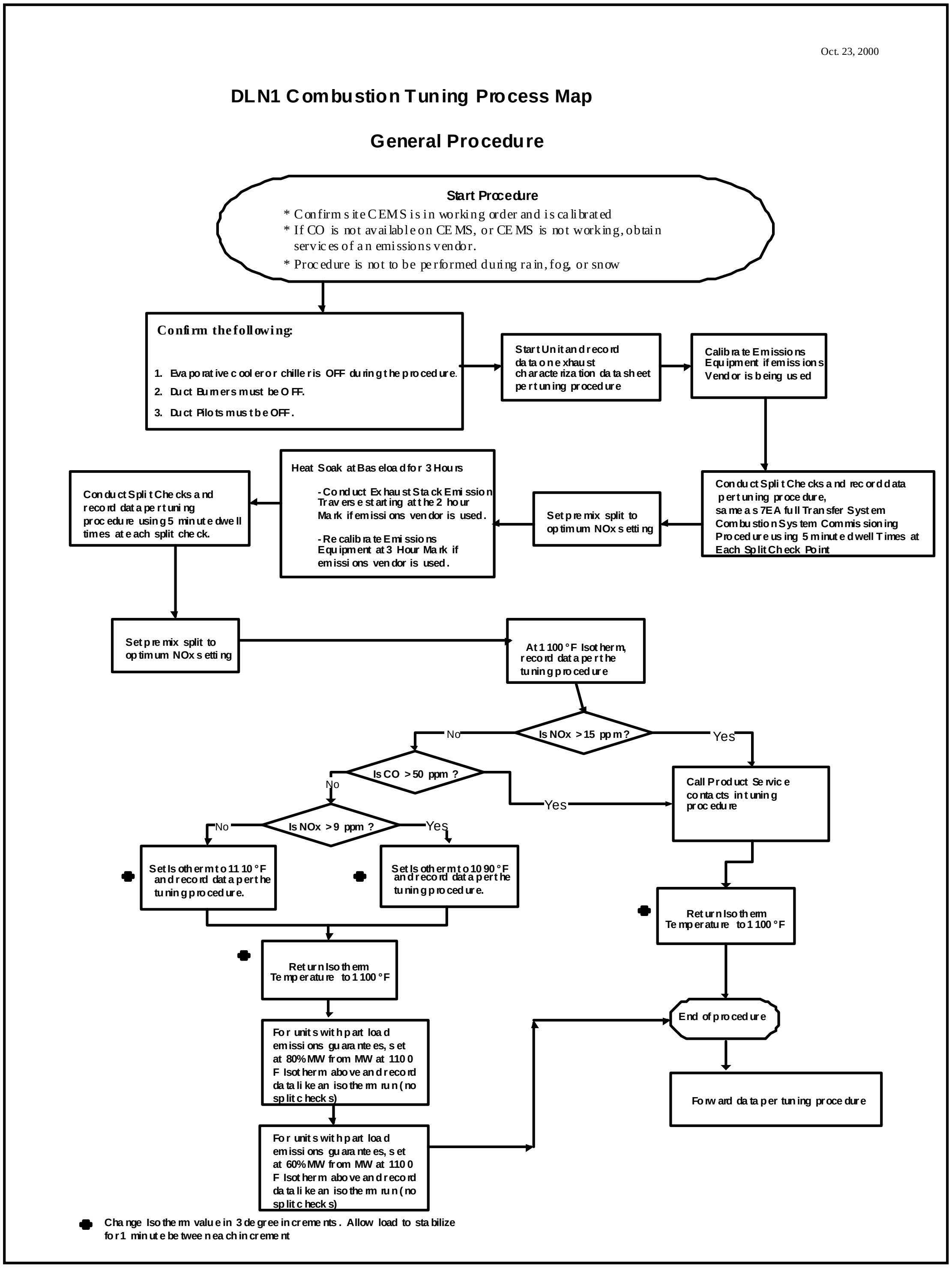


Figure 3-3
DLN1 Combustion Tuning Process Map

Table 3-1
DLN1 Combustor Premix Gas Split Optimization Data Sheet

Begin Split Check Ambient Temp			62			
Begin Split Check Wet Bulb Tem			54			
Test	Split FXSP	Load	TTRF1	Nox	CO	O2
Point	% - Primar	MW	deg F	Ppm	Ppm	%
1	81 (FSRGS	82.1	2022	9.8	2.2	15
2	81.5	81.8	2023	9.2	2.4	15
3	82 (FSRGS	81.5	2025	9.5	1.7	15
4	82.5					
5	83 (FSRGS	82.6	2023	9.8	2	15
6	81 (FSRGS= %)					
7	80 (FSRGS= %)					
8	79 (FSRGS= %)					
9	78 (FSRGS= %)					
10	77 (FSRGS= %)					
11	81 (FSRGS= %)					
12	Optimum					
End Split Check Ambient Tempe			63			
End Split Check Wet Bulb Temp			54			
Post Heat Soak Formal Split Che			2:45 PM			
Begin Split Check Ambient Temp			68			
Begin Split Check Wet Bulb Tem			60			
Test	Split	Load	TTRF1	Nox	CO	O2
Point	% - Primar	MW	deg F	Ppm	ppm	%
1	81 (FSRGS	79.5	2021	8.7	0	15
2	81.5	79.9	2023	8.4	0	15
3	82 (FSRGS	79.2	2023	8.2	0	15
4	82.5	79.5	2023	8	0	15
5	83 (FSRGS	79.3	2025	7.8	0	15
6	83.5	79.2	2023	7.7	0	15
7	84 (FSRGS	79.3	2024	7.9	0	15
8	79 (FSRGS= %)					
9	78 (FSRGS= %)					
10	77 (FSRGS= %)					
11	81 (FSRGS= %)					
12	Optimum					
End Split Check Ambient Tempe			68			
End Split Check Wet Bulb Temp			59			

Table 3-2
DLN1 Combustor Isotherm Run Datasheet

DLN1 Combustor Isotherm Run Datasheet (Do Not Perform Runs During Rain, Fog, or Snow)		
Customer	Site	Unit#
A:	Date:	Serial #

Category	**Parameter**	**Header**	**Isotherm 20min Start**	**Isotherm 20min Finish (ave.)**	**Isotherm 20min Start**	**Isotherm 20min Finish (ave.)**
Environment	Time of Day		11:20	11:40	12:20	12:40
	Tambient (Dry Bulb)		32	34	35	37
	Tambient (Wet Bulb) OR Relative Humidity		32	27	27	27
	Pambient (psia or in-Hg)	AFPAP	29.5	29.4	29.4	29.4
	Evaporative Coolers (on/Off)		Off	Off	Off	Off
	IGV angle	CSGV	84.1	84	84	84
Temperatures	Tinlet (F)	CTIM	28	46	37	48
	Tcd (F)	CTD	645	649	645	651
	Treference (F)	TTRF1	2040	2044	2025	2028
	Tex (F)	TTXM	993	1001	982	989
	Tex spread-1 (F)	TTXSP1	49	42	43	43
	Tex spread-2 (F)	TTXSP2	43	41	42	41
	Tex spread-3 (F)	TTXSP3	43	40	39	40
Pressures	Pcd	CPD	174.0	169.3	173.8	169.8
	dP Inlet (in.H2O)	AFPCS	2.3	2.2	2.2	2.3
	dP Outlet (in. H2O)	AFPER	2.5	2.4	2.2	2.3
General	Indicated Fuel Split	FSRXSR	84.00	84.00	84.00	84.00
	Load (MW)	DWATT	88.0	83.6	87.5	83.8
	Fuel Flow (pps)	FQG	12.36	12.07	12.31	11.96
	Splitter Valve Feedback	FSRGS	82.02	82.09	82.02	82.01
	% IBH Flow	COBHP	0.86	1.85	0.16	1.17
Emissions	NOx – raw (ppm)		9.4	8.8	7.5	7.5
	CO – raw (ppm)		8.9	6.6	26.7	16.8
	% O2		15.1	15.1	15.1	15.15
Performance	Total Airflow (pps)	AFQ	671.4	662.8	675.7	661.6
	Pressure Ratio	CPR	13.11	12.78	13.19	12.82
	Shaft Speed (rpm)	TNH-RPM	3599	3600	3599	3598
	Power Factor	DPF	1.000	1.000	1.000	0.999
	Fuel Temp	FTG	87	87	87	87
	Fuel LHV					
Control		TTKXCOEF	1.000	1.000	1.000	1.000
Constants		TTK0 I	1100	1100	1090	1090
		TTK0 C	8.65	8.65	8.65	8.65
		TTK0 S	24.5	24.5	24.5	24.5
		TTK1 I	1100	1100	1090	1090
		TTK1 C	8.48	8.48	8.48	8.48
		TTK1 S	23.2	23.2	23.2	23.2

If possible get a second reference in addition to AFPAP – e.g. Local Airport,

Values of NOx and CO we would like to see

Values of O2 less than 14.9 and greaqter than 15.2 are

GE DLN 2.0 COMBUSTOR

High firing temperatures of the GE “F” class engines necessitate combustors that release more energy per unit of volume. These high volumetric heat release rates require strong turbulent mixing rates in the combustor primary zone, which can be realized by increasing the pressure drop in the combustor. The increased turbulence intensity associated with the enhanced mixing produce a strong source of broad band acoustic pressure unsteadiness. The white noise can couple with acoustic resonant modes of the combustion chamber or with other components such as the fuel supply system and produce intense pure tones known as combustion dynamics. An example of a spectrum of pressure pulsations caused by interaction of the combustion pressure waves with the natural gas fuel supply system is shown in Figure 3-4. When the chamber pressure, near the fuel nozzle, increases due to an acoustic wave in the chamber, the fuel flow is reduced. Conversely, a decrease in pressure near the fuel nozzle causes an increase in fuel flow. A positive destabilizing feedback loop is established when the increased fuel injection, results in increase energy release which in turn increases the driving of the pressure waves. The increased pressure results in decreased fuel injection, which reverses the cycle by decreasing the energy release and thus the combustor pressure. This feedback loop, which is causing amplified pressure pulsations can occur only when a low fuel-nozzle pressure drop exists, permitting such effect on the fuel flow rate. In order to determine an acceptable range of fuel-nozzle pressure drops, stability maps (Figure 3-5) have been developed from tests run on the Gas Turbine machines. This map is used to select fuel-nozzle designs, which ensure stable system operation. The latter burners consist of 15 nozzles that enrich the combustion air with fuel before entering the premix burners. In this way the capacity of the premix burners is increased and an extra possibility to stabilize the flames is created.

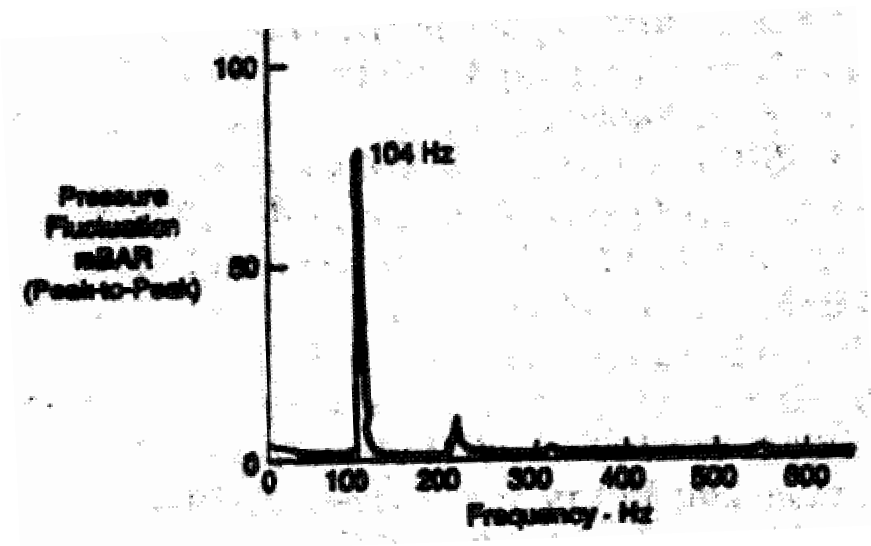


Figure 3-4
Combustion Dynamics Spectrum with Gas Operation of an “F” Class GT due to Interaction with the Fuel System

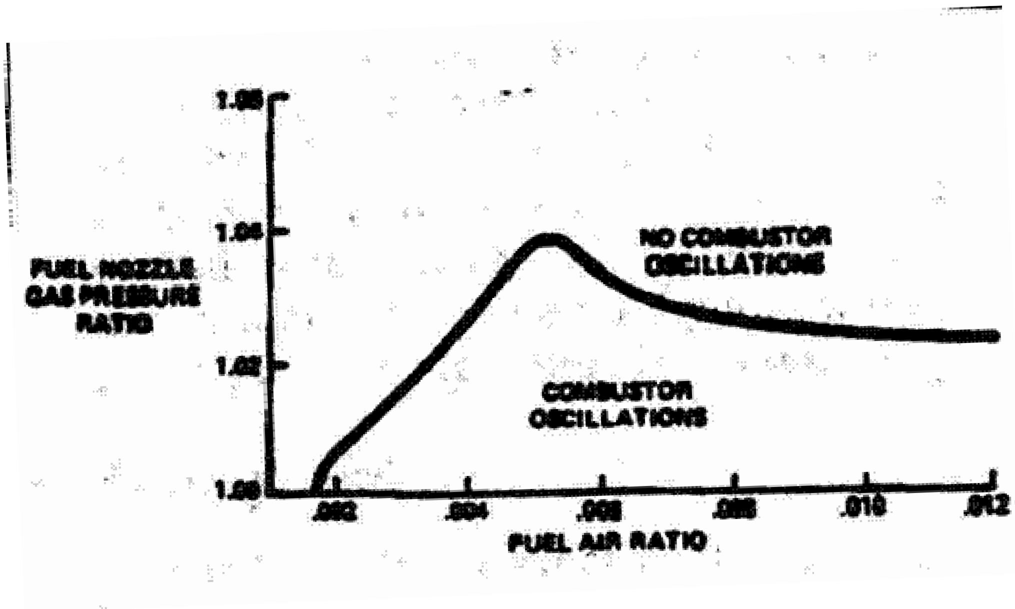


Figure 3-5
Stability Map of an "F" Class GE GT for Tuning a Necessary Pressure Drop Level at the Fuel Nozzle

Figures 3-8 through 3-13 illustrate the key elements of the DLN 2.0 fuel nozzles, cap and combustor liner. The primary supply feeds the diffusion burners that are used for start-up and for stabilisation of the premix burners. There are four secondary burners and one tertiary burner. These are lean premix burners of the DLN 2.0 system, where DLN stands for Dry Low NO_x. Premix burners are only used at higher loads. The tertiary burner comes in first, assisted by four primary diffusion burners. This is called the lean-lean mode. Subsequently the four secondary burners with the four diffusion burners situated in the middle of these premix burners raise the power output to 50-70% of base load. Then the diffusion burners are switched off and the premix steady state is reached. In this mode the quaternary burners come in. The diffusion burner inside the tertiary burner is not connected to the primary gas supply in the present GE DLN2.0 burner system.

The different regimes during run-up of power are:

- **Primary Mode**- gas through the four diffusion burners only
- **Lean-Lean Mode**- gas through the diffusion burners and the tertiary burner
- **Piloted Premix Mode**- the four diffusion burners and all premix burners are on
- **Premix Steady State Mode**- all premix burners and quaternary burners on

An important design feature of the DLN 2.0 is its fully premixed operation at full load. This makes the combustor more susceptible to minor changes in equivalence ratio and ambient temperatures.

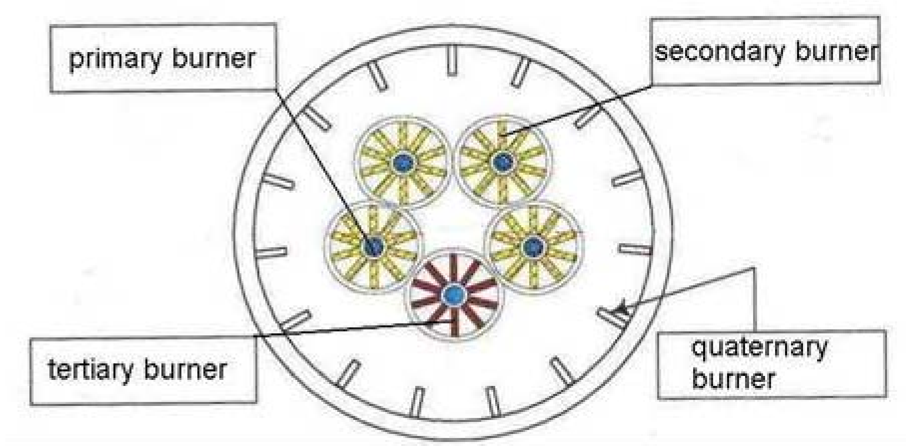


Figure 3-6
Cross-Section of the Four Types of Burners Present in a GE DLN 2.0 Gas Turbine Combustor

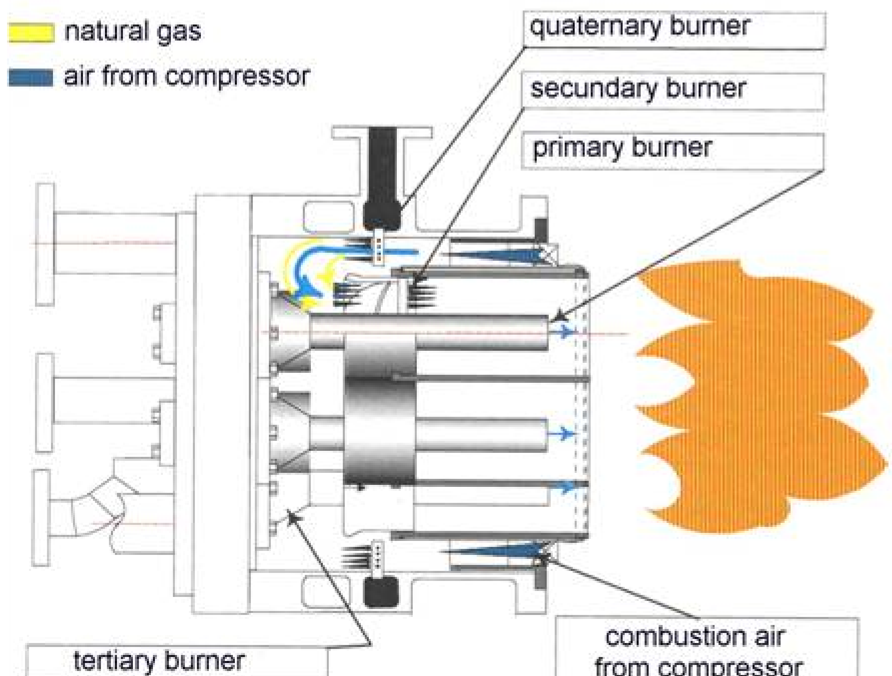


Figure 3-7
Side View of the Burner System of the DLN 2.0 Gas Turbine Combustor

Figure 3-8
Upstream Part of the Combustion Chamber with the Outlet of the Five Premix Burners and Embedded Diffusion Burners. The Burners are also Shown Separately.

