LM2500 engineering update
ETN Conference
Follow-Up to 2020 Meeting

March 4, 2021

GE Aviation participants

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Safety Moment

Safety Moment … CPLM Management

Definition

- Critical life-limited parts are those parts whose sudden failure could impact the structural integrity of the engine or its package.
- Critical life-limited parts must be removed from service before reaching their declared life limit.

Operation & Maintenance Manual

- Identifies specific parts of industrial gas turbines that are cyclic life limited.
- Provides instructions for tracking the operating hours and cycles on these parts.
- Reference Chapter 6 (LM2500 Base) and Chapter 12 (LM2500 Plus and +G4) .

Owner/User Responsibilities

- Creating and maintaining a data sheet or each critical part throughout its entire life.
- Monitoring the status of the parts to ensure that their published life limits are not exceeded.

Critical Parts Tracking System Data Sheet Example

CRITICAL PARTS TRACKING SYSTEM

NOMENCLATURE :	PART NUMBER :	PART SERIAL NUMBER :
NEXT HIGHER ASSEMBLY :	ENGINE SERIAL NUMBER :	ENGINE CUSTOMER/LOCATION :

EVENT DATE	EVENT DESCRIPTION SEE NOTE (a)	OPERATING HOURS SINCE LAST EVENT	FULL CYCLES SINCE LAST EVENT	PARTIAL CYCLES SINCE LAST EVENT	TRIP (OR STOP-COCK) CYCLES SINCE LAST EVENT	ACCUMULATED CYCLES SINCE LAST EVENT SEE NOTE (b)	TOTAL HOURS SINCE NEW	TOTAL ACCUMULATED CYCLES SINCE NEW	PART LIFE LIMIT (CYCLES)	CALCULATED PERCENT OF (CYCLIC) LIFE CONSUMED	RECORDED BY	LOCATION

NOTE (a) :

EVENT DESCRIPTION - USE ONE OF THE FOLLOWING :

1. PART INSTALLATION
2. SERVICE BULLETIN INCORPORATION
3. REPAIR
4. LIFE LIMIT CHANGE
5. CHANGE IN CALCULATION OF EFFECTIVE LIFE
6. INSPECTION
7. ENGINE OPERATION OR DUTY CYCLE CHANGE
8. PART REMOVAL
9. PART RETIREMENT
10. OTHER (EXPLAIN)

NOTE (b) :

ACCUMULATED CYCLES = K_f x (FULL CYCLES) + K_p x (PARTIAL CYCLES) + K_{sc} x (TRIP OR STOP-COCK CYCLES)
WHERE FULL, PARTIAL, AND TRIP OR STOP-COCK CYCLES ARE TAKEN FROM CONTROL SYSTEM OPERATING LOG.

Safety Moment … Cross-Fleet Utilization

1 Cross-Fleet Utilization … LM1600 engines/parts moved from commercial marine application to an industrial application

Improvement: Update to cautionary statements in O&M and IRM manuals

Parts approved for use in LM1600 gas turbines and gas generators are identified in the Illustrated Parts Breakdown (IPB) list.

- Engines and/or parts previously used in **aircraft** engines shall be not used in marine (commercial and naval) or **industrial** applications.
- Engines and/or parts previously used in **industrial** gas turbine and gas generator applications shall not be used in **marine** (commercial and naval) applications.
- Engines and/or parts previously used in **marine** (commercial and naval) applications shall not be used in **industrial** gas turbine and gas generator applications.
- Engines and/or parts previously used in **commercial marine** applications shall not be used in **naval** applications.
- Engines and/or parts previously used in **naval** applications shall not be used in **commercial marine** applications.

Cross-fleet utilization is not allowed

Safety Moment … LLP Parts with Unknown History

2 Unknown Part History … LM1600 parts with unknown cycles/hours and ambiguous history

Improvement: Clarify guidance in O&M manual

If the part's cycles or hours are unknown, replace the part at next shop visit.

Maintain CPLM records and work with your service provider to understand part history

Safety Moment … Calculating Remaining Cycles

3 Use of common LLP parts in multiple LM2500 applications

Improvement: SL2500-IND-21-002 issued to clarify applicable Limit for life limited parts (LLP) that are used in different LM2500 models

HPCR

Row Labels	LM2500 Industrial	LM2500+	LM2500+G4
Spacer 1-2		L50588P04	L50588P04
Stg 1 Disk		L50507P03	L50507P03
Stg 10-13 Spool	L50509G01	L50509G01	
	L50509G03	L50509G03	
	L50509G04	L50509G04	
	L50509G05	L50509G05	
	L50509G08	L50509G08	L50509G08
Stg 14-16 Spool	L50510P01	L50510P01	
	L50510P03	L50510P03	
	L50510P04	L50510P04	
	L50510P05	L50510P05	L50510P05
Stg 2 Disk		L44742P01	L44742P01
Stg 3-9 Spool	9021M64P13	9021M64P13	
	9021M64P14	9021M64P14	9021M64P14

HPTR

Row Labels	LM2500 Industrial	LM2500+	LM2500+G4
Fwd Shaft	9208M79P09	9208M79P09	
	9208M79P10	9208M79P10	
Rear Shaft	L31304G02	L31304G02	
Spacer		L47519P04	L47519P04
Stg 1 Disk		L47518P01	L47518P01
Stg 2 Disk		L38380P02	L38380P02

LPTR

Row Labels	LM2500 Industrial	LM2500+	LM2500+G4
Aft Shaft		L50525P02	L50525P02
Fwd Shaft		L21497P08	L21497P08
PB Seal	L16742P02	L16742P02	
	L16742P03	L16742P03	L16742P03
PB Seal Support	L14475P02	L14475P02	
	L14475P03	L14475P03	L14475P03
Stg 1 Disk		L50501P02	L50501P02
Stg 2 Disk		L50502P02	L50502P02
Stg 3 Disk		L50503P01	L50503P01
Stg 4 Disk		L50504P01	L50504P01
Stg 5 Disk		L50505P01	L50505P01
Stg 6 Disk		L50506P01	L50506P01

Safety Moment … Calculating Remaining Cycles

3 Use of common LLP parts in multiple LM2500 applications

Improvement: SL2500-IND-21-002 issued to clarify applicable Limit for life limited parts (LLP) that are used in different LM2500 models

The O&M Manual change will clarify the applicable limit to be applied when an affected part serial number is operated in one engine model, and then reinstalled in a different LM2500 model than the model from which it was removed. This change is intended to prevent a potential life limit exceedance.

Two options will be provided: A. Use the lowest life limit for the given P/N, among the various models in which the part has been operated, when insufficient documentation available to distinguish the number of cycles operated in each model application. B. Convert cycles remaining in one application into cycles remaining in another (i.e. Miner's rule).

The manual will allow either Option A or B depending on confidence in prior usage history of the part.

