TURBINE TECHNOLOGY SERVICES CORPORATION

Best Practices in the Operation and Maintenance of GE DLN Combustion Systems

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by

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The Goal of DLN "Best" Practices?

To identify

- Commonsense Measures
- Simple Operational and Maintenance Procedures
- Key Data to Acquire

in order to

- Improve operational reliability of DLN systems
- Reduce the occurrence in-service DLN emissions and dynamics problems
- Simplify troubleshooting when problems do occur

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Source and Application of Best Practices

- Tuning and troubleshooting of DLN operational problems on over 100 GE DLN machines over the last 15 years

- Applicable GE Gas Turbines and DLN systems

DLN System	Turbine Model	Firing Temp. Range
DLN-1	5P, 5/2C, 3/2J	(1735 - 1770^{o}F)
DLN-1	7E/EA, 6B	(2020 - 2077^{o}F)
DLN-2	6FA, 7FA	(2350^{o}F)
DLN-2.6	7FA+(e)	(2390 - 2420^{o}F)

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DLN Operational Problems

- High NOx emissions
- High CO emissions
- High combustion dynamics → wear, mechanical distress
- Failed mode transfers → inability to reach premixed mode
- Primary Re-ignition (DLN1) → inability to maintain premixed mode
- Lean Blow Out (LBO) Trips
- Flashback → flame holding in premixer → melting, thermal distress

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Multiple Fuel Streams and Tuning

- All DLN systems employ staging of multiple fuel streams to achieve precise fuel/air ratio control within the combustor in order to balance the often competing demands of NOx and CO emissions, combustion dynamics, and lean blow out margin.

- DLN Tuning is process of optimizing the staging of these multiple fuel streams – by adjusting the ratio of fuel to each fuel stream – over the load range of the turbine

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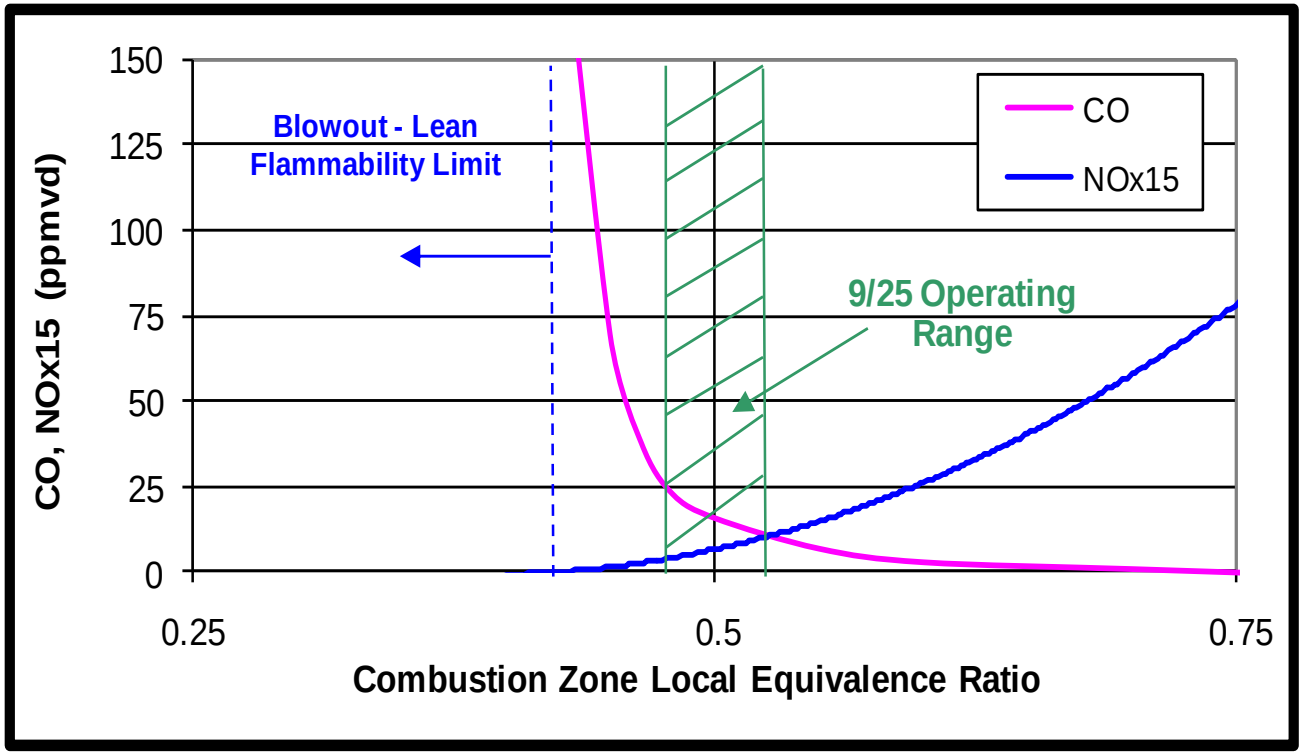
Fuel/Air Ratio Impact on Emissions



$$E.R = \frac{(f/a)_{actual}}{(f/a)_{stoich}}$$

- DLN Combustors operate very close to the Lean Flammability Limit
- DLN Combustors have a very narrow Equivalence Ratio operating range

