One Team —
swift, decisive, resilient and respected

Air and space power for Australia's security

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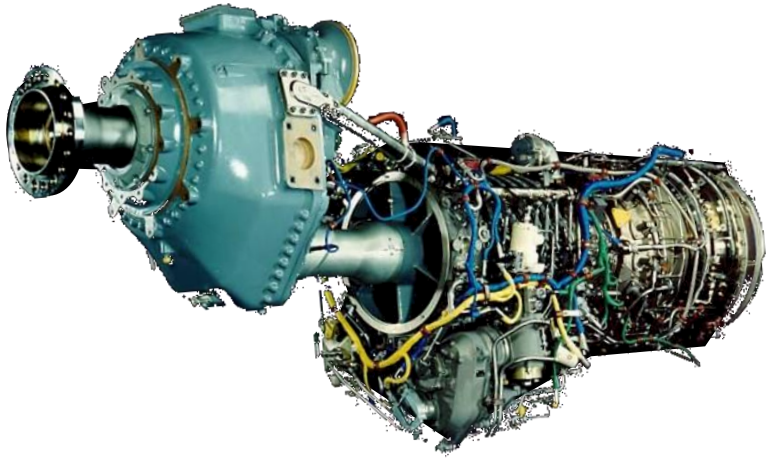
RAAF AE2100D3
Engine Health Management



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AE2100D3 EHMS
ALSPO Propulsion Systems Engineering
Royal Australian Air Force

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Acknowledgements

- FSGT Brendan Church CSC, Co-Author

- ASLPO Propulsion Systems Engineering Section
- 37SQN Engine Cell – RAAF Richmond, NSW
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- Rolls Royce PLC – Indianapolis, USA
- Standard Aero – Winnipeg, Canada
- QinetiQ Australia – Melbourne, VIC

- SGT Andrew Wade – Research Paper "Effective Condition Monitoring of an On Condition Engine." Submitted to UNSW to for fill the requirements of MScTech (Aviation) – Oct 2012.

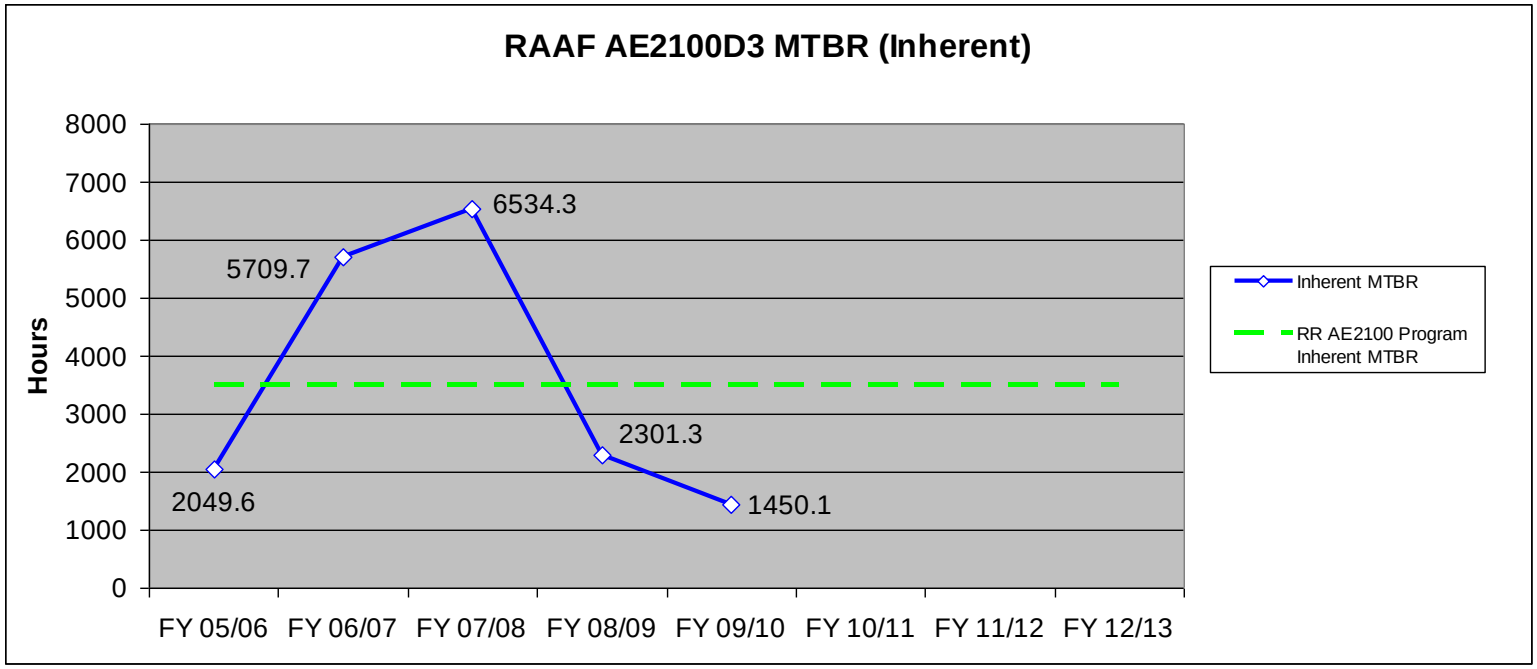
Historical Overview

- **RAAF AE2100D3 FLEET consists of 58 Engines (48 installed, 10 spare / above fit)**
- **AE2100D3 has “on condition” maintenance philosophy.**
- **On condition philosophy managed by RAAF as a “fly to failure” approach.**
- **Fly to failure approach employed over 10 year period preceding January 2010.**

Result…

- In flight events increasing year by year
- Inherent engine removal rate greater than repair turn around time
- Unmanageably low serviceable engine asset levels
- Budget overruns
- C130J Power Plant operational confidence all time low in late 2009

Inherent Failure MTBR (2005 – 2009)



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Inherent Off Wing Drivers 2005 - 2009

Removal Reason	# of Failures	Percentage
Low MGT Margin	14	20.59%
Vibration	12	17.65%
High P/S Oil Pressure	8	11.76%
1st Stage Vane / Blade Distress	7	10.29%
PGB Metal on Mag Plugs	5	7.35%
Compressor Flooding - Oil Drain Down	5	7.35%
Integral Plumbing Oil Leak	4	5.88%
#2 Bearing Rivet Failure	4	5.88%
2nd Stage Track Distress	3	4.41%
Smelly Bleed	2	2.94%
4th Stage Cover Plates missing	2	2.94%
Over Torque	1	1.47%
Torquemeter contact with Sensors	1	1.47%

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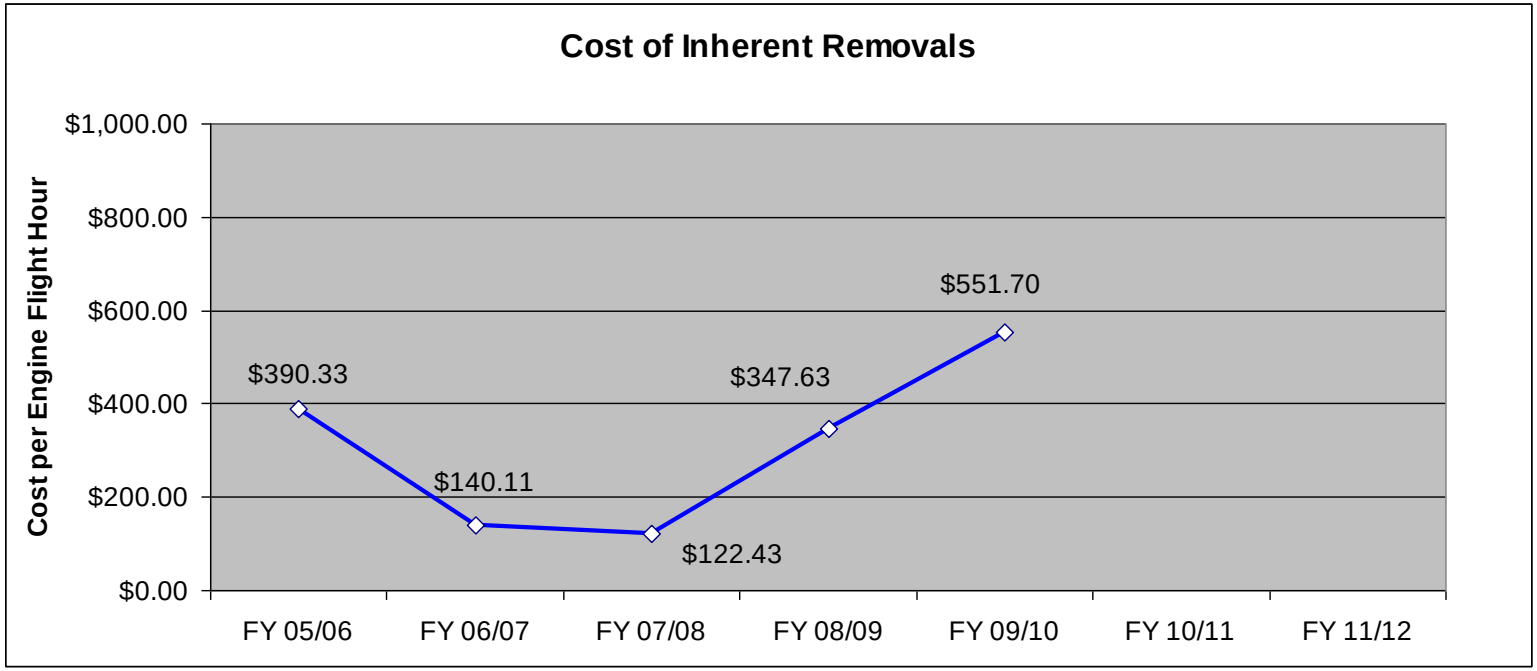
Inherent Off Wing Drivers 2005 - 2009

Removal Reason	# of Failures	Percentage
Low MGT Margin	14	20.59%
Vibration	12	17.65%
High P/S Oil Pressure	8	11.76%
1st Stage Vane / Blade Distress	7	10.29%

- **Top four drivers are performance or health related.**
- **Equates to 60.3% of inherent removals 2005 - 2009.**
- **60% of all RAAF AE2100D3 engines were subjected to a shop visit during the period 2008 – 2010.**

Cost of Inherent Removals $ / EFH (2005 – 2009)



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2010 Onwards

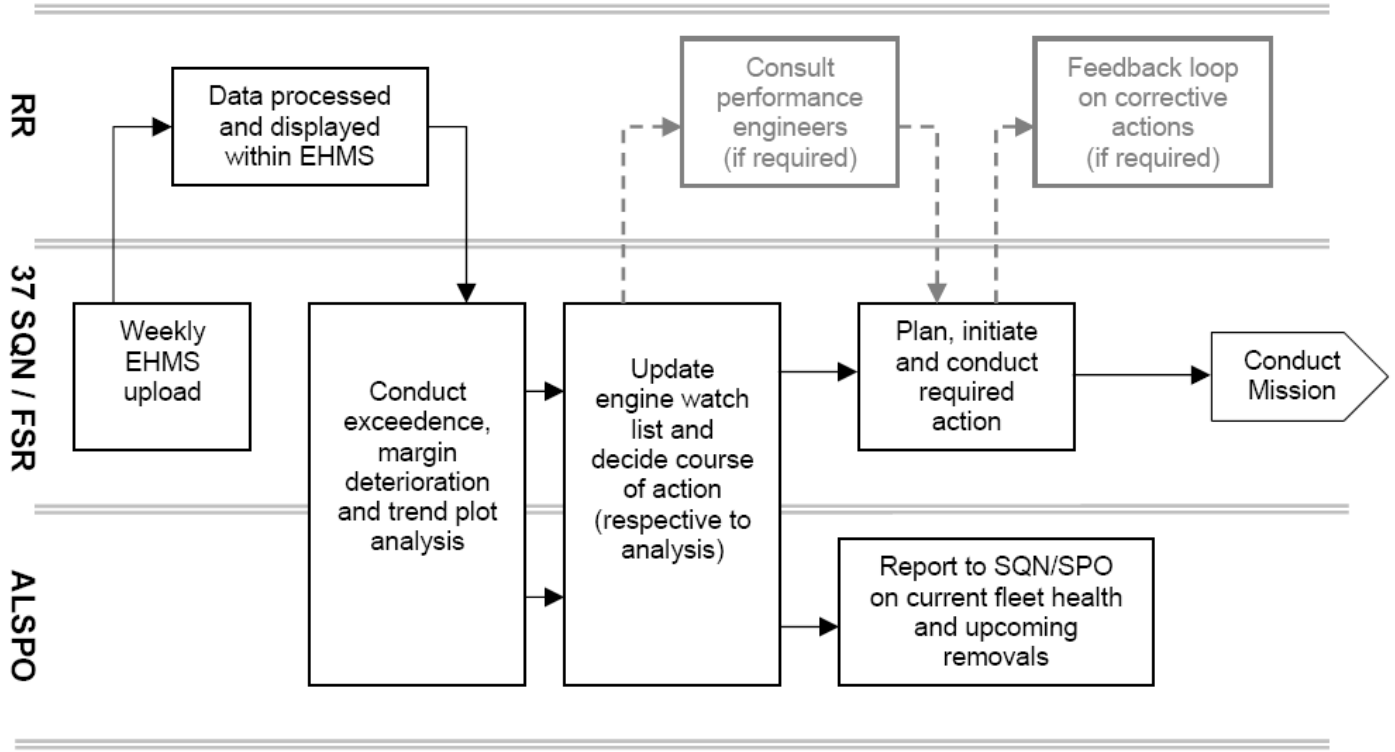
- **Fundamental change required in the fleet management of AE2100D3**

- **Goals**
  - Maximize / optimize time on wing
  - Reduce in flight events
  - Contain / reduce sustainment costs
  - Increase serviceable spare asset levels
  - Plan engine removals prior to failure or in flight event
  - Restore C130J power plant operational confidence

Engine Health Management

- **Maximizing time on wing is key to effecting all other goals.**
- **Identifying and correcting step change degradation of engine health was key to increasing time on wing. – Done through the use of EHMS (60.3% of all inherent removals).**
- **The development of an Engine Condition Management Program to help the operator plan the maintenance of their fleet, detecting problems before critical failures occur.**

EHMS Process Map



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EHMS
Performance Signatures

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Optimum Performance

- *MGT Deterioration Rate* <-5°C/1000hrs
- *CDP* >190psi (>5% delta)
- *Fuel Flow* steady
- *NG Deterioration Rate* <1%/1000hrs

Optimum Performance [1]
(All parameters steady)

[1] If no step changes are observed across the measured parameters, engine is considered to be at its optimum performance relative to that engine's turbine condition. MGT margin should be compared against the other three installed engines to ensure performance shift is not relative to environment (high temperature and/or high altitude airfield take-off). For example, if MGT margin (across all four engines of an aircraft) is fluctuating in parallel, then the performance shift is relative to the environment. If however one engine's measured parameter deviates from the parallel movement of the other three engines (step change), then the performance shift is relative to LRU deterioration or failure.

