ANSV AGENZIA NAZIONALE PER LA SICUREZZA DEL VOLO

FINAL REPORT

SERIOUS INCIDENT
Aircraft B787-8 registration marks LN-LND,
Rome Fiumicino International Airport, Italy,
10th of August 2019

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OBJECTIVE OF THE SAFETY INVESTIGATION

The Agenzia nazionale per la sicurezza del volo (ANSV), instituted with legislative decree No 66 of 25 February 1999, is the Italian Civil Aviation Safety Investigation Authority (art. 4 of EU Regulation No 996/2010 of the European Parliament and of the Council of 20 October 2010). **It conducts, in an independent manner, safety investigations.**

Every accident or serious incident involving a civil aviation aircraft shall be subject of a safety investigation, by the combined limits foreseen by EU Regulation No 996/2010, paragraphs 1, 4 and 5 of art. 5.

The safety investigation is a process conducted by a safety investigation authority for the purpose of accident and incident prevention, which includes the gathering and analysis of information, the drawing of conclusions, including the determination of cause(s) and/or contributing factors and, when appropriate, the making of safety recommendations.

The only objective of a safety investigation is the prevention of future accidents and incidents, without apportioning blame or liability (art. 1, paragraph 1, EU Regulation No 996/2010). Consequently, it is conducted in a separate and independent manner from investigations (such as those of Judicial Authority) finalized to apportion blame or liability.

Safety investigations are conducted in conformity with Annex 13 of the Convention on International Civil Aviation, also known as Chicago Convention (signed on 7 December 1944, approved and made executive in Italy with legislative decree No 616 of 6 March 1948, ratified with law No 561 of 17 April 1956) and with EU Regulation No 996/2010.

Every safety investigation is concluded by a report written in a form appropriate to the type and seriousness of the accident or serious incident. The report shall contain, where appropriate, safety recommendations, which consist in a proposal made with the intention of preventing accident and incidents.

A safety recommendation shall in no case create a presumption of blame or liability for an accident, serious incident or incident (art. 17, paragraph 3, EU Regulation No 996/2010).

The report shall protect the anonymity of any individual involved in the accident or serious incident (art. 16, paragraph 2, EU Regulation No 996/2010).

This report has been translated and published by the ANSV for the English-speaking concerned public. The intent was not to produce a factual translation and as accurate as the translation may be, **the original text in Italian is the work of reference**.

GLOSSARY

(A): Aeroplane.
AAIB (UK): Air Accidents Investigation Branch (UK).
AC: Advisory Circular.
AD: Airworthiness Directive.
ADR: Aeroporti di Roma SpA.
AIP: Aeronautical Information Publication.
AMC: Acceptable Means of Compliance.
ANSV: Agenzia nazionale per la sicurezza del volo, Italian Safety Investigation Authority.
AOC: Air Operator Certificate.
AOHE: Air Oil Heat Exchanger.
APU: Auxiliary Power Unit.
ASDA: Accelerate-Stop Distance Available.
AT: AutoThrottle.
ATC: Air Traffic Control.
ATCO: Air Traffic Control Officer.
ATL: Aircraft Technical Logbook.
ATPL: Airline Transport Pilot Licence.
ATS: Air Traffic Services.
BCAR: British Civil Airworthiness Requirements.
BFU: Bundesstelle für Flugunfalluntersuchung, German Safety Investigation Authority.
CAA: Civil Aviation Authority.
CAS: Crew Alerting System.
CAT: Commercial Air Transport.
CAW: Continued AirWorthiness.
CCM: Cabin Crew Member.
CFL: Corrosion Fatigue Life-model.
CM: Certification Memorandum.
CM 1/2: Crew Member 1, Crew Member 2.
CMDR: Commander.
CPL: Continuous Parameter Log.
CPT: Captain.
CRM: Crew Resource Management.
CS: Certification Specification.
CS-E: Certification Specification for Engines.
CVR: Cockpit Voice Recorder.
DCA: Display and Crew Alerting.
DIFSD: Dual In-Flight Shut Down.
DML: DeMarcation Line.
EAFR: Enhanced Airborne Flight Recorder.
EASA: European Union Aviation Safety Agency.
EDX: Energy Dispersive X-ray spectroscopy.
EEC: Engine Electronic Controller.
EGT: Exhaust Gas Temperature.
EHM: Engine Health Monitoring.

EICAS: Engine Indicating and Crew Alerting System.
EMU: Engine Monitoring Unit.
ENAV SPA: Società nazionale per l'assistenza al volo, Italian air navigation service provider.
ESN: Engine Serial Number.
ETOPS: Extended-range Twin-engine Operational Performance Standards.
FAA: Federal Aviation Administration.
FCOM: Flight Crew Operating Manual.
FD: Flight Deck.
FDR: Flight Data Recorder.
FO: First Officer.
FOD: Foreign Object Debris.
FOHE: Fuel Oil Heat Exchanger.
FT: Foot.
FTL: Flight Time Limitation.
GM: Guidance Material.
GPWS: Ground Proximity Warning System.
GS: Ground Speed.
HP: High Pressure.
HPT: High Pressure Turbine.
IAS: Indicated Air Speed.
ICAO: International Civil Aviation Organization.
IFR: Instrument Flight Rules.
IFSD: In-Flight Shut Down.
ILS: Instrument Landing System.
IP: Intermediate Pressure.
IPT: Intermediate Pressure Turbine.
IPTB: Intermediate Pressure Turbine Blade.
IR: Instrument Rating.
KT: Knot.
JAA: Joint Aviation Authorities.
JAR: Joint Aviation Regulation.
JAR-E: Joint Aviation Regulation Engines.
LDA: Landing Distance Available.
LP: Low Pressure.
LPT: Low Pressure Turbine.
METAR: Aviation routine weather report.
MFD: Multi-Function Display.
MTOM: Maximum Take Off Mass.
ND: Navigation Display.
NGV: Nozzle Guide Vane.
NITS: N (Nature of the emergency) I (Intentions) T (Time available) S (Supplementary Informations).
NM: Nautical Miles.
NMSB: Non-Modification Service Bulletin.
NOSIG: No Significant Changes.
NSIA: Norwegian Safety Investigation Authority.
NTSB: National Transportation Safety Board, United States Safety Investigation Authority.

ODMS: Oil Debris Monitoring System.
OEI: One Engine Inoperative.
OM: Operative Manual.
OPT: On-Board Performance Tool.
PA: Public Address.
PDA: Parts Detached from Aeroplanes.
PEA: Piano di emergenza aeroportuale, Airport Emergency Plan.
PF: Pilot Flying.
PFD: Primary Flight Display.
P/N: Part Number.
PNE: Predicted Number of Events.
RAT: Ram Air Turbine.
RCA (or **REL CPT**): Relief Captain.
RIPS: Recorder Independent Power Supply.
RPM: Rounds Per Minute.
RWY: Runway.
SAS: Secondary Air System.
SB: Service Bulletin.
SCCM: Senior Cabin Crew Member.
SEM: Scanning Electron Microscopy.
SID: Standard Instrument Departure.
S/N: Serial Number.
SOP: Standard Operating Procedures.
SRGC: Safety Recommendation of Global Concern.
SRUR: Safety Recommendation of Union-wide Relevance.
TCAS: Traffic alert and Collision Avoidance System.
TCC: Turbine Case Cooling.
TGT: Turbine Gas Temperature.
TODA: Take-Off Distance Available.
TORA: Take-Off Run Available.
TPR: Turbofan Power Ratio.
TRA: ThRottle Angle.
TWAS: Terrain Avoidance Warning System.
TWR: Aerodrome Control Tower.
UTC: Universal Time Coordinated.
VMC: Visual Meteorological Conditions.
VOR: VHF Omnidirectional radio Range.
VVF: Vigili del fuoco, Fire Fighters.

FOREWORD

The serious incident occurred on the 10^{th} of August 2019, at 14.46', at the International Airport of Rome Fiumicino "Leonardo da Vinci" and involved the aircraft type Boeing 787-8 registered in Norway with identification marks LN-LND.

Shortly after take-off, the left engine exhibited excessive vibrations and at the same time, due to the failure in progress, ejected fragments of turbine blades. These high temperature parts hit the wing, the fuselage, the horizontal stabilizer, falling thereafter over the city of Fiumicino (RM).

The ANSV was informed of the event the same day when the investigation was launched and also the first survey took place.

The ANSV notified the serious incident, under the provisions of the Annex 13 to the Convention on International Civil Aviation and EU Regulation no. 996/2010, to:

- NTSB, representing the State of Design and Manufacture of the aircraft;
- UK AAIB, representing the State of Manufacture of the engine;
- BFU, representing the State of Design of the engine;
- NSIA, representing the State of Registration of the aircraft and of the operator.

These investigative authorities appointed their accredited representatives in the safety investigation conducted by ANSV. Each of them appointed technical advisers, listed below, as allowed by the aforementioned international and EU legislation:

- Boeing, designer and manufacturer of the B787 for NTSB;
- Rolls-Royce, designer and manufacturer of the Trent 1000, engine of the aircraft of the event, for BFU and UK AAIB;
- Norwegian Air Shuttle, operator of the event aircraft for NSIA;

Based on the provisions of the Regulation EU 996/2010, the ANSV appointed EASA as its technical adviser.

All the times shown in this investigation report, unless otherwise specified, are expressed in **UTC** (Universal Time Coordinated,), which, on the date of the event corresponded to the local time minus 2h.

CHAPTER I

FACTUAL INFORMATION

1. GENERAL

Evidence collected in the safety investigation are described below.

1.1. HISTORY OF THE FLIGHT

On the 10^{th} of August 2019 the B787-8 registration marks LN-LND (photo 1), flight DY7115, planned FCO-LAX, took off from runway 16R of the Rome Fiumicino International Airport at 14.45’35”.

At 14.46’07”, after 32” being airborne, at 1028 ft radio altitude and 200 kt groundspeed over the city of Fiumicino, the flight crew felt strong vibrations followed by malfunction messages relating to the left engine: “EEC MODE L” (14.46’08”), “LOSS OF TPR L”, “ENG L EGT RED” (14.46’14”), “ENG LIMIT EXCEED L” (14.46’16”) and “OVERHEAT ENG L” (14.46’20”). Soon afterwards commanded IFSD of the left engine and the return to departure airport was decided (route followed by the aircraft in figure 1). The crew commanded the In-Flight Shut Down (IFSD) of the left engine and elected to turn back to departure airport. An overweight one engine inoperative (OEI) landing took place 15.10’10”.

The aircraft left the runway autonomously, stopping at taxiway H where, already deployed, the Fire Brigade was waiting. This, observing a fire starting from the main landing gear, suppressed it by means of portable powder fire extinguishers. At the end of this activity, the passenger disembarkation procedures took place without further inconvenience.

Photo 1: B787-8 marks LN-LND.

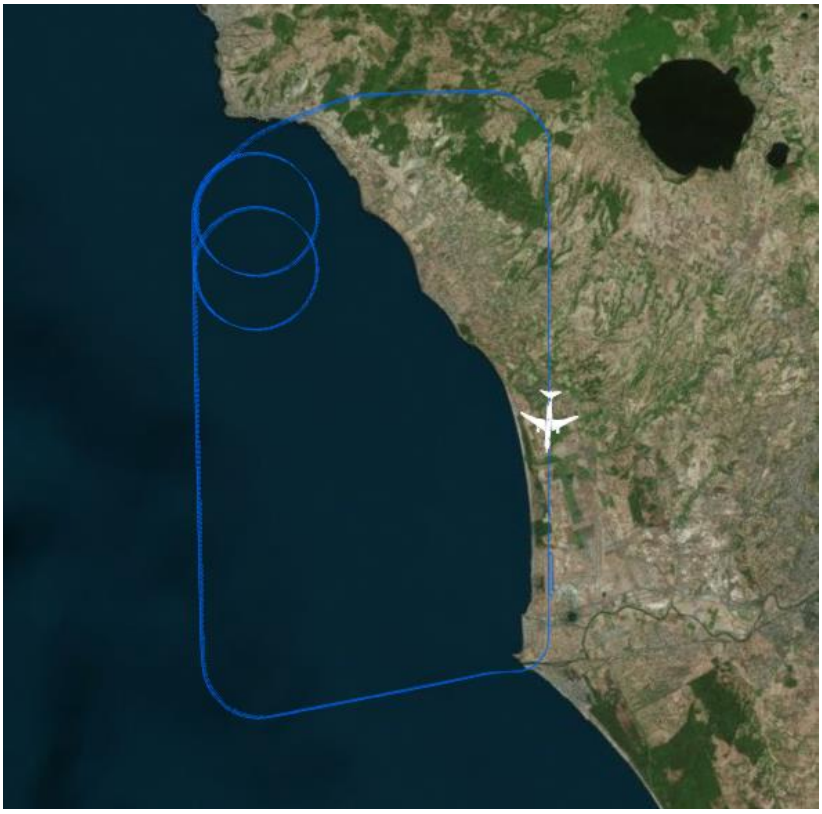

Figure 1: B787-8 marks LN-LND, track.

1.2. INJURIES TO PERSONS

Injuries	Crew	Passengers	Total on-board	Others
Fatal	0	0	0	0
Serious	0	0	0	0
Minor	0	0	0	0
Nil	12	286	298	0
Total	12	286	298	0

1.3. DAMAGES TO AIRCRAFT

The B787-8 marks LN-LND was equipped with two Rolls-Royce Trent 1000 G/01A package B. After the event, the left engine showed no particular signs of external damage, with the exception of two stages of the turbine blades and one of vanes seriously damaged.

Numerous fragments were found in the exhaust cone. Left engine last stage turbine damage was visible from the outside (photo 2).

The aircraft showed holes and impact marks under flap # 2, flap fairing and on the horizontal stabilizer (photos 3-7). Several small impacts were also found on the fuselage (photo 8), mainly made of carbon fiber composite material. The tires of the left main landing gear deflated due to the high temperature induced by the braking as a result of the overweight landing (photo 9). Shortly after the event, borescope inspection was carried out on the left engine. This highlighted how the primary damage was generated by the detachment of an IPT blade (photo 10), which also caused the detachment of the trailing blade and subsequently a series of further damages, that will be described in detail in paragraph 1.16.

Photo 2: left engine damage as visible from the outside.

Photo 3: damage to the flap.

Photo 4: damage to the flap.

Photo 5: wing damage.

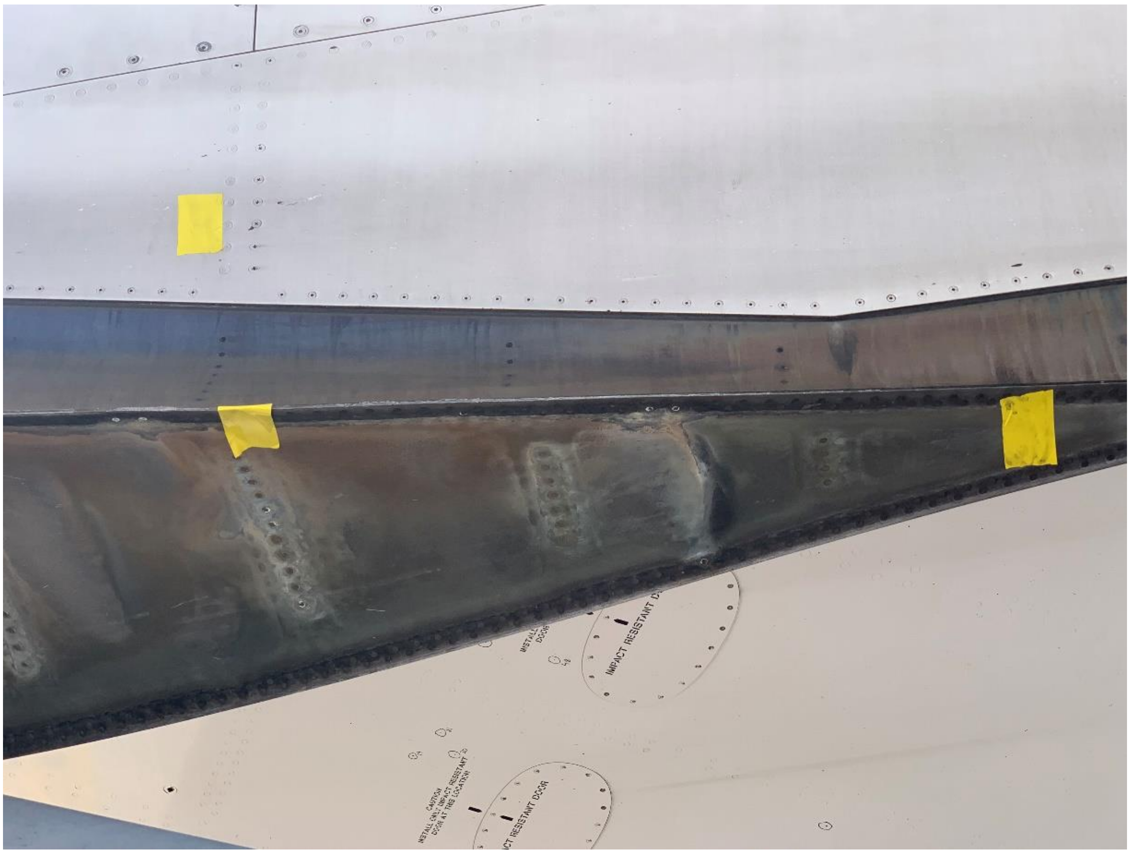

Photo 6: damage to the aft pylon fairing.

Photo 7: external damage of the horizontal stabilizer.

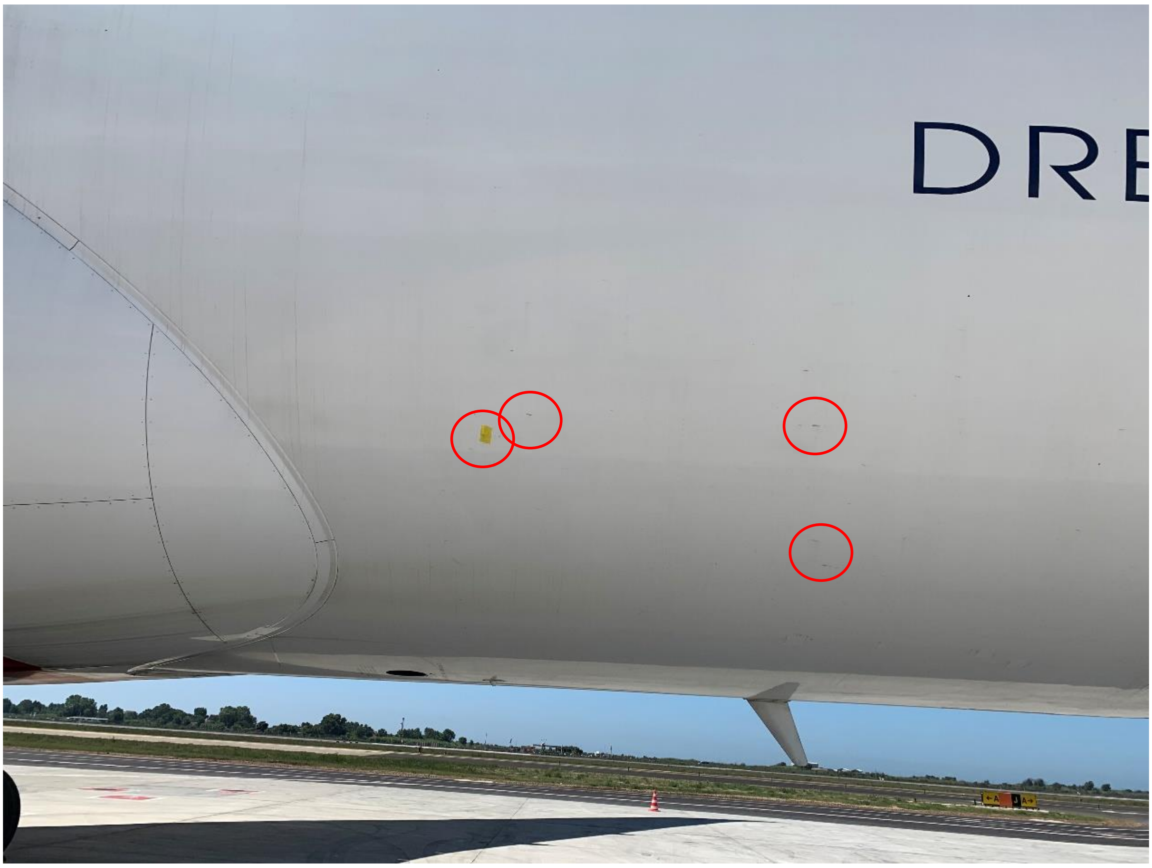

Photo 8: fuselage damage points.


Photo 9: left main landing gear tires deflated.

Photo 10: fracture surface of the primary damage consisting of the detachment of an IPT blade which led to the breakage of the adjacent one and then the further damage to the engine as described in paragraph 1.16.

1.4. OTHER DAMAGES

About 4 kg of debris (mainly fragments of turbine blades, photo 11) ejected from the left engine were recovered from the streets of Fiumicino (the city nearby the airport, detail in the red rectangle in figure 2), along the direction of the runway, where several damages to cars (mainly broken windows, photo 12, and indentations on the car body) and buildings (mainly holes in awnings) were reported by the population. No debris were found within the airport area. The larger fragments found weighed of about 100 g. The subsequent analysis of the engine made by the manufacturer suggested that about 38.2 kg was the total weight of the parts ejected from the engine.

