



N146DU Accident Investigation Findings & Analyses

(SafranHE ref. RA 2017/238)

22 Sept. 2020



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□ Abbreviations :

AEO	All Engine Operative	NPT	Power Turbine speed
AHD	Airbus Helicopters Deutschland	OEI	One Engine Inoperative
DPI	Die Penetrant Inspection	PT	Power Turbine
EDS	Energy Dispersive Spectroscopy	RH	Right Hand
EPC	Engine Power Check	SafranHE	Safran Helicopter Engines
FCU	Fuel Control Unit	SB	Service Bulletin
FOD	Foreign Object Damage	SEM	Scanning Electron Microscope
GG	Gas Generator	SL	Service Letter
HOGES	Hover Out of Ground Effect	SOA	Spectrometric Oil Analysis
HP	High Pressure	T45	Turbine temperature (HP turbine outlet)
HPT	High Pressure Turbine	TSN	Time Since New
IFSD	In Flight Shut Down	TU	Name given to modifications to SafranHE equipment (followed by the modification number)
LH	Left Hand	VARTOMS	Variable Rotorspeed and Torque Matching System
LP	Low Pressure		
N/A	Not Applicable		
NG	Gas Generator speed		
NGV	Nozzle Guide Vane		

Background

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☐ Event details :

Date of event : 8 Sept. 2017

Location : North Carolina, USA

Operation : EMS

Aircraft : EC145 s/n 9474, registration N146DU

Engines : Arriel 1E2 s/n 47292 (LH) and 47346 (RH), TSN 2711hrs

☐ Circumstances initially reported to SafranHE :

The aircraft crashed in a field for an unknown reason.

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Additional circumstances [extract from NTSB's preliminary information report] :

Preliminary data transmitted from the helicopter showed that it departed NC98 to the northwest, climbed to about 1,000 ft mean sea level (msl) and then turned west. The helicopter climbed to about 2,500 ft msl and continued on a westerly track at a groundspeed of about 120 knots. About 8 minutes after takeoff, the helicopter began a turn toward the south. About 1 minute later, the transmitted data ended at an altitude of about 1,200 ft msl and a groundspeed of 75 knots, while the helicopter was on a southeasterly track.

Several witnesses reported observing smoke trailing behind the helicopter while it was in flight. The smoke was described by some witnesses as "heavy" or "dark", while others reported the color as "black", "dark blue" or "blue." One witness reported that the helicopter was "hovering" and "not travelling forward" while it was a "couple of hundred feet" above the wind turbine farm. Another witness reported hearing a "popping noise," he then observed the helicopter turn left, then right. It then descended quickly and appeared "in control" with the rotors turning before he lost sight of it.

The helicopter impacted a shallow turf drainage pathway, about 30 ft wide and 2,000 ft long, located between two fields of 8 ft tall grass, on a wind turbine farm. The fuselage came to rest in a 7 ft wide ditch in the center of the pathway, and was oriented on a heading of 261° magnetic. No ground scars were present leading toward or away from the main wreckage.

Examination of the wreckage revealed that all the major components of the helicopter were present at the accident site. The cabin had collapsed downward and was partially consumed by a postcrash fire. The tailboom remained largely intact. Flight control continuity was established from the cockpit area to the rotor systems and engines. All main and tail rotor blades remained attached to the rotor hubs. The No. 4 (red) main rotor blade was found rotated about 180° in the hub with its pitch links fractured and partially melted. None of the main or tail rotor blades exhibited leading edge damage, chordwise scratches, or other evidence of rotation. The outboard 4 ft of No. 1 (yellow) blade came to rest in the 8 ft tall grass adjacent to the drainage path. The grass on either side of the blade was undisturbed. The tail rotor shaft remained attached to the transmission. The transmission could not be rotated by hand.

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☐ **Additional circumstances** [extract from NTSB's preliminary information report] :

No foreign object damage was found on the axial compressor blades of either engine. No damage was observed on the visible portions of the turbine blades at the rear of either engine. The gas generator of the No. 1 engine moved freely when rotated by hand, the No. 2 engine gas generator would not rotate. The No. 1 engine fuel shutoff valve was found in the open position. The No. 2 engine fuel shutoff valve was damaged and its position could not be determined during the field examination. The No. 2 engine rear turbine shaft bearing exhibited discoloration consistent with overheating and lack of lubrication. The bearing roller pins were worn down to the surface of the bearing race. The end of the turbine shaft aft of the nut exhibited rotational nonuniform damage.



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□ NTSB examinations :

- Shut-off valves [\[from NTSB's e-mail dated 27 Feb. 2018\]](#) :
Shut-off valves found in the wreckage were X-rayed by NTSB : both were in the open position
- Fire extinguisher bottles [\[extracts from NTSB's lab e-mail dated 27 Dec. 2017\]](#) :
Examination by NTSB : “whether the bottles operated based on the overpressure valve condition is inconclusive.” “There was considerable fire damage in the interior of the valves” “those findings are also inconclusive.”
- 3-way unions [\[extracts from NTSB's e-mail dated 8 Feb. 2018\]](#) :
Examination by NTSB : “no evidence of coking material has been identified in either of the deck fittings or line remnants.” “the burned black material that remains inside the #1 deck fitting preliminarily looks similar to shrink tubing.”
Further examinations are under way.

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☐ **Engines' manufacture :**

LH engine s/n 47292 : 1st Dec. 2010 (EASA Form 1)

RH engine s/n 47346 : 8 Dec. 2010 (EASA Form 1)

☐ **Installation on aircraft :**

Both engines installed at TSN = 0 hrs on N146DU (s/n 9474) on 17 June 2011

☐ **Maintenance history :**

See following pages

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Date	Eng1 s/n 47292 (hrs)	Eng2 s/n 47346 (hrs)	Time to accident (hrs)	Periodic check	Actions	Other reports of interest
1-Nov-16	2211	2211	501	Zone 8	50hr EPC check Leak test of deceleration control unit Check of FCU characteristics	
23-Nov-16	2255	2255	457	30hr Zone 9	Check MO1 & MO5 magnetic plugs 50hr EPC check Boroscope inspection HPT1 blades Permeability check fuel injection manifold Oil check SOAP	
16-Dec-16	2295	2295	417	30hr	Check MO1 & MO5 magnetic plugs 50hr EPC check	
19-Dec-16	2300	2300	412	Zone 10	Test of overspeed monitoring syst. Free Turbine	Eng1 overspeed drain valve is leaking. Item replaced (iaw 73-16-20-900-801-A01).
9-Jan-17	2338	2338	374	30hr	Check MO1 & MO5 magnetic plugs 50hr EPC check	Eng1 overspeed drain valve is leaking. Item replaced (iaw 73-16-20-900-801-A01).
12-Jan-17	2341	2341	371	300hr/12month Zone 11	Check elect. mag plugs Test PT OVSP monitoring syst. Drain & replace oil Oil check SOAP Inspect and clean electrical magnetic plugs (general return and rear bearing)	Eng2 start drain valve is leaking. Item replaced (iaw 73-16-11-900-801-A01).
27-Jan-17	2357	2357	355	30hr	Check MO1 & MO5 magnetic plugs	
3-Feb-17	2368	2368	344			1200hr checks escalated till 2499 EFH
9-Feb-17	2379	2379	333	30hr Zone 12	Check MO1 & MO5 magnetic plugs Check oil filter 50hr EPC check	
14-Feb-17	2391	2391	321		Oil servicing (Mobil Jet II)	
17-Feb-17	2394	2394	318	2400hr	Inspect engine mounts (D3114)	Remove engines
March-17	2406	2406	306	30hr 1200hr 2400hr Zone 1	Check MO1 & MO5 magnetic plugs Clean oil return tube Check 3 struts for oil tubes Inspect engine mounts (D3114) 50hr EPC check Oil check SOAP Check position of HPT2 blades (SB 292 72 264) Vibration check after engine installation Compr wash (B/B3100) Clean engine operation in all atmosphere	Remove engines Eng1 oil cooler seal leaking. Replaced. Eng1 oil return line and clamp torn. Replaced clamp. Oil temperature warning switch worn. Replaced.
11-Apr-17	2423	2423	289		Oil servicing (Mobil Jet II)	Serviced engine oil to level with 1/2 qty.
13-Apr-17	2427	2427	285	30hr	Check MO1 & MO5 magnetic plugs	

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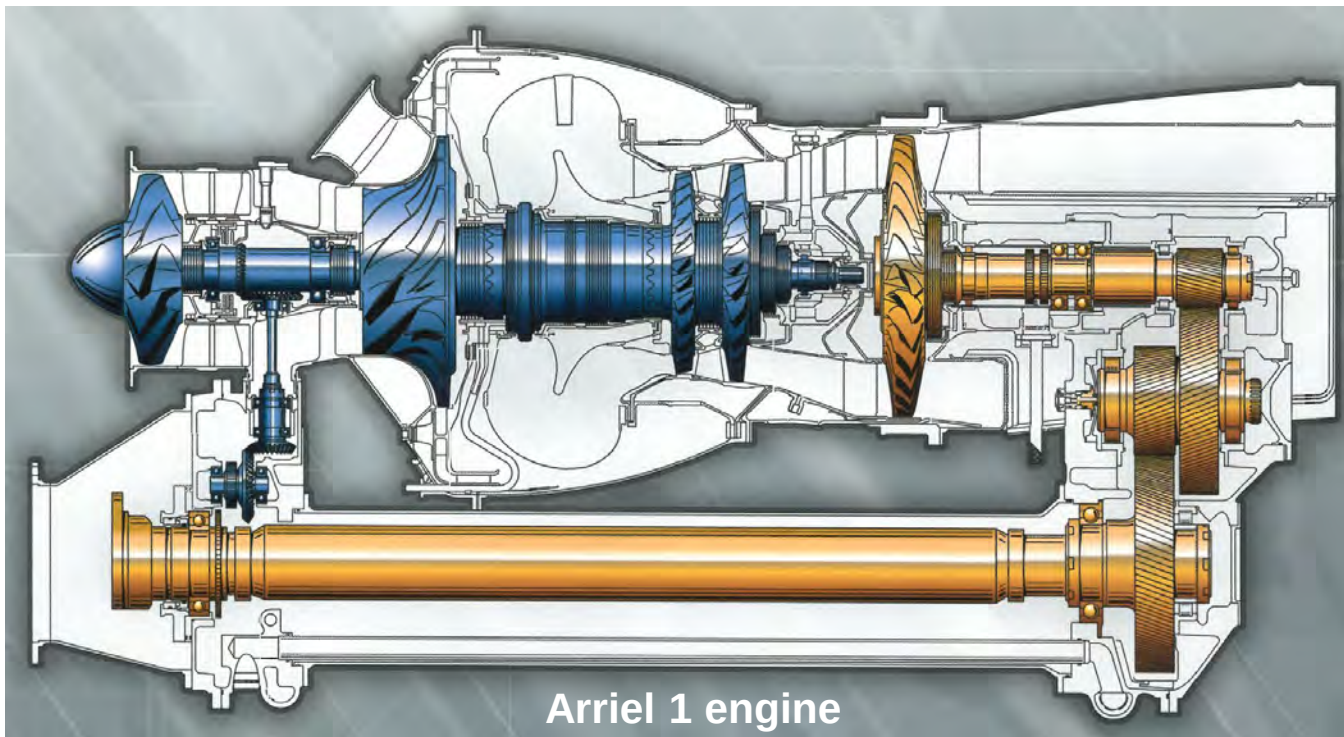
Date	Eng1 s/n 47292 (hrs)	Eng2 s/n 47346 (hrs)	Time to accident (hrs)	Periodic check	Actions	Other reports of interest
19-Apr-17	2444	2444	268	Zone 2	Compr wash (ZOK27) Clean engine operation in all atmosphere 50hr EPC check Leak test of deceleration control unit	
21-Apr-17	2451	2451	261	30hr	Check MO1 & MO5 magnetic plugs	
2-May-17	2472	2472	240	30hr	Check MO1 & MO5 magnetic plugs	
5-May-17	2480	2480	232	Zone 3	50hr EPC check Clean engine operation in all atmosphere	
9-May-17	2496	2496	216	30hr	Check MO1 & MO5 magnetic plugs	
10-May-17	2497	2497	215		Oil check SOAP	
19-May-17	2513	2513	199	30hr Zone 4	- Check MO1 & MO5 magnetic plugs - 50hr EPC check - Compr wash (ZOK27) - Clean engine operation in all atmosphere - replacement of life limited components that have completed published operating limits (eng s/n 47346) - overhaul of all components that completed published operating limit (eng s/n 47346) - Check for signs of corrosion - Compressor wash - Check front supports - Permeability test - Replace fuel filter - Check bleed valve thresholds - Check for leaks	Content of Zone 4 of eng s/n 47346 indicate : - replacement of life limited components that have completed published operating limits - overhaul of all components that completed published operating limits --> no details of components replaced or overhauled ?
22-May-17	2521	2521	191			Crew noticed burning smell. Checked A/C and electrical systems; no issues found.
2-Jun-17	2538	2538	174	30hr	Check MO1 & MO5 magnetic plugs	
13-Jun-17	2553	2553	159	Zone 5	50hr EPC check Compr wash (ZOK27) Clean engine operation in all atmosphere Check control and indicating harness Vibration check at engine rear part Inspect cables of overspeed sensor	Start of daily check of covered drain valve assembly SB A292 73 0853 rev.A for Eng1 (AD 2017-15-07)

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Date	Eng1 s/n 47292 (hrs)	Eng2 s/n 47346 (hrs)	Time to accident (hrs)	Periodic check	Actions	Other reports of interest
16-Jun-17	2559	2559	153	30hr	Check MO1 & MO5 magnetic plugs	
22-Jun-17	2568	2568	144			RPM surge from low to mid 90's to 103%. Torque spiked during take-off.
26-Jun-17	2571	2571	141			VARTOMS pitch compensation adjusted.
30-Jun-17	2584	2584	128	30hr	Check MO1 & MO5 magnetic plugs	VARTOMS out of adjustment. Adjusted.
3-Jul-17	2588	2588	124		Oil check SOAP	
10-Jul-17	2592	2592	120	300hr/12month Zone 6	Check oil filter Compr wash (ZOK27) Drain and replace engine oil (D1040) Clean engine operation in all atmosphere 50hr EPC check Inspect and clean electrical magnetic plugs (general return and rear bearing)	
13-Jul-17	2607	2607	105	30hr	Check MO1 & MO5 magnetic plugs	
20-Jul-17	2624	2624	88		Oil servicing (Mobil Jet II)	Oil to level with 1/2 qty.
21-Jul-17	2625	2625	87	30hr	Check MO1 & MO5 magnetic plugs	
26-Jul-17	2635	2635	77	300hr/12month Zone 7	50hr EPC check Inspect and clean electrical magnetic plugs (general return and rear bearing) Drain and replace engine oil (D1040) Clean engine operation in all atmosphere Note : no tasks applicable to engines Zone 7	Pilot reported VARTOMS spikes. Checked.
4-Aug-17	2652	2652	60	30hr	Check MO1 & MO5 magnetic plugs	
8-Aug-17	2665	2665	45		Compr wash (ZOK27) Eng 1	
9-Aug-17	2666	2666	46		Oil check SOAP	
15-Aug-17	2674	2674	38	30hr Zone 8	Check MO1 & MO5 magnetic plugs Leak test of deceleration control unit Check FCU characteristics 50hr EPC check Clean engine operation in all atmosphere	
25-Aug-17	2696	2696	16	30hr	Check MO1 & MO5 magnetic plugs	
31-Aug-17	2710	2710	2	Zone 9	Boroscope HPT1 blades Permeability fuel injection manifold 50hr EPC check Compr wash (ZOK27) Clean engine operation in all atmosphere	
6-Sep-17	2711	2711	1		Compr wash (ZOK27)	

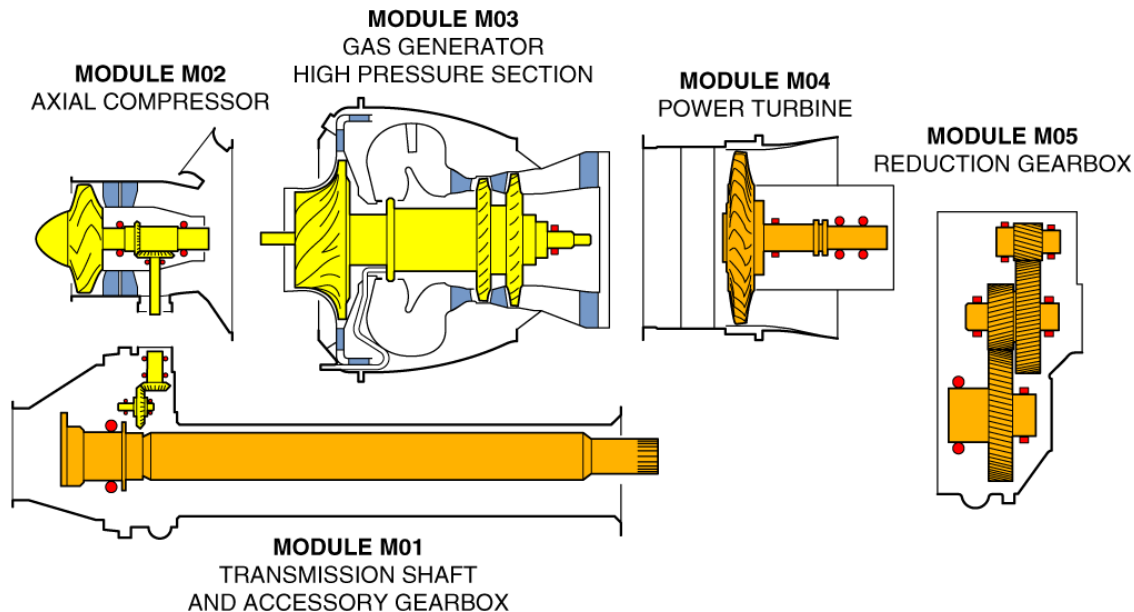
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□ Schematics :



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□ Schematics :



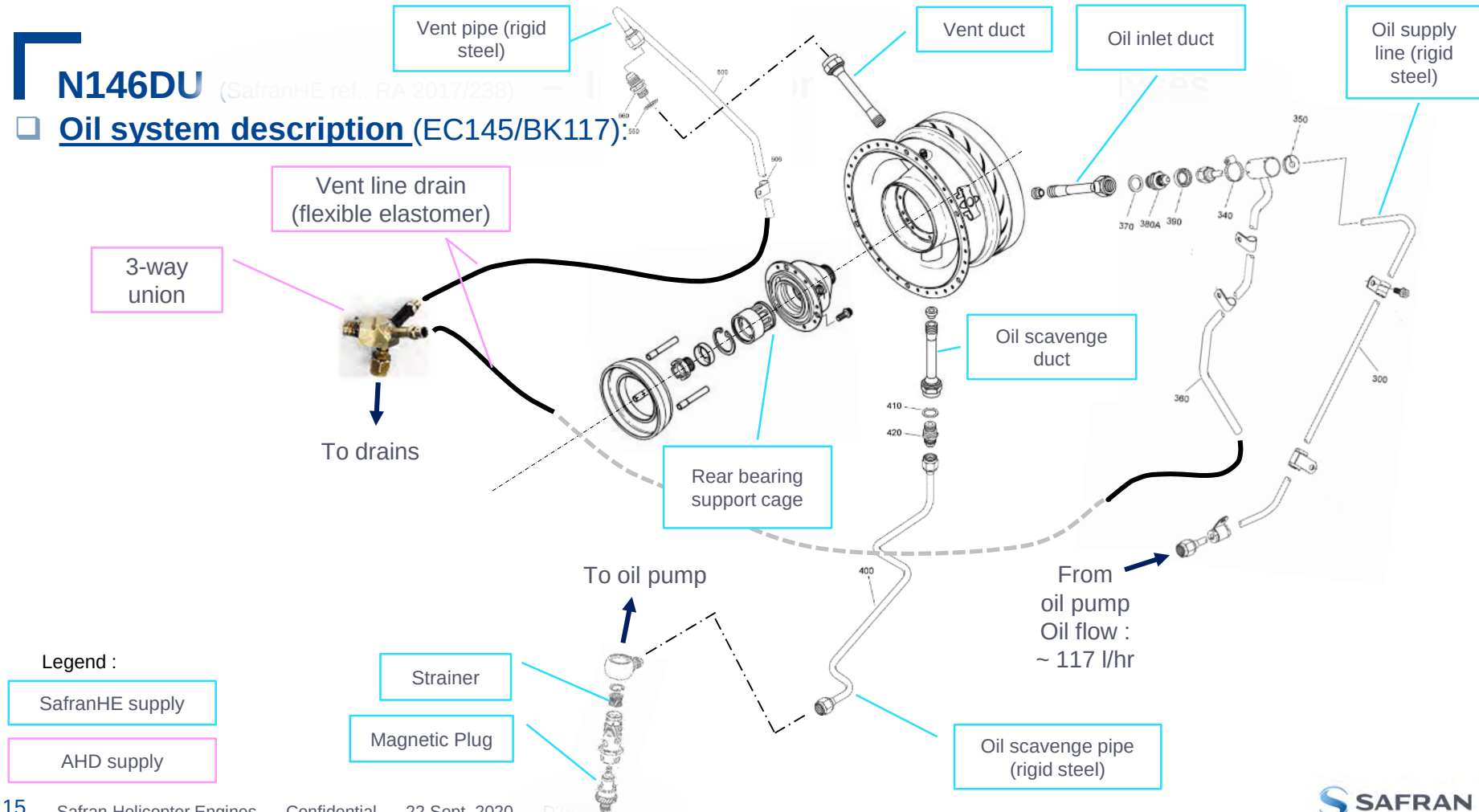
Arriel 1 : Modular Composition



N146DU

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Oil system description (EC145/BK117):



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Examinations

Engine 1 (LH) s/n 47292

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□ Examination main findings (status after engine tear-down in Dallas, Nov. 2017) :

- No FOD damage to compressor
- Fuel control lever on FCU was in closed position, consistent with twist grip in stop position
- Gas Generator could be rotated manually
- Engine tear-down : nothing remarkable found
- Coke was present in the rear bearing housing. Bearing was in good condition, rotated smoothly.
- 3-way union (deck fitting, AHD supply) of vent line found clogged.
- Rear bearing's scavenge line was clear (nominal condition).