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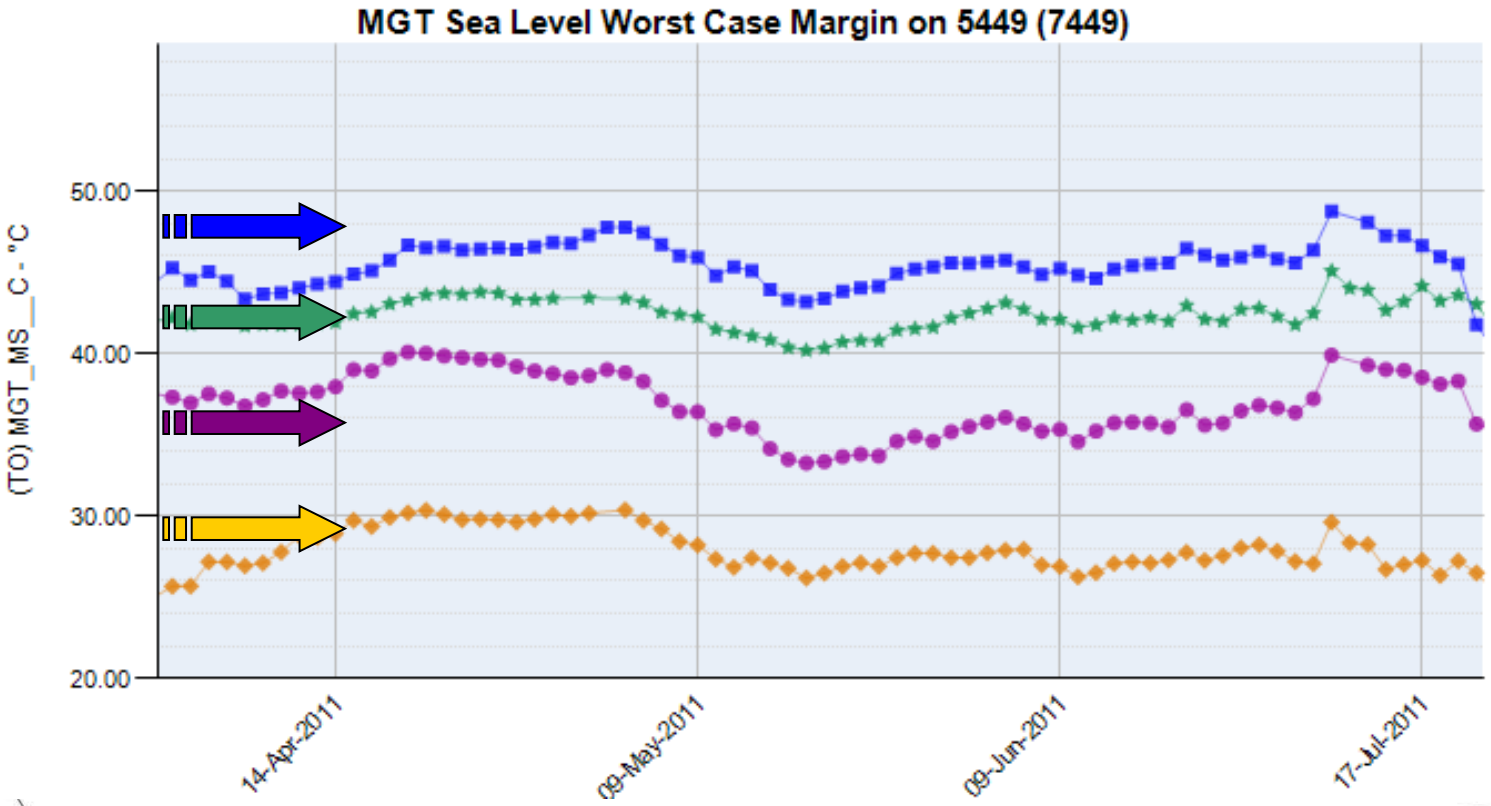
Optimum Performance

MGT Margin Parallel Movement



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EHMS Performance Signatures

10th STAGE BLEED LEAKS

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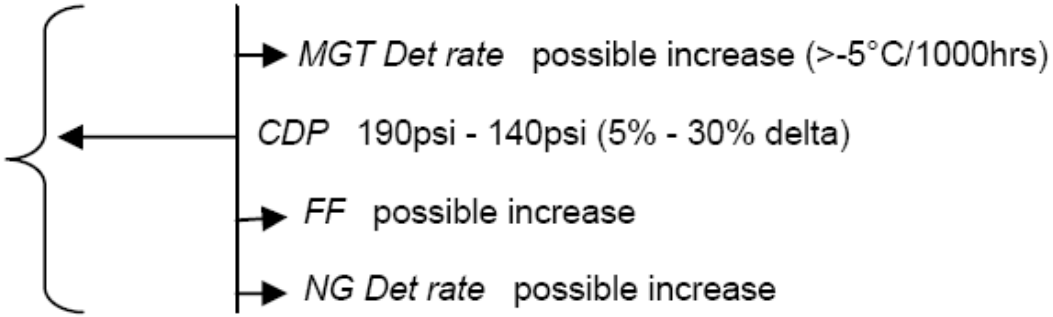
CDP Step Change <30% Delta

Partially open 10th Stage Acceleration Bleed Valves [2]
(CDP Step Change)



[2] No real noticeable effect on performance (corresponding MGT / FF / NG shift) until MGT Margin is <5°C or CDP is <140 psi (>30% delta). The most likely contributor to this fingerprint is a pressure drop across 14th stage control air plumbing (leak in the CDP system) causing 10th Stage Acceleration Bleed Valves (ABV) to partially open. This leak in the CDP system is caused by worn ABV rings and/or springs, a split/leaking compressor wash air line or an excessively worn piston in the Compressor Acceleration Bleed Valve Control Valve (CABCV). Fault is confirmed by using compressed air to leak check the 14th Stage control air plumbing via the compressor wash air line fitting located in drain mast and the at fault item is replaced.

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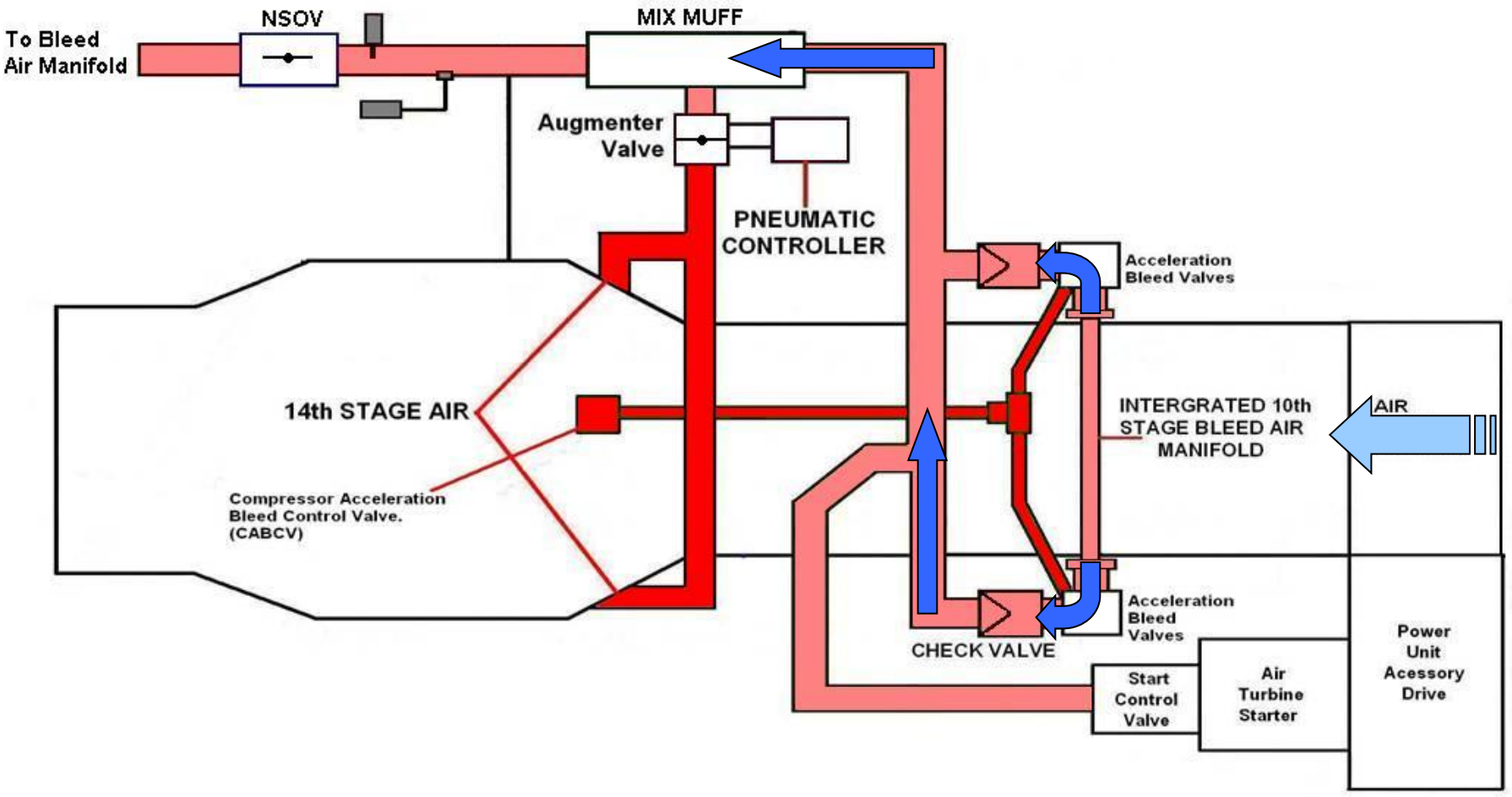
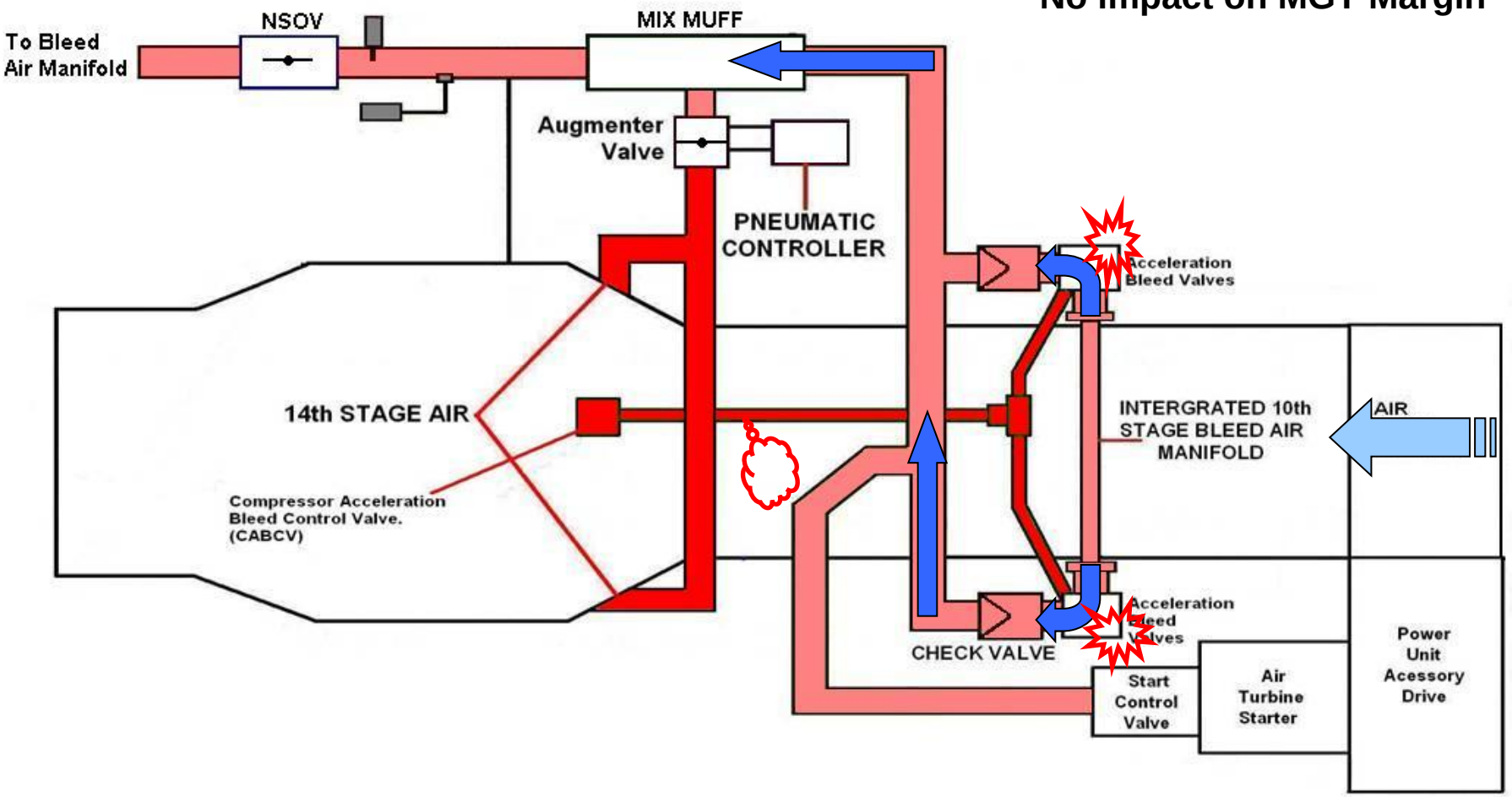
10th Stage Air – Normal Operation



10th Stage Air – Partially open ABVs

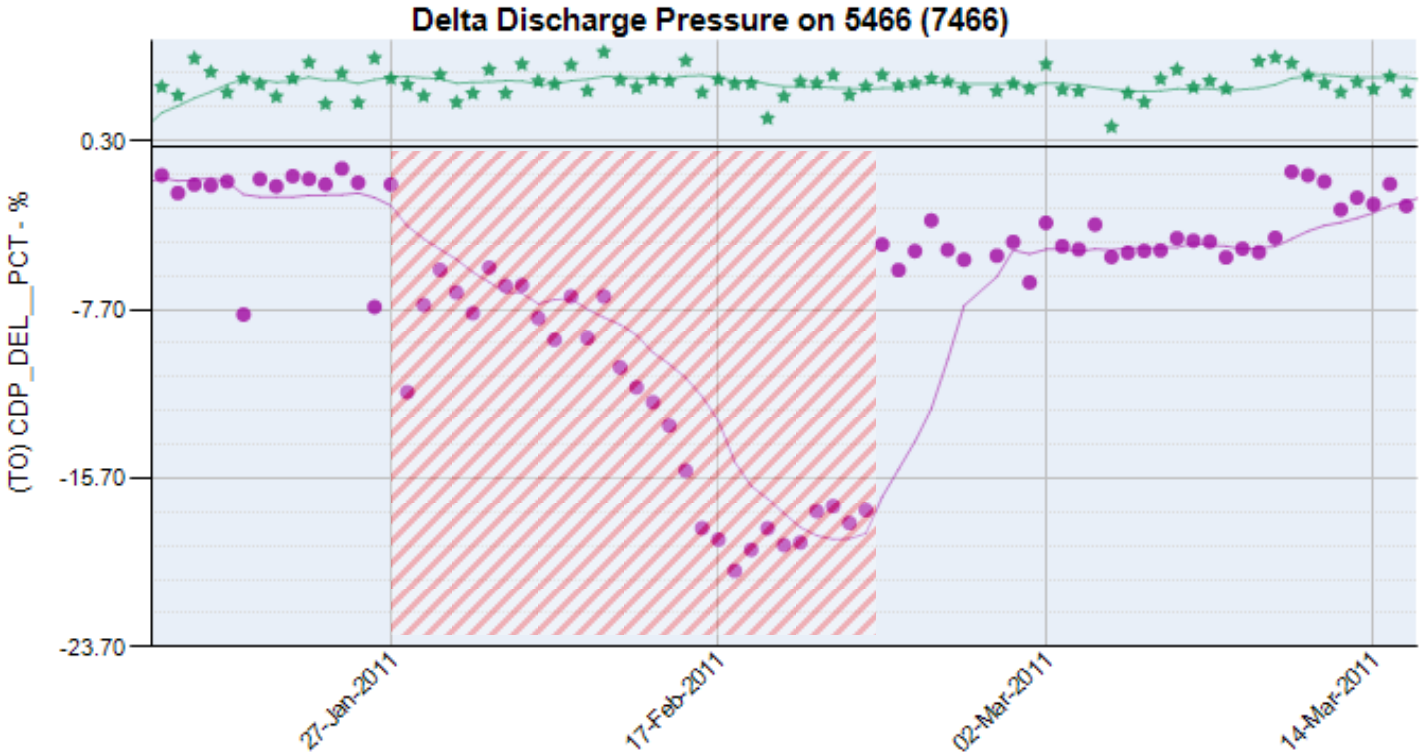
Small pressure drop in 14th stage control air plumbing - CDP loss <30% Delta

No impact on MGT Margin



Example. 27 Jan - 20 Feb, 2011

CDP Step Change <30% Delta - Partially open ABVs



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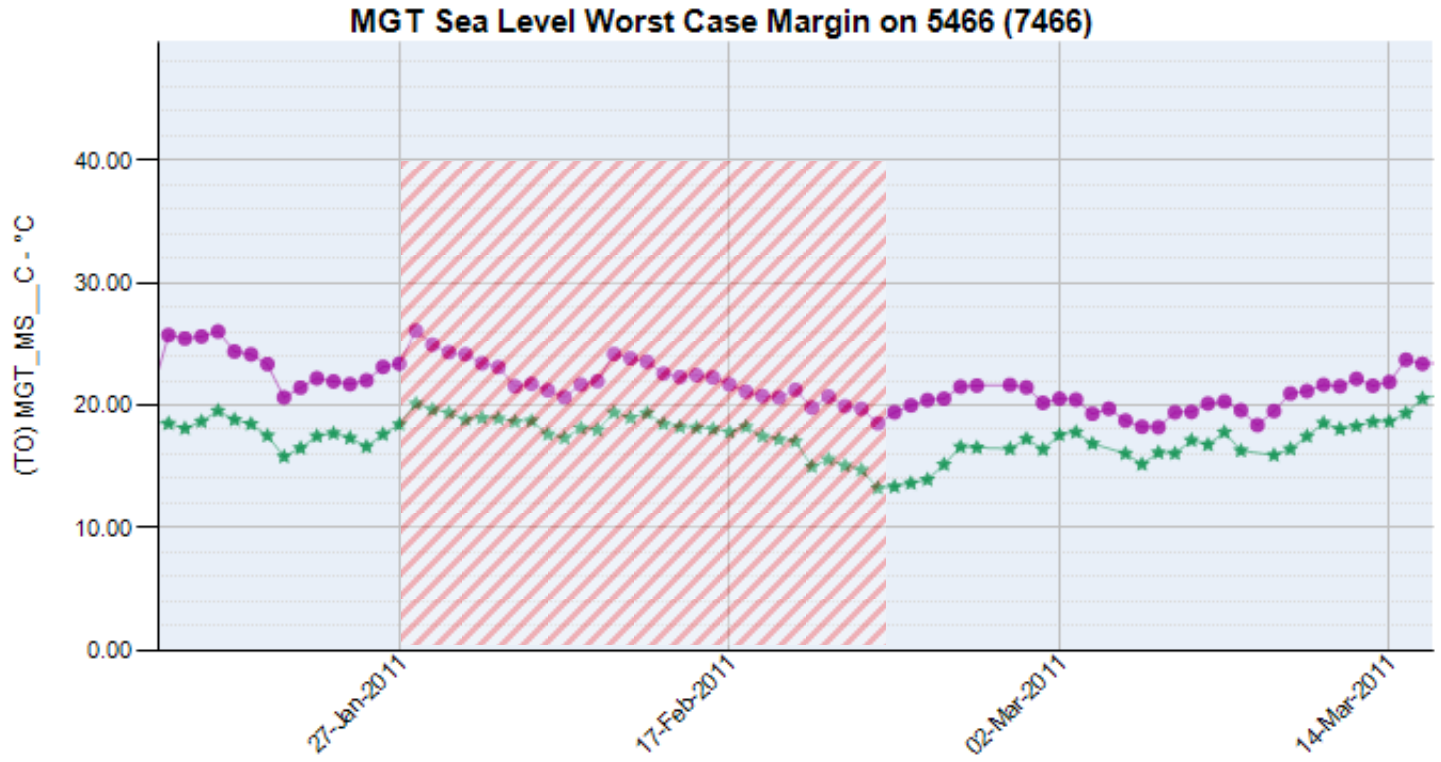
No MGT Margin Shift – Parallel movement