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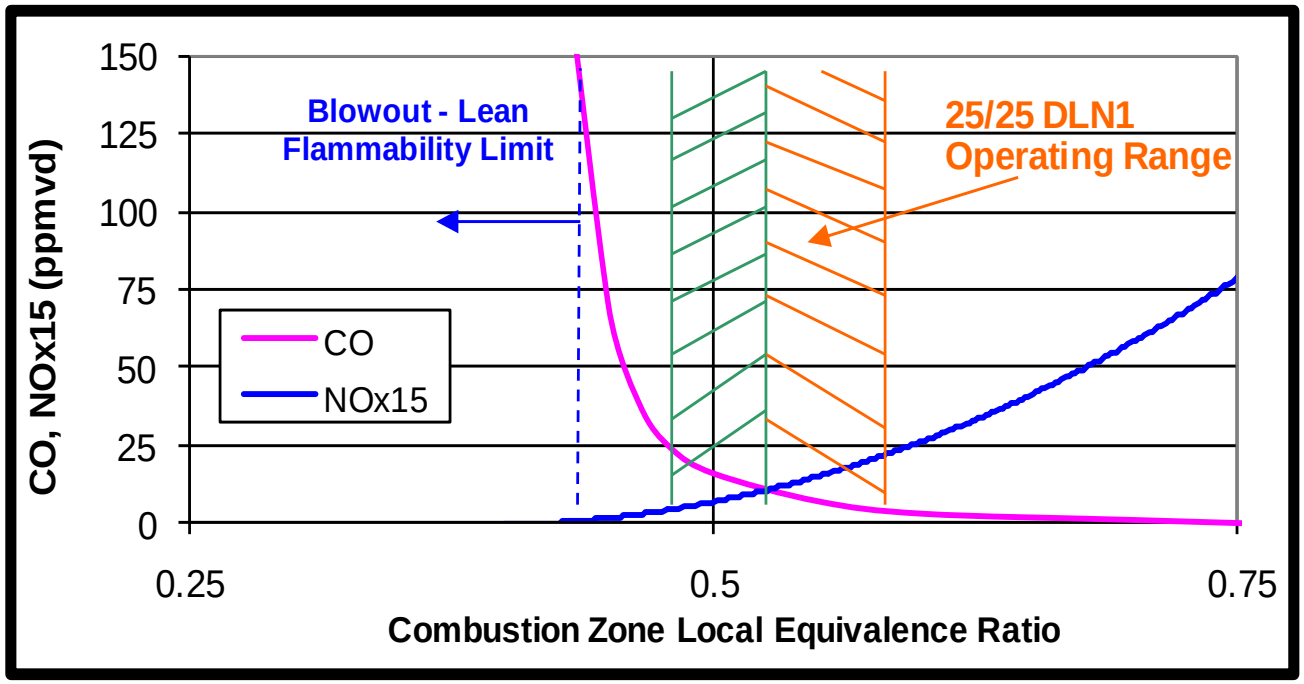
Fuel/Air Ratio Impact on Emissions



- 25/25 DLN has wider fuel/air ratio operating range than 9/25

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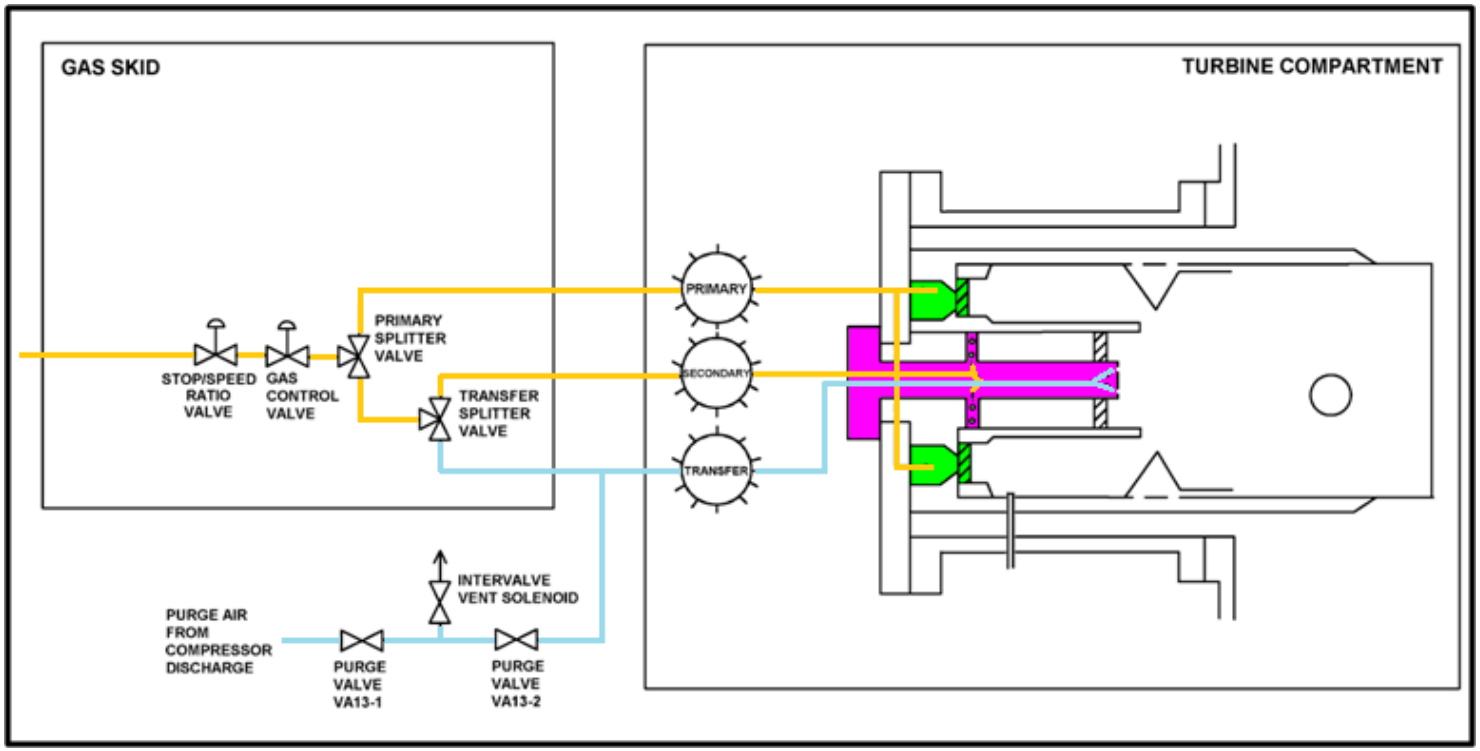
DLN-1



