Paper No: 05-IAGT-2.1

INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE

MEASURES EMPLOYED AT UNION GAS TO ADDRESS HIGH CYCLE FATIGUE IN THE AVON HP TURBINE

by

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ABSTRACT

Union Gas has operated four AVON powered compressor units since the early 1970's. These units have experienced a series of GG failures and near misses over their service history, culminating in two major failures on a single GG in 2003. Both the 2003 GG failures had occurred in less than 500 operating hours since overhaul. Virtually all failures and near misses since the 1970's were attributed to High Cycle Fatigue (HCF) in the HP Turbine, induced by poor fuel quality. To address this problem, Union Gas undertook a program, in 2004, to upgrade the fuel conditioning system, on-skid fuel gas piping, Fuel Control Valve and PLC based fuel control systems. In addition to these upgrades, Union Gas has also installed Rolls Royce Mod 5000 (Swirler Burners) on two 1535-161G AVON engines and has actively pursued the use of high temperature microphones, installed in boroscope ports, as a means of detecting the combustion disturbances suspected of causing HCF. This paper details Union's fuel system upgrade program, Union's operating experience with the swirler burner mod, and data/conclusions regarding the use of high temperature microphones as a method of detecting combustion disturbances.

ACKNOWLEDGEMENTS

The author would like to acknowledge the efforts of all the Union Gas employees involved in this project. Without the talented people who came together as a team to meet the seemingly impossible project deadlines, this paper would not have been possible. This paper merely chronicles the results of the tireless effort put forth by mechanics, operators, station technicians and management in the completion of this project.

1. INTRODUCTION

Union gas operates a fleet of five Rolls Royce AVON engines, four or which were originally installed in the early 1970's. Several of these units have experienced a series of HP Turbine failures and near misses over their service history, culminating in two particularly disturbing failures of a single engine (Serial Number 37425) in 2003. The first failure occurred on January 21st, 2003, only 419 hours after it had returned from repair. The second failure occurred on December 6th, 2003, only 178 hours after a complete replacement of the hot-end. Both failures were attributed to High Cycle Fatigue (HCF), arguably, brought about by poor fuel quality.

Given the magnitude of the losses, Union Gas undertook a program of identifying all known contributors to the onset of HCF (not just fuel quality) and ensure that all possible steps were taken to prevent and/or detect the occurrence HP Turbine HCF.

This paper provides a brief background on the engines in question, and details Union's fuel system upgrade program, Union's operating experience with the swirler burner mod, and data/conclusions regarding the use of high temperature microphones as a method of detecting combustion disturbances.the program implemented by Union Gas

2. BACKGROUND

General Operational Service Information

In the early 1970's, Union Gas installed and began operating four AVON powered compressor plants in support of a very high capacity gas Transmission system. The first two AVON's were 1533 configurations installed in 1970 and 1972 at the Lobo compressor station. Two more units were installed at the Bright station in 1973 and 1975 and these were 1534 configurations. Initially the AVON's were operated either individually or in series, depending on system requirements.

As the Transmission system grew, RB211's were installed to operate in conjunction with the AVON's. Yard piping was reconfigured at both Lobo and Bright in 1988/89, to allow for a wide variety of operating modes including: individual operation of each plant, parallel operation of any combination of plants, and, most importantly, the yard configuration for a "design day" whereby the AVON's operate in parallel, feeding the RB211 plant in series. The design day yard configuration is referred to as Mode 9.

Mode 9 operation can yield station flow capacities in excess of 127 $10^6 m^3/d$ (4.5 bcfd) at a lift of 1400 kPa (200 psi).

In addition to the yard reconfigurations of 1988/89, both Lobo AVON's and the Bright A2 AVON were also upgraded for peaking service. This upgrade was performed in 1987 and required significant modifications to the power turbines at Lobo, plus installation of titanium "00" stages compressor blades on all three AVON's. Nozzle match area of the 1533 power turbines was reduced, rim cooling was installed, and drive couplings were replaced.

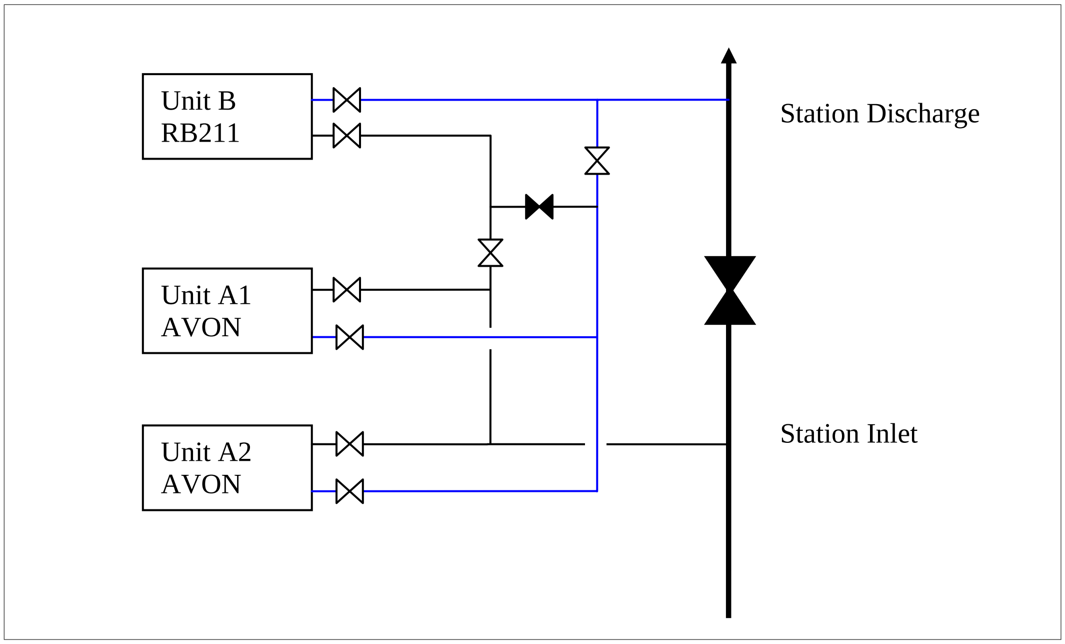


Figure 1 – Yard Configuration For Individual Unit and Parallel Unit Operation

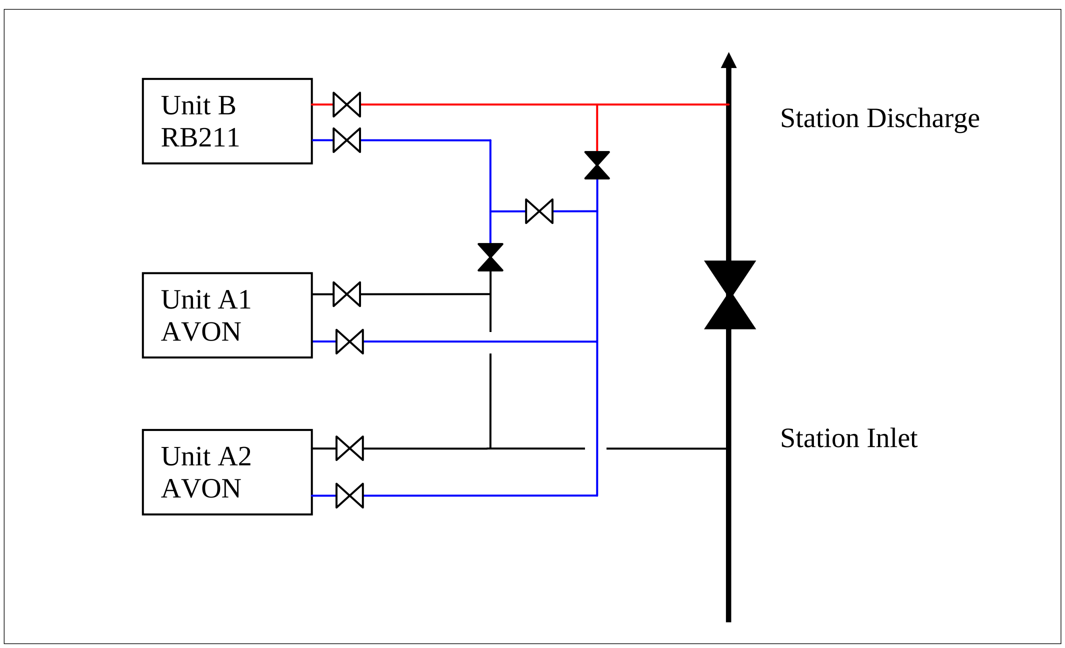


Figure 2 – Mode 9 Yard Configuration

During the various modifications to the Lobo and Bright yard configurations, the piping inside the compressor buildings has been modified only slightly. Prior to the 2004 upgrades, fuel gas filtration and regulation were pretty much unchanged from the original 1970's design. Changes to the fuel gas conditioning process were undertaken in 1982, when fuel gas supply was switched from suction gas to discharge gas, and a heat exchanger was also installed upstream of the filter/separator. Later review of the heat exchanger showed that it was significantly undersized. Coalescing filters were also installed on a trial basis at Lobo, however, they were installed at an ineffective location.

Current Operating Hours & Start Frequency

Typical annual operating hours for the AVON fleet currently operated by Union Gas are shown below.

	LOBO A1 **GG# 38425 (161G)** (Original Parkway)	**LOBO A2** **GG# 38148 (161G)** (New Acquisition)	**BRIGHT A1** **GG# 37433 (101G)** (Original Bright A2)	**BRIGHT A2** **GG# 37842 (76G)** (Original Lobo A2)	**PARKWAY** **GG# 37813 (76G)** (Original Lobo A1)
Operating Hours	1200	1200	600	600	2000
Peak Hours	120	120	60	60	200
Start/Stops	30	30	20	20	35

HP Turbine Repair History

HP turbine blades and discs have been an ongoing problem, with the first serious incident occurring in 1981. Evidence from the 1981 HP disc failure (engine 37433) provided strong indication that liquids were in the fuel gas, and measures were implemented to avoid a repeat occurrence. Fuel gas piping was re-routed to supply the unit with fuel gas from the discharge side of the compressor and small fuel gas heaters were also installed.