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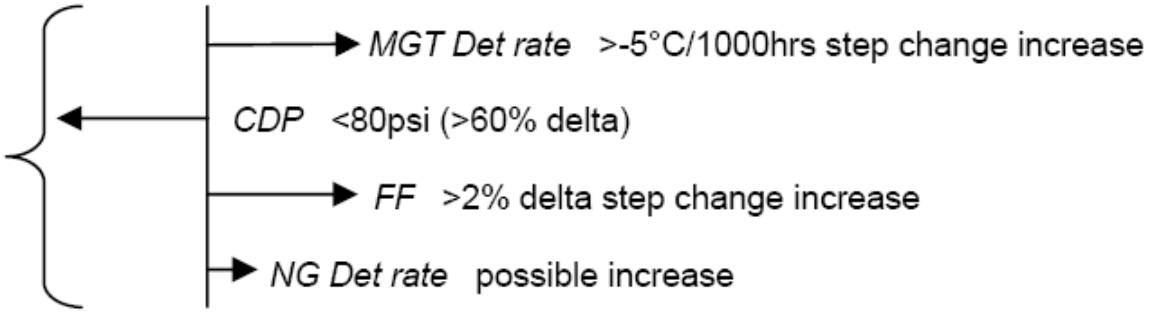
CDP Step Change >60% Delta

Fully open 10th Stage Acceleration Bleed Valves [3]
(CDP Step Change)



[3] Noticeable effect on performance as evidenced by a corresponding MGT margin and FF shift. The most likely contributor to this fingerprint is complete pressure loss across 14th stage control air plumbing causing 10th Stage Acceleration Bleed Valves (ABV) to fully open. This is caused by loose/disconnected 14th stage control air plumbing, loose/disconnected compressor wash air line (maintenance error) or one of the aforementioned plumbing has completely ruptured (structural failure). Fault is confirmed via visual inspection for loose/disconnected fittings or structural defects. If not able to be identified, compressed air is used to leak check the 14th Stage control air plumbing via the compressor wash air line fitting located in drain mast and the at fault item is replaced.

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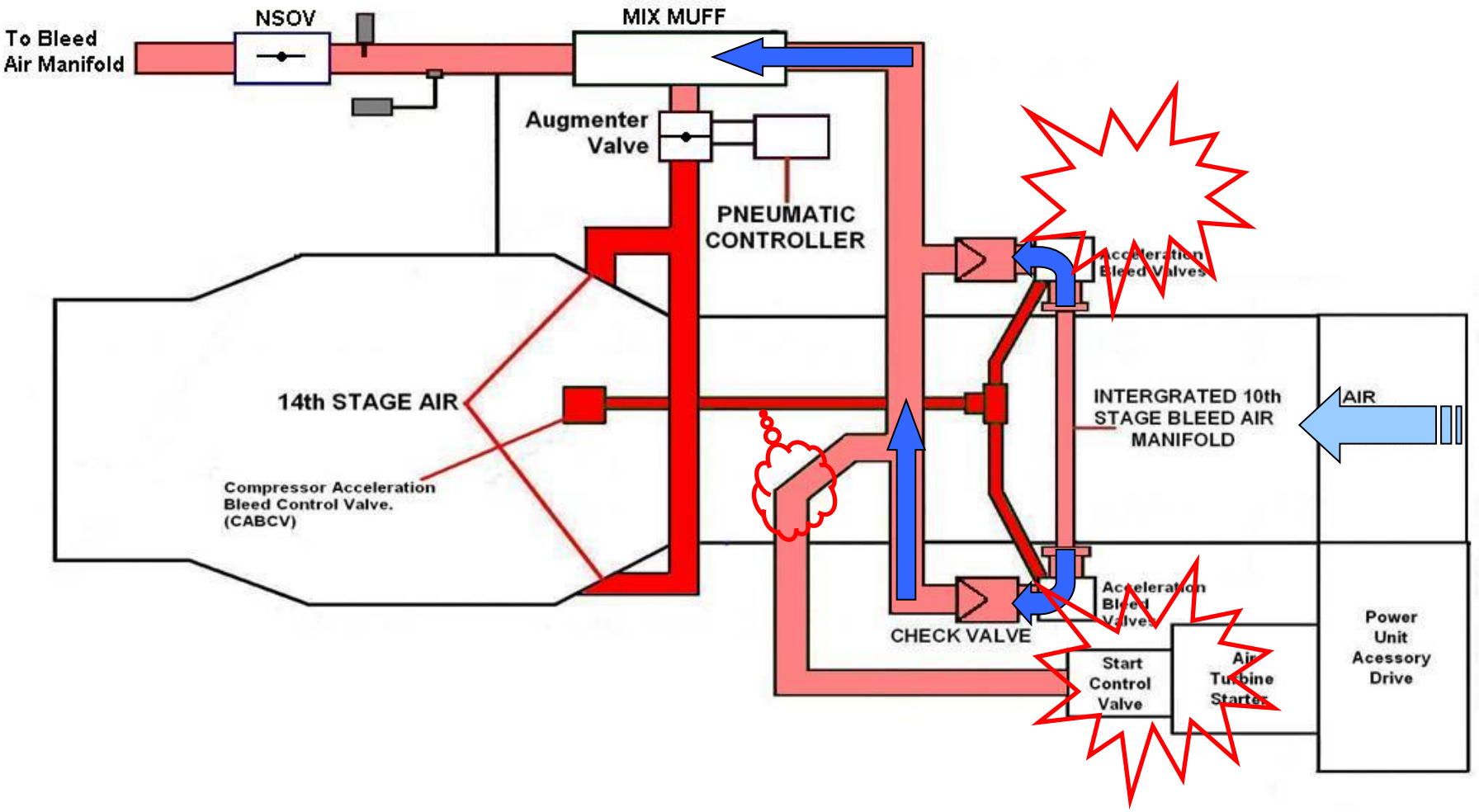
10th Stage Air – Fully open ABVs

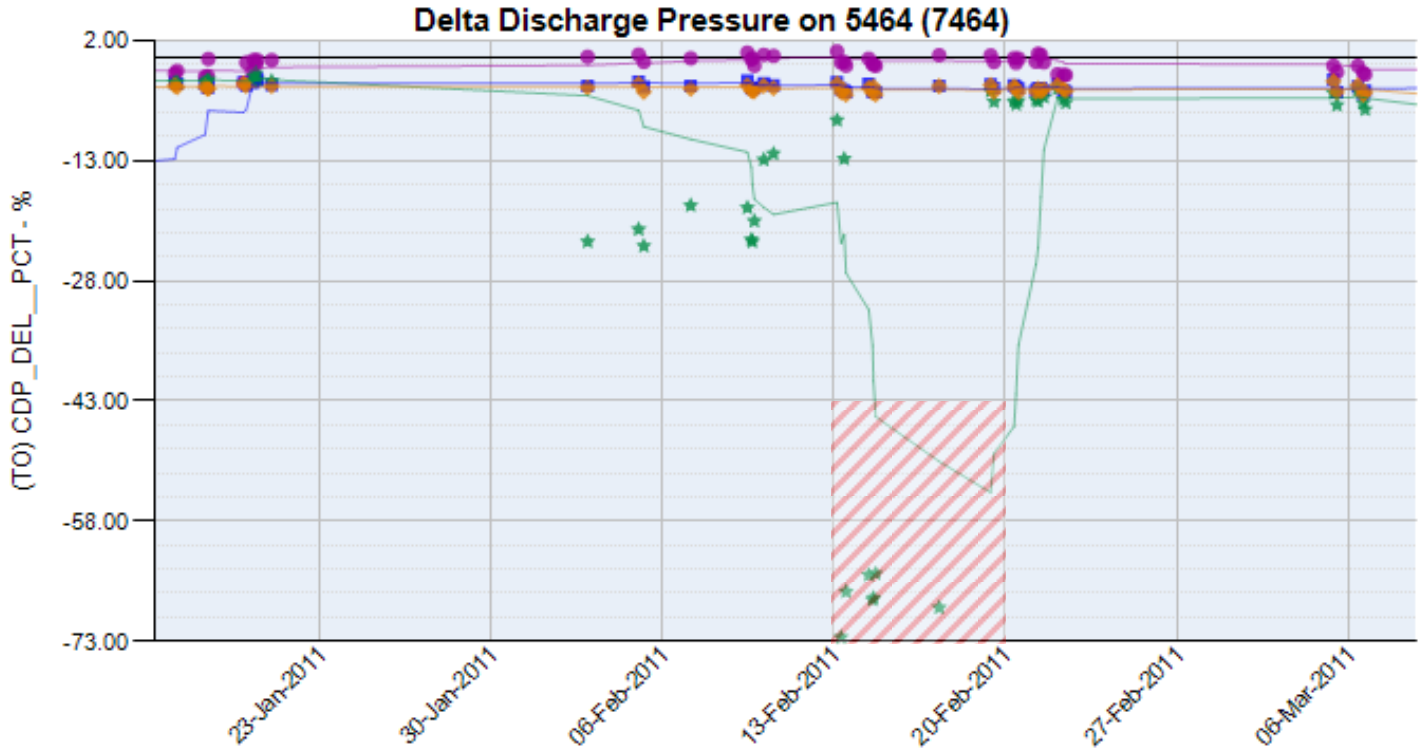
Large pressure drop in 14th stage control air plumbing - CDP loss >60% Delta

Significant MGT Margin loss



Example. 13 - 20 Feb 2011

CDP Step Change 70% Delta - Fully open ABVs



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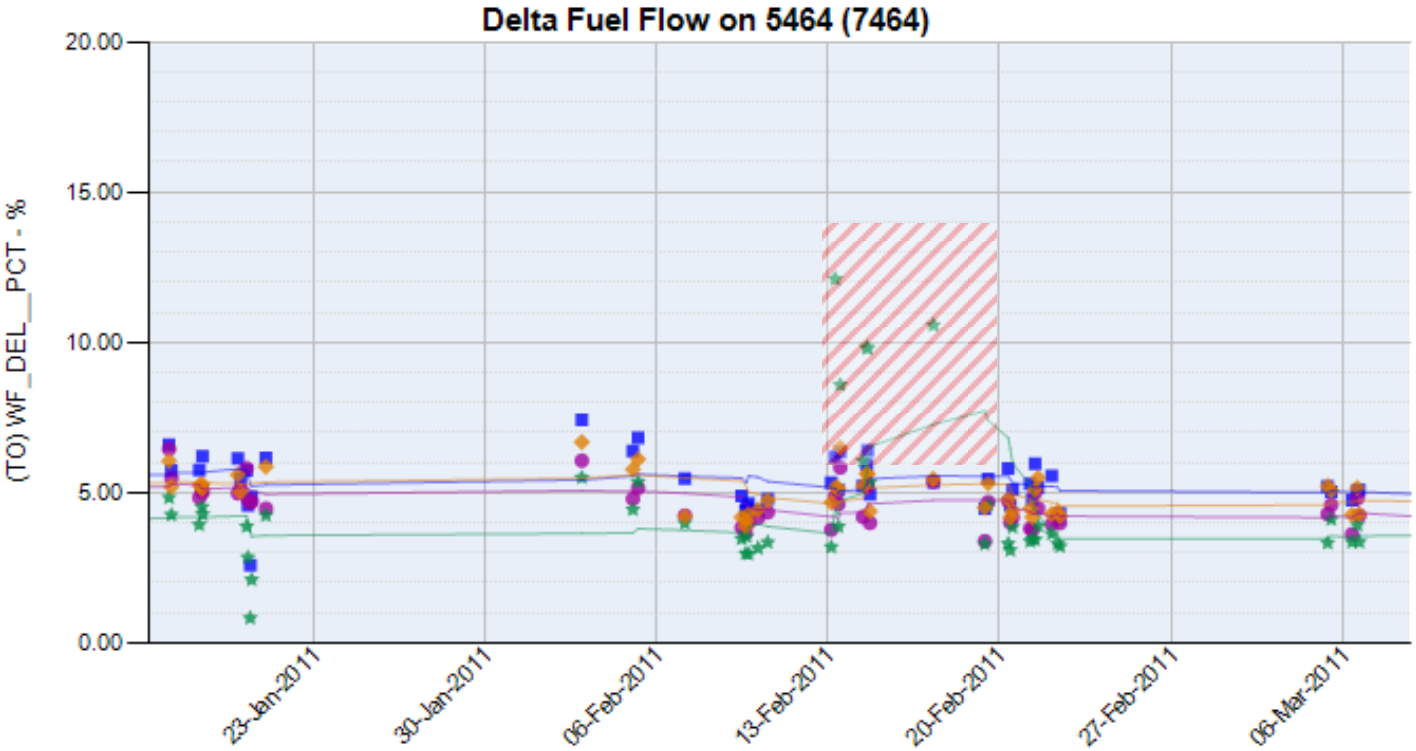
Fuel Flow - 6% Delta increase



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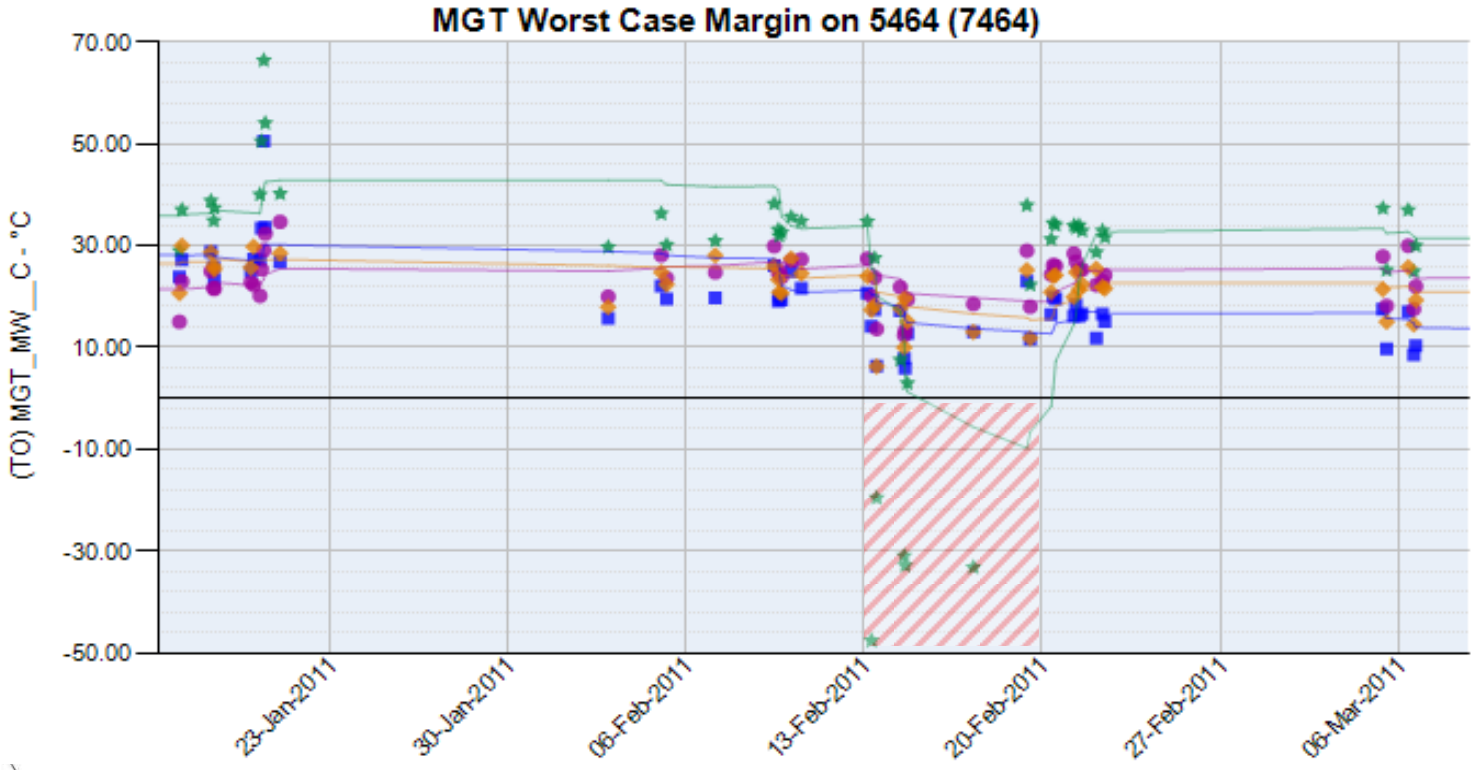
80˚C MGT Margin loss + Nacelle O/Heat ACAWS (Mission Abort)