Review SL2500-IND-21-002 to calculate remaining cycles as applicable

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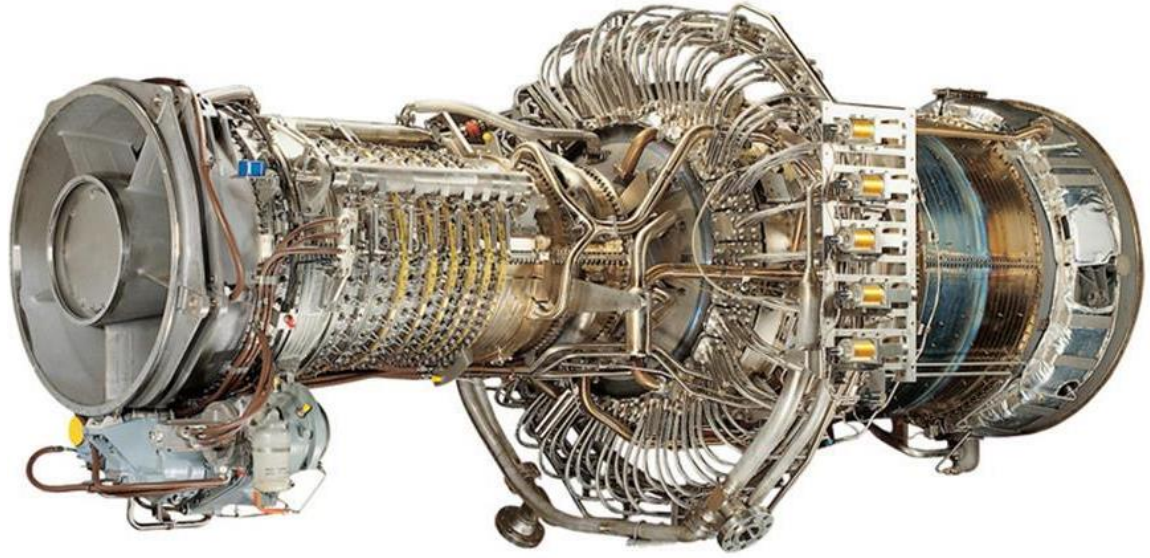
ETN Operations Update



March 4, 2021

AERO REPAIRS LANDSCAPE

ANZGT

TRANSCANADA TURBINES

IHI

MTU Aero Engines

GE AUTHORIZED SERVICE PROVIDERS

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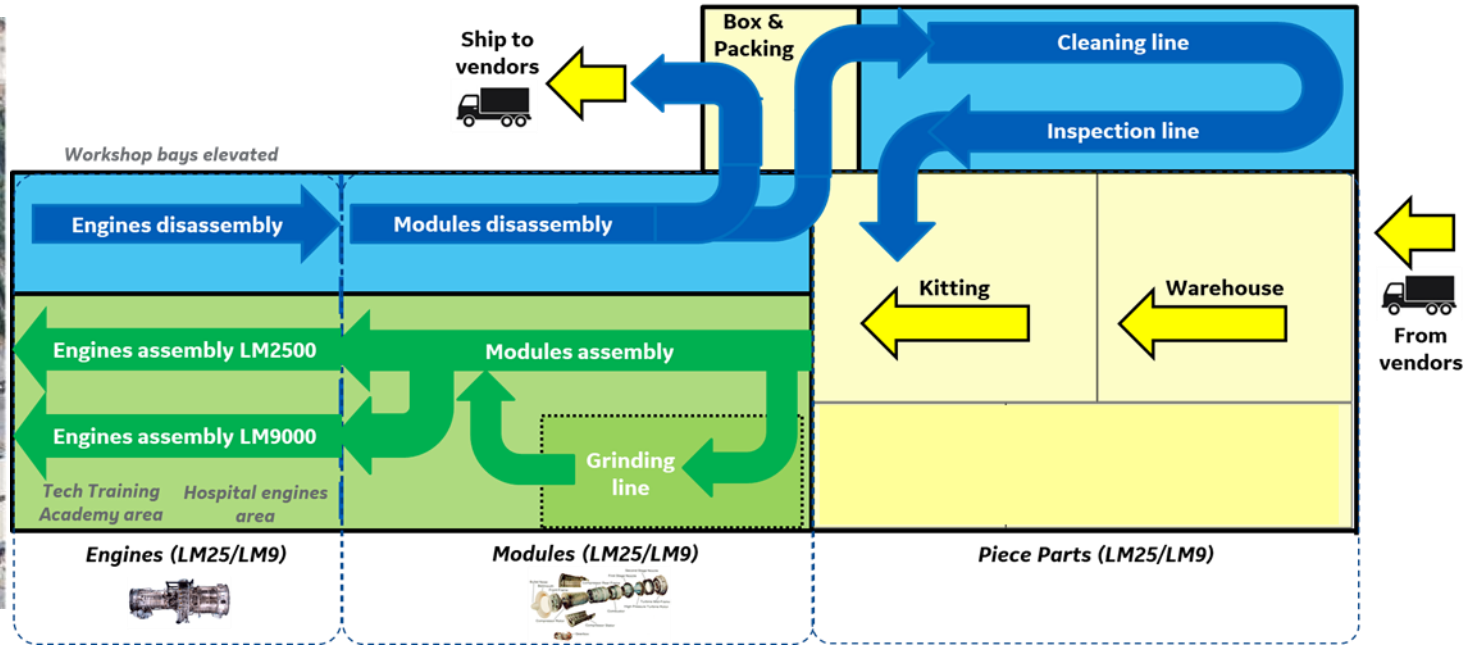
Massa Shop Relocation

New facility - Area Gaspari Menotti

- Total area 61000 mq
- Workshop 16500 mq

New Service Center lay-out and Material Flow



Highlights

- Lines by process to have higher flexibility
- 3 main areas … Engine – Modules – Parts with different capabilities and requirements (bays height, cranes, cleanliness etc)
- Single piece flow U-line
- Materials flow & lines sizing according to Lean/3P concepts … 3P AWOs on going

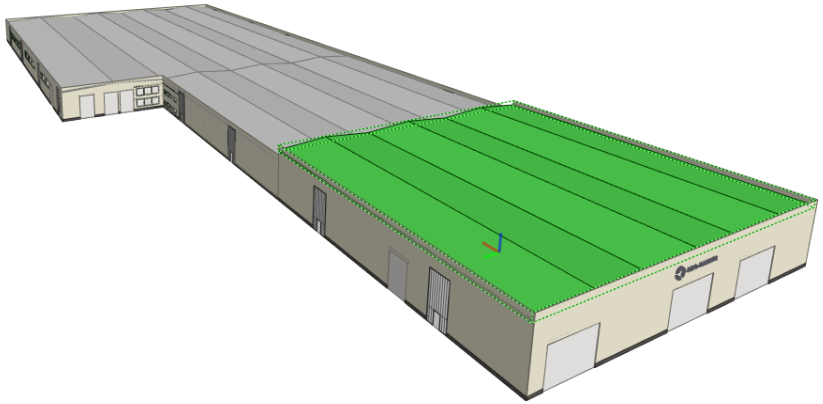
New technologies introduction (2020)

High Speed Grinding lines

Cleaning & Inspection lines

Main upgrades of new facility

Roof elevation



Floor resination

Bridge cranes upgrade

Air circulation system + confined spaces

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Quality

Aero Alliance 2020 Quality KPIs

Quality Escapes

	Jan	Feb	Mar	1Q	Apr	May	Jun	2Q	Jul	Aug	Sep	3Q	Oct	Nov	Dec	4Q	YTD	Goal	Closed	Open
# Escapes	1	4	3	8	1	0	2	3	0	0	1	1	2	2	0	4	16	0	8	1
# Concerns	4	20	6	30	8	4	4	16	8	5	3	16	11	6	4	21	83	n/a	32	29
# Severe Events	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	3	3	0	0	0