- Findings were consistent with the engine 1 being at stand-still at the time of impact
- Reason for fuel control in stop position (0°) not determined

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☐ List of possible origins for twist grip in stop position (as discussed in Dallas on 14th Nov. 2017)

- Non intentional
 - Pilot went past idle to stop
 - Pilot selected wrong engine
- Intentional
 - Low Fuel P
 - Flame-out / Engine Fail warning
 - Overspeed activation (real or spurious)
 - T4 overtemp
 - Low Oil P
 - Oil Temperature
 - Chip light
 - Engine fire
 - Vibrations

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□ List of possible origins for twist grip in stop position (as discussed in Dallas on 14th Nov. 2017)

- Non intentional

- o Pilot went past idle to stop
- o Pilot selected wrong engine

} Information not available at engine level

- Intentional

- o Low Fuel P
- o Flame-out / Engine Fail warning
- o Overspeed activation (real or spurious)
- o T4 overtemp
- o Low Oil P
- o Oil Temperature
- o Chip light
- o Engine fire
- o Vibrations

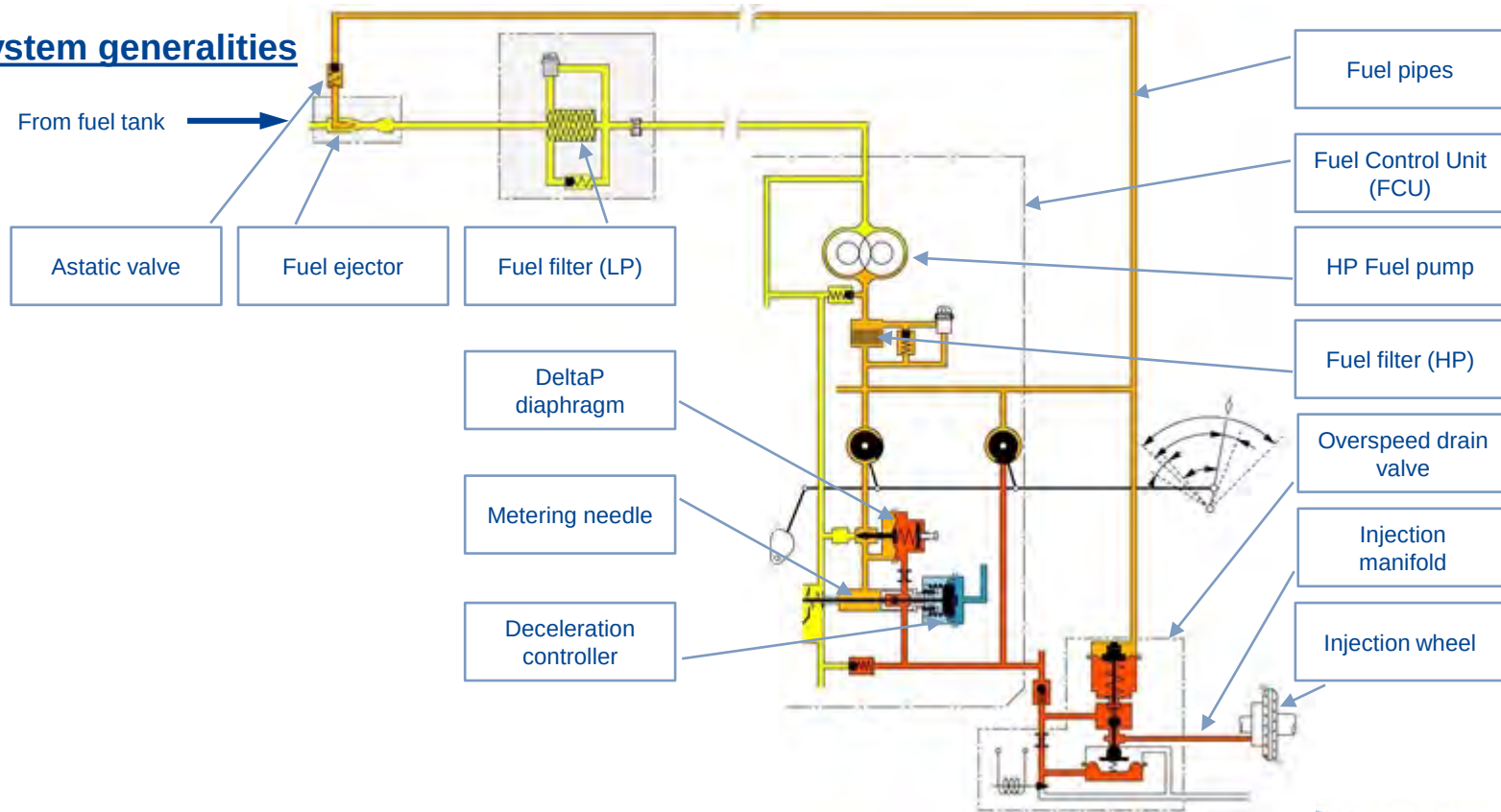
Examinations on engine systems :

- Fuel system
- Air intake*, compressor, Gas Generator, accessories gearbox, oil system, fuel system, FCU, fuel supply upstream of engine*, drain valve assembly
- Tacho-box, NPT overspeed sensor, ΔP diaphragm, loss of power drive train continuity*, pilot actions*
- FCU, HP Turbines
- Oil system
- Reduction gears
- Magnetic plug assemblies
- Shut-off valves*, fuel & oil pipes, oil system Gas Generator
- Engine spools, vibrations from outside engine*

Note * : Outside of SafranHE's scope. Information not available at engine level

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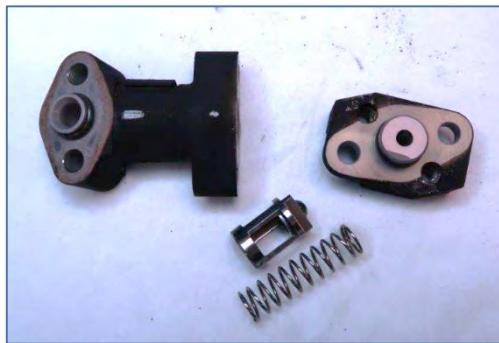
□ Fuel system generalities



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□ Fuel ejector

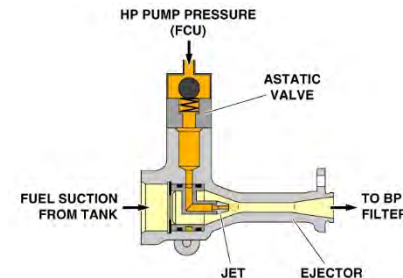
- Fuel ejector covered with soot externally and otherwise in good condition
- Internal holes clear with no foreign object
- Jet in place within ejector
- Astatic valve in good condition



Astatic valve



Ejector assembly



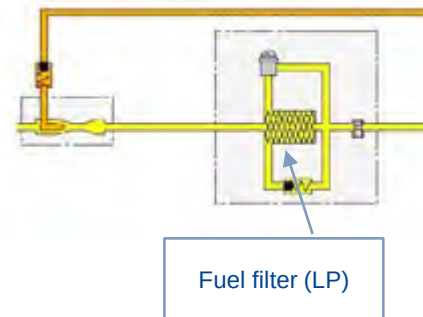
→ No findings to report for fuel ejector

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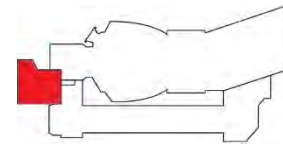
□ Fuel Filter (LP)

- The fuel filter (LP) was in good condition

→ No findings to report for fuel filter



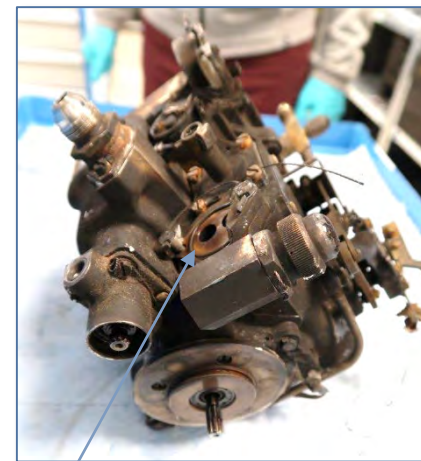
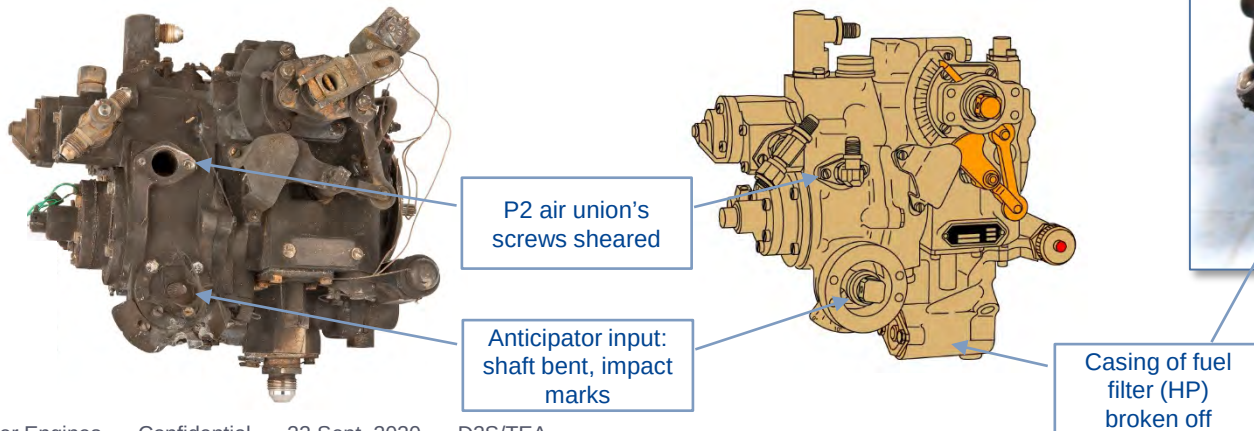
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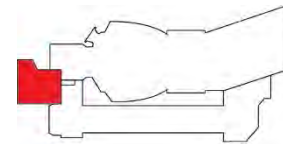
□ Fuel Control Unit (FCU)

- According to maintenance records, the FCU was checked at TSN 2674 hrs (38hrs before accident).
- Fuel control unit was externally covered with soot
- Drive shafts could not rotate manually
- Several impact damages associated with the accident and/or the wreckage recovery effort : anticipator input shaft bent, impact marks on its fixing ring, P2 air union's screws sheared, fuel filter (HP) casing broken off (found attached on site).
- Due to its condition it could not be tested on a test bench

→ **Damages extremely likely due to the crash** (engine could not operate like this)



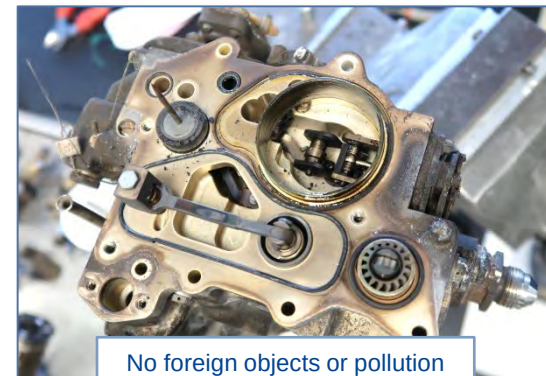
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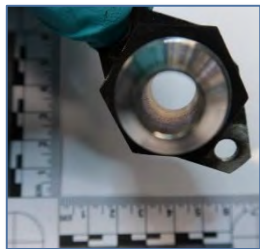
□ Fuel Control Unit (FCU) : internal system

- Internal fuel system was bone dry
- No presence of foreign objects or pollution found in internal fuel system
- All elastomers were caked and crumbled on contact or during disassembly (little black debris as can be seen on photo)

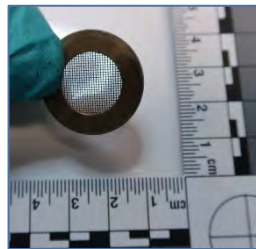
→ **No findings to report for FCU's internal components**



No foreign objects or pollution
in internal fuel system



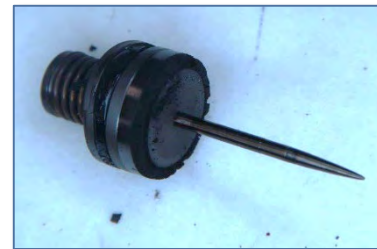
Fuel inlet union
clean



Fuel inlet
strainer clean



Fuel filter (HP)
clean

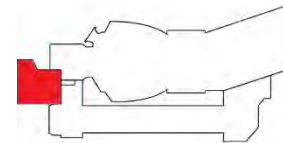


Metering needle
no findings



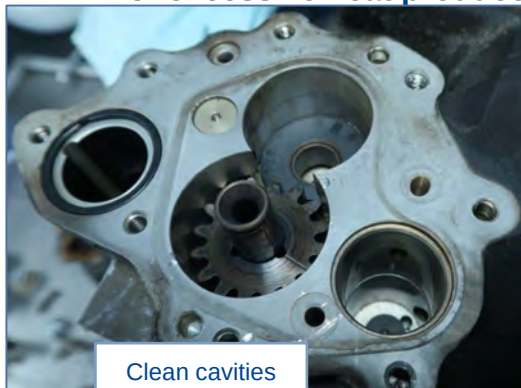
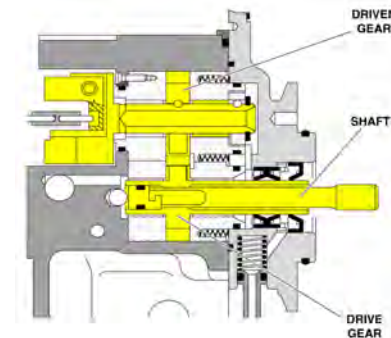
Deceleration controller :
no findings

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□ Fuel Control Unit (FCU) : HP pump

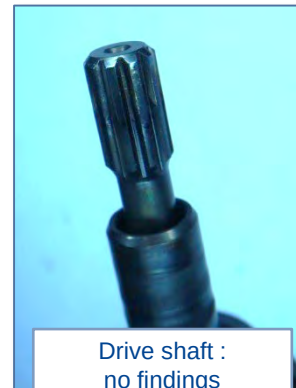
- The HP fuel pump was seized
- Gears were in good condition with no findings to report. No scratches on gears' faces nor on adjacent plates. Cavities were clean.
- The gears left an imprint of their shapes in the adjacent plates. This imprint resulted from dried layer of fuel after the engine shut-down which acted as glue thus explaining the impossibility to rotate the gears manually
→ the seizure was due to the post-crash fire heat
- The drive shaft was in good condition
→ **No significant findings to report for the HP fuel pump other than signs of excessive heat produced by the post-crash fire**



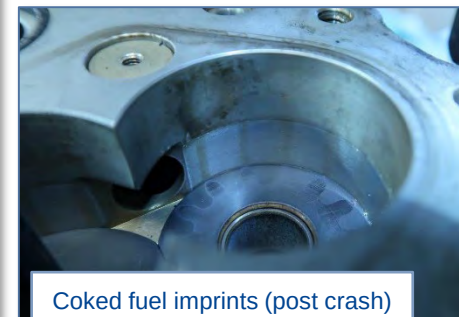
Clean cavities



Pump's gears : no findings

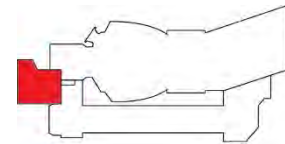


Drive shaft : no findings



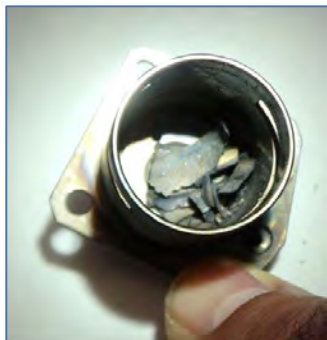
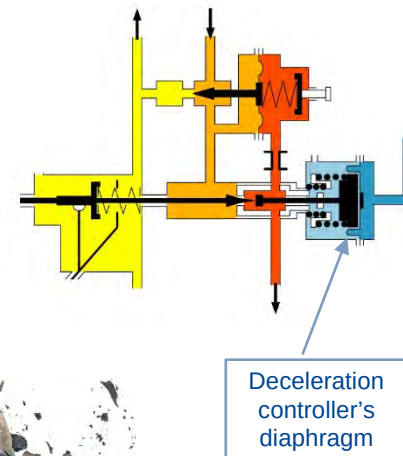
Coked fuel imprints (post crash)

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□ Fuel Control Unit (FCU) : deceleration controller's diaphragm

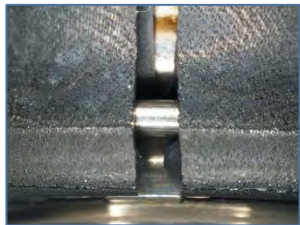
- The deceleration controller's diaphragm was found ruptured in small pieces in its casing. Was very brittle and snapped like glass (normally very soft and flexible).
- Elastomer cooked. Condition consistent with that of the other elastomers in the FCU. Material deteriorated due to post-crash fire heat producing a hard carbon product.
 - **No other known case of similar fracture feature**
 - **Rupture consistent with exposure to the heat of the post-crash fire**
- During operation, the diaphragm rupture leads to the engine slowing down to idle.



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□ Fuel Control Unit (FCU) : DeltaP Diaphragm

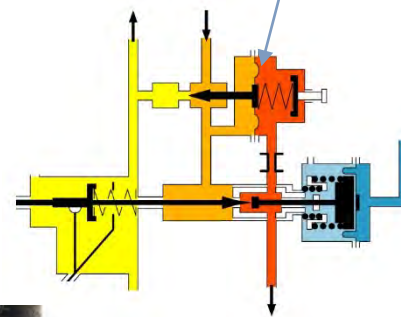
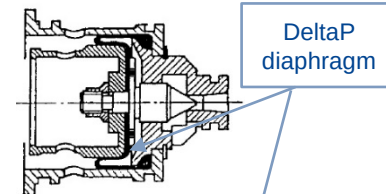
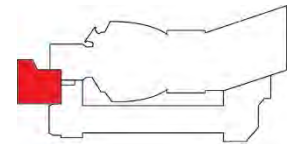
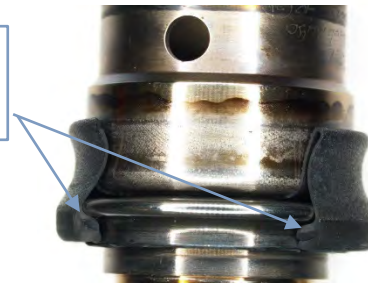
- Diaphragm slit lengthwise. Not consistent with normal working section along folding.
- Diaphragm of Engine 1 was very brittle and snapped like glass. No movement possible without breaking it. Its material is normally very soft.



- Feature of fractured surface highly similar to that found when a portion of the diaphragm was snapped off for examination.

- No other known case of similar fracture feature
- Fracture surface consistent with sudden rupture during post-solidification cooling

Section removed
in lab.
→ Highly similar
fracture surfaces

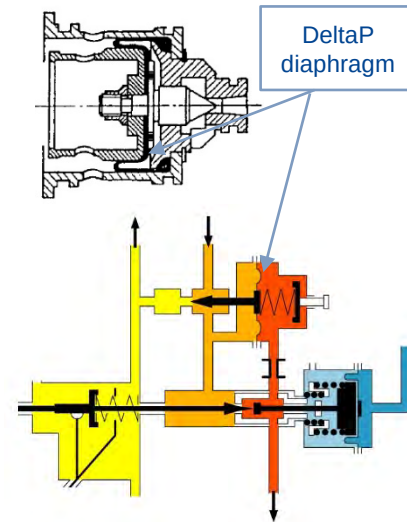
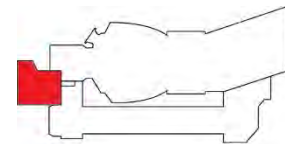


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□ Fuel Control Unit (FCU) : DeltaP Diaphragm

- Only one case of deltaP diaphragm rupture in service on Arriel 1 in June 2003 (2000-2017 period, 23 million flight hours). It had been installed the wrong way around. TU337 modification validated in Nov. 2003 introduced a fool-proofing on the bottom surface. FCU of Engine 1 was fitted with TU337.
- Does not correspond to other known cases of deltaP diaphragm ruptures (Arriel 1, Arrius 1 or Arriel 2 engines).
- Elastomer cooked and brittle. Consistent with other elastomers on FCU. Material deteriorated due to the post-crash fire's heat and resulted in a hard carbon product.
- No operation recorded in the FCU log card. This FCU was installed on engine 1 since new and was operated for 2711 hours without incident.
- Control of the engine's operation (including engine start) would only be possible in manual mode.

- **Diaphragm's elastomer deteriorated into a hard carbon product due to the heat of the post-crash fire**
- **Diaphragm's rupture was due to hardening and shrinkage during the post-solidification cooling**



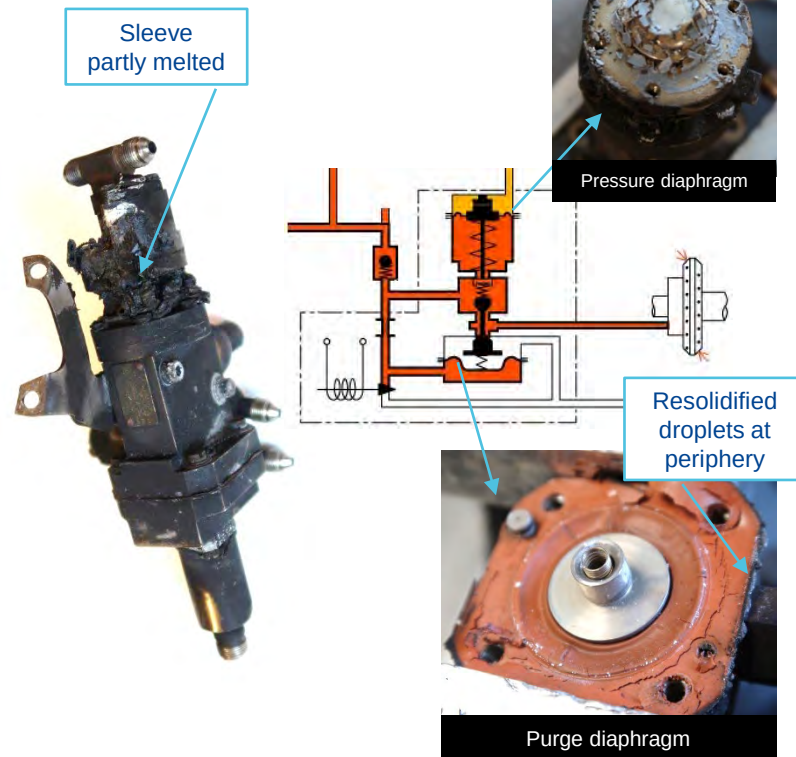
N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Drain valve assembly

- The assembly was covered with soot
- The upper part was partly covered with the remnants of the partly melted sleeve indicative of the implementation of covered drain valve assembly SB A292 73 0853. The diaphragm was shattered in small rigid fragments consistent with exposure to the post-crash fire heat.
- Maintenance records showed that SB was implemented since June 2017 (157hrs before accident). Daily checks records indicate no leak at the top diaphragm (pressure) level.
- The bottom diaphragm (purge) showed signs of delamination and local radial tears consistent with expansion and contraction during and after exposure to abnormal heat. Droplets of resolidified elastomer visible at the periphery. No signs of circular tears in the circular folds and no signs of holes in the diaphragm.

→ **The condition of the assembly and of both diaphragms was consistent with exposure to the heat of the post-crash fire.**

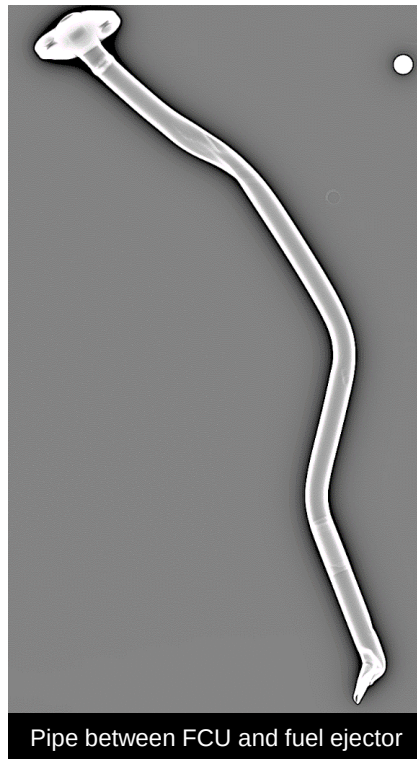
→ **No signs of tears or holes in the purge diaphragm**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Fuel system :

- **Fuel supply pipes** : X-Ray examination
→ **No deposits nor particles inside**
- Note : the pipe was ruptured and deformed either during the crash or the wreckage recovery.