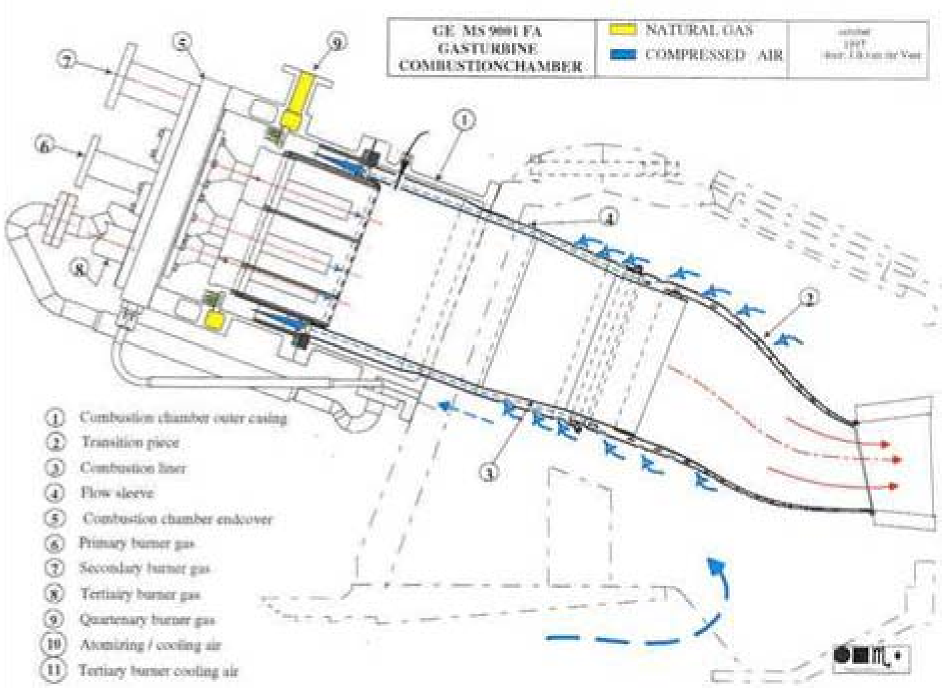


Figure 3-9
Cross Section of the Combustor of a GE FA Class Gas Turbine

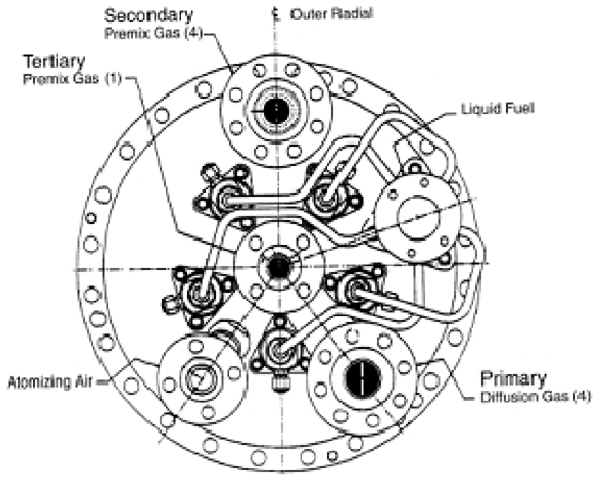


Figure 3-10
External View of DLN-2 Fuel Nozzle Mounted

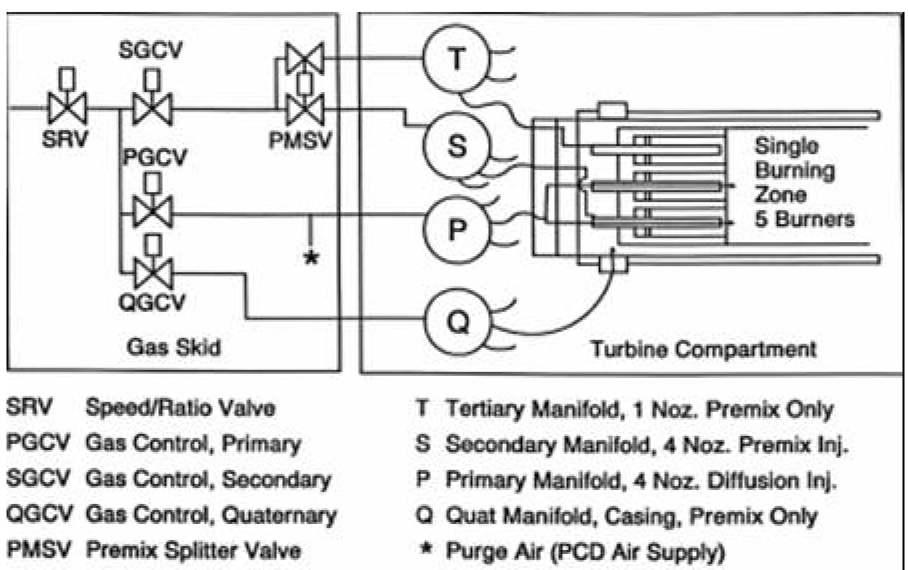


Figure 3-11
DLN-2 Gas Fuel System

To achieve the required emission performance in premix operation the combustion occurs close to or even below LBO when it is sustained only by tertiary gas flow. Flame instability and dynamics can develop if operating parameters are outside the design limits. The consequences of dynamics could be combustion chamber failure leading to forced GT outage, increased maintenance, reduced life, and high emissions.

The key parameters affecting the combustion process are:

- Air flow and its distribution in the combustor
- Inlet air pressure and temperature that are influenced by ambient conditions, compressor performance, load, grid frequency
- Gas supply pressure in which small fluctuations can lead to dynamics
- Gas flow rate
- Fuel nozzles and combustion chamber design and condition

Frequency spectrum of the 7FA DLN 2.0 shows a fundamental mode of 90 Hz and a harmonic of 130 Hz. The peak values depend on the fuel split between the secondary and tertiary fuel flows. The quaternary fuel reduces the 130 Hz mode but amplifies the 90 Hz. The target values are dynamics below 2 psi peak to peak and NO_x below 25 ppm. The variation between each combustion chamber and the differences in air flow between them necessitate individual tuning of each unit. Once this is done, retuning is needed only when the combustion chambers are dismantled.

In order to prevent spreading of instabilities from one combustion zone to the other through the fuel system, the fuel nozzles were modified to become “softer”. This means that the effect of pressure fluctuations in the combustion chamber on the gas supply pressure were minimized by installing an orifice upstream of the nozzle. This prevented the propagation of pressure fluctuations between different combustion zones through the common fuel pipe. The pressure drop across the swirler was increased to increase swirl number and thus enhance mixing. This resulted in increased flame stability without significant penalty in GT efficiency.

Even though the combustion chambers were constructed identically with the same nominal design of inlet and outlet pressures, there was variation between them. This could result in excessive tertiary fuel flow to suppress dynamics in the worth combustor unit, resulting in excess NO_x. The solution was to tune the system such that each zone gets the amount of fuel to match the different airflow. A fuel valve was added in the secondary gas fuel lines downstream of the secondary/tertiary flow split valves. Individual tuning is achieved by monitoring the pressure on each unit while changing the fuel flow rate. After initial tuning, no retuning is necessary unless fuel nozzles or combustion chambers are changed. The tuning is done by GE engineers and requires 4 hours. The turndown of a DLN-2 combustor tuned to 9 ppm NO_x and CO was estimated to be about 70% load, compared with 40% load for the 25 ppm NO_x and 15 ppm CO system

In DLN2.0, combustion instabilities are known to manifest themselves principally at the following FFT frequency bands:

- Band 1: Less than 140 Hz
- Band 2: 140 to 500 Hz
- Band 3: Greater than 500 Hz

Specifically, large resonant amplitude at specific frequencies indicates the following combustion instabilities:

- 10 Hz – Flameout
- 70 Hz – Chug
- 100 Hz – Flashback (axial instabilities)
- 175 Hz – Vibration (radial Instabilities)
- 200 Hz – Screech

Figure 3-14 shows the scan obtained on March 14, 2002 at 03:02:20. The bar charts indicate the alert levels when amplitudes reach set points. Table 3-1 shows data on engine operation that needs monitoring along with CD data in each combustor. For Band 1, the set points are at 2.4 and 2.6 psi. For Band 2, the set points are at 3.0 and 3.5 psi. For Band 3, the set point is at about 4 psi. Although Band 2 set limit is at 3.5, combustor damage due to vibration does not occur until amplitudes of 4.5 to 6 psi are reached. Therefore, the set points are established to give the operators sufficient time to adjust fuel flows and bring amplitudes back to the normal operating range with no impact on hardware.

For this particular frequency scan, only vibrational instabilities were sufficiently high to approach set points in some of the cans, specifically can number 2 and 10. Adjustments to the fuel flow for the affected cans are made only when the set points are reached. The data in Table 3-1 must be evaluated in conjunction with the FFT scans to obtain an overall evaluation of the changes that might have occurred to affect CD in a particular combustor and an accurate status of the combustion stability in the turbine. Table 2 includes key engine operating data, such as compressor inlet temperature (42 F), turbine load (167.5 MW), total fuel flow (20.91 lb/sec) and current secondary/tertiary (S/T) split and Quaternary fuel flow at 9 percent of the total. As indicated, the S/T split for that day was set at 77.38, which is slightly less than the even 80 (S)/20 (S+T) split, indicative of equal gas flow to the secondary and tertiary nozzles. PGE has found that the combustors operate more stably with a split in the range of 76 to 79.

When the CD scan shows an unacceptable amplitude for any of the 14 cans (i.e., pressure amplitude nears or exceeds the alert set points), an adjustment is made to the secondary fuel flow. This is possible by installing a manually controlled valve in the PM2 line to each combustor. Figure 3-15 and 3-16 show the placement and manual adjustment made to the valve.

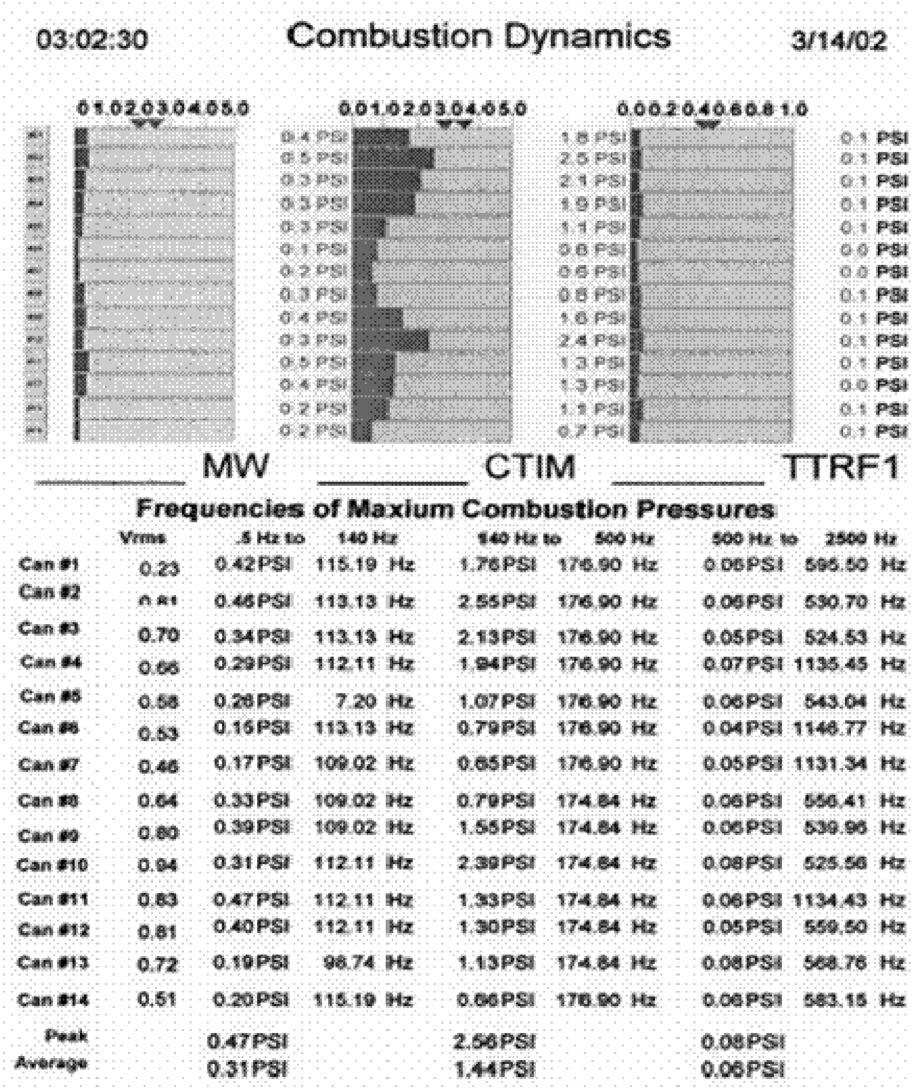


Figure 3-12
DLN 2.0 CDMS Signal Display Showing Combustors 2 and 10 CD Approaching Alarm Limits

Table 3-3
User Defined Display – 7FA (Reproduced Form Printout)

Signal	Description	Value	Units	Signal	Description	Value	Units
STATUS	Base Load			WI_PPR	WI Press Ratio	0.95	prs_R
DLN MODE	Premix			AA_PPR	Atom Air Press Ratio	0.97	prs_R
TTRF1	Combustion Ref Temp	2356	deg F	LF_PPR	Fuel Oil Press Ratio	0.96	prs_R
DWATT	Load	167.5	MW	AAMANPR	Atomizing Air Pressure	-7.6	psi
CSGV	IGV Angle	88.1	DGA	WICHKPR	Water Injection Pressure	-2.8	psi
FSRXSR	Primary Split (P/(P+S+T+Q)	0.00	%SPLT	LFCHKPR	Fuel Oil Pressure	-0.4	psi
FSRXPR	Secondary Split (S/(S+T))	77.38	%SPLT	FSGR	SRV Position Feedback	57.83	%
FSRQT4	Quaternary SpltQ/(P+S+T+Q)	9.00	%	FSRP	Fuel Split Primary	0.00	%
FXKSPMSB	Premix Split Bias	0.00	%SPLT	FSRS	Fuel Split Secondary	60.16	%
FQLM1	Liquid fuel Mass Flow	0.00	#/sec	FSGX	Fuel Gas Cont VIv LVDT (Premix)	63.95	%
WQ	Water Injection Flowrate	0.00	#/sec	FSGQ	Fuel Gas Cont (VIv LDTV (Qt)ua	13.86	%
CSRBH	DLN Bleed Heat Flow	3.00	%	CPR	Compressor Press Ratio	15.40	prs_R
CTD	Compressor Disch Temp	706	deg F	FQG	Fuel Gas Mass Flow	20.91	#/sec
CPD	Compressor Disch Press	213.3	psi	FSR	Fuel Stroke Reference	66.15	%
CPDABS	Comp Disch Absolute Press	228.2	psi	FXKSPMSB	Premix Split Bias	0.00	%SPLT
TTRX	Exhaust Temperature	1093	deg F	FXKSPMSBMX	Premix Split Bias Set (max)	1.25	%SPLT
TTXM	Mean Exhaust Temperature	1093	deg F	FXKSPMSBMN	Premix Split Bias Set (min)	-3.00	%SPLT
TTXSP1	Exhaust Spread 1	81	deg F	CMHUM	Fuel/ Air Ratio	0.0048	#H/#A
TTXSP2	Exhaust Spread 2	69	deg F	AFPAP	Atmospheric Press	30.4	in Hg
FTG	Fuel Gas Temp	56	deg F	CTIM	CT Inlet Temp	42	deg F

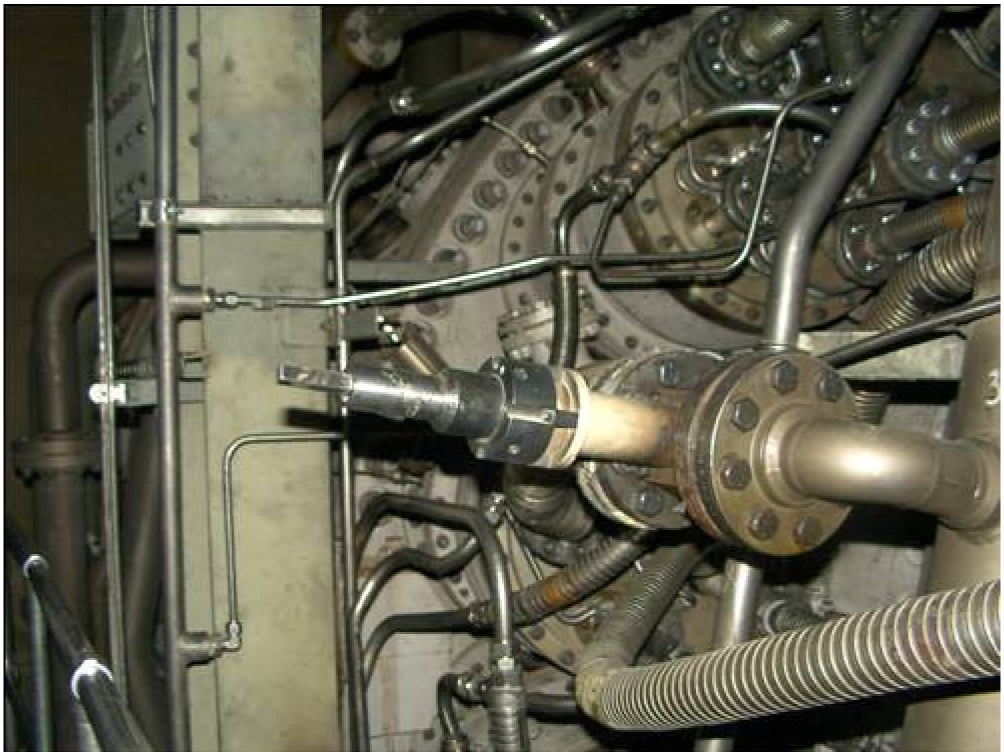


Figure 3-13
Another View of the Secondary Gas Flow Tuning Valve Serving Can Number

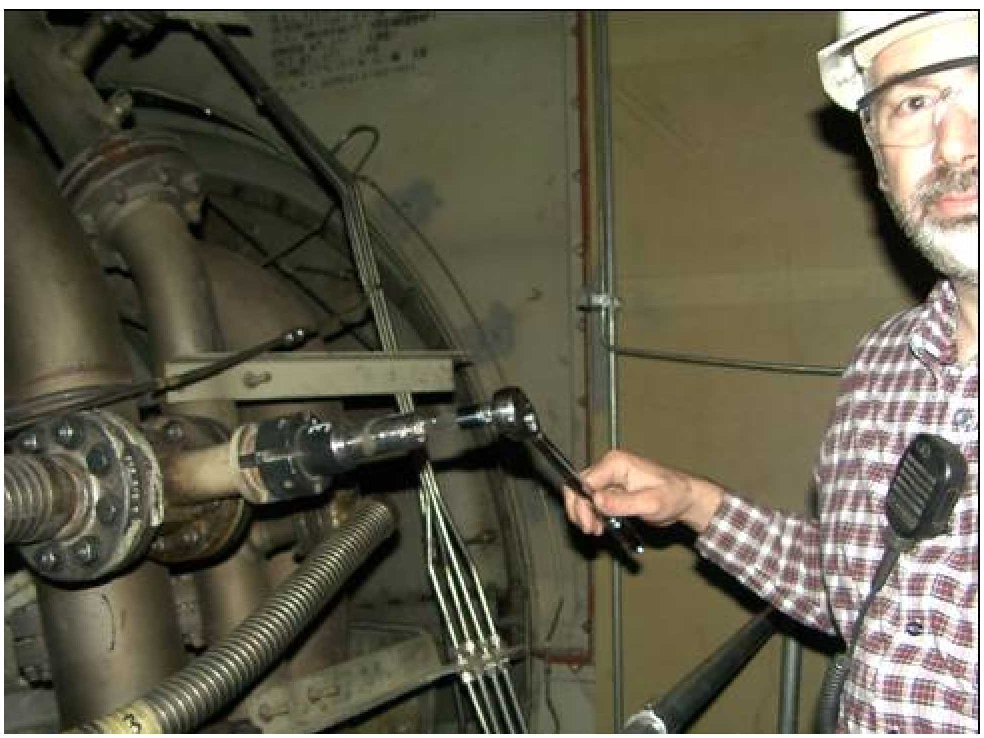


Figure 3-14
Manual Adjustments to Secondary Fuel Flow to Affected Combustor Can

Whether tuning for axial dynamics or exhaust spread in the DLN2.0, the tuning valves should all start 12 turns from full closed position. Since there is no mechanical stop at full open, the valve position is referenced to the full closed condition and then opened 12 full turns to reach the full open position. The effect of the tuning valve on the secondary fuel flow is shown in Figure 3-17. As shown, because the effect is not linear, one has to maintain accurate record of the valve position at all times to generate new adjustments.