- Escapes **36%** improvement from PY
- TD Severe Events **40%** improvement from PY

NCRs

	Jan	Feb	Mar	1Q	Apr	May	Jun	2Q	Jul	Aug	Sep	3Q	Oct	Nov	Dec	4Q	YTD	Goal
# TOTAL	185	225	232	642	163	225	298	686	188	117	210	515	177	205	209	591	2,434	2,540
# Closed	179	219	222	620	145	195	255	595	165	89	163	417	145	142		287	1,919	95%
# Open	6	6	10	22	18	30	43	91	23	28	47	98	32	63	209	304	515	5%
Ageing	*Jan*	*Feb*	*Mar*	*1Q*	*Apr*	*May*	*Jun*	*2Q*	*Jul*	*Aug*	*Sep*	*3Q*	*Oct*	*Nov*	*Dec*	*4Q*	*YTD*	
< 1 week	*2*	*2*	*2*	*6*	*13*	*19*	*11*	*43*	*8*	*7*	*17*	*32*	*13*	*27*	*22*	*62*	*143*	
1-4 weeks	*2*	*2*	*4*	*8*	*2*	*5*	*12*	*19*	*9*	*3*	*17*	*29*	*14*	*20*	*61*	*95*	*151*	
1-3 months	*2*	*2*	*2*	*6*	*2*	*5*	*12*	*19*	*3*	*10*	*18*	*31*	*7*	*8*	*1*	*16*	*72*	
3-6 months	*0*	*0*	*2*	*2*	*1*	*11*	*11*	*23*	*3*	*9*	*4*	*16*	*3*	*1*	*0*	*4*	*45*	

- Systemic issues identified & addressed
- **NCR number decrease as volume increases**

First Pass Yield (FPY)

	Jan	Feb	Mar	1Q	Apr	May	Jun	2Q	Jul	Aug	Sep	3Q	Oct	Nov	Dec	4Q	YTD	Goal
# Tested 1st time	10	15	13	38	12	13	18	43	12	17	26	55	8	22	26	56	192	n/a
# Rejects	2	2	2	6	3	1	0	4	1	1	1	3	0	2	0	2	15	n/a
FPY%	80%	87%	85%	*84%*	75%	92%	100%	*91%*	92%	94%	96%	*95%*	100%	91%	100%	*96%*	*92%*	**92%**

- FPY Baseline at start of year 87%
- Target for YE 92%
- **5%** improvement from PY

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Spare Parts Forecasting – improvement journey

✓ STEP 1 (Apr '20)	✓ STEP 2 (Sep '20)	✓ STEP 3 (Dec '20)
1. PARTS CLASSIFICATION	**2. STATISTICAL MODEL TUNING**	**3. EVENT BASED MODEL**
• **Classified** 11.000 Active parts by: **$ Value** (**ABC model**) based on demand quantity and cost **Demand Frequency & stability** (**XYZ model**) based on historical consumption pattern in term of stability and frequency	• **Statistical techniques fine tuning** in Demantra Oracle System based on historical patterns (stability and frequency). • **Safety Stock policy optimization** to balance between inventory investment and stock availability to support operations	• Defined **Transfer Function:** JV shop visits -> parts forecast **Scheduled/Unplanned shop visit (JV shops)** X **BoM quantities** X **Scrap Rates** X **Service Bulletin**
Foundations for setting up forecast and safety stock policy	**Increased forecast accuracy + SS optimization**	**Increased forecast accuracy + Inventory optimization (over/under)**

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Spare Parts Delivery

Integrated Aero Alliance & GE Aviation overhaul needs process

- Daily prioritization management … connectivity from overhaul induction ESN needs to part shipment tracking
- Executing inputs from Event Based Model Forecasting with Aligned S&OP processes