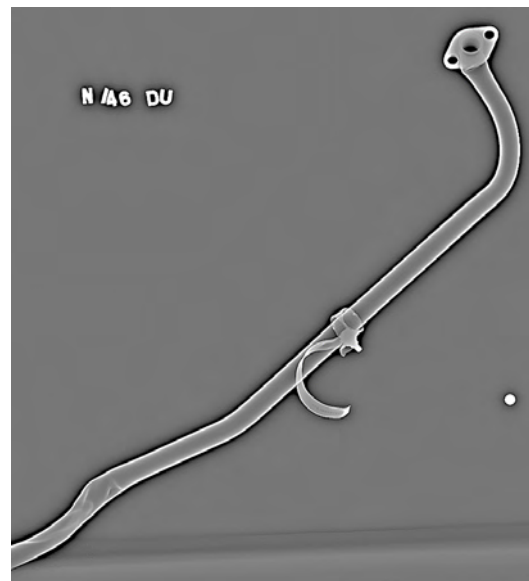
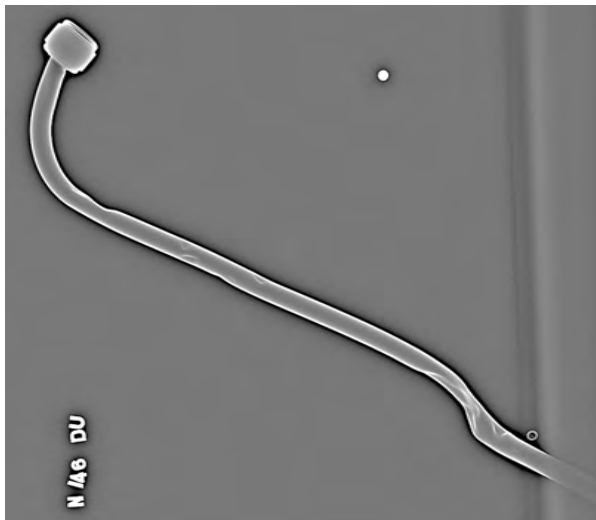


Pipe between FCU and fuel ejector

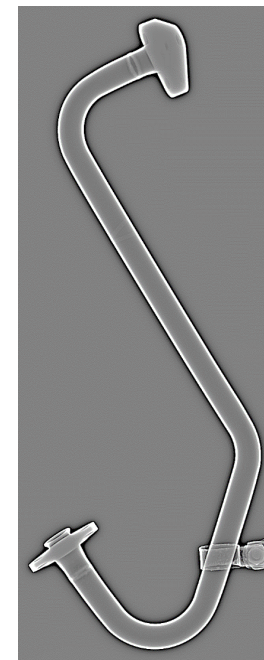
N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Fuel system :

- **Fuel supply pipes** : X-Ray examination
→ **No deposits nor particles inside**
- Note : the pipes were ruptured and deformed either during the crash or the wreckage recovery



Pipe between fuel filter (LP) and FCU



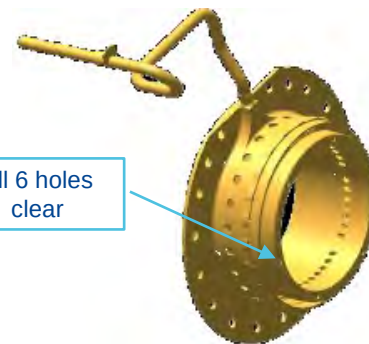
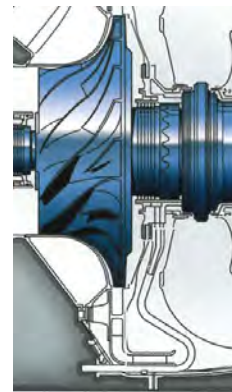
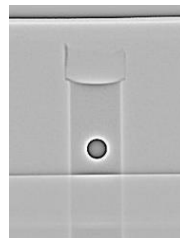
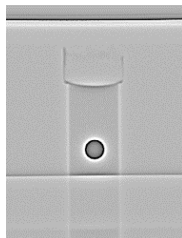
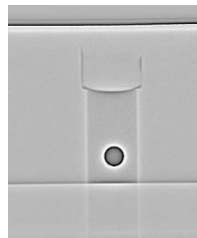
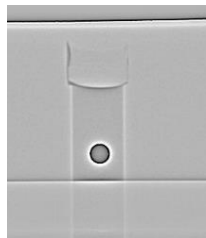
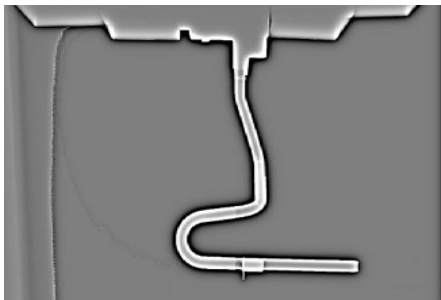
Pipe between fuel ejector & filter (LP)

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Fuel injection manifold

- According to maintenance records, the permeability check of the fuel injection manifold was performed at TSN 2710 hrs (1 flight hour before the accident).
- X-ray check : no deposits nor particles inside the pipe nor inside the 6 holes

→ **No findings to report for the fuel injection manifold**



All 6 holes
clear

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Overspeed sensor

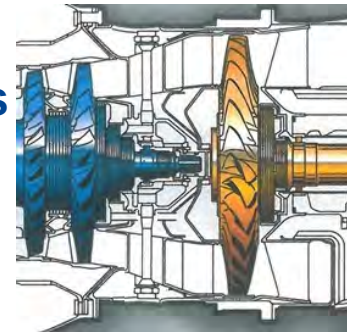
- No contact between the sensor and the phonic wheel
- Head of sensor intact
- O-ring caked due to hot temperature consistent with post-crash fire
- Sheath of harness missing consistent with post-crash fire
- Back of tube damaged during disassembly from Module 4
- Due to its condition, the sensor could not be tested

→ **Damages to overspeed sensor associated with post-crash fire or removal from engine**

→ **No other findings to report**



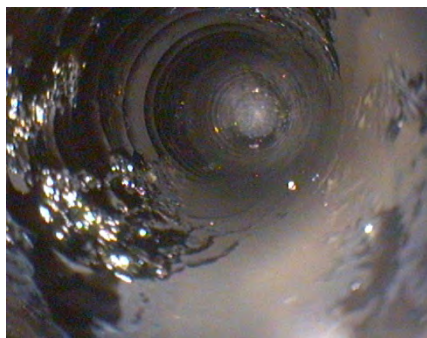
N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



□ Gas Generator :

- **Tubes to / from rear bearing chamber**

- Scavenge tubes and vent tube : Layer of coked oil adherent to inner surfaces. Holes clear.
- Oil supply : Presence of thin layer of coke
- The three tubes are not obstructed.



Oil supply tube



Scavenge tube



Vent tube

→ **No significant reduction to oil flow**

→ **Condition of internal surfaces of tubes in line with experience**

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

■ Gas Generator :

• **Rear bearing examination**

○ Metallic composition checks :

- Outer race : 80DCV40
- Roller : 80DCV40
- Cage : 40NCD7
- Inner race : 80DCV40

→ All materials comply with specification

○ Hardness checks :

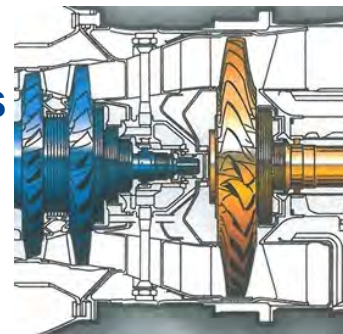
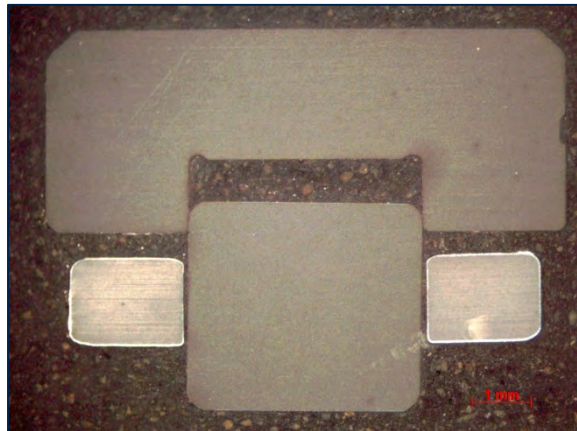
- Outer race : 62-63 HRC (spec 61-64 HRC)
- Roller : 62 HRC (spec 61-64 HRC)
- Cage : 28 HRC (spec 25-33 HRC)

→ Hardness checks comply with specification

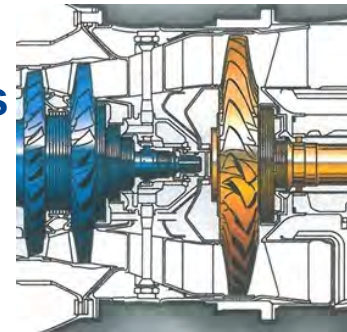
○ Rear Bearing examination :

- Presence of coked oil deposit
- Rollers in good condition
- Bearing rotates smoothly under manual rotation

→ **Bearing in good condition**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



□ Gas Generator

- **internal cavities around rear bearing chamber**
 - No traces of oil on front face of rear bearing chamber
 - No traces of oil on internal cup plates
 - No traces of oil on Power Turbine's NGV in main air path or in the hollow vanes

→ **No signs of oil out of rear bearing chamber**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Magnetic plugs and oil filter

- The examination of the magnetic plugs and oil filter did not reveal any metallic particles
- The housing and strainer for the rear bearing's magnetic plug (TU208) contained only oil as normal

→ **No metallic particles on the magnetic plugs nor in oil filter**



Rear bearing's mag plug (TU208) housing assembly

SAFRAN

HELICOPTER ENGINES USA

SafranHE On Site Examination Report

Engine 1 On Site Examination

Equipment	Condition	Equipment	Condition
MO1 Magnetic Plug	sludge	Eng Electric Chip Det	Could not be removed from housing
MOS Magnetic Plug	sludge	TU208 Electric Chip Det	sludge



Module 1 magnetic plug



Module 5 magnetic plug



Rear bearing chip detector

SAFRAN

HELICOPTER ENGINES USA

SafranHE On Site Examination Report

Engine 1 On Site Examination

Equipment	Condition	Equipment	Condition
Oil Filter	Burnt no contamination	FCU Fuel Filter	Not removed

Oil Filter



Oil Filter

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil system :

- **Oil pump general examination**

- The pump was found seized
- The drive shaft was in place and in good condition
- Due to its condition it could not be tested on a test bench



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil system :

• Oil pump tear-down and examination

- The pump was oily as normal
- All elastomers (O-rings and lip seals) were stiffer than normal and broke easily indicative of exposure to abnormal heat.
- The gears left an imprint of their shapes in the adjacent plates. This imprint resulted from a dried layer of oil after the engine shut-down which acted as glue thus explaining the impossibility to rotate the gears manually → the seizure is due to the post-crash fire heat
- The overpressure valve was in place. Its spring was tested and found conform to the specification.
- Oil supply stage : gears in good condition, no scratches.
- All scavenge stages (accessories gearbox, reduction gearbox and rear bearing) : no significant scoring at periphery and on adjacent plates.

→ **Oil pump in good condition. Was exposed to heat from post-crash fire. No other findings to report**



Oil supply stage



Rear bearing scavenge stage



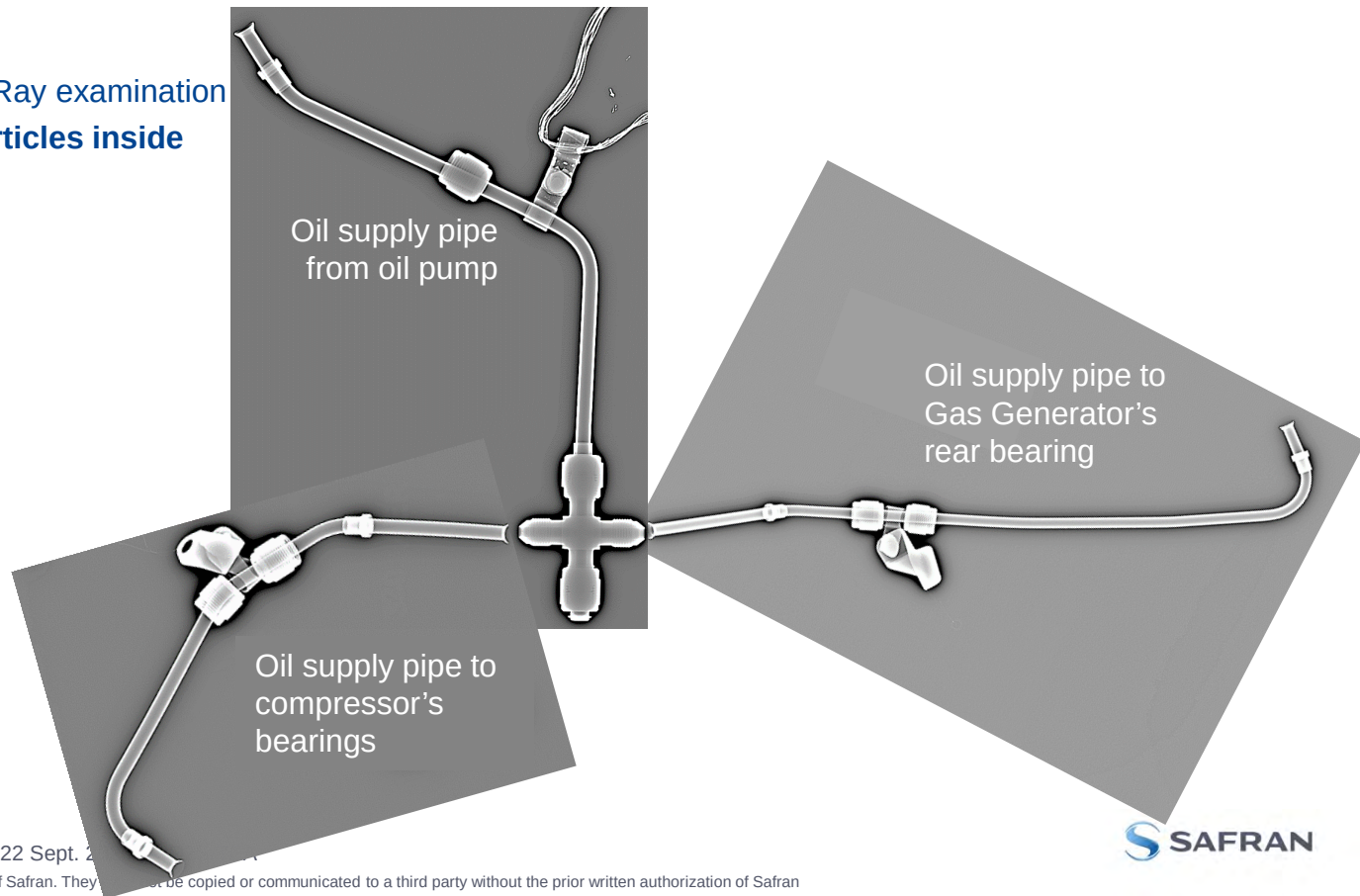
MO1 scavenge stage

MO5 scavenge stage

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil system :

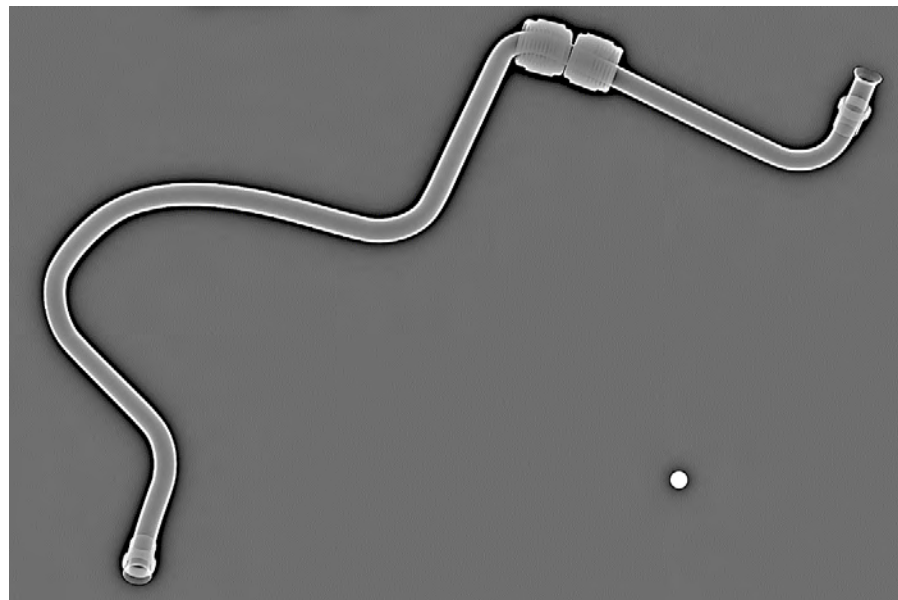
- **Oil supply pipes :** X-Ray examination
→ **No deposits nor particles inside**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil system :

- **Oil scavenge pipe :** X-Ray examination
→ **No deposits nor particles inside**



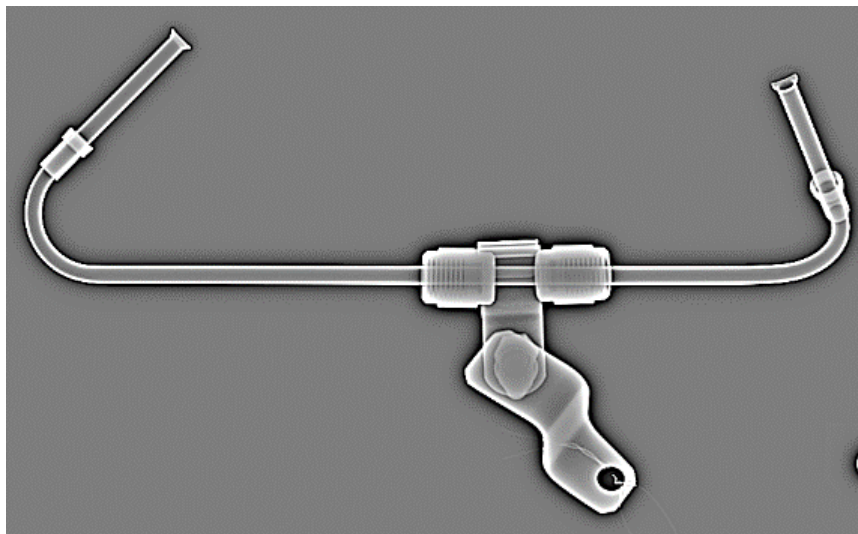
To rear bearing
chamber

To magnetic plug &
strainer assembly

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil system :

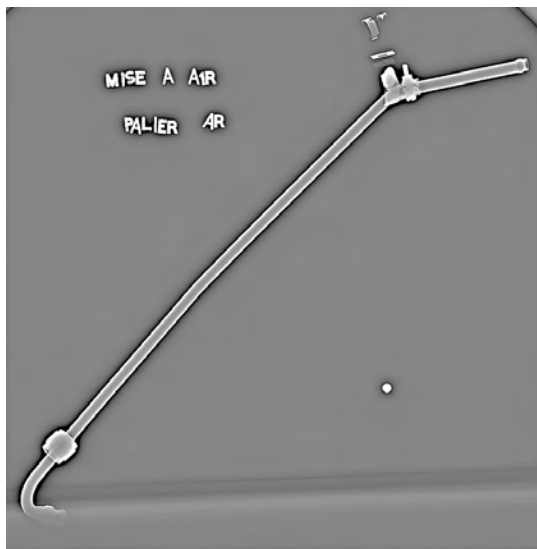
- **Oil pipe to low oil pressure switch : X-Ray examination**
→ No deposits nor particles inside



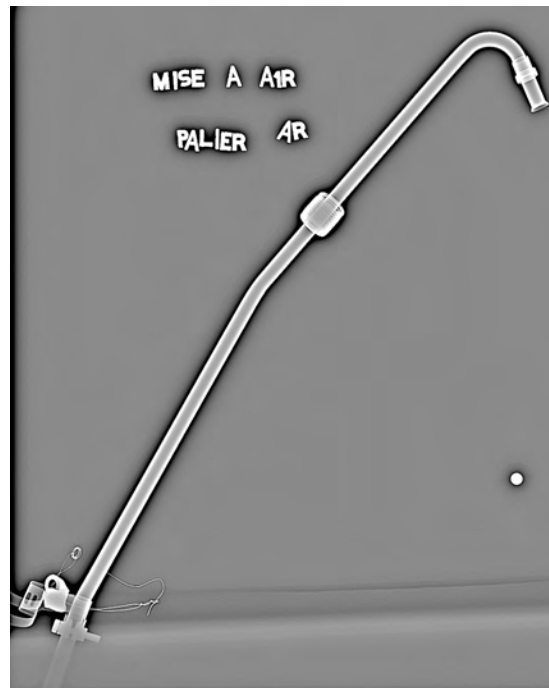
N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Air system :

- **Vent pipe : X-Ray examination**
→ **No deposits nor particles inside**

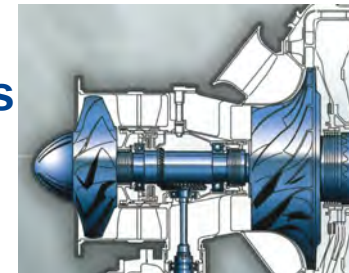


Aircraft side
(outlet)



Engine side
(inlet)

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



□ Compressor

• Axial wheel and impeller

- Rough leading edges with numerous small impacts
- All blades affected the same way
- No FOD impacts
- No significant erosion

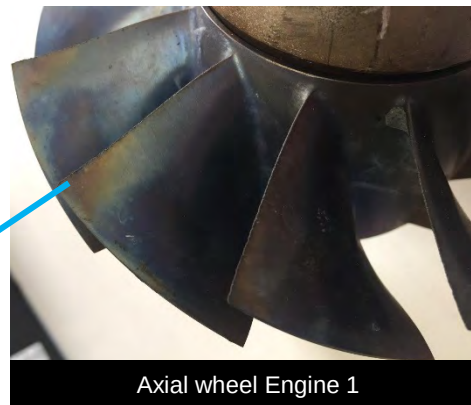
• Centrifugal diffuser

- Vanes in good condition. No erosion, no FOD impacts.

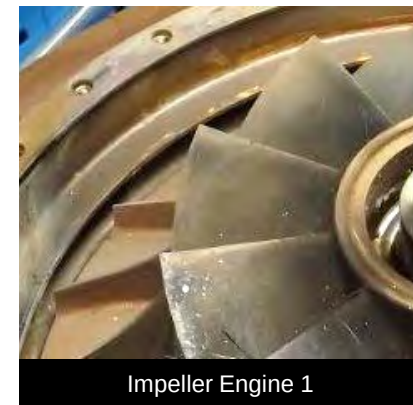
→ **Small impacts due to homogenous grit-like ingestion**



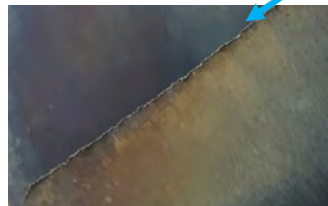
Centrifugal Diffuser Engine 1



Axial wheel Engine 1



Impeller Engine 1



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Gas Generator

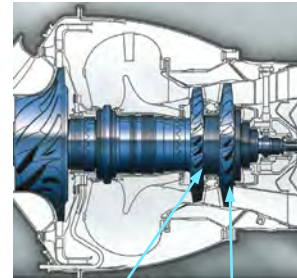
• **Combustion chamber**

- No findings to report.