- 3 fuel streams
- 2 fuel streams in Premixed Mode

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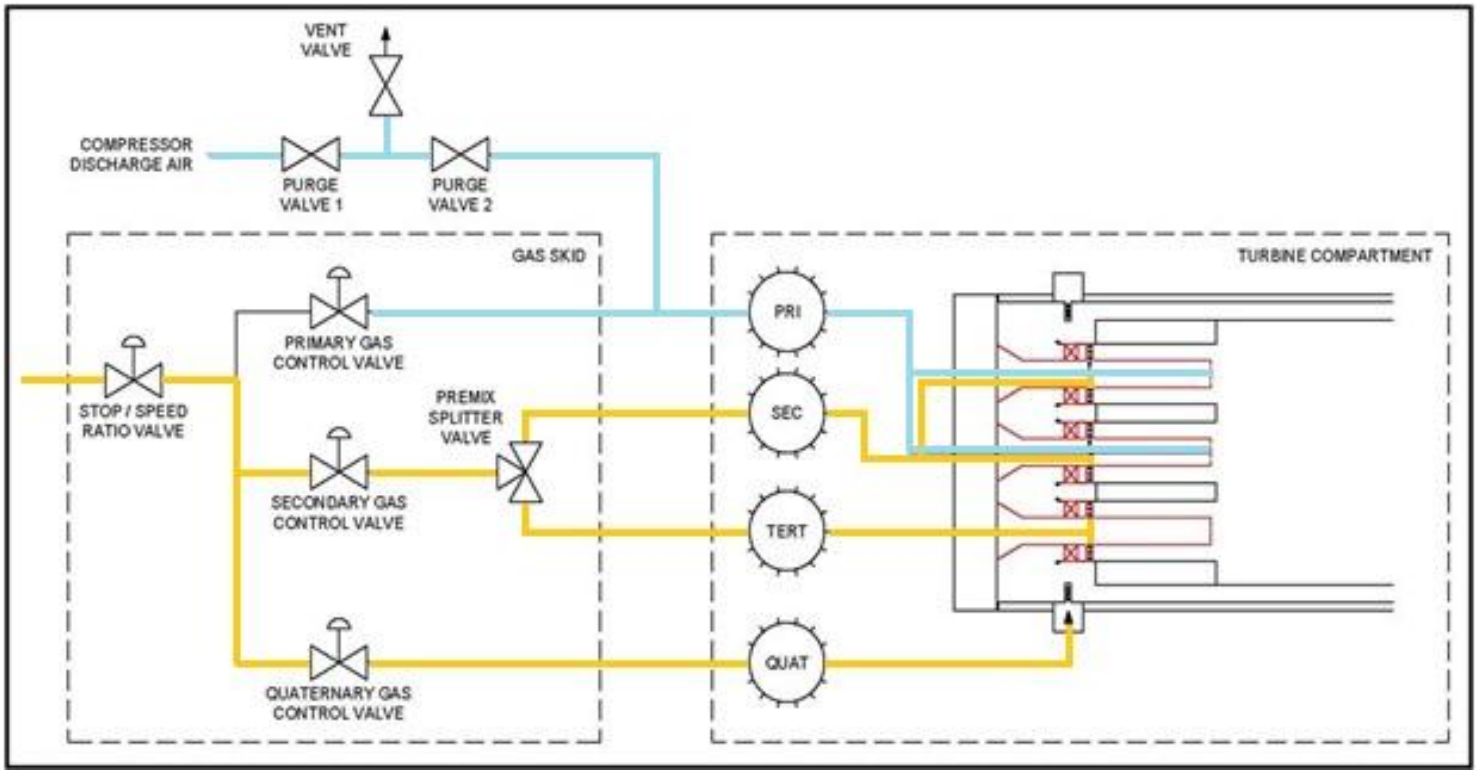
DLN-2



- 4 fuel streams
- 3 fuel streams in Premixed Mode

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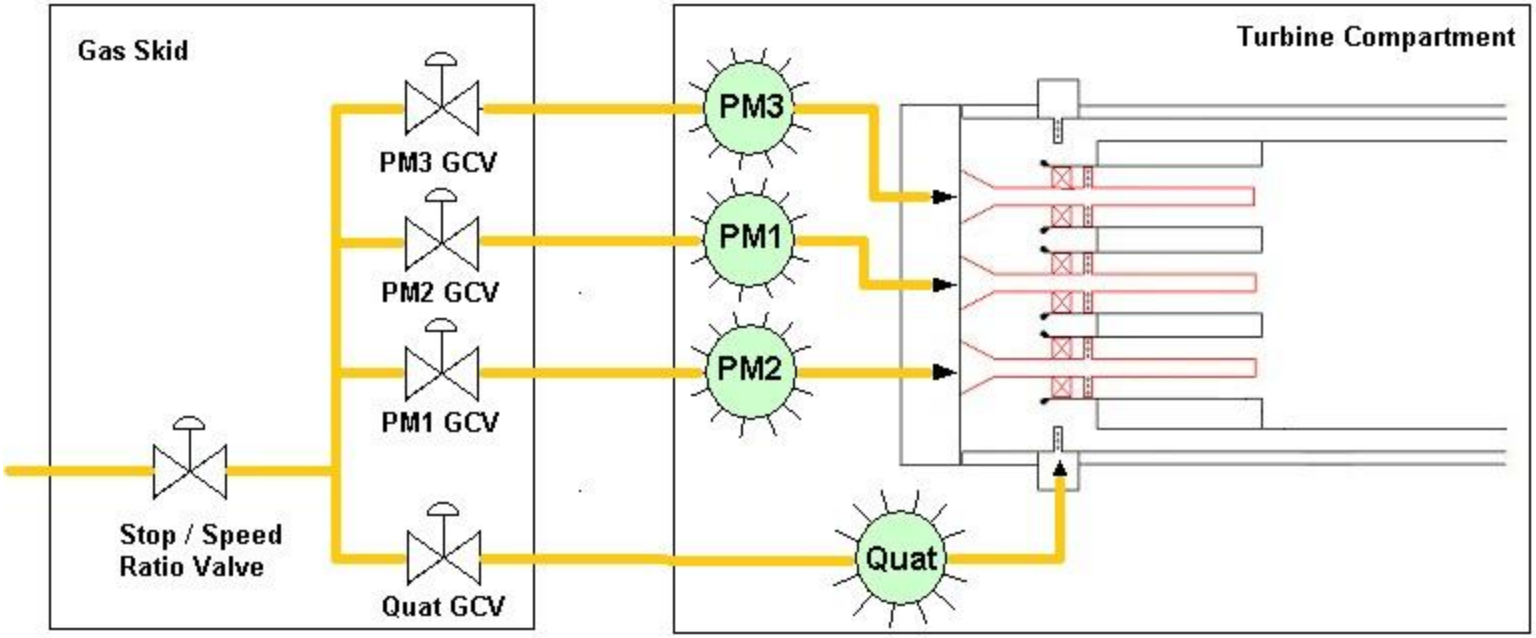
DLN-2.6



- 4 fuel streams
- 4 fuel streams in Premixed Mode (Mode 6)