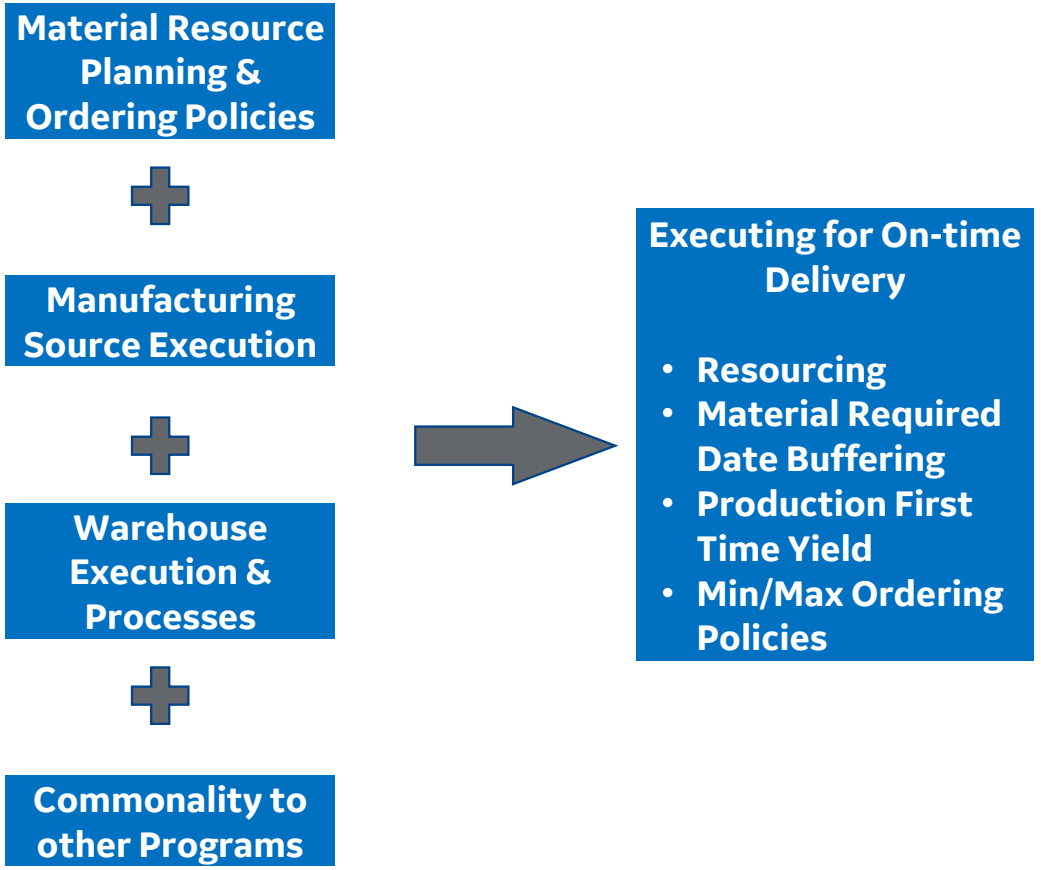
Daily operating rhythms

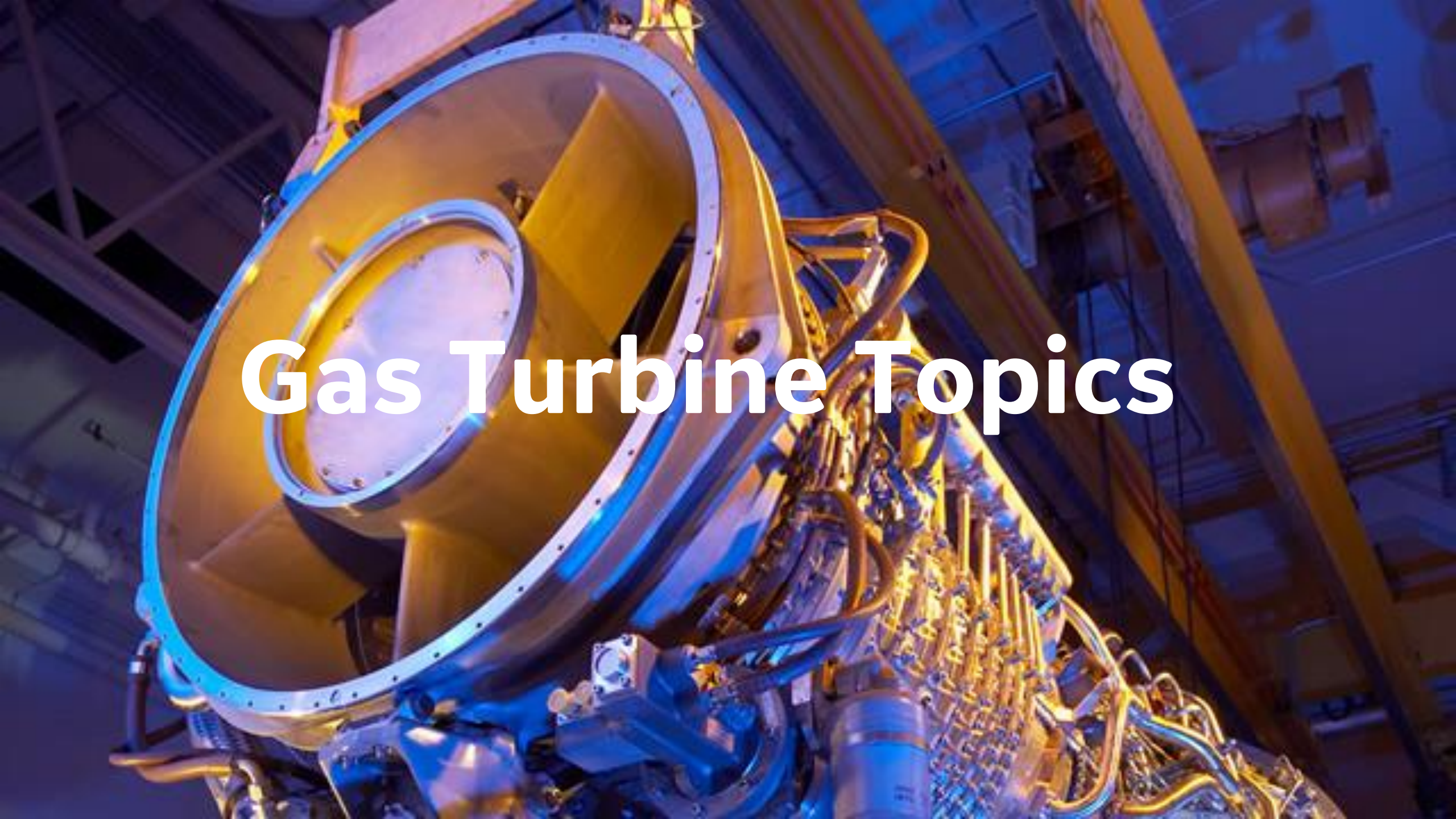
- Senior Executive engagement
- Dedicated Integrated Product Team (IPT) with Product Line, Engineering, Supply Chain, Material Scheduling, Quality, and Assembly

Progress Since Q3 2020

- Maintained production throughout COVID-19 challenges
- >40% reduction in spare part delinquencies and part numbers

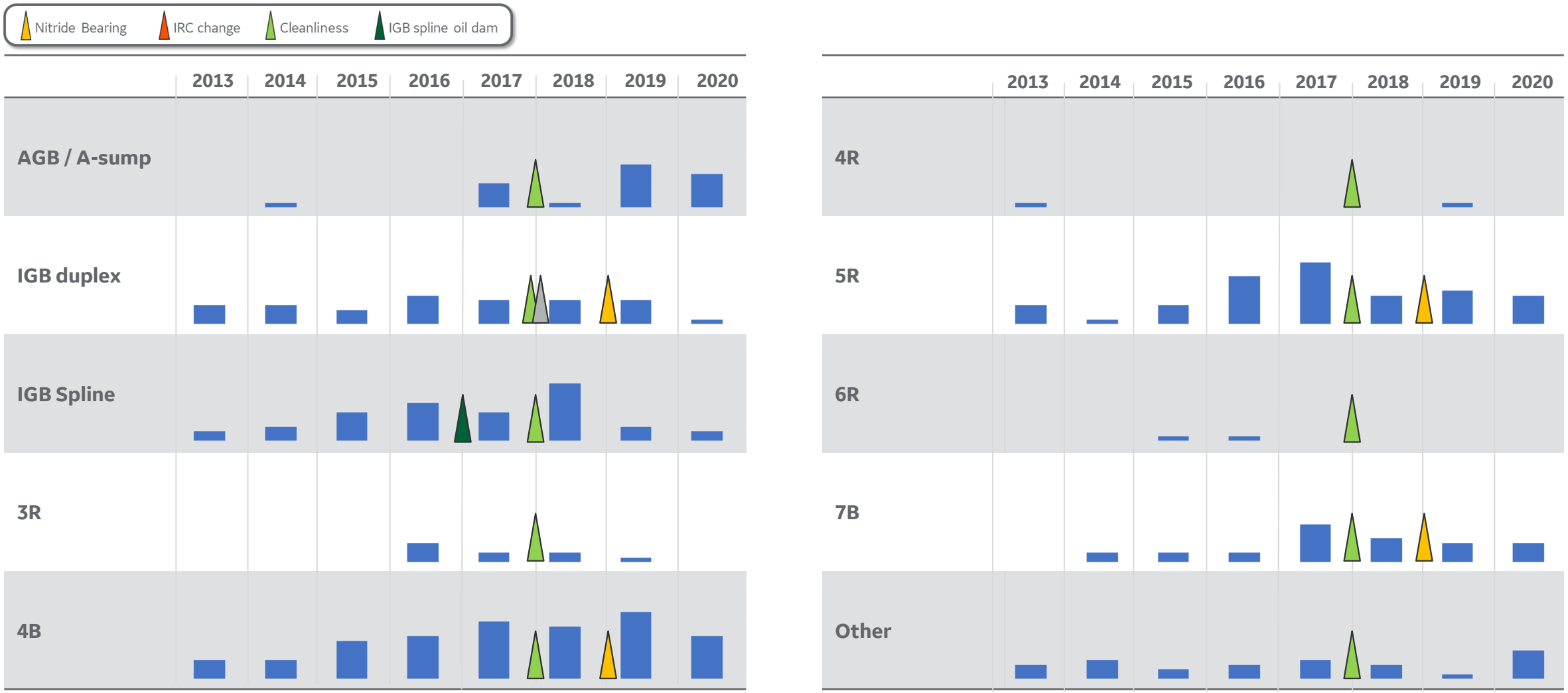
LEAN Toolbox – Problem Solving Report process