The steps for tuning for dynamics are as follows:

- Take a reference dynamics scan of all combustors
- Locate the combustor with the highest dynamics (pressure amplitude)
- Note the position of each combustor with high dynamics in relation to all the other affected combustors (dynamics in adjacent combustors can be affected by one mistuned combustor)
- Reduce secondary fuel to the affected combustor in 1 to 2% steps either up to 8% or to where a different combustor has the highest dynamics. A new dynamics scan should be taken with each step.
- Repeat the step above with each of the affected combustors, even new ones affected by the last change
- If the dynamics continues to be excessive with a full 8% reduction, additional tuning can be tried by cutting fuel to the adjacent combustors. If no effect, return the secondary fuel to the adjacent combustors to the same level and cur the secondary fuel to the affected combustor to a maximum of 10%

As noted in Figure 3-17, small or large number turns in the valve can produce 1-2% fuel changes, depending on the valve's position from its fully open position. Normal temperature spreads in fully premixed combustion should register levels below 80 ^oF. Tuning of combustors is also necessary if the spreads are in excess of 100-140 ^oF. In this situation, the fuel to the combustor responsible for the recorded increase in temperature spread should be reduced in 1-2% incremental steps. Each percent reduction in fuel should reduce the exit temperature by 10 ^oF.

Tables 3-2 and 3-3 provide general tuning and OEM diagnostic guidelines for the DLN2.0 combustors.

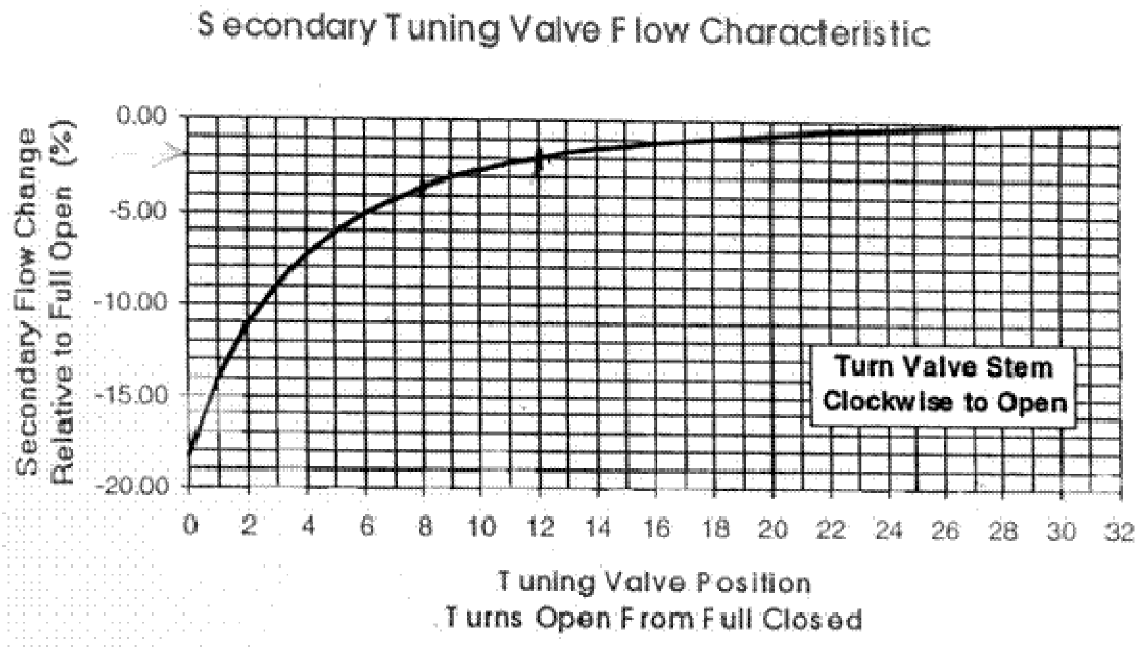


Figure 3-15
Secondary Tuning Valve Flow Characteristics for DLN2.0 Tuning

Table 3-4
DLN-2 Fuel Split Effect on Emissions and Dynamics

Symptom	**Possible Causes**
High NO_x	Tertiary split too high. Quaternary too low
High CO	Tertiary split too high
High 150-180 Hz Dynamics	Tertiary and quaternary splits too low
High 100-130 Hz Dynamics	Quaternary split too high. Tertiary too low

Table 3-5
Matrix of DLN-2 Operational Problems and Tuning Fixes

Problem/Symptom	Cause	Actions
High spread and/or flameout during the premix transfer	Secondary split too high	Decrease secondary split bias by one percent
	Premix transfer in temperature too low	Lock unit out of premixed mode, load unit to 50 °F above normal premixed transfer temperature, unlock premixed mode. If successful contact engineer regarding permanent change to transfer temperature
	Blockage in secondary fuel passage to one or more combustors	Repeat to verify spread locations, check pigtails in suspect chamber(s) and /or flow check the passages
High spreads due to “hot spot”	Missing quaternary, flange orifice fuel nozzle defective or damaged missing fuel nozzle seals	
	Tuning valve left full closed blockage in secondary, or quaternary feed over aired or under fueled chamber	

GE DLN 2.6 COMBUSTOR

The only utility-scale gas turbine currently marketed with single-digit NO_x guarantees is GE Power Systems Frame 7FA outfitted with DLN-2.6. The new DLN combustion system, the “DLN-2.6,” has entered commercial operation with emission levels of less than 9 ppm NO_x corrected to 15% O_2 and less than 9 ppm CO from approximately 50 to 100 percent load at “F” class conditions while operating on natural gas. These results were achieved on a GE MS7001FA (7FA) with a firing temperature of 23~5°F. The first of these units was placed in service in March 1996 by Public Service Co. of Colorado. The DLN-2.6 combustor evolved from the DLN-2 system that operates at 25/15 ppm NO_x /CO emissions. This required 6% more air to pass through the premix nozzles in the combustor due to reductions in cap- and liner-cooling airflows and increased cooling effectiveness. In addition to achieving single digit emissions and extended turndown, the DLN-2.6 improves low load CO and UHC emissions relative to the DLN-2. This new system can be retrofit to existing 7FA DLN-2 gas turbines. Emissions performance of the DLN-2.6 is 9 ppm NO_x and CO over a 50% load range.

The new combustor configuration was developed based on the DLN-2.0 burner because of its desirable flame-stabilization characteristics and operating experience. DLN systems achieve low NO_x levels by operating at very lean conditions. NO_x production is highly dependent upon flame or reaction zone temperature as proposed by Zeldovich (1946). The excess air dilutes the flame zone in a manner that suppresses peak reaction zone temperatures and minimizes NO_x production. Reduction of NO_x levels from the DLN-2 at 25 ppm to 9 ppm required that approximately 6 percent additional air needed to pass through the premix nozzles. This change was accomplished through reductions in cap and liner-cooling flows that necessitated improved cooling effectiveness. Lower flame temperatures reduced NO_x production rates.

However, without changes in staging, turndown would have been adversely impacted. The key feature of the new configuration is the addition of a sixth burner located in the center of the five existing DLN-2 burners. Figure 3-18 shows the nozzle arrangement of the DLN2.6. The presence of the center nozzle enables the DLN-2.6 to extend its 9 ppm NO_x and CO turndown well beyond the five-burner DLN-2.0. By fueling the center nozzle separately from the outer nozzles, the fuel / air ratio can be modulated relative to the outer nozzles. The fuel / air ratio in the center burner can be reduced below its local lean flammability limit while maintaining the outer burners above their lean limit. In this way, the overall combustor fuel / air ratio can be reduced to a lower value than would otherwise be possible with uniformly fueled burners.

A new staging scheme was proposed to start the machine and operate at low load in premixed mode. Otherwise, addition of this center nozzle to the DLN-2.0 system would have required five fuel manifolds for the DLN-2.6 compared to four on the DLN-2. The new configuration uses four circuits with three premixed manifolds staging fuel to the six burners, plus a fourth premixed manifold, quaternary fuel to reduce combustion dynamics. The first three premixed manifolds, designated PM1, PM2, and PM3, are configured such that any number (1 to 6) of burners can be operated at any time. The PM1 manifold fuels the center nozzle, the PM2 manifold fuels the two outer nozzles, and the PM3 manifold fuels the remaining three outer nozzles. Development of the 9 ppm NO_x system was accelerated through application of DLN-2.0 technology and hardware. The outer fuel nozzles are identical to those used by the DLN-2.0 system, where they have been proven to provide excellent premixed flame stability and strong premixing performance over the necessary operating range. The center nozzle is similar but with simplified geometry to fit within the available space. The presence of the center nozzle enables the DLN-2.6 to extend its turndown beyond the five-burner DLN-2.0. By fueling the center nozzle separately from the outer nozzles, the fuel / air ratio can be modulated relative to the outer nozzles. The fuel / air ratio in the center burner can be reduced below its local lean flammability limit while maintaining the outer burners above their lean limit. In this way, the overall combustor fuel / air ratio can be reduced to a lower value than would otherwise be possible with uniformly fueled burners. The liner cooling method evolved from the DLN-2 configuration that uses enhanced convection of the outer surface.

The fully premixed low NO_x DLN2.6 system has 6 fuel nozzles that need to be fired at a certain sequence from ignition to full load. Therefore, there are 6 modes of operation as shown in Figure 3-19. The quaternary fuel is used for tuning to control dynamics especially when ambient temperature is low.

In regard to the use of quaternary fuel, it depends on the individual tuning of each site. It is usually not used unless the unit runs below 35F ambient temperature or when the fuel is preheated (360F) on the DLN2.6 unit. Gas quality including 1% hydrogen in fuel can have effect on dynamics. Pressure drop of 430-500 psi in gas supply line can be handled with no problem but gas temperature had to be lowered from 360 F to 320 F to avoid dynamics.

The combustion system is typically set to a standard fuel split and then tuned around it by changing the PM3, PM2 and quaternary split by ±2%. The tuning is required to balance between stability, dynamics, and NO_x and in the E class machines also CO. On the 7241FA engines, the dynamics limits are 2-3 psi on the fundamental frequency. Other units could require dynamics below 1 psi. GE's goal is to tune only during the combustion inspections and not to change anything in between. The schematic of the DLN 2.6 combustor is shown in Figure 3-20.

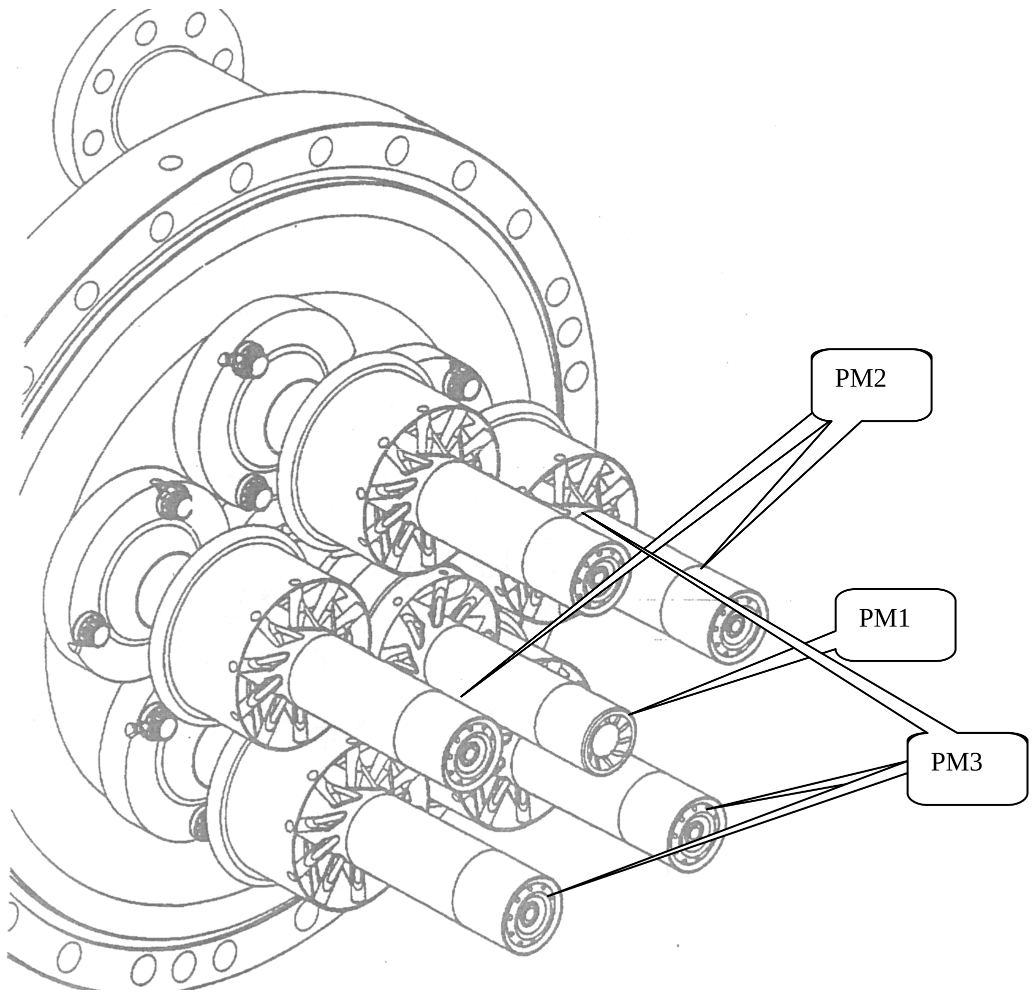


Figure 3-16
DLN 2.6 Fuel Nozzle End Cover Downstream Face with Partial Fairings

Mode 3:	PM1+PM2	Ignition to 18% speed
Mode 2:	PM2	18% to 95% speed
Mode 1:	PM1	95% speed to 10% load
Mode 3:	PM1+PM2	10% load to 25% load
Mode 4:	PM1+PM3	25% load to 50% load
(Originally, Mode 5:	PM2+PM3	transfer mode on start)
Mode 6 or 6Q:	PM1+PM2+PM3+(quaternary)	50% to 100% load

GE is planning to establish an integrated process for tuning and performance tests when the engine enters service. The DLN 2.0 engines had a tuning valve that allowed individual adjustments of each can. This was an added complexity, which is not required in the DLN-2.6 and in fact was removed from some DLN-2.0 units as well. IGV's are not used for control unlike Westinghouse/Siemens 501 engines.

A new staging scheme was proposed to start the machine and operate at low load in premixed mode. Otherwise, addition of this center nozzle to the DLN-2.0 system would have required five fuel manifolds for the DLN-2.6 compared to four on the DLN-2.0. The new configuration uses four circuits with three premixed manifolds staging fuel to the six burners, plus a fourth premixed manifold, quaternary fuel, for dynamics abatement. The first three premixed manifolds, designated PM1, PM2, and PM3, are configured such that any number (1 to 6) of burners can be operated at any time. The PM1 manifold fuels the center nozzle, the PM2 manifold fuels the two outer nozzles, and the PM3 manifold fuels the remaining three outer nozzles.

The quaternary fuel passage differs from the others in that it is located upstream of the premixers. It consists of fuel pegs as opposed to nozzles. These approximately 2-inch long pegs are spaced circumferentially around the casing. This fuel is delivered upstream of the fuel nozzles in small proportions of total fuel flow and only at high loads for control of combustion dynamics are the only function of quaternary fuel. Dynamics are also suppressed through "tuning" of the PM1, PM2, and PM3 fuel splits.

Fuel to the DLN-2.6 combustor is staged to operate the machine over the entire load range. Burners are brought on in stages, starting at Full Speed No Load (FSNL) with the center burner only and turning on additional burners as load is increased. The staging is accomplished by using four fuel systems. Each fuel system consists of a different number of nozzles coupled together via a common manifold. These systems are used alone or in combination with one another to maintain fuel / air ratio within a desirable range in the reaction zone. The mode names reflect the number of burners that are being fueled in that mode. The suffix Q in mode 6Q reflects the fact that quaternary fuel may be in use. Mode 6Q spans the load range for 9/9 ppm NO_x / CO operation.