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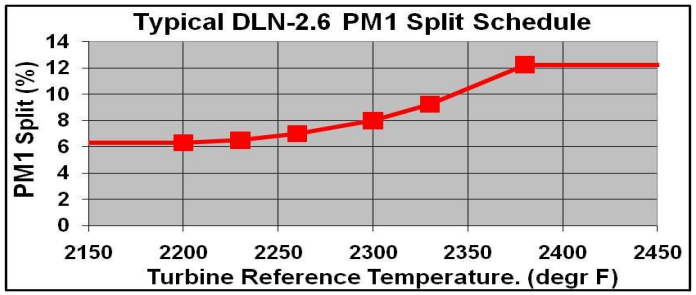
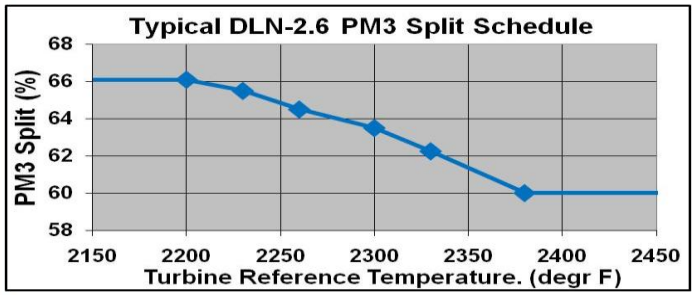
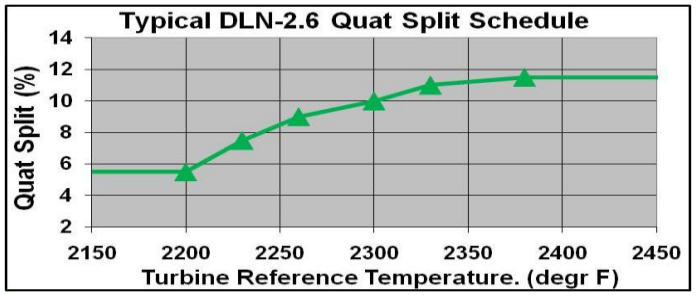
Fuel Split Schedules







- As unit loads/unloads, split schedules modulate the percentage of total fuel to each manifold as a function of *Turbine Reference Temp*, a calculated value approximating Firing Temp.
- The number of required split schedules is always one less than the number of fuel manifolds
- Adjustments to fuel split schedules are primary means of “tuning” the GE DLN combustors to optimize the competing requirements of NOx, CO, LBO margin, and combustion dynamics

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Tuning…. And its Limitations

- Tuning occurs at only a single point in time
- Even well-tuned machines are subject to factors which can negatively impact fuel/air ratio control and degrade DLN operability over time
  - Wear and degradation of combustor hardware over maintenance cycle
  - Drift or failure of pressure and temperature instrumentation
  - Improper installation of control components (gas/purge valves, spark plug)
  - Improper operation of fuel conditioning equipment
  - Poor quality control in combustion hardware repair
  - Drift or poor calibration of emissions monitoring equipment
  - Improper installation or configuration of dynamic monitoring equipment

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Impact of Pressure Instrumentation

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Key Pressure Measurements

Parameter	Description	Transmitter Name	Redundancy
P_{cd}	Compressor Discharge Pressure	96CD	triple
P_{bar}	Barometric Pressure	96AP	triple
ΔP_{inlet}	Inlet Total Pressure Drop	96CS	single
ΔP_{exh}	Exhaust Pressure Drop	96EP	single

- P_{cd}, P_{bar}, ΔP_{inlet},
  - Inputs to Base Load Exhaust Temperature Control Curve
  - Sets base load firing temperature
- ΔP_{exh}
  - Input to combustion reference temperature (TTRF1) calculation
  - Directly impacts fuel split schedule that proportions fuel among multiple streams
- Measurement errors in these transmitters are the single biggest source of post-tuning DLN operational problems

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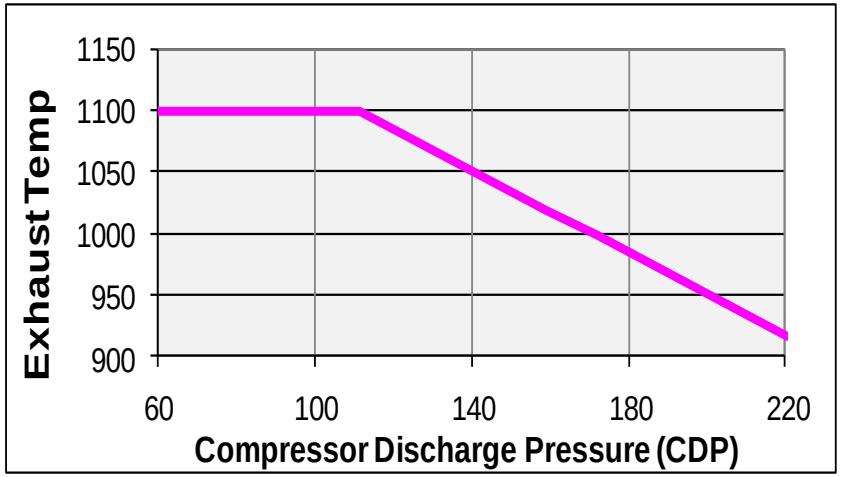
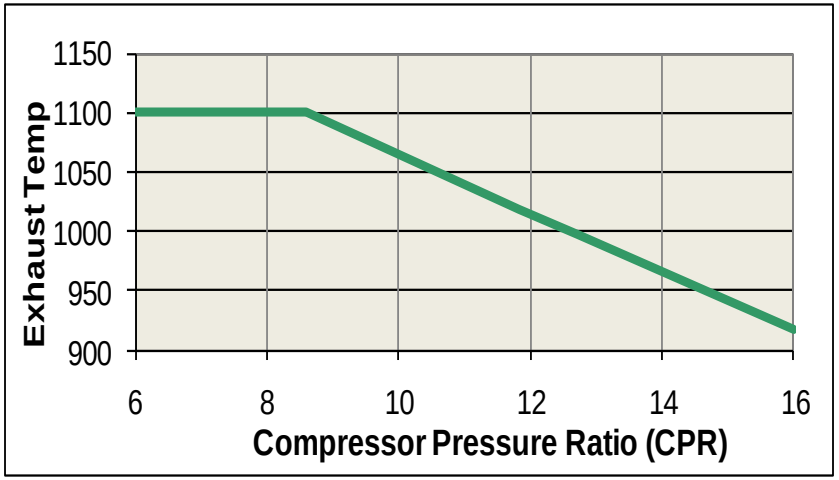
Base Load Control Curve





Standard (non-DLN) Combustor

$$T_x = f(P_{cd})$$

DLN Combustor

$$T_x = f(CPR) = f(P_{cd}, P_{bar}, \Delta P_{inlet})$$

$$CPR = \frac{P_{cd} + P_{bar}}{P_{bar} - \Delta P_{inlet}}$$

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Barometric Pressure Measurement Error