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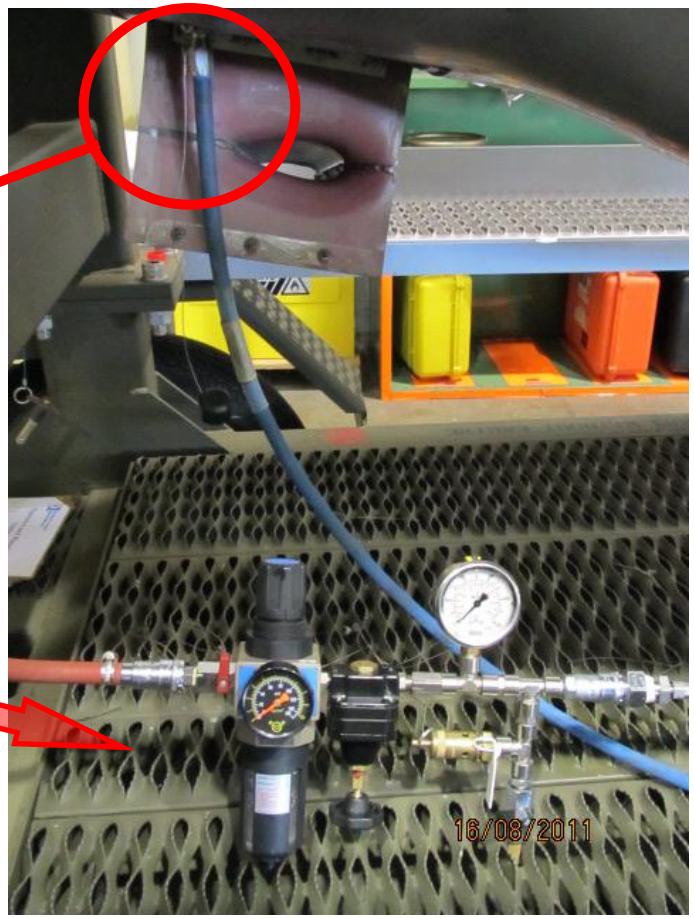
14th Stage ABV control air plumbing

Compressed Air Leak Test

Compressor wash air line connected to drain mast

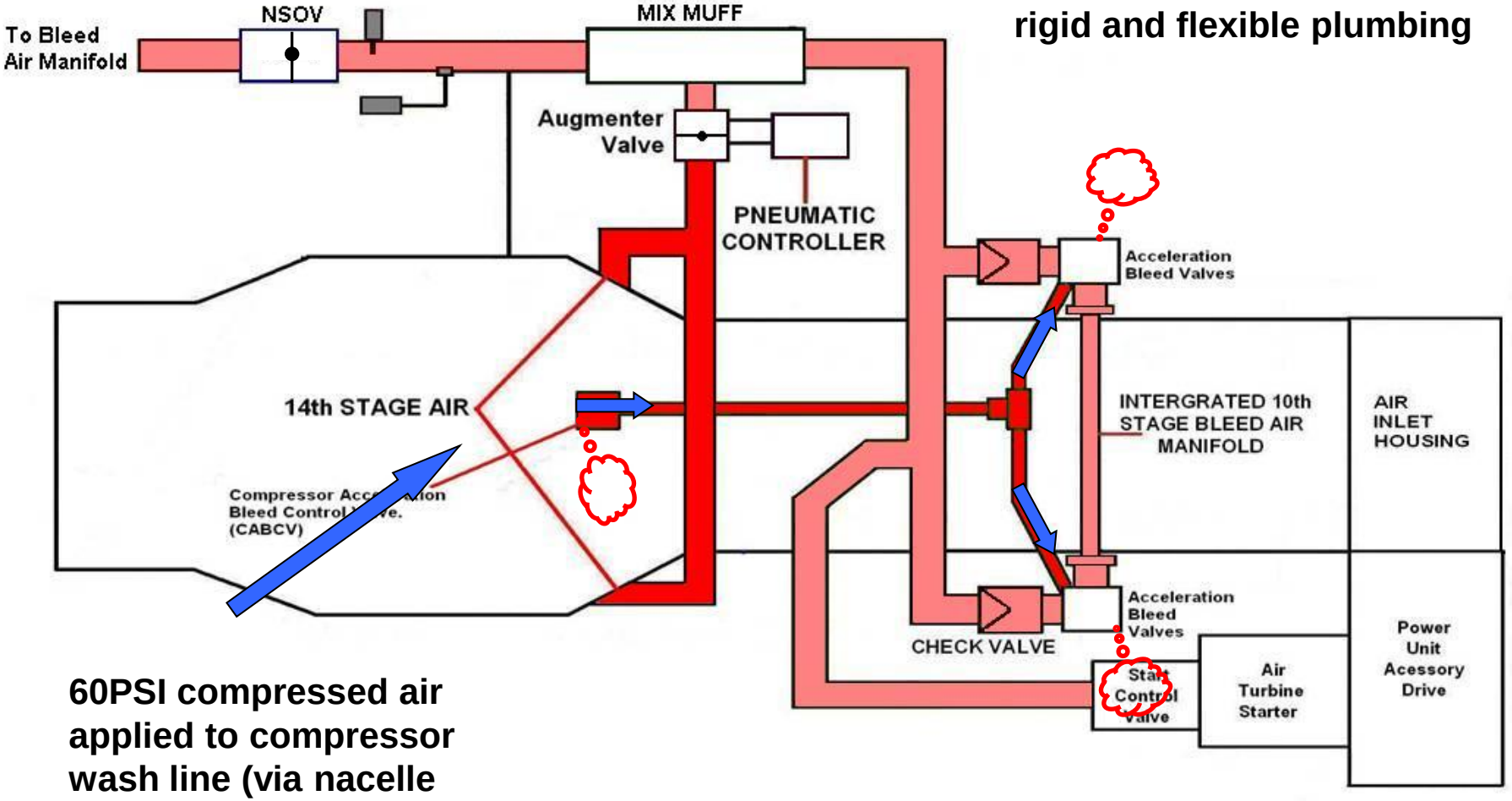
Compressed air supply regulated to 60PSI



14th Stage ABV control air plumbing

Leak check using compressed air

Leak checks carried out on ABVs, CABCV, and associated rigid and flexible plumbing



60PSI compressed air applied to compressor wash line (via nacelle drain mast)

Summary - 10th Stage Bleed Leaks

- Faults confirmed via compressed air through 14th stage ABV control air plumbing – compressor wash air line connection
- 2 CDP leaks effecting performance (>60% delta) corrected in last 12 months

EHMS Performance Signatures

14th STAGE BLEED LEAKS

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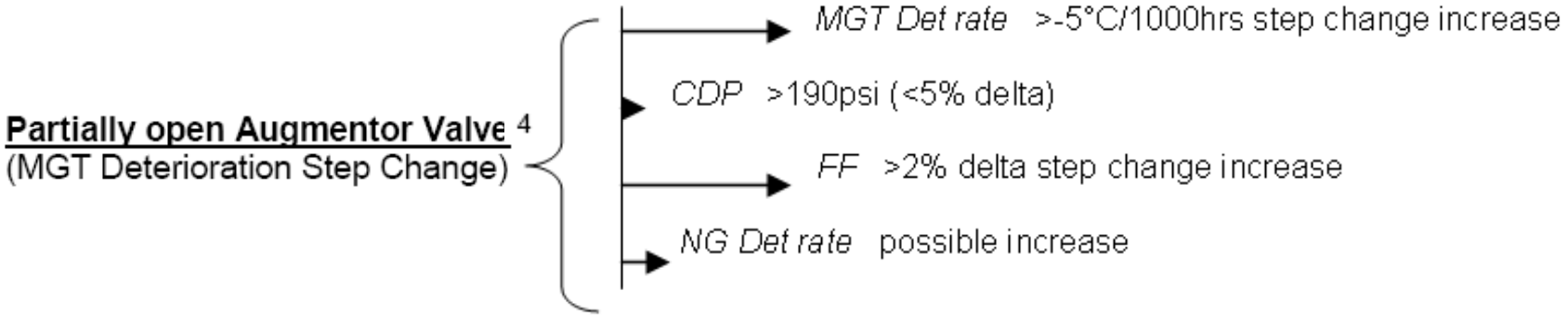
Step Change MGT Margin Loss >15˚C



[4] This fingerprint will be characterised by a rapid fall in hours remaining until zero MGT margin over a short period of time. For example, if an engine displays a reduction in hours until zero MGT margin from >5000 hours to 1500 hours over a period of one week, and this fingerprint is displayed, then the most likely contributor is the 14th Stage Augmentor Valve being partially open at all power settings. This failure mode disrupts essential 14th stage turbine cooling air from the compressor, thereby increasing MGT and accelerating turbine degradation. When fault is confirmed (via 14th stage duct bleed air test kit), Augmentor Valve is replaced.

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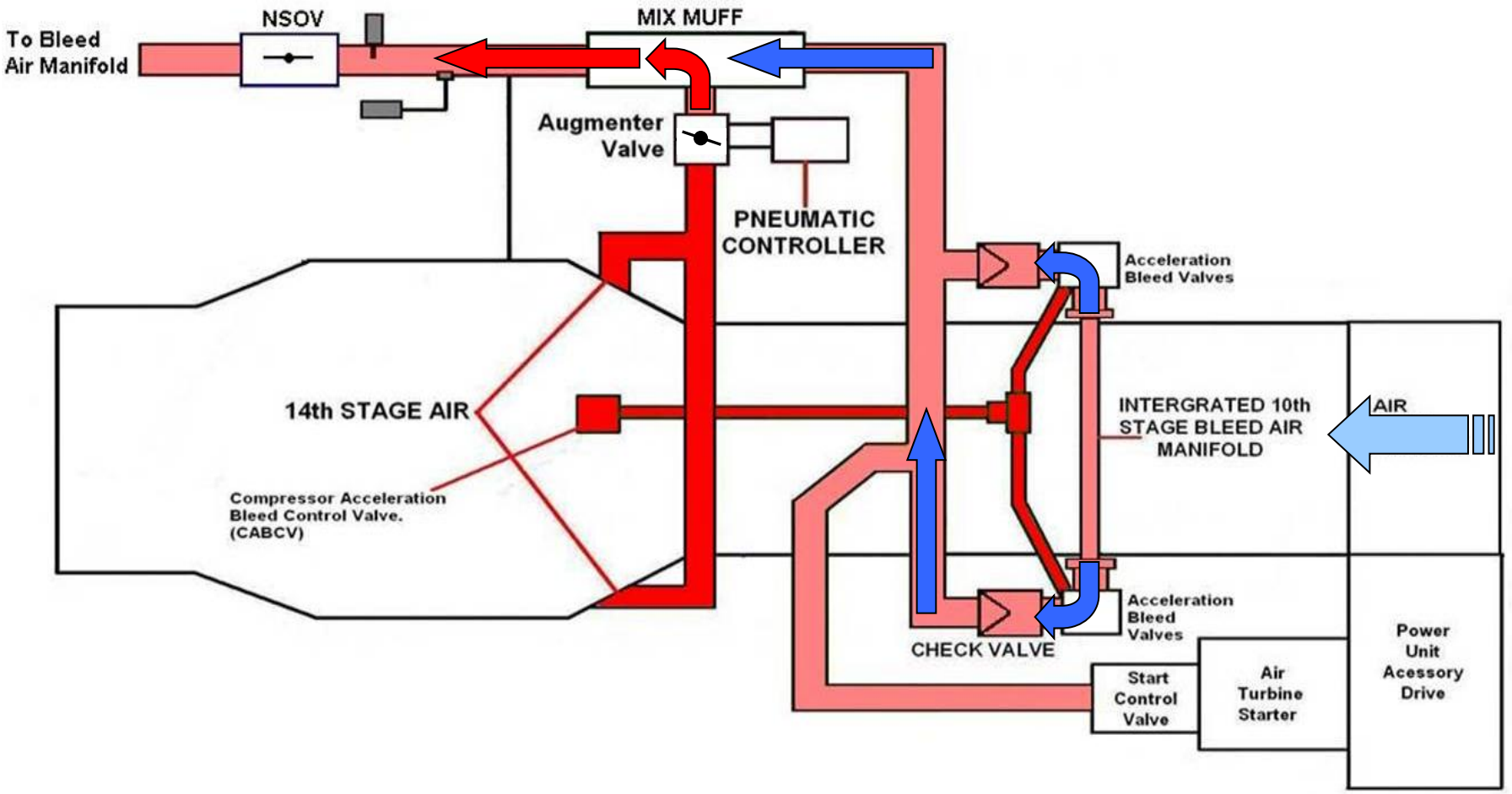
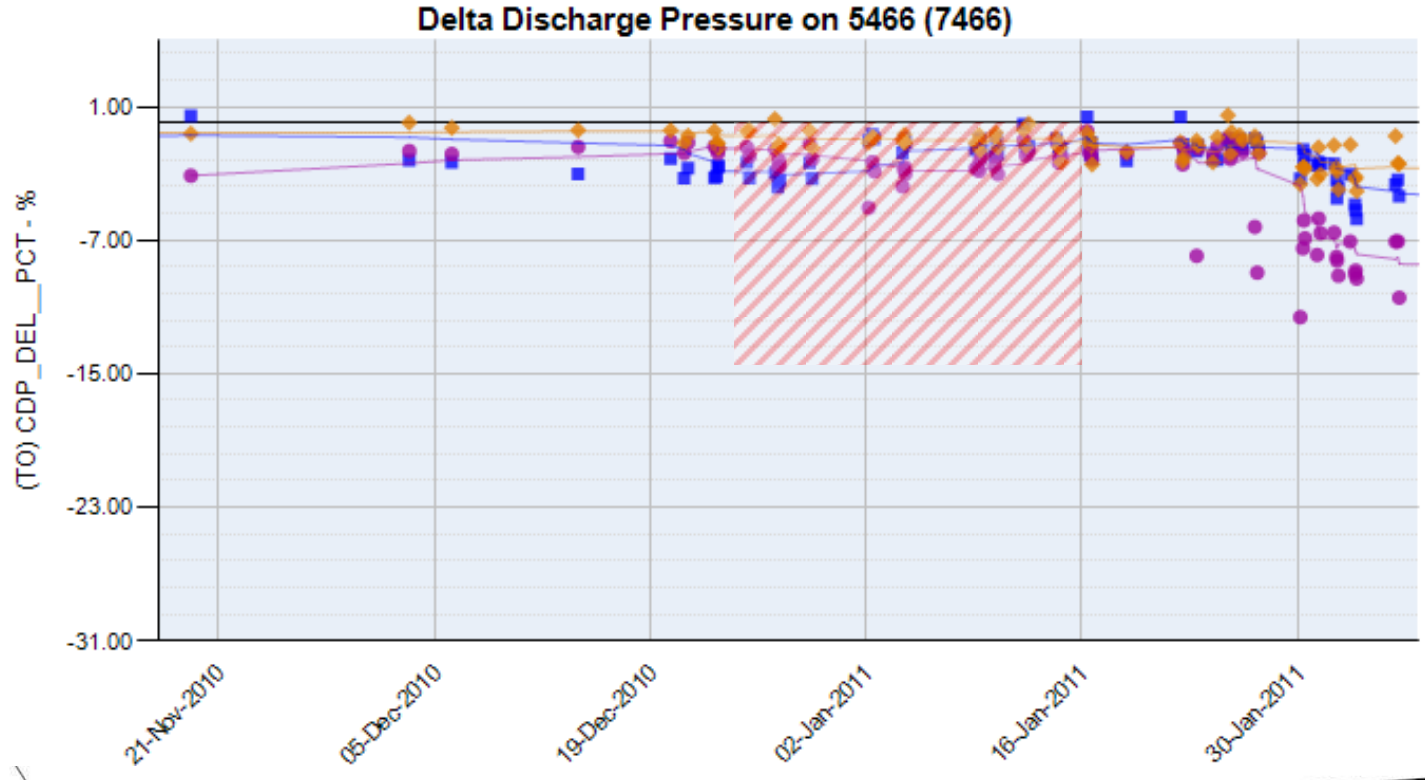
14th Stage Bleed Leak