A noticeable worsening of the HP Turbine repair history also began to occur after modifying units for peak operation. Initial modification of three AVON's for peak service in 1987, was followed six years later by repairs/replacement (both minor and major severity) of HP Turbine discs and blades on two of the three uprated engines. Early in 2003, the first of two HP Turbine failures of engine 37425 occurred only 419 operating hours after being modified for peaking service in 2001. Late in 2003, the same unit failed a second HP Turbine after only 178 operating hours.

Shown below is the HP Turbine repair history for all AVON units owned by Union Gas.

	S/N 37813 (76G) (Orig'l Lobo A1)	**S/N 37842 (76G)** (Orig'l Lobo A2)	**S/N 37425 (101G)** (Orig'l Bright A1)	**S/N 37433 (101G)** (Orig'l Bright A2)	**S/N 38425 (161G)** (Orig'l Parkway)	**S/N 38148 (161G)** (Replacement)
1982				HP Disc Failure (contained)		
1993	HP Blade Shrouds			HP Disc Cracked		
1998					HP Disc Cracked	
2003			HP Disc Failure (contained) HP Disc Failure (contained)			
2004			SCRAPPED	Cracked Discharge Nozzles	HP Disc Cracked	PURCHASED
2005	Broken Chin Strap Broken Bracket	Unknown	N/A	Broken Chin Strap Broken Bracket	Broken Chin Strap	Unknown

As indicated above, Union Gas has avoided more failures than it incurred. Early detection of some very serious HP Turbine problems has been possible because the Lobo and Bright AVON units are primarily required for winter operation. Operations personnel have been very diligent in their maintenance practices during the off-season, to schedule inspections that are consistent with the repair history of these units. This has enabled Operations personnel to uncover many impending problems before they could escalate and has allowed the Operations group an opportunity to manage the risks.

3. HP TURBINE FAILURES – HIGH CYCLE FATIGUE

In virtually all cases of AVON HP turbine distress at Union Gas, the damage mechanism has historically been attributed to High Cycle Fatigue (HCF). HCF was official failure mechanism cited for both HP Turbine failures of engine 37425 in 2003.

HCF refers to the tendency of many materials to develop sub-microscopic cracks when exposed to repeated stress reversals. As the level of stress applied to the material decreases, more cycles are required before encountering an ultimate failure. If the stress level is reduced sufficiently, infinite fatigue life can be achieved provided that the materials being used possess desirable fatigue characteristics. An example of desirable fatigue characteristics is illustrated in Figure 3 below.

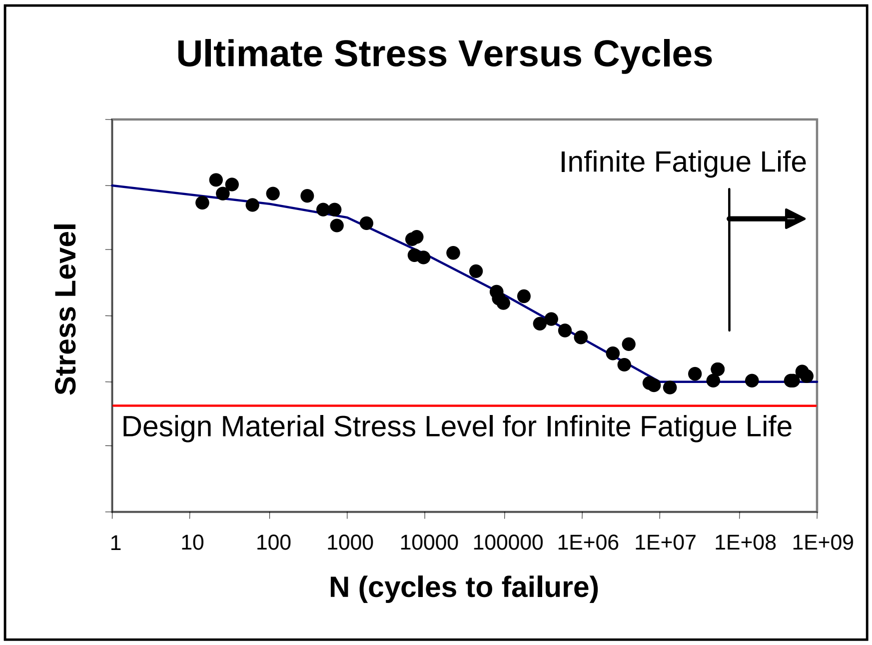


Figure 3 – Typical Fatigue Characteristics

Figure 3 would normally be determined by destructive testing in a laboratory environment, whereby known stress reversals are applied to a rotating test specimen and the cycles required to induce a failure are counted. Each point on the illustrated graph of Figure 3 is intended to represent the actual failure condition for a single test of a single test specimen.

By design, fatigue characteristics for materials used in high temperature turbine applications are intentionally selected, and stress levels in these materials are engineered, to ensure that the blades are operating within the acceptable tolerances needed to achieve infinite fatigue life. Such a safe operating condition is illustrated as the line labelled "Design Material Stress Level for Infinite Fatigue Life", in the Figure 3.

In the case of the AVON engine, conditions may occur (typically fault conditions) at the HP Turbine that can elevate stresses beyond that which can be tolerated for infinite fatigue life. Once the stresses in the HP turbine components exceed the ability of the materials to support these stresses infinitely, fatigue cycles begin to accumulate through the formation and propagation of sub-microscopic cracks. Once a fatigue cycle has occurred and induced it's almost imperceptible fatigue damage, any further fatigue cycles become additive. The initial sub-microscopic fatigue damage can be reversed through heat treatment, provided that the fatigue damaged has not progressed to the point where cracks become visible.

Most faults capable of producing HCF in the AVON HP turbine can be described as combustion related problems, and these include (but are not limited to):

- poor fuel quality (liquids),
- pressure pulsations in the fuel delivery system,
- instability of fuel modulating valve,
- flame-out (complete/partial) during light-off and ramp-up,
- flame-out (complete/partial) caused by high accel/decel rates – i.e. controls, and
- distorted flame due to blocked/dirty fuel nozzles

Other mechanical faults can yield HCF as well, including (but not limited to):

- loose combustor discharge nozzles, and
- fuel nozzle mis-alignment.

While these "root cause" fault conditions would pose a serious threat to any gas turbine engine, the experience of Union Gas has been that the AVON HP Turbine appears to possess a certain "sensitivity" to combustion disturbances. This "sensitivity" is thought, within Union Gas, to increase the tendency of the HP turbine to accumulate HCF cycles under conditions of low to moderate combustion/flow disturbance. Susceptibility of the

AVON engine to HCF related damage is the primary justification for the AVON upgrade program undertaken by Union Gas in 2004.

4. MEASURES EMPLOYED AT UNION GAS TO CONTROL ROOT CAUSES OF HCF

Based on the root cause analysis of HCF contributors and the perception that the AVON engine appears to be overly sensitive to combustion/flow disturbances, Union Gas undertook a program aimed at minimizing all possible sources of HP Turbine mechanical excitation, and monitoring, where possible, for signs of unusual combustion or flow disturbances through the AVON engine. To date, these efforts have included:

- Fuel Quality Improvement.
- Installation of MOD 5000 (Swirler Burners) for improved engine tolerance to low fuel quality.
- Fuel Control upgrades.
- Replacement of Fuel Modulating Valves.
- Experimentation with CP103 High Temperature microphones as a combustion/flow disturbance monitor.

<u>Fuel Quality Improvement:</u>

As installed in the 1970's, each of the four AVON units at Lobo and Bright were equipped with a filter/separator located upstream of the 1st cut fuel gas regulator. No additional filtration or heating was originally installed. Fuel gas was supplied to all AVON units from the suction side of the compressor.

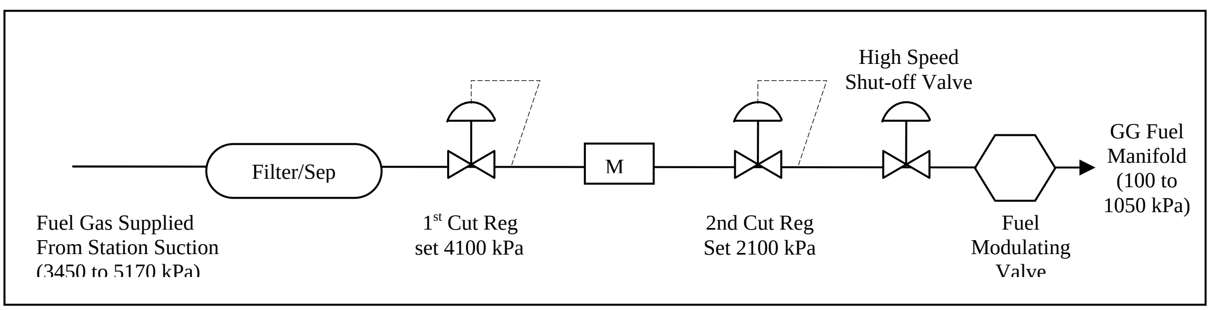


Figure 4 – Fuel Gas Conditioning Skid As Originally Installed

Following the first HP Turbine failure in 1981, it was concluded that the damage was a direct result of liquids formation between the filter separator and the fuel gas manifold on the GG. Evidence of this fuel contamination is shown in the photographs below. Irregular burn patterns can be seen on the trailing edges of the HP NGV's (right) and were thought to be typical of combustible liquids being ingested by the engine.

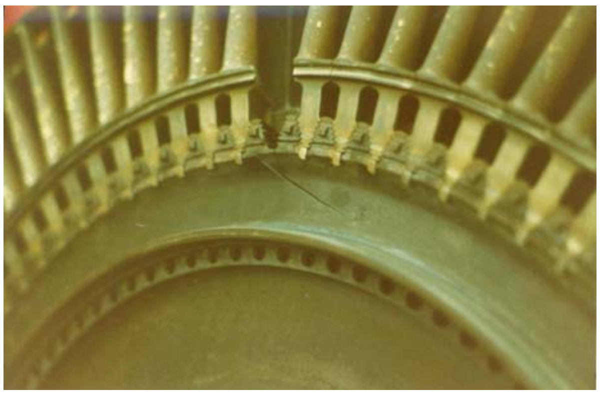


Figure 5 – HP Disc Cracked

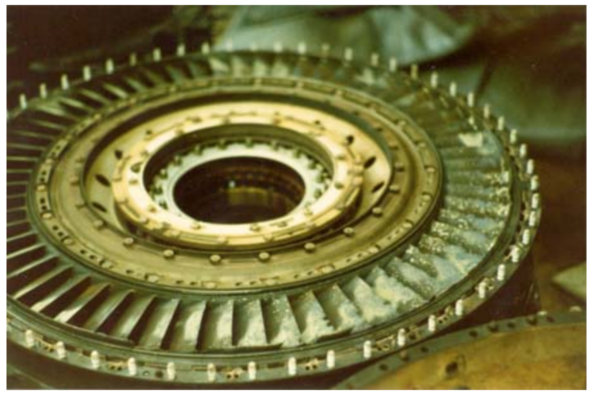


Figure 6 – HP NGV Damage

Even if the filter/sep had been operating with extraordinary liquid removal efficiency, heavy hydrocarbons in the vapour phase could easily pass through, and could then condense into a liquid phase during the pressure cuts which follow.