Site Elevation	P_{bar} Actual psia	P_{bar} Indicated psia	CPR Actual	CPR Indicated	Texh Expected ^oF	Texh Actual ^oF	Tx error ^oF	Tfire error ^oF
Sea Level	14.7	14.40	12.7	13.00	995.1	988.1	-6.9	-11.8
Sea Level	14.7	14.70	12.7	12.70	995.1	995.1	0.0	0.0
500 ft	14.4	14.70	12.7	12.47	995.1	1001.3	6.2	+10.5
1000 ft	14.2	14.70	12.7	12.24	995.1	1007.3	12.3	+20.8
1500 ft.	13.9	14.70	12.7	12.02	995.1	1013.4	18.3	+31.2

- Impact of barometric pressure is significant at high elevation
- Using sea level value (29.92" HG or 14.7 psia) at elevated sites will increase T_{fire} by 10^oF for each 500 ft of elevation
- Can not "calibrate" barometric pressure transducers using airport or weather values from the internet – these values are altitude-corrected and will always read in the range of 30" Hg
- Low P_{bar} readings cause under-firing → increased CO emissions (E-class), lost BL output
- High P_{bar} readings cause over-firing → increased NOx emissions, reduced hardware life

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Inlet Pressure Drop Measurement Error

	ΔP_{inlet} in. H20	P_{bar} psia	P_{cd} psig	CPR	Texh ^{o}F	Tx error ^{o}F	Tfire error ^{o}F
Sensor Failed High	9.0	14.70	171.0	12.92	989.4	-4.6	-7.8
Baseline Case	3.5	14.70	171.0	12.74	994.0	0.0	0.0
Sensor Failed Low	0.0	14.70	171.0	12.63	996.8	2.9	+4.9

- ΔP_{inlet} measured by a single transducer – is not triple redundant as are P_{bar} and P_{cd}
- Sensor can fail either high or low
- Sensor failing high causes under-firing → increased CO emissions on E-class machines (T_{fire} = 2020^{o}F)
- Sensor failing low causes over-firing → increased NOx emissions, reduced hardware life

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Exhaust Pressure Drop Measurement Error

Scenario	Load	Actual ΔPexh	Indicated ΔPexh	Actual TTRF1	Indicated TTRF1	**TTRF1 Error**	PM1 Split @ Actual TTRF1	PM1 Split @ Indicated TTRF1	PM3 Split @ Actual TTRF1	PM3 Split @ Indicated TTRF1	**PM1 Split Error**	**PM3 Split Error**
	MW	in. H2O	in. H2O	degr F	degr F	degr F	%	%	%	%	%	%
SC, Fail High	110	4	19.4	2280	2249	-31	17.75	18.25	65.15	66.35	+0.50	+1.20
CC, Fail Low	110	10	0	2288	2306	+18	17.05	16.60	64.68	64.00	-0.45	-0.68

- ΔP_{exh} is an input to calculated TTRF1, Combustion Reference Temperature. When ΔP_{exh} fails, TTRF1 is calculated incorrectly.
- ΔP_{exh} → TTRF1 → Fuel Split Schedules → NOx
- If ΔP_{exh} fails high → indicated TTRF1 lower than actual → fuel split results in higher NOx
- If ΔP_{exh} fails low → indicated TTRF1 higher than actual → fuel split results in lower NOx
- For 7FA DLN-2.6, excessively low NOx emissions can lead to lean blow out trip

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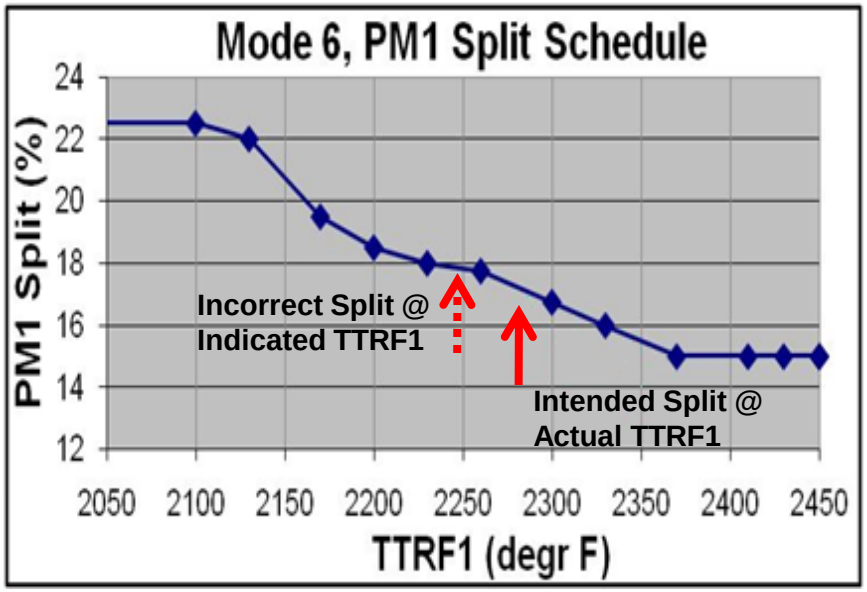
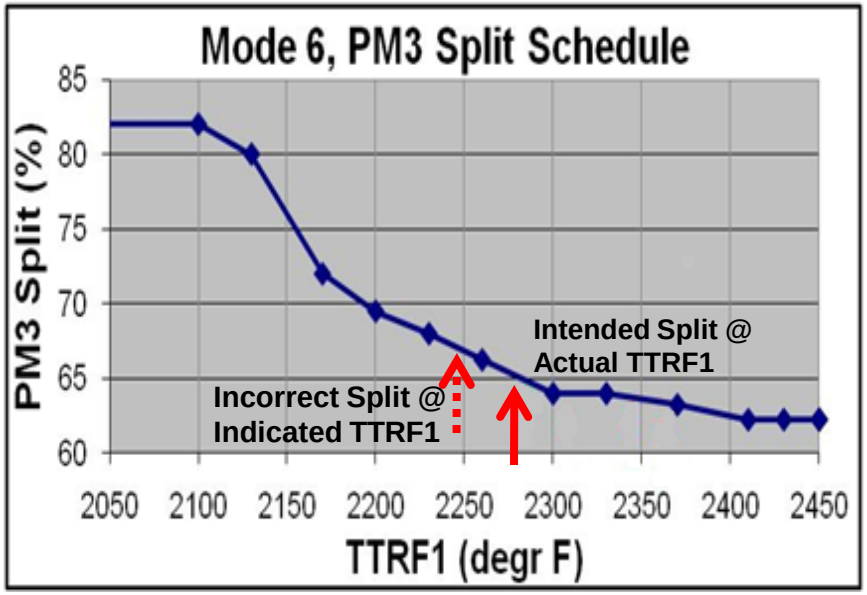
Impact of Exhaust Pressure Transmitter Failing High