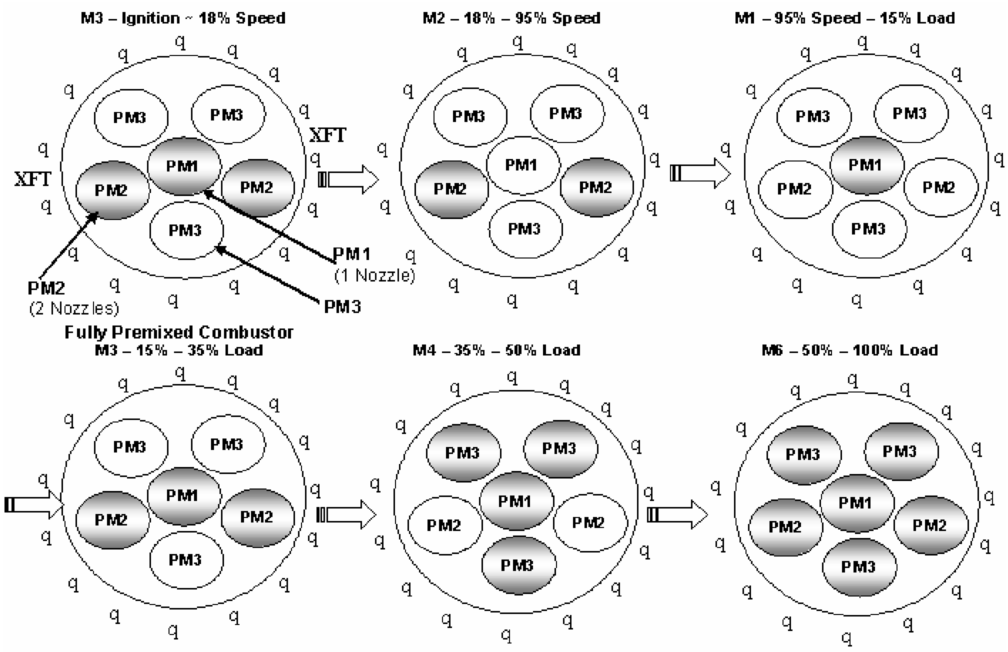


Figure 3-17
DLN 2.6 Six Operational Modes

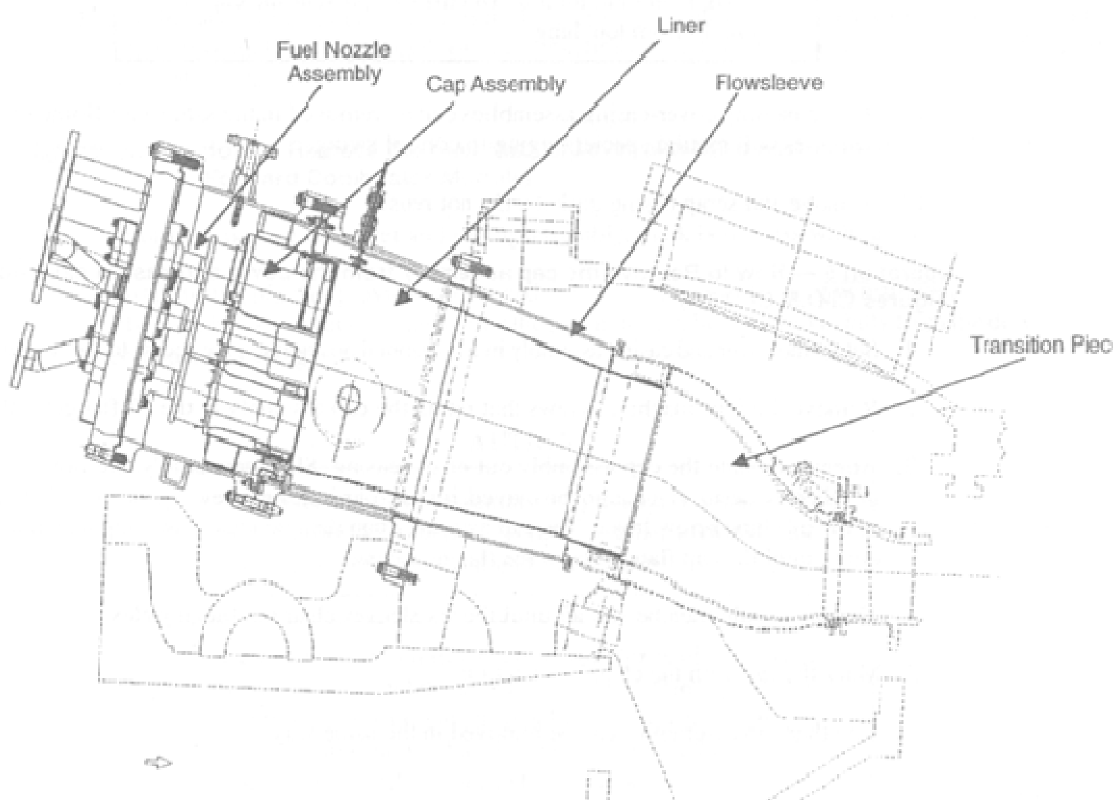


Figure 3-18
DLN 2.6 Combustion Chamber Arrangement

The machine lights on the PM2 and PM1 circuits. Following ignition, the PM1 nozzles are turned off and the PM2 nozzles support combustion while the unit ramps to 95 percent speed. At 95 percent speed, the unit transfers from mode 2 to mode 1 for continued acceleration to full speed no load (FSNL) and leading to synchronization. At approximately 10 percent load, the PM2 manifold is turned back on (3 nozzles = mode 3) and continues until 25 percent load. At this transfer point, the PM2 manifold is switched off, with the PM3 manifold turned on for operation in mode 4 to 50 percent load. All nozzles are turned on to enter mode 6 or 6Q with quaternary. Originally, the system also used modes 5 or 5Q with the five outer nozzles in operation. However, this mode was eliminated to simplify the staging and controls strategies. Figure 3-21 shows the nominal PM3 split schedule and the split percentage is with PM2.

The unloading sequence is an approximate reversal as shown in the figure below, but with the transfer "out" temperatures reduced by about 60°F. This provides the maximum load turndown conditions. For example, the mode 6 to 4 transfer occurs at lower than 50 percent load. On a breaker open event, the load rejection to FSNL uses the PM2 to support the flame during the early stages of the transient, but then shifts over to the PM1 in preparation for steady-state operation at FSNL. On a fired shutdown, the unit will decelerate in mode 1 to flame-out, which occurs at approximately 25 percent speed.

Fuel to the DLN-2.6 combustor is staged to operate the machine over the entire load range. Burners are brought on in stages, starting at Full Speed No Load (FSNL) with the center burner only and turning on additional burners as load is increased. The staging is accomplished by using four fuel systems. Each fuel system consists of a different number of nozzles coupled together via a common manifold. These systems are used alone or in combination with one another to maintain fuel / air ratio within a desirable range in the reaction zone.

To achieve the required emission performance in premix operation the combustion occurs close to or even below LBO when it is sustained only by tertiary gas flow. Flame instability and dynamics can develop if operating parameters are outside the design limits. The consequences of dynamics could be combustion chamber failure leading to forced GT outage, increased maintenance, reduced life, and high emissions. The key parameters affecting the combustion process are:

- Air flow and its distribution in the combustor
- Inlet air pressure and temperature that are influenced by ambient conditions, compressor performance, load, grid frequency
- Gas supply pressure in which small fluctuations can lead to dynamics
- Gas flow rate
- Fuel nozzles and combustion chamber design and condition

Main considerations in the design of DLN2.6 include improved mixing, better flame stabilization, flashback/autoignition safety, higher thermal efficiency (minimize ΔP), reduced cost, more adjustment capability for dynamics tuning. Better mixing was achieved by a "swozzle" (swirler+nozzle) design in which fuel is injected through the swirler vanes. For better stabilization higher swirl number was introduced by increasing vane angles (50-55 degrees). However, higher swirl angle increases flashback sensitivity. To prevent flashback, the boundary layer axial velocity profile is controlled to be as narrow as possible near the wall. To decrease ΔP, the swirler vanes aerodynamic design is optimized to minimize the wake behind the vanes. The vane aerodynamics also ensures no flow separation by maintaining a limit angle and by proper design of solidity. The design includes multiple fuel circuit to facilitate tuning for reduced dynamics. This capability is important because lab conditions rarely show actual dynamic behavior, so field operators need adjustment capabilities to implement corrective actions for tuning. The overall objective in combustion tuning is to introduce some degree of unmixedness while avoiding potentially excessive NO_x emissions due to reduced mixing. Injection of the fuel through the vanes (using the “swozzle” concept) allows for better control of the unmixedness

In order to prevent spreading of instabilities from one combustion zone to the other through the fuel system, the fuel nozzles were modified to become “softer”. This means that the effects of pressure fluctuations in the combustion chamber on the gas supply pressure were minimized by installing an orifice upstream of the nozzle. This prevented the propagation of pressure fluctuations between different combustion zones through the common fuel pipe. The pressure drop across the swirler was increased to increase swirl number and thus enhance mixing. This resulted in increased flame stability without significant penalty in GT efficiency.

Even though the combustion chambers were constructed identically with the same nominal design of inlet and outlet pressures, there was variation between them. This could result in excessive tertiary fuel flow to suppress dynamics in the worth combustor unit, resulting in excess NO_x. The solution was to tune the system such that each zone gets the amount of fuel to match the different airflow. A fuel valve was added in the secondary gas fuel lines downstream of the secondary/tertiary flow split valves. Individual tuning is achieved by monitoring the pressure on each unit while changing the fuel flow rate. After initial tuning, no retuning is necessary unless fuel nozzles or combustion chambers are changed. The tuning is done by GE engineers and requires 4 hours.

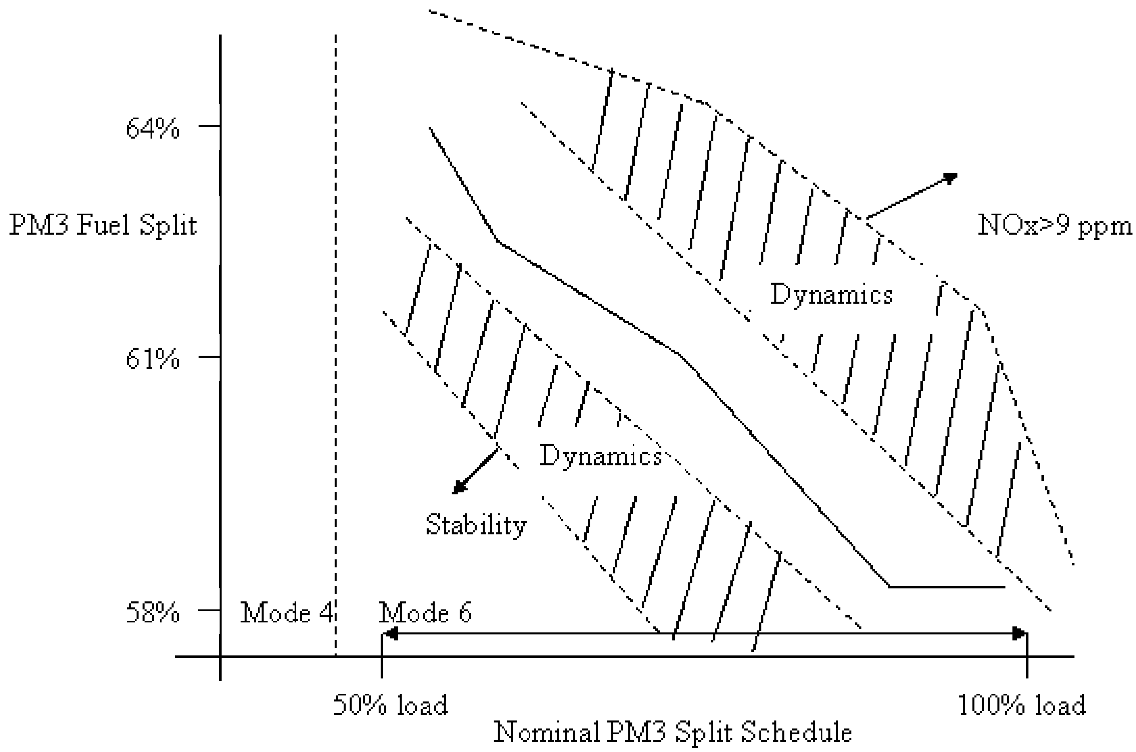


Figure 3-19
Stability Diagram of DLN-2.6

The graph shows approximate trends and is not precise.

4

TUNING PRACTICES AND GUIDELINES – S/W DLN COMBUSTORS

The Siemens/Westinghouse Dry Low NO_x (DLN) combustor for the 501F engine is a partially premixed combustor, which uses a pilot nozzle and eight main fuel nozzles in each combustion chamber. The primary function of the pilot nozzle is to produce a stable diffusion flame that can maintain high flammability in the premixed flame. As the engine transitions from ignition to full load, the pilot fuel is initially increased and then decreased to a minimum level during full load operation while the main fuel increases continuously up to maximum level at full load. The ratio of pilot to main fuel is called PLCSO (Pilot Ratio Control Signal Output) and it is one of the most important parameters for combustion tuning of this DLN design. The PLCSO is set higher at ignition, acceleration, and lower load, and it is progressively reduced with increasing load conditions in order to reduce emissions.

Figures 4-1 to 4-5 illustrate the various components of the DLN combustor. Figure 4-1 shows the combustor with its air bypass configuration. The purpose of this bypass valve is to maintain a nearly constant fuel-air ratio at the combustion chamber for different load conditions. The bypass valve modulates during transient conditions, ignition, acceleration and partial load operation, and it moves toward the closed position with increasing load. This valve is also used to prevent flame-out, combustion oscillations and flashbacks, which can be induced by changes in the total airflow that result from the position changes of the Inlet Guide Vanes (IGV). Because of improvements made by Siemens in response to combustion instabilities and to improve performance and emissions, the air bypass introduced with the original version has been eliminated from production engines. Several retrofits of existing 501F engines have also resulted in the elimination of the bypass and installation of new transition pieces, which historically have shown the greatest damage due to combustion-induced vibration. The removal of the air bypass has resulted in significant reduction in combustion dynamics and emission levels. Figure 4-2 illustrates the existing DLN combustor without the air bypass. Figure 4-6 illustrates the combustor basket with its eight premix nozzles and center gun.

In the combustor, the gas fuel is injected into three or four stages: pilot, A, B, and C (for configurations with top hat injection). The pilot is a diffusion flame injector, and provides stability for the premixed A-, B-, and C-stage. Because a diffusion flame has high NO_x emissions it is necessary to minimize the amount of flow through the pilot. The majority of the fuel is injected upstream of the pilot through the main A and B stages. The main fuel is injected tangential to the flow direction through 8 fuel rockets each with 4 fuel injection holes. This fuel premixes with the air before reaching the combustion zone. The C-stage is a small amount of fuel that is injected in the top hat region before the flow enters the basket. The C-stage provides additional premixing of the fuel and air and allows a reduction in the pilot fuel flow. Typically the DLN combustor is ignited on the pilot and A stage. The B stage is initiated at 30% load and the C stage is initiated at 50% load. Table 4-1 and Figure 4-7 illustrate the fuel staging sequence of the existing combustors and standard settings for fuel splits and IGV for a 501F engine.

SWPC has recently redesigned the DLN for its 501F and W501D5A class gas turbines to improve its low NO_x capability to levels below 9-ppm and improve its dynamics performance. To lower NO_x from 15 to less than 9 ppm, SWPC had to increase the amount of fuel burned in a premixed configuration. Therefore, the key enhancements to the existing DLN were made to the existing diffusion pilot. In its current configuration, the fuel to the pilot is burned in a diffusion flame, which increases NO_x albeit with more combustion stability. Its redesigned configuration is shown on the top portion of Figure 4-8. The new pilot has been reconfigured to include a premixed fuel stage, which uses swirling fuel injectors for flame stability. The fuel for the premixed portion of the pilot flame is injected off the surface of the vanes and premixed before burning. Thus, SWPC has added a D stage to the design and its new firing sequence is shown in Table 4-2. Note that, the new sequence allows for fully premixed firing with all stages on at 45% of capacity whereas before this occurred at 50% capacity. Thus, the new design also achieves an improved combustion stability, which should diminish the dynamics. Indeed, SWPC has reported that in addition to lower NO_x, dynamics have also improved as illustrated in Figure 4-9. Test results reported by Bland, et al at SWPC show that dynamics have been reduced by 50 percent on average. In addition, both emissions and dynamics exhibit no effect due to fuel temperature changes and Wobble Index changes expected with the introduction of LNG.

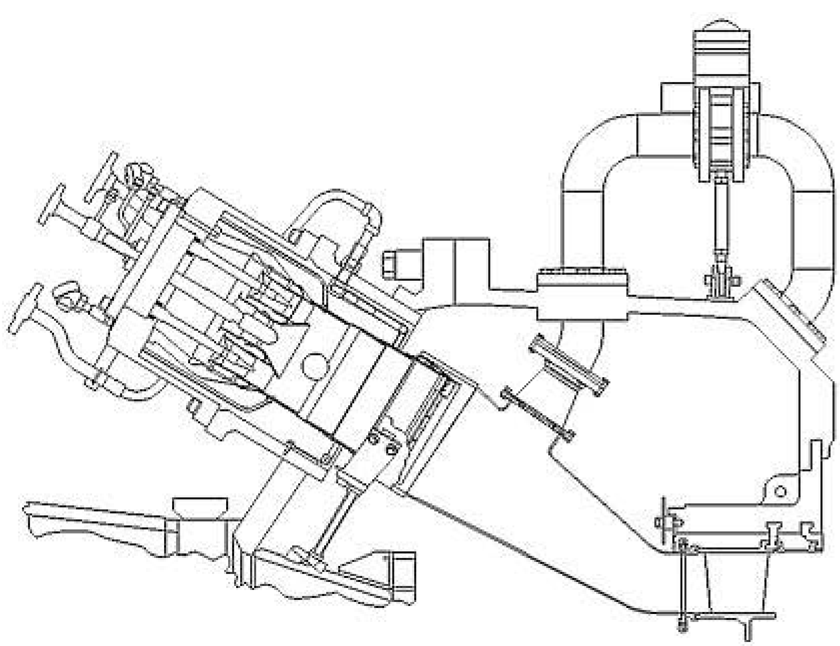


Figure 4-1
501FC DLN Combustion System Engine Installation

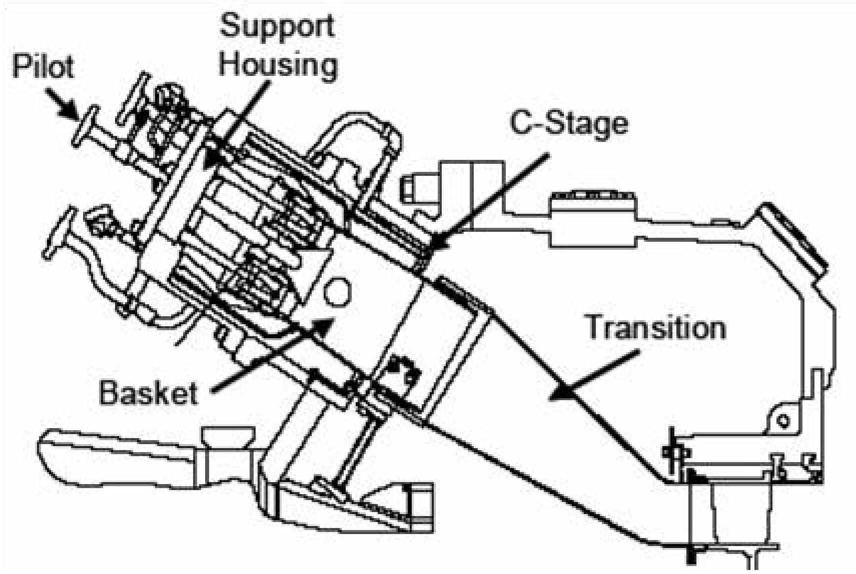


Figure 4-2
Second Generation SWPC Premix Combustor Cross Section (15 ppm)

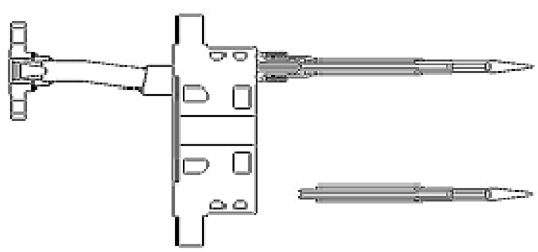


Figure 4-3
Main Nozzle Side View

Two of eight A/B injectors are shown.