The HP turbine failure in 1981 was the first recognition that there might be a problem with fuel gas conditioning on the AVON's. From 1982 to 1999, several modest attempts were made to modify the fuel gas piping with the intention of resolving any fuel gas quality problems. However, the second failure of unit 37425 on December 6th, 2003 suggested very strongly that sweeping changes were necessary.

In order to improve fuel gas quality to the greatest extent possible, the fuel gas conditioning process was re-designed to include a coalescing filter followed by a heat exchanger (HE), as shown below.

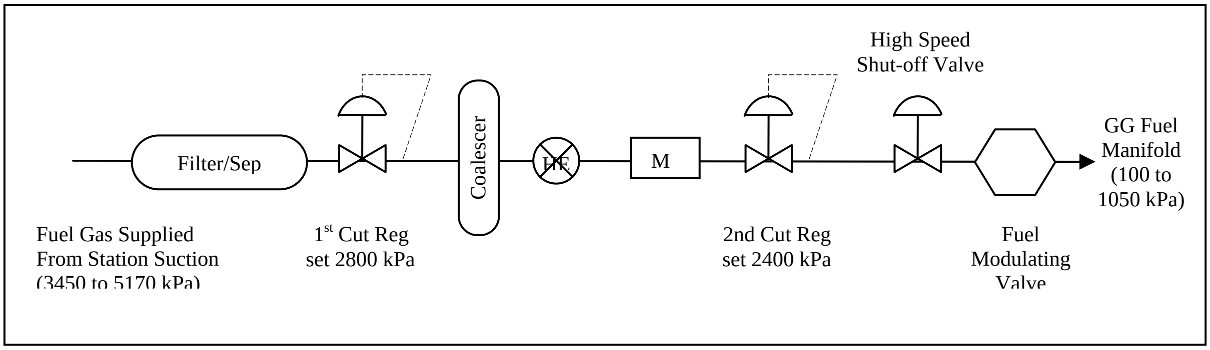


Figure 7 – Upgraded Fuel Gas Conditioning Schematic

In this configuration, the phase composition of the fuel gas supplied to the fuel conditioning skid can be carefully controlled to ensure that heavy hydrocarbons never condense into a liquid phase.

To illustrate the effect of the regulator/coalescer/HE combination, consider the following phase envelop (Figure 8) constructed using actual gas chromatograph test results, obtained on December 9th, 2003. Any operating condition (temperature and pressure) contained within the phase envelop curve has the potential to generate condensed hydrocarbon liquids. Gas analysis reports of this nature have always indicated that fuel gas quality was normally sufficient to avoid the formation of hydrates or condensation of heavy hydrocarbons. While the gas sample was obtained 3 days after the second failure of engine 37425, there could be no guarantee that gas quality was adequate just prior to the HP Turbine failure.

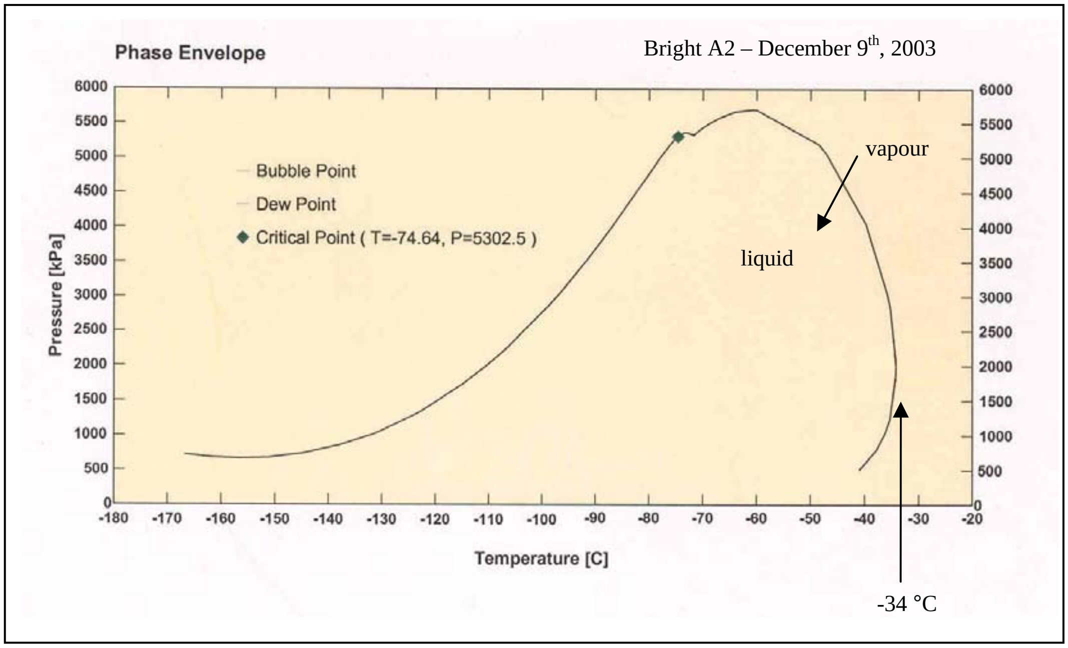


Figure 8 – Phase Envelop Constructed Using GC Results

The data above suggests that the fuel gas entering the unit would remain in the vapour phase provided that the gas temperature always remained higher than -34 °C.

Now consider a phase envelop for fuel gas of arbitrary quality (Figure 9), specifically gas that is rich in heavy hydrocarbons. Pressure regulation is used to create the conditions needed to produce condensed liquids – i.e. move from state 1 to 2. Coalescing filtration captures the liquids, thereby modifying the phase envelop downstream of the coalescing filter. Superheating (by the heat exchanger) ensures that further pressure reduction, downstream of the heater, cannot produce any additional liquids. Superheating also has the ability to vapourize any aerosol sized liquids of low volatility – like oils.

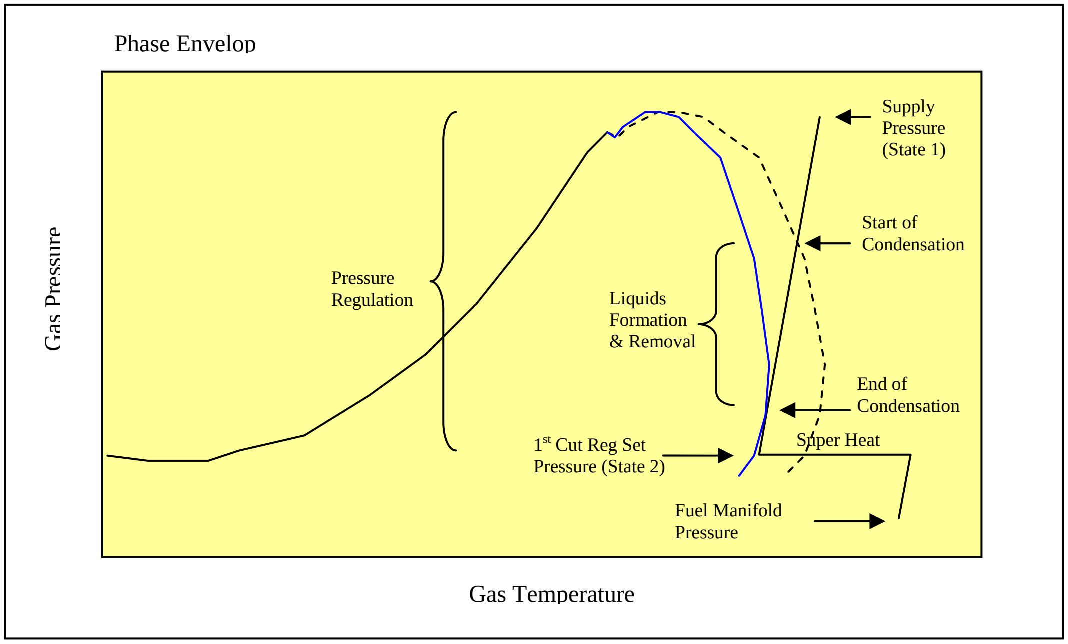
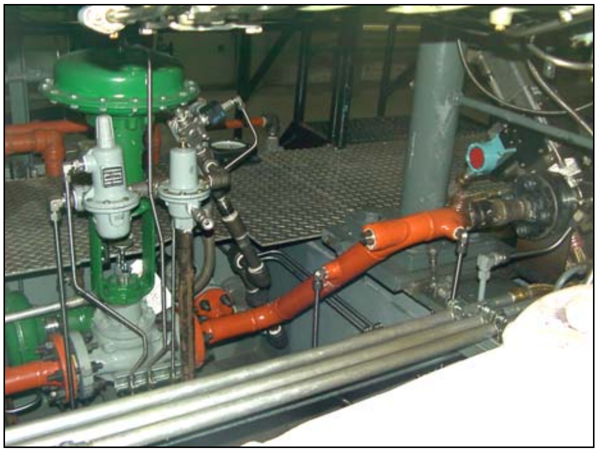


Figure 9 – Regulator/Coalescer/Heater Effect On Gas Composition

Key considerations for highest efficiency of liquids removal (when combining a regulator/coalescer/HE) include the following:

- 1st cut regulator must be set as low as possible. This means minimizing pressure drops through all piping components downstream of the 1st cut regulator. In the case of the Union Gas upgrade program, this meant replacing the original High Speed shut-off valve with a quick closing Fisher ET globe valve, and replacement of a 'Y' strainer downstream of the gas meter (from 2" to 4") – see photographs below.
- 2nd cut regulator should be selected and sized for operation at a minimum possible pressure cut. Regulation should be just enough to maintain a steady supply pressure into the Fuel Modulating Valve under all operating conditions, but no more than necessary.
- Heater should be sized to provide at least 30 °C temperature increase – this is the industry standard. Union Gas AVON installations now employ a temperature rise of 50 °C through the HE to allow some margin in the event of an upset, and to better vapourize any oil aerosols (low volatility) which might escape through coalescing filter. Design fuel gas temperature, after the heat exchanger, is 50 °C.