Photo 11: fragments of turbine blades recovered from the streets of Fiumicino.

Photo 12: damage to a car (source Repubblica.it).

Figure 2: position of the aircraft at the time of activation of the discrete FDR parameter "Eng1 Vib Warn"; detail of the streets where most of the turbine blade fragments were found.

1.5. PERSONNEL INFORMATION

The flight crew composition for the B787 is two pilots, a captain and a first officer. The operator's OM, in agreement with the provisions of the EU regulation 83/2014 (regulation relating to FTL)[1], allows the possibility of augmented flight crew with one additional crew member, the relief captain. This allows crew members to take rest shifts and, if necessary, to be replaced by qualified personnel. The duties and responsibilities of the relief captain are detailed in the operator's OM. In fact, during the flight of the event there was also a relief

[1] Commission regulation EU No 83/2014 of 29 January 2014 laying down technical requirements and administrative procedures related to air operations.

captain in the cockpit who is second in command when the captain leaves the cockpit. In the presence of the captain can be used as a co-pilot. In addition, the third crew member plays a monitoring and decision support role as well as being able to carry out any tasks delegated to him directly by the captain. The operator organizes an “RCA Course” for captains who perform relief captain functions where operational situations are practiced in augmented crew, covering and deepening aspects of CRM and MCC in the “RCA upgrade course”.

1.5.1. Flight Crew

Captain

General:	male, Austrian nationality, age 49.
Licence:	ATPL(A) valid.
Qualifications:	B777, B787, IR.
English Proficiency level:	ICAO level 6.
Periodical checks:	proficiency check B777, B787, IR renewed on the 21st April 2019.
Medical examination:	valid first class medical certificate.

Captain flight experience

- last 90 days flight hours: 115;
- last 30 days flight hours: 34;
- last 7 days flight hours: 0;

Total flight experience 12.903 hours, 1393 hours on B787.

Relief Captain

General: male, German, age 37.

License: ATPL (A) valid.

Qualifications: B777, B787, IR.

English Proficiency level: ICAO level 6.

Periodical checks: proficiency check B777, B787, IR renewed on the 10th of March 2019.

Medical examination: valid first class medical certificate.

Relief Captain flight experience

- last 90 days flight hours: 204;
- last 30 days flight hours: 92;
- last 7 days flight hours: 8;

Total flight experience 8356h; 673h on the B787.

First Officer

General: male, Danish, age 37.

License: ATPL (A) valid.

Qualifications: B777, B787, IR.

English Proficiency level: ICAO level 6.

Periodical checks: proficiency check B777, B787, IR renewed on the 04th May 2019.

Medical examination: valid first class medical certificate.

First Officer flight experience

- last 90 days flight hours: 156;
- last 30 days flight hours: 44;
- last 7 days flight hours: 24;

Total flight experience 2882 hours, 953 hours on B787.

1.6. AIRCRAFT INFORMATION

1.6.1. General[2]

The Boeing 787 Dreamliner (figure 3) is a twin-engine wide-body turbofan airplane used as a medium and long-haul airliner, developed by the US company Boeing.

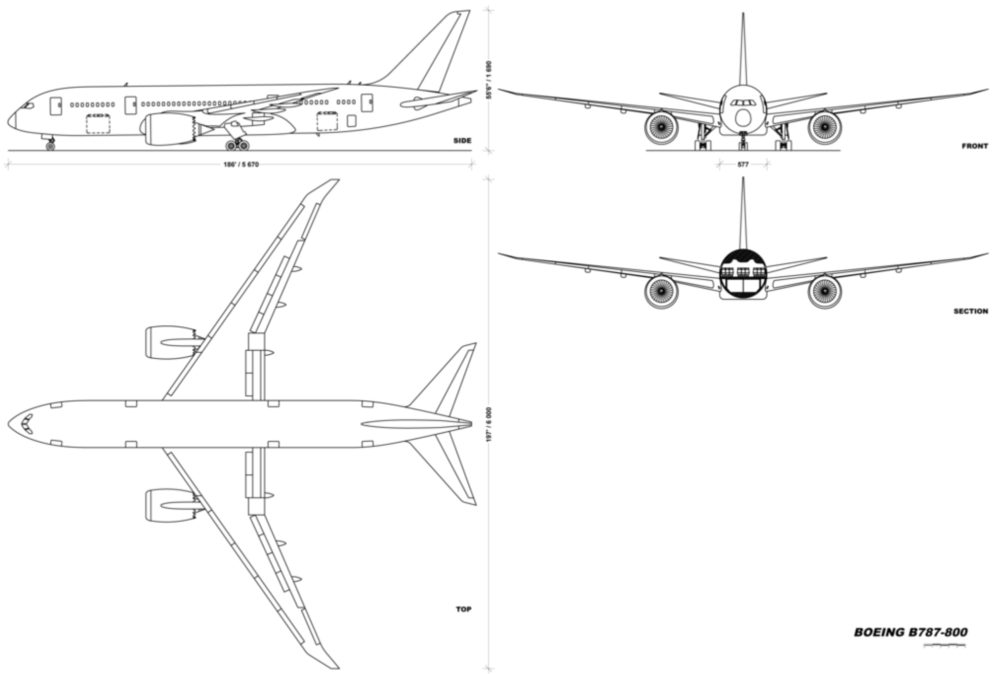

Figure 3: Boeing 787-8 schematic views.

The aircraft has ETOPS certification. More than 50% of the aircraft is made of carbon fiber

[2] Source of the images of this paragraph is BOEING, 787 Systems – Rolls-Royce Engines, Rev 1.0.

The aircraft is equipped with a DCA which provides the crew with audio and video information necessary for conducting the flight. The Primary Flight Displays (PFD), Multi Function Displays (MFD), and EICAS provide information on:

- air data;
- inertial reference data;
- navigation data;
- engine data;
- airplane system data;
- communication data;
- checklist data.

The purpose of the EICAS is to provide the crew with immediate communication about the non-normal conditions that are occurring. The messages concern the following conditions and are of audio, video and tactile typology:

- stall warning;
- crew alerting;
- configuration warnings;
- altitude alert.

The following functions are also integrated:

- weather radar;
- TCAS;
- TWAS.

The information is presented on the MFDs which can alternatively show the following specific pages (figure 4):

- EICAS;
- ND;
- control display unit;
- status display;
- electronic checklist displays;
- communication management display;
- synoptic display;
- maintenance pages.

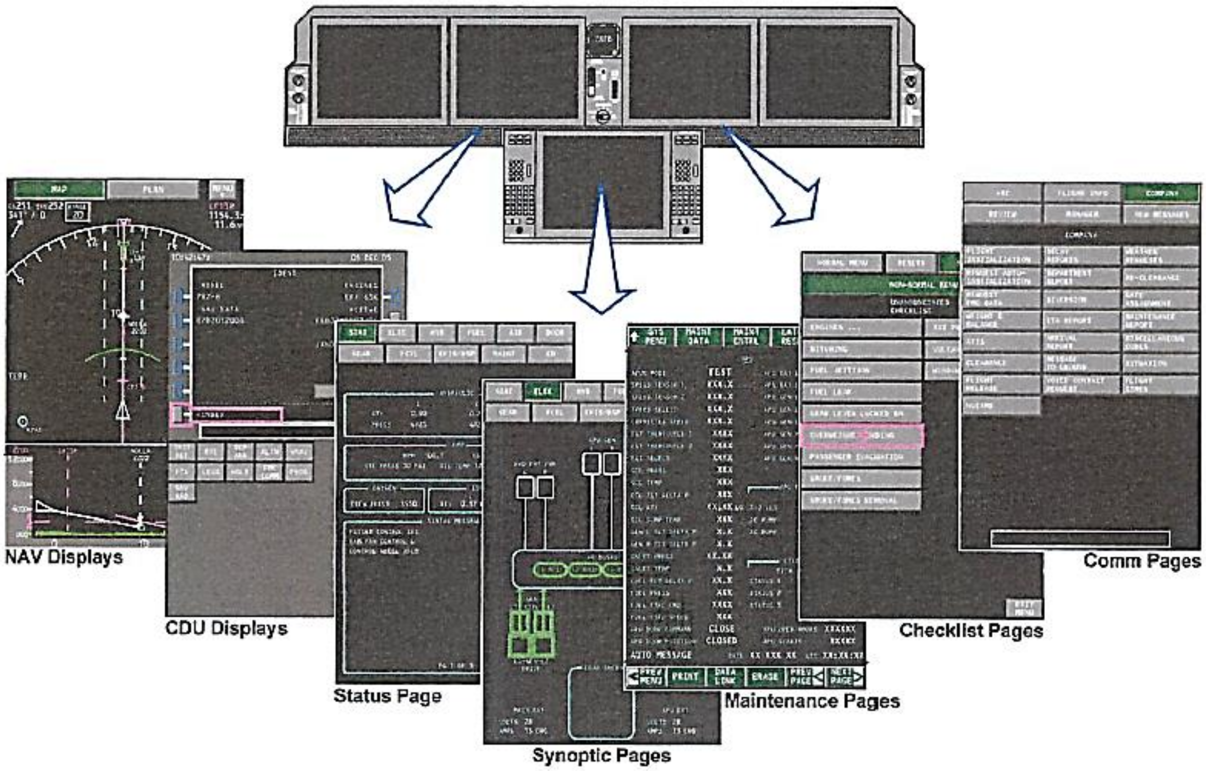

Figure 4: MFD display possibilities.

In detail, it is of interest for the discussion of the event to list the data shown by EICAS under normal conditions (figure 5):

- Total Air Temperature;
- Thrust mode;
- Selected temperatures derate;
- TPR;
- N1 rotor speed;
- EGT;
- N2 rotor speed;
- N3 rotor speed;
- Fuel flow;
- Oil pressure;
- Oil Temperature;
- Oil quantity;
- Engine vibration;
- Crew Alert messages;
- Status alert;
- Inflight start information;
- Landing gear position;

• Flap/Slat position;

• Horizontal stabilizer position;

• Rudder trim;

• Airplane Gross Weight;

• Total fuel weight;

• Static air temperature;

• Fuel temperature.

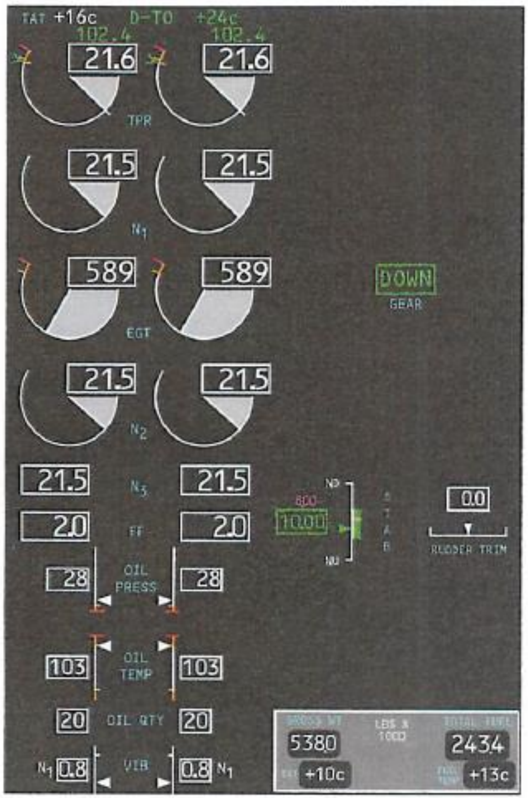

Figure 5: EICAS normal display mode.

In non-normal conditions (figure 6) the engine indications are shown in red, amber or white to highlight the exceedances and the relative severity levels. The alert messages are of the following type.

- *Warnings* (red), require immediate action by the crew. They are associated with sound effects (bell, siren or voice);
- *Cautions* (amber), require immediate knowledge by the crew of the condition that generated them. They are associated with sound signals (beeps);
- *Advisories* (amber), require the crew's knowledge of the condition that generated them;
- *Communications* (white), require knowledge from the crew of the condition that generated them. They are associated with sound signals (high or low tones);
- *Memo* (white), are reminders for the crew of the condition that generated them.

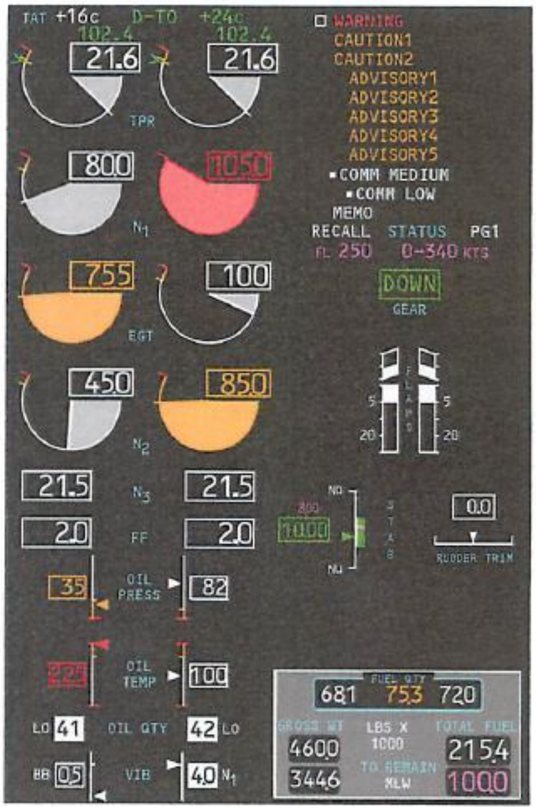

Figure 6: EICAS non-normal display mode.

In aircraft management, the crew can select the display of the electronic checklists on the MFDs (figure 7). The NORMAL checklists can be viewed:

- preflight;
- before start;
- after start;
- before takeoff;
- approach;
- landing;
- shutdown;
- secure.

The NON-NORMAL checklists are instead:

• unannunciated checklists;

• airplane general, emergency equipment, doors, windows;

• air systems;

• anti-ice and rain protection;

• automatic flight;

• communications and datalink;

• electrical;

• engines and APU;

• fire protection;

• flight controls;

• flight instrument and displays;

• flight management and navigation;

• fuel;

• hydraulics and RAT;

• landing gear;

• warning systems and tail strike.

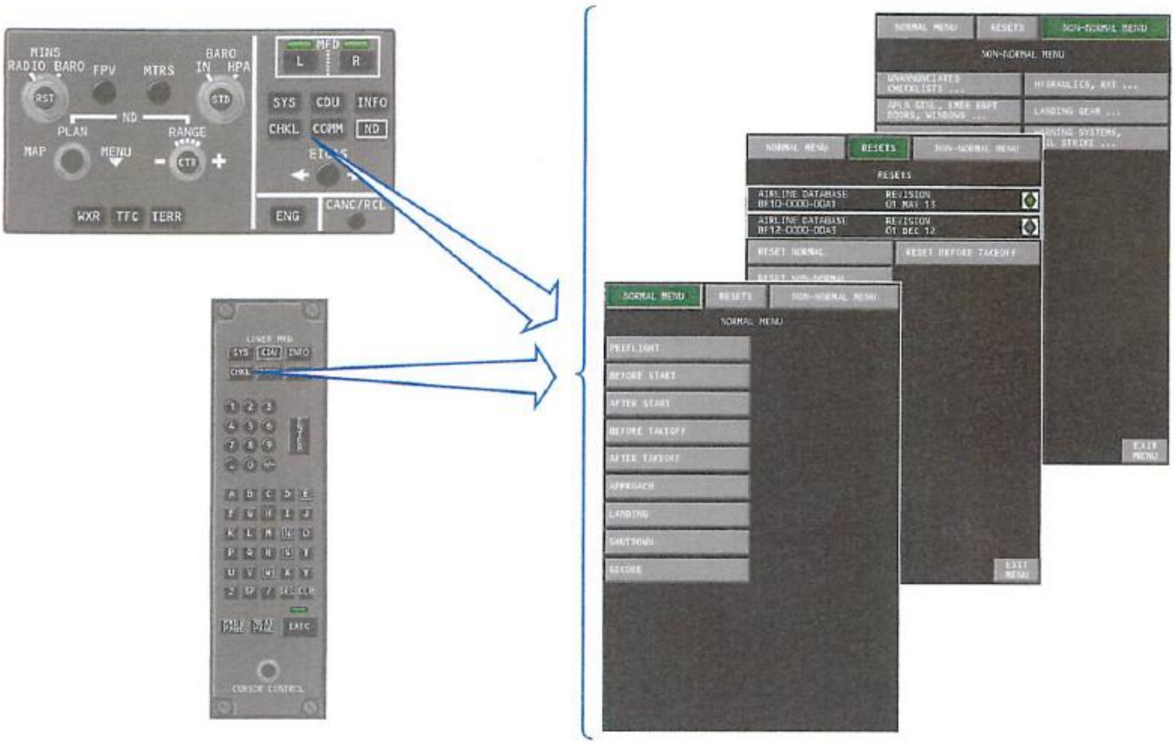

Figure 7: EICAS checklist presentation.

1.6.2. Engine

The Boeing 787 is produced with two different engines: General Electric GEnx and Rolls-Royce Trent 1000. In detail, the B787 of the event had this latter type.

The Trent 1000 is a three-shaft turbofan with a high bypass ratio (figure 8) approximately 10:1.

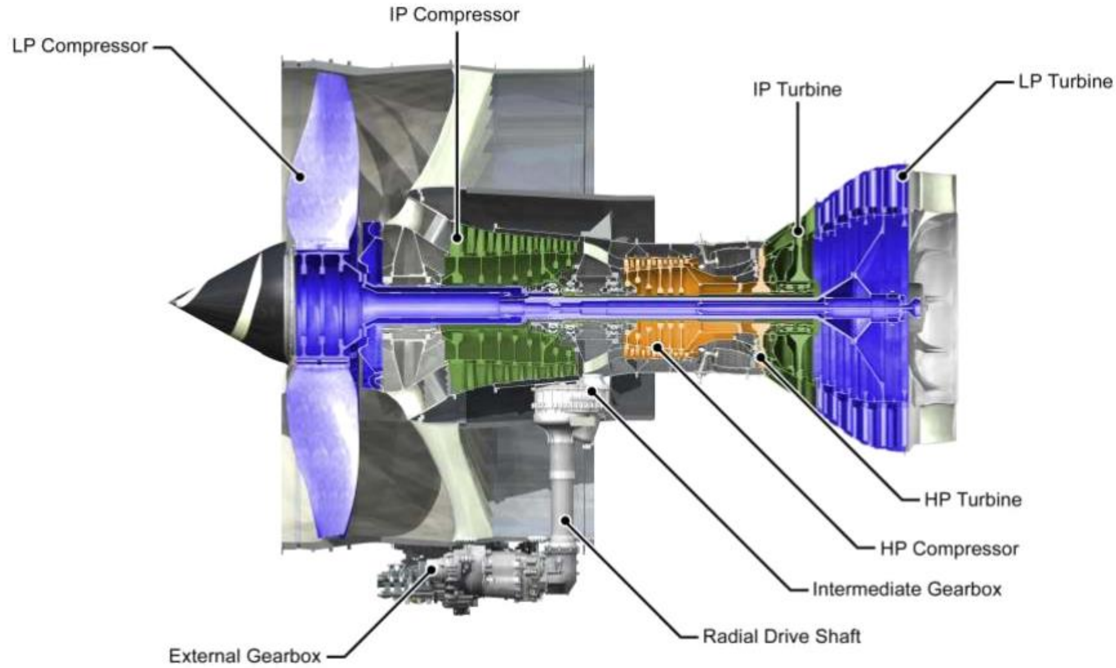

Figure 8: TRENT 1000, schematic view (source Rolls-Royce).

The low pressure shaft, is connected to the fan (2.85 m diameter) and to a six-stage low pressure turbine (LPT). In an engine of this type, during take-off, the fan provides 80% of the thrust. The intermediate pressure shaft is also connected to the gear box of the accessories as well as to 8 compressor stages and to the single IPT stage. The HP shaft, is connected to six compressor stages and to the single HPT stage.

The engine is equipped with the following main components (figures 9 and 10):

- EMU - is a unit that employs a suite of sensors throughout the engine to provide data to the flight crew on the level of vibration of the rotating shafts, whilst also monitoring the health of the engine to help with engine availability and maintenance predictions;
- ignition exciters;
- EEC;
- AOHE;
- HP3 bleed valve;

- HP/IP TCC;
- LP TCC;
- SAS valve;
- FOHE;
- oil tank;
- ODMS and relative sensor;
- LP filter;
- Flowmeter.