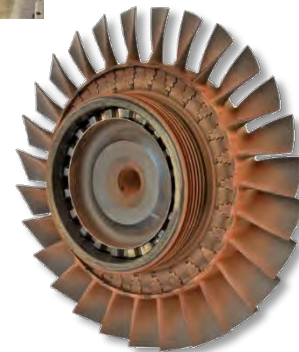
• **HP Turbines**

- No tip rubs on all blades (HPT1 and 2)
- No blade ruptures
- Dimensional checks : wheels conform to specification

→ **HPT1&2 Wheels in good visual condition**



HPT1 HPT2



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

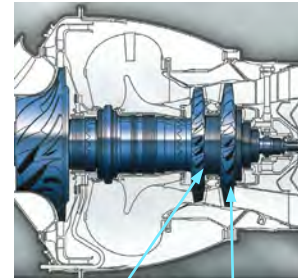
□ Gas Generator

• HP Turbines : HPT1

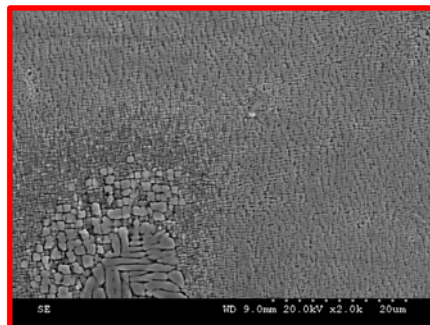
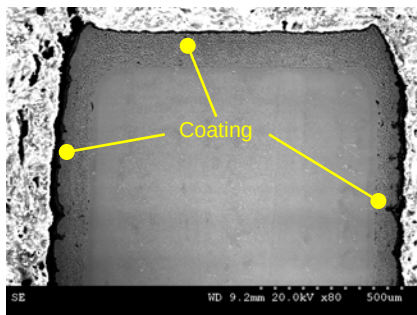
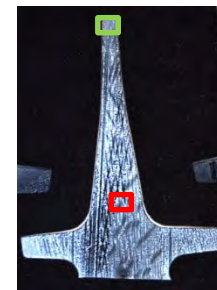
- Coating present all round and in good condition
- Slight evolution of the metallographic structure from blade foot to tip in line with experience

→ **HPT1 blades' condition in line with experience**

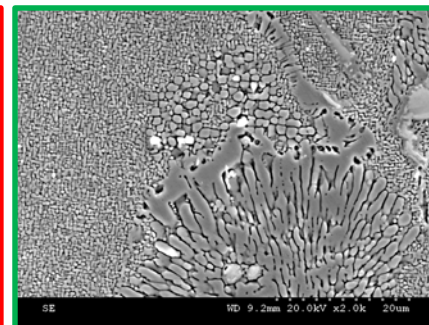
→ **No signs of overtemperature**



HPT1 HPT2



Blade foot



Blade tip

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

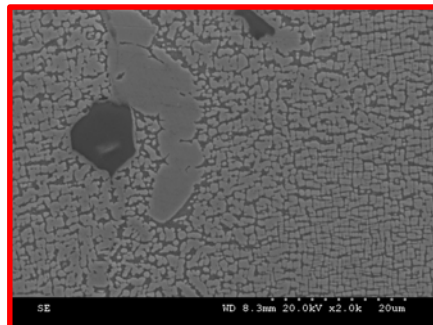
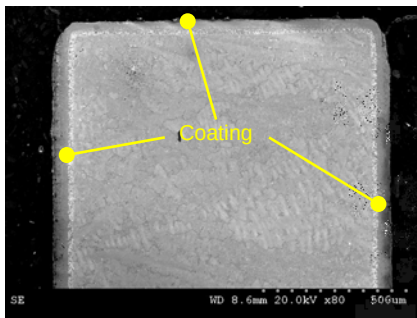
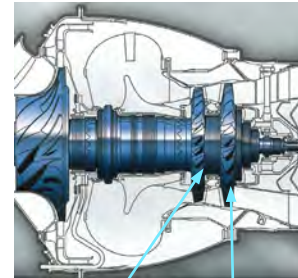
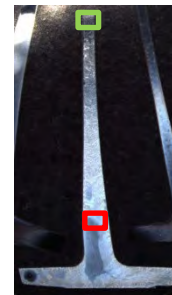
□ Gas Generator

• HP Turbines : HPT2

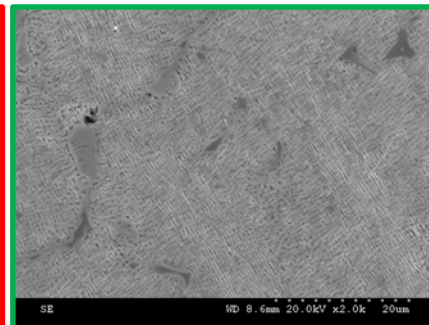
- Coating present all round and in good condition
- Slight evolution of the metallographic structure from blade foot to tip in line with experience

→ **HPT1 blades' condition in line with experience**

→ **No signs of overtemperature**



Blade foot

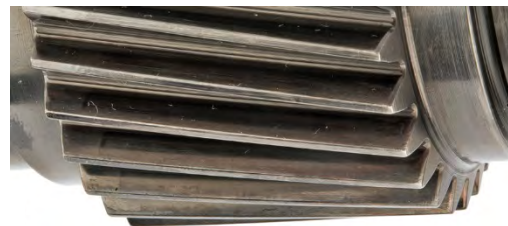


Blade tip

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Reduction gearbox

- The reduction gearbox was opened. Gears and bearings were unremarkable.



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil analysis

- Oil quantity in the reduction gearbox and in the accessories gearbox was too small to be analysed.
- SOA records according to operator's documentation :

Sample Date	Eng Time	Oil Time	Add	Fe	Cr	Pb	Sn	Mg	Si	Cu	Ag	Ni	Al
11/30/2016	2255	80	1	0.12	0.0	0	0.0	0.0	5	0.0	0.3	0.0	0.1
01/16/2017	2341	300	1	0.12	0.0	0	0.0	0.0	7	0.0	0.3	0.0	0.6
04/03/2017	2406	100	1	0.50	0.0	0	0.0	0.0	7	0.0	0.3	0.0	0.4
05/15/2017	2497	0	2	0.08	0.0	0	0.0	0.0	8	0.0	0.1	0.0	0.3
07/07/2017	2587	253	1	0.10	0.0	0	0.0	0.0	6	0.0	0.1	0.0	0.5
08/14/2017	2665	73	1	0.06	0.0	0	0.0	0.1	6	0.0	0.1	0.0	0.2

→ The SOA analyses do not reveal any abnormal levels

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Review of possible origins for twist grip in stop position

- Intentional

- o Low Fuel P

- Fuel ejector checked. No findings to report.
 - Fuel filters checked. No findings to report.
 - HP pump checked. No findings to report.
 - Fuel supply at engine's interface (air bubbles, pressure drop, lack of fuel,...)

- o Overspeed activation (real overspeed or spurious activation)

- ΔP diaphragm slit due to post-crash fire otherwise unremarkable
 - NPT overspeed sensor : no contact with phonic wheel
 - Loss of continuity of power drive train (engine side) : reduction gearbox train and engine power output shaft checked. No findings to report.
 - Untimely activation of tachometer box : could not be checked (destroyed and not recovered from wreckage)
 - Pilot's action leading to NR overspeed and tachometer box's activation
 - Loss of continuity of power drive train (aircraft side)

- o T4 overtemp

- Condition of HP turbines unremarkable
 - ΔP diaphragm slit due to post-crash fire otherwise unremarkable

Legend :

Text in green : condition could be excluded

Text in grey : cannot confirm

Text in orange : out of SafranHE's scope

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ List of possible origins for twist stop position (as discussed in Dallas on 14th Nov. 2017)

• Intentional

o Flame-out or Engine Fail warning

- No FOD on compressor
- Grit-like impacts on compressor wheels and centrifugal compressor but combustion chamber unremarkable
- Rotating parts ok
- No gear rupture
- No NGV deterioration
- No HP or Power Turbine blade rupture
- All bearings in good working condition
- No output power shaft rupture
- Pipes found in place and attached (although some were damaged by the accident)
- Harnesses found in place and attached (although some were damaged by the accident)
- Metering valve checked. No findings to report.
- No signs of fuel pollution in fuel system
- Drain valve : destroyed due to heat produced by post-crash fire. Maintenance records showed that SB A292 73 0853 was implemented since June 2017 (157hrs before accident). Daily checks records indicate no leak at the pressure diaphragm (pressure) level.
- Drain valve : no signs of tears or holes in the purge diaphragm (other than tears due to heat produced by post-crash fire)
- Deceleration diaphragm : destroyed due to heat produced by post-crash fire, could not be checked. Leads to engine to idle.
- No clogging of injection manifold
- Fuel shut-off valve check : found in open position (NTSB information)
- Obstruction of air intake
- Fuel supply at engine interface (air bubbles, pressure drop, lack of fuel,...)

Legend :

Text in green : condition could be excluded

Text in grey : cannot confirm

Text in orange : out of SafranHE's scope

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ List of possible origins for twist grip in stop position (as discussed in Dallas on 14th Nov. 2017)

• Intentional

- o Low Oil P
 - Pipes clear
 - Oil pump : no findings to report.
- o Oil Temperature
 - Condition of gears & bearings unremarkable (reduction gearbox)
- o Chip light
 - Gas Generator rear bearing (TU208) strainer clean
 - No metallic particles on magnetic plugs
- o Engine fire or smoke
 - Pipes found in place and attached (although some were damaged by the accident). Scavenge pipe clear.
 - No signs of oil out of rear bearing chamber
 - Gas Generator rear bearing (TU208) strainer clean
 - Fuel shut-off valve check : found in open position (source : NTSB)
- o Vibrations from the engine
 - Rotating parts checked. No findings to report.

Legend :

Text in green : condition could be excluded

Text in grey : cannot confirm

Text in orange : out of SafranHE's scope

- The examinations carried out did not reveal discrepancies that could explain the twist grip in the stop position
- Considering the information available and the engine's condition (post-crash fire, crash and recovery damage), some of the possible origins could not be checked or are outside SafranHE's scope



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

Examinations

Engine 2 (RH) s/n 47346

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyse

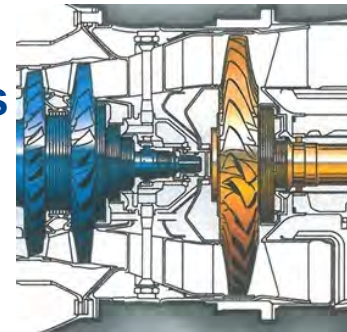
□ Examination main findings (status after engine tear-down in Dallas, Nov. 2017)

- No FOD damage to compressor
- Fuel control lever on FCU was in full-open position
- Rear bearing damage due to seizure. No evidence of coking.
- Metallic (magnetic) debris found on rear bearing's magnetic plug
- 3-way union (deck fitting, AHD supply) of vent line found clear, unobstructed
- Blue stains on axial compressor's shaft at bearings' and bevel gear locations
- Contact marks on Gas Generator's components consistent with bearing's seizure
- Imprints by NPT's blades on NGV consistent with no PT rotation at time of crash



- Findings were consistent with the engine 2 being at stand-still at the time of impact
- Origin of rear bearing seizure not determined

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



□ Generalities

- Possible contributing factors leading to bearing deterioration :
 - Lack/insufficient lubrication
 - Excess of oil in chamber
 - Pollution of oil system
 - Excessive loading
 - Material discrepancy
 - Internal discrepancy
 - Dimensions out of tolerances
 - Improper assembly
 - Misalignment (between rings)
 - Excessive oil temperature
 - Mishandling of engine
 - Oil quality

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil system

- **Oil pump general examination**

- The oil supply inlet boss on the back plate was broken.
No dirty (no soot) static fracture surface
→ probably happened during recovery effort
- The pump was found seized
- The drive shaft was in place and in good condition
- Due to its condition it could not be tested on a test bench

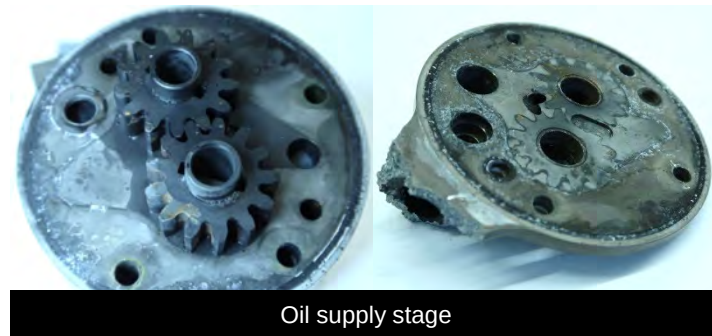
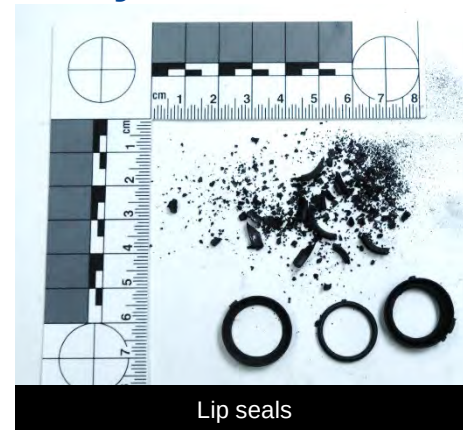


N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil system

• Oil pump tear-down and examination

- The pump was slightly greasy at places but mainly dry inside
- All elastomers were cooked. They crumbled on contact. The lip seals between the pressure and scavenge stages shattered in many fragments (only support rings remained intact).
- The gears left an imprint of their shapes in the adjacent plates. This imprint resulted from a dried layer of oil after the engine shut-down which acted as glue thus explaining the impossibility to rotate the gears manually → the seizure is due to the post-crash fire heat
- The overpressure valve was in place. Its spring kept its “in position” height probably due to the post-crash fire’s heat.
- All gears exhibited a few traces of oxidation which can be associated to the storage time since the event.
- Oil supply stage : gears in good condition, no scratches.



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil system

• Oil pump tear-down and examination

- Accessories and reduction gearboxes scavenge stages : light superficial scoring at periphery and on adjacent plates in line with experience



MO1 scavenge stage



MO5 scavenge stage

- Rear bearing scavenge stage :
 - Heavy scoring at periphery
 - Heavy scoring on adjacent plates
 - Presence of debris

→ Oil pump was exposed to heat from post-crash fire

→ Condition of rear bearing scavenge stage consistent with rear bearing deterioration



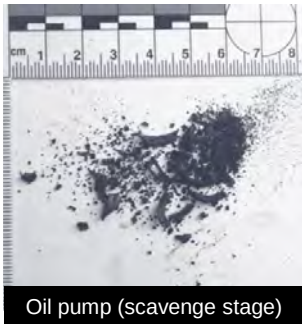
Rear bearing scavenge stage

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

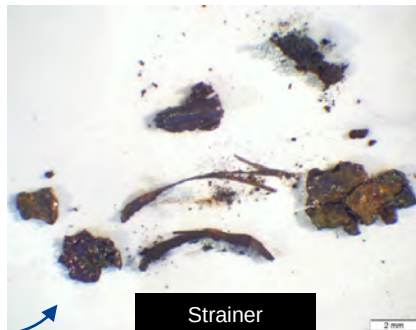
Oil system

Particles Analysis (SEM + EDS) : scavenge line

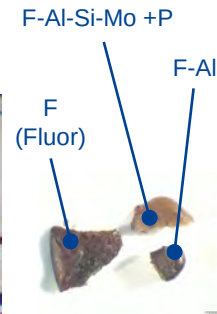
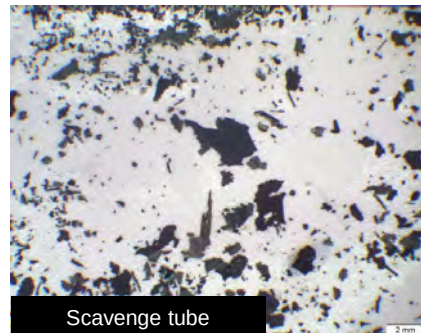
C-Zn-Pb-P-Na-S-Sn-Fe-Al /
C-F-Ca-Mg / C-F-Ca-Mg-Al /
C-Zn-Fe-Ti / C-O-Zn-P-S-Al /
C-O-Zn-S-P-Na-Fe /
C-O-Zn-S-P-Fe-Ag /
C-Zn-S-P



Ag, C, O, P, S / Ni-Fe / Fe-Sn-P /
Ni-Cr-Fe-S-Si-Mo / Fe-Ni-Sn-Cr-S-Si /
Fe-Cr-Mo-V-Mn-Si-Ni-Al



Fe-F-Cr-Mn-Al-Ni-Mo-Ti-Si /
Fe-Cr-Zn-F-Cu-Ni-Al-S-Mn /
Fe-Cr-F-Zn-Ag-Si-Ti-Al-Mn-S



- The metallic debris could not be identified. They could be the result of the final deterioration in the rear bearing chamber with different components involved.
- **All metallic components indigenous to the rear bearing assembly and oil**
- **Numerous debris show that oil flowed through the rear bearing chamber and the scavenge system (duct, pipe, mag plug assembly, strainer and pump)**
- The pieces found in the Module 5 could originate from an O-ring and many particles found in the oil pump originate from the elastomer lip seals separating the pressure stage from the scavenge stages.

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil system

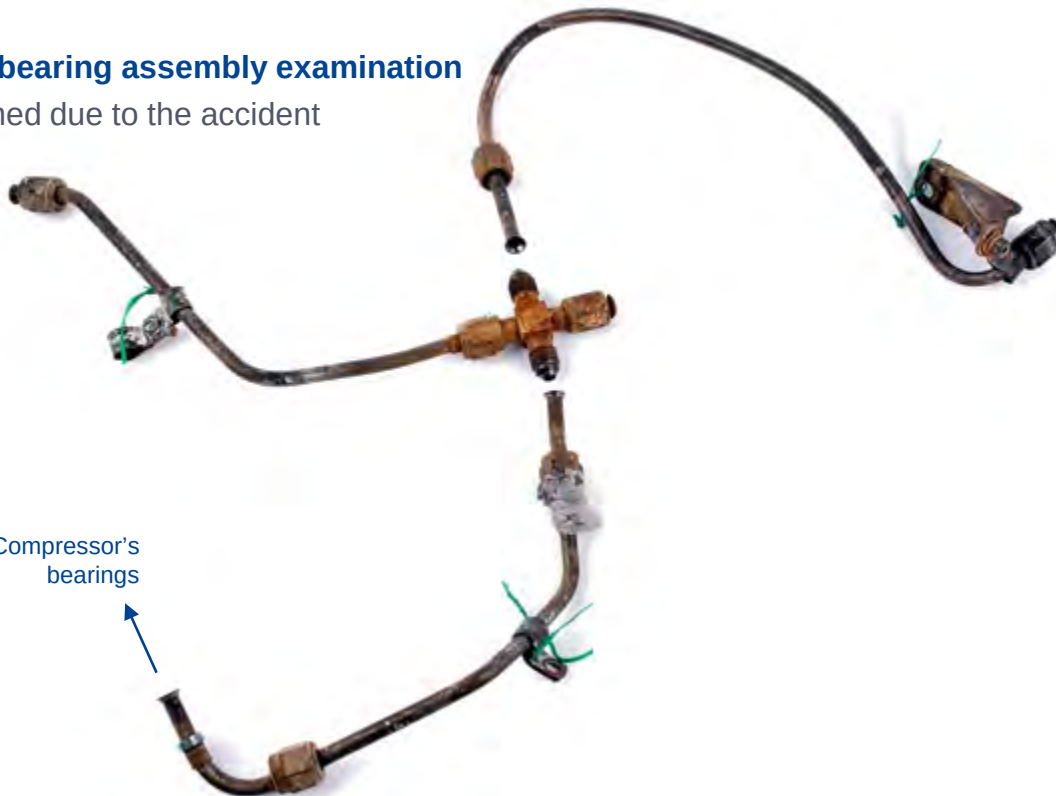
- **Oil pipes to rear bearing assembly examination**

- Pipes are deformed due to the accident

Oil supply
from oil pump

Oil to Compressor's
bearings

Oil to Gas Generator
rear bearing



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil system

- **Oil supply pipes : X-Ray examination**

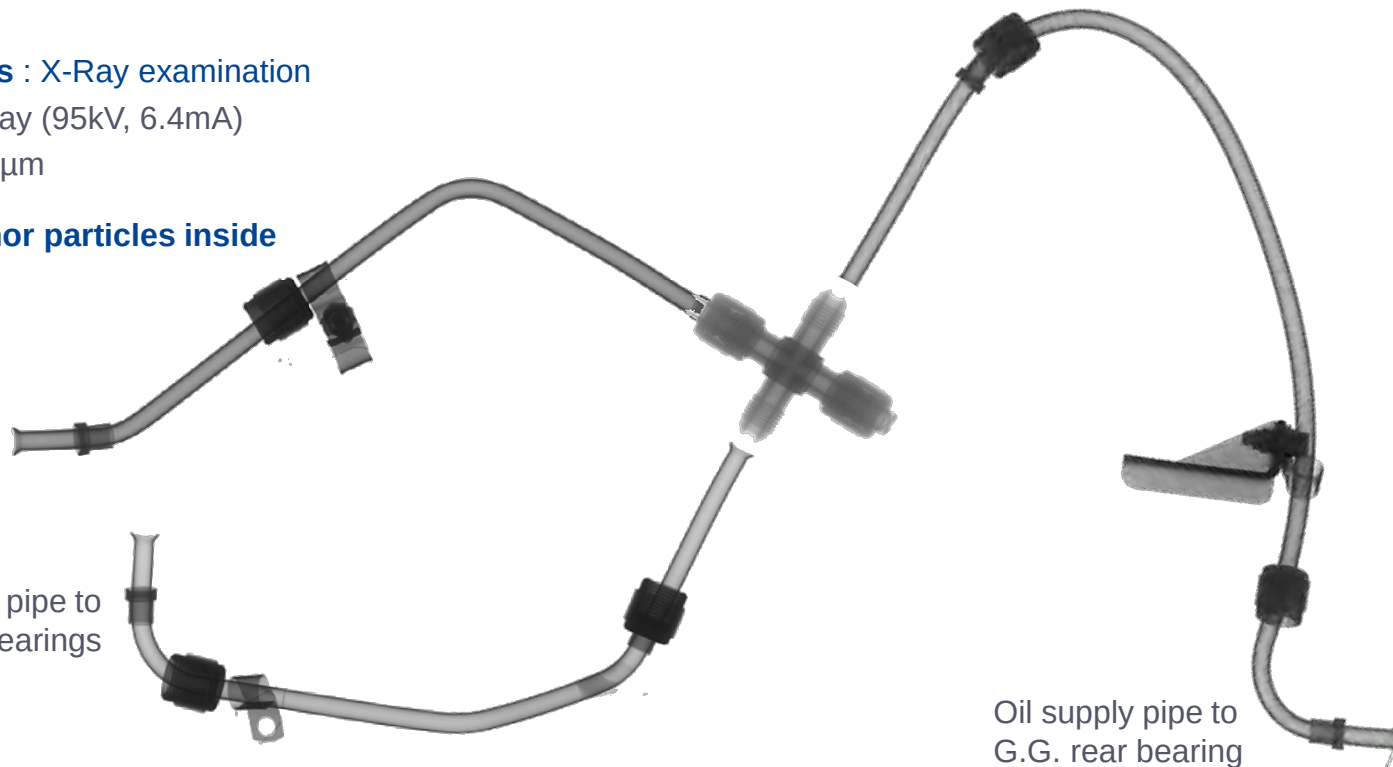
- Directional X-Ray (95kV, 6.4mA)
- DDA 16 bit 200µm

→ **No deposits nor particles inside**

Oil supply pipe
from oil pump

Oil supply pipe to
compressor's bearings

Oil supply pipe to
G.G. rear bearing



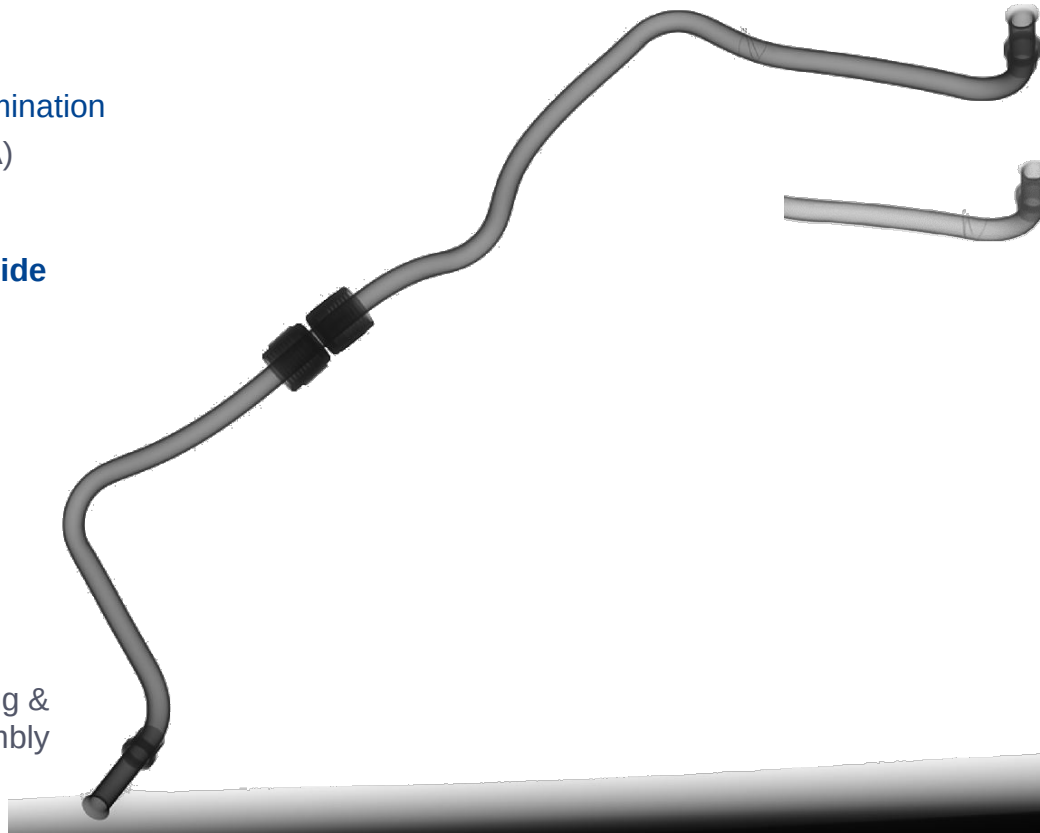
N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil system