High Speed Shut-off Valve (Left)
Fuel Modulating Valve (Right)

4” Y-strainer (Left)
2nd Cut Regulator (Right)

Coalescing Filter (Centre)
1st Cut Regulator
Filter/Separator (Right)

Heat Exchanger (Left)
Coalescing Filter (Right)

MOD 5000 Swirler Burners

The second HP turbine failure of engine 37425 in 2003 caused such extensive secondary damage that it proved to be more economical to purchase a zero-houred (overhauled) 1535 AVON, complete with swirler burners, than to simply repair the original unit. The added value of the swirler burners factored heavily into the decision to replace rather than repair engine 37425.

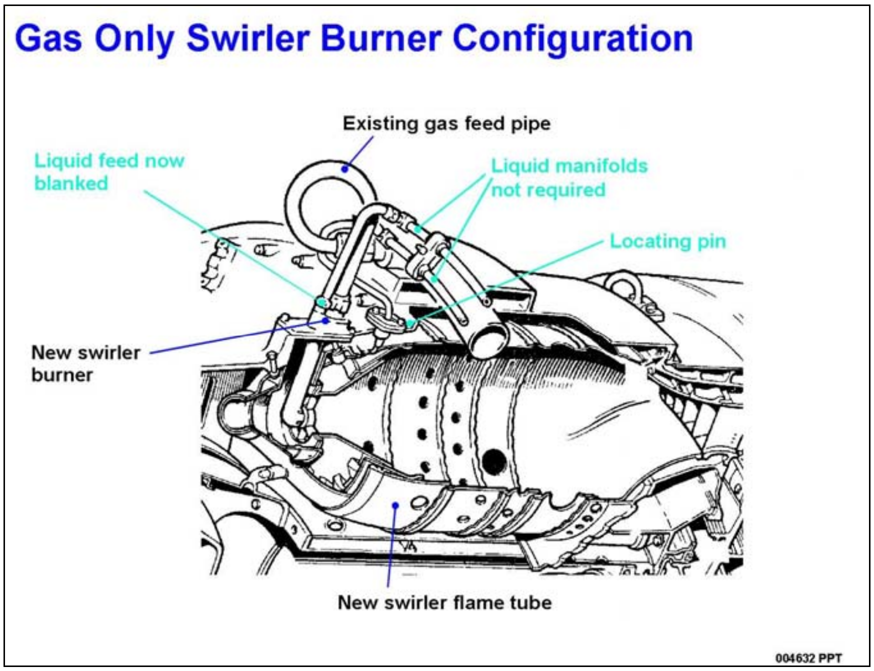


Figure 10 – Swirler Burner Assembly – Engine Cutaway (courtesy Rolls Royce)

Swirler burners were developed by Rolls Royce to specifically address the problem of condensed hydrocarbon liquids in the fuel supply, typically for off-shore applications. Mod 5000 involves the replacement of the burner nozzles and the flame tubes (i.e combustors), in order to introduce a high swirl of combustion air and fuel. As the fuel and air mix, the high swirl is better able to break up any liquid (in the fuel) into smaller droplets, allowing them to evapourate and burn more uniformly.

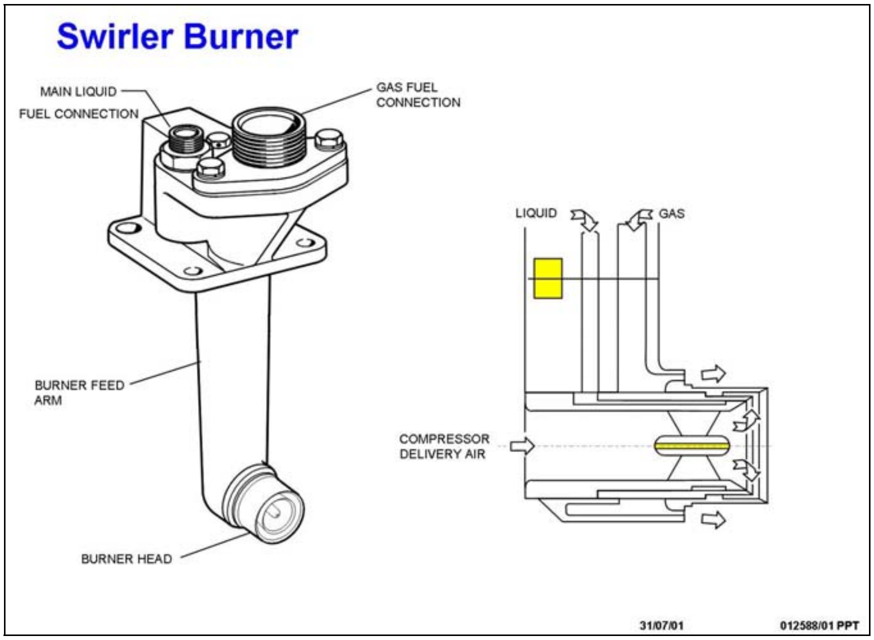


Figure 11 – Swirler Burner Nozzle (courtesy Rolls Royce)

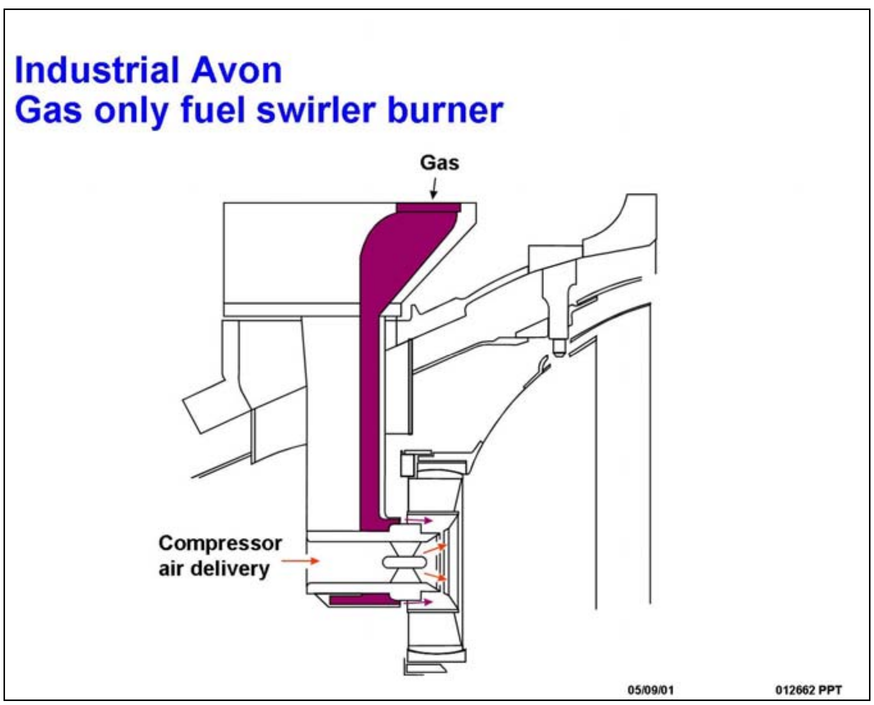


Figure 12 – Gas Only Swirler Burner Assembly Schematic (courtesy Rolls Royce)

Mod 5000 requires the replacement of all eight burner nozzles and eight flame tubes.

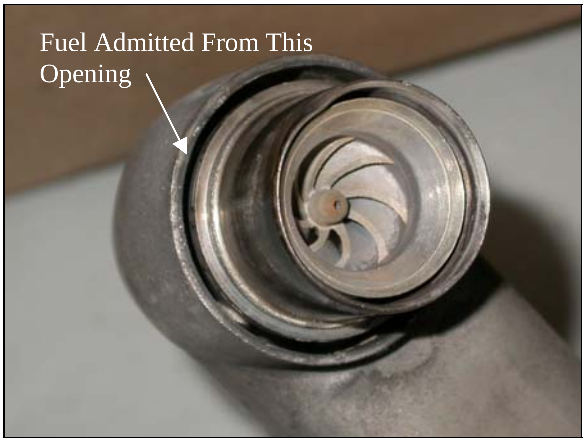


Figure 13 – Swirler Burner Nozzle

Figure 14 – Swirler Burner Flame Tube

Flame tubes have been modified to accept the swirler burner nozzle. The burner nozzle (see Figure 13) induces rotation to inlet air through the centre vanes. Fuel is admitted into the nozzle through the outer (concentric) opening. The burner nozzle fits into the centre opening of the flame tube (see Figure 14), and the fuel is swirled through a secondary set of vanes as indicated in Figure 14. The final result is a swirling core of air at the centre of the flame, surrounded by fuel swirling in the same direction, all surrounded by more swirling combustion air.

Operating characteristics of the swirler burner were found to differ appreciably from a standard flame tube (single dish or triple dish), with standard burner (pepper pot or pintle). Allowable exhaust thermocouple spread is much higher for the swirler burner configuration than the standard configuration. With the swirler burners, exhaust T/C spreads are now allowed to reach 60 °C before an alarm and 70 °C before shutdown. Previously, exhaust T/C spreads were allowed to achieve 50 °C before alarm, and 60 °C before shutdown, for a standard natural gas burner/combustor.

Operating data shows that Exhaust T/C spreads of 35 to 45 °C were commonplace during the first operating season. With the standard combustor configuration, such T/C spreads would have been considered symptomic of combustor problems, however, this does in fact seem to be normal for the swirler burners.

Further comments regarding the operating characteristics of the swirler burners are not possible due to discharge nozzle damage discovered during hot-end inspections. Peculiar ECT trends were noticed early in the operating season, however, it was impossible to conclude whether the observed trends were a result of discharge nozzle damage or were a natural operating characteristic of the swirler burners.