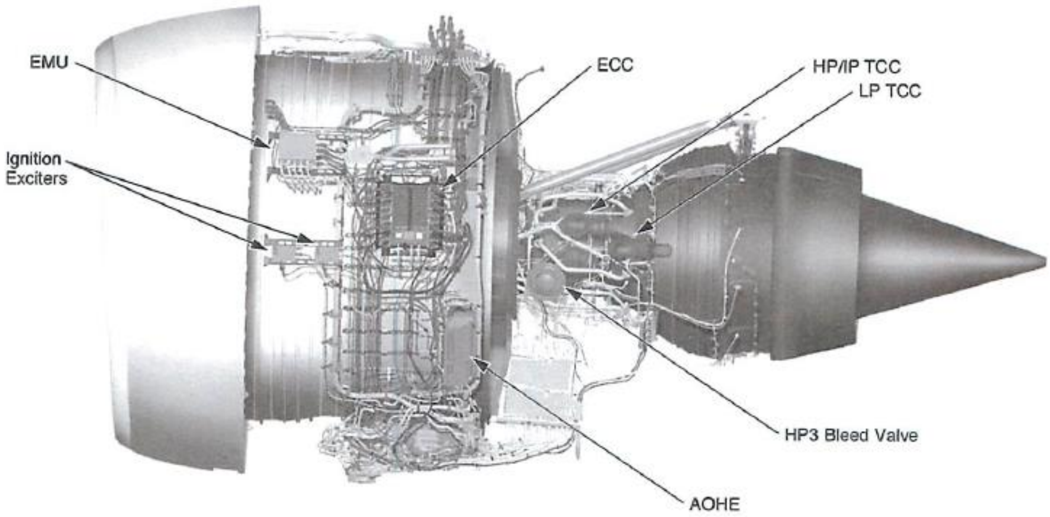

Figure 9: TRENT 1000 accessories, left side view.

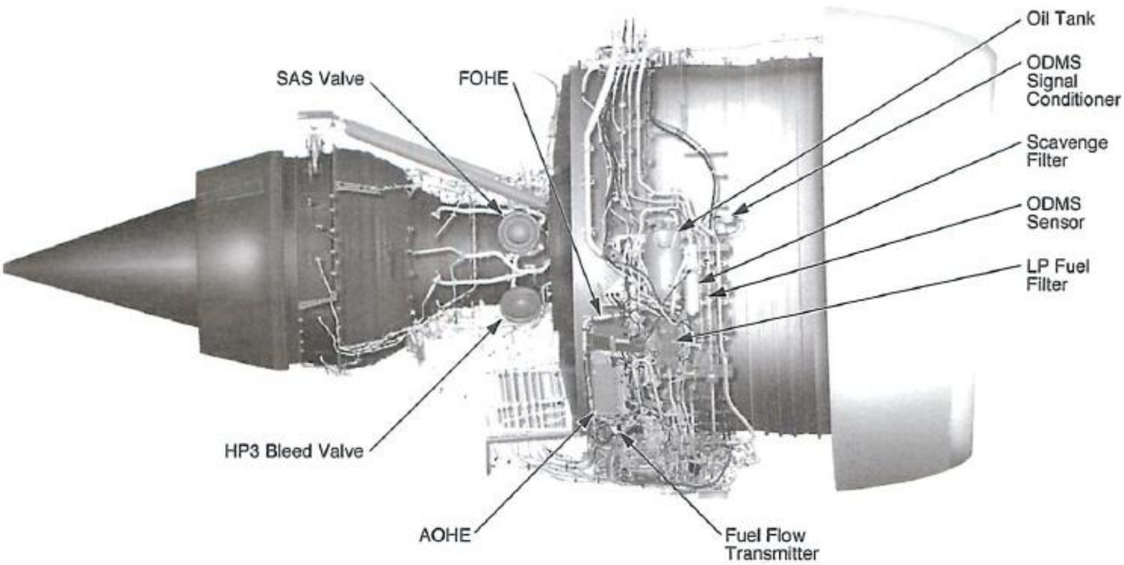

Figure 10: TRENT 1000 accessories, right side view.

The event of this report occurred when some problems relating to the Trent 1000 were already known.

In particular, from 2015 and including the 10th of August 2019 event, 11 cases of progressive fracture of one of the blades of the IPT occurred (figure 11). Only 2 of the events resulted in an uncommanded IFSD. In 7 of the events (including the subject one) the pilots commanded a shutdown of the engine in flight. In the remaining 2 events the engine was not shut down whilst in flight. The primary damage for all the events including the one of the 10th of August 2019, was associated to a progressive corrosion-fatigue failure mechanism (see paragraph 1.16.2.). Ten of eleven cases of detachment of the blades occurred at take-off or during climb. One event occurred during cruise several hours after take-off. The table shows how NMSB 72-AK186 was issued in October 2018 and how the blades that originated the failures are all from a standard pre-modification SB 72-H818. This introduced modified blades into the fleet with respect to those that fractured in service. This SB was issued on November 14th of 2016, after 5 of the 11 cases had already occurred between October 2015 and August 2016.

	Event Date	ESN	IPTB FC	IPTB Life	IPTB Failure mechanism
1	21st Oct 2015	10159	1409	*Pre NMSB 72-AK186	Corrosion fatigue
2	22nd Feb 2016	10079	1984	*Pre NMSB 72-AK186	Corrosion fatigue
3	3rd Mar 2016	10072	2739	*Pre NMSB 72-AK186	Corrosion fatigue
4	18th Mar 2016	10179	1370	*Pre NMSB 72-AK186	Corrosion fatigue
5	20th Aug 2016	10176	4849	*Pre NMSB 72-AK186	Corrosion fatigue
6	11th Feb 2017	10209	2145	*Pre NMSB 72-AK186	Corrosion fatigue
7	5th Dec 2017	10231	1545	*Pre NMSB 72-AK186	Corrosion fatigue
8	6th Dec 2017	10227	1455	*Pre NMSB 72-AK186	Corrosion fatigue
9	6th Jul 2018	10086	3184	*Pre NMSB 72-AK186	Corrosion fatigue
10	15th May 2019	10202	1440	1455	Corrosion fatigue
11	10th Aug 2019	10166	1210	1410	Corrosion fatigue

***NMSB 72-AK186 introduced blade hard life in October 2018**

All failed blades are pre-modification SB 72-H818

Figure 11: list of the ESN that experienced IPTB release attributed to the corrosion-fatigue phenomenon (source Rolls-Royce).

The modification involves change of the alloy base material, from TMS138A to RR3010 (both single crystal structure). Moreover, a different application of the coating is also prescribed by this modification: the blade is fully encapsulated by coating instead of being terminated at the root shank. Furthermore, the coating is made of Chromium and Platinum, the previous version was only Platinum instead. In order to verify the effectiveness of this modification, the

Manufacturer is pro-actively removing blade from service examining for them for cracks. At the time this report is published, the post-modification blades have not shown any defects associated with those discussed in this report.
figure 12 shows the different configurations.

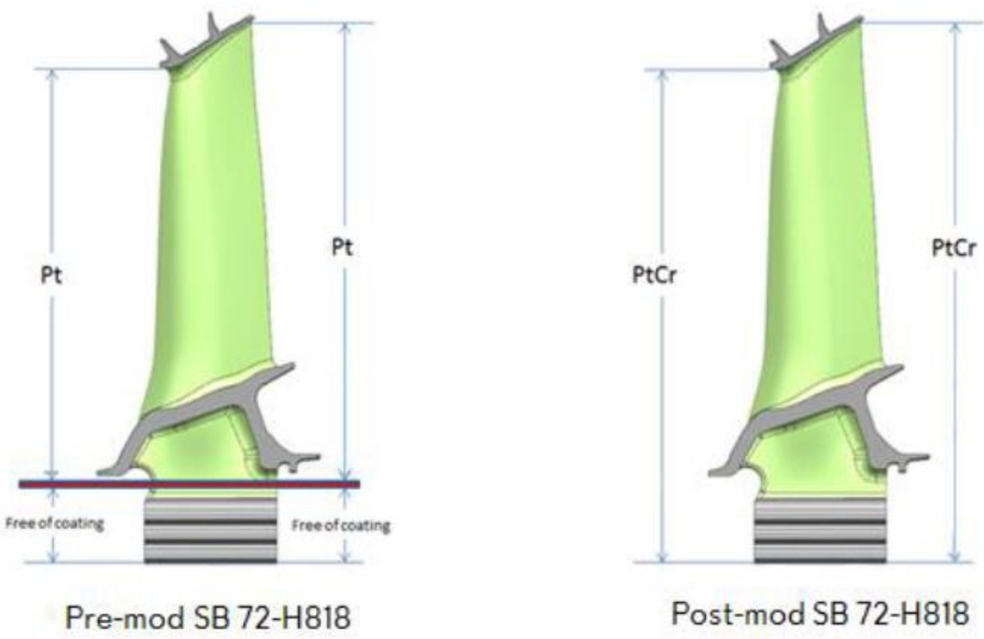

Figure 12: different configurations of the TRENT 1000 IPT blades (source Rolls-Royce).

The initial service management of the pre-modification IPT blades was dictated by NMSB 72-AJ575 dated 29th November 2016, which advised that Rolls-Royce would issue notifications to operators advising when each engine should be scheduled for removal to have the IPT blade set replaced. The lives used for this were derived from the CFL model, driven by EHM data. This NMSB was mandated by EASA through AD 2017-0056 dated 19th April 2017. The reason for the AD was:
«During a recent flight of a Trent 1000-powered Boeing 787, following reports of N2 vibration and multiple other messages, the flight crew performed an engine in-flight shut-down (IFSD) and returned to the departure airport, landing uneventfully. The post-flight boroscope inspection of the affected engine revealed an intermediate pressure (IP) turbine blade missing at the shank. This is the fifth reported occurrence of an IP turbine blade failure on a Trent 1000 engine. The failures are driven by sulphidation corrosion cracking. This condition, if not detected and corrected, could lead to IP turbine blades shank release, possibly resulting in an IFSD and consequent reduced control of the aeroplane. To address this potential unsafe condition, RR issued Alert Non-Modification Service Bulletin (NMSB) TRENT 1000 72-AJ575 to provide instructions for engine removal from service when any IP turbine blade with

a high level of sulphidation exposure is identified by corrosion fatigue life (CFL) model. For the reason described above, this AD requires removal from service of certain engines, to be corrected in shop.».

After the NMSB 72-AJ575 and following further 3 events in 2017, the manufacturer also issued the NMSB 72-AJ992 on the 20th December 2017. This was issued to de-pair higher life engines and further reduce the potential risk of IPT blade fracture in both engines on the same flight. The NMSB 72-AJ992 was made mandatory by EASA emergency AD 2017-0253 dated 22nd December 2017. This was aimed to de-pairing of the pre-modification SB 72-H818 engines.

The NMSB 72-AJ992 underwent three revisions ratified by EASA through AD 0086-2018 and then AD 0139-2018 aimed at the introduction/removal of some ESNs in the list of applicability.

In this framework, the outcome of the tear down of the engine ESN 10231 related to the 7th case of IPTB fracture was of particular importance (figure 11, event dated 5th December 2017, tear down performed in 2018), since, among the consequences, also damage to the LPT1-2 drive-arm was found. This could cause an LPT stage 1 overspeed, burst and uncontained high energy debris (concept is commented in para 1.17.). These considerations prompted the engine manufacturer to abandon the CFL for fleet management and to assume a more conservative approach: a fixed life (hard life) was introduced for the Trent 1000 IPTBs. NMSB 72-AK186 whose first version is dated 8th October 2018, shortly after revised on the 31st of October and mandated by EASA on the 12th December 2018 by means of the AD 0257-2018. The adoption of the hard life was considered sufficiently precautionary to remove the de-pairing constraint for pre-modification engines.

Revision 2 of NMSB 72-AK186 dated 16th April 2019 expanded the applicability of the hard life to seven “TEN” engines in addition to those of packages “B” and “C”. The provision was ratified by EASA with AD 0135-2019 of dated 11th June 2019. Shortly before, on the 15th of May 2019, the tenth case of IPTB fracture occurred.

1.6.3. Specific information

Aircraft

Manufacturer:	The Boeing Company.
Type:	B787-8.
Serial number:	35310.
MTOM:	227.930 kg.
Construction year:	2014.
Registration marks:	LN-LND.
Registration certificate:	16.3.2015.
Operator:	Norwegian Air Shuttle ASA.
Total flight hours:	29.090.
Total cycles:	3346.

The ETOPS certification for the B787-8 marks LN-LND was limited to a diversion time up to 180 minutes.

Compliance to technical documentation with current legislation/directives: yes.

The Tabulation Number for the B787 marks LN-LND aircraft was ZA578: this number indicate the normal and emergency procedures in the FCOM applicable to the specific serial number.

Airplane Number	Registry Number	Serial Number	Tabulation Number
001	LN-LNA	35304	ZA576
002	LN-LNB	35305	ZA577
004	LN-LND	35310	ZA578
006	LN-LNF	35313	ZA579

Engines

Manufacturer:	Rolls-Royce PLC Derby England.
Model:	TRENT 1000 G/01-A, pack B.

Left engine

Serial number:	10166.
Total hours since new:	21193:20.
Total cycles since new:	2470.
Hours since last installation:	5298:48.
IPTB life (in cycles):	1210.
IPTB life limit (EASA AD 2019-0135):	1410.
Remaining IPTB cycles at the date of the event:	200.

Right engine

Serial number:	10140.
Total hours since new:	22438:17.
Total cycles since new:	2636.
Hours since last installation:	11880:18.
IPTB life (in cycles):	1337.
IPTB life limit (EASA AD 2019-0135):	1440.
Remaining IPTB cycles at the date of the event:	103.

ATL shows that on the 10th of August 2019, before the event, some minor maintenance activities are reported. They were not related to the event.

1.7. METEOROLOGICAL INFORMATION

Following the METARs applicable at the time of the event:

101220 METAR LIRF 101220Z 27009KT CAVOK 33/20 Q1015 NOSIG=
101250 METAR LIRF 101250Z 27012KT CAVOK 31/23 Q1015 NOSIG=
101320 METAR LIRF 101320Z 27011KT CAVOK 31/22 Q1015 NOSIG=
101350 METAR LIRF 101350Z 27010KT CAVOK 32/22 Q1015 NOSIG=
101420 METAR LIRF 101420Z 28012KT CAVOK 31/20 Q1015 NOSIG=
101450 METAR LIRF 101450Z 28012KT CAVOK 30/21 Q1015 NOSIG=
101520 METAR LIRF 101520Z 29010KT CAVOK 30/21 Q1015 NOSIG=
101550 METAR LIRF 101550Z 29011KT CAVOK 30/22 Q1015 NOSIG=
101555 METAR LIRF 101550Z NIL=
101555 METAR LIRF 101550Z 29011KT CAVOK 30/22 Q1015 NOSIG=

1.8. AIDS TO NAVIGATION

Not relevant.

1.9. COMMUNICATIONS

The flight NAX7115 (DY7115), after take-off at 14.45’35” from runway 16 R, contacted the ATCO Rome Radar on the 130.900 Mhz frequency at 14.46’31”.

On this frequency, after the engine failure, the emergency phase was managed up to 15.07’53”, when the communication changed to Fiumicino TWR for landing.

UTC	CALLING STATION	COMMUNICATION TEXT
14.46’31”	NAX7115	Radar NAX7-1-1-5 heavy, 1500 climbing 4000 feet.
	ATCO	Giorno NAX7-1-1-5, radar contact, standard departure, climb to FL 8-0.
	NAX7115	NAX7-1-1-5 we’d like to continue on heading 2-4-0, we have an engine problem.
	ATCO	Roger 7-1-1-5, HDG 2-4-0 is approved and climb to 6000 feet and let me know as soon as possible your intentions, thank you.
	NAX7115	Climb to 6000 NAX7-1-1-5.
14.49’06”	ATCO	NAX7-1-1-5, ehm, are you climbing to 6000 or, or what?
	NAX7115	OK, NAX7-1-1-5, mayday, mayday, mayday, we are engine out, we’re [*incomprehensible*] check this light request [*incomprehensible*] vector for relanding 1-6 if they can keep us to the airport somewhere.
	ATCO	Roger, NAX 7-1-1-5 turn right on heading 3-2-0.
	NAX7115	Right on heading 3-2-0, NAX 7-1-1-5.
14.49’38”	ATCO	NAX 7-1-1-5, if possible climb to 3000, 3000 feet minima.
14.49’47”	NAX7115	[*incomprehensible*] 3000 feet? [*superimposed call*].
	ATCO	Affirm NAX 7-1-1-5, are you able to climb to 3000?
	NAX7115	Affirm.
	ATCO	Thank you. Climb to level, climb to 3000 feet, right on heading 3-4-0.
	NAX7115	Right heading 3-4-0 NAX 7-1-1-5.
14.50’40”	ATCO	NAX 7-1-1-5 would you give me the numbers of passengers on board and the … the engine where you have got the problem.
	NAX7115	Ah, NAX7-1-1-5 stand by, we call you back shortly.
	ATCO	Roger.
14.51’26”	NAX7115	[*incomprehensible*] 7-1-7-5 [*wrong call sign*].
14.51’51”	NAX7115	Roma, NAX7-1-1-5 heavy, we have 2-9-8 souls on board.
	ATCO	2-9-8 souls on board, thank you, and the problem … which engine have you got the problem?
	NAX7115	Is the left hand engine and we shutted it down and for your information we have … ehm … 71,5 tons of fuel on board right now.
	ATCO	Thank you very much.
	NAX7115	And we call you back for further intention.
14.52’35”	ATCO	NAX7-1-1-5 report be ready to turn inbound.
	NAX7115	We need a couple of minutes, I’ll call you back, approximately like 5 to 10 minutes.
	ATCO	OK, NAX7-1-1-5, 1-6 R, it’s OK for you?

	NAX7115	Ehm, NAX7-1-1-5, 1-6 R is fine.
	ATCO	OK.
	NAX7115	And give me the latest weather please.
	ATCO	Last weather report wind 2-8-0° 11 knots, visibility more than 10 km, CAVOK and QNH 1-0-1-5, temperature 3-0 with 21.
	NAX7115	Roger temperature 3-0 copied, QNH 1-0-1-5 and the rest copied, thank you very much NAX 7-1-1-5.
	ATCO	NAX 7-1-1-5 we have to know are you carrying dangerous good?
	NAX7115	Negative, NAX 7-1-1-5.
14.53’37”	ATCO	NAX 7-1-1-5, due to radar minima you have to maintain present position and make a 3-60 on right turn or left turn, let us know which is better.
	NAX7115	Roger … ahh … we do a 3-60 to the right NAX 7-0, correction, 7-1-1-5.
	ATCO	Copied, make a 3-60 on the right.
14.57’35”	NAX7115	NAX7-1-1-5 we completed one 3-6-0 we gonna do one more time to the right 3-6-0°.
	ATCO	OK.
15.00’29”	ATCO	NAX7-1-1-5 are you exceeding your maximum landing weight?
	NAX7115	NAX7-1-1-5 yes sir, that’s affirm, we reque … ehm … can you give us a vector for … approximately … 20 miles final for RWY 1-6 R? And affirm, this is an overweight landing, for your planning we will vacate the runway but, after that, we will need the tow truck to get us back to parking position.
	ATCO	OK, no problem and you may turn right since now on HDG 0-3-0.
	NAX7115	Roger, right on HDG 0-3-0 NAX 7-1-1-5.
15.01’37”	ATCO	NAX7-1-1-5 mayday, able to climb 4000 feet due to radar minima?
	NAX7115	Ehm … negative, we’d like to take it [*incomprehensible*] short, we can fly along the coast for a visual NAX7-1-1-5.
	ATCO	OK. Fly heading 0-5-0.
	NAX7115	0-5-0 NAX7-1-1-5.
15.02’44”	ATCO	NAX7-1-1-5 heading 0-7-0 base.
	NAX7115	Right heading 0-7-0 NAX7-1-1-5, we’re starting to reduce speed.
	ATCO	Roger.
	ATCO	Confirm NAX7-1-1-5 mayday on ground contact?
	NAX7115	Affirm, we have VMC, we have everything in sight, no problem.
15.04’04”	ATCO	NAX7-1-1-5 turn right heading 1-2-0 to establish LLZ 1-6R.
	NAX7115	Right turn heading 1-2-0 to establish on the LLZ for 1-6 R, NAX 7-1-1-5.
	ATCO	NAX 7-1-1-5 mayday you are going to establish about 1-6 miles.
	NAX7115	That’s fine, NAX 7-1-1-5.
15.04’49”	ATCO	NAX 7-1-1-5 mayday you are clear for ILS Y 1-6 R.
	NAX7115	Clear ILS Y 1-6R, we are established LLZ NAX 7-1-1-5, and can give again the wind please?
	ATCO	Latest wind is 2-8-0° 10 knots.
	NAX7115	2-8-0° 10 knots copied, NAX 7-1-1-5.
15.06’22”	ATCO	NAX 7-1-1-5, last wind on the threshold is 2-8-0° 11 knots, general wind 2-9-0° 10 knots.

	NAX7115	Copied, NAX 7-1-1-5.
15.06’48”	ATCO	NAX7-1-1-5 mayday … ehh … for information parallel approach on left side is going on the other … other runway.
	NAX7115	In sight, NAX7-1-1-5.
15.07’53”	ATCO	NAX 7-1-1-5 mayday, 6 miles and half to run, call TWR 1-1-8.7.
	NAX7115	1-1-8.7 NAX7-1-1-5, grazie mille.
	ATCO	You’re welcome.