Gas Turbine Topics

Trends in LM2500 UERs … Bearing Focus (Complete 2020 data)

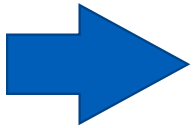


Nitride Bearing Field Experience

There are approximately 200 engines with nitride bearings … GE is aware of three bearing events involving nitride bearings:

1. **LM2500 Base DLE LSPT 5R bearing**
   - Event occurred 5758 hours after bearing replacement
   - F/A report noted that all rollers were locked relative to outer race for a period of time
   - Manufacturing defect is not suspected

2. **LM2500+G4 SAC HSPT 4B bearing**
   - Event occurred 308 hours after bearing replacement
   - F/A report noted assembly damage as root cause; bearing installed in Houston depot



4B bearing assembly procedure updated

3. **LM2500+G4 DLE LSPT 7B bearing / D-sump chips**
   - Event occurred 2682 hours after bearing replacement
   - 7B bearing damaged; root cause is unknown (bearing is in lab for F/A report)

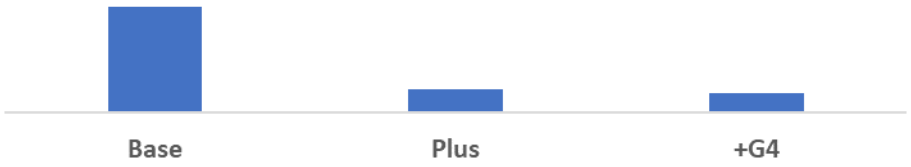
5R Bearing Experience

Background

- GE removed the Al2O3 coating on the aft shaft inner labyrinth seal in 1998 due to concerns of hard particle entrainment into the C-sump .
- The IRM manuals for the Plus and +G4 engines included this change.
- The IRM update for the Base engine was missed and updated in May 2019.

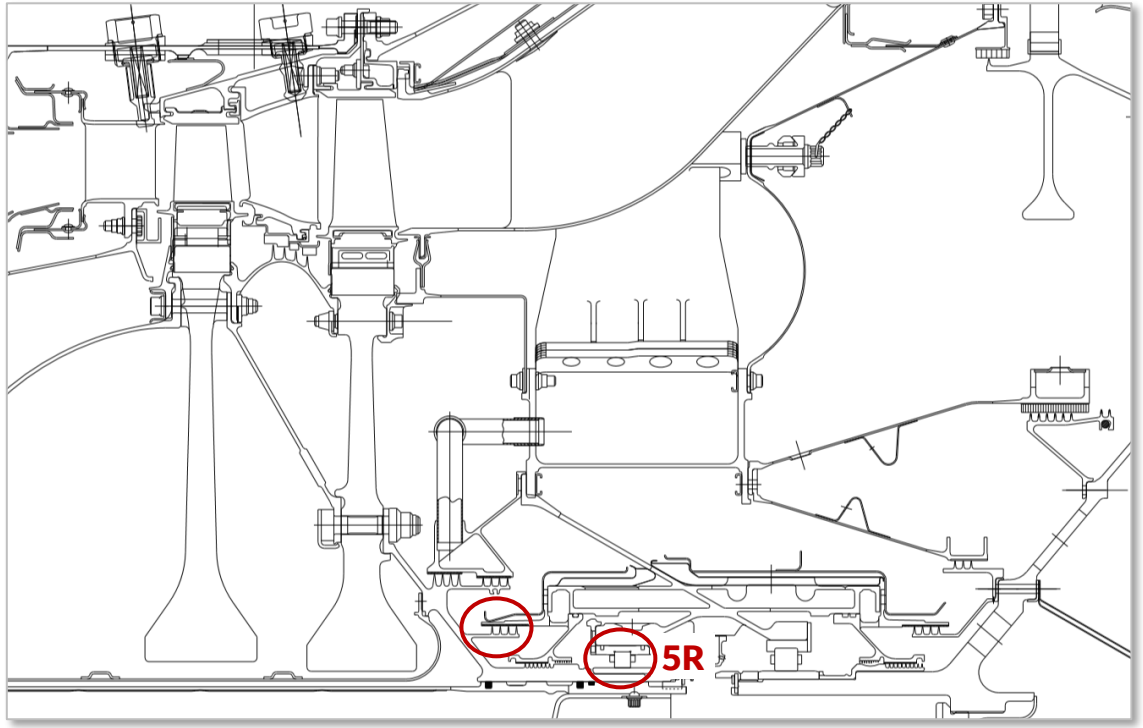
Field Experience

- Since 2016, there have been more 5R bearings events in Base engines than for Plus and +G4 engines:



- The discrepancy between Base engine new-make vs. repaired parts confounds correlation with the seal condition.
- Fleet experience, including repetitive events on specific engines, points to Al2O3 from the coating as a possible contributing factor along with other potential sources.

Location of 5R bearing



Break-out of 5R bearing event by cause

Model	Hard Particle	Corrosion	Assembly / Other	Inconclusive / No Data
Base	36%	6%	3%	55%
Plus	29%	43%	0%	29%
+G4	50%	0%	0%	50%

LM2500+/G4 High Pressure Recoup / Rotor Thrust

Background

- Rotor thrust algorithms have been investigated as part of recent 4B bearing events.
- GE has completed three instrumented engine tests since 2018.
- The G4 algorithm shows very good agreement with instrumented test data acquired at EIS (2007) and most recently in 2018.
- Compared to the algorithm, recent LM2500+ test data indicates a flatter load vs. speed relationship.
- There has been one confirmed 4B bearing skidding event in the LM2500+ fleet; engine was operating at low load for extended time.

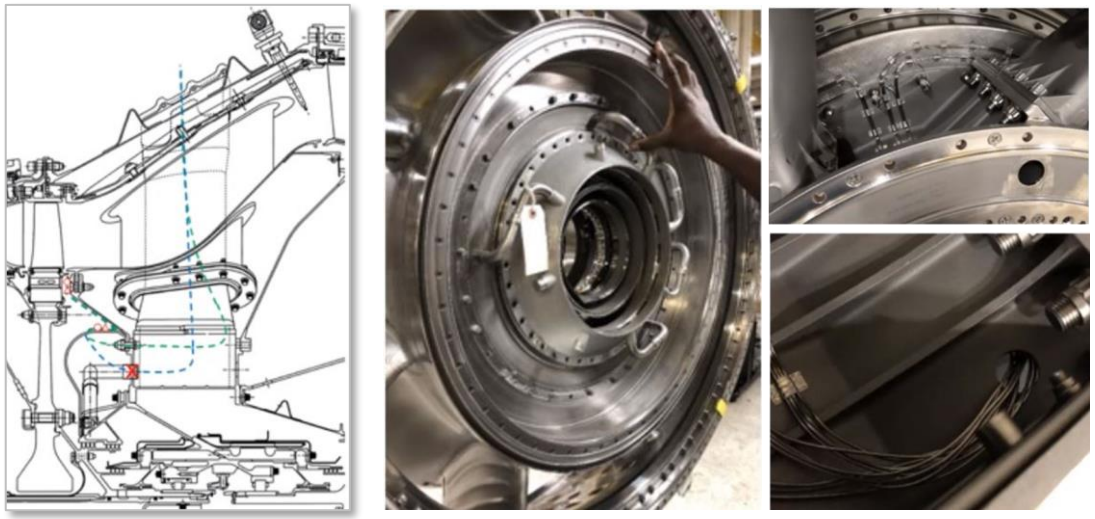
Next Steps for Plus Investigation

- There is good agreement between cavity pressures & measured thrust.
- LM2500+ design changes made since 1998 are being investigated to better understand the data.
- The LM2500+ algorithm may be updated in 2021; no changes will be made for the G4 algorithm.