Operators should also be aware that not all repair and overhaul facilities can perform an engine certification test on natural gas fuel, and this has implications when having a unit fitted with swirler burners. Union's experience has been that there is a difference in the swirler burner performance for liquid fuel versus natural gas fuel operation. Initial certification test results for the replacement engine, using liquid fuel, showed acceptable T/C spread measurements. Subsequent testing at a different facility was conducted using natural gas fuel and yielded higher than acceptable T/C spreads. Operators are encouraged to ensure that the R/O facility chosen to install MOD 5000 can also test the engine using the appropriate fuel supply for their operation.

Fuel Controls:

As a direct result of the double HP Turbine failure on engine 37425 in 2003, Rolls Royce Energy Systems performed an audit of the fuel control system employed for the Union Gas AVON's.

In 1998 (?), Union Gas converted the main AVON fuel control program to operate on an Allen Bradley PLC5. Programming of the fuel control system was performed without RRES approval or knowledge, however, a sincere attempt was made by RRES in 2004 to compare the Union Gas fuel control program to the current "new build" standard.

Results of the audit suggested that some ramp accel/decel rates were higher than recommended, but not excessively. Where possible, ramp rates were adjusted to be more consistent with RRES standards, however, meeting the standard was not always possible. For example, quick acceleration through known engine, PT and compressor critical speeds is needed to avoid excessive unit vibration and resulting shutdowns. Slower accel rates would have the tendency to linger at these critical speeds, allowing vibration levels to climb. In some cases the recommended engine accel rates could have resulted in a unit that was difficult, or even impossible, to put on-line. Therefore, changes to engine accel rates became a compromise.

In the course of the fuel control audit, it also became clear that the Union Gas fuel control program did not incorporate the principles of SB64 (or current equivalent). SB64 is a bulletin released by Rolls Royce in 1992, as a Partial Flame-out prevention recommendation. SB64 calls for the measurement and control of fuel flow against CDP, to ensure that the fuel/air ratio within each combustor remained between pre-defined "Over-Fuelling" and "Weak Extinction" limits. Since the Lobo/Bright AVON units had been installed well before the release of SB64, the original fuel controls had never used CDP as a means of limiting accel/decel rates. Fuel controls were subsequently modified in 2004 to employ the latest RRES standard for limiting accel/decel rates using direct CDP measurement and fuel flow inferred from the Fuel Modulating Valve position.

Another portion of the fuel control program in need of updating was the light-off sequence. Light-off was identified as a critical factor to prevent flame-outs (partial and complete) in the AVON engine. As noted in SB64, the AVON was proven to be incapable of re-establishing a "complete stable light round" by "accelerating the engine to higher power" after suffering a flame-out[1]. Instances were reported by Rolls where exhaust T/C's had shown positive indication that the combustor had re-lit under load, but SB64 provided clarification that the resulting flame was likely not "complete and stable". Given Union's perceived susceptibility of the AVON HP turbine to HCF, an incomplete, unstable flame was interpreted as an increased HCF risk to HP turbine. As a result, Union Gas undertook to re-configure the light-off sequence of all AVON's to meet the latest Rolls Royce requirements.

[1] Rolls Royce Service Bulletin 64, 1992

Prior to 2004, all Bright/Lobo AVON's achieved light-off using the same sequence, originally established in the 1970's. Since the 1970's, light-off had traditionally been achieved at speeds of 1600 RPM. Speed at light-off had been determined by the natural speeds (high/low) of the two speed starter motor. Low speed employs a "soft-start" and is used for the purge cycle (880 rpm). High speed is engaged without a "soft-start" and tops out at 1800 rpm.

Currently, light-off event sequencing has been refined to yield a light-off speed in the range of 1100 to 1200 RPM on all Lobo/Bright AVON's. This ensures that the units conform to the Rolls Royce standard, which requires light-off between 1000 and 1250 RPM.

<u>Fuel Modulating Valve Replacement:</u>

Replacement of the existing Fuel Modulating Valve (FMV) was determined to another high priority in Union's effort to minimize combustion and flow disturbances through the HP Turbine. Prior to the 2004 upgrade, controls were configured such that a steady valve position setpoint was supplied to the FMV position controller, but the controller feedback signal would oscillate slightly, by about 0.25% of full scale. As a result, the existing FMV was suspected of inducing a small oscillation in valve position as it hunted to achieve the setpoint.

While this level of fuel pressure fluctuation is small, the maximum allowable total fluctuation prescribed by Rolls Royce for the AVON engine was about 1.5%. Consequently, FMV positioner oscillation was deemed a significant, albeit secondary, contributor to HCF excitation.

Installation of the newest style electric FMV, approved by Rolls Royce Energy Systems, is shown in the photograph below (Figure 15). A 45 degree orientation of the valve was determined to be the best fit, to reduce the overall footprint of the valve and reduce trip hazards.

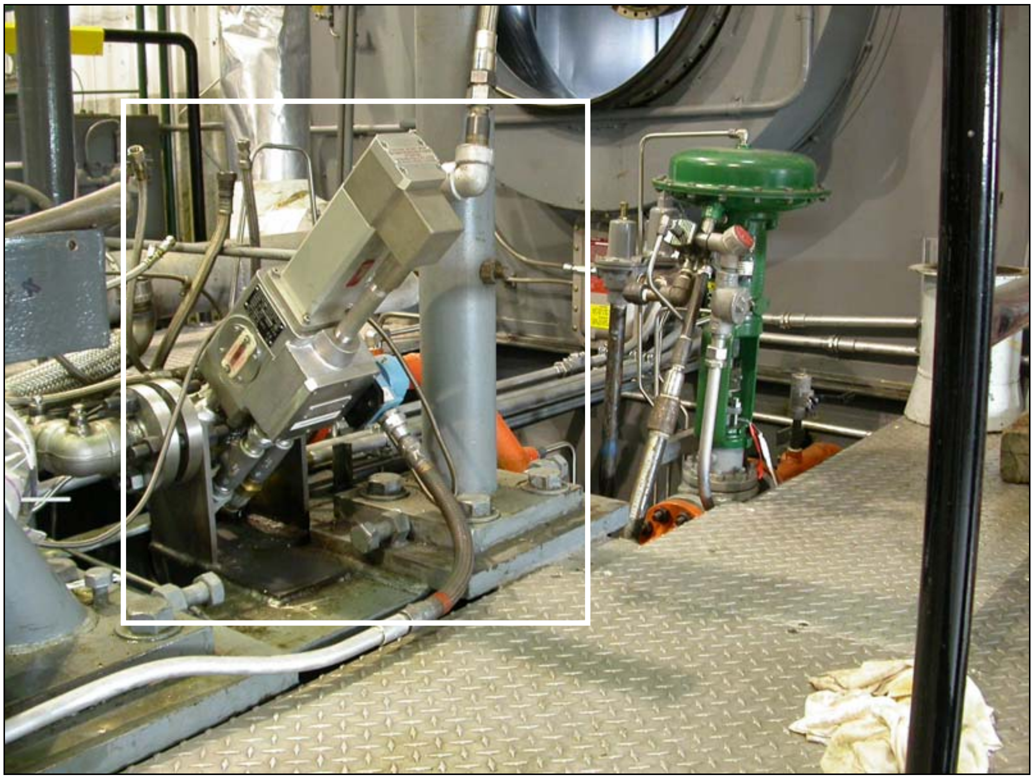


Figure 15 – New Electric Fuel Modulating Valve

RRES provided Union Gas with the flow calibration for each of the four valves purchased. This flow calibration was subsequently used as the primary fuel flow measurement device, required to implement the rich/lean fuel limit control lines as prescribed by SB64.

CP103 Installation:

One of the more novel aspects of the AVON HCF Mitigation effort at Union Gas has been the experimentation with CP103 microphones, as a means of combustion/flow disturbance monitoring.

CP103 microphones are standard issue components for the fuel control system on all DLE RB211's. Normally, the CP103's are mounted on the hot side of DLE combustors (i.e. downstream of the flame), and are used as a means of detecting combustion instability at the lean combustion limits needed to achieve Dry Low Emissions (NOx) reductions.

Engineering consultants in Europe and North America have established themselves as specialists in monitoring and analyzing the CP103 signals, on the hot side of the combustor, to diagnose combustion acoustic problems. Poor combustion acoustics can translate into severe mechanical degradation of combustors and turbines.

In the case of the AVON engine, there has never been provision for installation of high temperature microphones on the hot side of the combustor. Fortunately, the CP103 sensor is small enough to fit into the boroscope ports (Mod 4554 "Large Boroscope Ports" only) of the AVON engine.

The primary difference between the RB211-DLE and AVON installation of the CP103's is that the AVON boroscope ports are located on the cold side of the combustors – i.e. upstream of the flame. While this CP103 location falls outside the scope of almost all existing technical experience in the industry, it does seem to have the potential to at least detect combustion/flow anomalys within the engine. In general it is believed that a single CP103 microphone, located on the cold side of the combustors, will be sensitive to disturbances in any of the eight flame tubes. Therefore, the CP103's may have the potential to detect combustion/flow related problems but would never be able to diagnose a specific problem with any great detail.

Since Union's primary focus has been the prevention of HCF damage on the AVON HP Turbine, the CP103 has been considered worthwhile experiment, with some encouraging results.