1.10. AERODROME INFORMATION

Rome Fiumicino Airport

The “Leonardo da Vinci” international airport of Rome Fiumicino, located in the Municipality of Fiumicino, is located about 19 NM West/South-West from the city of Rome and has an elevation of 14 feet.

The airport is managed by ADR (Aeroporti di Roma) SpA; the ATS service provider is ENAV SpA.

The airport has the following runways:

- 07/25, length 3307 m, width 45 m;
- 16L/34R, length 3902 m, width 60 m;
- 16R/34L, length 3902 m, width 60 m.

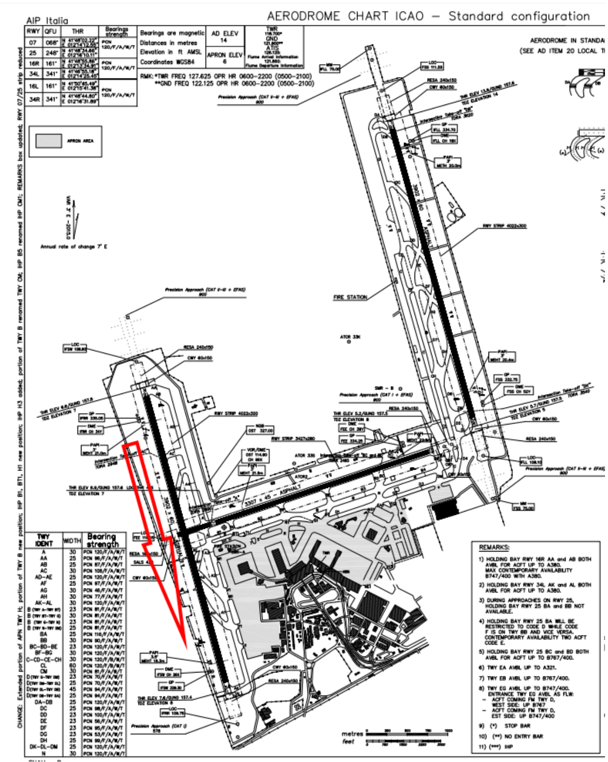

Figure 13: the aerodrome airport (source AIP Italy).

The flight was authorized by ATC for take-off from RWY 16R and SID SOSIV 6B (figure 14) with SOVAN 6A transition and initial climb to 4000 ft. The SID foresees, upon reaching point RF601 (located on the radial 168° at 2NM from the VOR OST), the turn to the right until reaching the heading 310°.

At the emergency the crew decided to return to RWY 16R, the same used for take-off, as proposed by ATCO. Roma radar provided vectors for the interception of the final ILS Y RWY 16R procedure (figure 15).

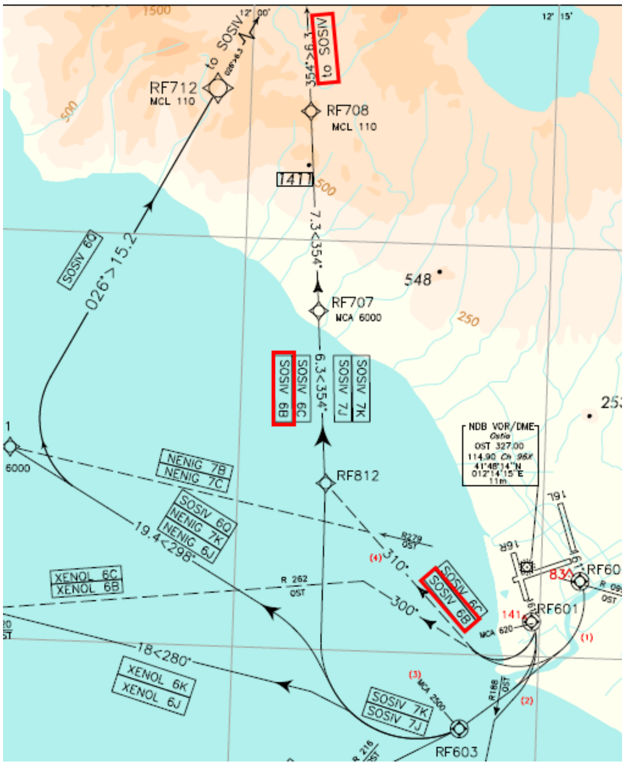

Figure 14: SID SOSIV 6B (source AIP Italy).

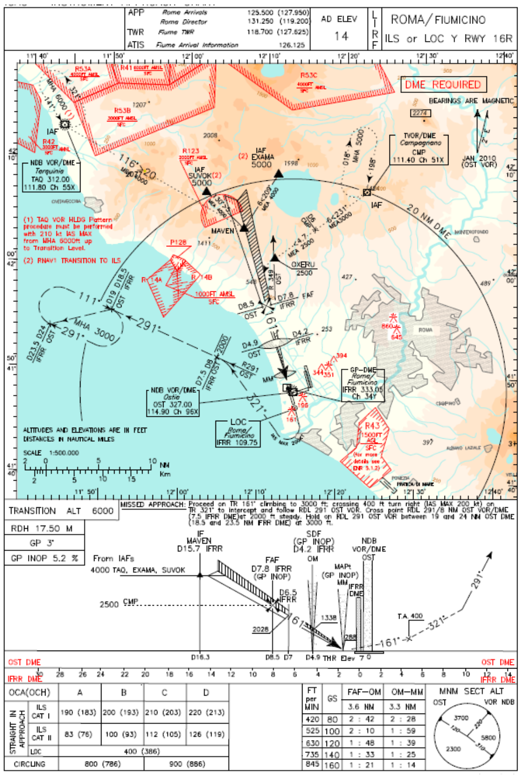

Figure 15: ILS Y RWY 16R (source AIP Italy).

1.11. FLIGHT RECORDERS

In this chapter is discussed the information about the recorder units that were onboard.

1.11.1. General

The aircraft had two EAFRs protected against the consequences of an accident. Each one of those incorporate the functions of FDR and CVR. In addition to the EAFRs, there were additional non-volatile memories capable of recording data.

In detail, in relation to the specific event under discussion, the EMUs, units designed for monitoring the operation of engines, are of particular relevance.

1.11.2. Recorders conditions

The two EAFRs installed on board (photo 13) are identical but installed in different positions. One is at the tail of the aircraft while the other is installed near to the cockpit. Both devices were found undamaged, disassembled from the aircraft and subjected to data recovery at the ANSV laboratories.

Each EAFR records more than 2000 parameters for a minimum of 25 hours and the audio tracks of the cockpit conversations for a minimum of 2 hours.

EMUs are unprotected units mounted on the engines. The relevant data were downloaded directly at the airport by the maintenance personnel.

These two also showed no damage.

Photo 13: EAFR installed on board the LN-LND.

1.11.3. Data

FDR and EMU.

Analysis of the EAFR data shows that at 14.46’05” an abrupt decrease of left engine N1 (from 90% to less than 60%, figure 16). At the same time, slightly increased left engine N2 and N3, oil temperature and pressure (figure 17). From the point onward the overall vibration level of the left engine increased (figure 18 and 19). The EAFR data show that at 14.46’11”, after 36” from take-off, at about 1200 feet and 200 kt groundspeed, while the aircraft was flying over the city of Fiumicino, the message” Eng1 Vib Warn” linked to strong vibrations was activated (figure 20).The left engine IFSD was commanded by the crew at 14.48’06” UTC.

At the same time, the data from the right engine did not show any anomalies.

The engine manufacturer reviewed the EMU (5 Hz sampling rate) data, confirming the above evidence as well as highlighting, in addition, that the behavior of the engine was compatible with an IPT blade damage. In more detail, the EMU data showed that the drop in N1 occurred after IP tracked order vibration increased (as a result of the IPT blade release). Therefore, the most likely sequence of events is (figure 21):

- IPT blade release resulting in IP tracked order vibration increase (14.45’56.8”);
- IPT blade release causes downstream damage to the Low Pressure (LP) turbine and a reduction in LP shaft speed and increase in LP tracked order vibration;
- the engine control system then attempted to restore power before the crew commanded the IFSD.

At the time of the IPTB failure, the TGT recorded by the EMU was 876 °C.

No significant variations in the vibration level or other engine related parameters were recorded from the left and right engines prior to the event.

Further data from the FDR will be presented in the next paragraph to comment on the communications that took place in the cockpit (CVR).

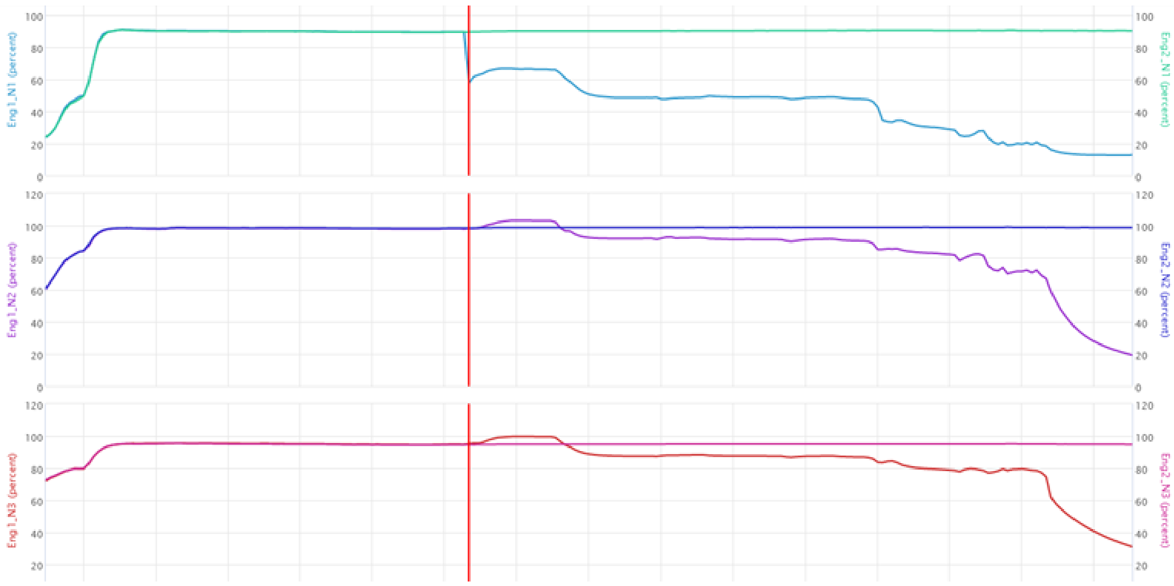

Figure 16: EAFR parameter selection, red line at the time 14.46’05”, comparison between ENG1 (left engine) and ENG2 (right engine).

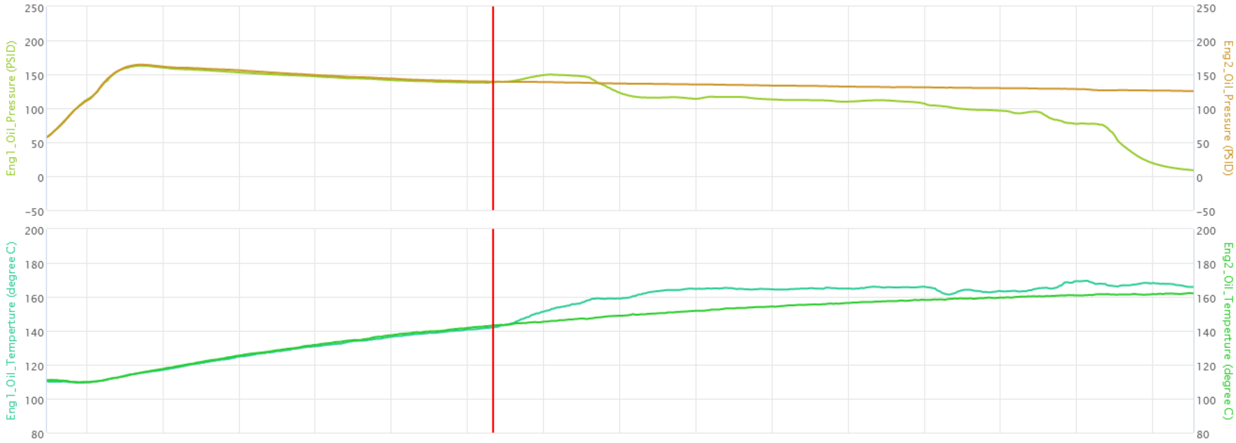

Figure 17: EAFR parameter selection, red line at the time 14.46’05”, comparison between ENG1 (left engine) and ENG2 (right engine).

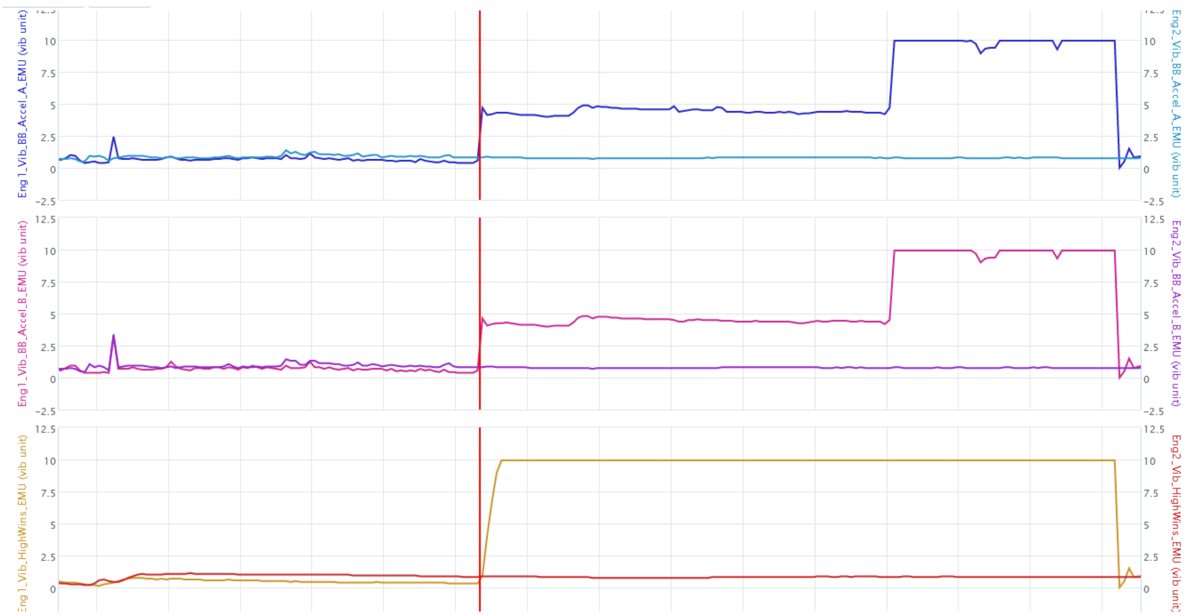

Figure 18: EAFR parameter selection, red line at the time 14.46’05”, comparison between ENG1 (left engine) and ENG2 (right engine).

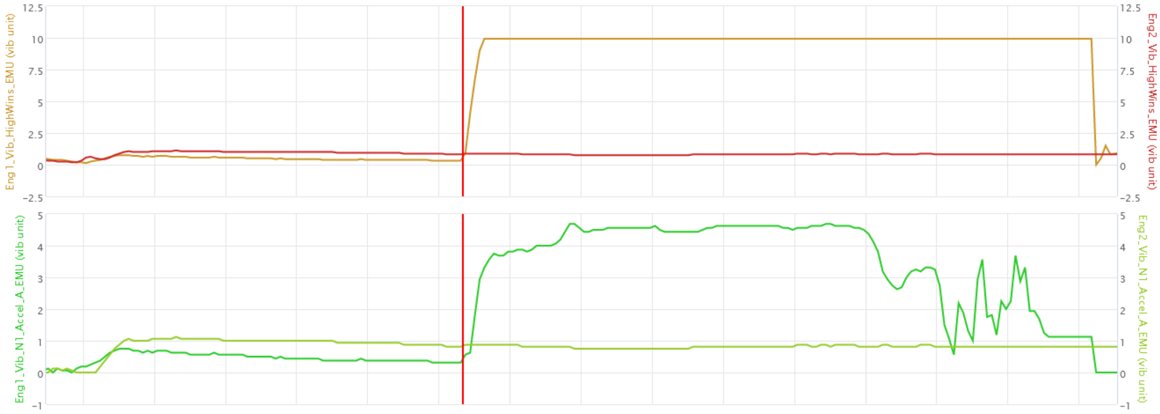

Figure 19: EAFR parameter selection, red line at the time 14.46’05”, comparison between ENG1 (left engine) and ENG2 (right engine).

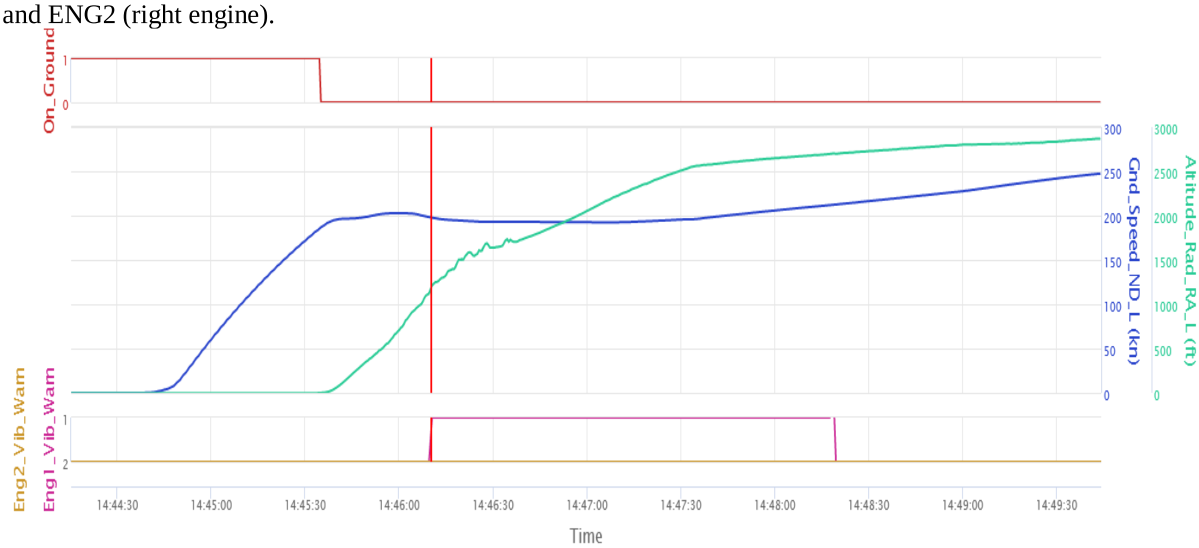

Figure 20: selection of EAFR parameters, the red line indicates the time 14.46’11”.

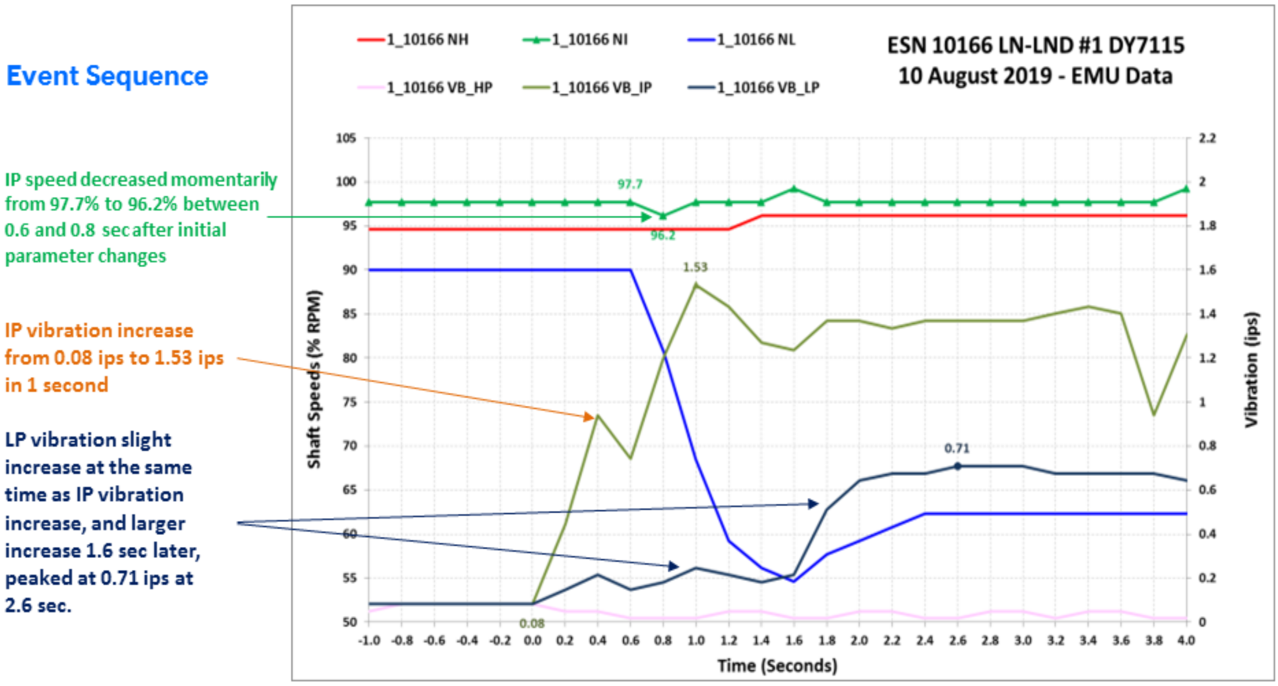

Figure 21: reconstruction of the sequence of events based on the EMU parameters (source Rolls-Royce).