- When ΔP_{exh} fails high
  - Indicated TTRF1 is lower than the Actual TTRF1 and
  - fuel splits operate at higher split values than intended

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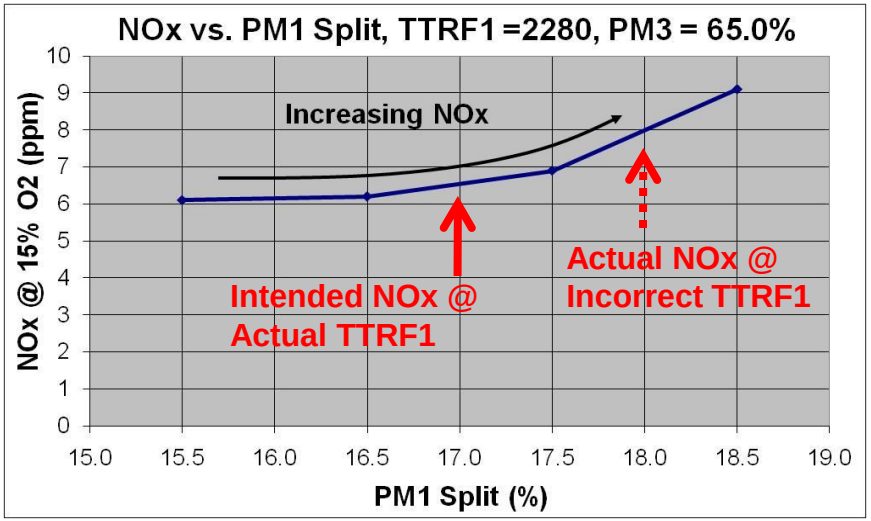
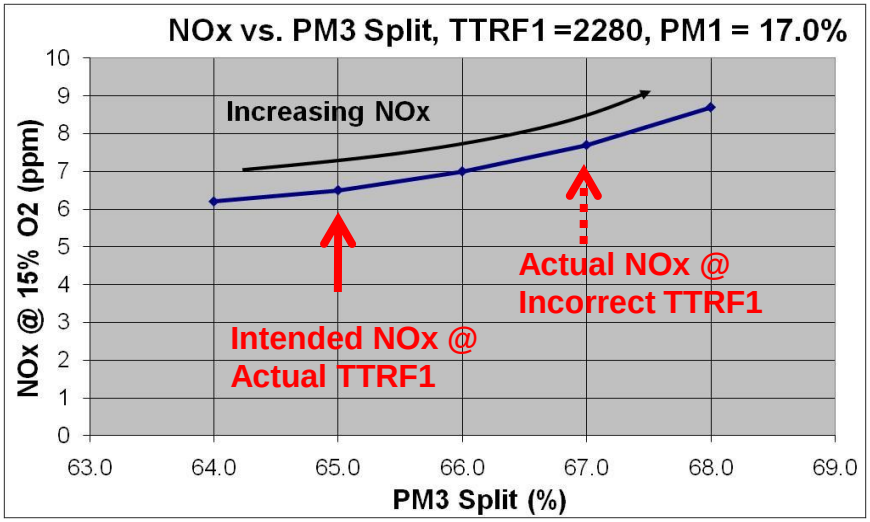
Impact on NOx of Exhaust Pressure Transmitter Failing High





- Intended Split at Actual TTRF1 of 2280: PM1 = 17.0%, PM3 = 65.0
  → Intended NOx = 6.5 ppm
- PM1 Split Increased from 17.0 to 18.0% → +1.5 ppm NOx
- PM3 Split Increased from 65.0 to 67.0% → +1.2 ppm NOx
- NOx at Incorrect Split = 9.2 ppm

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Fuel Nozzles

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DLN vs. Diffusion Fuel Nozzles

- DLN Combustor - Multiple fuel nozzles per combustor with a numerous small metering and discharge orifices to achieve precise fuel/air ratio control – small size makes orifices easily susceptible to plugging or fouling

- Standard Combustor – Large, single fuel nozzle per combustor with large discharge orifices; less susceptible to plugging from debris

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Fuel Nozzles and Uniform Fuel/Air Ratio

- Uniform can-to-can fuel/air ratio is one of the most critical requirements for optimal DLN combustor operation
- Fuel nozzles that are “well-balanced”, that is, that minimize can-to-can variation in fuel nozzle effective area, are key to achieving uniform fuel/air ratio distribution
- Accurate and repeatable flow testing is critical to achieving minimal can-to-can effective area variation.
- Proper fuel system conditioning and O&M practices are necessary to maintain minimal can-to-can effective area variation over the maintenance cycle of the combustor

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Consequences of Poor Can-to-Can F/A Ratio Distribution

- High CO emissions – DLN-1, E-class machines
- Lean Blow Out Trips – 7FA DLN-2.6
- High Combustion Dynamics
- Flashback (7FA DLN-2/2.6)
- Primary Re-Ignition (DLN-1)
- Reduced Load Turn Down – all DLN systems
- High NOx emissions – all DLN systems