Partially open Augmentor Valve
- MGT Margin loss >15˚C



Example. 26 Dec 2010 - 16 Jan 2011

25˚C MGT Margin Loss – Partially open Augmentor Valve



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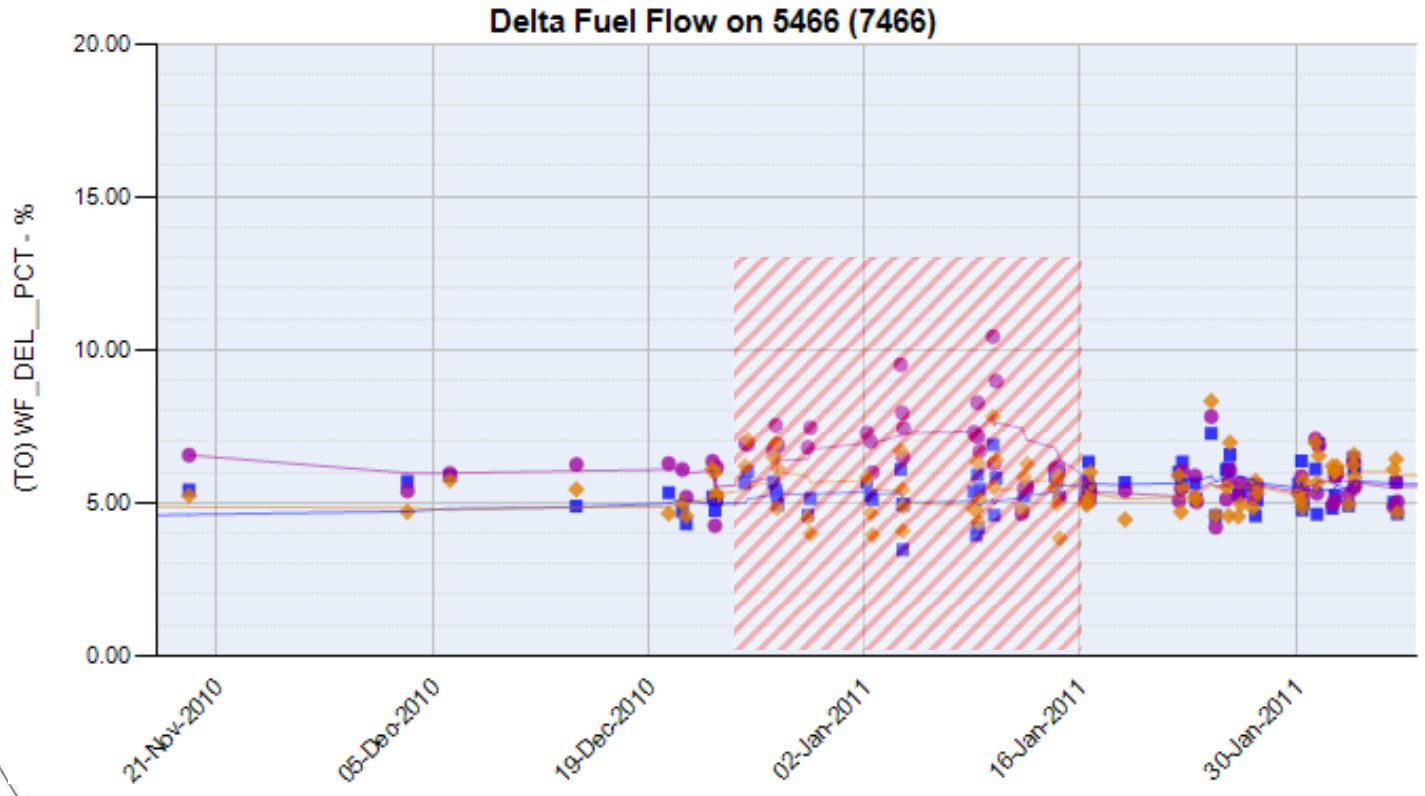
Fuel Flow - 5% Delta increase



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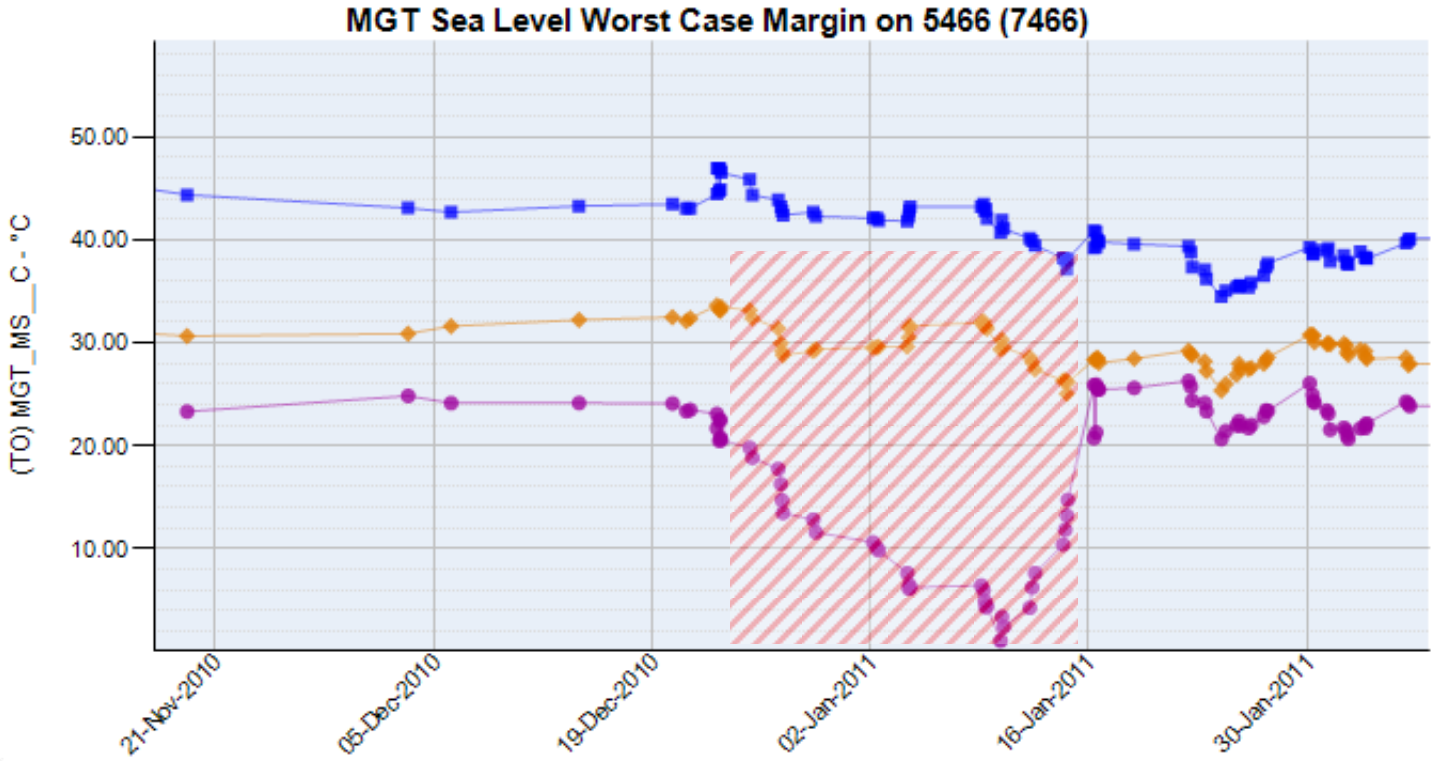
25˚C MGT Margin loss – Augmentor Valve Replaced



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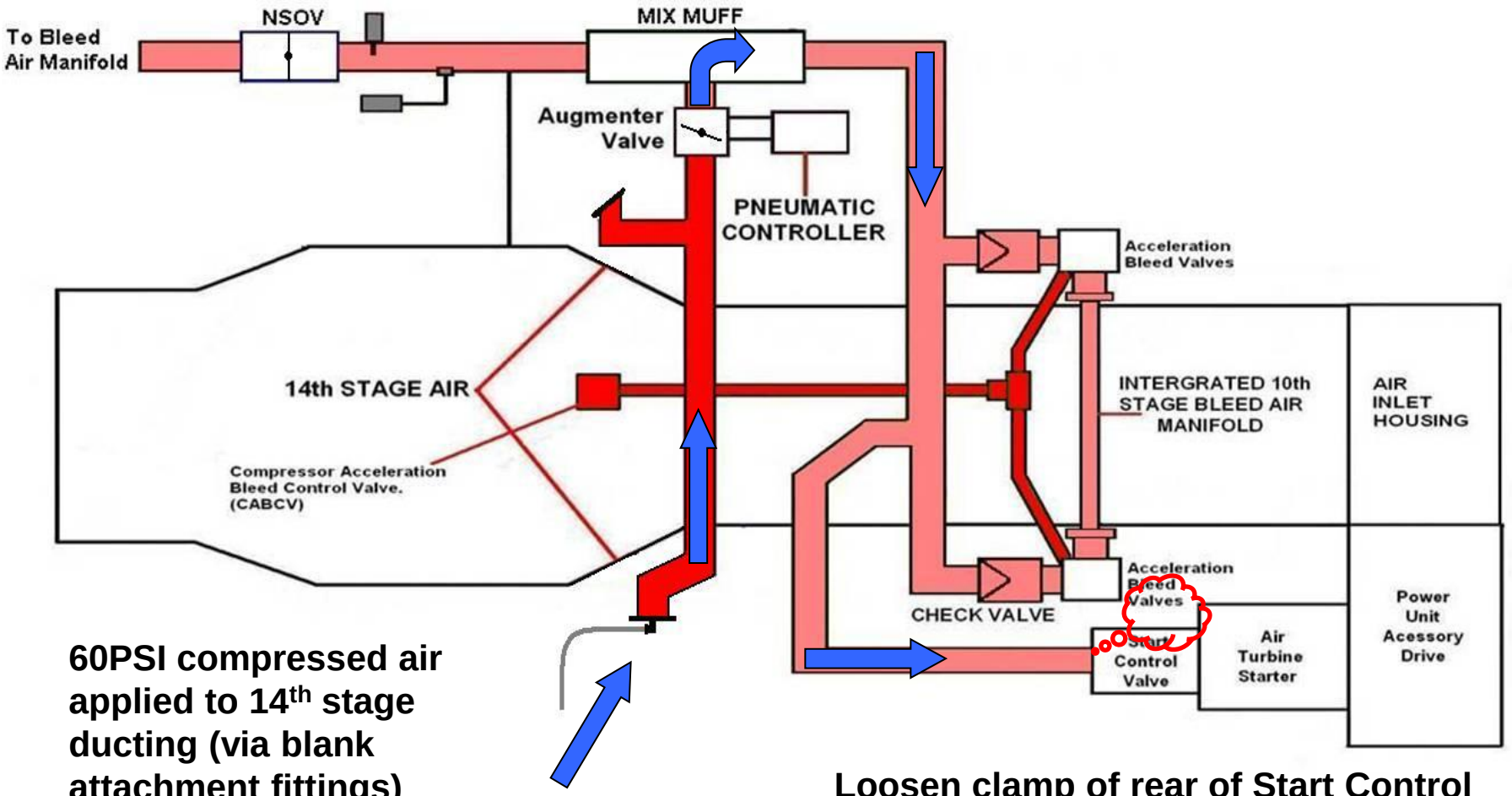
Summary - 14th Stage Bleed Leaks

- Partially open valve causing >15˚C MGT Margin loss.
- Fault confirmed via compressed air through 14th stage ducting.
- 30 Augmentor Valves removed in last 12 months for this failure mode.

14th Stage Augmentor Valve Check

Leak check using compressed air



60PSI compressed air applied to 14th stage ducting (via blank attachment fittings)

Loosen clamp of rear of Start Control Valve, and feel for excessive air

14th Stage Ducting

Compressed Air Test Kit

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FUEL DELIVERY

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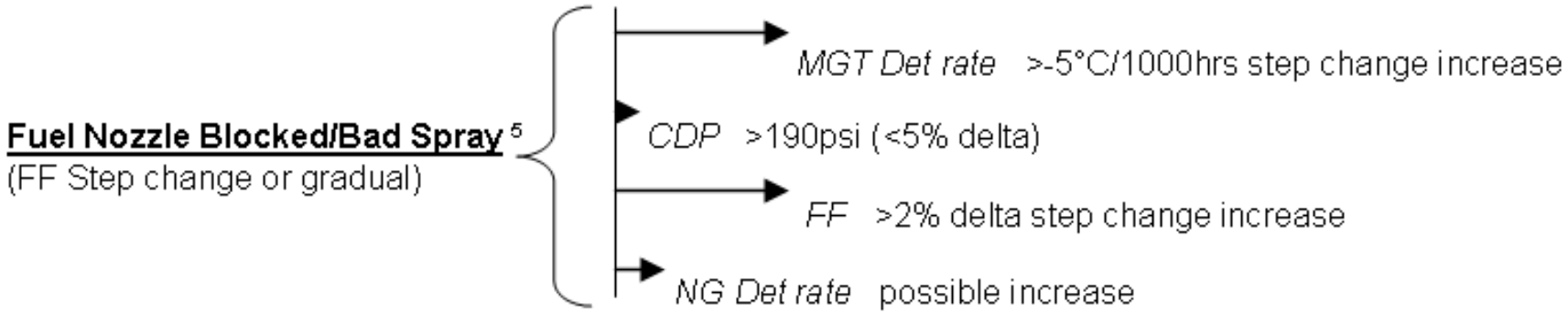
Step Change MGT Margin Loss >15°C



[5] This fingerprint will be characterised by a gradual fall in hours remaining until zero MGT margin over a relatively short period of time. For example, if an engine displays a reduction in hours until zero MGT margin from >5000 hours to 1500 hours over a period of two/three weeks worth of operation, and this fingerprint is displayed, then the most likely contributor is blocked/coked fuel nozzles causing bad spray patterns and inefficient burn. When fault is confirmed (via borescope inspection for fuel nozzle condition), fuel nozzle set (x16) is replaced.

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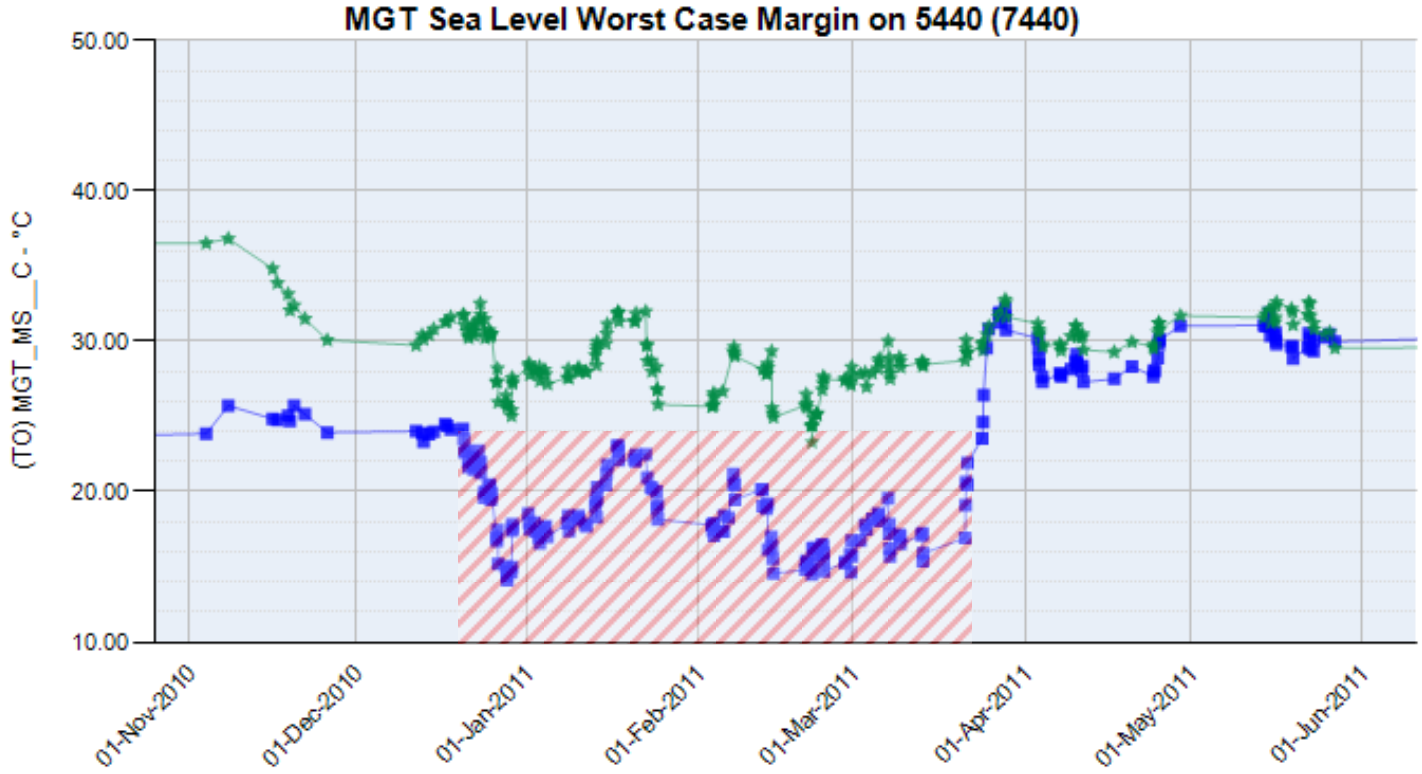
Example. 20 Dec 2010 - 20 Mar 2011