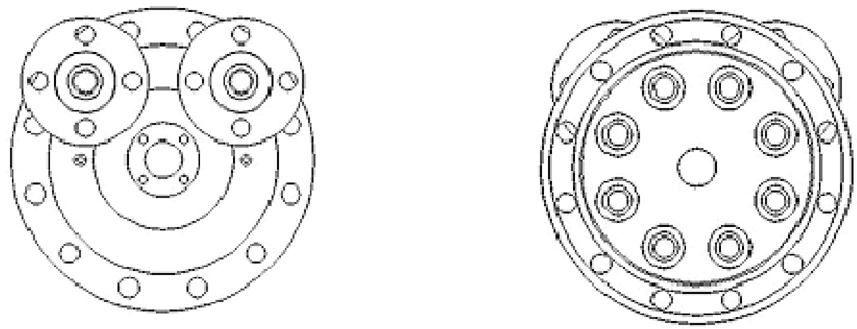


Figure 4-4
501F Main Nozzle Support Housing (a) Rear Face, External Connections, (b) Front Face, Internal Fuel Injectors

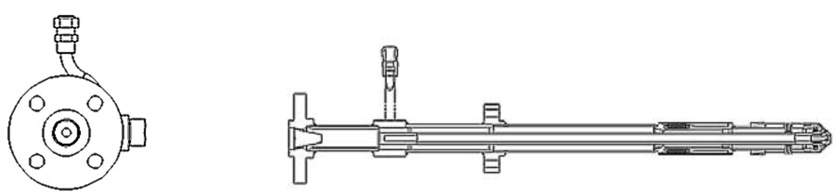


Figure 4-5
S/W 501 DLN Dual Fuel Pilot Nozzle

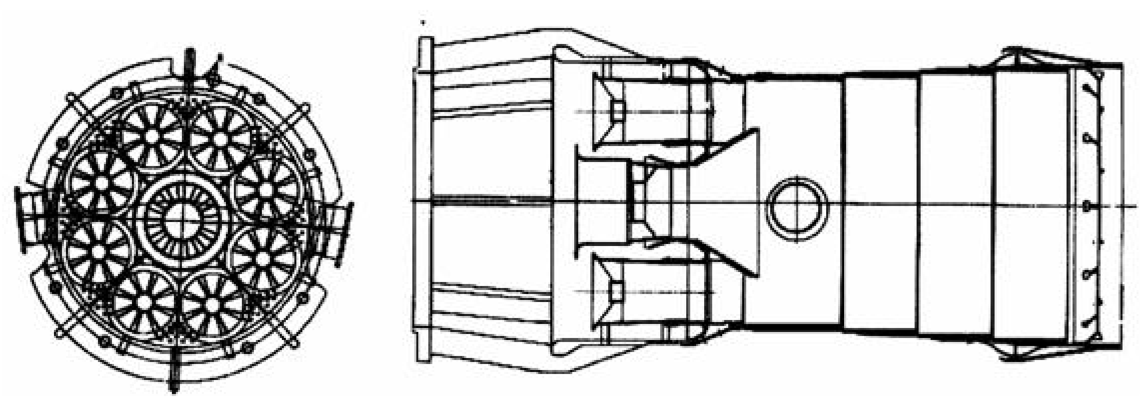


Figure 4-6
Siemens/Westinghouse DLN Combustor Basket for 501F Engine

Table 4-1
Existing 15/25 ppm DLN Combustor Fuel Staging Sequence

15/25ppm DLN Staging Strategy	
Load Range	**Stages Active**
Ignition to Synch Speed	Pilot, A stage
Synchronization to 25% load	Pilot, A stage
25% to 50% load	Pilot, A, B stage
50% load to Base	Pilot, A, B, C stage

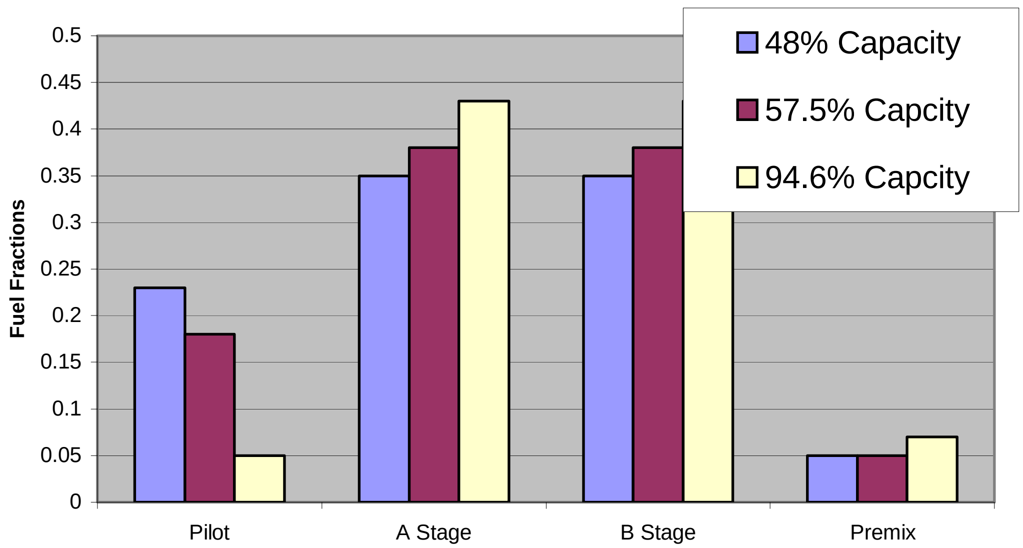


Figure 4-7
Standard Fuel Splits and IGV Settings for 501F at 50 to 100% Load

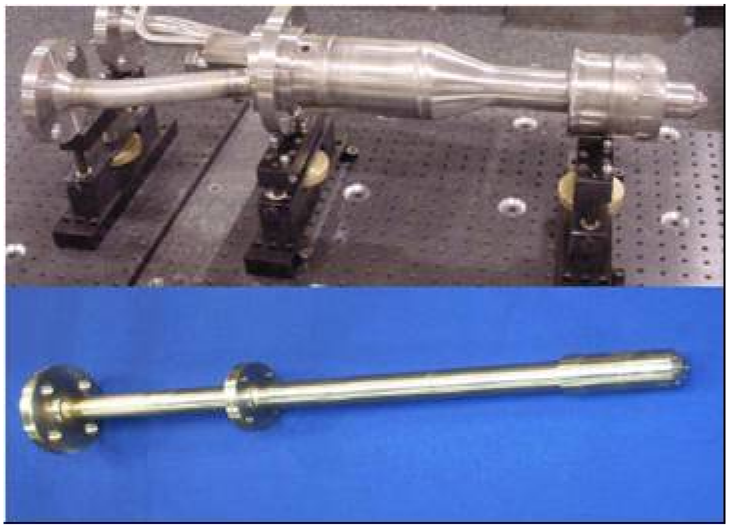


Figure 4-8
New ULN Pilot (top) Compared with Existing Pilot (bottom)

Table 4-2
New ULN Combustor Fuel Staging Sequence

Load Range	Stages Active
Ignition to Synch Speed	Pilot, A stage
Synchronization to 25% load	Pilot, A + D stage (Premix Pilot)
25% to 45% load	Pilot, A, B + D stage
45% load to Base	Pilot, A, B, C + D stage

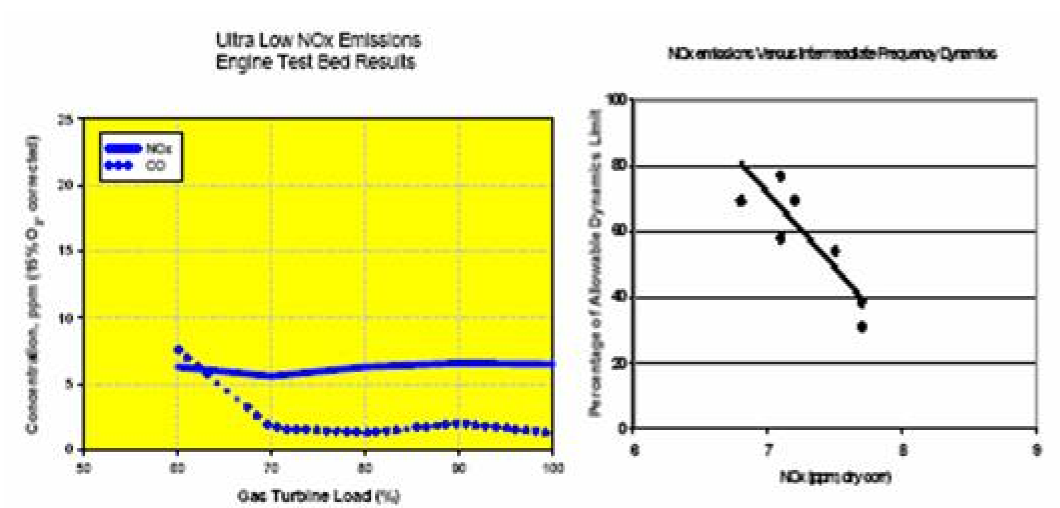


Figure 4-9
ULN Emissions Test Results (left) and Dynamics Relative to Existing DLN (Bland, et al, 2003)

Figure 4-10 illustrates the typical dynamic spectra of an existing 501F DLN combustor. As indicated in Section 3, the dominant frequency is in the range of 120 to 145 Hz. Amplitudes in the frequency are below 1 psi. Alarm levels are set at 0.5 and 1.0 psi below a frequency of 100 Hz and extend to 2.0 psi above the dominant frequency of about125 Hz. Combustion tuning specific to selected combustors where spike in pressure pulsations is recorded in the dominant frequency range may require adjusting the fuel flow to the pilot to provide greater stability. Increased dynamics in affected combustors most likely will straddle across to the adjacent combustors via crossfire tubes. This pattern will held detect the primary combustor requiring inspection, repair, or combustion tuning. Below 50 Hz, as the sample indicated in Section 3, the potential for flashback can be significant. After confirmation via flashback temperature increases, this will require inspection of all nozzles in the combustor because the installed flashback thermocouples cannot be selective in pinpointing affected nozzles.

Field tuning of the sister Mitsubishi DLN gas turbine is achieved by adjusting the pilot ratio, combustor bypass valve and IGV position to cover the full range of operating loads without inducing combustion dynamics. Since dry low NO_x system are sensitive to sudden changes in operating conditions such as large changes in fuel heating value or large changes in ambient temperature, they need continuous combustion tuning. The latest generation of protective systems includes automatic self-tuning capability in addition to the basic protective function. The control system makes continuous adjustments without human intervention in order to maintain low pressure fluctuation levels and low emission values.

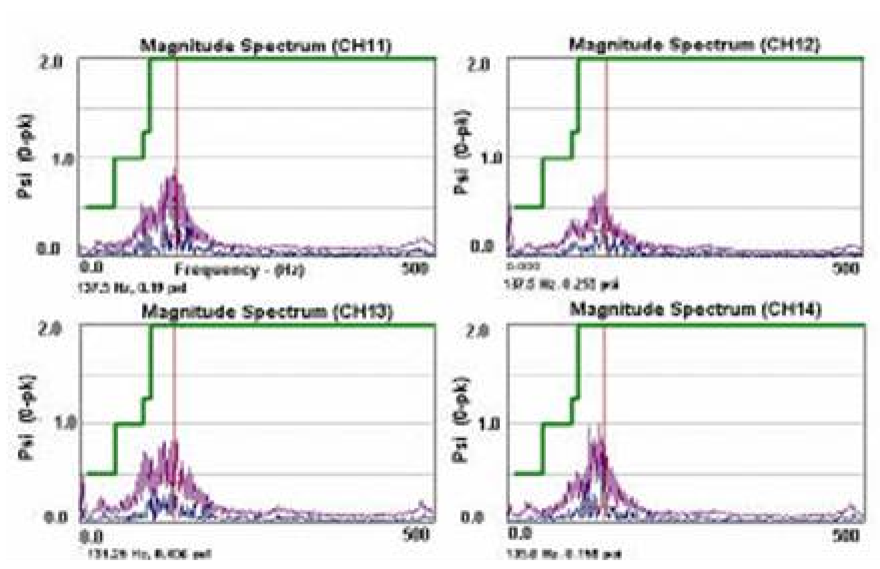


Figure 4-10
Dynamics Spectrum Typical of Existing DLN in 4 of 16 Combustors in a SWPC 501F Engine

Mitsubishi developed an Advanced CPFM (ACPFM) with this self-tuning capability. This system is based on the earlier CPFM but has additional features such as:

- Faster data acquisition and analysis speed
- Real-time evaluation of the combustor pressure fluctuation for estimation of the firing stability margin
- Automatic adjustments of the control parameters by calculating optimal correction based on the estimated stability margin

These added functions are performed through a dedicated computer system linked to the gas turbine controller. The system periodically receives, stores and transforms the measured data through Fast Fourier Transform (FFT) analysis in order to be able to quickly create mathematical models of combustion based on non-linear multiple regression analysis. Because the characteristics of the pressure fluctuations can be different for each combustor, the mathematical modeling is applied to every combustor. The system estimates a stable region as a function of the control parameters and determines a combustion stability map by using the resulting models as shown in Figure 6-2. Accumulated data from the previous operation of the gas turbine is used to determine the combustion dynamic pattern of that particular unit. Therefore the estimations are more precise as the system “learns” the behavior of that unit.

Figures 4-11 and 4-12 explain how the stability region is displaced in the event of a large perturbation such as large change in fuel composition, large swing in ambient temperature, and grid disturbances, with the corresponding increase in combustion dynamic activities. These activities return to normal levels after the operating point is automatically moved toward the center of the stable region.

The features of the Advanced CPFM system improve the availability and reliability of modern DLN pre-mix combustors. It has been validated in the T-point power plant in Japan where Mitsubishi tests its designs. During testing, combustion dynamics were intentionally induced by perturbations. The Advanced CPFM system quickly responded by bringing the unit back to a stable condition through automatic adjustments of the combustor by-pass valve, pilot ratio and IGV position. The commercial version of the advanced CPFM was installed early this year in two new plants in Egypt and Malaysia, which are demonstrating the functionality of the system.

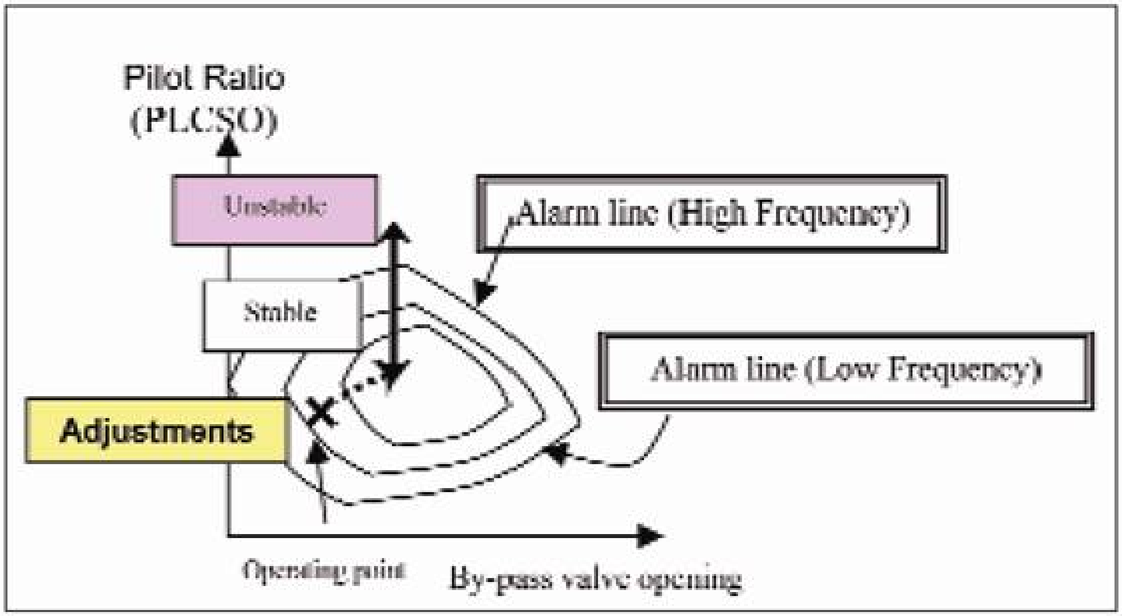


Figure 4-11
The Advanced System Evaluates Stable Operating Regions and Regulates the Main, Pilot and Bypass Valves Accordingly

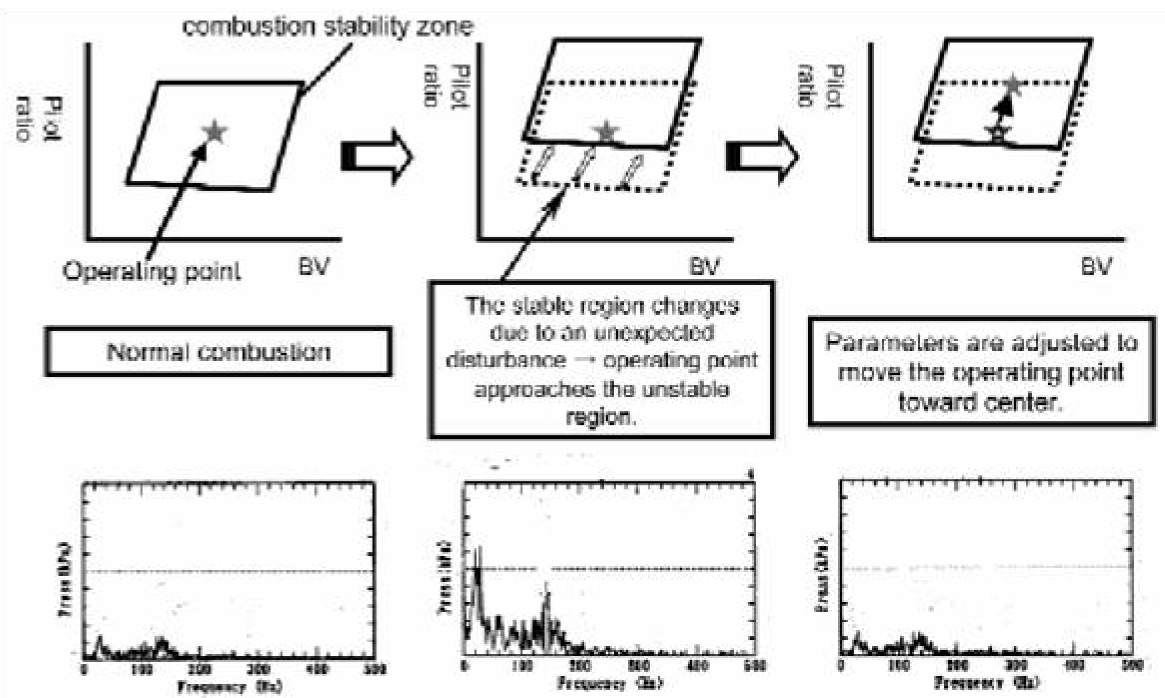


Figure 4-12
Mitsubishi's ACPFM Responds to Instabilities by Pushing the Operating Point to the New Stable Region

5 DESIGN IMPROVEMENTS AND TUNING CAPABILITIES FOR ALSTOM EV/SEV COMBUSTORS

The most advanced of the Alstom power generation turbines are the sequential combustion GT24/GT26 engines. These engines offer the greatest performance and power density than any of the Altom line of gas turbines. Either the 60 Hz GT24 or the 50 HZ GT26 engine are guaranteed to 15 ppm NO_x emissions, although the performance of most recent installations have shown consistently single digit NO_x performance. The GT24 and GT26 were developed by ABB as part of their Advanced Cycle System (ACS) gas turbines and introduced to the market in 1995. The technical data of the two machines is summarized in Table 3-1 (Joos et al. 1996).

The unique feature of this gas turbine is the sequential combustion system or the reheat process, which enables to decouple the efficiency and emissions. In traditional design, higher efficiency is achieved by increasing the turbine inlet temperature (TIT) resulting in increased NO_x emissions and increased exposure of the turbine to undesired high temperatures, leading to high materials and cooling costs and reduced life cycle. The sequential combustion concept yields high specific power, high efficiency, high reliability, and low emissions. GT24 for example yields 50% more output than the GT11N2 with a similar footprint of 10 x 5 m^2. Also the exhaust temperature is designed for combined cycle operation.