- **Oil scavenge pipe** : X-Ray examination
 - Directional X-Ray (95kV, 6.4mA)
 - DDA 16 bit 200µm
- **No deposits nor particles inside**

To magnetic plug &
strainer assembly

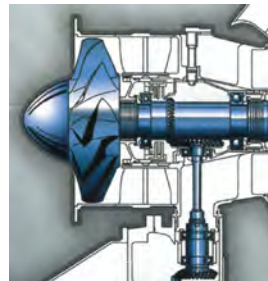
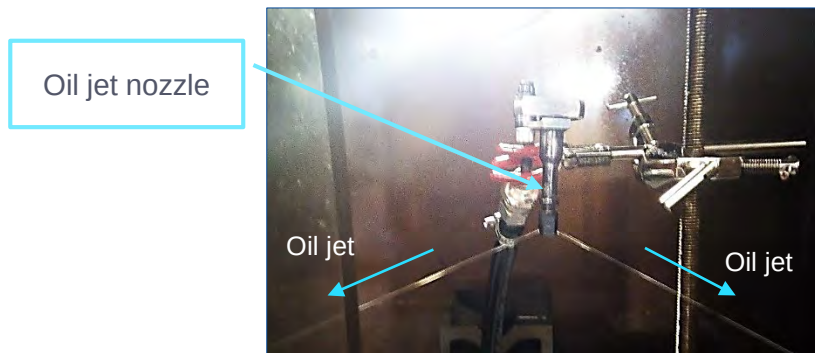
To rear bearing
chamber



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil system

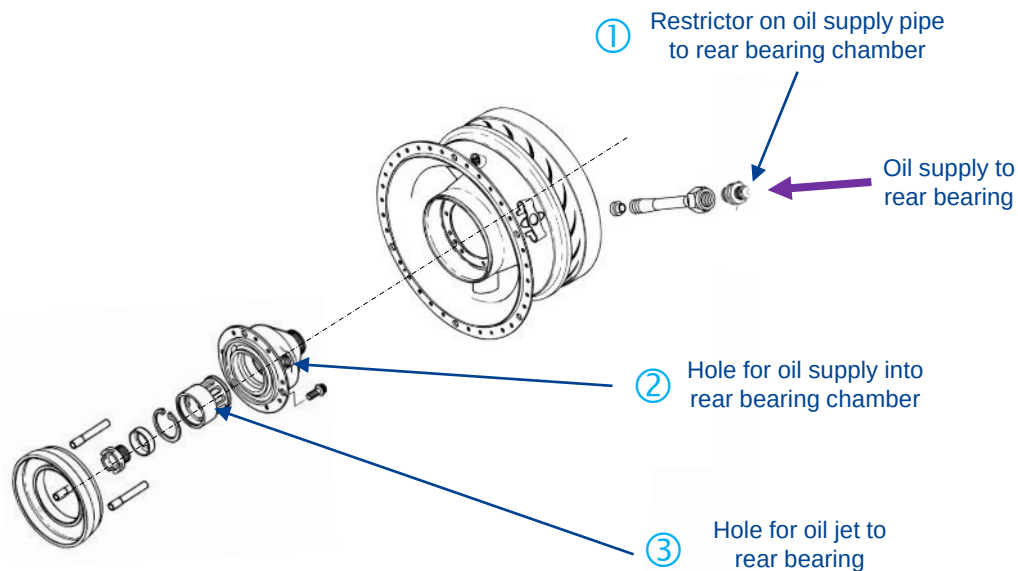
- **Oil lubrication jets for compressor's bearings**
 - The oil jet nozzle was tested on a specific test bench and the result was satisfactory
- **No obstruction of the oil jets**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

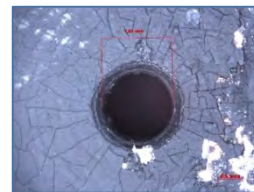
Oil system

- Oil restrictors and jet on supply line to Gas Generator's rear bearing



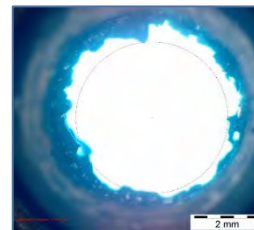
→ Oil restrictors : no significant reduction to oil flow passage

①



Ø 1.45 average
for 1.4 +0.1 / 0
nominal

②

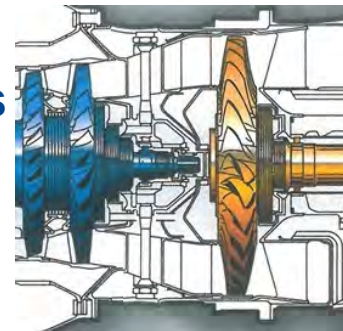


Ø 5.3 average
for 6 ± 0.2 nominal

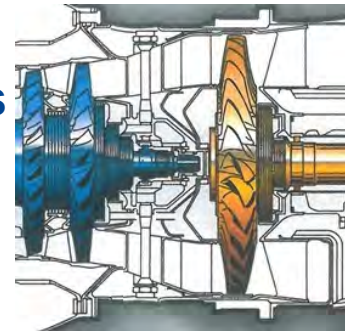
③



Ø 1.9 average
for 2 +0.06 / -0.02
nominal



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

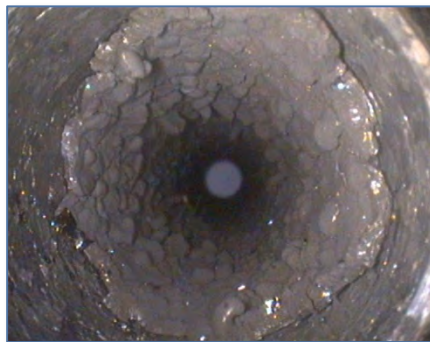


Oil & Secondary air systems

- **Tubes to / from Gas Generator's rear bearing chamber**
 - Oil supply and scavenge tubes : Layer of coked oil adherent to inner surfaces. Holes clear.
 - Vent tube: Presence of thin layer of coke
 - The three tubes are not obstructed.



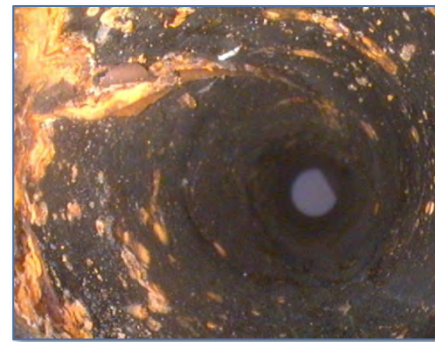
Oil supply Scavenge Vent



Oil supply tube



Scavenge tube



Vent tube

→ **Tubes : no significant reduction to oil/air flow passage**

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Secondary air system

- **Vent pipe** : X-Ray examination
 - Directional X-Ray (95kV, 6.4mA)
 - DDA 16 bit 200µm

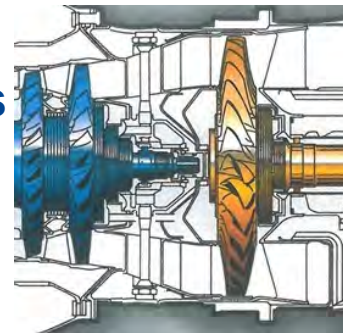
→ **No deposits nor particles inside**



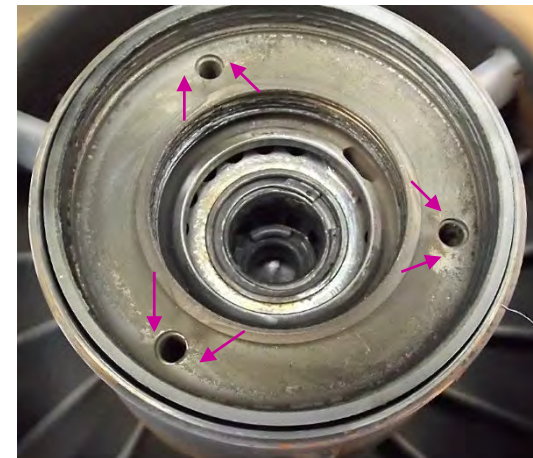
N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Secondary air system

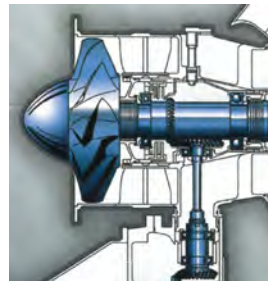
- Internal cavities around rear bearing chamber
 - No traces of oil on front face of rear bearing chamber
 - No significant traces of oil on internal cup plates
 - No traces of oil on Power Turbine's NGV in main air path or in the hollow vanes.
 - Light soot run off marks towards the three horizontal tubes and towards the main air path (behind the Power Turbine). No significant "swirl" patterns.
- **No significant signs of oil out of rear bearing chamber**
- **No signs of fire in the rear bearing chamber and cavities around it**



Light soot run-off marks
No "swirl" patterns



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



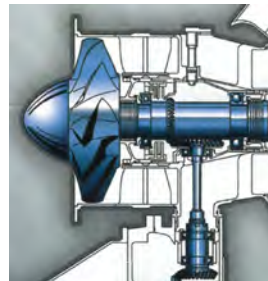
□ Compressor

• **Axial shaft**

- Blue marks on shaft below bearings and bevel gear
- Bearings' components bear dark coloration
- Bearings in good condition
- No rotation of the rings on the shaft



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

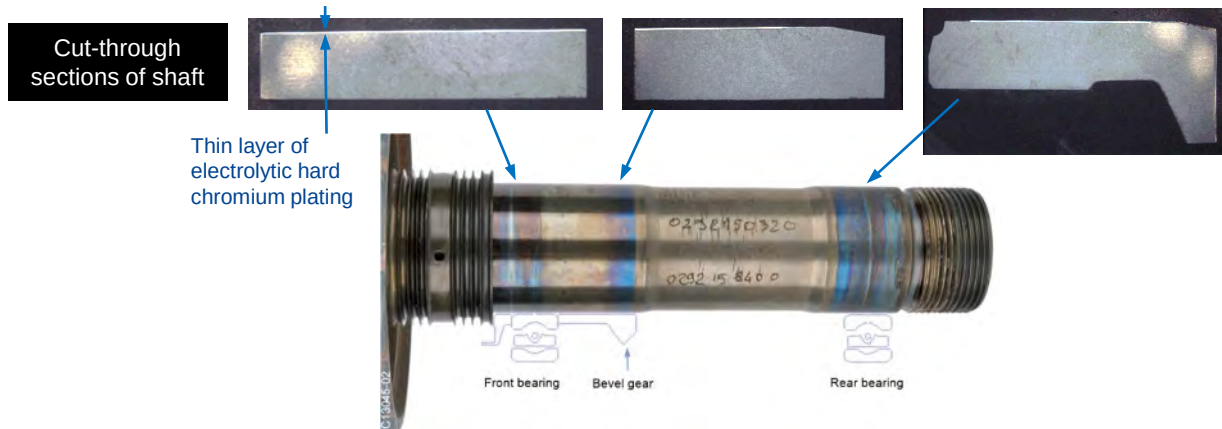


Compressor

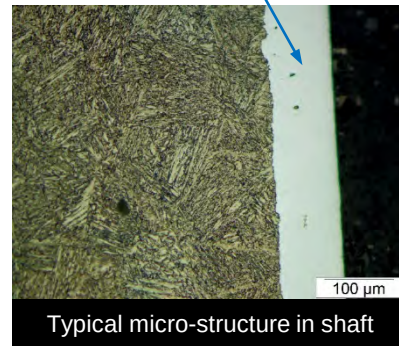
• Axial shaft

- Hardness → conform to specifications
- Micro structure → conform to material
- Cut-through sections of shaft : no signs of heat penetration beyond chromium plating (which took a blue colour)

→ **Blue stains = coloration of chromium plating under heat**

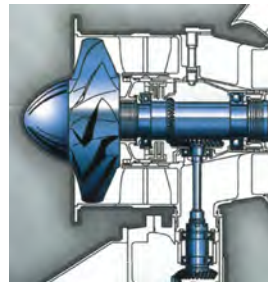


Electrolytic hard chromium plating



→ **Rare blue colorations associated with heat coming from bearings and gear in normal static position/contact related to the shaft**

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



□ Compressor

• Bearings (front and rear)

○ Examination

- All balls' blackish colour associated with high temperature
- Balls left black colour marks on inner and outer races due to post-crash fire
- No visual indication of flaking on balls and races

○ Chemical composition

- Outer race : 80DCV40
- Balls : 80DCV40
- Cage : 40NCD7
- Inner races : 80DCV40

→ **All materials comply with specification**

○ Microstructure

→ **Conform to material**

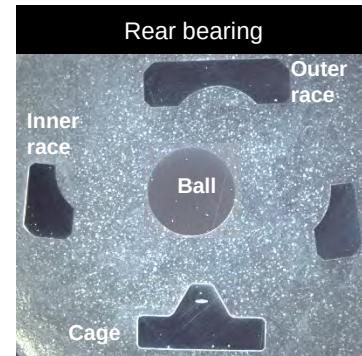
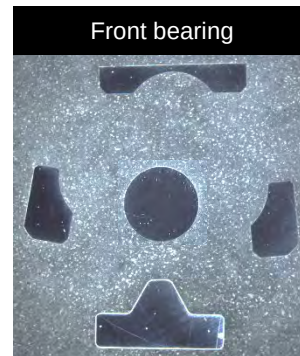
○ Hardness

- Outer race (Spec : 61-64 HRC)
- Inner races (Spec : 61-64 HRC)
- Balls (Spec : 61-65 HRC)
- Cage (Spec : 30-35 HRC)

→ **Hardness measurements comply with specification**

→ **The bearings' condition indicate operation with high temperature**

→ **High temperature not associated with unsatisfactory lubrication**



Measurements

63 HRC

61-64 HRC

63-64 HRC

32 HRC

63-63.5 HRC

61-64 HRC

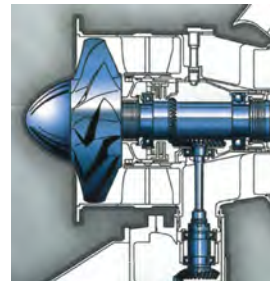
63-64 HRC

32-33 HRC

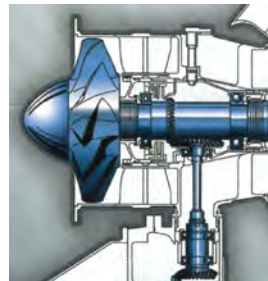
N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Compressor

- **Bevel gear 35-42 teeth**
 - Surface deposit on both gears. Peels off easily.
 - Flanks and splines unremarkable with no findings to report



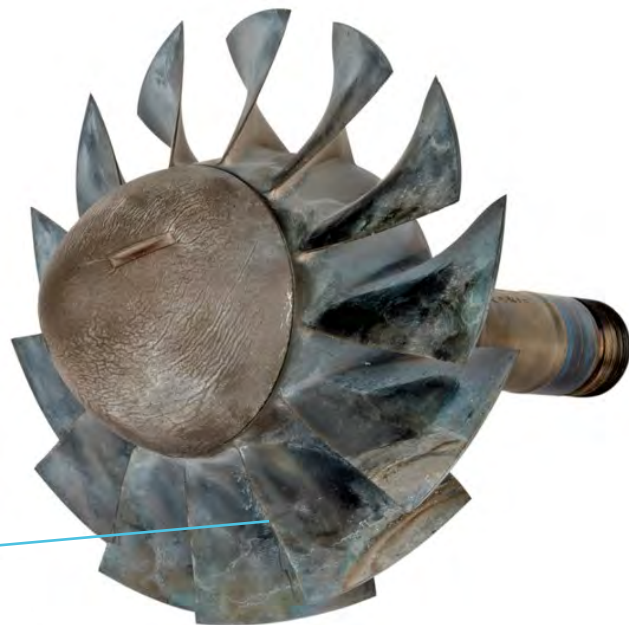
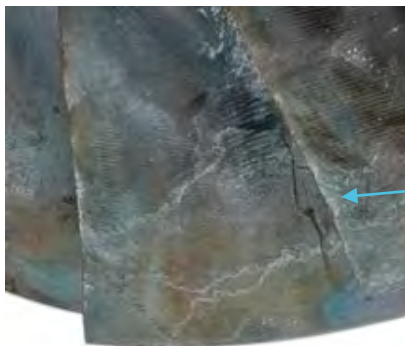
N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



□ Compressor

• Axial Wheel

- Heat generated wrinkles on inlet cone
- Dark blue coloration of blades (titanium)
 - **Axial compressor exposed to high heat consistent with the post-crash fire**
- All leading edges rough with numerous small impacts
- All blades affected the same way
- No significant erosion
 - **Impacts due to homogenous grit-like ingestion**

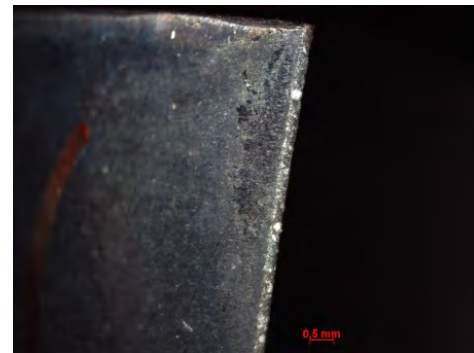


N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Compressor

• Centrifugal impeller

- Rubs at blade tips due to contacts with cover consistent with rear bearing deterioration
 - All leading edges rough with numerous small impacts
 - All blades affected the same way
 - Consistent with the axial wheel's condition
 - No significant erosion
- **Impacts due to homogenous grit-like ingestion**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

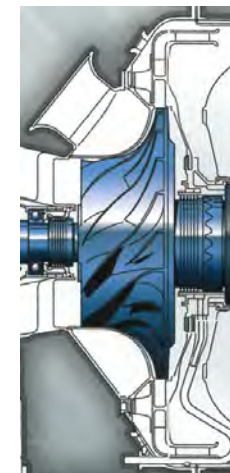
□ Compressor

• Centrifugal diffuser

- Leading edges in good condition
- No erosion
- No FOD impact marks

→ **No findings to report for the centrifugal diffuser**

→ **Grit ingestion exceptional and not sustained**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

Compressor

Summary of findings

Axial wheel

- All leading edges rough due to grit-like ingestion
- Whitish deposit on all blades and dark blue coloration due to post-crash fire

Nose cone

- Wrinkles due to post-crash fire

Bearings

Dark colour consistent with operation at high temperature

Centrifugal diffuser

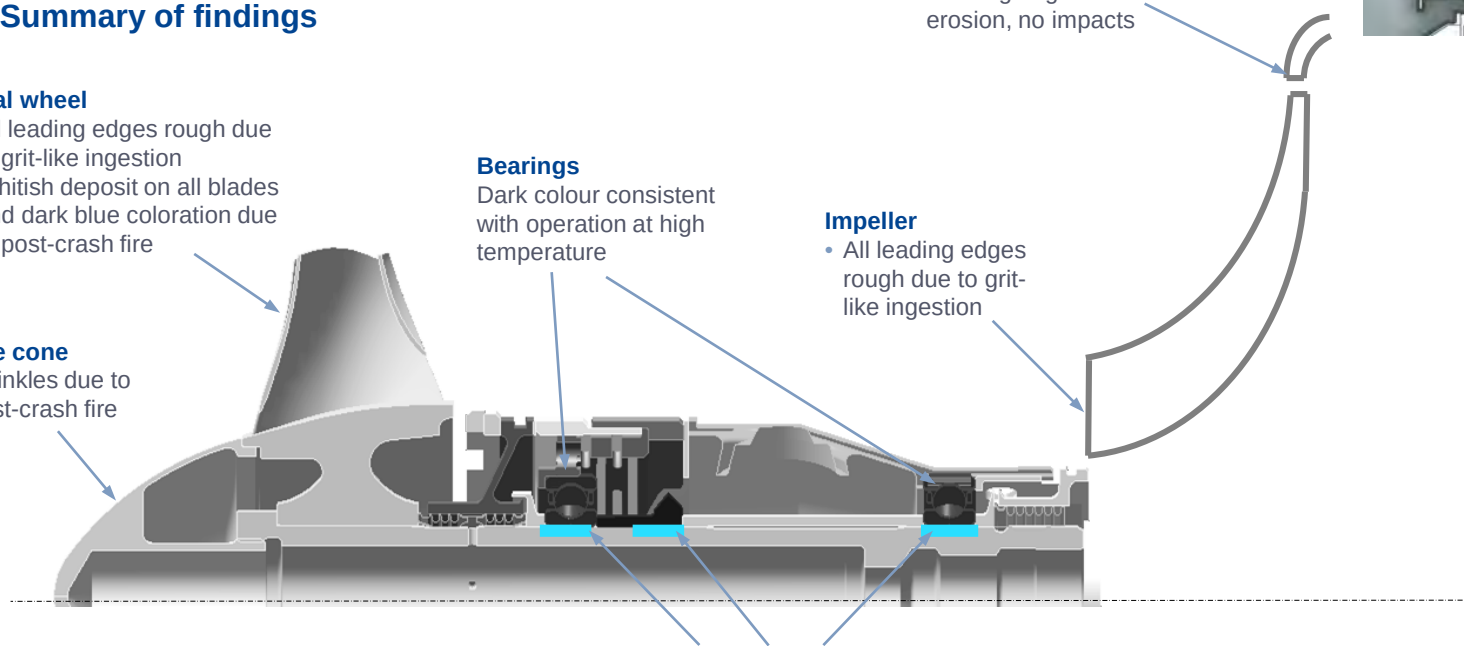
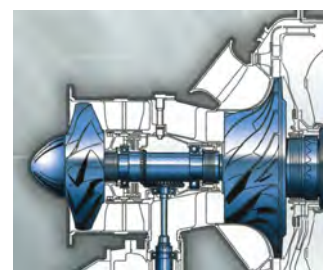
- Leading edges : no erosion, no impacts

Impeller

- All leading edges rough due to grit-like ingestion

Axial compressor shaft

- 3 significant local colorations due to high heat transfer from bearings and gear
- No indication of relative rotation with the shaft of inner races and 35 teeth gear



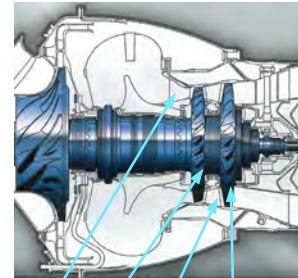
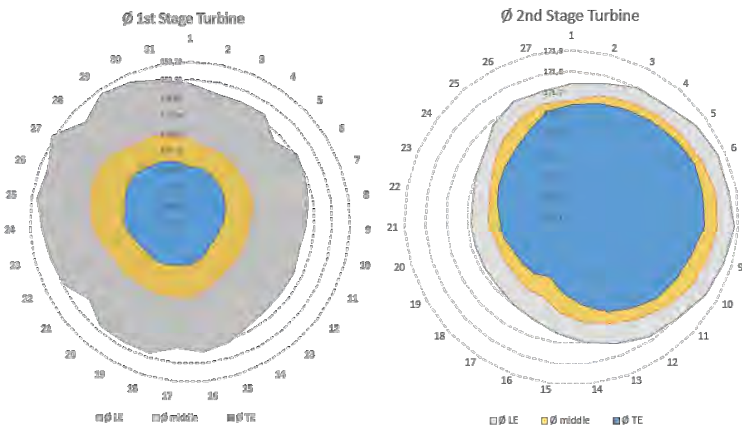
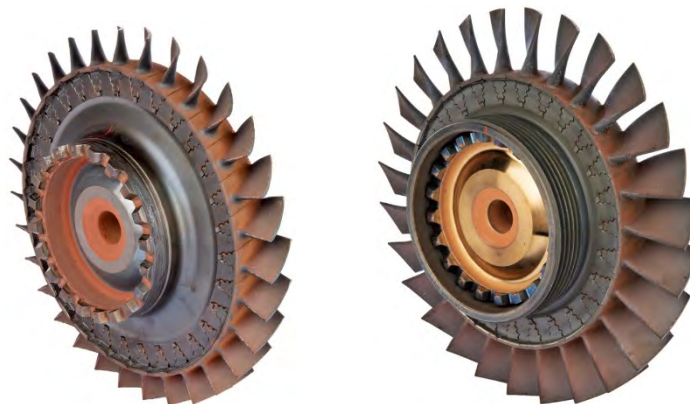
N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Gas Generator