1.11.4. CVR

Below the sequence of events obtained by listening to the CVR recordings. The flight was divided into the following phases:

- from the alignment phase for take-off to the onset of the failure;
- from the onset of the failure to the after take-off check list;
- from the after take-off check list to the approach;
- from approach to landing;
- actions after clearing the runaway.

From the alignment phase for take-off to the onset of the failure

14.39’00”: The FO carries out the SID briefing. When specifying the route in case of emergency, it states «Straight ahead …6000 feet essentially, but visual today». The CPT confirms: «Anything happen before the turn, we go straight» and then adds «we can continue outbound to the sea, if you want».

14.41’40”: the FO repeats the instruction provided by the ATC «Line up and wait 16 right». While waiting for the take-off authorization, the checks are completed.

14.44’21”: the CPT reads the indication of fuel (73 and a half tons).

14.44’29”: the FO repeats the take-off authorization.

14.44’33”: the CPT pass control of the aircraft to the FO which confirms.

14.44’42”: the take-off run begins.

14.44’59”: the CPT confirms «Thrust set».

14.45’07”: The CPT carries out the standard call out of the 80 kt.

14.45’29”: activation of the audio warning “V1”.

14.45’31”: the CPT calls the rotation.

14.45’35”: the take-off takes place.

14.45’39”: the CPT confirms «Positive» (climb) and the FO requests the retraction of the landing gear.

14.46’05”: the CPT answers to ATC that instructs the crew to change frequency.

From the onset of the failure to the after take-off check list

14.46’07”: the CPT, immediately after the communication with the ATC, made an exclamation of surprise (1028 ft radio altitude).

14.46’11”: the CPT comments on the appearance of the warning “Engine EEC mode left” (FDR: Eng1 EEC alternate mode activation 14.46’08”).

14.46’15”: the CPT comments «EGT» (ENG EGT left RED parameter activated 14.46’14”, figure 22[3]).

14.46’16”: the activation of the master caution takes place (figure 22).

14.46’17”: the CPT orders the FO to reduce the engine. A new activation of the master caution is heard.

14.46’17”: the CPT requests the FO to further reduce the engine (FDR: the disconnection of the autothrottle is recorded at 14.46’18” figure 23).

14.46’23”: the REL CPT suggests memory items. The CPT asks to wait and states «Identify the problem».

14.46’31”: the CPT makes the radio call to the ATC communicating an engine problem and the intention to continue with heading 240°. After the call at 14.46’58”, control of the radio goes to the FO.

14.47’13”: the CPT comments that the indications of N1 appear normal but that vibrations are felt. The indications of the vibratory level confirm the anomalous vibrations (FDR: the indication of the increase in the vibratory rate is recorded starting from 14.46’11”, figure 20).

[3] Note that the EGT values plotted in figure 22 are the values that would have been displayed on the EICAS, which are not actual measured gas temperatures. On the Trent 1000, to ensure consistent cockpit display across large gas turbines the value of Turbine Gas Temperature (TGT), which is measured at the LPT Stage 1 NGVs, is adjusted by the EEC to align display and actual limits as the EICAS parameter EGT. The measured TGT of 876 °C when the IPT blade failed reflects the air temperature local to the IPT blade at the time of the primary damage. A peak TGT value of 998 °C was subsequently observed due to loss of efficiency of the engine, which corresponds to the EGT peak value of 927 °C shown in figure 22.

14.47’28”: at the request of the FO, the CPT confirms the need for further reduce the engine.

14.47’32”: a variation in the background noise of the engine with roughness and blows is heard. The CPT comments: «engine failure».

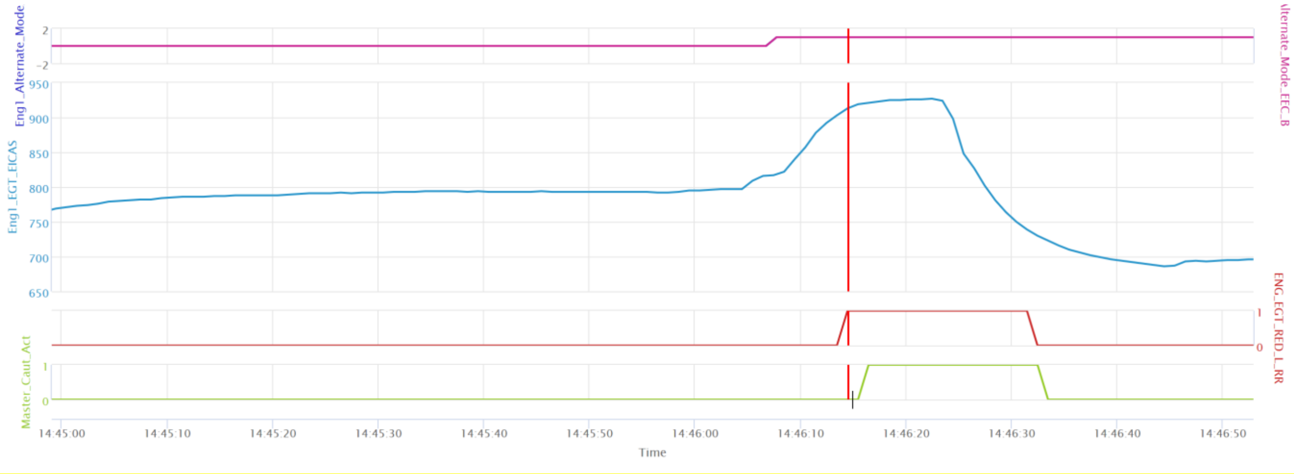

Figure 22: selection of EAFR parameters the red line indicates the UTC time 14.46’14”.

14.47’38”: the CPT comments «Regular engine failure».

14.47’51”: the REL CPT suggests the need to shut down the engine; the CPT confirms.

14.47’55”: the CPT announces the need to carry out the memory items (it is not specified for which fault) and confirms the selection of the autothrottle switch of the left engine to OFF.

14.48’00”: The CPT states: «Left engine idle».

14.48’01”: The FO confirms «Idle» (FDR: action confirmed by parameter eng. 1/2 TRA, figure 23).

14.48’02”: The CPT states: «Fuel control switch left OFF».

14.48’04”: The FO confirms «OFF» (FDR: positioning recorded on off at 14.48’04”, figure 23, parameter eng fuel cutoff).

14.48’06”: The left engine is turned off. (1’59 “after the failure was detected, 2’01” after the onset of the malfunction).

14.48’13”: the CPT comments «No damage, no fire».

14.48’24”: the CPT announces the need to carry out the «non normal checklist for engine failure» checklist. At the same time, the sound of the Cabin call is heard. The CPT asks the REL CPT to answer the call.

14.48’38”: the FO asks the CPT if they should carry out the engine shut down checklist. The CPT confirms.

14.48’48”: the CPT suggests to clean configuration first.

14.48’57”: The flaps are selected in “Flaps 1” position (figure 24).

14.49’04”: the REL CPT intervenes by pointing out to the flight crew that the aircraft is directed away from the airport.

14.49’15”: the CPT declares “Mayday” together with the nature of the problem and requesting directions to land on runway 16. The flight is instructed to turn right up to 320°.

14.49’36”: the CPT asks the checklist to be carried out. He says “Engine failure” and then, immediately after, correct himself by saying “Severe damage checklist”.

14.50’05”: the FO requests the positioning of the flaps in the “UP” position (figure 24), after a request made to the CPT 4 seconds earlier while the latter was engaged in a radio call.

14.50’09”: the CPT states «non normal checklist menu, engines, severe damage checklist».

14.50’27”: the FO announces the selection of “max continuous thrust” (FDR: action confirmed by switching the parameter AT continuous limit, figure 24).

14.50’30”: the CPT reads the “severe damage checklist”. Levelling takes place at 3000 ft.

14.50’39”: the CPT reads «left engine switch confirm pull... confirm?» (after confirmation by the FO, «Pull») (FDR: parameter eng1 fire switch pulled switches at 14.50’47”, figure 24).

14.51’17”: the REL CPT discuss with the FO the presence on board of 286 passengers +12 crew members, 298 people in total, and 71,5 tons of fuel. These data will be shortly after communicated to the ATC.

14.51’23”: the CPT reads the “engine severe damage checklist page 2” in this phase the APU is started (FDR: APU power on 14.51’52”; selection of the GPWS on FLAPS OVERRIDE at 14.52’23”, figure 24), and the calculation is made for the landing with the flaps at 20° (figure 24).

14.53’48”: the REL CPT communicates to the ATC to perform a 360°.

14.54’33”: the CPT announces the execution of the after take-off checklist.

From the after take-off check list to the start of the approach

14.54’42”: when the CPT communicates to carry out the overweight checklist, the REL CPT and the FO suggest first setting the avionics for the approach and then carrying out the overweight checklist. There is a brief discussion on this.

14.55’00”: the CPT confirms the need to communicate the state of the situation to the cabin crew.

14.55’47”: the CPT asks the REL CPT to call the assistant head of the cabin in the cockpit.

14.56’24”: the CPT carries out the NITS briefing notifying the “single engine” condition, the intention to return to Fiumicino for a normal landing, estimated in 10 or 15 minutes, and the need for towing once on ground.

14.57’14”: the CPT asks the assistant cabin chief to repeat the NITS.

14.57’30”: the CPT asks the FO to perform a second 360° turn.

14.57’59”: the CPT suggests to the FO to access the Diversion Page so that the operative is informed of the return of the flight to the departure base.

14.58’07”: the CPT asks the REL CPT to find the frequency of the Rome operation and to warn them that they are returning.

14.58’17”: the CPT makes the announcement to passengers explaining the situation and methods of return. The announcement ends at **14.59’00”**.

14.59’04”: reading of the Overweight landing checklist.

15.00’14”: the CPT informs the FO and the REL CPT that he will take control for the landing as it is a “non-standard” situation.

From the beginning of the approach to the landing

15.00’29”: the FO informs the CPT that it has already entered the approach set up data.

15.00’35”: the CPT makes radio communication to the ATC, requesting to be positioned for a long final at 20 NM. He announces that the landing will be carried out in “overweight” conditions and the need for towing once on the ground.

15.01’25”: the CPT takes the control of the aircraft.

15.01’32”: the FO begins the briefing of the ILS Y 16R approach.

15.02’15”: the CPT asks the REL CPT to inform the flight attendants of the upcoming landing (call of 10 minutes on landing).

15.02’30”: the CPT, during the approach briefing carried out by the FO, tells him to select the autobrake system at level “4”.

15.02’53”: the CPT asks the FO to select the flaps on position “1”.

15.03’53”: the CPT notifies the FO that it will use one reverse for deceleration.

15.04’17”: the FO suggests starting to reduce the speed.

15.04’26”: the CPT asks the FO to select flaps “5°”.

15.04’30”: activation of the “Cabin ready” audio signal.

15.05’10”: the FO announces the aircraft is stable on the localizer. The CPT asks the FO to select the flaps on the “15°” position.

15.05’29”: the FO carries out the descent checklist with notes which reiterates the flaps 20° configuration upon landing. The FO confirms, among other things, the autobrake selection at level “4” and the approach speed 167 kt.

15.06’59”: the CPT asks the FO to select the landing gear in the “down” position.

15.07’14”: the REL CPT confirms the landing performance data (2800 meters). The CPT asks the FO to select the Flaps on position “20” (FDR: at time 15.07’18” the flaps are in position 20°, figure 24).

15.07’35”: The landing checklist is enunciated (FDR: at 15.07’36” the preselection of the speed brakes takes place, figure 25).

15.08’30”: the CPT carries out a quick briefing by reviewing the actions in the event of a Go around. The autopilot is deactivated (FDR: autopilot deactivation at 15.08’30”, figure 25).

15.09’01”: the CPT instructs the FO to ask the ATC for presence of fumes or flames from the engine.

15.09’08”: the standard call of the stable condition at about 1000 ft height is made (FDR radio altitude 993 ft, PFD L 172 kt, flaps 20, LG down, ENG 2 62% N1, GS 188 kt, figure 26).

15.09’44”: the CPT comments on the presence of 10 kt of tail wind.

15.10’11”: landing (FDR: at 15.10’07” the selection of both T/R takes place. At 15.10’11” the activation of the T/R of engine 2 takes place, figure 27).

15.10’34”: Call of the 80 kt.

15.10’50”: The runway is cleared at the “AH” taxiway.

Actions after landing, after clearing the runway

15.11’39”: execution of the checklist for hot brake.

15.11’57”: execution of the call “Cabin crew remain seated situation under control”.

15.12’24”: ATC is requested to intervene by the Fire Brigade to check the brake assy.

15.13’11”: engine N° 2 is switched off (land + 03:00).

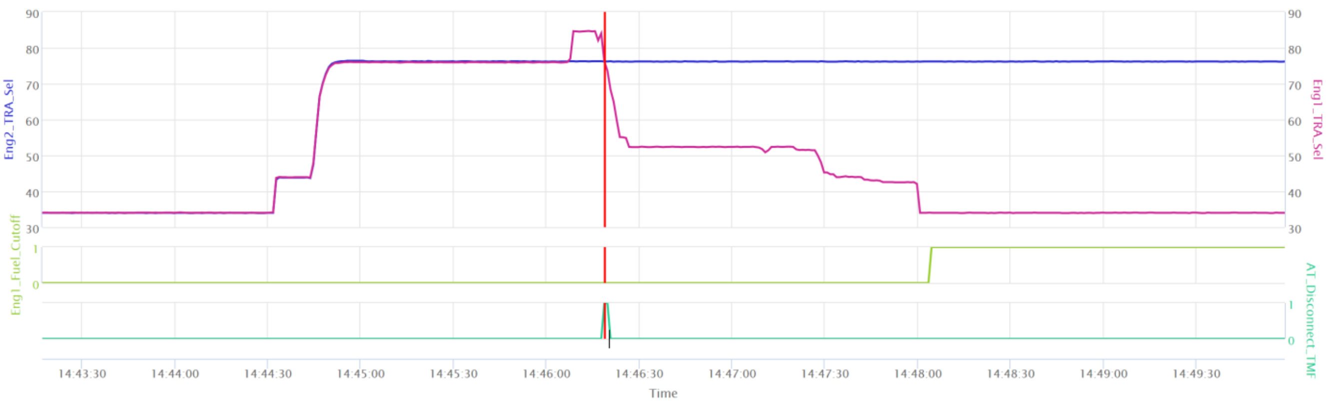

Figure 23: selection of EAFR parameters the red line indicates the UTC time 14.46’18”.

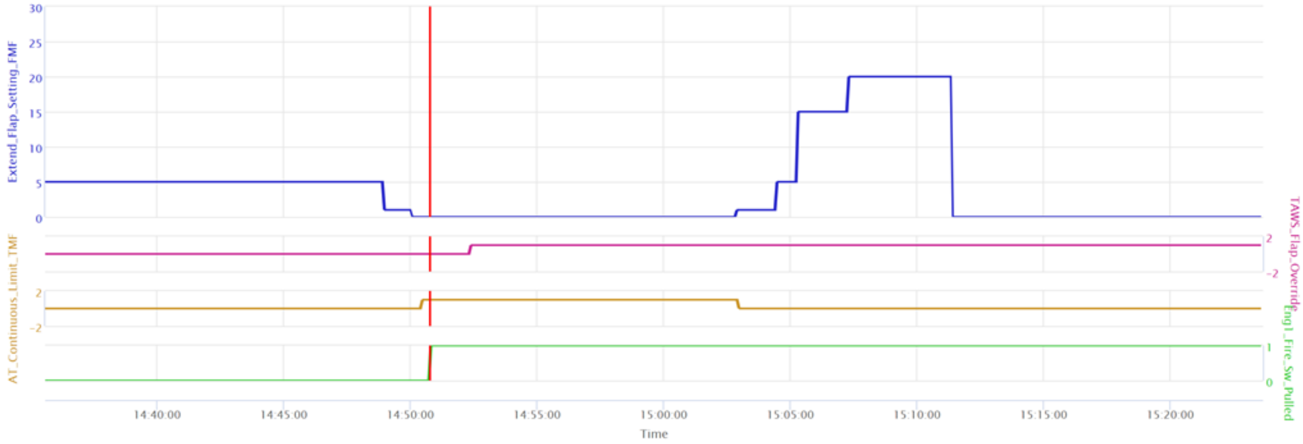

Figure 24: selection of EAFR parameters: the red line indicates the UTC time 14.50’47”.

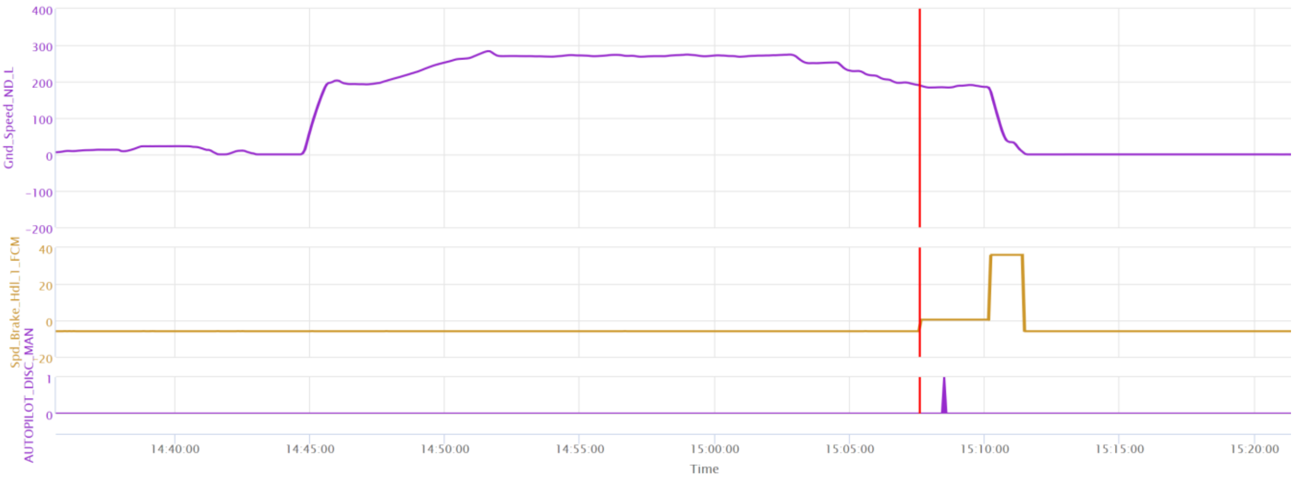

Figure 25: EAFR parameter selection: the red line indicates the UTC time 15.07’36”.

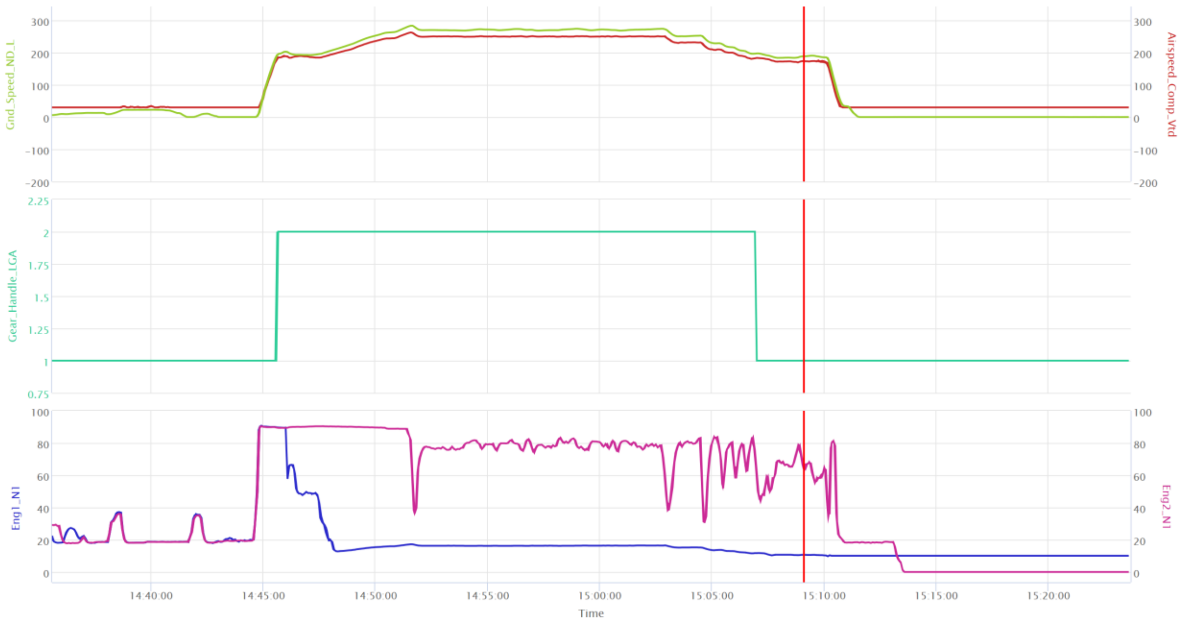

Figure 26: selection of EAFR parameters: the red line indicates the UTC time 15.09’08”.