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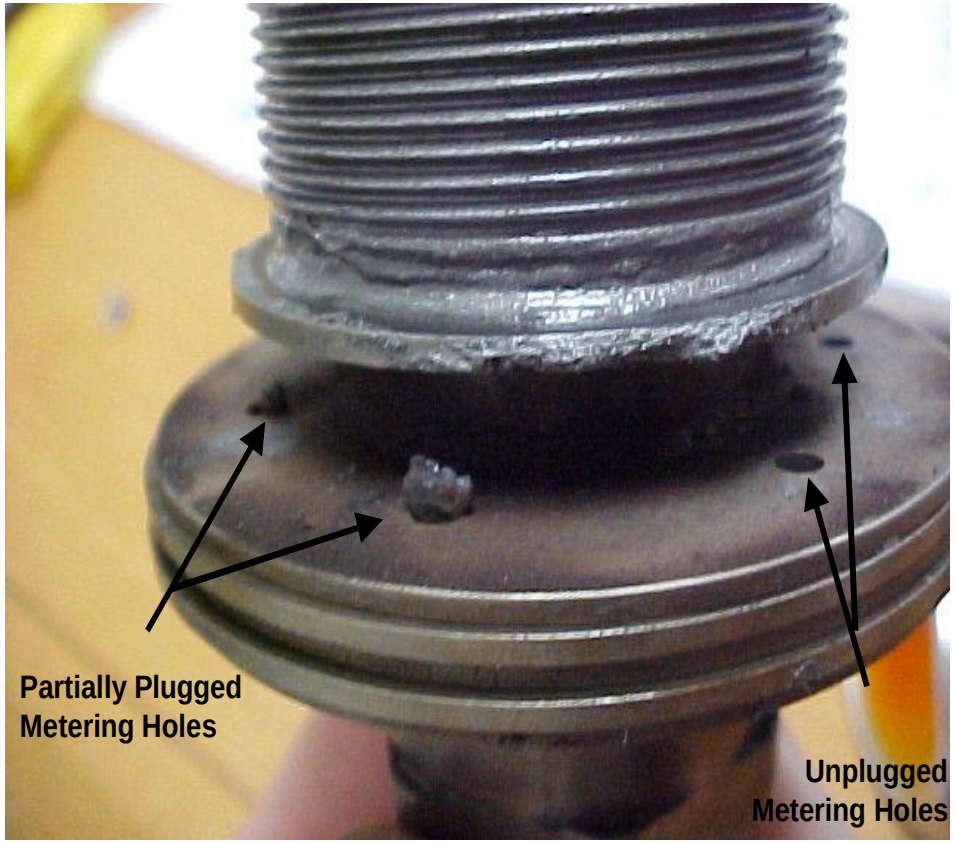
DLN-1 Example: Sensitivity of CO to Effective Area Variation



- Dual-Fuel Primary Nozzle:

  6 gas metering orifices per fuel nozzle, 6 nozzles per combustor
- 360 primary metering orifices per machine
- Site Z – three orifices total in two nozzles on one primary end cover partially plugged with debris
- Debris came from primary purge during liquid fuel operation

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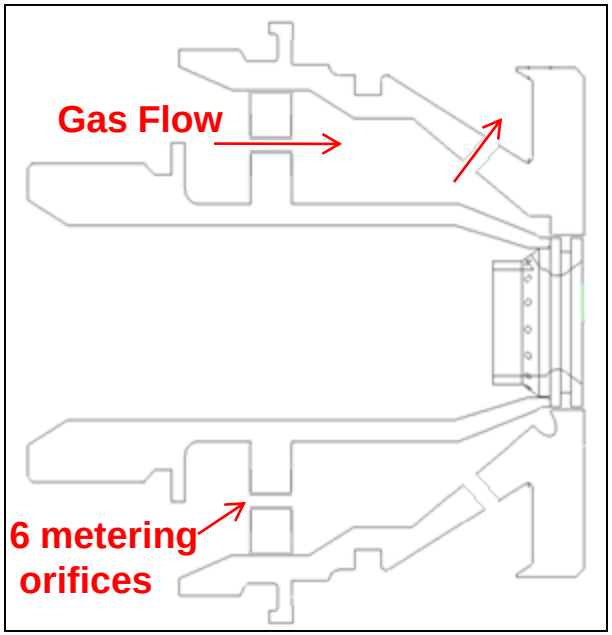
DLN-1 Example: Sensitivity of CO to Effective Area Variation

1 of 10 end covers with 6 primary nozzles



1 of 6 primary nozzles with 6 metering orifices

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DLN-1 Example: Sensitivity of CO to Effective Area Variation

Can #	Primary Effective Area (sq. in.)	
1	0.3866	
2	0.3868	
3	0.3882	
4	0.3877	
5	0.3893	
6	**0.3735**	
7	0.3860	
8	0.3885	
9	0.3861	
10	0.3863	
10 Can Average	0.3859	
Max	0.3893	0.89%
Min	**0.3735**	**-3.22%**
High 9 Average	0.3873	
Max	0.3893	0.53%
Min	0.3860	-0.32%

- Partial plugging in 3 of 360 metering orifices caused CO increase from 15 to 35 ppm
- Flow data shows that combustor was only 3.2% low in effective area relative to 10-can average
- 20 ppm increase in machine CO due to one can → CO in the can with plugged nozzles increased by 200 ppm (200 ppm /10 = 20 ppm)
- Plugging was not discernable as cold spot in exhaust temperature spread

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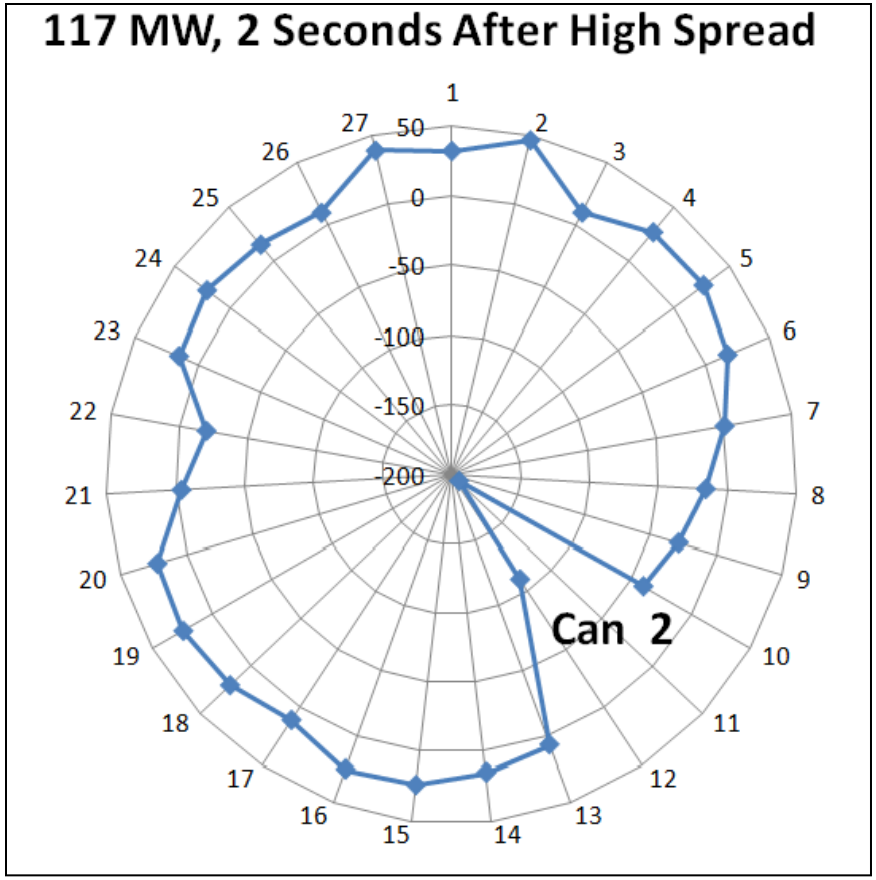
DLN-2.6 Example: Lean Blow Out Trip