• HP Turbines

- Tip rubs on all blades (HPT1 and 2)
- No blade ruptures
- DPI checks on blades : no cracks
- Contact marks on Nozzle Guide Vanes' shrouds with metal transfer (120° of circumference on NGV1 and 90° on NGV2)

→ Even wear at HPT1&2 blades' tips due to light contact with shrouds



NGV1 HPT1 NGV2 HPT2



NGV1 sector of contact



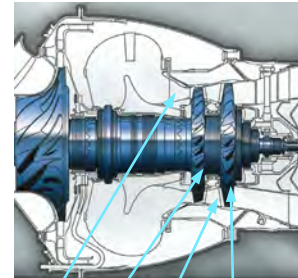
NGV2 sector of contact

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

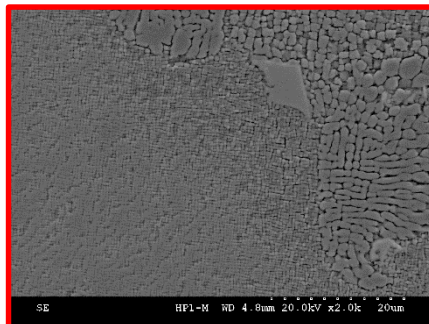
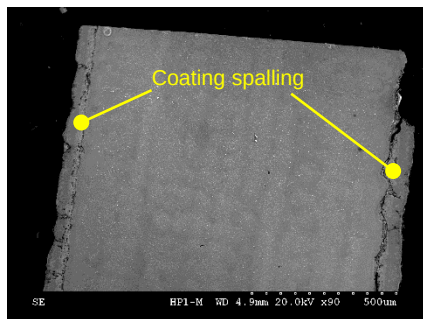
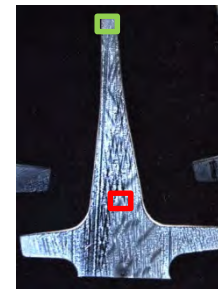
□ Gas Generator

• HP Turbines : HPT1

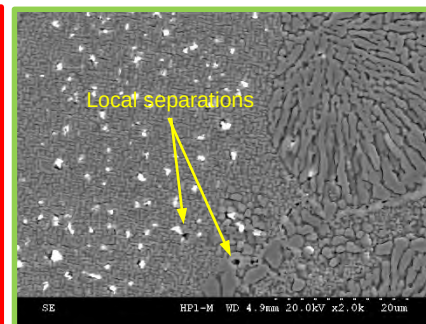
- Coating spalling near blade's tip
- Metallographic structure evolution from blade foot to tip indicative of metal temperature increasing towards the tip
- Local separations at grains' boundaries near the blade tips indicative of light creeping phenomenon
 - **HPT1 blades' condition in line with experience and does not indicate excessive usage beyond the normal range**
- Presence of thin layer of resolidified blade metal on tips
 - **HPT1 blades' tips condition indicative of sustained rubbing with shroud**



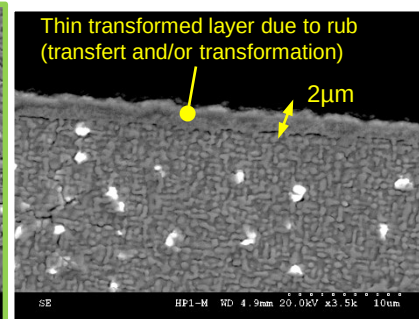
NGV1 HPT1 NGV2 HPT2



Blade foot



Blade tip



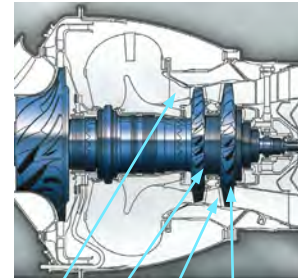
Rub on tip

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

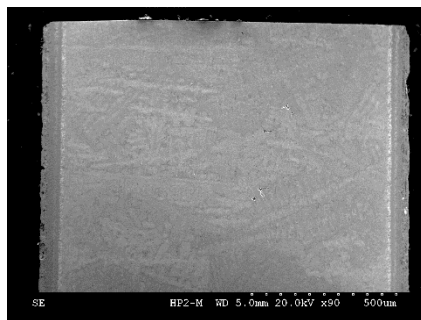
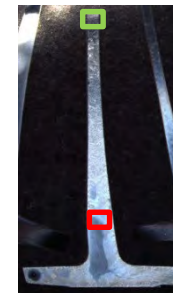
□ Gas Generator

• HP Turbines : HPT2

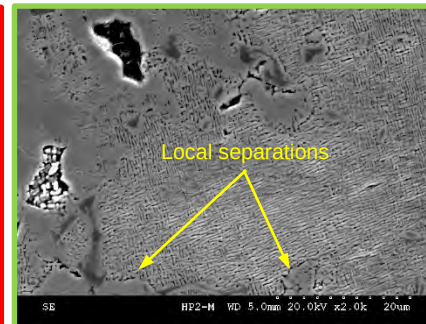
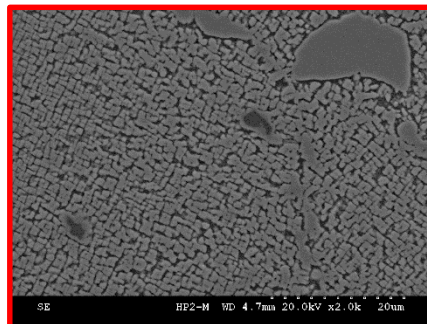
- Coating spalling near blade's tip
- Metallographic structure evolution from blade foot to tip indicative of metal temperature increasing towards the tip
- Local separations at grains' boundaries near the blade tips indicative of light creeping phenomenon
 - **HPT2 blades' condition in line with experience and does not indicate excessive usage beyond the normal range**
- Presence of thin layer of resolidified blade metal on tips
 - **HPT2 blades' tips condition indicative of sustained rubbing with shroud**



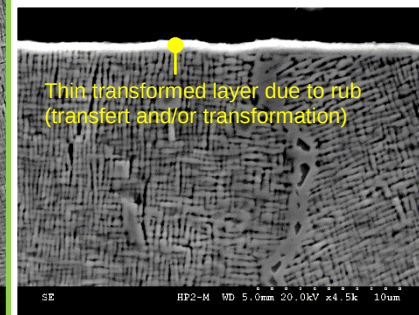
NGV1 HPT1 NGV2 HPT2



Blade foot

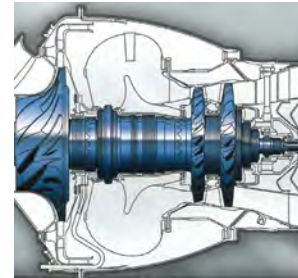


Blade tip



Rub on tip

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

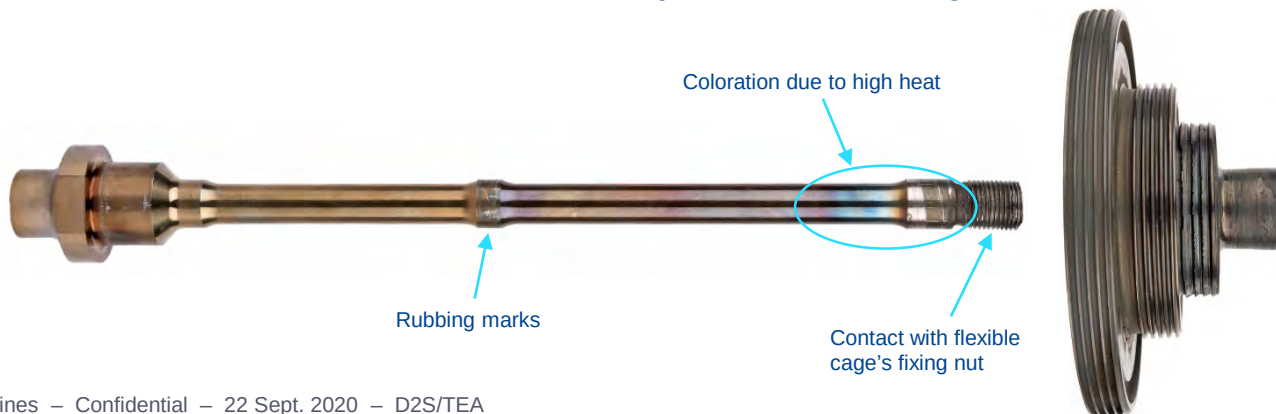


□ Gas Generator

• Tie bolt and piston shaft

- Light even circular wear of the large and middle labyrinths
→ no significant unbalance has occurred
- Pronounced wear of the small labyrinth due to contact with the ring that separated from the rear bearing casing
- Heavy wear marks with metal transfer on the rear shaft where the bearing's inner ring normally sits
- Tie bolt shows stains indicative of high heat in area normally below the rear bearing
- Threads worn at bolt's end due to contact with rear of bearing's casing after bearing's deterioration

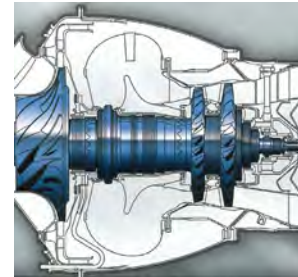
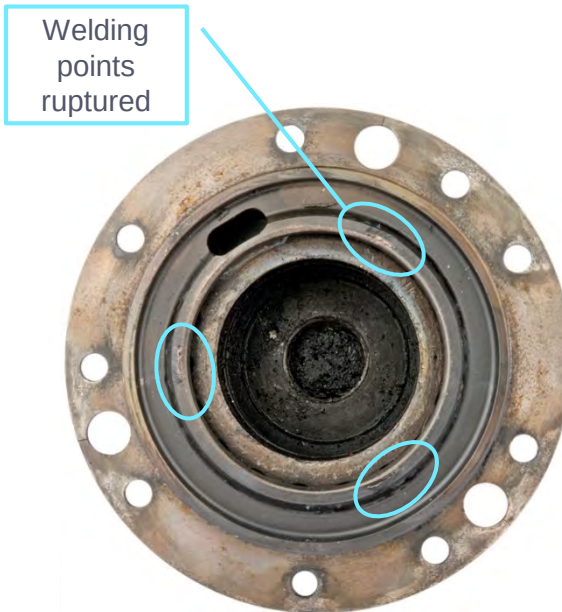
→ **Signs of deterioration and wear are indicative of operation without high unbalance and with seized bearing**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

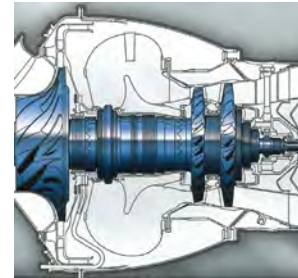
□ Gas Generator

- **Main rear bearing assembly components**



- | | | |
|---|--------------------------------------|---|
| o Rear bearing seizure | o No significant amount of coking | o No significant amount of coking |
| o Rollers flattened
(see also following pages) | o Lubrication hole clear | o Small labyrinth's outer ring had separated. Three welding points ruptured. (see also following pages) |
| | o Material check : 15CDV16 (Conform) | |

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



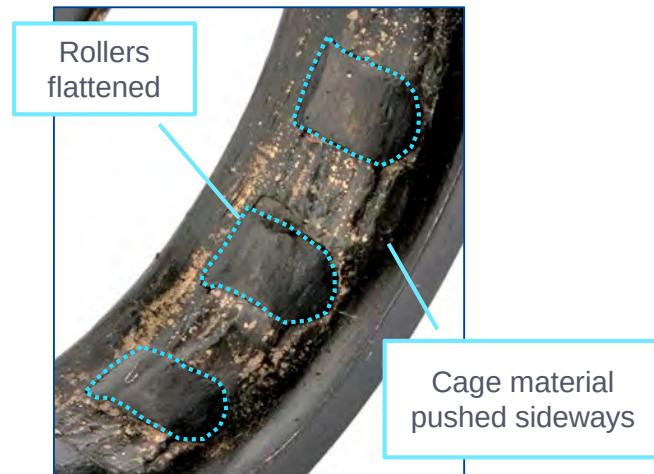
Gas Generator

Rear bearing examination

General examination :

- Bearing totally seized with all its rollers flattened due to rubbing with the inner race
- Separating cage showed plastic deformation with material pushed forward and backwards (see also photos on following pages). It shows signs of circular rubbing against the inner race.

→ Operation with seized rollers rubbing against the inner race



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Gas Generator

• **Rear bearing examination**

○ General examination :

- Track in outer race shows friction marks left by rollers.
- Friction of limited extent as geometry of outer race mainly intact.
- Rollers exhibit a flat top where they rubbed with the outer race.
- Surface of “flat top” limited

→ **Operation with seized rollers locked in position with respect to the outer race**

- No signs of movement (rotational or longitudinal) of the outer race inside its support cage.

→ **No signs of unsatisfactory installation**

Outer race :
no signs of
movement



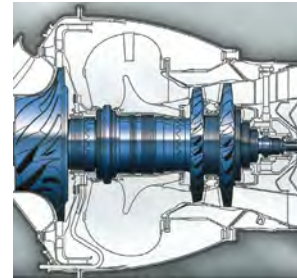
Rollers with
flat tops



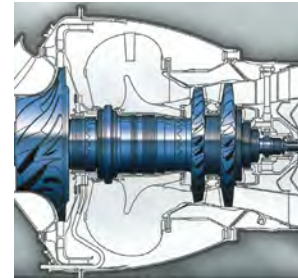
Friction marks
on track



Cut-off section of outer ring



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



□ Gas Generator

• **Rear bearing examination**

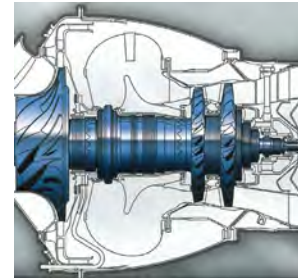
○ Inner race :

- Race fractured into small fragments.
- The sum of the fragments did not allow to reconstitute the whole ring. Other fragments destroyed into small debris and found downstream (magnetic plug, strainer, oil pump).
- The fragments' thickness was progressively reduced to approx. a third of the race's nominal thickness.
- The fragments' lamination and deformations consistent with sustained friction with the seized rollers.
- Some material of the race has transferred to the "Piston" shaft under friction (see p.88)

→ **Final condition of the inner race indicative of sustained rubbing with seized rollers**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



Gas Generator

Rear bearing examination

Metallic composition checks :

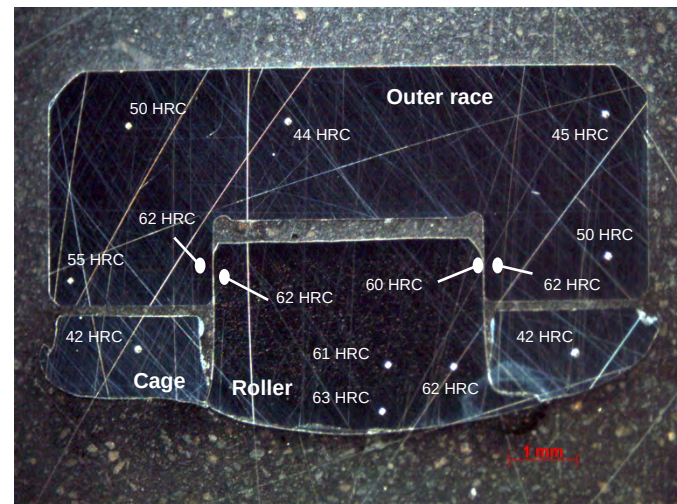
- Outer race : 80DCV40
- Roller : 80DCV40
- Cage : 40NCD7
- Inner race : 80DCV40

→ All materials comply with specification

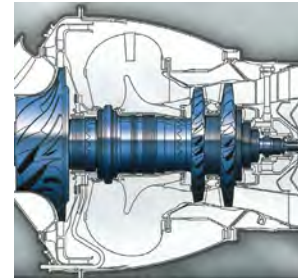
Hardness checks :

- Outer race : 44-62 HRC (spec 61-64 HRC)
- Inner race : Fragments too small
- Roller : 60-63 HRC (spec 61-64 HRC)
- Cage : 42 HRC (spec 25-33 HRC)
- Under rising temperature conditions, the hardness for these metals initially drops and then increases again. This could indicate that the temperature experienced by the rollers was higher than that experienced by the outer race.

→ The hardness levels found are consistent with the friction with the inner race



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



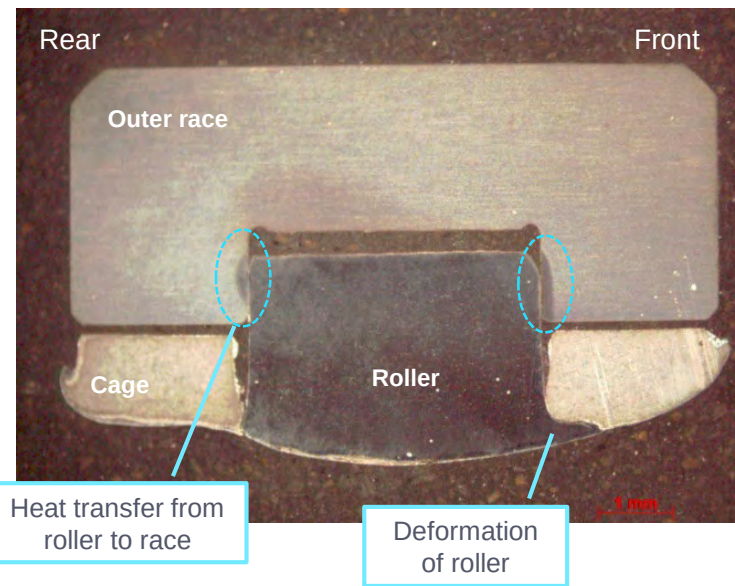
Gas Generator

Rear bearing examination

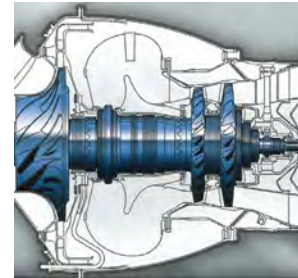
Microstructure examination :

- A section of the bearing was cut and polished. It was submitted to a Nital etch surface treatment and examined with a SEM.
- For each component taken separately, the etch treatment showed uniform coloration thus indicative of homogenous temperature throughout each component. The colour difference between the roller and the outer race (same material) could indicate that the temperature experienced by the two components was different.
- The cut section shows the plastic deformation of the separation cage indicative of friction and high temperature
- Two darker local areas on the outer race are indicative of heat transfer by conduction from the rollers to the outer race.
- Deformation of the rollers with spread of material at the area that rubbed with the inner race.

→ **Seized rollers transferred rubbing heat to the outer race**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



□ Gas Generator

• **Rear bearing examination**

○ Summary of examination :

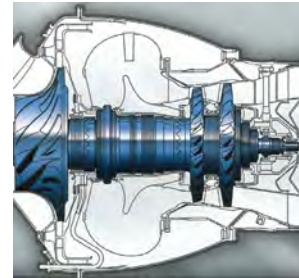
- No signs of unsatisfactory installation
- All materials comply with specification
- Operation with seized rollers rubbing against the inner race
- Final condition of the inner race indicative of sustained friction with rollers

○ Manufacturing history :

- Delivered to SafranHE on 29 Sept. 2010
- No non-conformances recorded
- Fitted to module 3 s/n 25263 (new build in factory) which was released 29 Nov. 2010
- Module 3 fitted to engine s/n 47346 (new build in factory) which was released 8 Dec. 2010

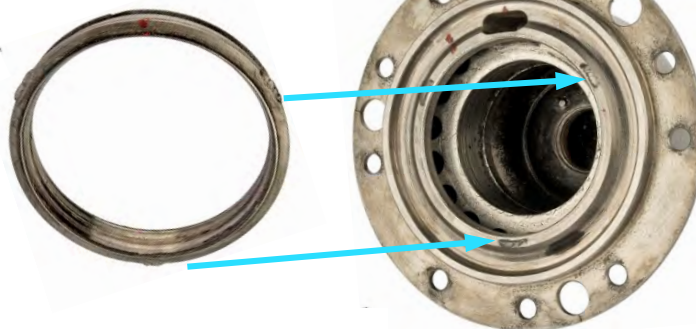


N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



□ Gas Generator

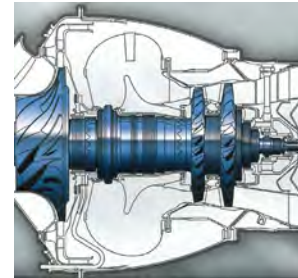
- **Small labyrinth and ring** (note : photos taken after cleaning of components)
 - Even circular grooves inside the ring due to radial penetration of the labyrinth's lips
 - No rupture of and no cracks in the ring
 - No colour change of the ring indicative of no sustained operation with light contact of lips' tips with ring
 - Three welding points ruptured straight through
→ Sudden static rupture



- At engine shut-down, the Gas Generator runs through resonance modes when slowing down
- The deteriorated rear bearing allowed for abnormal radial play thus allowing contact between labyrinth and ring

→ **It is very likely that the labyrinth's ring separated due to sudden contact with the piston shaft's small labyrinth when the Gas Generator experienced resonance modes when slowing down after engine shut-down**

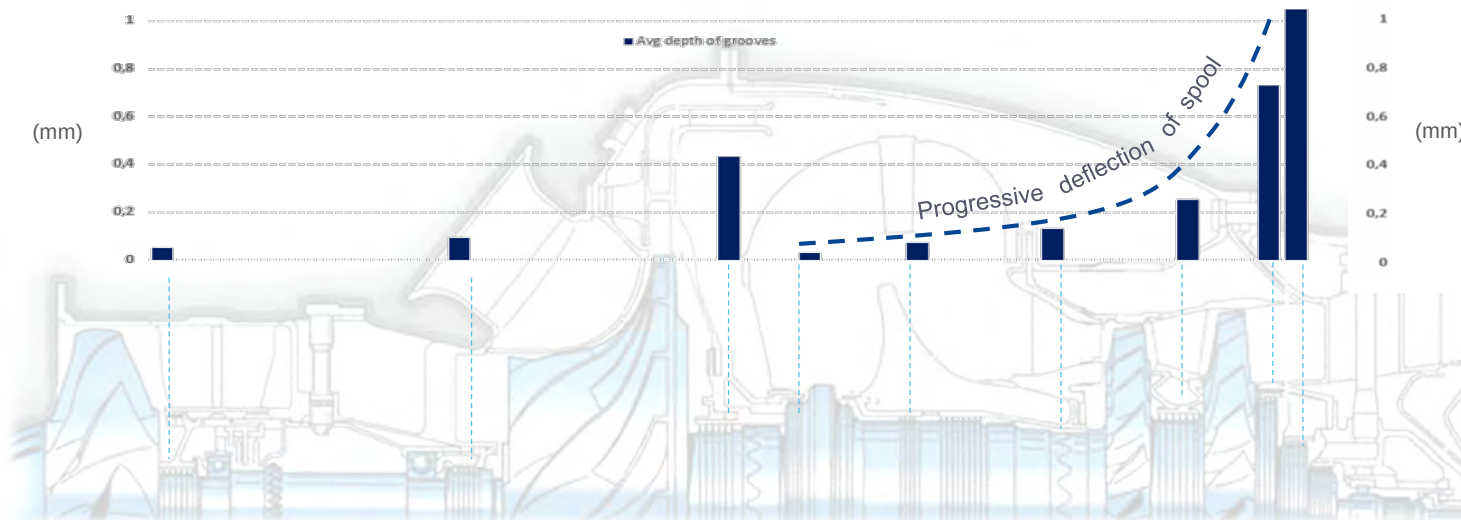
N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