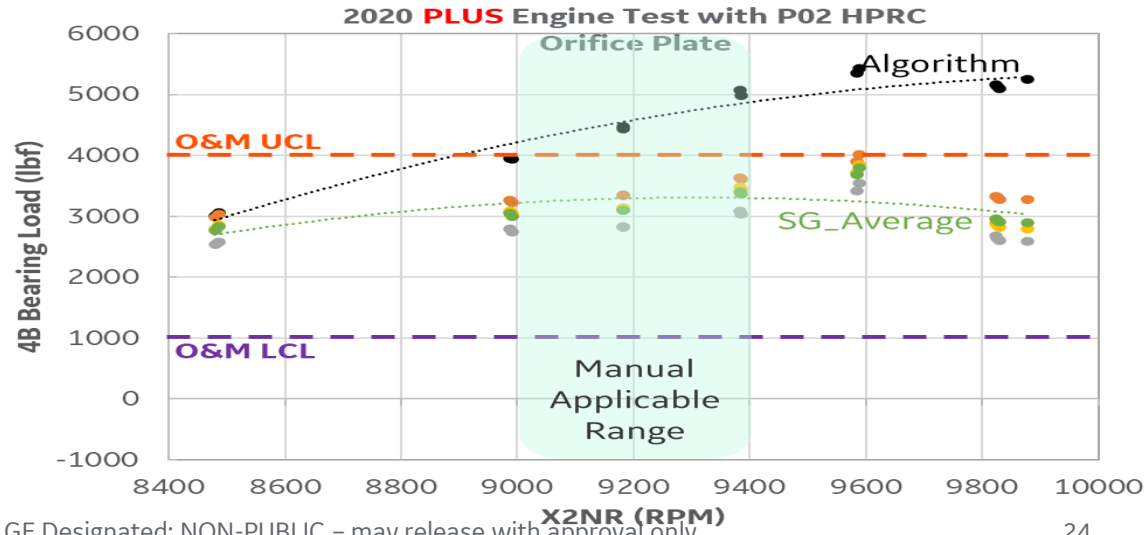
Field Recommendations

- Continue to follow manual recommendations for HPRC orifice sizing.
- Contact Baker Hughes or GE Power for additional guidance as needed.

Location of Bearing Housing and Forward/Aft Cavity Instrumentation



LM2500+ algorithm and measured thrust



SAC Dual Fuel Gas Circuit Backflow

Base Plus +G4
SAC DLE

Background

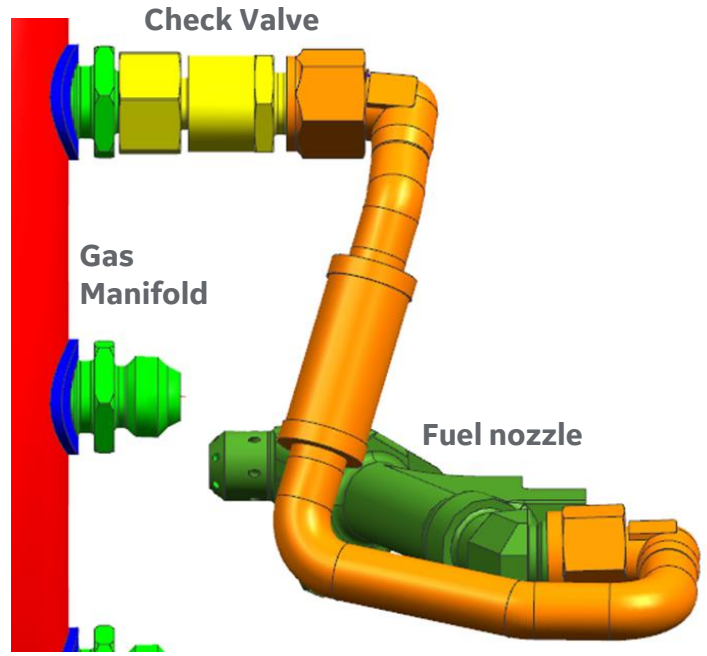
- Partially-burned hydrocarbons can contaminate the gas fuel circuit during liquid fuel operation, causing subsequent T48 spread issues during gas fuel operation.

Investigation Status

- Back flow occurs due to nozzle-to-nozzle pressure variation and/or loose B-nut fittings.
- Fuel quality is an important variable.

Enhancements

1. Check valves
   - A field service evaluation showed check valves mitigated but did not eliminate gas circuit fouling.
   - After hundreds of hours of liquid operation, a high T48 spread occurred after switching to gas fuel operation.
   - Check valves eliminated cross talk between nozzles as the gas manifold was free of coke deposits.
   - The fuel tubes exhibited a light varnish; 5 of 30 fuel nozzles were obstructed.
2. CDP forward purge of gas fuel circuit while operating on liquid fuel.



Hydrocarbon deposits in the gas circuit

SAC Dual Fuel Gas Circuit Backflow … Status Update

Check valves are available for field service evaluation

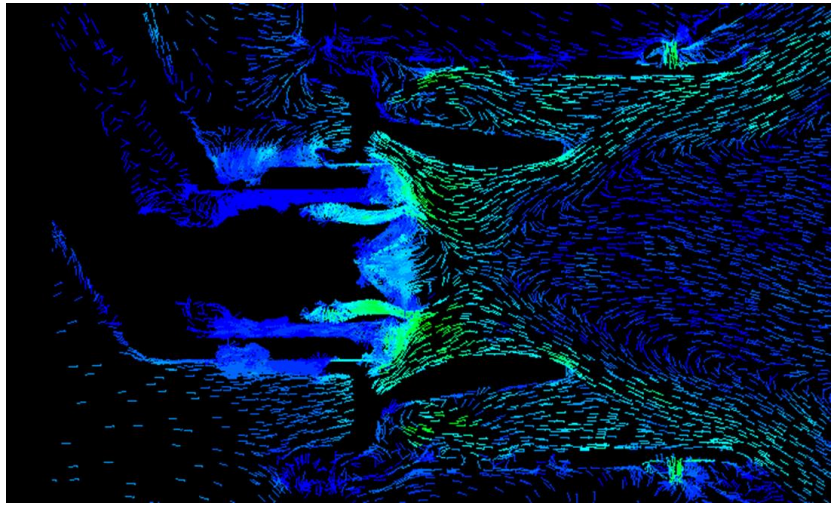
CDP Forward Purge (Actions and Timing)

- Flow network simulation and CFD modeling are being used to better understand purge flow requirements across all operating conditions … expected completion is March 2021.
- IDM update with robust gas purge pressure requirements … April 2021.
- BH and GE Power are working package modifications for positive purge of gas circuit … implementation dates are TBD.

Field Recommendations

- Ensure fuel fittings/connections are properly tightened.
- Ensure liquid fuel meets specification.
- Consider using check valves to improve gas circuit cleanliness.
- Work with your packager to incorporate a forward purge system.