15˚C MGT Margin Loss – Coked Fuel Nozzles



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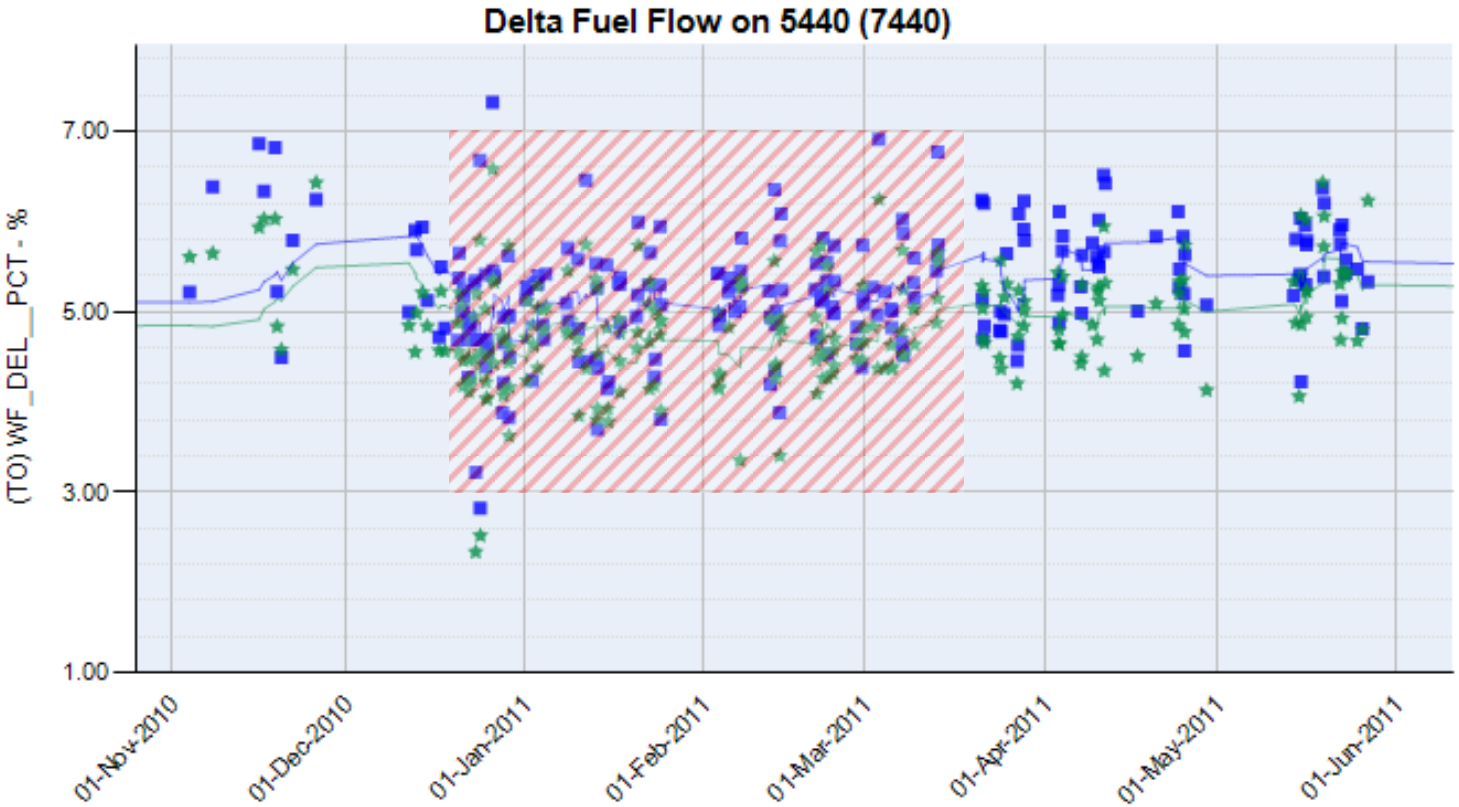
Fuel Flow – No noticeable increase



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Coked Nozzles

Typical Flow Test Results (pre-clean)

Item	Spray Quality	Spray Angle (100 to 130 deg)		Flow Test		C/Valve	Patternation	Pass/Fail
	230psig	100 psig	270 psig	12.9 - 15.1	144.2 - 166.0	>5psig	40%@270psig	Nozzle
1	Streaks	95	82	20.9	99.2	3	Streaks	Fail
2	Streaks	85	111	17.7	141.1	6	Streaks	Fail
3	Voids/Streaks	80	111	19.8	146.7	5	Voids/Streaks	Fail
4	Drouling	101	123	17.1	144.3	6	OK	Fail
5	Streaks	90	115	18.2	144.1	6	Streaks	Fail
6	Streaks	102	122	16.9	144.8	6	Streaks	Fail
7	Voids/Streaks	84	110	17.2	142.8	6	Streaks	Fail
8	OK	101	121	17.1	144.7	6	OK	Fail
9	Streaks	92	114	17.6	143.4	7	Streaks	Fail
10	OK	102	121	17.4	143.8	6	Streaks	Fail
11	Streaks	102	119	17.4	142.3	7	Streaks	Fail
12	OK	102	124	16.5	143.1	7		Fail
13	Streaks	88	109	17.1	142.3	7	Streaks	Fail
14	Streaks	84	115	21.7	143.6	6	Streaks	Fail
15	OK	101	124	14.9	146.9	6	OK	Pass
16	Streaks	101	125	18.9	145.8	5	OK	Fail

Standard Aero - 2010

Summary - Fuel Delivery

- Coked fuel nozzles causing >15˚C MGT Margin loss are all Piloted Orifice variant. (No occurrences so far related to PuAB)
- Coked nozzles - confirmed via borescope inspection.
- 20 Fuel Nozzle sets (x 16) removed in last 12 months for this failure mode.
- All removed fuel nozzle sets had accrued ~1000 hours since last Bay Service (2400 hour BS interval)

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VIBRATIONS

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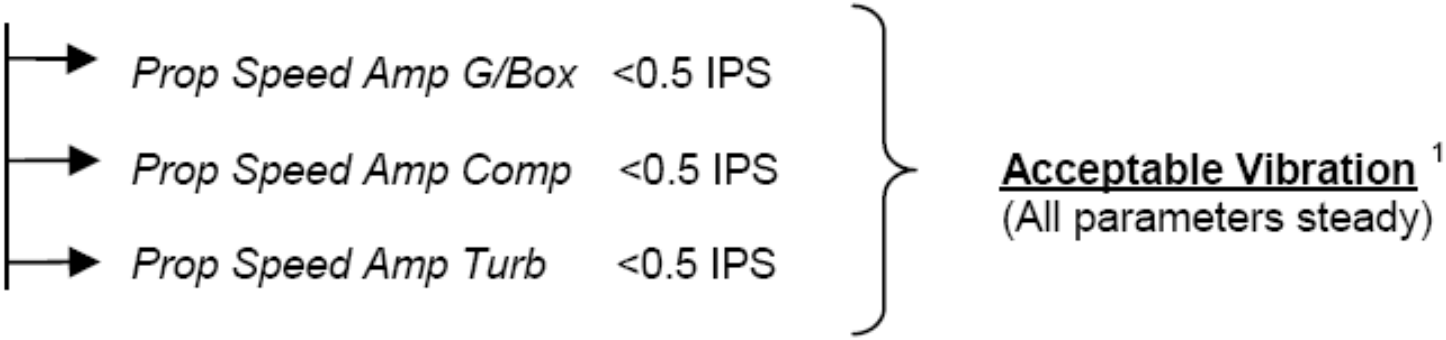
Acceptable Vibration



[1] Vibration readings <0.5 IPS are considered acceptable (not requiring maintenance action). If no step changes are observed across the measured parameters, engine is considered to be within an acceptable vibration range relative to the propeller/engine marriage and engine mount condition. Measured parameters of an engine should be compared against each other to ensure vibration readings are fluctuating in parallel. For example, a series of three take-off data points for one engine should show the G/box, Comp and Turb sensors all moving in the same direction (all three sensors increase, all three sensors decrease etc) with relatively similar deflections. If however one sensor deviates from the similar movement of the other two sensors (G/box increase, Comp and Turb decrease) then the vibration reading shift is most likely an indication error (loose/dirty plug, faulty sensor/harness/NIU).

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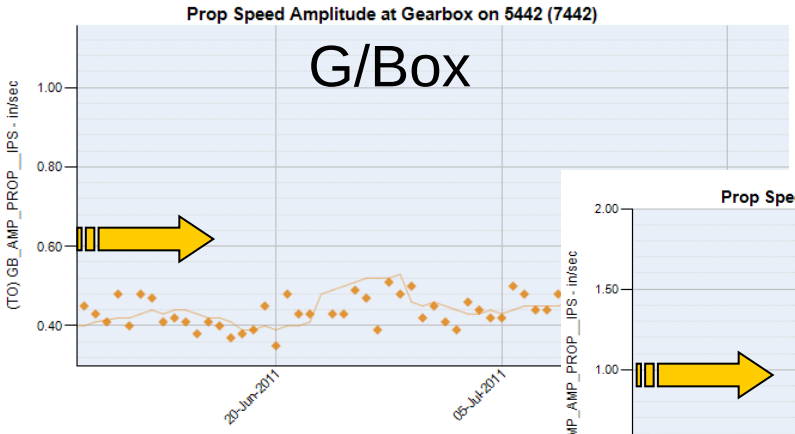
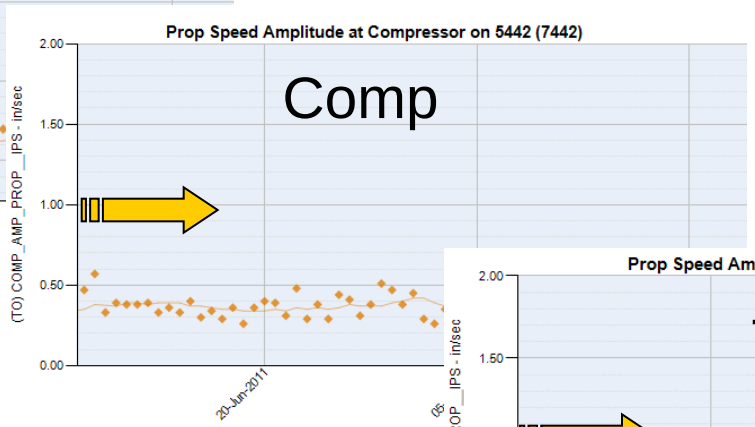
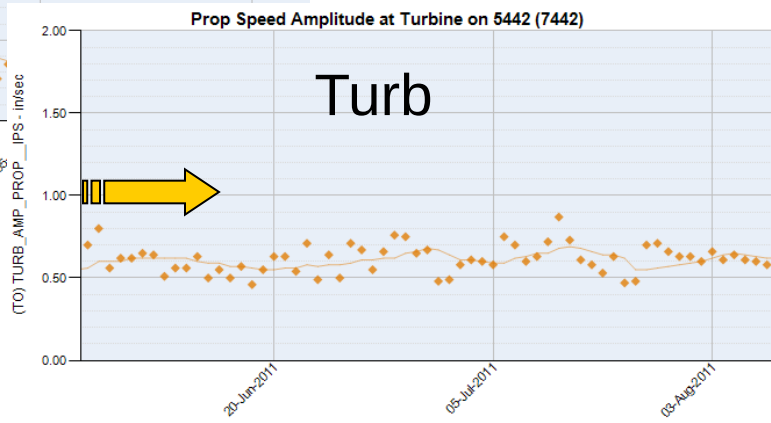
Acceptable Vibration

Parallel Movement – Prop Speed Frequency







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EHMS Performance Signatures

ACTUAL VIBRATION

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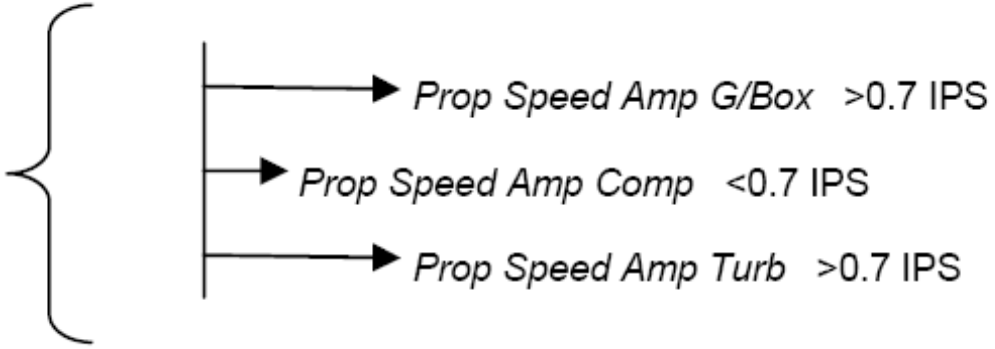
Propeller out of balance

Propeller out of balance [2]
(Step change or gradual)

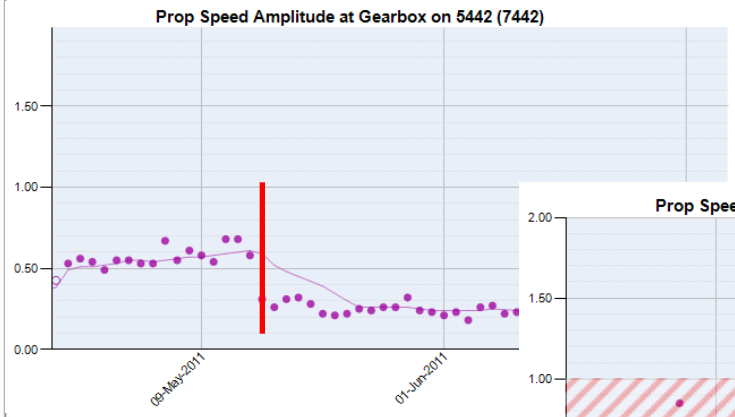


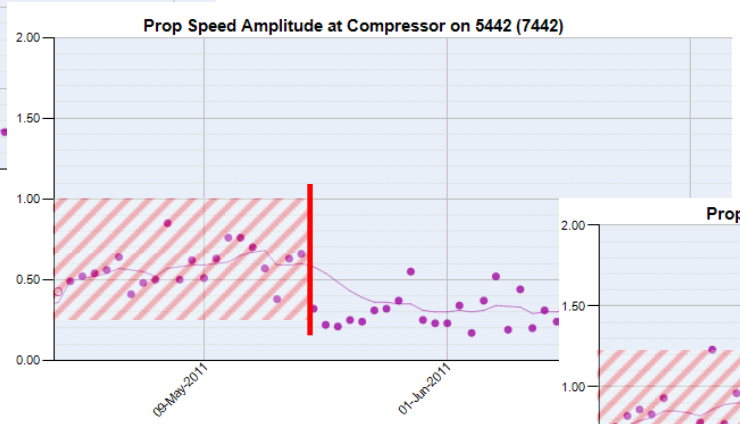
[2] This fingerprint is characteristic of an actual vibration (not indication error), in that a minimum of two of the three sensors are indicating vibration readings >0.7 IPS. An engine that has vibration readings within the acceptable range should not have readings increase out of range (over a minimum of two sensors) unless the propeller has been replaced, there is a physical change within the propeller or the engine mounts are deteriorating. All step change vibration increases should be investigated for any unserviceabilities that have been recorded or maintenance that has been recently conducted that could have an effect on vibration readings. For example, if an engine's vibration readings over two sensors increase from <0.5 IPS to > 0.7 IPS over a few operations (step change), then the propeller may have been recently replaced, have oil leaking into the hub or have developed an excessive grease leak from the blade root/s. A gradual increase from <0.5 IPS to > 0.7 IPS would be indicative of a minor grease leak from the blade root/s or deteriorating engine mount/s.

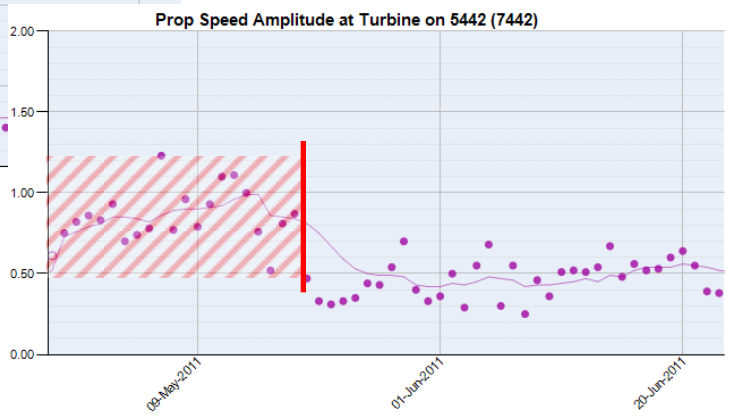
Church - 2011

Example. 1 Apr – 16 May 2011

Actual Vibration – Prop out of Balance







2 of 3 sensors >0.7 IPS

PBS Solution 16 May 11

~0.4 IPS reduction

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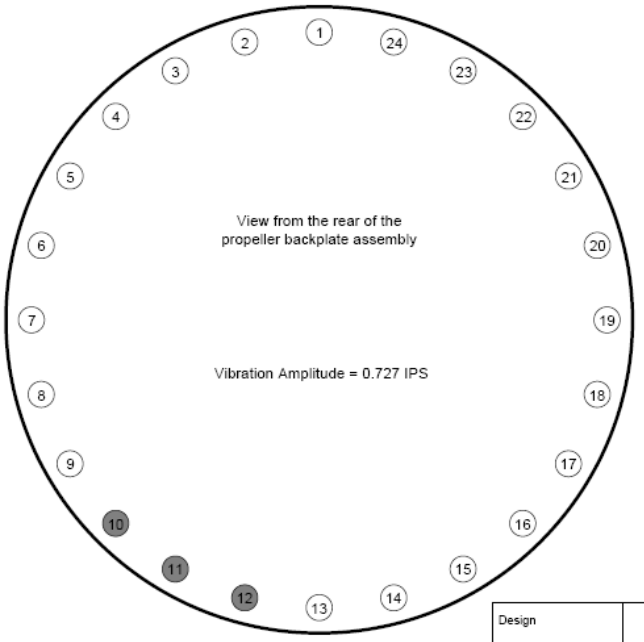
Prop out of Balance
– Software Solution Applied

GMS Filename	*engine2.005.5442.1125*	UNCLASSIFIED
File Date	*14 May 2011 05:49:33 A*	



Aircraft Tail No.: 5442 **Engine No.: 2**

Propeller Serial Number: 442_2

Location	Baseline Weight (g)	Recommended Weight (g)	Actual Weight (g)
1			
2			
3			
4			
5			
6		56.23	
7		60.00	
8		60.00	
9		42.97	
10	Quarantined to static balance weight		
11	Quarantined to static balance weight		
12	Quarantined to static balance weight		
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			

Note: There are 24 balance weight holes on the propeller backplate assembly. Balance weight hole 1 is located directly above the dual target screws on the propeller backplate assembly.