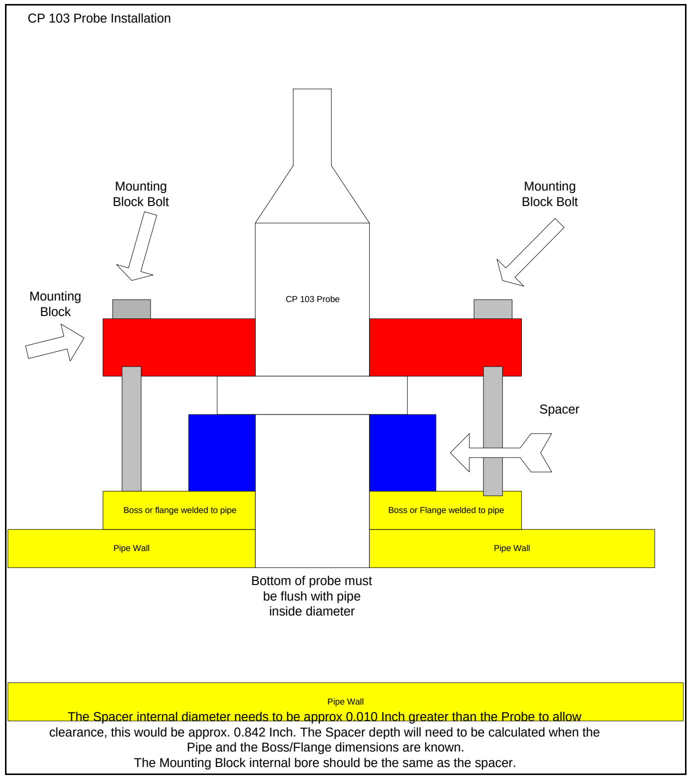


Figure 16 – CP103 Installation Recommendation From Rolls Royce

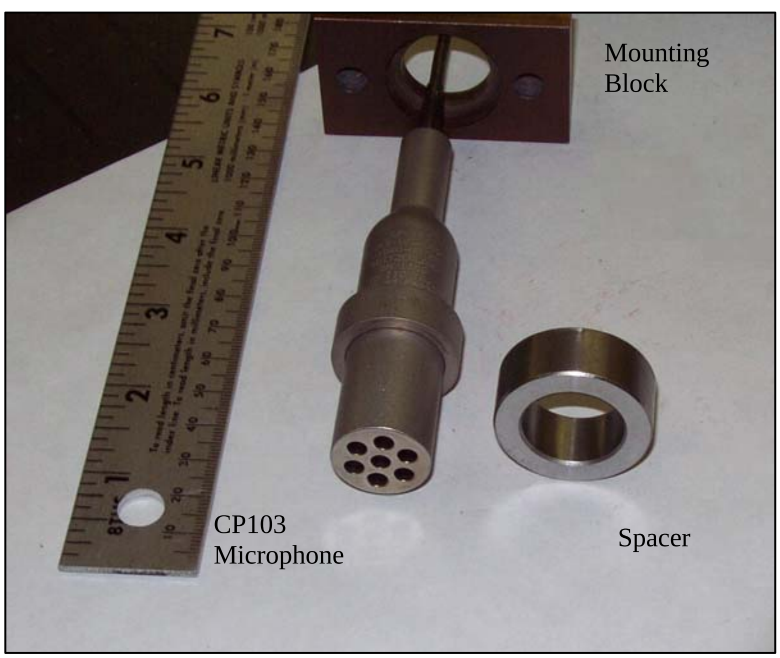


Figure 17 – CP103 Components For AVON Installation

Actual location of the CP103 transducer on the AVON engine is shown below.

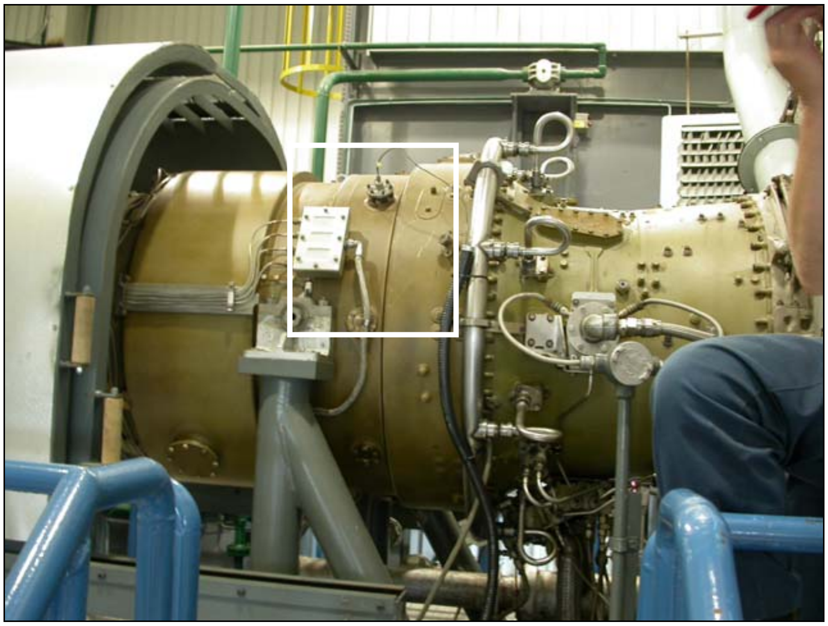


Figure 18 – CP103 Mounted In Large Boroscope Port

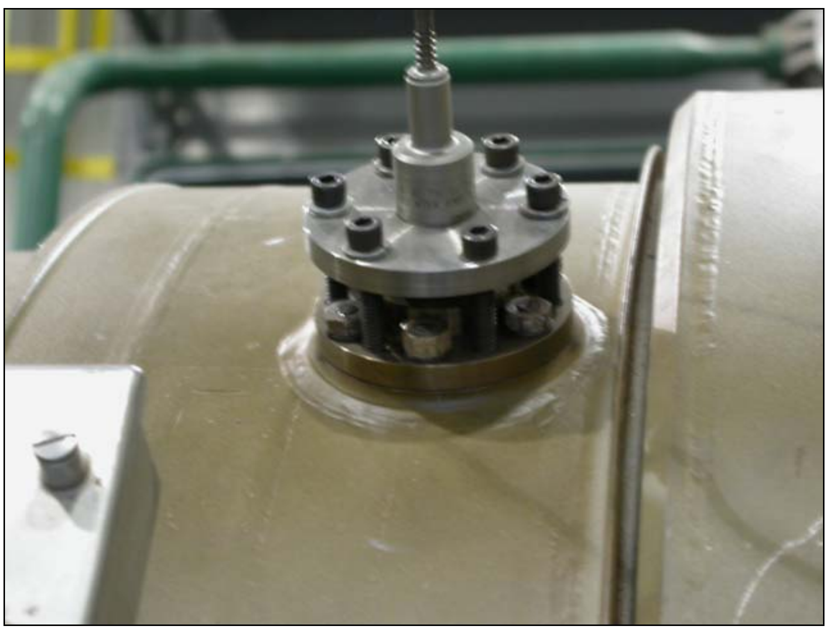


Figure 19 – CP103 Installation – Close-up

A single CP103 transducer was mounted on each of the four AVON's at Lobo and Bright. In all cases, CP103's were installed in the boroscope port located between flame tubes #7 and #8. This particular location was selected on the advice of Rolls Royce, because flame tube #8 was one felt, by Rolls, to be one of the most likely combustors to be affected liquids in the fuel gas – i.e. it was at a closed end of the fuel manifold.

During the 2004/2005 operating season data was collected using a standalone computer, which was not yet interconnected to the PLC.

Raw CP103 signals required a great deal of averaging, in order to remove transients. A typical sample size was 10 minutes, at a sample rate of 3000 samples/sec. This made for huge data files of 1.8 million time samples. Time samples were averaged, filtered using a Hanning window, and processed through an FFT algorithm.

Results showed that the CP103 frequency spectra were relatively unaffected by engine speed, once the bleed valves were closed. Slight changes in the frequency spectra did correlate with engine speed, but mostly at frequencies below 500 Hz. Therefore, extensive averaging was performed with the expectation that there would not be any significant loss of steady state information, even if engine speed was changed during the 10 minute sampling interval.

Typical CP103 frequency spectra for 1533, 1534 and 1535 AVONs are shown below.

1533 AVON:

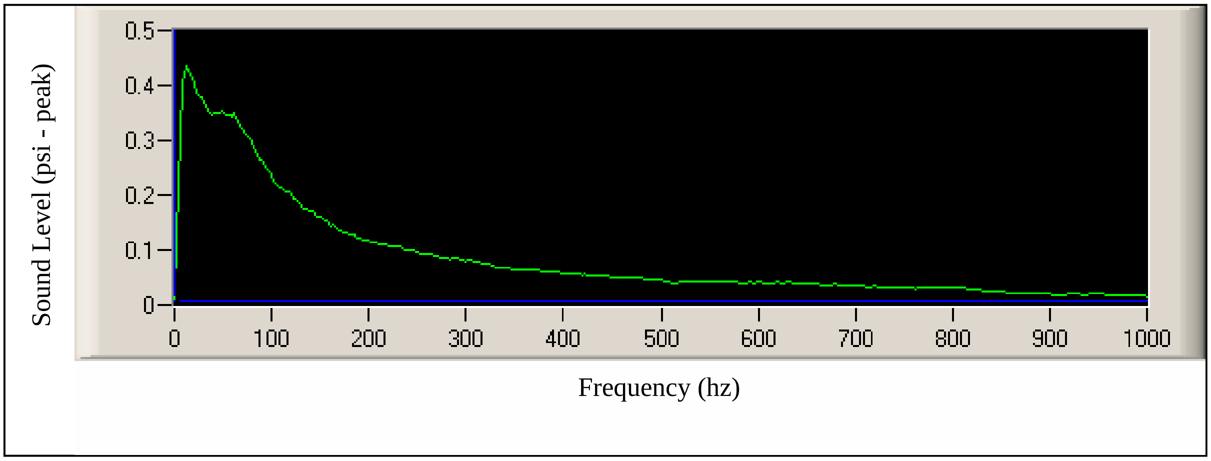


Figure 20 – Bright A2 (Engine 37842): December 20th, 2004.

Typical CP103 measurements for the 1533 engine show that low frequency noise levels are much higher than found at any of the 1534 or 1535 engines being monitored. Factors unique to the 1533 engine shown above include: the use of single dish combustors and the use of pintle style burner nozzles. There is insufficient comparative data to establish a definitive link between combustor configuration and the low frequency noise characteristics of the 1533 engine.

CP103 data obtained from a like engine (1533 AVON - Engine 37813 – see Figure 21) shows a similar tendency towards high noise levels at low frequencies and very similar frequency distribution. Unfortunately, engine 37813 has been fitted triple dish flame tubes, so a direct comparison to engine 37842 would be inconclusive.