□ Gas Generator

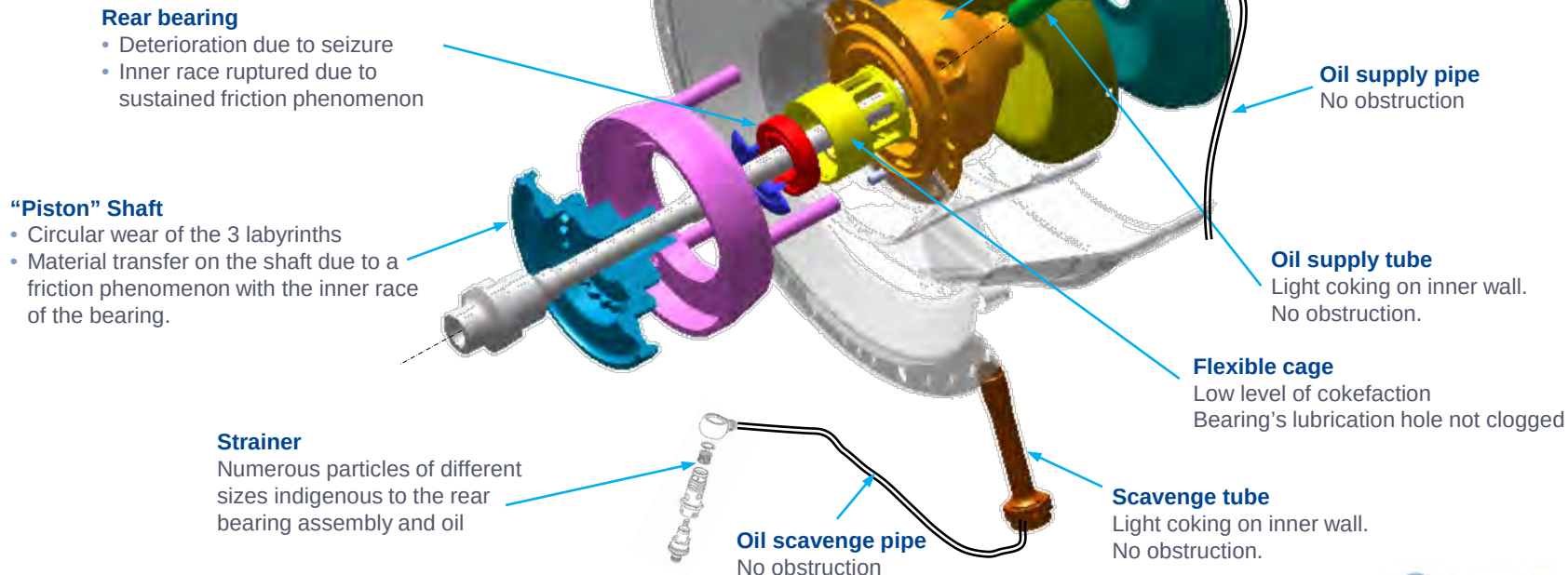
• Labyrinths

- Circular wear of the labyrinths along the Gas Generator spool → **no significant unbalance has occurred**
- Labyrinths' seals cut grooves in their respective rings with progressive increase of grooves' depth when progressing towards the back → **Progressive deflection of the Gas Generator spool consistent with rear bearing deterioration**

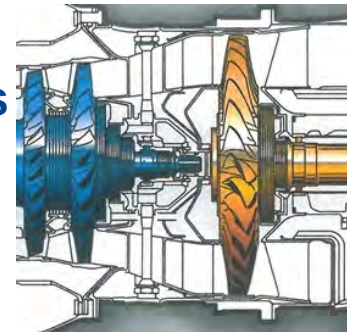


N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Gas Generator



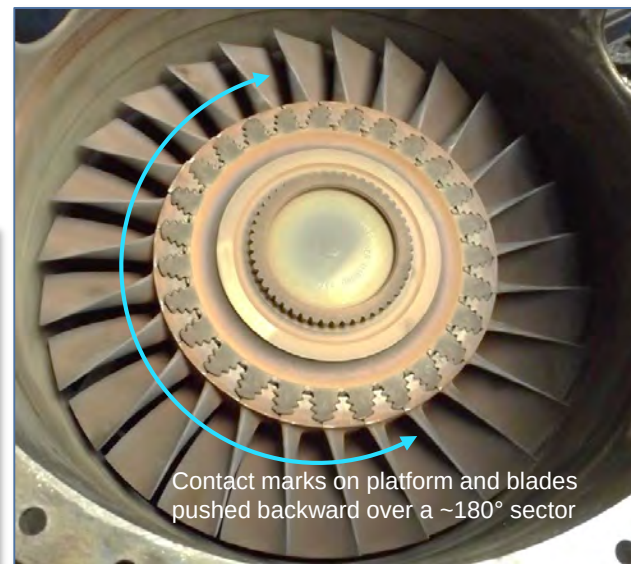
N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses



□ Power Turbine

- Impact marks on front face of PT blades' platforms over a ~180° sector with blades pushed backwards and wire lock lifted
- Imprints in the back face of the PT_NGV at places coinciding with the position of the PT blades' forward platforms

→ **The PT wheel impacted the PT_NGV at standstill**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Reduction gearbox

- The reduction gearbox was opened.
- No findings to report regarding the gears and the bearing races
- An oil sample was collected for analysis (see next page)
 - **No signs of operation with insufficient lubrication or with oil over-temperature**



Drive input gear

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil analysis

- Oil type : Mobil Jet II
- The oil sample was collected in the reduction gearbox

• Spectrometric Oil Analysis (SOA)

Elément chimique	Concentration
Fe	2,3
Cr	0,31
Ni	6,29
Al	< 0,01
Cu	0,07
Zn	3,39
Ti	< 0,01
Mg	0,84
Ag	< 0,01
Sn	< 0,01
Si	0,96
Cd	13,34
Pb	< 0,01

→ Metal levels globally low except for Nickel and Cadmium

→ **The oil exhibited degraded physico-chemical characteristics**

→ **It could not be determined if the degradation occurred prior or after the post-crash fire**

• Oil Quality Analysis (RULER)

- ◆ Not Conform
- ◆ Residual additives: 9 %
- **Lower than min antioxidant level set at 70% by specification**

• Oil Viscosity

- ◆ Viscosity at 40°C = 28.8 cSt
- **For comparison, viscosity specified on a new oil sample > 23 cSt (i.a.w. MIL-PRF-23699)**

• Oil acidity

- ◆ Acidity = 22 mg KOH/g
- **For comparison, the acid index measured on a new oil sample was 0.05 mg KOH/g**

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Oil analysis

- SOA records according to operator's documentation

Jump (value doubled)

Sample Date	Eng Time	Oil Time	Add	Fe	Cr	Pb	Sn	Mg	Si	Cu	Ag	Ni	Al
11/30/2016	2255	80	1	3.00	0.0	0	0.0	0.0	8	0.0	0.3	0.0	0.3
01/16/2017	2341	300	1	2.55	0.0	0	0.0	0.0	7	0.0	0.1	0.0	0.4
04/03/2017	2406	100	1	3.20	0.0	0	0.0	0.0	1	0.0	0.3	0.3	0.2
05/15/2017	2497	0	2	6.20	0.1	0	0.0	0.1	3	0.1	0.3	0.0	0.2
07/07/2017	2587	253	1	6.75	0.3	0	0.0	0.0	5	0.0	0.6	0.3	0.5
08/14/2017	2665	73	1	4.19	0.0	0	0.0	0.1	5	0.0	0.5	0.0	0.1

Oil change
65 hrs after oil change
Engine removed
156 hrs after oil change
246 hrs after oil change
73 hrs after oil change (Oil changed at 2592 hrs)

- High concentration of Iron (Fe) in all samples
- From May 2017 onwards, high jump in Iron (Fe) value with Chrome (Cr) showing up and rising
- Oil time recorded on 15 May 2017 is odd (0 hours). Last recorded oil change 156 hrs earlier on 12 January 2017
- Iron high in last sample considering the low oil time
- Alert criteria : Fe = 7,5ppm
- Removal criteria : Cr $\geq$ 0,7 and Fe > 6 OR Fe = 15ppm

→ **The SOA analysis reveals increasing Iron levels with a jump between April and May 2017, between 214 and 305 hours before the accident**

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Engine 2's bearing condition vs typical bearing deterioration modes

• General causes of deterioration : Matching findings on Engine 2 :

- **Lack/insufficient lubrication** → All oil supply pipes, restrictors and jet found clear. Debris need oil flow to be carried to the magnetic plug. Oil pump and reduction gears and bearings : no signs of operation under lack/insufficient lubrication. No information about possible flights with one engine deliberately shut-down (windmilling).
- **Excess of oil in chamber** → No indication that scavenge line was blocked prior to bearing deterioration. No signs of oil out of rear bearing chamber.
- **Pollution of oil system** → Oil analysis : all metallic components found in debris were indigenous to rear bearing assembly and oil. Possible coarse sand/grit ingestion. High level of Iron and rising level of Chromium in SOAP.
- **Excessive loading** → No signs of operation under excessive unbalance or overload.
- **Material discrepancy** → Materials checked and found correct.
- **Internal discrepancy** → Bearing showed damage limiting the extent of the examination. No discrepancy found during its examination. No non-conformances before delivery. The engine was operated for 2711hrs since new.
- **Dimensions out of tolerances** → Bearing showed damage preventing dimensional checks. However, its examination did not reveal any discrepancy and the engine was operated for 2711hrs since new.
- **Improper assembly** → No sign of movement of bearing in the cage. No disassembly since new according to the maintenance records and engine was operated for 2711hrs since new.
- **Misalignment (between rings)** → Same as above
- **Excessive oil temperature** → Reduction gears : no signs of operation under excessive temperature.
- **Mishandling of engine (shocks, fall,...)** → Engine was removed 305hrs before the accident during deep aircraft maintenance. Doubling of Iron value and rising value of Chromium in SOAP afterwards.
- **Oil quality** → The oil exhibited degraded physico-chemical characteristics.
It could not be determined if the degradation occurred prior or consequently to the post-crash fire.

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Rear bearing's condition summary

- The investigation identified potential contributing factors to the deterioration of the rear bearing :
 - Pollution of the oil system due to sudden coarse sand/grit ingestion
 - Mishandling during engine removal 305hrs before the event
 - Oil quality
- The participation of the potential contributing factors could not be demonstrated

→ **Potential contributing factors to the deterioration of the rear bearing were identified**

→ **Considering the information available and the engine's condition (post-crash fire, crash and recovery damage and rear bearing's deterioration), the origin of the bearing's seizure could not be confirmed**

Gas Generator's rear bearing context



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

☐ Rear bearing and environment – Design evolutions

- **TU 267** : Increase of bearing's radial play
Implemented since 2004
- **TU 347** : Redesign of 2nd stage HP turbine (N/A for Arriel 1E2)
Implemented since 2007
- **TU 357** : Increased clearance in small labyrinth
Implemented since 2007
- **TU 360** : Redesign of the hollow shaft to reduce dust/laterite accumulation
Implemented since 2009



❑ Rear bearing and environment – Maintenance documentation evolutions

- Review of the maintenance manuals in order to mitigate the effect of known contributors :
 - Maintenance Manual (levels 1 & 2) : bearing assembly / disassembly tasks reviewed (particularly circlips installation and bearing cage installation tasks in Chap 72-43-10) and found unambiguous.

However, in 2010, following points added :

- Task to check the bearing's condition and its replacement if in doubt (rear bearing installation procedure)
- Details relative to precautions to be taken regarding bearing handling, cleaning and protection
- Task to check proper installation of bearing and flexible cage assembly in bearing chamber

Addition of vibration check (AD 2012 – 0117) in flight up to 98 % NG following rotating component replacement.

- Maintenance Technical Instruction manual (level 3 maintenance) : in 2010, update to clarify further the marking and alignment process of the Module 3 rotating parts.
- Service Letter N° 2825 issued in December 2011 :

Reminder regarding the Flight Manual and EMM recommendations in case of “chip” light illumination in flight and particles found on Module 3 rear bearing electrical chip detector.

Review and Analysis of findings
Engines 1 & 2

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Review and analysis : Engines 1 & 2 condition

- Aircraft was not fitted with sand filters on the air intakes
- Axial wheels and impellers : rough leading edges on both engines. No FOD impacts.
- Centrifugal diffusers' vanes : good condition. No erosion, no FOD impacts.
- SOA records : high value "Si" for both engines on all recordings.
- Examination of both combustion chambers was unremarkable.

Findings consistent with exceptional ingestion of coarse sand/grit by both engines.

→ Possible migration in the oil system

Combustion chambers' conditions unremarkable and not obstructed with coarse sand/grit.

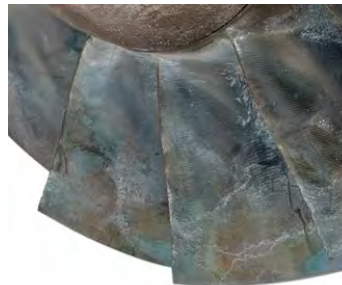
→ Does not support engine flame-out for last flight



Axial wheel Engine 1



Centrifugal diffuser Engine 1



Axial wheel Engine 2



Centrifugal diffuser Engine 2



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Review and analysis of findings : Engine 1 condition

- The examinations showed that the engine was in a good condition with no pre-crash damage found.
 - Considering the information available and the engine's condition (post-crash fire, crash and recovery damage), some of the possible origins for the the fuel control lever in the stop position could not be checked or are outside SafranHE's scope.
- **The examinations carried out did not reveal discrepancies that could explain the fuel control lever in the stop position and the engine at stand-still**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Review and analysis of findings : Engine 2 condition

- SOA records : Iron (Fe). Values significantly higher on Engine 2 than on Engine 1. Value doubled after deep aircraft maintenance (engine was removed from aircraft).
- Start of presence of Chrome (Cr) coincided with Iron (Fe) value's jump.
 - **Progressive wear of a steel component in Engine 2**
 - **Worsened after engine removal and re-installation on aircraft, 305hrs before accident**
- Even circular wear of labyrinths and HP turbine wheels
- Gradual increase of labyrinths' wear towards the rear of the Gas Generator
- Presence of thin layer of resolidified blade metal on tips indicative of light tip rub with shroud
- “Laminated” rear bearing's inner race. Broken into several large fragments and numerous small fragments
 - **Progressive wear of rear bearing led to progressive Gas Generator rotor / stator contact**
- Rear bearings' progressive wear would increase the load on and temperature of the compressor's bearings
 - **Unusual blue marks on compressor's shaft consistent with increased load as rear bearing's wear increased**
- Heavy presence of metallic particles in rear bearing scavenge line (strainer & oil pump) and on magnetic plug
 - **Progressive wear of rear bearing released numerous particles down the scavenge line**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

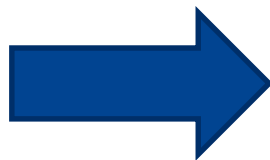
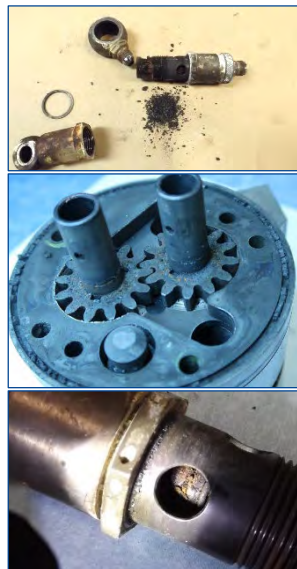
□ Review and analysis of findings : Engine 2 condition (continued)

- Considering the information available and the engine's condition (post-crash fire, crash damage and rear bearing's deterioration), the origin of the bearing's seizure could not be determined, although the following potential contributors were identified :
 - **Mishandling during engine removal 305 hrs before the event**
 - **Pollution of the oil system due to sudden coarse sand/grit ingestion**
 - **Oil quality**
- No signs of sudden rotor / stator contacts except at “Piston” shaft small labyrinth's level
- No signs of oil out of the rear bearing chamber
 - **Separation of small labyrinth's ring occurred during engine shut-down (contact likely due to resonance modes when Gas Generator is slowing down)**

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

❑ Review and analysis of findings : Engine 2 condition (continued)

- Numerous metallic particles found on the electric magnetic plug for the Gas Generator rear bearing and scavenge stage of the oil pump
- Normally, the activation of the electric magnetic plug leads to an “ENG CHIP” caution in the cockpit



→ **Metallic particles on electric magnetic plug should have led to “ENG CHIP” caution in cockpit**

N146DU (SafranHE ref.: RA 2017/238) – **Investigation Findings & Analyses**

Review and analysis of findings : Fire and Smoke

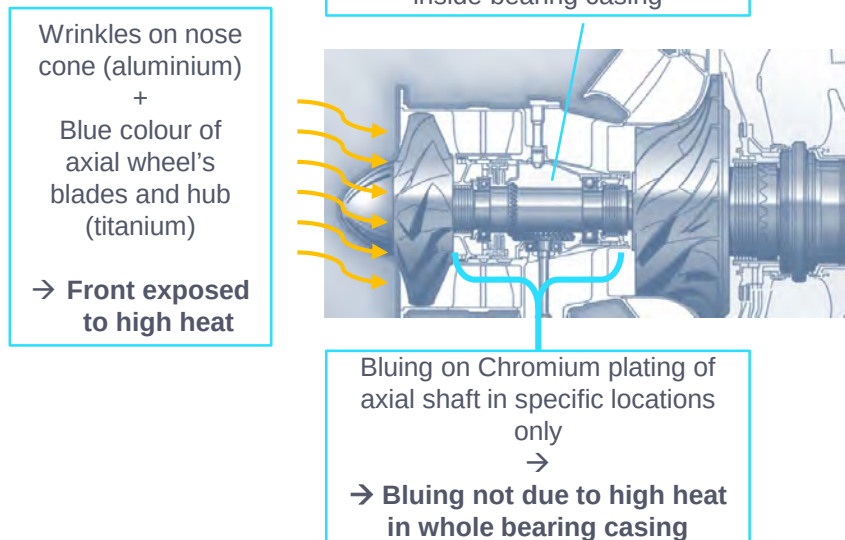
- Engine 1 :
 - No signs of oil out of the rear bearing chamber
 - No discrepancy found in oil system
 - No indications of oil run-off in main air path
 - No discrepancies (other than crash-related damage) found with Engine 1 fuel, oil and vent pipes

→ **Smoke or fire due to oil escaping from Engine 1 appears very unlikely**

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Review and analysis of findings : Fire and Smoke

- Engine 2 : axial compressor



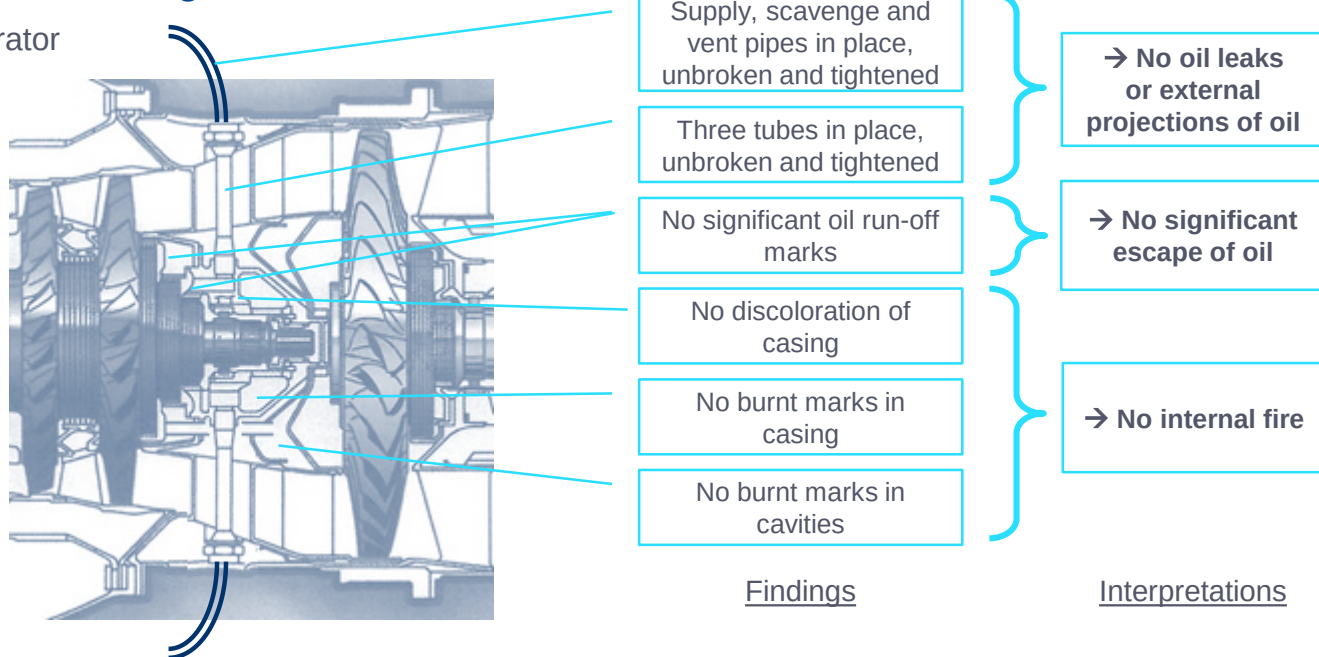
→ No indications of fire originating from inside the compressor bearing casing

→ Heat damage at front due to the post-crash fire

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Review and analysis of findings : Fire and Smoke

- Engine 2 : Gas Generator



→ No indications of internal fire in Engine 2's rear bearing environment

→ No external projection of oil on hot engine components around rear bearing's environment



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Review and analysis of findings : Fire and Smoke

- Engine 2 : Gas Generator (continued)
 - Progressive wear of the rear bearing of the Gas Generator
 - **Progressive wear of the piston shaft's labyrinths**
 - Separation of the small labyrinth during the engine shut-down
 - **Escape of oil mist from rear bearing chamber possible during engine shut-down**
 - Light soot run off marks on the front face of the rear bearing chamber. No significant “swirl” pattern.
 - **Light escape of oil towards main air path (could be during engine shut-down)**
 - Bearing wear, reduced clearance at HP Turbine level and/or rapid changes in direction of the aircraft very likely led to increased rotor/stator friction and to wear of the HP turbine tips.
 - **Engine flame out cannot be excluded which, by experience, produces puff of smoke at the back of the engine.**
 - **It is very likely that the damaged HP Turbine and the rotor/stator friction led to degraded combustion and gas flow conditions as well as to smoke at the exhaust.**

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

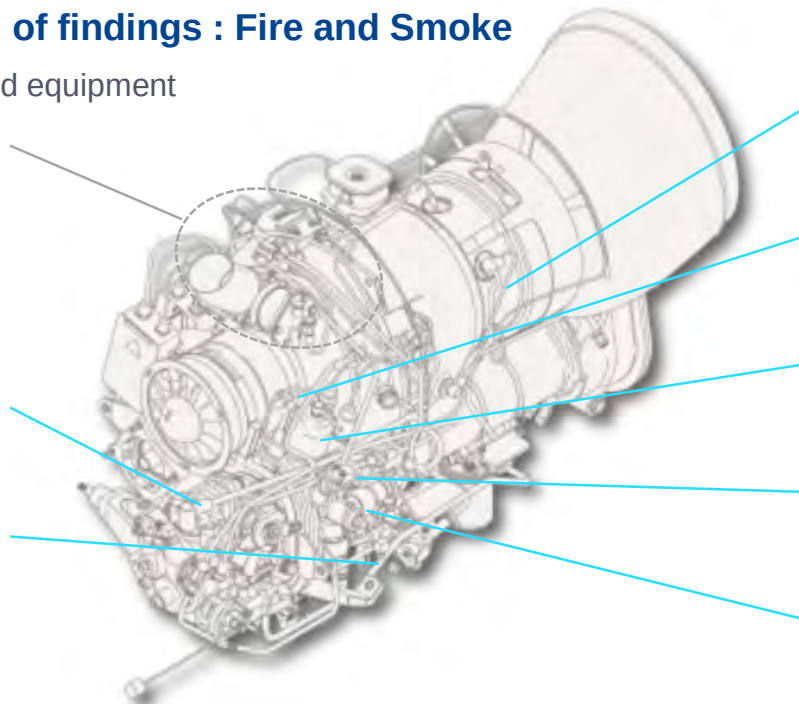
□ Review and analysis of findings : Fire and Smoke

- Engine 2 : Dressing and equipment

Post-crash fire damage to valve assembly and bleed valve.
Cannot be assessed

Fuel control unit place,
unbroken and tightened

Fuel pipes in place, unbroken
and tightened



Oil pipes to/from rear bearing in
place, unbroken and tightened

Oil pipes to/from compressor in
place, unbroken and tightened

Oil filter assembly in place,
unbroken and tightened

Oil pump in place, unbroken
and tightened

Magnetic plug assembly in
place, unbroken and tightened

→ **No discrepancies found with pipes and equipment of Engine 2**

→ **Escape of oil or fuel very unlikely**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Review and analysis of findings : Fire and Smoke

- Engine 2 : Summary

→ Heat damage at front of compressor due to the post-crash fire

- No indications of fire originating from inside the compressor bearing casing
- No indications of internal fire in Engine 2's rear bearing environment
- No discrepancies compatible with external projection of oil on hot engine components around the rear bearing's environment
- No indications of significant escape of oil in vent pipe
- No discrepancies found with pipes and equipment of Engine 2

→ Fire due to escape of oil or fuel under the cowlings is very unlikely

- Light escape of oil towards main air path (could be during engine shut-down)
- Degradation of the secondary air system around the rear bearing chamber and/or engine flame-out could produce puff of smoke at the back of the engine
- Operation with degraded combustion conditions very likely led to smoke at the back of the engine

→ With rear bearing degraded, smoke at the back of the engine is very likely

**Engines' Performances and
Operation Analysis**
Engines 1 & 2

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Engines 1 & 2 performance analysis

- Engines' power check results :

Date	TSN (hrs)	Time to accident (hrs)	NG Margin s/n 47292 (%)	NG Margin s/n 47346 (%)	
10 January 2017	2338	373	0.3	0.4	On ground
9 February 2017	2379	332	1.1	1.2	On ground
1 April 2017	2407	304	1.4	1.9	On ground
19 April 2017	2444	267	0.8	0.6	On ground
4 May 2017	2480	231	1.2	1.4	On ground
19 May 2017	2513	198	1.2	0.7	On ground
13 June 2017	2553	158	0.3	1	On ground
10 July 2017	2592	119	5	5	In flight
26 July 2017	2635	76	0.9	0.9	On ground
15 August 2017	2674	37	1	0.9	On ground
		Average (on ground)	0.9	1.0	

- The last power checks for both engines were performed 37 hours before the accident and the results were in line with the 2017 averages

→ **The engines' performance margins were positive throughout 2017**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Engines 1 & 2 performance analysis

- **Engines' performance calculation estimates – Generalities.**
 - The power ratings of an Arriel 1E2 engine could be estimated with our computerized engine model for an average aged engine in the known flying conditions before the event.
 - Before the rear bearing deterioration, Engine 2 is considered able to deliver the same power as Engine 1.
 - The rear bearing deterioration led to friction at HP Turbines' tips, increase of the tips' clearances and decrease of the Turbines' efficiency. Using our computerized engine model, assuming no abnormal friction and the HP Turbines' efficiency drop, theoretical power ratings could be estimated for Engine 2.