The GT24/26 sequential combustion system is shown in Figure 5-1. The air is compressed through a 22-stage subsonic compressor yielding a compression ratio of 32:1. This ratio is similar to an aero-derivative gas turbine. It is then fed into the first combustor with 30 EV burners (EV stands for EnVironmental) where it is heated in an annular EV combustion chamber. The EV burners can operate with both gaseous and liquid fuels. The burners are constructed of two half cones that are somewhat displaced relative to each other to form two inlet slots with constant width along the entire burner (Figure 5-2).

The original EV design caused significant operational problems and combustion instabilities that led to several hardware failures. More recently, Alstom has introduced some changes to the EV design, which include repositioning of the pilot lance and resizing the premix nozzles. According to Alstom, these design changes have significantly improved performance and reliability.

Combustion air enters the cones through these slots while the main gaseous fuel (premixed operation) is injected through a series of small holes that are situated along the two slots. The fuel jets are initially mixed with the combustion air in the slots and subsequently inside the cone by the swirling motion induced by the split cone configuration. The gaseous pilot fuel and entire liquid fuel are injected through nozzles at the cone tip. The fuel and the air are mixed well as both swirl inside the cone. After adding about 60% of the fuel at full load, the combustion gas expands through a single stage high-pressure turbine (HPT) dropping the pressure by a factor of 2 (16 bars). The additional 40% fuel is added in a second combustor (SEV combustor). The gas is reheated to the maximum TIT of the LP turbine and expands again through a 4-stage low-pressure turbine (LPT).

Table 5-1
Technical Data for Alstom GT24 and GT26 Engines

		GT24	GT26
Frequency	Hz	60	50
Load Output	MW	171	268
Electrical Efficiency			
SC	%	36.5	37
CC	%	58	58.5
Heat Rate	Btu/kWh	9348	9222
Compressor Ratio		32	32
Exhaust Mass Flow	Kg/sec	410	545
Exhaust Temperature	^{0}C	615	615
Shaft Speed	rpm	3600	3000
NO_x Emission			
Gas	vppm	<25	<25
Oil	vppm	<42	<42
No. of Stages Compressor		22	22
No. of Stages Turbine		1 HP + 4 LP	1 HP + 4 LP
No. and Type of Single Annular Combustors		1 x EV 1 x SEV	1 x EV 1 x SEV
No. of Burners EV/SEV		30-A(20-B)/24	30-A(24-B)/24

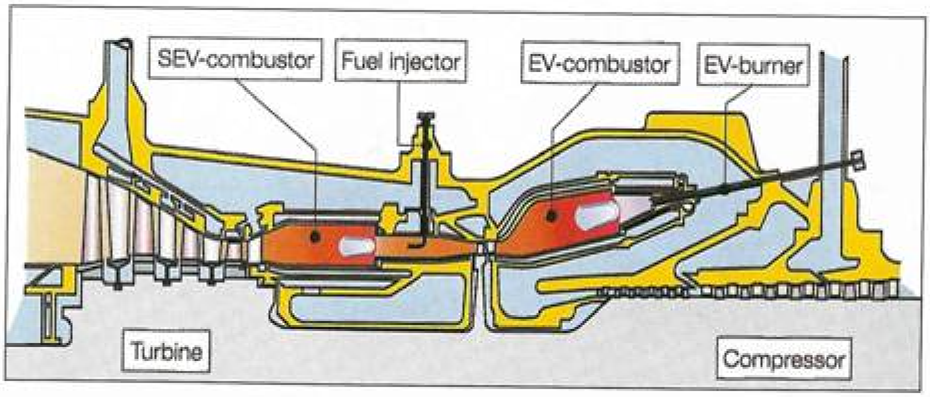
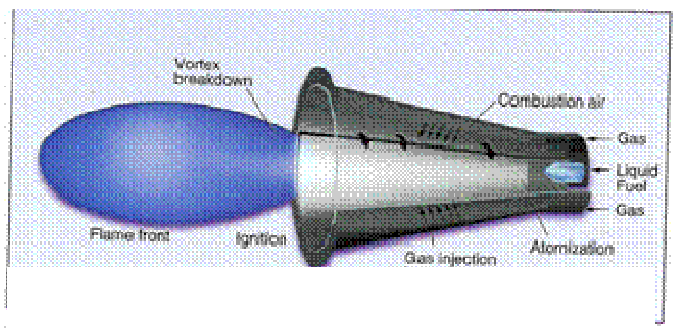


Figure 5-1
Sequential Combustor System of the GT24 and GT26 Gas Turbines



vppm NOx on natural gas (dry) and 42 vppm on oil (with water injection).

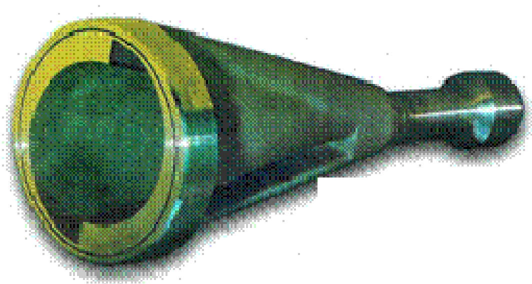


Figure 5-2
The Split-Cone EV Burner

The thermodynamic cycle is shown in Figure 5-3 in an h-s diagram where it is compared with the cycle of a conventional gas turbine. In the conventional cycle, in order to increase the power output and the cycle efficiency the compressor ratio has to increase and/or the maximum temperature at the combustor exit and at the inlet to the HP turbine has to increase. This requirement for higher TIT imposes severe structural and material requirements on the turbine blades. With the reheat cycle of the GT24/GT26 gas turbines, the compression ratio is increased relative to conventional gas turbines. Also, only about 60% of the fuel is added in the first EV combustion chamber and after expansion in the HP single stage turbine, the remaining 40% fuel are added in the secondary SEV combustor. The final expansion comes in the LP four stages turbine. In this manner, the same output power can be achieved with lower maximum TIT.

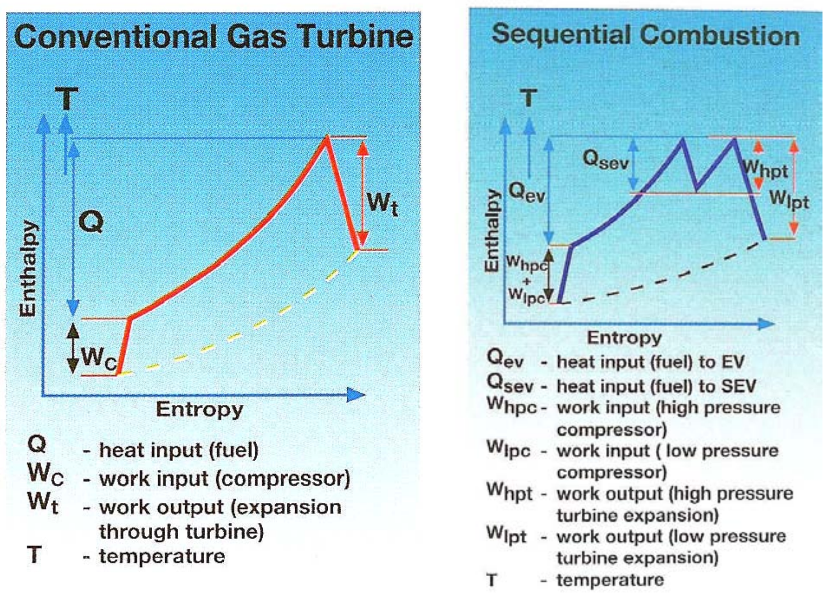


Figure 5-3
Comparison between a Conventional Thermodynamic Cycle on the Left, and a Sequential Combustion Cycle on the Right on an h-s Diagram

The first combustor is annular with 30 dry low NO_x EV burners. Nearly all the compressor air enters the burners were the flame is stabilized by a “vortex breakdown” concept. This eliminates the need for mechanical flame holders and cross firing tubes. The SEV combustion occurs without an external ignition source due to the high temperature of the combustion gases entering from the HPT. In order to achieve low NO_x the secondary fuel injection in the SEV has to be thoroughly mixed with the hot inlet combustion air before auto ignition occurs to prevent combustion in rich partially mixed zones. The fuel in the SEV burner is injected with the aid of carrier air bled from the compressor. This air is acting as a premixing enhancer and also increases the fuel jet momentum. Mixing with the hot air entering from the HPT is achieved by a group of ramp-like delta wings that are mounted on all four walls of the SEV burner. The vortices produced by these delta wings help in mixing and in flame holding by a second “vortex breakdown” process.

NO_x emissions are minimized by operating at low temperatures and reduced residence time. The EV operates in a fully premixed mode and thus the flame temperature is not higher than the combustor exit temperature. Both EV and SEV have 50% shorter residence time relative to conventional combustors. The SEV can burn CO and UBHC faster than the EV burner due to the high inlet temperature. Due to depleted oxygen in the inlet combustion air of the SEV, less oxygen is available to produce NO_x. The initial high temperature requires lower temperature increase in the SEV combustor thus minimizing NO_x formation. Due to all these features the amount of NO_x in the SEV outlet is lower than in the inlet. The hot gases from the secondary combustion expand through the four low-pressure turbine stages.

High thermal efficiencies and low emissions even during part load are achieved by separate control of each combustor and three rows of adjustable inlet guide vanes (IGVs) that allow reduction of combustion air by up to 60% of the full load mass flow rate (Joos et al. 1998). The gas turbine starts up with a static starting device (Figures 5-4 and 5-5). As soon as ignition speed is reached, all the EV burners are ignited simultaneously. Two fuel distribution systems supply fuel to the pilot ignition nozzles at the tip of the EV cone, and to the premix holes that are distributed along the two air inlet slots between the split cone. Initially, to maintain stability, the EV burner starts with a pilot mode, which utilizes a diffusion flame. At about 20% engine load, the EV burners are switched from pilot to premix operation. In the case of liquid fuel operation, the fuel continues to be injected through the nozzles at the EV cone tip. The turbine increases speed until it reaches the operating speed when it is synchronized (Figure 5-5). The acceleration process to full speed lasts for 6 minutes. For low part load operation only the EV annular combustion is operating and the three inlet guide vanes rows are closed (Scherer and Scherer 1996). At approximately 25% load, the self-ignition temperature of the SEV annular combustor is reached. The SEV combustor starts operation by simply injecting fuel. At this part load, the full operating temperature of the EV combustor is reached. The EV burner then maintains constant temperature, while the temperature of the SEV combustor is increased until the full exhaust temperature is reached at less than half load. The exhaust temperature is now kept constant until the full load is reached. As more fuel is supplied to the two combustors the inlet air flow is increased by opening the three rows of the variable inlet guide vanes. The VIGVs start opening close to 40% engine load. When the VIGVs are fully open the full load is reached by slight increase in combustion temperature. The SEV reaches its maximum operating temperature when full load is reached. The EV burners operate from 25% up to full load with only premixed fuel and no pilot is required. All the EV burners operate throughout the full load range. The SEV exit temperature and the VIGV position can be adjusted for optimal operation.

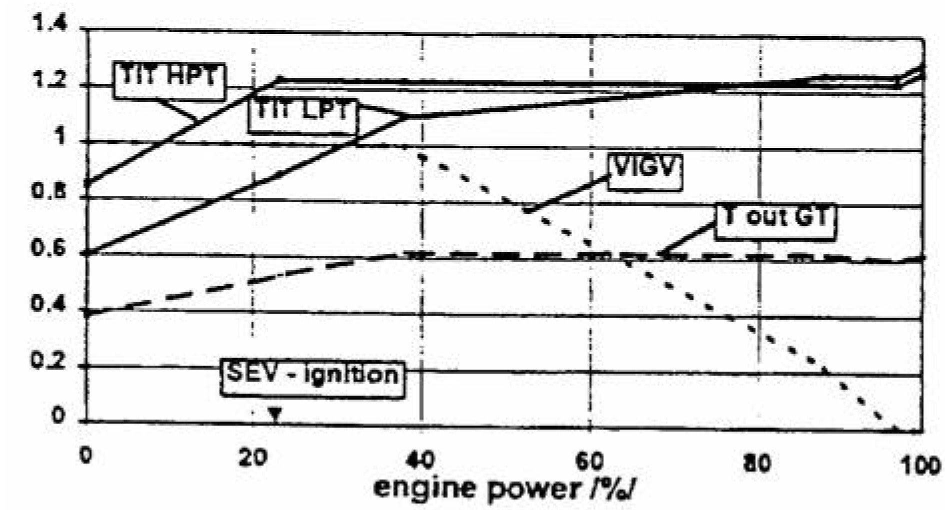


Figure 5-4
GT24/GT26 Operation Concept

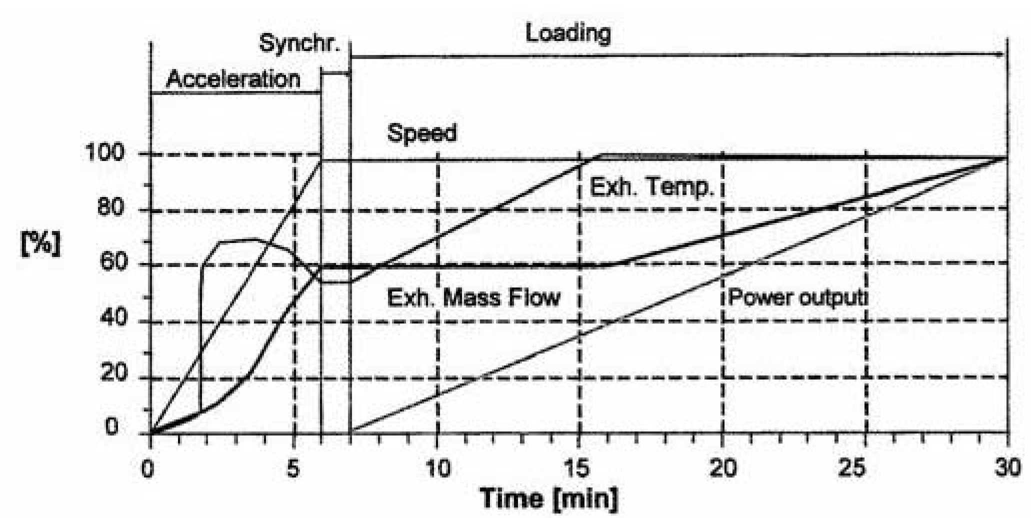


Figure 5-5
Start-up Diagram of GT26

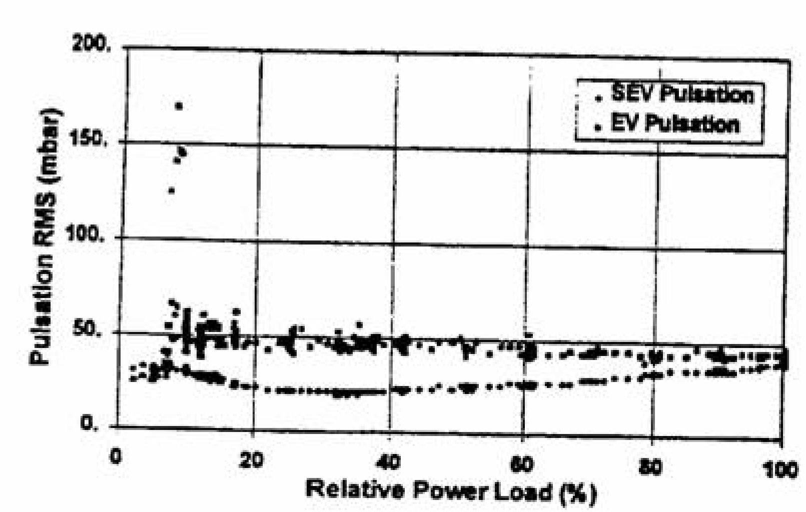
This operational concept allows the EV burners to reach full operating temperature early in the process and to maintain constant exhaust temperature over a wide load range. This way thermal stresses are minimized, the EV combustor can work in a premised mode even at part load conditions resulting in low NO_x, and the gas turbine achieves high part load efficiencies.

Control of the GT24/GT26 machines is particularly important during transient events such as startup, load reduction, and frequency support (Mukherjee 1997). The demands on the controller are particularly important when constraints are imposed on the operating range. Requirements such as high efficiency and stability contradict strict low emissions.

Dry low NO_x systems tend to operate near the LBO limit thus exacerbating issues of flame and combustion stability. These restrictions effect, for example, temperature related requirements, extinction limits, pulsations zones, and compressor surge limits. Operation outside the allowed zone can cause damage to the gas turbine, reduction in Equivalent Operating Hours (EOH) and reduced availability. The dual combustion system of the GT24/26 affords more control flexibility. ABB/Alstom developed a hierarchical control concept that provides fuel controller for the EV and SEV burners during load change, and compressor guide vanes adjustment for air mass flow rate change. A dynamic gas turbine simulator was developed as part of a Computer Aided Control System Design (CACSD) environment. The simulator also allows on-line process monitoring. Differences between the simulation and the physical operation help in designing maintenance schedules.

Another system that was developed is the protection system. It relies on sensing disturbance events such as excessive temperature on certain components or high-pressure pulsations. The protection system ensures operational reliability by preventing damage to the engine, but may adversely affect availability if it is activated too often or stops operation when no real risk is imminent. The availability problem can be alleviated with certain redundancy, automatic test procedures, and rugged components. The two important functions of the protective system are the Protective Load Shedding (PLS) system that reduces the load to zero within 2 minutes, and the gas turbine trip. The first is activated in case of potential medium level danger to the machine while the latter occurs for serious danger. The latter one is a last resort and should be avoided to minimize stress on the machine.

The possibility to individually control each one of the two combustors and the three rows of adjustable inlet guide vanes (VIGVs) that allow reduction of combustion air by up to 60% of the full load mass flow rate provides another tool for tuning. Pulsation levels with gas operation are lower in the SEV relative to the EV and are at about 25 mbar RMS for the SEV and 50 mbar for the EV (Figure 5-6 top). During switch over from pilot to premix operation the EV pulsation reach a level of 175 mbar for a very short time. With oil operation, the EV pulsations are at 25 mbar RMS while the SEV pulsations are higher at a level of 60-70 mbar (Figure 5-6 bottom).