- Three high exhaust spread trips occurred over two consecutive operating days
- Based on OEM's exhaust swirl chart, the cold spot in exhaust thermocouple array indicated the same combustor blowing out in all three trips → Can #2

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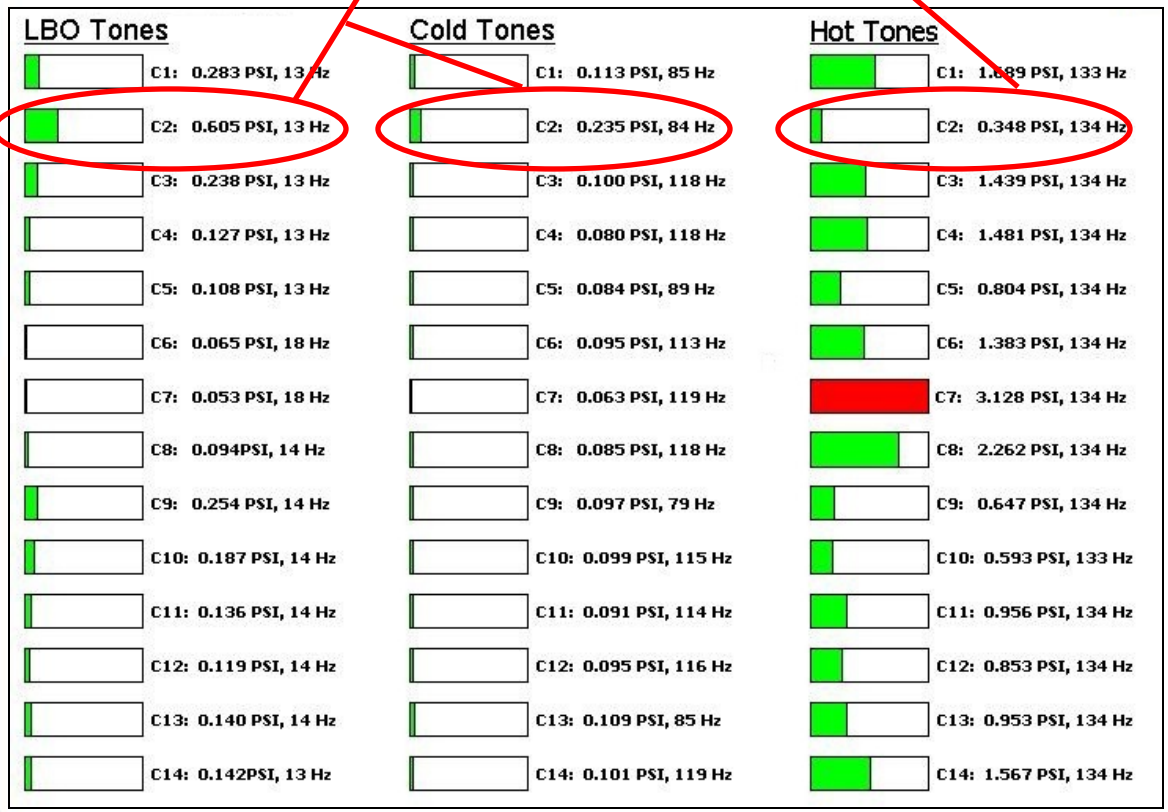
DLN-2.6 Example: Lean Blow Out Trip

Highest Amplitude LBO and Cold Tones

Lowest Amplitude Hot Tone



- Combustion dynamics provide further evidence of f/a ratio problem in Can #2
- Highest LBO and Cold Tones and lowest Hot Tone imply leaner f/a ratio in Can #2 than in other cans
- Tuning to eliminate high LBO Tone can result in high Hot Tone amplitudes in other cans → increased wear and mechanical distress

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Fuel Nozzles and Flow Testing

Understanding the methods, criteria, and quality control procedures used by vendors in repairing and flow testing fuel nozzles is key to optimizing combustor performance and minimizing effective area (A_e) variation

- What is the criteria for allowable A_e variation?
  - vendor and customer should establish this prior to flow testing
- What is the absolute A_e target?
  - Need OEM original flow data or manufacturing spec
  - Impacts combustion dynamics
- Is flow stand calibrated against a master standard part?
- Is leak testing of flow stand part of test procedure?
- Is leak testing of nozzle seals on end cover part of test procedure?
- Are individual nozzles flow tested? How are they distributed around unit?
- What are the calibration procedures for flow test stand instrumentation?

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Fuel Nozzles and Flow Testing

- Flow testing of fuel nozzles before disassembly
  - A means of identifying O&M problem that led to increased area variation
  - Nozzles with large variation should be disassembled and inspected with goal of pinpointing the specific cause of the variation
- Post-assembly flow testing
  - Ensure nozzles meet absolute area target
  - Ensure nozzles meet target area variation limits
    - Difficult to find OEM criteria on allowable A_e variation
    - Lower NOx/CO limits (9 ppm) require tighter criteria than higher limits (25 ppm)
    - More difficult to achieve tighter limits on single vs. multiple nozzle assemblies
      - Single nozzle assemblies: DLN-1 secondary; DLN-2.6 PM1 nozzle
      - Multiple nozzle assemblies: DLN-1 primary; DLN-2.6 PM2/3 nozzles
  - Recommended variation for 9 ppm, multi-nozzle assemblies: +/- 1%

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DLN Operational Reliability and Fuel Conditioning

- Properly designed Fuel Cleanup System is key to maintaining minimal effective area variation and reliable operation during combustor maintenance cycle
- Gas particulate filtration – not commonly a problem
  - Poor maintenance practices – debris falling into fuel or purge lines during outages
- Liquid Removal System
  - Auto-ignition of even small liquids droplets in combustor can cause flashback in DLN-2/2.6 combustors (severe damage) or primary re-ignition in DLN-1's (reliability problem)
  - Maintaining adequate superheat (~50^{o}F) above hydrocarbon dew point is critical to preventing auto-ignition – superheat commonly found to be inadequate
  - Must be sized large enough to handle unexpected liquid slugs in gas supply
    - Liquid deposits on nozzle orifices can form coke/varnish, changing nozzle effective area
    - Liquid deposits on control valves can form varnish, altering valve calibration & fuel splits

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