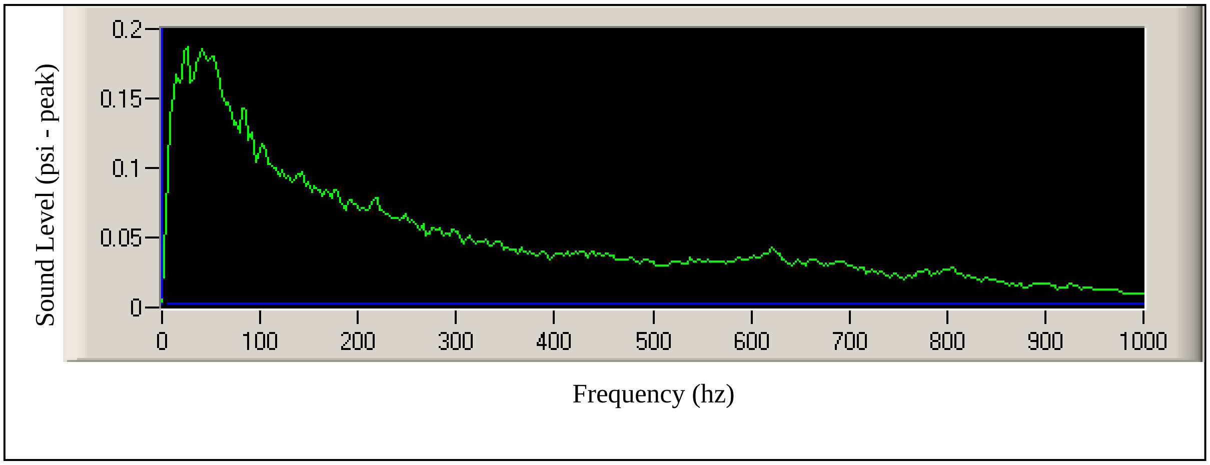


Figure 21 – Parkway (Engine 37813): October 28th, 2004.

1534 AVON

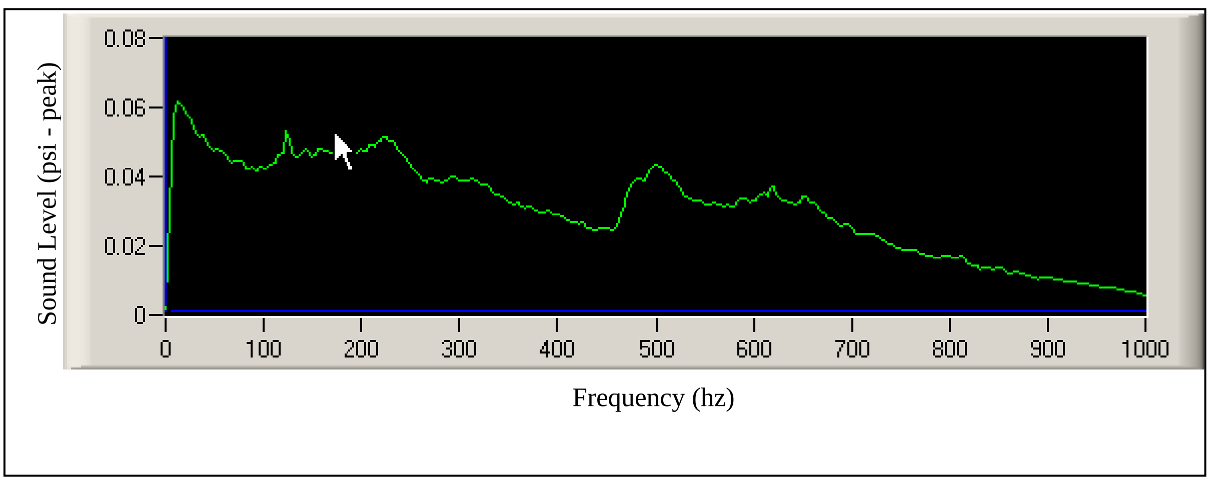


Figure 22 – Bright A1 (Engine 37433): June 27th, 2005

Normal frequency spectra for the 1534 engine (pintle burners and triple dish flame tubes) are believed to be as shown above. The spectrum above was produced using the CP103 signal obtained immediately after repair during the week of June 6th, 2005. Only a single 1534 engine remains in the Union Gas fleet, so it is not possible to compare like 1534 engines.

1534 AVON – c/w Broken Discharge Nozzle Bracket and Broken Chin Strap

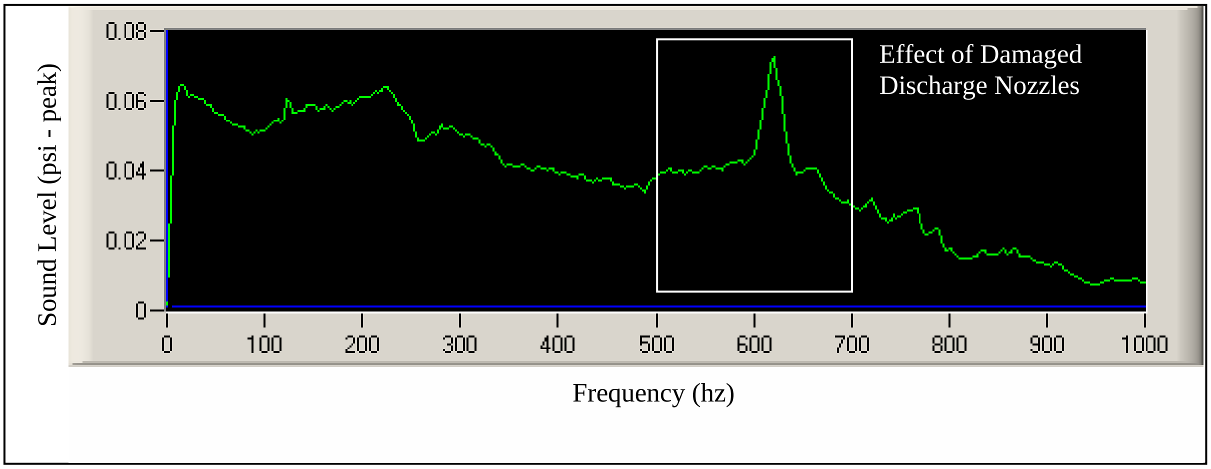


Figure 23 – Bright A1 (Engine 37433): May 6th, 2005

During the hot end inspection of engine 37433 (June 6th, 2005), it was discovered that the discharge nozzles had suffered from a broken chin strap at discharge nozzle #8, and a broken bracket joining discharge nozzles #6 and #7. Comparison between the CP103 traces of a healthy 1534 engine (see Figure 22) and an engine with damaged discharge nozzles (Figure 23), shows that the failed discharge nozzles generate elevated combustion noise levels in the 500 to 700 hz range, with a strong peak at around 600 hz.

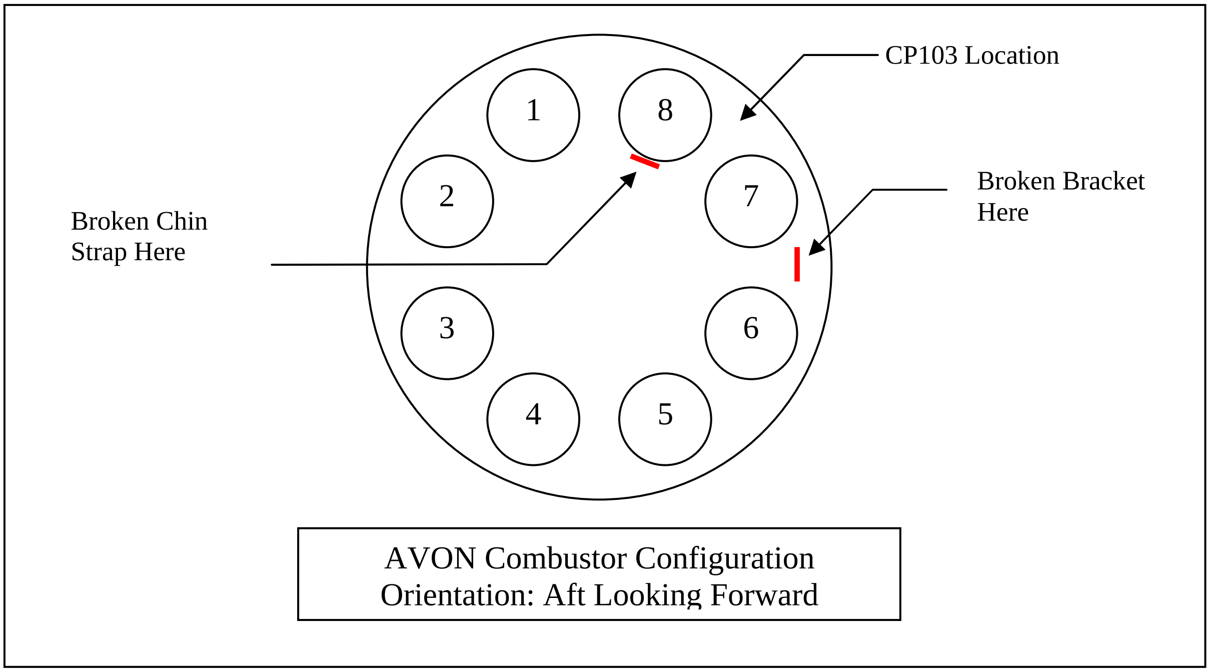


Figure 24 – Discharge Nozzle Damage Location (Engine 37433)

The exact location of the damaged components, relative to the CP103 transmitter location, is shown above (Figure 24).

Further monitoring will be required to determine if the CP103 transmitter location has an impact on the ability of the transmitter to detect discharge nozzle damage.

1535 AVON – c/w Triple Dish Combustors

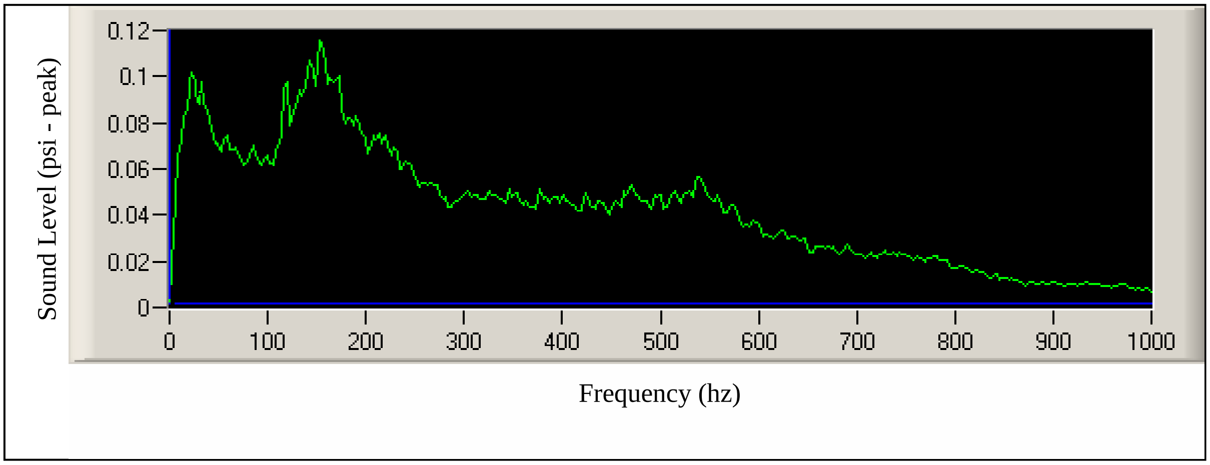


Figure 25 – Lobo A2 (Engine Lease): March 11th, 2004

Baseline CP103 data was collected from a leased 1535-161 engine (c/w triple dish combustors) at the end of the 2003/2004 operating season. Results are provided for reference purposes only.