Reference: AAP7211.031-2-61JG-00-1, 2-5-3, A2.

Design	C-130J-30 Propeller Balancing Software Version 1.0.0	*QinetiQ* Level 3, 210 Kingsway South Melbourne, VIC 3205	
Technician		TITLE *C-130J-30 Propeller Balancing Solution for Aircraft A97-5442, Engine 2*	
Supervisor		Calculation Date: 16 May 2011	
Work Performed (Date)		DRG No.: *PBS_5442_2_140511_45* Rev No.: *1*	Sheet Size A4
UNCLASSIFIED		Not to Scale	Sheet 1 of 1

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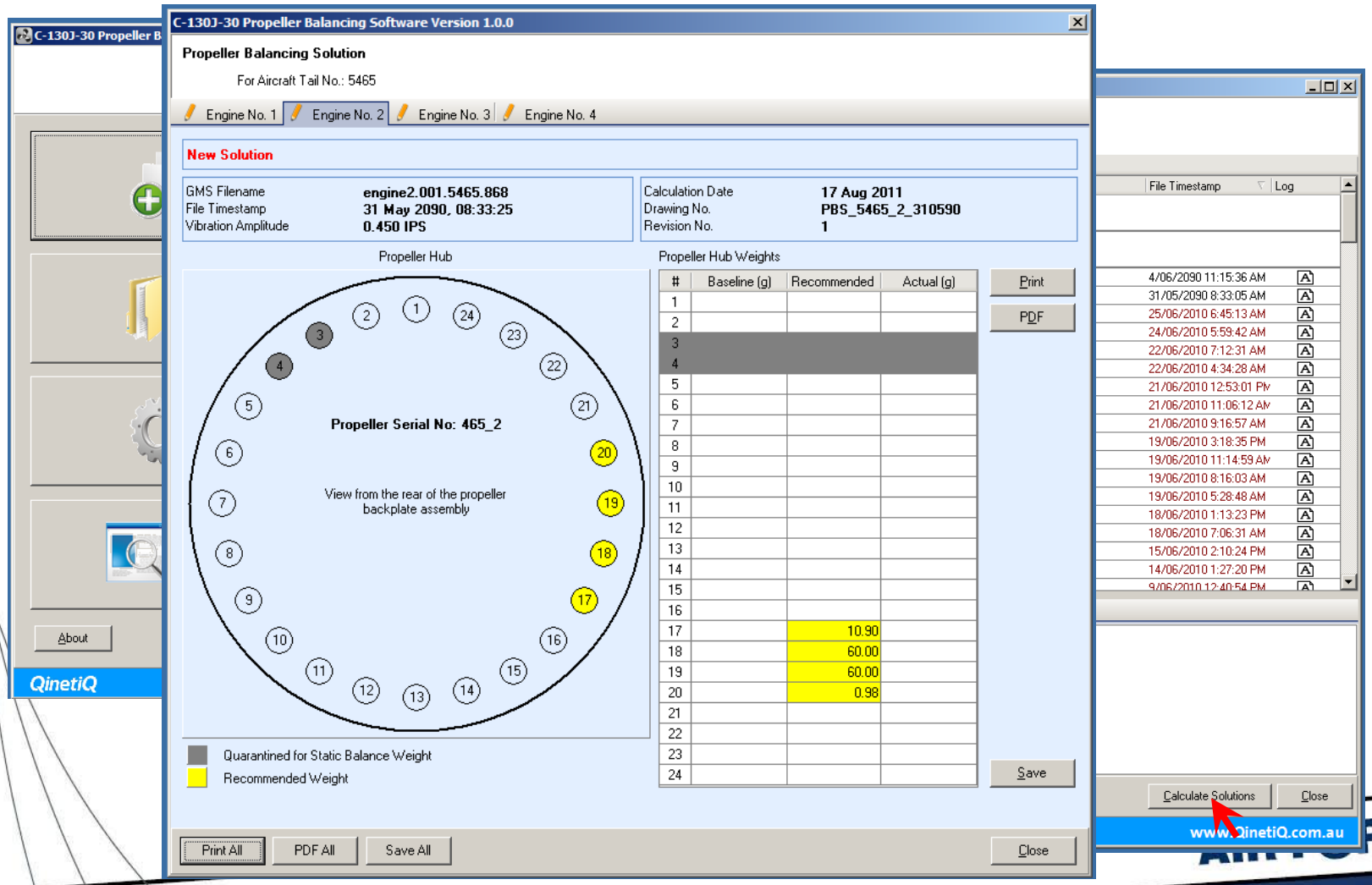
Prop Balance Software



EHMS Performance Signatures

INDICATION ERROR

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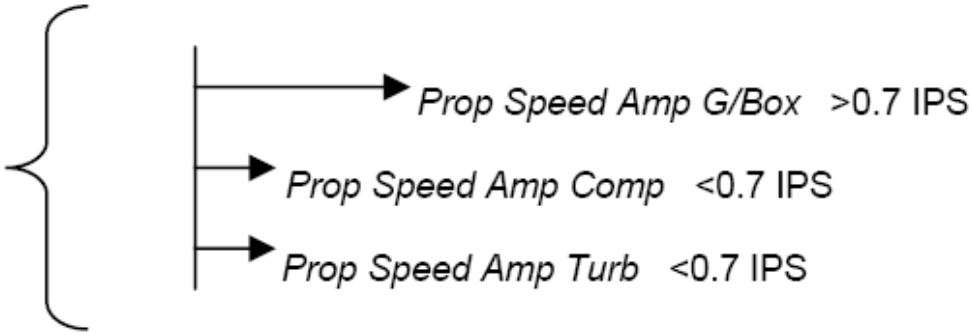
Vibration indication error

Vibration Indication error [3]
(Step change)



[3] This fingerprint is characteristic of a vibration indication error, in that only one of the three sensors are indicating vibration readings >0.7 IPS. All step change vibration increases over a single sensor should have maintenance action performed as soon as possible to prevent an in flight vibration event (IFSD). Single sensor deviation will appear erratic by not following the data point movement pattern of the other two sensors. For example, if an engine's vibration readings over one sensor increase from <0.5 IPS to > 1.0 IPS over a few operations (step change), then there is an error with the indication system. Fault would be confirmed by visual inspection of the offending sensor's receptacle for contamination or damage, harness plug for security or damage. If there is no visible contributor, sensor would be replaced.

Church - 2011

Summary - Vibrations

- Pro-active Prop Balances occurring when two of three sensors record >0.7 IPS at prop speed freq.
- Significantly slowed (if not eradicated) occurrence of Forward Nacelle cracking and Exhaust Nozzle cracking.
- 26 propellers dynamically balanced using a software solution in last 12 months.

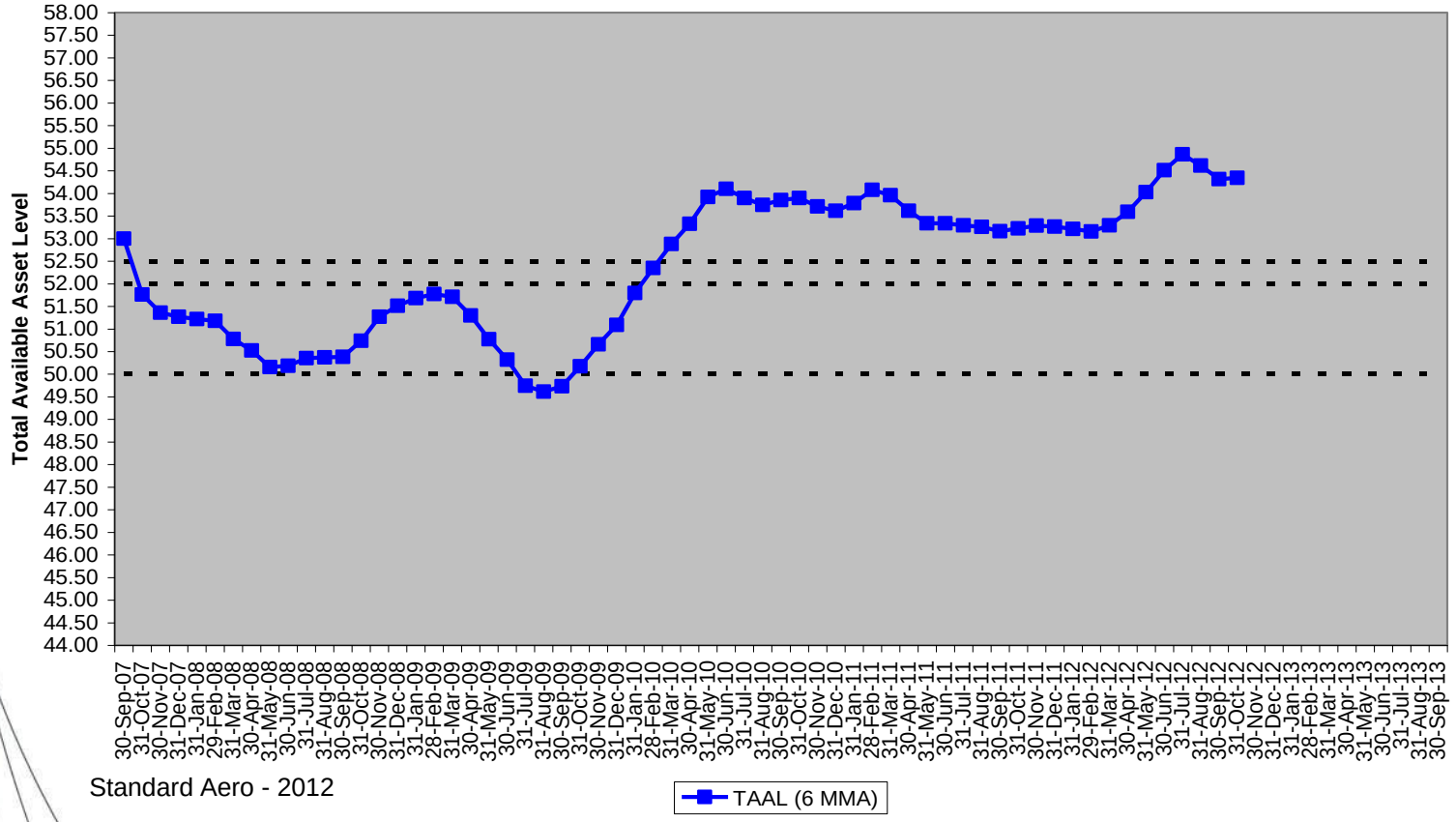
Engine Health Management

- Understand the health of your fleet
- Understand engine system operation
- Understand the environment your engines are operating in
- Perform corrective maintenance on step change engines
- Plan engine removals prior to performance failure event

Results – 2010 to present

- Reduction of in flight events by ~80%
- 11 fold increase of spare engine availability
- Only 24% of the RAAF AE2100D3 engines have been subject to a shop visit. With 86% of these engine removal planned removals
- Operational confidence restored
- AE2100D3 logistics support budget on target for the past 2 fiscal years.
- Development of and Engine Condition Management program.

QEC Availability



Standard Aero - 2012

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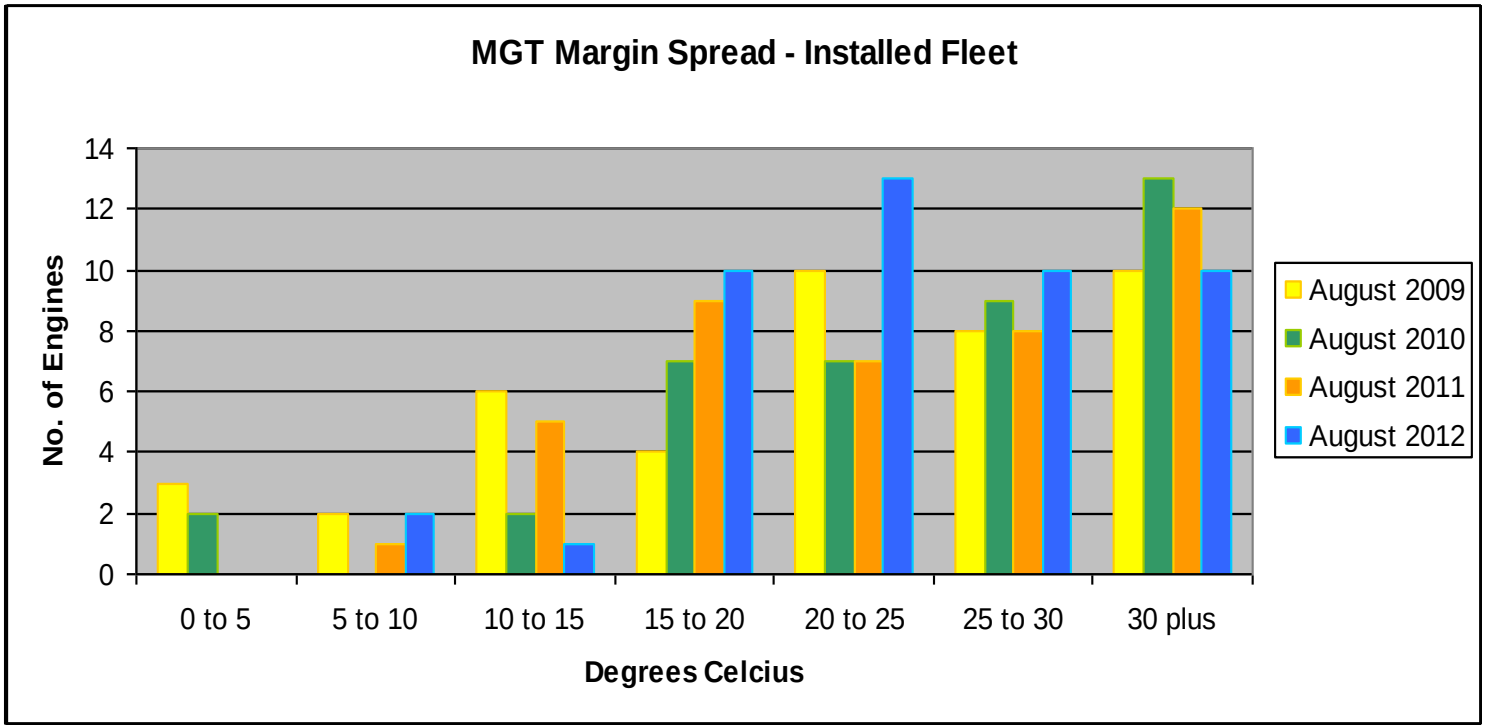
MGT Margin Spread Installed Fleet (2009 vs. 2012)