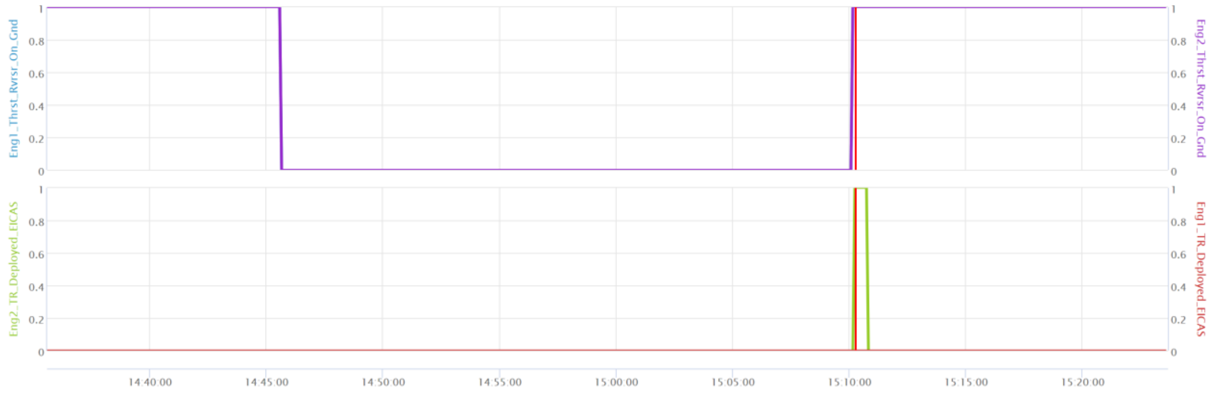

Figure 27: selection of EAFR parameters: the red line indicates the UTC time 15.10’11”.

1.12. WRECKAGE AND IMPACT INFORMATION

Not applicable.

1.13. MEDICAL AND PATHOLOGICAL INFORMATION

Not applicable

1.14. FIRE

See paragraph 1.15.2.

1.15. SURVIVAL ASPECTS

1.15.1. Aerodrome Emergency Plan (Pea)

The PEA was activated from the tower after the MAYDAY declaration. The yellow level was assigned to the emergency[4]. This caused the prompt distribution of information to all divisions and entities interested in the event. In detail, at 14.55’ the personnel and the vehicles alerted gathered in stand 802 as per manual.

Before landing, at 15.06’, an inspection of runways 16R and 25 was carried out. The outcome of the inspection did not reveal the presence of foreign objects debris or other anomalies.

The landing took place at 15.10’ and the Fire Brigade vehicles, already deployed, immediately went alongside at taxiway H after the aircraft stopped.

Runway 16R/34L from 15.11’ to 15.21’ was inspected without finding any anomaly or any presence of FOD.

[4] «Situation in which there is certainty of danger for an aircraft and its passengers and an accident is considered to be possible or there has been a large leakage of fuel or there has been presence of fumes in the cabin», courtesy translation from the Italian text of the PEA document.

1.15.2. Actions of the Fire Brigade

Once back at the departure airport and after clearing the runway, the aircraft stopped at taxiway H waiting for an external check by the firefighters on duty at Fiumicino airport.

These having been alerted by the tower, were already in position. The service report of the Fire Brigade highlights that the crew, in communication with the tower, requested a check of the main landing gears, which were at a high temperature due to the braking action exerted by the aircraft: the brakes were overheated due to overweight landing. In fact, the service report of the Fire Brigade states that the personnel on the spot observed smoke and therefore monitored the temperature by means of a thermal imaging camera. After the right engine was turned off, a small fire on the left main landing gear is described, which required intervention by portable powder extinguishers. During the ANSV interview, the crew reported they would have liked to be able to communicate with the Fire Brigade in order to understand what the external conditions were and possibly also to take any precautionary actions from inside the cockpit. However, the crew and the Fire Brigade were not in direct communication with each other, but only indirectly via the tower. This generated a momentary and slight sense of confusion in the crew waiting in the aircraft for the outcome of the fire brigade. However, this did not induce further consequences.

1.15.3 End of the aerodrome emergency

At 15.30' the Fire Brigade authorized the disembarkation of the passengers. This happened normally and ended at 15.58'. The state of emergency ended at 17.00'.

At 18.27', after replacing the tires, the aircraft was towed to stand 905.

1.16. TESTS AND RESEARCH[5]

1.16.1. Tear Down left engine ESN 10166

The left engine was investigated by the manufacturer in order to analyze in detail all the damage suffered during the event. This was also done in order to verify the consequentiality to the primary damage, considered to be the detached IPTB blade. In this framework, it should be pointed out that the area where the cracks discussed in this report propagate cannot be seen during borescope inspection.

In detail, the investigation allowed to confirm the absence of damage upstream of the IPT module and to characterize the secondary damage occurred on the left engine in the IPT and

[5] Source for figures and photos in this paragraph: Rolls-Royce.

LPT stages. In order to better explain the parts under investigation please refer to figure 28. The main evidence gathered is shown below.

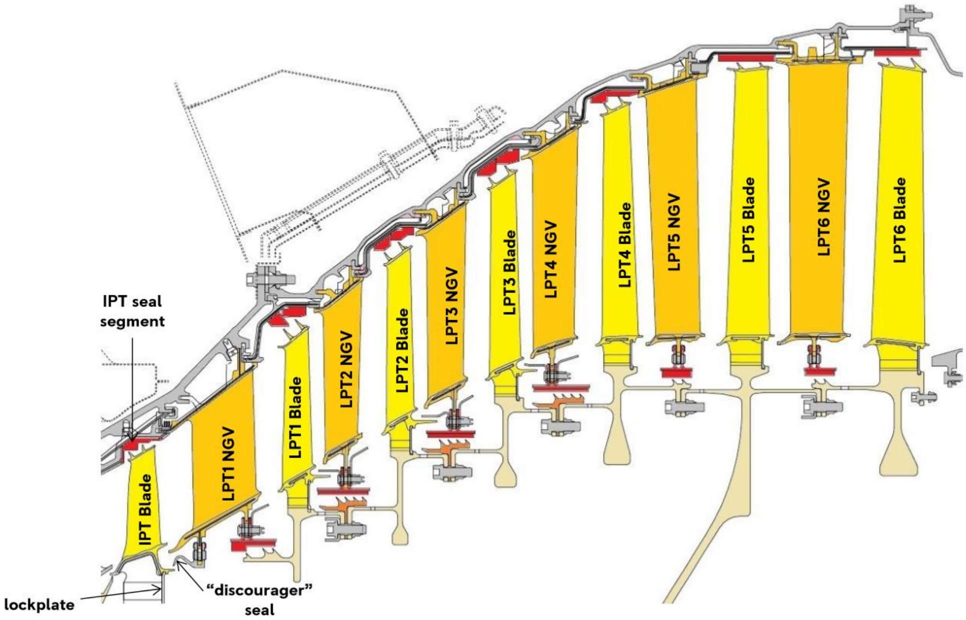

Figure 28: detailed diagram of IPT and LPT stages.

The NGV IPT stage is made of 22 vanes. One of these suffered slight damage on the trailing edge (figure 29). Regarding the IPT rotor stage, this consists of 114 blades. Most of them showed impact damage, mainly in areas other than the leading edge. Only the blade in position number 79 failed below the base platform (photo 14). The trailing blade, n.80, was also fractured but above the base platform. The failure analysis of the detached blade, which was placed in position n °79, will be presented in the next paragraph.

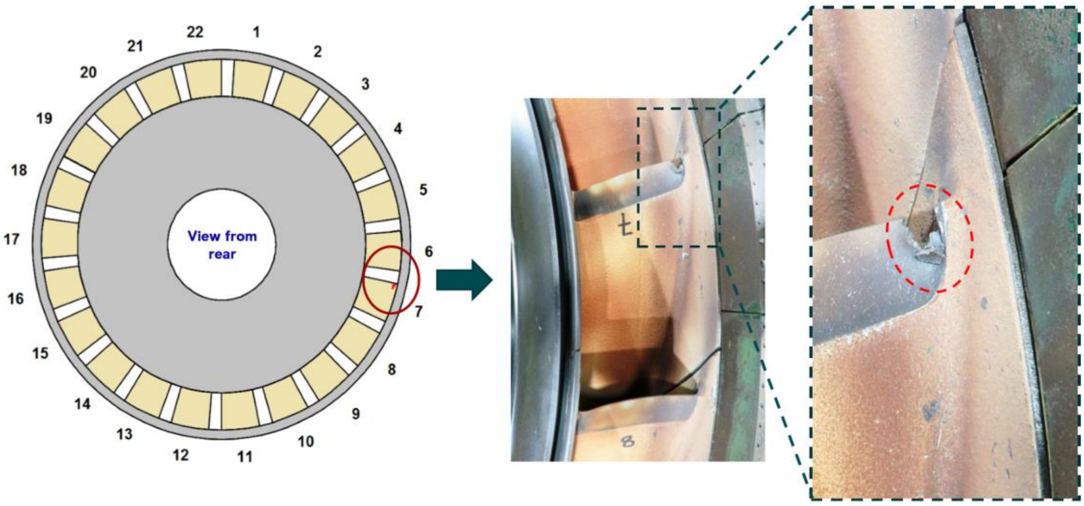

Figure 29: NGV IPT damage.

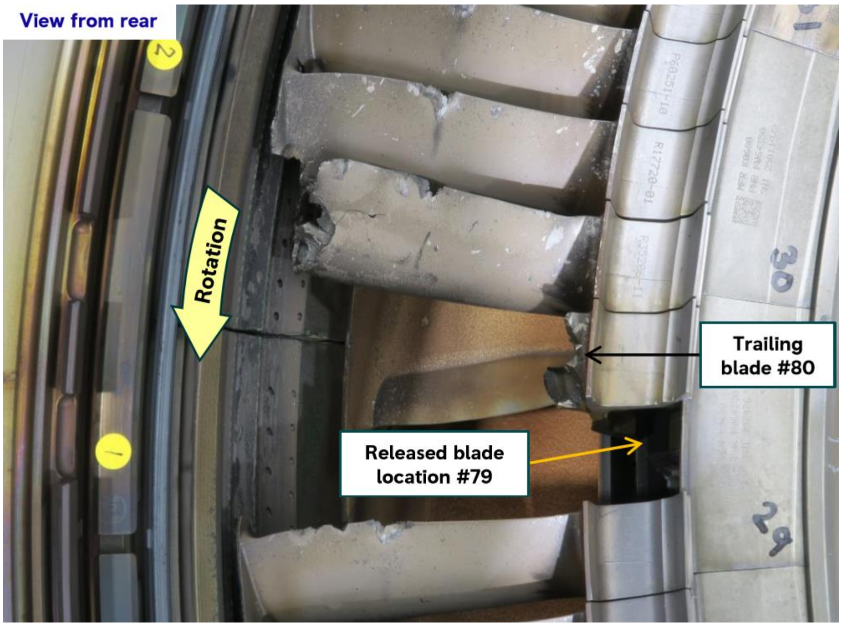

Photo 14: IPT damage.

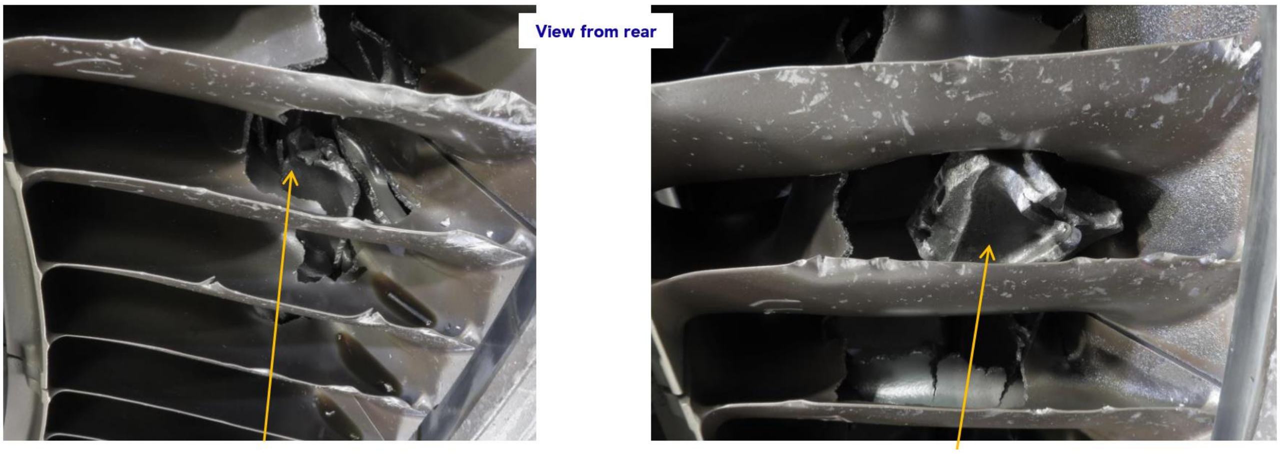

Photo 15: IPT fragments blocked in the LPT NGV.

Two fragments of IPT blade remained stuck in the first LPT NGV (photo 15). Extensive damage to the LPT discourager seal (photo 16) was probably caused by the displacement of the platform of the IPT 79 blade.

Photo 16: discourager seal damage.

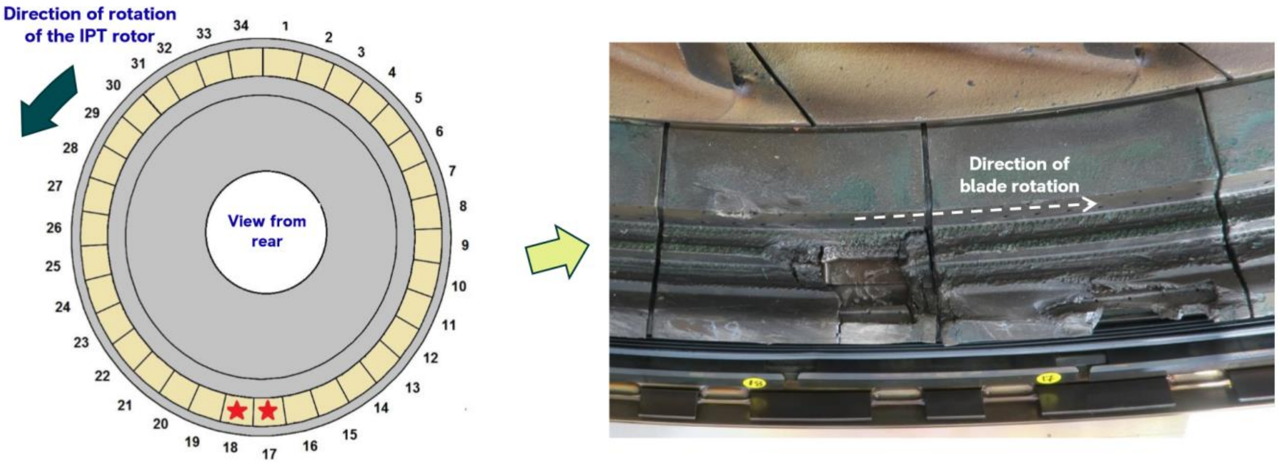

Figure 30: damage to the seal segment of the IPT stage.

Regarding the IPTB seal segment, this is made up of 34 parts. Damage is concentrated on sections 17 and 18 (figure 30).

Damages to the HP/IP bearings (figure 31) were also found.

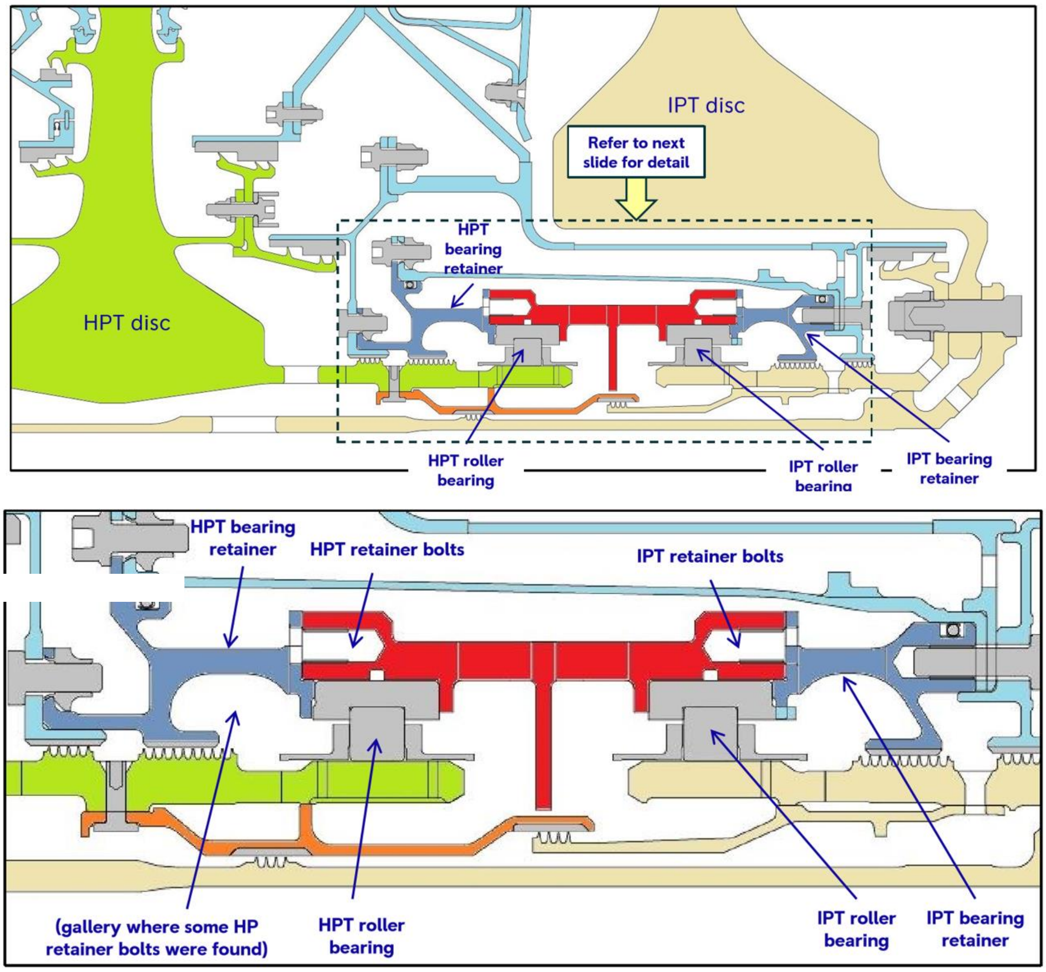

Figure 31: HP/IP bearing housing diagram.

The IPT roller bearing retainer was fixed by 15 bolts, all found with a tightening torque lower than expected. This is most likely due to the anomalous stresses that acted on the assembly. The 4 roller bearing anti-rotation slots were found deformed (photo 17).

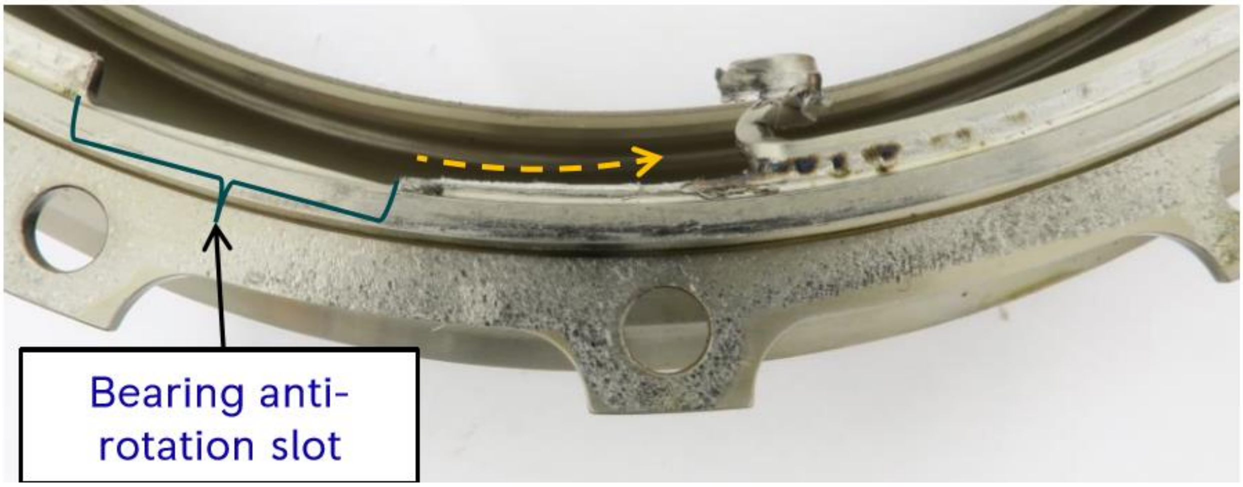

Photo 17: anti-rotation slots.

Fretting marks were also observed on the bolted flange faces. Also on the IPT bearing, deformations and damage on the (anti-rotation) locations dogs were observed (photo 18). However, the bearing appeared to be in good condition: all the cylinders moved freely.