1535 AVON – c/w Swirler Burners

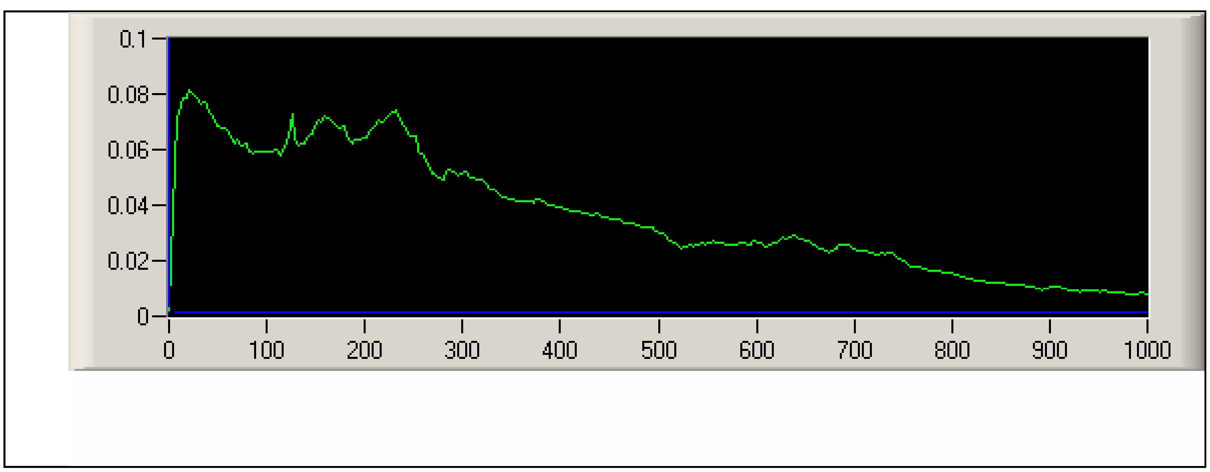


Figure 26 – Lobo A1 (Engine 38425): April 12th, 2005

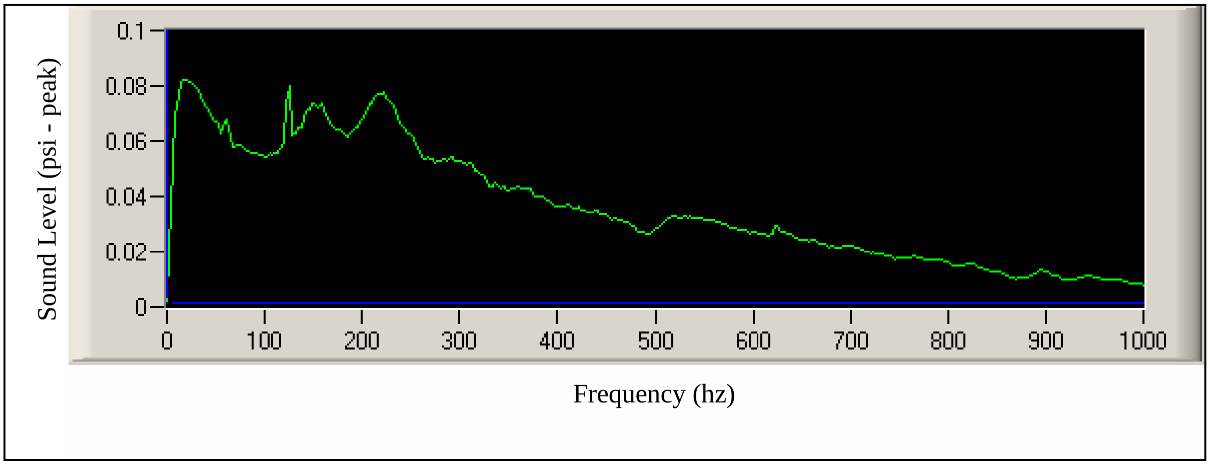


Figure 27 – Lobo A2 (Engine 38148): March 9th, 2005

Both AVON engines at Lobo are now 1535-161G engine configurations c/w swirler burners – see Figure 26 and Figure 27 for respective CP103 spectra. Installation of two identical engine configurations provides some insight into the consistency of the CP103 signal among like engines, in a similar maintenance condition.

Both Lobo engines exhibit well correlated frequency spectra (see Figure 26 and Figure 27). Of interest is the double peak at 150 hz and at 225 hz. This bi-modal characteristic may be related to the separate frequencies being generated by the swirling air at the centre of each burner nozzle, and the swirling gas as it enters the combustor.

Note that a small amount of signal noise can be seen at 60 and 120 hz. These are thought to be electrically generated noise that is unique to the Lobo station.

Although the hot-end inspection of engine 38425 revealed yet another broken chin strap (at discharge nozzle #1), there appears to be no significant indication of this problem by the CP103 Transmitter. Note that only the chin strap failed, all 8 brackets remained intact. Several possible explanations could account for the lack of CP103 signal:

- CP103 Transmitter location. The location of the transmitter (relative to the failed chin strap) may affect the signal strength.
- Chin strap failure may have occurred at the very end of the operating season and was not captured by the CP103 transmitter. This possibility cannot be ruled out since there was very little frettage wear found on the damaged discharge nozzle.
- Chin strap failure is not detectible. The affect of the chin strap may be far less severe than that of the bracket.
- Swirler burners may have a lower tendency to make the discharge nozzles fret when the supports fail.

Continued monitoring, and time, is needed to assess the combination of parameters which could be affecting the CP103 signal level.

5. RESULTS OF AVON UPGRADE PROJECT

Fuel Conditioning

Installation of this process design and operation through the 2004/2005 winter yielded a small quantity of unexpected liquids. Liquids were found in the sump of the Lobo A2 coalescer and were characterized as being two immiscible liquids, the primary being “kerosene like” and the other being “glycol based”. Sample quantities were insufficient for a detailed chemical analysis – see Figure 28 below. The suspected source of these liquids is either pipeline cleaning fluids or naturally occurring “kerosene” from storage pools.

Figure 28 – Liquids Removed From Lobo A2 Coalescing Filter

Hot-End Inspections

Hot-end inspections were carried out on all four AVON's at Lobo and Bright after the first operating season with new fuel conditioning and controls (at both Lobo and Bright) and swirler burners (at Lobo only). Results of the inspections were somewhat disappointing, in that problems have continued to occur with discharge nozzles. Union's experience has been that the discharge nozzles have been a traditional weakness of the AVON engine, and the fuel conditioning, fuel control and swirler burner upgrades do not seem to have rectified this problem.

Only two hot-end inspections could be completed prior to completion of this paper. The condition of these two engines is summarized below:

1. Engine 37433. Failed chin strap at discharge nozzle #8. Failed bracket connecting discharge nozzles #6 and #7. Four HP NGV's were damaged by a small piece of the chin strap that was released into the HP Turbine. Scored rear bearing. All other indications were normal. Damaged components had only 900 hours since repair or replacement.

Figure 29 – Failed Chin Strap

Figure 30 – Failed Nozzle Bracket

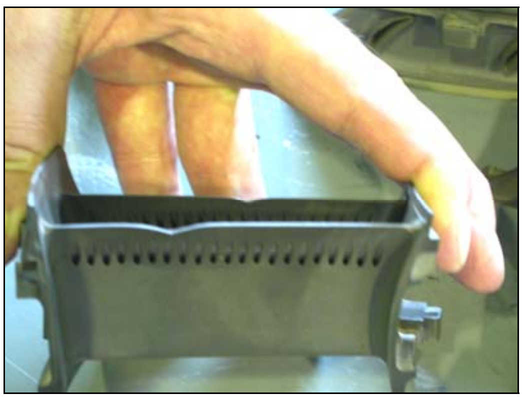


Figure 31 – Damaged HP NGV

Figure 32- Failed Nozzle Bracket

2. Engine 38425. Failed chin strap at discharge nozzle #1. Four additional discharge nozzles were found to be cracked and in need of repair. All other indications were normal. Unit had 1300 hours of operation – approximately 10% were peak operating hours.

Figure 33 – Failed Chin Strap

While the failure of this chin strap is a disappointment, it should be noted that there was very little frettage wear around the discharge nozzle. This suggests that the chin strap failure was either very recent or that the remaining supports were sufficient to keep the nozzle from vibrating. This is consistent with the CP103 signal data, which showed no significant indication of a problem.

6. CONCLUSIONS

1. Fuel gas conditioning (i.e. addition of coalescer and heat exchanger) has proven to be a good investment. Combustible liquids were removed from the sump of the Lobo A2 Coalescer, proving that fuel quality improvements were in fact necessary.
2. Fuel control upgrades and replacement of the Fuel Modulating Valve have increased Union's comfort level that the problems experienced after the 2004/2005 operating season were not related to the engine auxiliary systems.
3. Discharge Nozzles continue to be a problem regardless of swirler burner installation. Since damaged discharge nozzles can create flow instability through the engine, and hence increase the risk of High Cycle Fatigue, the swirler burners themselves cannot be guaranteed to prevent HCF. Rolls Royce is now offering a single material discharge (MOD 4604), which may help alleviate the problem.

4. Detection of significant damage to discharge nozzles appears to be possible using the CP103 transmitter. Monitoring and detection of discharge nozzle problems (i.e. using the CP103) may prove to be a useful Reactive Maintenance tool, capable of reducing the potential for a more significant HP Turbine failure.