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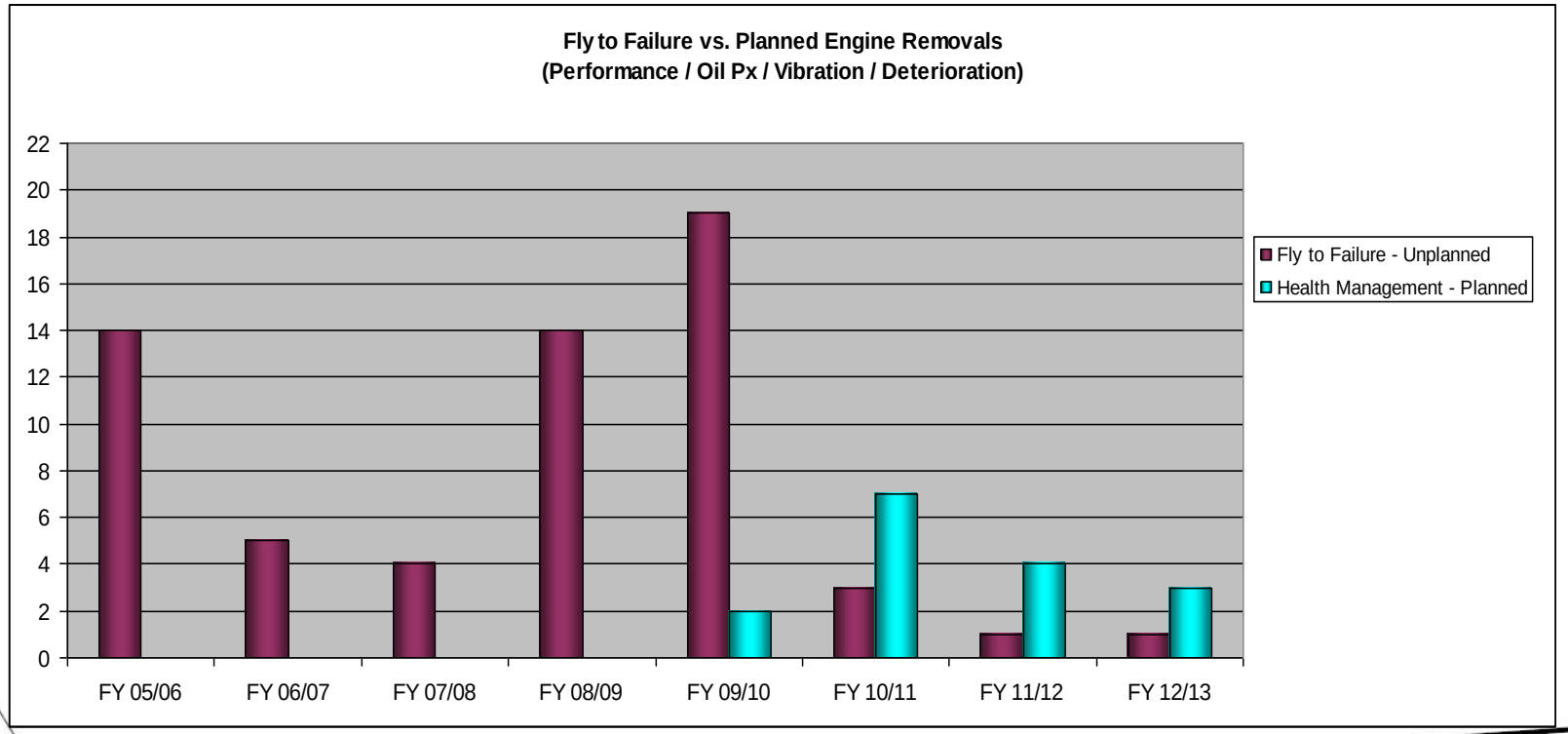
Fly to Failure vs. Planned Engine Removals (2005 – present)



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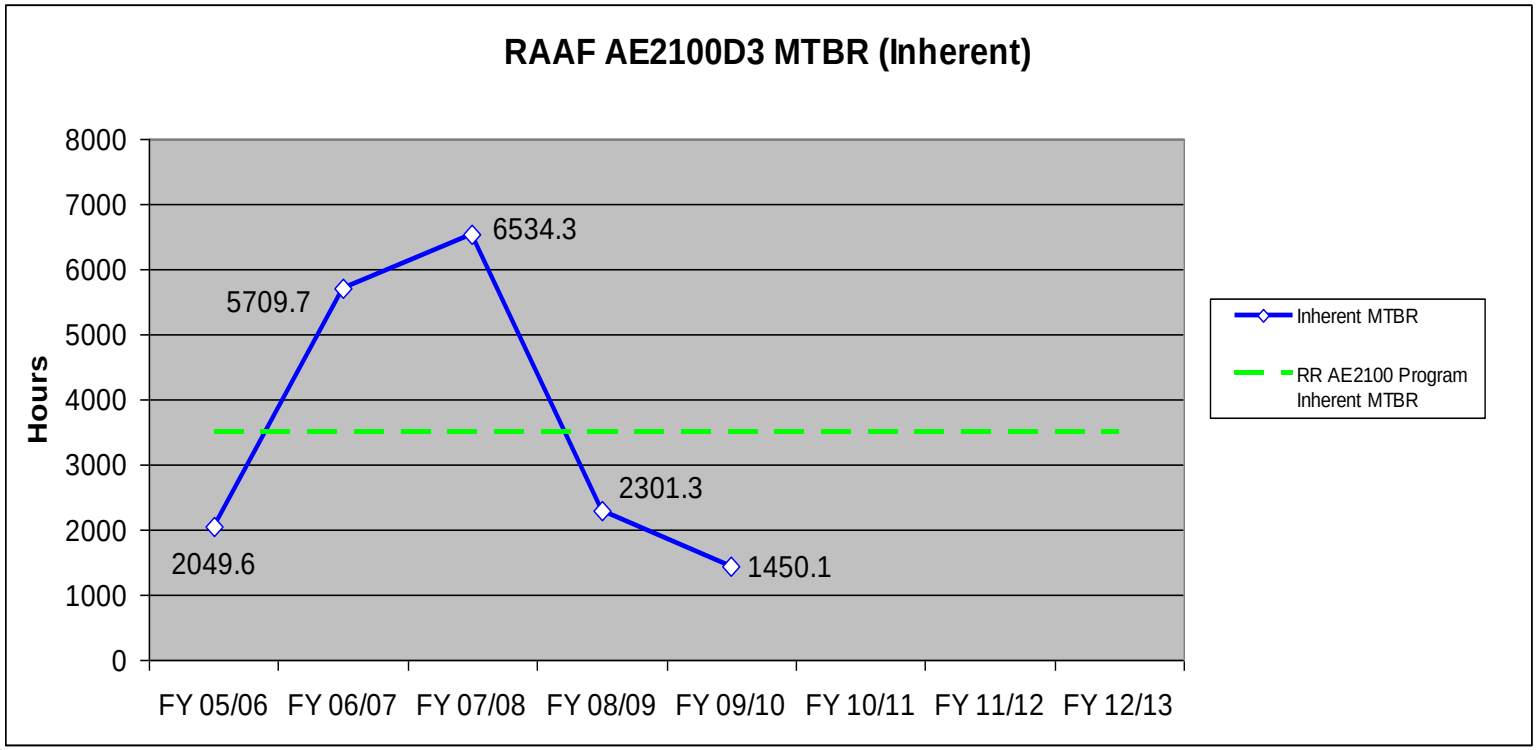
Inherent Failure MTBR (2005 – 2009)



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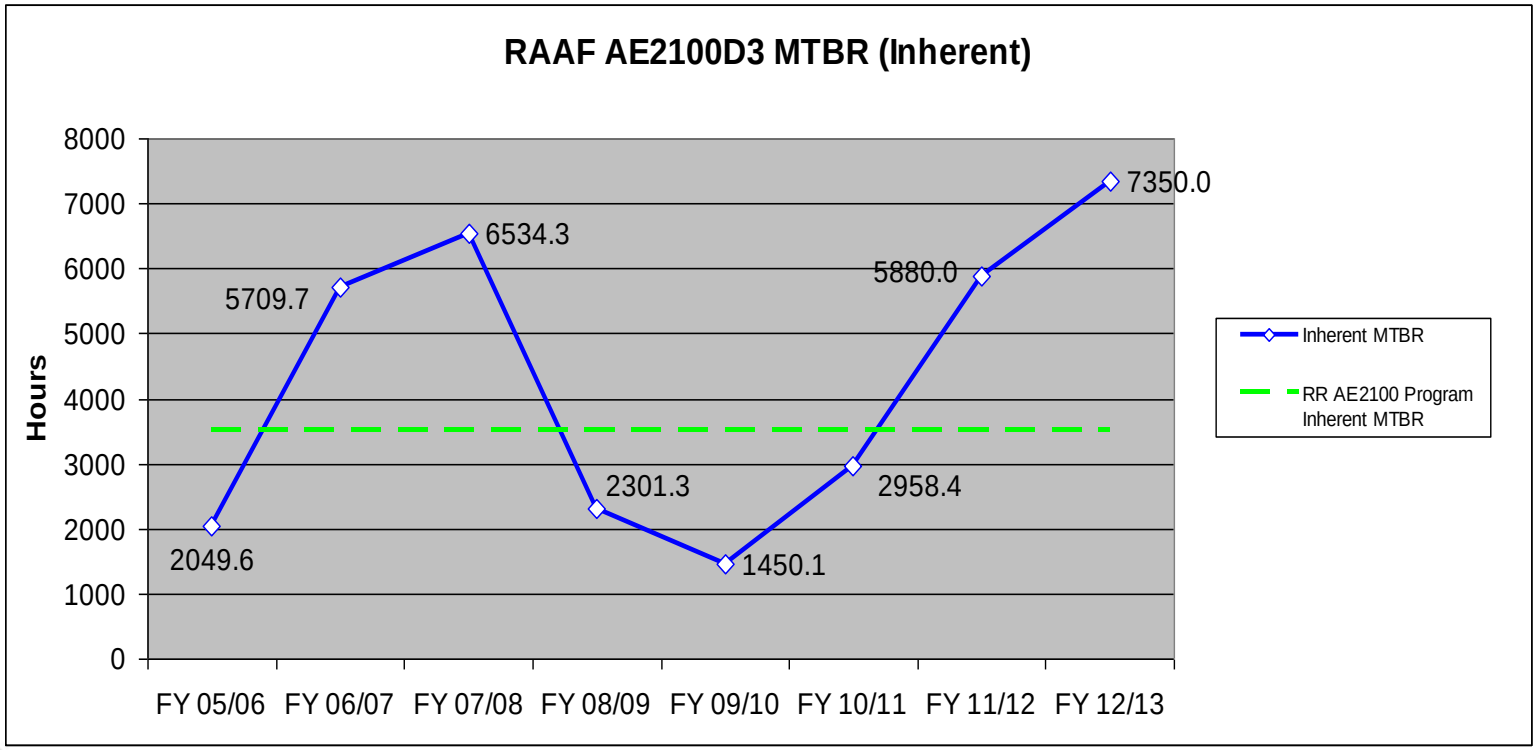
Inherent Failure MTBR (2010 – present)



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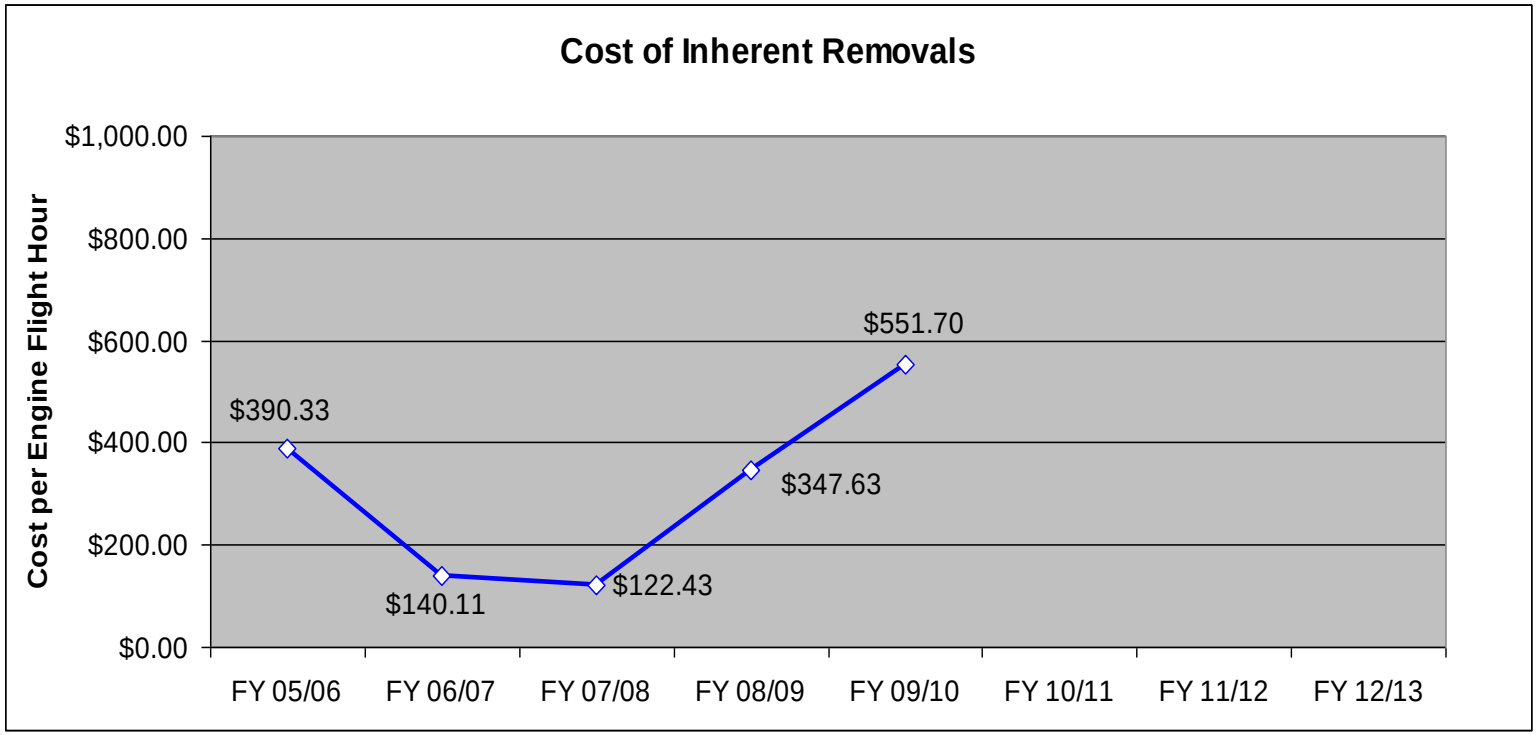
Cost of Inherent Removals
$ / EFH (2005 – 2009)



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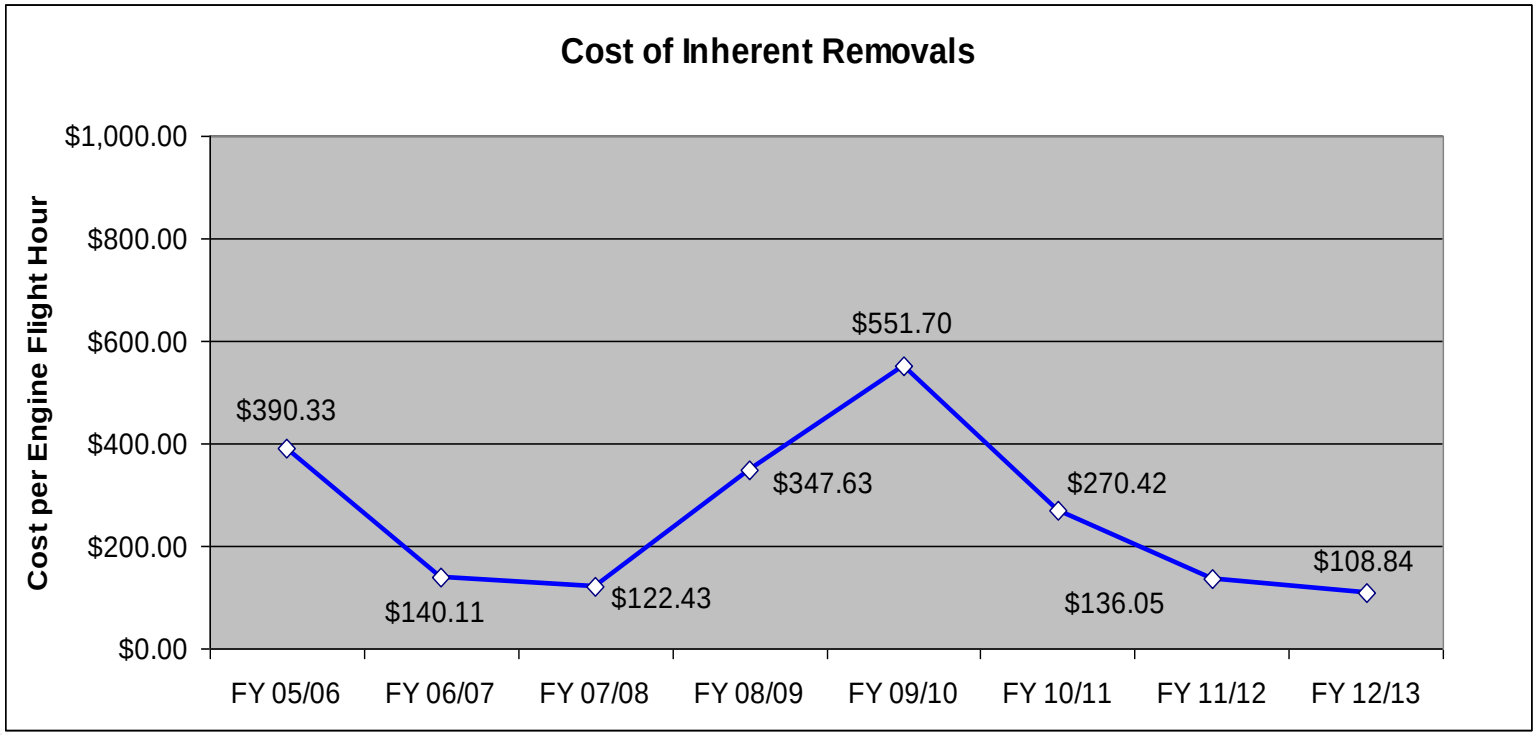
Cost of Inherent Removals $ / EFH (2010 – present)



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