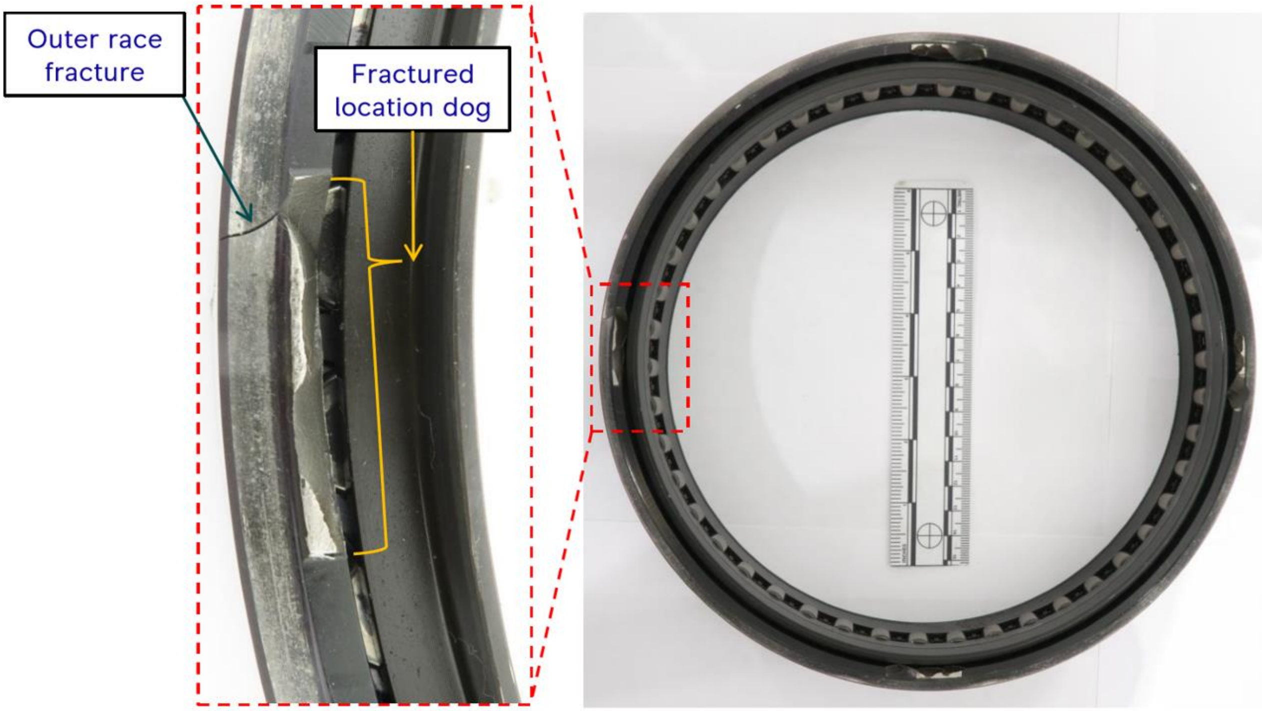

Photo 18: damaged (anti-rotation) location dogs.

About the high pressure bearing, all 15 fastening bolts were found to have released due to abnormal stresses suffered during the event. The relative housing holes were also found deformed and damaged (photo 19).

Photo 19: deformation of the holes for the HP bearing fixing bolts.

The HP bearing showed the same damage already observed for the IP bearing at the anti-rotation slots (photo 20).

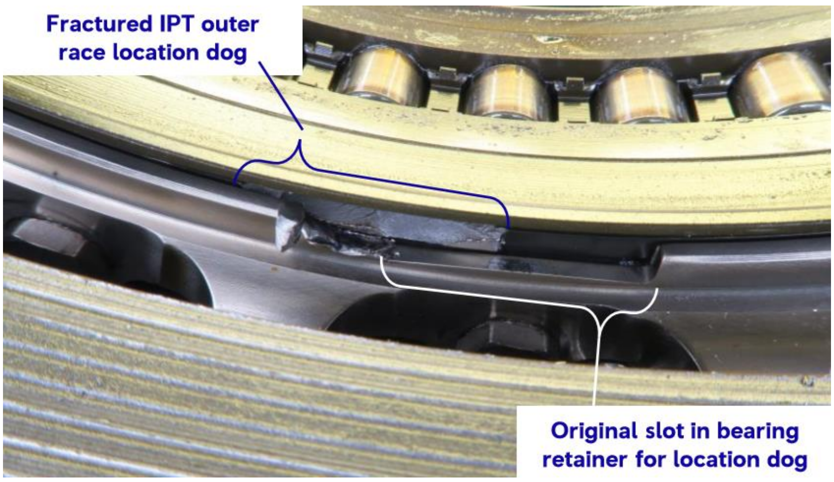

Photo 20: damaged anti-rotation slots.

Substantial damage was also observed on the IPT shaft (photo 21). In detail, heavy rubbing was found, probably due to vibrations and imbalance, subsequent to the detachment of the 79 IPT blade. In the central part of the rubbing, deformation and fracture through thickness was found (photo 22). Similar damage was found on same earlier events. This was assessed by the engine manufacturer to understand the cause and identify any potential safety concerns. The original assessment concluded the observed damage was a secondary effect of the IPT blade release, being caused by rubbing due to the IPT rotor being out of balance when the blade released at certain operating conditions. The localized frictional heating of the shaft resulted in the cracking and no subsequent fatigue propagation was found. Based on the shaft design and experience of other turbine blade releases in other engine types, the assessment concluded that there was very little risk of shaft separation if any future IPT blade release events occurred. The details of the event and damage on 10166 were compared to those which had previously been analyzed and it was concluded by the manufacturer that the damage was consistent with previous experience.

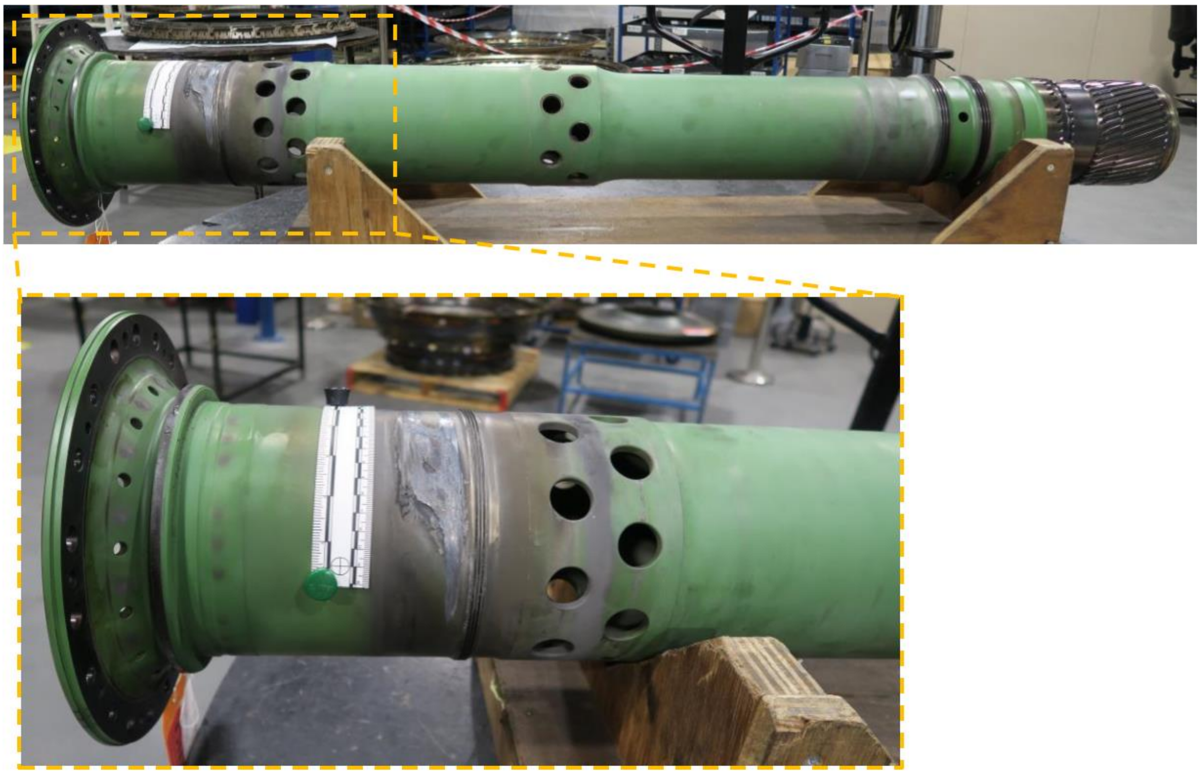

Photo 21: IPT shaft damage.

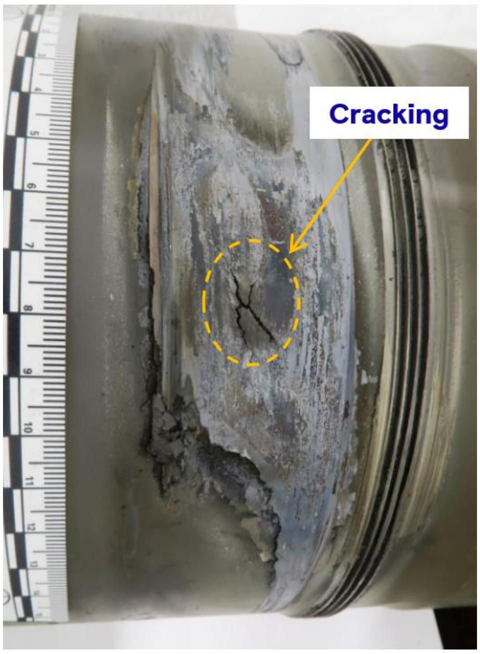

Photo 22: IPT shaft damage.

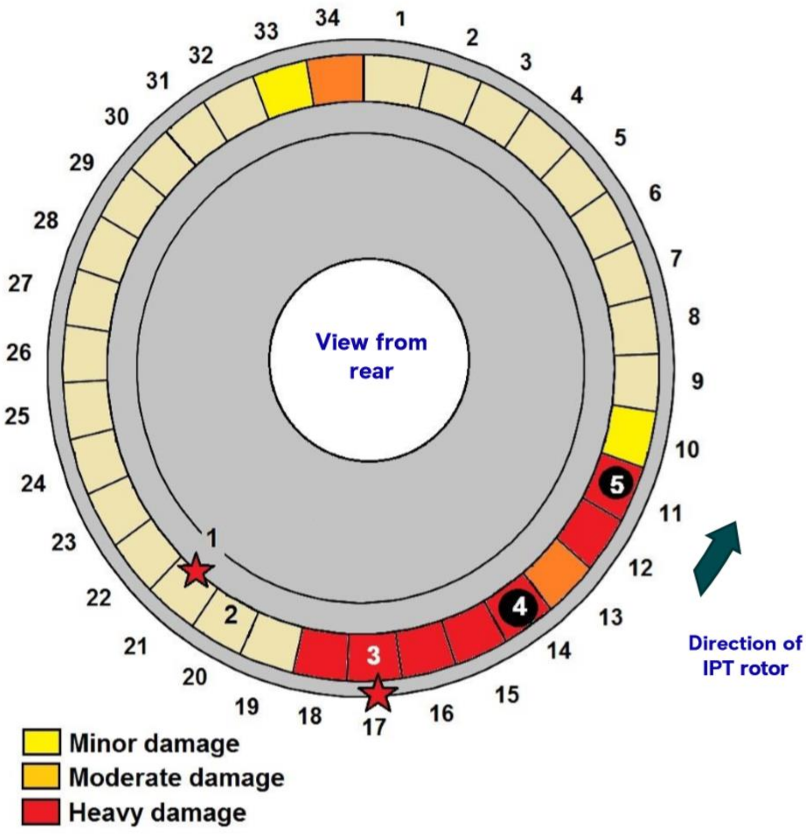

Figure 32: scheme of the LPT1 NGV.

Regarding the LPT1 NGV stage, it is made up of 34 sectors each one 3-off vanes per pack, for a total of 102 vanes. The greatest damage was found to the leading edges through an arc of ~80° between sector 11 and 18 (figure 32 and photo 23, the trajectories of the fragments that caused the damage are also illustrated). All the rest are also damaged to a lesser degree.

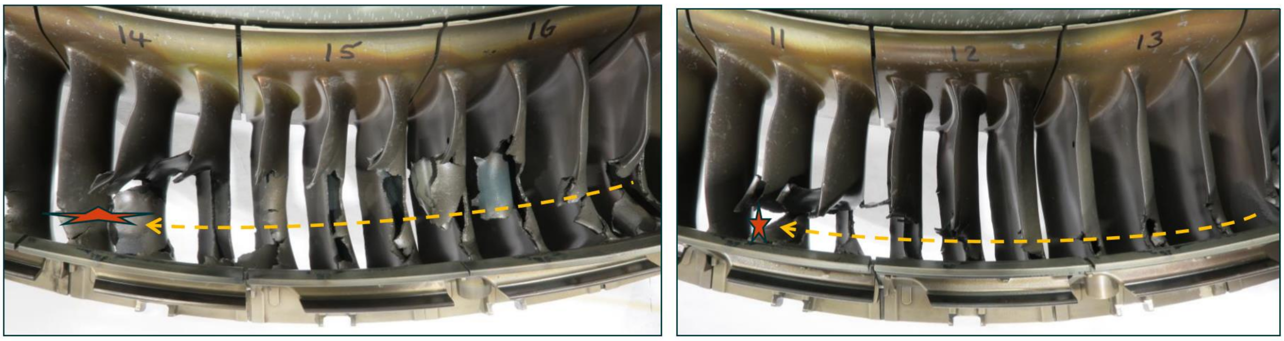

Photo 23: LPT1 NGV damage.

Photo 24: 1st stage LPT rotor damage.

The first rotor stage LPT consists of 170 blades in sectors of two. It is evident that a lot of material from the blades is missing and on the almost intact blades there are conspicuous deformations (photo 24). Similar evidence can be observed on all the successive guide vanes and rotor stages (photos 25-31). In the 2nd stage LPT seal segments, the projection of a fragment created a through thickness indentation on the containment case (photo 27 and photo 32). However no fragment exited through the casing.

Photo 25: damage to NGV 2nd stage LPT.

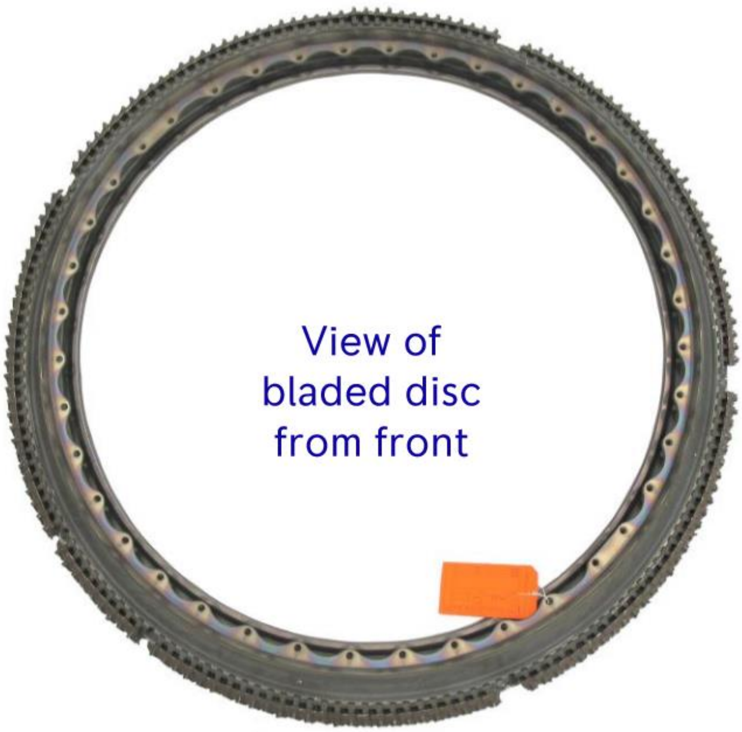

Photo 26: 2nd stage LPT rotor damage.

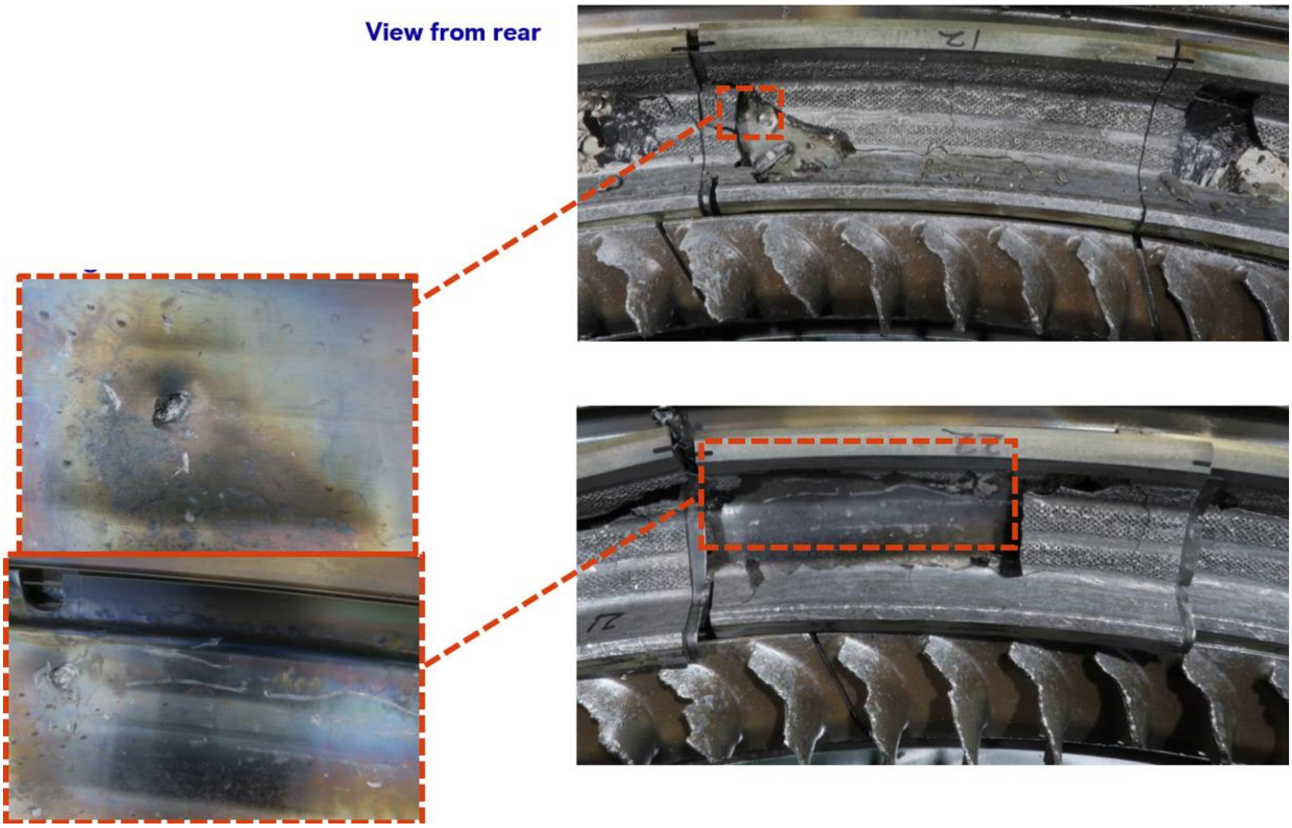

Photo 27: damage to 2nd stage LPT seal segments.

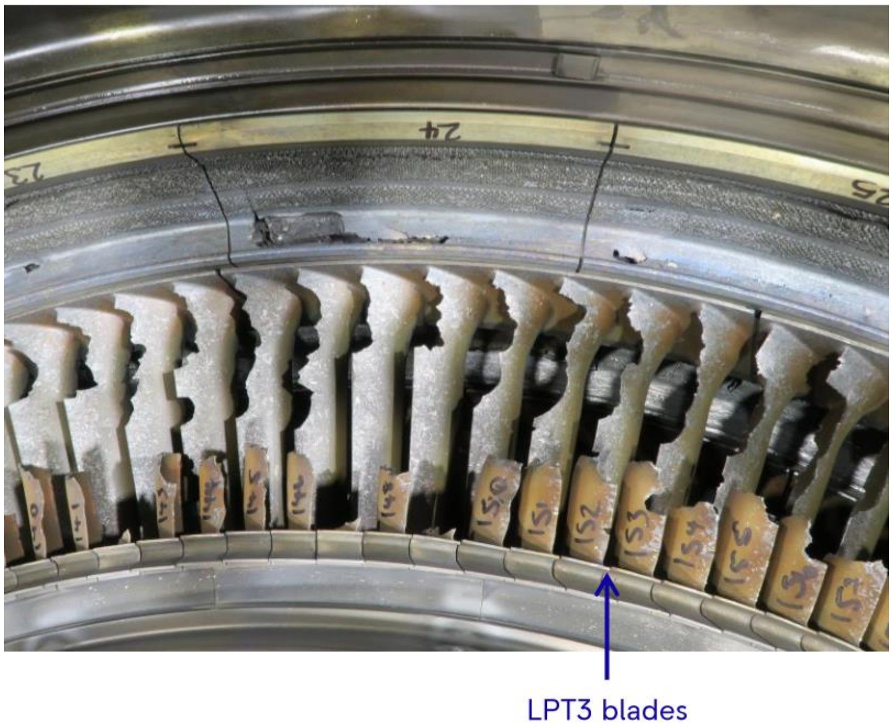

Photo 28: LPT 3rd stage damage.