Flow field inside and in the vicinity of the gas circuit injection orifices



LM2500+ and +G4 HPC Stage 0 Blisk

Background

- Blisks operating in saltwater environments can develop corrosion pitting on the airfoils and shaft interior.

Repair Development

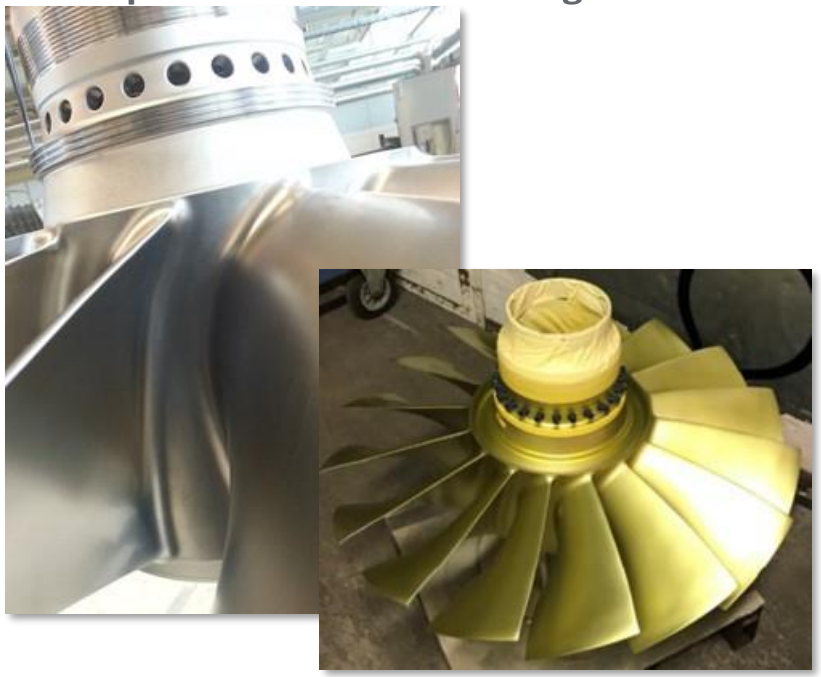
- A blend repair procedure is being developed for flow path pitting.
- Different blend geometries will be used for various pitting locations.
- Reduction in cyclic life limit is expected post-repair.
- Target repair availability by end of 2020.

Next Steps for 2021

- Sermetel coating application available for all blisks exhibiting corrosion pitting.
- Evaluate expansion of repairable regions

Flow path corrosion pitting

Post Repair with Sermetel Coating



HPC Blisk Repair for Corrosion Pitting

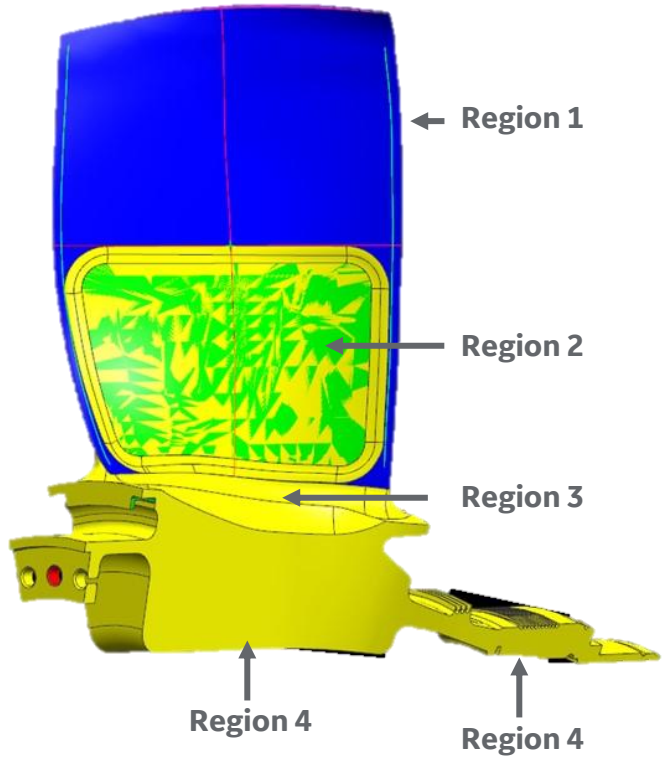
Manual Blend Repair Development for Flow Path Surfaces

- *Region 1: Upper 50% of airfoil*
  - This region generates and delivers the shock wave of the transonic airfoil tip.
  - Repair limited to local blending no deeper than 0.006 mils.
  - Repairs approved via departure record (Aviation repair engineering approval).
- *Regions 2 and 3: Lower 50% span of airfoil, fillet radius, and platform*
  - Generalized repair document in development to allow blend repairs to 0.020 mils in depth.
  - Includes L/E and T/E blend regions in already-issued Repair Document.
  - No departure record required.
- *Region 4: Bore and Shaft ID*
  - No blending allowed.

Blend Repair Document is planned to issue 2Q21

- Life assessments for blend-repaired blisks have been completed … declared life to for repaired blisks has been reduced to 4,000 cycles since new.
- Blending will require P/N change and O&M manual updates.

Areas where repairs are allowed / not allowed



Blisk Part Numbers

Model	Uncoated Blisk	Coated Blisk at New-Make	Coated Blisk at Overhaul	Blend-Repaired and Coated Blisks
LM2500+	K070P02	K070P03	K770P01	K682P01
LM2500+G4	K690P01	K690P02	K790P01	K686P01

Base Plus +G4
SAC DLE

LM2500+G4 SAC Combustor Dome Distress

Background

- Some G4 SAC engines have experienced combustor dome plate cracking/oxidation.

Investigation Status

- Early removals (~10k hours) have been attributed to poor fuel quality.
- Other removals have occurred after 25k hours of operation, but with more hardware distress relative to LM2500+ experience.

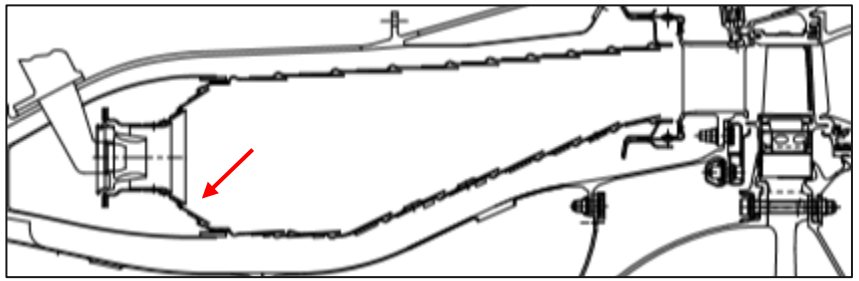
Enhancements

- An upgraded G92 combustor has been introduced to improve durability in NOx water applications.
- The improvement has been substantiated by analysis and field service evaluation.
- The G92 design is also expected to improve durability in dry applications.

Field Recommendations

- Ensure that gaseous and liquid fuels meet specification to prevent early distress.
- If needed, the G92 combustor is available beginning 1Q21.