Cautions :

- **For Engine 2, the calculations are purely theoretical and performed on the basis that it may have been able to run with reduced friction at times (gyroscopic effect from the Gas Generator's rotation (~51000 RPM) and/or aircraft's trajectory) including, possibly, moments of rotation without friction.**
- **However, the calculations do not take into account the significant variations of power output that very likely occurred due to unquantifiable friction levels when the bearing started seizing. Moreover, bearing wear, reduced clearance at HP Turbine level and/or rapid changes in direction of the aircraft very likely led to increased rotor/stator friction. Engine flame out cannot be excluded.**
- **The calculations do not take into account any possible effects of the VARTOMS system.**
- **Results must be considered as indicative only.**

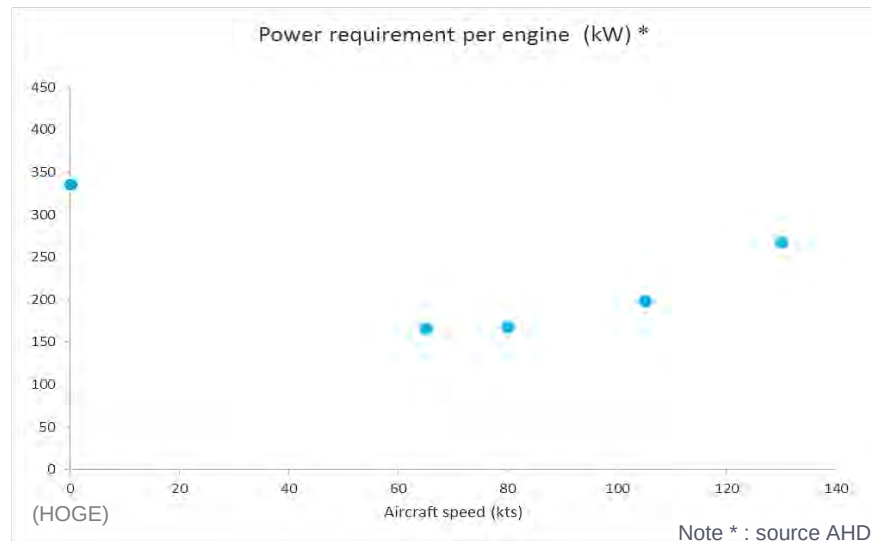
N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

Engines 1 & 2 performance analysis

- Engines' performance calculation estimates AEO conditions

Aircraft power requirements :

IAS (kts)	Alt. (ft)	T0 (°C)	Aircraft Power requirement per engine* (kW)
130	2500	24	268
105	2500	24	198
80	1200	26.6	168
65	2500	24	166
HOGE	1200	26.6	336



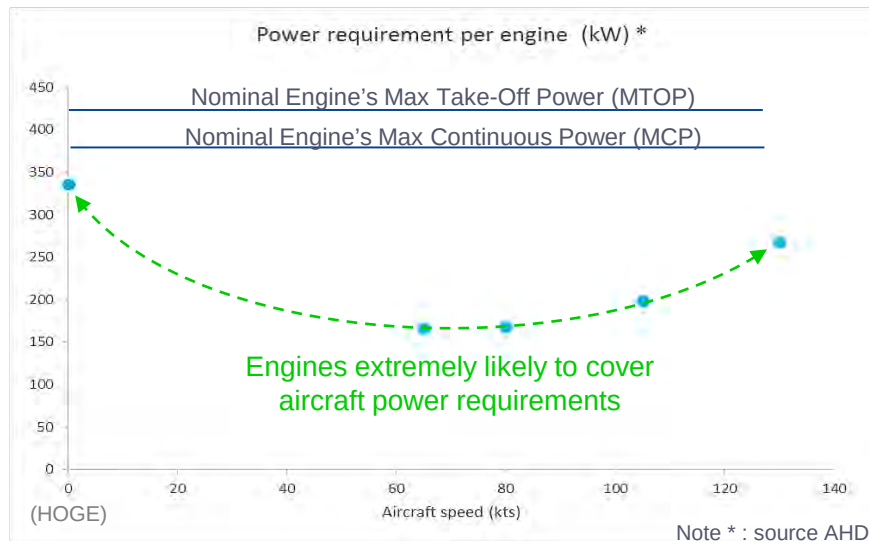
N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

Engines 1 & 2 performance analysis

- Engines' performance calculation estimates
AEO conditions with both engines in nominal condition

Estimates for an average aged Arriel 1E2 engine in nominal condition

	HOGE conditions	Continuous max Power	Take-off max Power
Engine Power	336 kW	382 kW	418 kW
T45	771 °C	818 °C	851 °C
NG	97.6 %	100 %	101.9 %



→ In the known flying conditions at the moment of the accident, it is extremely likely that both engines (in nominal conditions) were capable to meet AEO power requirements

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

Engines 1 & 2 performance analysis

- Engines' performance calculation estimates AEO conditions

Engine 1 in nominal condition

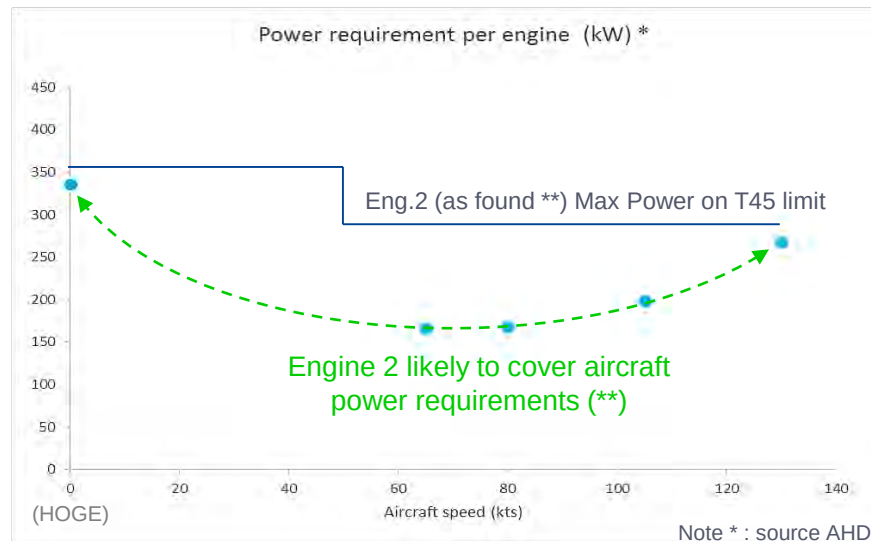
Engine 2 as found (**)

Calculation estimates :

- if T45 maintained below the transient limit (920°C), Engine 2 as found could deliver 357kW (with NTL=101% / IAS < 55kts).
- if T45 maintained below the AEO limit (845°C), Engine 2 as found could deliver 275kW (with NTL=97% / IAS > 55kts).



Note : ** Assumes no abnormal friction in Gas Generator
→ **Results must be considered as indicative only**



→ With Eng.1 nominal & Eng.2 as found (**), it is likely that the aircraft AEO power requirements could be met

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

Engines 1 & 2 performance analysis

- Engines' performance calculation estimates AEO conditions

Engine 1 in nominal condition

Engine 2 as found (**)

Calculation estimates show differences of T45 (significant increases) and NG (slight decreases) between Engine 1 and Engine 2.

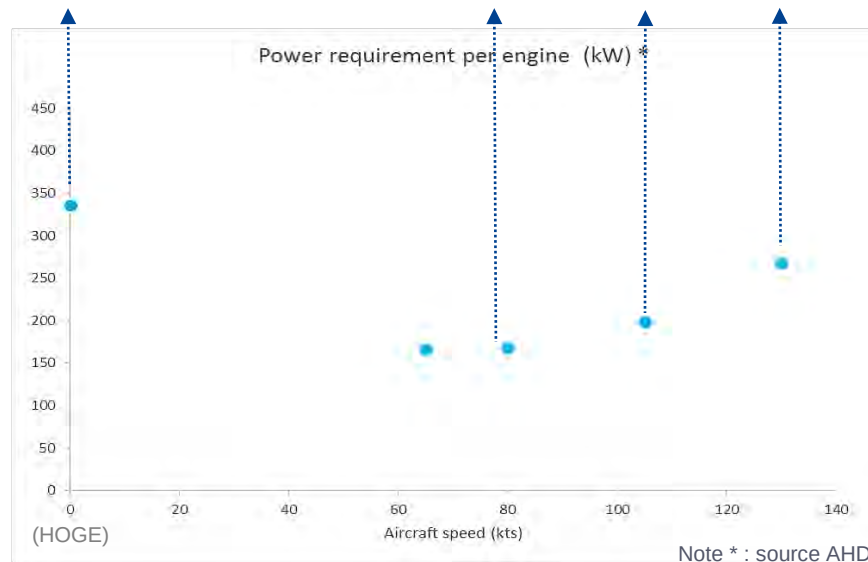
At moderate and high speed (>60kts), the T45 would remain below the AEO limit (845°C).

In HOGE, T45 of Engine 2 may reach 898°C which is above the AEO limit (845°C) but below the transient limit (920°C).



Note : ** Assumes no abnormal friction in Gas Generator
→ **Results must be considered as indicative only**

$\Delta T45^{**}$	+127°C	+81°C	+86°C	+68°C
ΔNG^{**}	-2%	-2.4%	-2.6%	-4.5%



→ **It is extremely likely that the deterioration of Engine 2's bearing led to significant increases of T45 and slight decreases of NG**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Engines 1 & 2 performance analysis

- Engines' performance calculation estimates
AEO conditions
Engine 1 in nominal condition
Engine 2 as found (**)

Summary :

It is likely that Engine 2

- would be able to deliver AEO power requirements;
- would operate with slightly lower NG and significantly higher T45 than a nominal engine;
- for aircraft speed > 60kts, its T45 would remain below the T45 AEO limit;
- in HOGE conditions, its T45 could reach 53°C above the AEO T45 limit but still below the transient limit.



Note : ** Assumes no abnormal friction in Gas Generator
→ **Results must be considered as indicative only**

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

Engines 1 & 2 performance analysis

- Engines' performance calculation estimates OEI conditions

Aircraft power requirements :

IAS (kts)	Alt. (ft)	T0 (°C)	Aircraft Power requirement for engine* (kW)
130	2500	24	535
105	2500	24	397
80	1200	26.6	336
65	2500	24	332
HOGE	1200	26.6	672



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

Engines 1 & 2 performance analysis

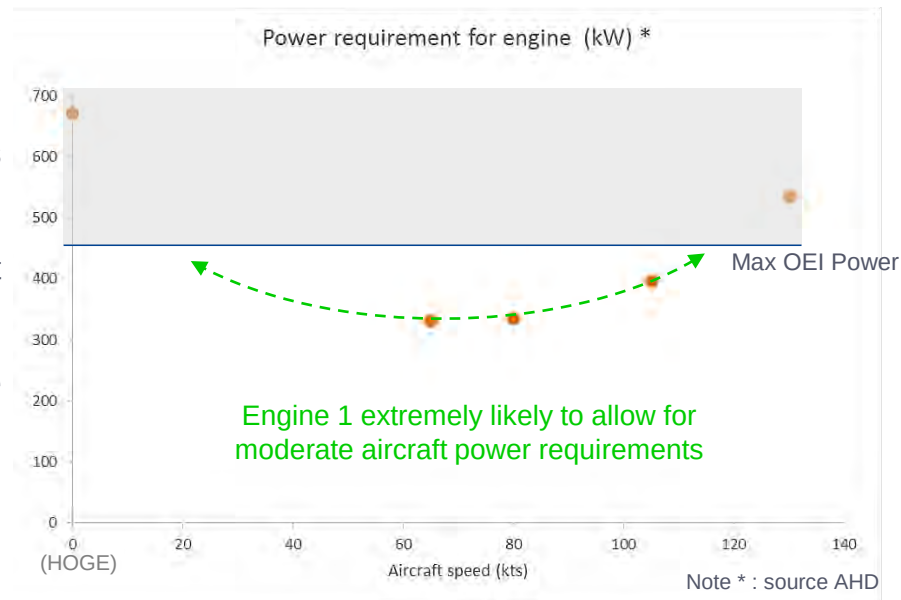
- Engines' performance calculation estimates
OEI conditions

Engine 1 in nominal condition

Calculation estimates showed that Engine 1 would be able to deliver up to 460kW in OEI conditions (@2500 ft).

This power availability would be lower than that required for high aircraft speed or for HOGE.

This power availability would allow for moderate aircraft speeds.



→ In the known flying conditions at the moment of the accident, it is extremely likely that Engine 1 (in nominal condition) would be able to meet moderate OEI aircraft power requirements

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

Engines 1 & 2 performance analysis

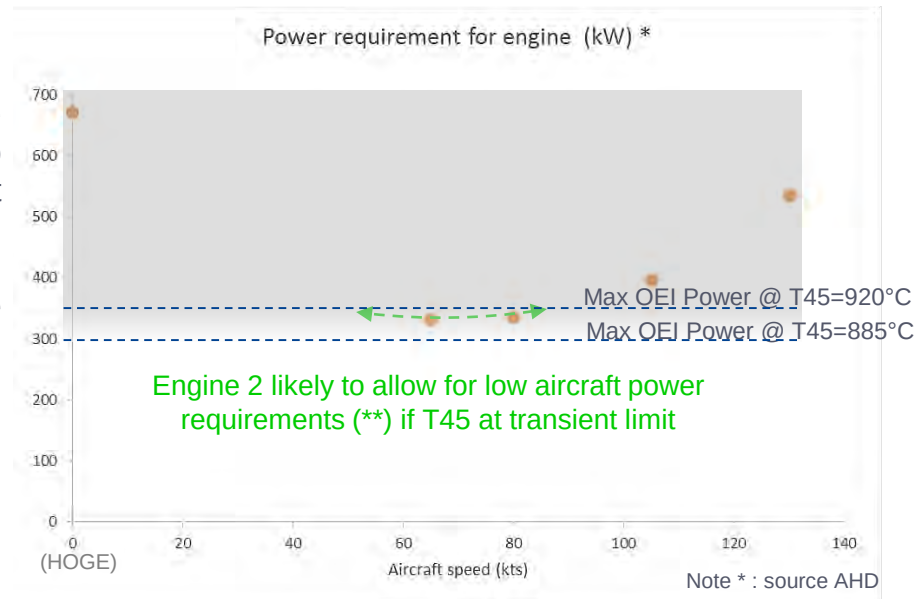
- Engines' performance calculation estimates
OEI conditions
Engine 2 as found (**)

Calculation estimates showed that Engine 2 in the as found condition would be able to deliver up to 357kW if pilot allowed for T45 up to the transient limit (920°C).

At the OEI T45 limit (885°C), Engine 2 would be able of 304kW.



Note : ** Assumes no abnormal friction in Gas Generator
→ **Results must be considered as indicative only**



→ **In the known flying conditions at the moment of the accident, it is likely that Engine 2 (as found) would be able to meet low OEI aircraft power requirements(**) if pilot allowed for T45 at the transient limit**



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

□ Engines 1 & 2 performance analysis

- Engines' performance calculation estimates OEI conditions

Summary :

- A nominal average aged Arriel 1E2 engine, would be capable to deliver up to 460 kW (@2500 ft & 24°C OAT)
 - **It is extremely likely to allow for moderate aircraft power requirements**
 - **Neither Engine 1 nor Engine 2 (HPT nominal or as found) could deliver OEI power requirements in HOGE**
- An average aged Arriel 1E2 engine with HPT as found on Engine 2 would be capable to deliver 357 kW at 2500 ft and with T45 at the transient limit (**)
 - **It could allow for low aircraft power requirements**



Note : ** Assumes no abnormal friction in Gas Generator
→ **Results must be considered as indicative only**

N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

Engines warnings in cockpit

- Highly likely engine related warnings or cautions in the cockpit based on findings & analyses :

Condition	Detection	Caution / indication
Deterioration of Engine 2 Gas Generator rear bearing	Metal particles on magnetic plug of Engine 2	ENG2 CHIP
Friction and wear at Engine 2's HP turbine level → Increased clearance at blade tips No discrepancy found on Engine 1's HP turbine	Parameter discrepancy between Engine 1 and Engine 2 : T45 split > 80°C and/or NG split > 4% for more than 5 sec	ENG PA DIS
For Engine 2's Gas Generator : rotor / stator contacts with friction and rubbing. → Unquantifiable friction levels very likely led to significant variations of Engine 2's power rating	Torque split > 15% (note : other criteria apply also) If torque split returns to < 15%, then VARTOMS returns automatically to normal operation	VAR NR
	When NG difference of 10% or more	ENG SPLIT
In case of Engine 2 significant loss of power or flame-out	When NG drops below 50%	ENG2 FAIL

→ Findings on Engine 2 could match conditions for warning/caution indications in the cockpit

- Note : this review only covers warnings related to the deterioration of Engine 2's bearing and does not cover other possible warnings.

Summary of Findings and Analyses

Examinations

- Engine 1 : examinations did not reveal any discrepancies that could explain its fuel control lever in the stop position and the engine at stand-still.
Some possible origins could not be checked or are outside SafranHE's scope.
Smoke or fire due to oil escaping from Engine 1 appears very unlikely.
- Engine 2 : with the information available and the engine's condition, the bearing's seizure's origin could not be determined. Potential contributors were identified : engine mishandling during maintenance, oil pollution & oil quality.
Heat damage at front of compressor due to the post-crash fire.
No discrepancies compatible with external projection of oil on hot engine components around the rear bearing's environment.
Fire due to escape of oil or fuel under the cowlings is very unlikely.
With rear bearing degraded, smoke at the back of the engine is very likely.

Indications to pilot

- ① When Engine 2's rear bearing started to wear, it released particles down the scavenge line and on the scavenge electric magnetic plug :
→ **“ENG CHIP”** caution in cockpit extremely likely
- ② Progressive wear of rear bearing then led to significant increase of T45 and slight decrease of NG :
→ **T45** indication rise extremely likely
- ③ T45 rise and NG variations due to rotor/stator friction :
→ **“ENG PA DIS”** caution in cockpit very likely
- ④ Once the bearing started seizing, unquantifiable friction levels very likely led to significant variations of power output :
→ Cautions **“VAR NR”** and **“ENG SPLIT”** very likely
- ⑤ In case of Engine 2 significant loss of power or flame-out :
→ **“ENG2 FAIL”** indication likely



□ Engines' operation

- Calculation estimates showed that it is extremely likely that the engines could deliver the required power to allow for AEO flying conditions (even with Engine 2's HP Turbine as found if rotation without friction).
- Neither Engine 1 nor Engine 2 (HPT nominal or as found) could deliver OEI power requirements in HOGE.
- In OEI conditions, with only Engine 2 operating with its bearing as found, during moments of rotation without friction and with T45 at the transient limit, it is likely that the engine could deliver up to 357 kW (sufficient to allow for low aircraft power requirements).
- Engine 2 may have been able to run with reduced friction at times including, possibly, moments of rotation without friction. Changes in direction of the aircraft very likely led to increased rotor/stator friction.
 - Engine's significant loss of power likely and flame out cannot be excluded
- Degradation of secondary air system and/or engine flame-out.
- Degradation of the HP Turbine and rotor/stator friction very likely led to degraded combustion conditions.
 - Smoke at rear of Engine 2 very likely

Conclusion



N146DU (SafranHE ref.: RA 2017/238) – Investigation Findings & Analyses

- For Engine 1 : no discrepancies can explain its fuel control lever in the stop position and the engine at stand-still. Smoke or fire due to oil escaping from Engine 1 appears very unlikely.
- For Engine 2 : the origin of the rear bearing's seizure could not be determined. Potential contributors were identified : engine mishandling during maintenance, oil pollution & oil quality.
The HPT's condition following the rear bearing's seizure could explain significant losses of power or flame-out. It also led to degraded combustion conditions. Smoke at rear is then very likely.
No indications of internal fire. No discrepancies compatible with external projection of oil on hot engine components around the rear bearing's environment. Fire due to escape of oil or fuel under the cowlings is very unlikely.
- "ENG CHIP" caution and T45 (turbine temperature) rise were extremely likely for Engine 2,
- "ENG PA DIS", "VAR NR" and "ENG SPLIT" were very likely,
- "ENG FAIL" likely in case of Engine 2's significant loss of power or flame-out.
- It is extremely likely that AEO flying conditions were achievable even with Eng.2's HPT as found if rotation without friction.
- It is extremely likely that Engine 1's power allowed for moderate aircraft power requirements in OEI flying conditions.
- If rotation without friction with its HPT as found and T45 at the transient limit, it is likely that Engine 2's power could have met low OEI aircraft power requirements.



Thank you for your attention