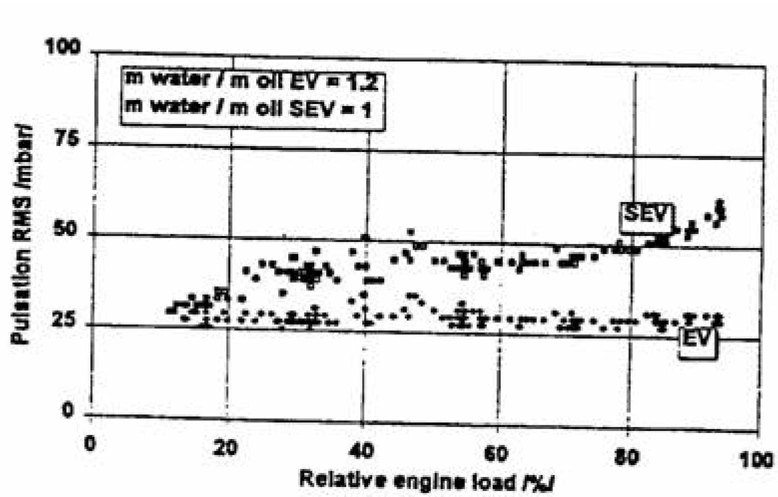


Figure 5-6
Measured Pressure Pulsations in the GT24. Gas Operation (top); Oil Operation (bottom)

In July 2000, Alstom admitted technical difficulties with the GT24/26 machines. Reliability problems were reported and the machine could not meet the contractual performance and lifetime obligations. They initiated a design review program to solve the problems (International Power Generation 2003). They redesigned certain sections on the turbines and implemented modifications in the 79 machines in the fleet (then). In addition, they reached settlements with affected customers. Alstom sold a total of 80 machines, 50 GT24 (60 Hz for the North America market) and 30 GT26 (50 Hz). In addition, 74 units have been commissioned, 22 out of them in 2002. Alstom introduced an uprated “B” model that included higher output through the redesigned EV burners and improved the turbine aerodynamics and cooling system. About 50,000 operating hours were reached when the “B” machines were introduced. The number of EV burners was decreased in the GT24 from 30 to 20 and in GT26 from 30 to 24. The burners were made retractable for easy maintenance. The burner is now manufactured as a cast burner rather than a welded design. The fuel input is unaltered in the first stage but increased in the

SEV burner resulting in 20^o C higher exhaust temperature. This change increases the power output without affecting NO_x emissions. The exit temperature of the first stage remained the same. However, blade-cooling problems were still encountered in a GT26 machine in Enfield, UK due to issues related to the distribution of cooling air to the second stage blade of the LP turbine. This affected both the GT24 and GT26 "B" machines. Cracks were detected in the EV burners of the GT24 machine at the Agawam CC plant in the US. In order to address this problems, new parts were installed in the entire fleet to change the natural frequency of the combustor. Agreement between Alstom and Rolls-Royce that was signed in February 2002 helped in addressing these technological issues. Alstom adapted diagnostics tools such as thermal paint tests for blade temperature indicators and finite element analysis and CFD calculations methods. An upgraded compressor was designed and implemented on GT24 for increased power.

With the introduction of the "B" machines in September 1999, the operating hours reached 500,000 today. The GT26 machine in Enfield achieved an average reliability of 99.8% on baseload operation in 2003.

ABB/ALSTOM GT24/26: Combustion dynamics, vortex dynamics, mitigation strategies

Figure 5-7 illustrates a typical EV pressure dynamics spectra. Pressure pulsations of up to 175 mbar RMS were measured during switch over from pilot to premix operation of the first combustor with the EV burners (Joos et al. 1998). The high peak lasted for about 1 sec during which the flame changed location from being held within the EV burner's cone to just downstream of this cone. This phenomenon is observed only for gas operation. Occurrence of combustion dynamics problems were associated with several features of the machines:

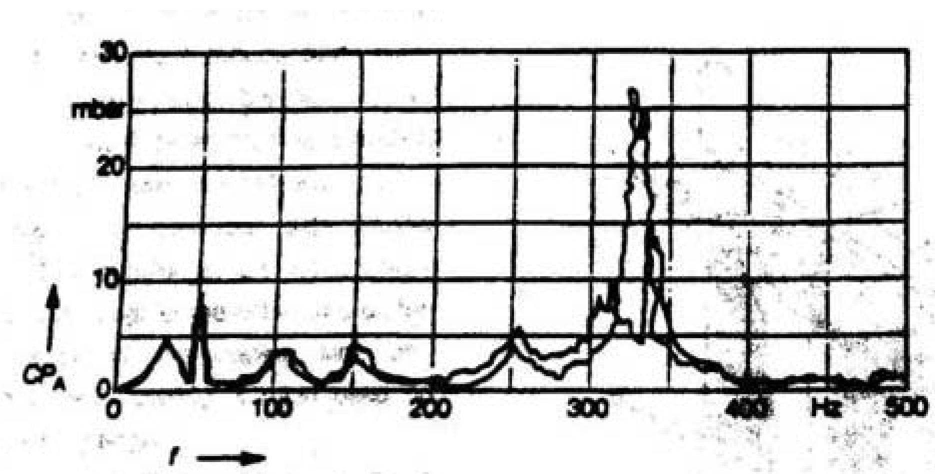


Figure 5-7
Combustion Pulsations during High Load Conditions

After adding about 60% of the fuel at full load, the combustion gas expands through a single stage high-pressure turbine (HPT) dropping the pressure by a factor of 2. The additional 40% fuel is added in a second combustor (SEV combustor). The gas is reheated to the maximum TIT of the LP turbine and expands again through a 4-stage low-pressure turbine (LPT).

The following mitigation strategies were implemented by ABB/Alstom.

Switching between Pilot and Premix Operation

Two fuel distribution systems supply gaseous fuel to the pilot ignition nozzles at the tip of the EV cone, and to the premix holes that are distributed along the two air inlet slots between the two segments of the split cone. Initially, to maintain stability during the cold start with a lean mixture, the EV burner starts with a pilot mode which utilizes a diffusion flame. During this phase the flame is anchored inside the cone at the downstream section. At about 20% engine load, the EV burners are switched from pilot to premix operation. During this switch the flame is intermittently stabilized internally and externally of the EV cone, leading to the observed low frequency instability. Typical remedy to this instability is to accelerate the transition between the pilot to premix operation such that the instability is not able to reach maximum amplitude or to cause component damage.

Switching between Gaseous to Liquid Fuel

The first stage EV burner maintains stability during liquid operation because the fuel continues to be injected through the nozzles at the EV cone tip and the flame is partially a stable diffusion type flame. At this part load, the full operating temperature of the EV combustor is reached and is maintained constant as the load continues to increase. This is important because this is the temperature necessary to stabilize the flame of the SEV annular combustor by self-ignition. The SEV combustor starts operation by injecting fuel. The temperature of the SEV combustor is increased until the full exhaust temperature is reached at less than half load. The exhaust temperature is now kept constant until the full load is reached. As more fuel is supplied to the two combustors the inlet air flow is increased by opening the three rows of the variable inlet guide vanes. The SEV reaches its maximum operating temperature when full load is reached. Increase in the pulsation level of the SEV combustor occurs at 80% load. At slightly over 90% load the SEV pulsation level doubled and is further increasing as full load is approaching. In order to overcome this instability, changes in the design of the SEV fuel injector were implemented to modify the fuel distribution pattern.

Cold Engine Start and Start-up at Low Ambient Temperature

Similar to observations in other OEM gas turbines, combustion dynamic issues are exacerbated during cold start and particularly when the ambient temperature is low. Mukherjee 1997 emphasizes that control of the GT24/26 machines is particularly important during transient events such as startup. At these conditions even pilot operation can be unstable. A passive control method was implemented in the GT24 and GT26 "B" machines to stabilize the flame and prevent low frequency pulsations at these conditions. This modification was aimed to control the combustion instability that was associated with flame stabilization by vortex breakdown. The pressure oscillations were linked to fluctuations in the flame location, which were in turn affected by changes in the vortex breakdown characteristics. When the flame stabilized outside the burner, initiation of vortex breakdown could be observed inside the burner. When the flame was pushed by increased combustion pressure into the burner, the decreased density resulted in the elimination of vortex breakdown. Subsequent to the disappearance of this swirl-based stabilization mechanism, the flame exited the burner, stabilizing downstream of the burner's exit at the sudden expansion. As the burner temperature dropped and density increased, the internal vortex breakdown was re-established and the instability cycle repeated itself.

In order to prevent the instability mechanism which was shown to be associated with large amplitude movement of the vortex breakdown location and the resulting flame oscillations in and out of the burner; passive control was applied to stabilize the vortex breakdown location. The stabilization was achieved by extending the pilot fuel lance into the burner. Extension of the lance into the burner eliminated the high pressure pulsations observed in mixed and purely piloted operation. The optimal extended lance length was approximately 70% of the burner's length. The pressure pulsations were suppressed by more than 12 dB in piloted operation. The improvement of the operation in pilot mode did not result in degradation of the premixed operation. Without the extended lance an increase of pulsations was observed when the burner power or the flame temperature was increased. The extended lance completely eliminated excitation of pressure oscillations for start-up conditions with pilot operation.

Other concerns associated with the extended lance were possible internal stabilization of flame on the lance and flashback safety. The position of the vortex breakdown was determined to be well downstream of the tip of the extended lance. This vortex breakdown location prevented the flame from being stabilized close to the lance tip with possible lance overheating. Flashback tests confirmed that the extended lance did not adversely affect the flashback safety. The main improvement of the long lance could be seen in the start-up while the long lance yielded smooth start-up procedure and the pulsation levels were reduced by 90%.

The operating behavior of the burner with the long lance was verified in a test engine. The main improvement of the long lance could be seen in the startup procedure. With the original burner high pulsation levels were observed during startup at a normalized RPM range between 0.68-0.85 (Figure 5-8). Using the long lance the startup procedure was smooth and the pulsation levels were reduced by 90% (Figure 5-9).

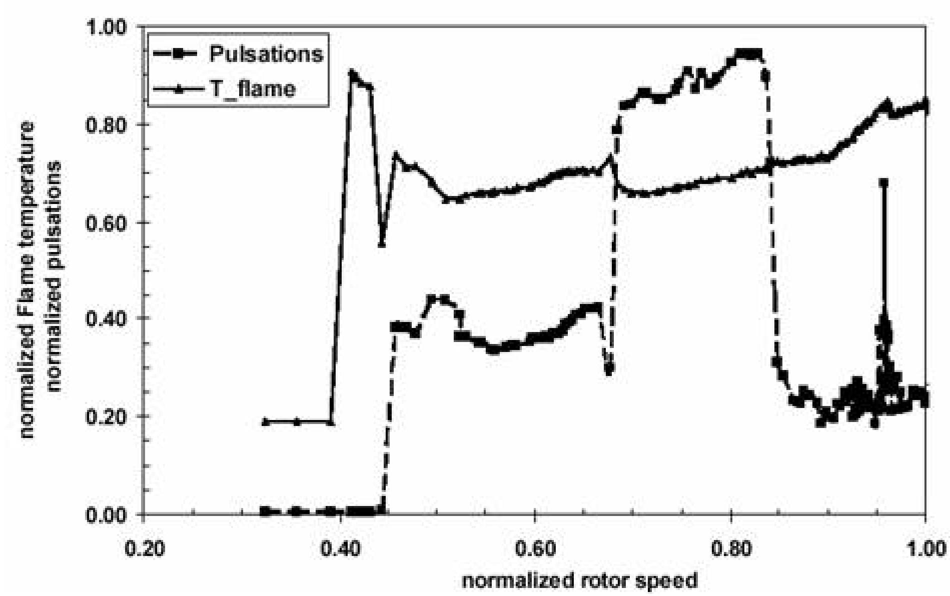


Figure 5-8
Start-Up Test in the Test Engine

This graph shows the behavior of the original burner configuration.

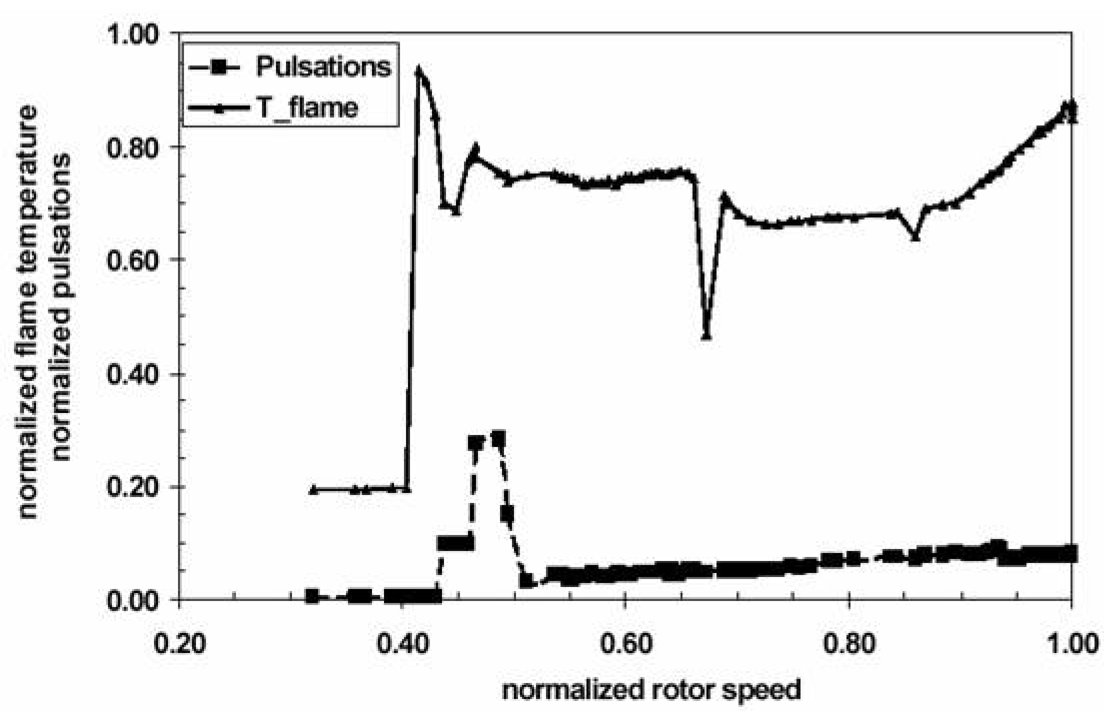


Figure 5-9
Start-Up Test in the Test Engine

The pulsations were reduced by using the long lance.

Several modifications were implemented to address all cases that were susceptible to pressure pulsations. “B” model engines have redesigned EV burners that include increased air and fuel flow through them. This alternate design that changed the flow and mixing patterns enabled to decrease the number of EV burners in the GT24 from 30 to 20 and in GT26 from 30 to 24. The burners were made retractable for easy maintenance. Since cracks were detected in the EV burners of the GT24 machine, new parts were installed to change the natural frequency of the combustor and prevent structural resonance during pressure pulsations.

Alstom developed a hierarchical control concept that provides separate fuel controllers for the EV and SEV burners during load change, and compressor guide vanes adjustment for air mass flow rate change. These controllers enable tuning during commissioning, operations and maintenance. Monitoring probes were added to alert when the machine was operating outside the desired range. The controllers were then able to change fuel split or air flow rate to recover acceptable operation parameters. In some cases operational procedures were implemented such as monitoring of fuel temperature or requirement to let the engine heat before activating transient operational steps.

Another system that was developed is the protection system. It relies on the monitoring system to sense disturbance events such as excessive temperature on certain components or high-pressure pulsations. The protection system ensures operational reliability by preventing damage to the engine, but may adversely affect availability if it is activated too often or stops operation when no real risk is imminent. The two important functions of the protective system are the Protective Load Shedding (PLS) system that reduces the load to zero within 2 minutes, and the gas turbine trip. The first is activated in case of potential medium level danger to the machine while the latter occurs for serious danger. The latter one is a last resort and should be avoided to minimize stress on the machine

New requirements regarding the operation range of gas turbines emphasize high efficiency and low emissions. This translates into restrictions on the temperature, flammability limits, pulsation areas, surge limits, etc. The gas turbine controller thus needs to satisfy new demands that are particularly critical during transient events including start-up, load reduction, and frequency support. The sequential combustion concept offers additional flexibility that enabled Alstom to develop a hierarchical control concept that provides separate fuel controllers for the EV and SEV burners during load change, and compressor guide vanes adjustment for air mass flow rate change. These controllers enable tuning during commissioning, operations and maintenance. A dynamic gas turbine simulator developed by Alstom enables on-line process monitoring by comparing the actual machine process to the computer model and detecting possible discrepancies.

Monitoring probes were added to alert when the machine was operating outside the desired range. The controllers were then able to change fuel split or air flow rate to recover acceptable operation parameters. In some cases, operational procedures were implemented such as monitoring of fuel temperature or requirement to let the engine heat before activating transient operational steps.

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The possibility to individually control each one of the two combustors and the three rows of adjustable inlet guide vanes (VIGVs) that allow reduction of combustion air by up to 60% of the full load mass flow rate provides another tool for tuning.

In an effort to further improve the CD characteristics of the EV burner system, Alstom recent activities include:

1. A closed-loop controller that is being developed under a European program called
2. "FuelChief" (FuelChief Project (NNE5/382/2001) from EU). The main target is to ptimize the fuel distribution according to engine emissions and combustor pulsation levels. The model-based controller developed under this program is described in more details below.
3. Development of a fast gas composition monitoring system which is attached to the engine control system. This work is based on extensive experience gained with engines running with large variations of gas quality. The work is mainly driven by combustion performance.
4. The GT13E2 is using fuel staging as a controls measure to balance pulsations and emissions. Details on this concept are given below.

Alstom Fuel Staging Strategy for Tunable EV Burners

In order to improve on the EV burner family, an improved burner was introduced (AEV family) with an additional mixing section after the conical swirl generator for further enhancing the mixing of the fuel and combustion air. This additional mixing section makes it possible to further increase the mixing efficiency and therefore to reduce harmful emissions.

Figure 5-10 shows a sketch of a tunable burner system with staged fuel injection. It includes an EV burner with a split cone swirl generator: (1). Premixed fuel is introduced into the air stream through distributed injection holes along the two slots, (2). Pilot fuel is introduced at the apex of the cone through lance, (3). The premixed fuel is introduced through two separate fuel supply groups (4a, 4b) along the slots. The first group (4b) is arranged downstream from the second group (4a). The burner system includes combustion emissions measurement system (9), and a controller (10) of the two stages (4a, 4b) for premixed fuel injection as required for optimized operation of the system under changing operating and environmental conditions.

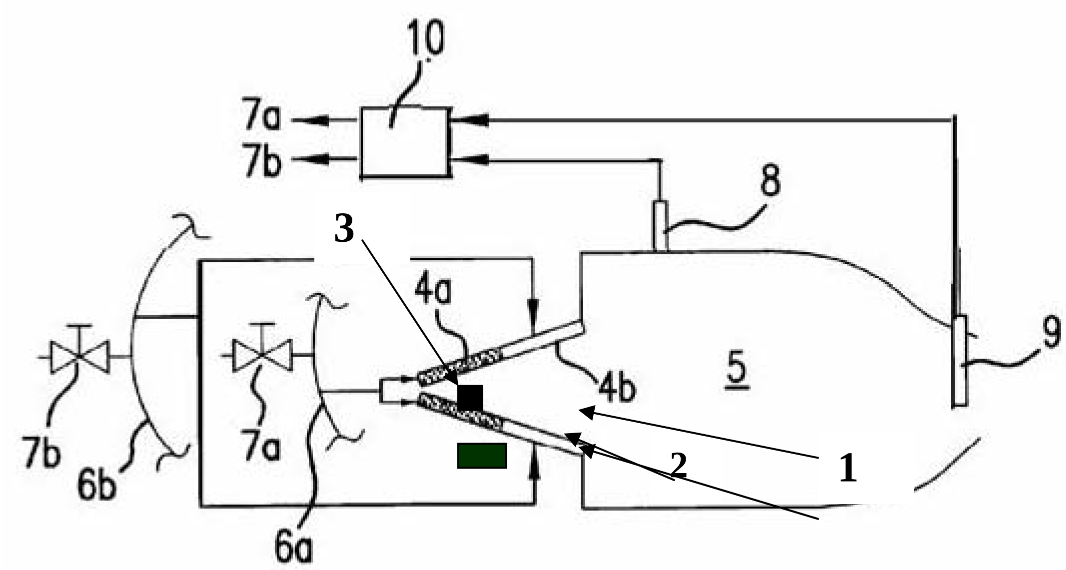

Figure 5-10
Schematic Illustration of the Fuel Staging Controlled EV Burner System

Parts Identification:

1	EV Burner
2	Fuel injection slots
3	Pilot lance
4 a	Fuel supply for the first stage
4 b	Fuel supply for the second stage
5	Combustion chamber
6 a	Fuel distribution system for the first stage
6 b	Fuel distribution system for the second stage
7 a	Control valve of first stage
7 b	Control valve of second stage
8	Pulsation sensor
9	Emissions sensor
10	Controller

Standard EV burner systems are designed with a single-stage supply of the fuel during premix operation (Figure 5-11). Size, distribution, arrangement, spacing, and the number of fuel injection holes along the burner slots is optimized to achieve low emissions, wide flammability limits, flashback safety, and combustion stability. It is very difficult to fulfill all these requirements with a fixed distribution of the premixed fuel when operating and environmental conditions change. The fuel distribution, injection pattern, and mixing is determined in such a way as to optimize the above mentioned performance parameters. The injection system has to be adapted to a particular system because an annular combustion system, for example, is different from a silo combustion chamber.