Combustor cross-section

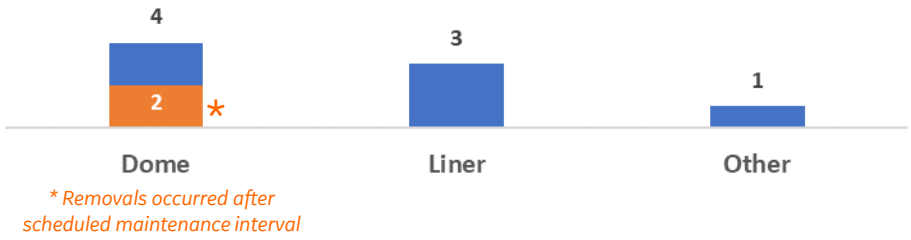


Combustor cross-section

SAC Dry Combustor Fleet Experience

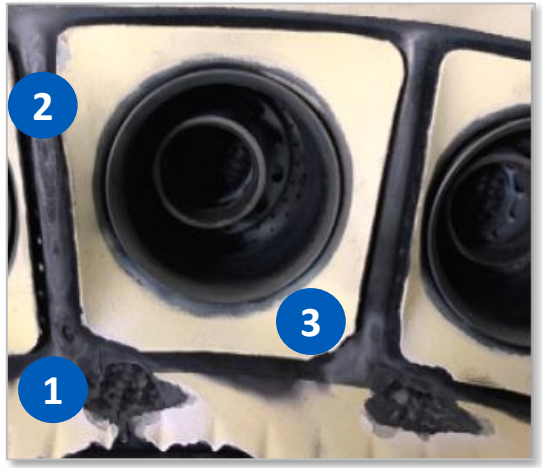
Fleet Experience

- There are approximately 1,100 LM2500 SAC-dry engines in service; maintenance interval dependent on fuel type
- Since 2013, there have been relatively few unplanned engine removals:



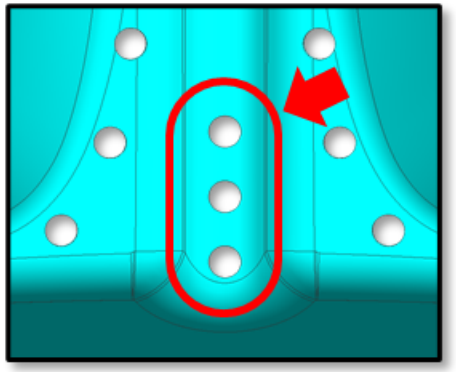
Distress Modes

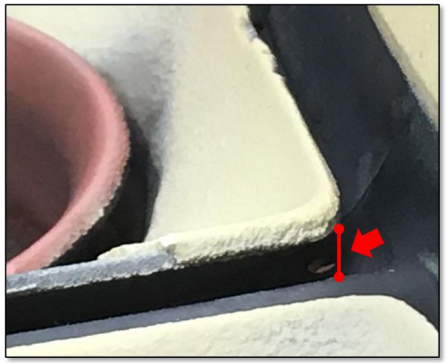
1. Oxidation at dome inner band location … life limiting area
2. Oxidation at dome plate rib location between cups … high-time issue
3. Missing material at splash plate corners



Common Combustor

- Updated versions of SAC combustors are being introduced for both wet and dry operation
- Enhancements include additional dome and splash plate cooling and improved splash plate gap control
- A field service evaluation is ongoing at an LNG site with positive results





DLE Dual Fuel B2-Ring Gas Fuel Hose Rupture

Background

- A B2 gas hose rupture noted after transition to gas operation after extended liquid operation.
- Gas hose rupture led to gaseous fuel leakage in package.

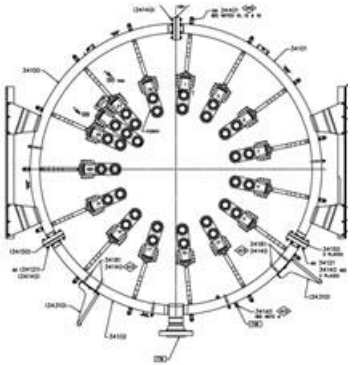
Investigation status – Two Causes Identified

1. During liquid operation, water can accumulate in gas manifolds in moist environments.
   - During switch to gas fuel, rapid evaporation of water can over-pressurize gas hose.
   - Source of water is combustion air that circulates in the gas fuel system due to premixer cross-talk.
2. Heavy hydrocarbon condensation in gas hose and subsequent autoignition with combustor air.

Enhancements

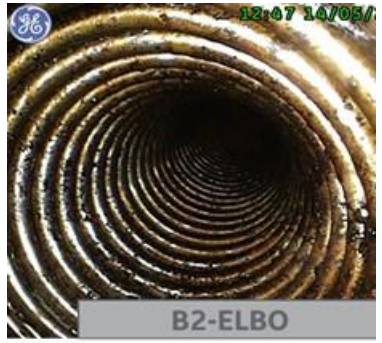
- Check valves prevent premixer-to-premixer cross-talk and eliminate the water source.
- Check valves via SB301 in April 2019.

B2-Ring Manifold



Presence of Water

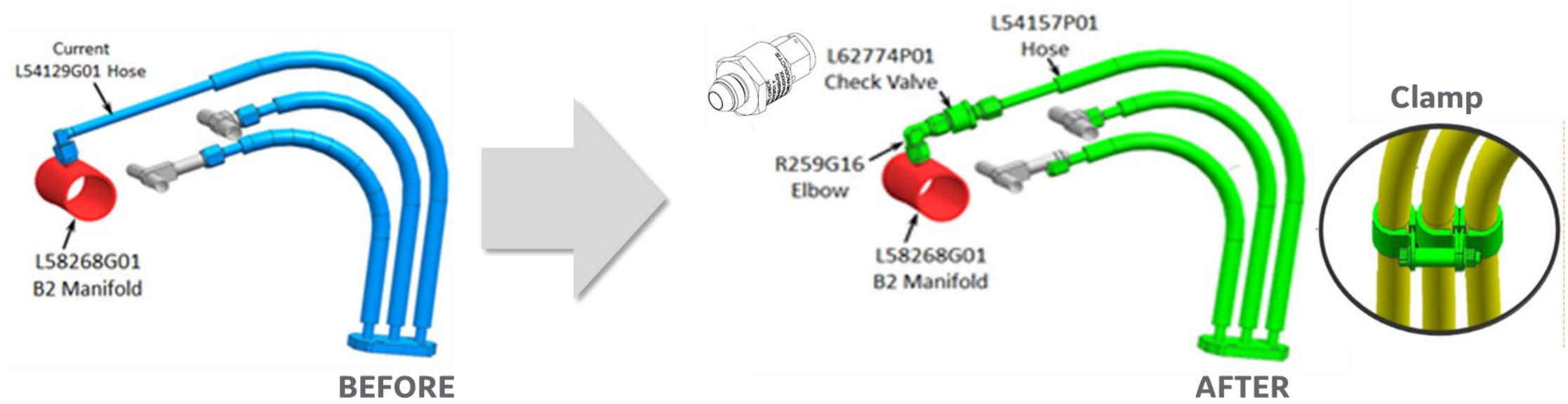
Fuel Contamination



Ruptured hoses

DLE Check Valve Experience … Status Update

Check valve location



Status Update

- The check valves have been installed in new G4 production engines since October 2018.
- SB301 compliance is 4/20 engines
- There have been no reports of DLE gas circuit distress after installation of check valves.
- GE is not aware of any other systemic issues with DLE gas manifolds