Additionally, the operating conditions of a system change over time due to increased leakage over time. A fixed distribution of the fuel cannot compensate for such effects.

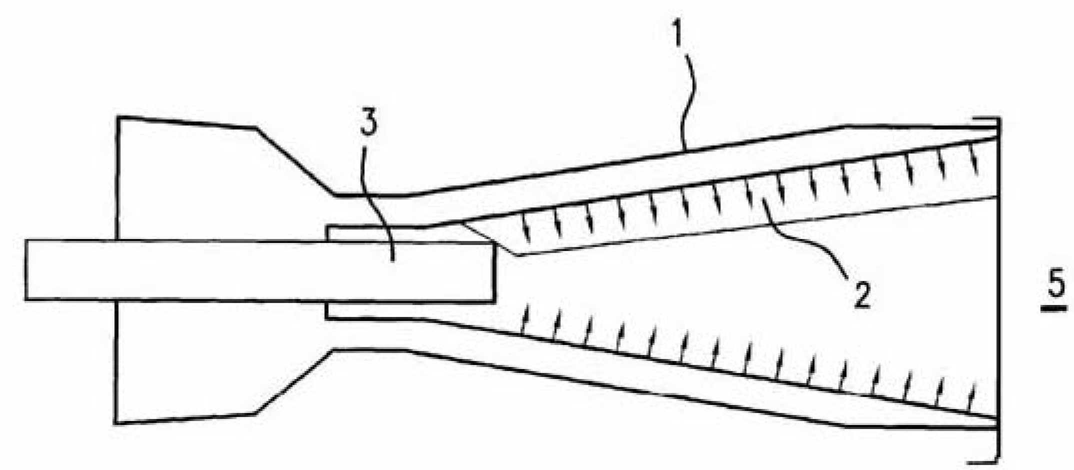

Figure 5-11
A Schematic Illustration of a Single-Stage EV Burner System

Premix burners are optimized for low emissions and low combustion oscillations under full load conditions. An additional pilot stage is necessary for starting up the burner and the gas turbine. At a certain operating load, at which the combustion can be sustained in the premixed mode of operation, the burner is switched from the pilot to the premixed stage. In the same manner, the shutting down of the gas turbine requires a switchover from premixed operation to pilot operation. These switchover processes cause strong combustion oscillations as well as large load oscillations. They require large amounts of inert gas to purge the fuel supply lines that are not used after the switchover. This is necessary to avoid ignition of the remaining fuel in the fuel lines due to circulating hot gases.

Switchover processes from liquid to gaseous fuel or vice versa are also difficult to accomplish using the existing fuel injection techniques due to the proximity of the injection nozzles to the inlet openings of the pilot system.

The tunable burner system includes a split cone EV or AEV swirl stabilized burners in which the gaseous premixed fuel is injected into the combustion air through two (or more) separate staged fuel outlets groups. A first premixed fuel group (first stage) is located at the aft section of the burner and a second fuel supply group (second stage) is located downstream of the first group. Additional groups of fuel outlets (stages) for more control of the premixed fuel distribution can be provided independently from the first and second group. The first and second fuel injection stages can also be distributed over the external circumference of the cone. The combustion system includes probes to measure combustion pulsations and other probes to measures the emissions from the combustion. The output of these probes is fed into a controller that determines the split between the two fuel stages such that combustion performance is optimized and adapted to desired specifications. The controller can provide input to multiple fuel injection stages that can be distributed along the burner's slots. Fuel valves are located on each one of the fuel lines to provide individual control of fuel flow rate in each stage.

A look-up table stored in the controller memory is used to determine the desired fuel split. The controller compares the measured pressure pulsations and emissions data with the stored look-up table in order to determine the current operating point of the burner system and change the fuel split towards the desired operating point.

Compared with single-stage burner systems, the use of a tunable burner system with staged fuel injection enables expanded operating range. A suitable arrangement of the individual stages of the fuel supply lines is sufficient and does not require any additional separate fuel line to achieve control authority. The independent controllability of the two stages of the burner system in enables continuous and safe operation with low pulsations from ignition to basic load while maintaining low NO_x emissions. An additional pilot stage, typically necessary for switchover operation, is not required in the tunable burner system, and switchover processes are possible without the usual associated pulsations or load oscillations. The operation of this burner system does not require inert gases (for example, N_2) purging cycle, thus reducing the operating cost of the system. The elimination of the pilot stage enables dual fuel operation with a simple switchover from fuel oil to gas, and vice versa.

A special advantage of the tunable burner system is the possibility to actively tune it using the controller, whereby an optimum operating point can be accomplished for different types of systems, for changing environmental conditions, to compensate for changes due to aging, and for various degrees of leakage that develop over time. In particular, the optimal operating point can be continuously modified to adapt to the variable parameters during the operation of the system. This feature permits optimum operation of the system under changing operating and environmental conditions.

In the present configuration of the burner system, the fuel supply line to the second stage branches off the fuel supply line of the first stage, and a control valve is mounted on that branch. Therefore, it is sufficient that the controller be connected to this single valve which then controls the fuel flow rate of both stages. The fuel split between the first and second stage is controlled in such a way as to minimize the pulsations and emission values. The control is accomplished by continuously comparing the current conditions with data stored in the control device that was determined during prior testing and that show dependence between the pulsations and emission values and the fuel split between the first and second stages. The predetermined conditions assure the fuel supply is controlled in such a way that the operating point is below a certain maximum level of the pressure pulsations, but allows to briefly exceeding the maximum during transient operation.

The tunable system shown in Figure 5-10 is a two-stage burner system formed by the separate fuel supply lines 4a and 4b. Downstream of the EV burner 1, the combustion chamber 5 is installed and the fuel/combustion air mixture produced by the premixing in the burner is burned. The fuel is supplied to the first stage 4a through fuel distribution system 6a and controlled by the control valve 7a. The second stage 4b is supplied with fuel via a second fuel distribution system 6b equipped with a control valve 7b**.** A high frequency response dynamics pressure transducer 8 is mounted on the walls of the combustion chamber 5, measures the level of the pressure pulsations and sends the information to controller 10.

An additional emissions sensor 9 is mounted at the combustion chamber outlet and transmits its data to the controller. The measured data is used to control the two control valves 7a and 7b with respect to emission values and pulsations to maintain or achieve a specified operating point. One of the control valves can be eliminated in a branching off arrangement described earlier. The first stage valve 7b can be controlled in such a way that a minimal amount of fuel flows through the second stage at any time for any operating load, so that no purging with inert gases is necessary. The overall control system can be simplified by using a single control valve.

Figure 5-12 shows an example of pulsations and emission values of a burner system as a function of the fuel portion supplied to the first stage relative to the total amount of fuel. The case illustrated here shows a range of stage 1 fuel percentage that results in a minimum level of NO_x emissions, but features maximum amplitude of pressure pulsations. This type of information is determined in preliminary tests and is subsequently stored in the controller. This programmed data based is used by the controller during operation to the fuel split that will avoid the undesired conditions and will allow maintaining or achieving low emissions with low pulsations. The data obtained by probes 8, 9 are compared with the stored control values in order to bring the operating point of the burner system to the left or right side of the pulsation peak shown in Figure 5-13. During stationary operation, the left side of the graph is preferred due to the low emission values. During transient operation, where emission considerations have a lower priority relative to maintaining low pressure in the burner, the right side of the pulsation peak is preferred.

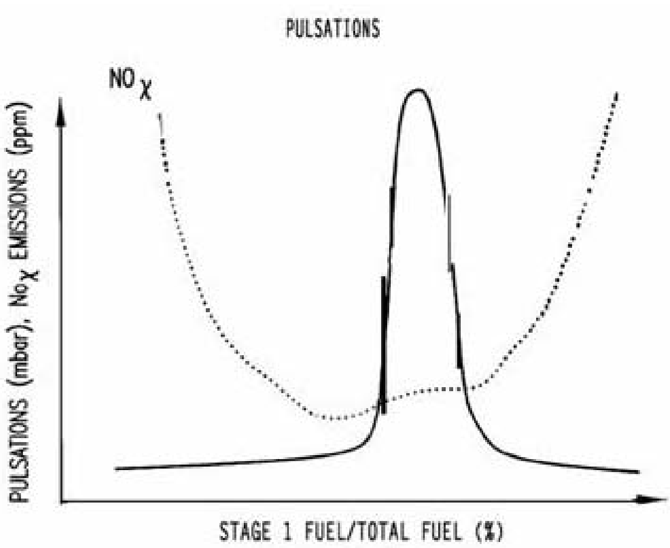

Figure 5-12
An Example of the Dependence of the Pulsations and Emission Levels of the EV Burner System on the Fuel Supply to the First Stage

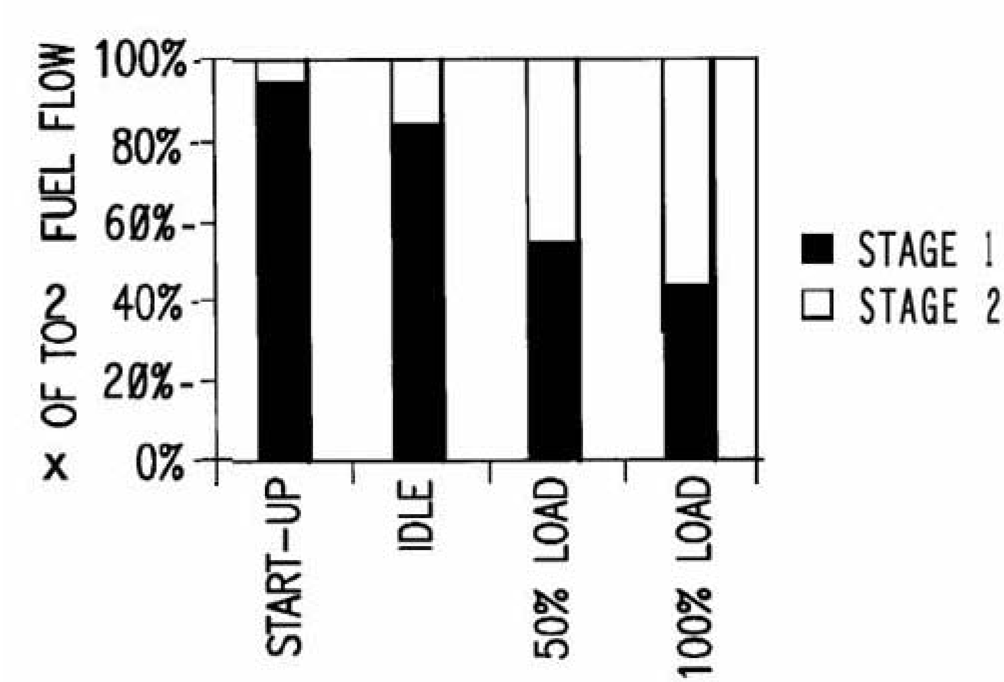

Figure 5-13
Fuel Split Scheduling between the Two Stages at Different Loads

In this way, the gas turbine can be operated from ignition to basic load without a separate pilot stage and with a single control valve. Figure 5-13 illustrates the operation of the tunable burner with two stages, each with 50% of the total burner system. The control valve controls the split of the supplied fuel flow to both stages. While the fuel is almost exclusively supplied to the first stage during ignition or start-up of the burner system or gas turbine, this ratio changes by gradually increasing the proportion of fuel provided to stage 2 during idling, at 50% load, and 100% load. At full load, the second stage is then supplied with somewhat more fuel than the first stage. Such an operating concept makes it possible to realize a stable operation of the burner system without an additional requirement of a pilot stage. The fuel distribution shown in Figure 5-13 will be modified by the controller during the operation of the system as the environmental conditions change or due to changes caused by system aging.

Figures 5-14 and 5-15 illustrate the importance of the tunable system for optimal operation in a wide range of equivalence ratios or adiabatic flame temperature. The graphs show that a fuel/air mixture that provides low NO_x emissions may have high pressure pulsations and vice versa. The tunable system allows adjusting the fuel split to optimize operation under these conflicting trends.

In order to develop advanced tuning techniques, a model for real time prediction of NO_x emissions and pressure pulsations is needed. Figure 5-16 shows the diagram developed by Alstom for this purpose.

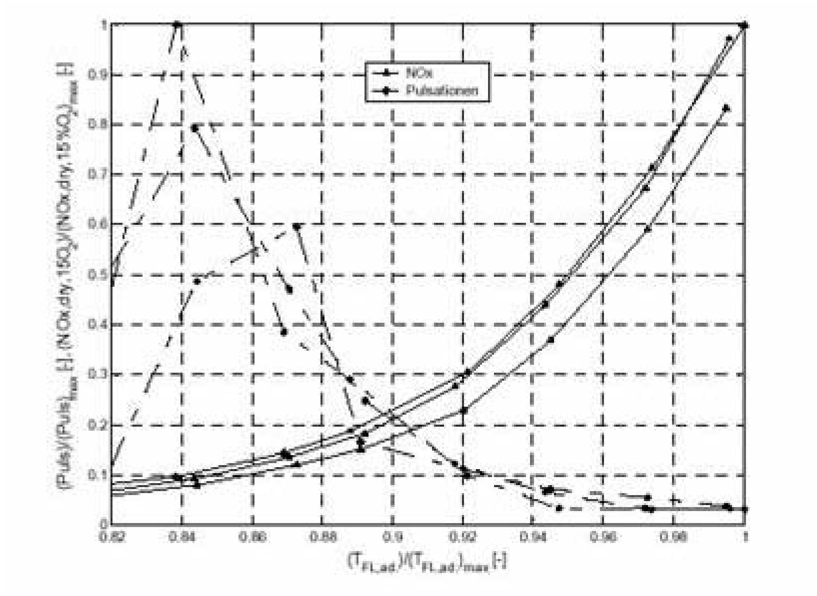

Figure 5-14
Normalized Pressure Pulsations and NO_x Emissions as a Function of Adiabatic Flame Temperature, with Variable Combustion Air Temperature, at a Constant Burner Velocity

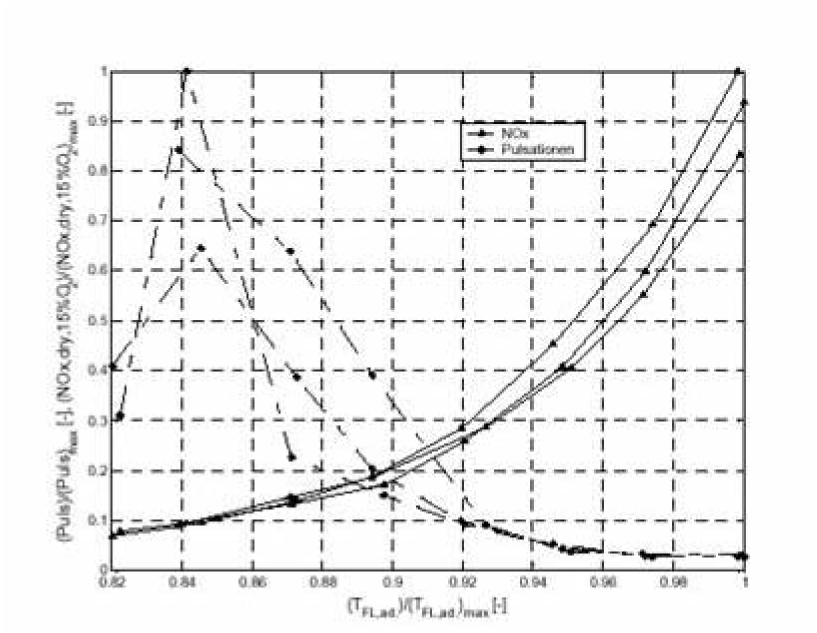

Figure 5-15
Normalized Pressure Pulsations and NO_x Emissions as a Function of Adiabatic Flame Temperature, with Variable Burner Velocity, at a Constant Combustion Air Temperature

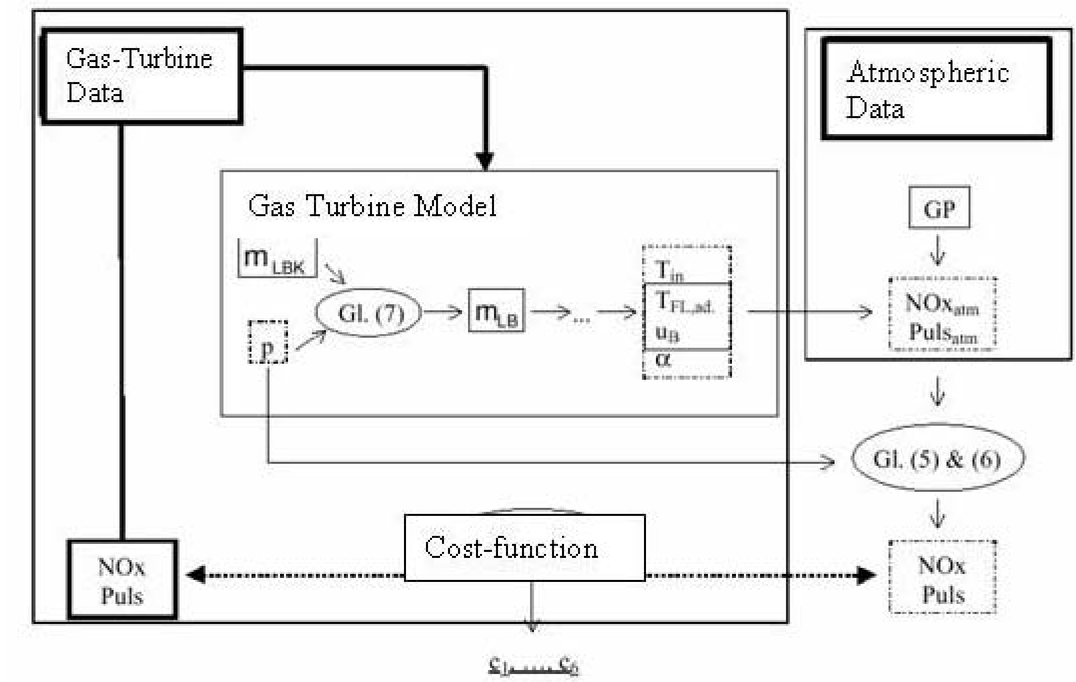

Figure 5-16
Optimization Logic to Assess Accuracy of Real Time Prediction of NO_x and Pulsations

GP-Gaussian Process; m_{LBK}- combustion chamber air mass flow rate; m_{LB}- burner air mass flow rate; T_{in}- combustion air temperature; $T_{FL,ad}$- adiabatic flame temperature; u_B- burner velocity; Gl. (5), (6), (7)- empirical equations relating atmospheric conditions to gas turbine conditions.

A
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