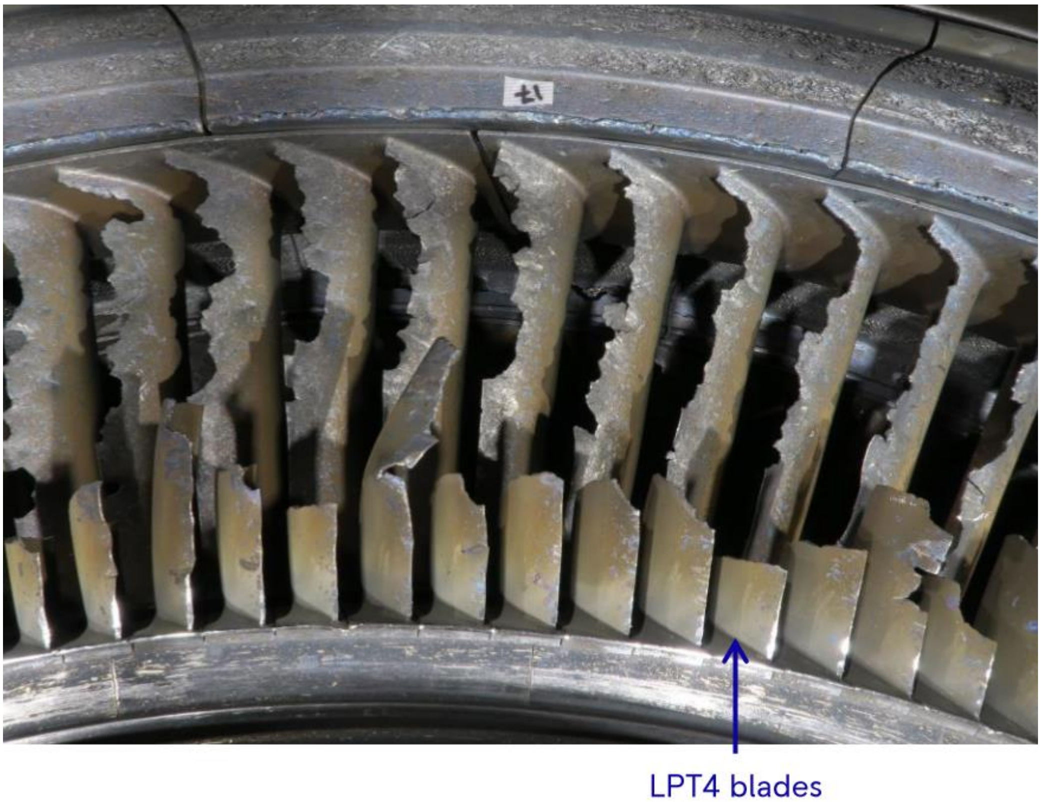

Photo 29: LPT 4th stage damage.

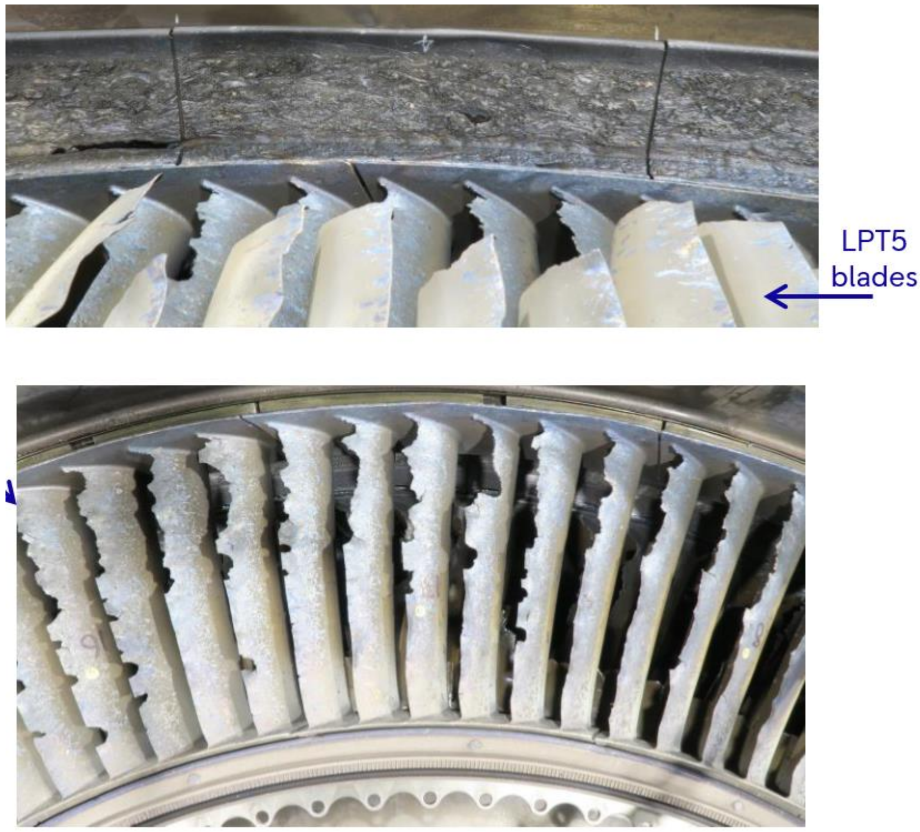

Photo 30: LPT 5th stage damage.

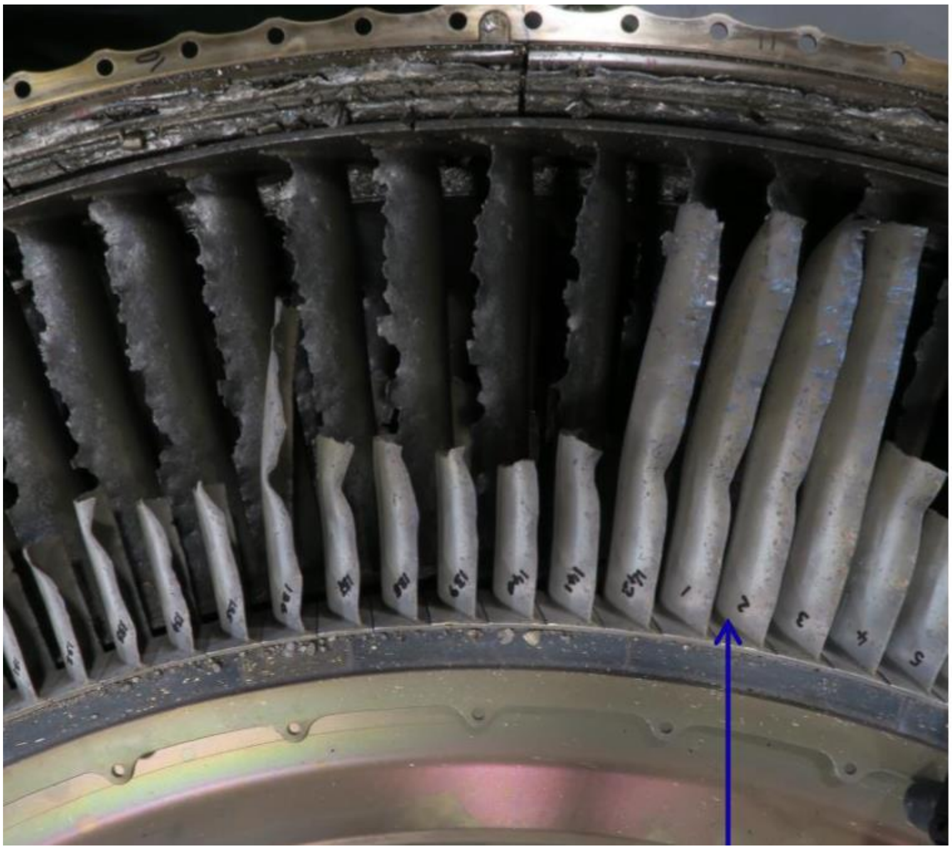

Photo 31: damage to the 6th stage LPT.

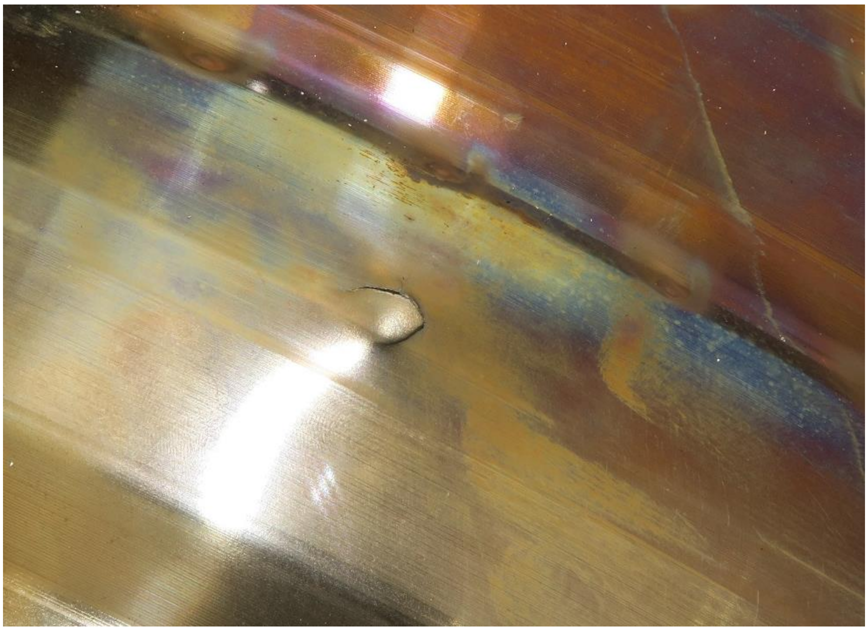

Photo 32: through thickness indentation 2nd stage LPT.

1.16.2. Failure analysis IPTB position 79 ESN 10166

The fractured blade, which was installed at position 79 of the IPT rotor was subjected to failure analysis in order to confirm that this damage was to be considered primary compared to all the others.

The blade had a single crystal structure, made of TMS138A (nickel based with aluminum, cobalt, tungsten, rhenium, tantalum).

In detail, the fracture surface of the aforesaid blade showed two distinct areas. The first, planar, was associated to the progressive part of the fracture (about 37% of the total cross section) and a part of progressive overload. The remaining part was oriented at about 45° (photo 33) and was associated to the overload occurred when the resistant section was no longer sufficient to withstand the applied loads. The progressive part of the fracture surface had a maximum depth of about 6.03 mm. That area appeared to be smooth as well as the area oriented at about 45°.

Photo 33: fracture surface.

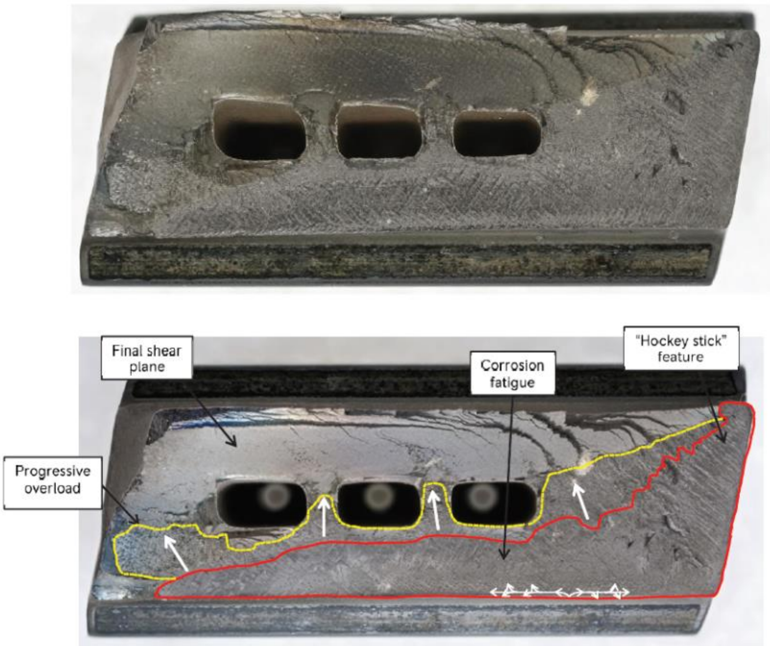

Photo 34: fracture surface.

In the planar zone the following characteristics were observed:

- the progression of the crack was via tunneling crack (approximately 200 µm). It grew towards the leading and trailing edges subsurface and branched toward the convex face and core;
- a "hockey stick" feature was present across the full width of the rear face (photo 34 and explanatory diagram of the characteristic in figure 33);
- from the tunneling the crack propagated along "fingers" through the thickness of the root downstream of the convex edge (photo 35, explanatory diagram of the characteristic in figure 33).

At the depth of approximately 5 mm the morphology of the crack changed and become stepped in appearance (arrow photo 35); these stepped features were parallel and block like and considered typical of progressive overload.

Photo 35: fracture surface detail.

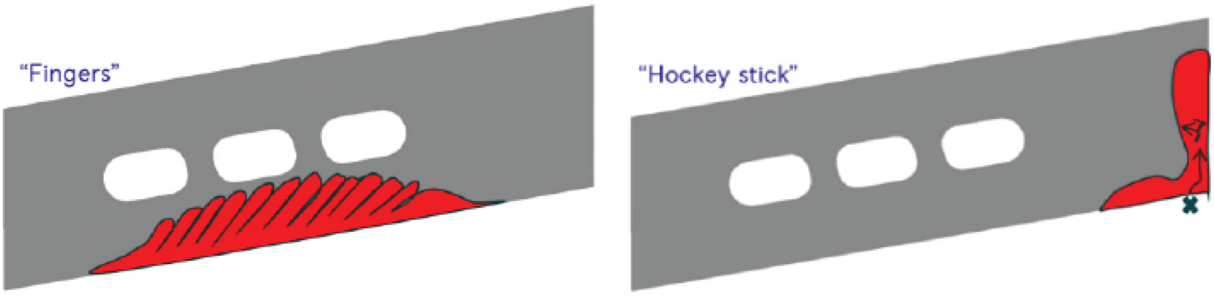

Figure 33: fingers and hockey stick.

Observing the fragment containing the fracture surface it is noted that this is generated at 14.6 mm from the base of the blade measured from the convex side of the profile. This is consistent with the fracture surface located at the DML whose position is expected to be between 14 and 16 mm: the DML is the line formed by the edge of the protective coating.

The observation at higher magnifications by SEM highlighted the presence of a single point origin (circle red in photo 33 and detail in photo 36). The EDX analysis carried out on the shank surface in that area highlighted high concentration of platinum which is anyway attributable to the coating normally used.

All the morphological characteristics observed on the ESN 10166 IPTB 79 (not necessarily in the same combinations) had already been observed in the previous analyses of the IPT blades detached in service.

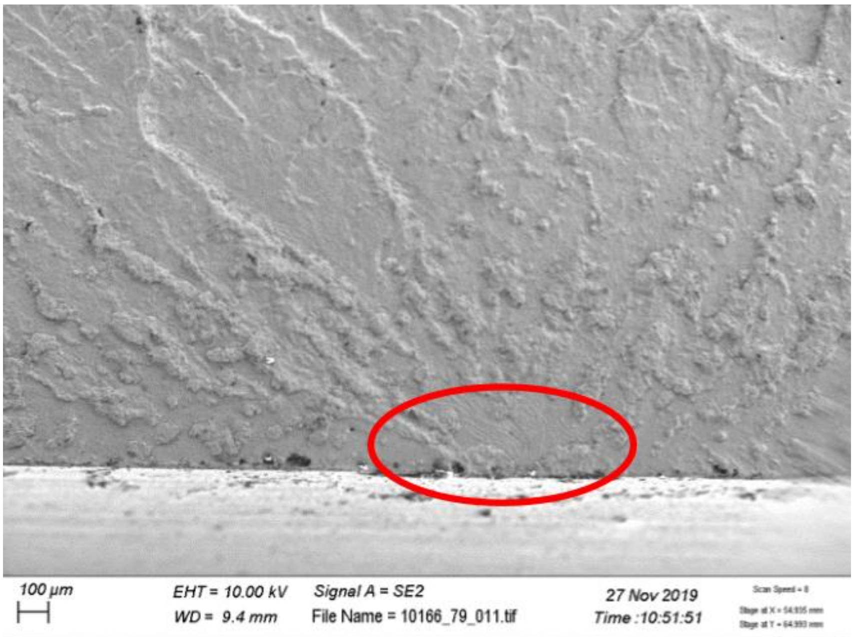

Photo 36: initiation.

Observation by SEM allowed to better observe the other characteristics already visible macroscopically.

Typical fatigue striations were clearly visible at the crack tip (photo 37), whose spacing, varying greatly from area to area (photo 38). However this feature was not observed in the bulk propagation making impracticable a detailed life estimation.

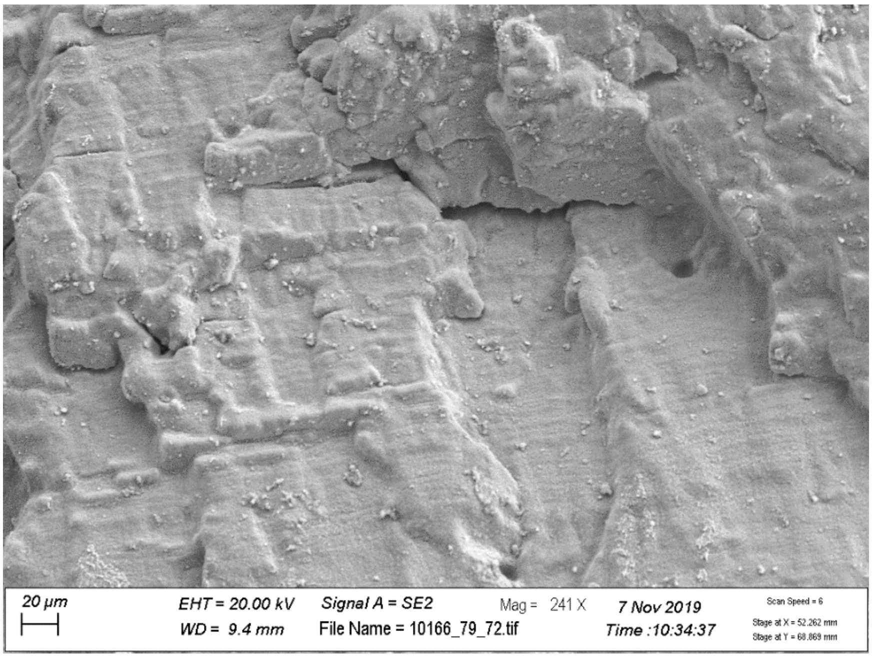

Photo 37: fatigue striations.

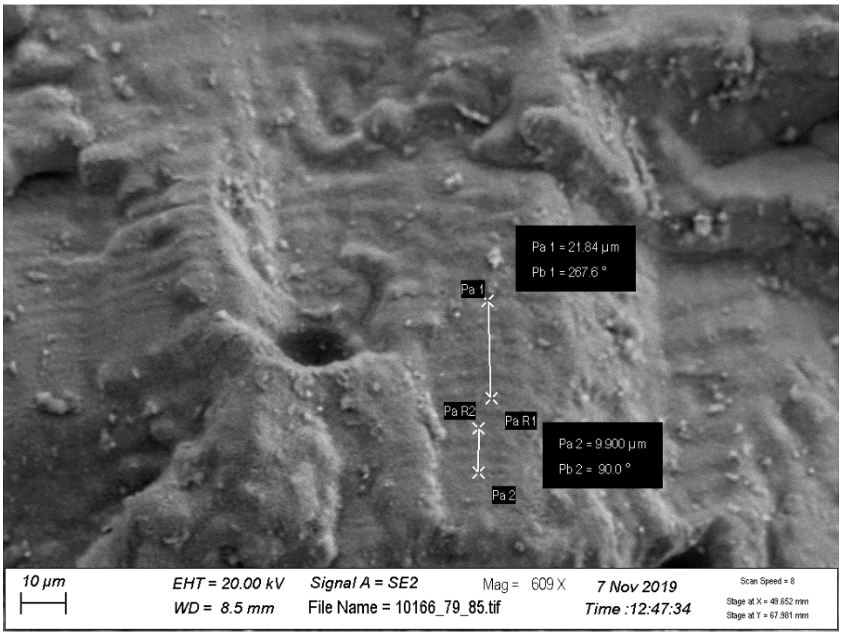

Photo 38: measurements for the calculation of striation spacing.

EDX mapping of the base metal confirmed compliance with the applicable specification. Sulphidation is a common form of corrosion-fatigue found on nickel-based turbine blades. However, the studies conducted by Rolls-Royce on the blade under discussion and on those characterized by a similar fracture mechanism, did not show sufficient quantities of contaminants capable of triggering and feeding a possible Type I or Type II sulphidation. Additionally, the characteristics of the cracks were not the same as sulphidation cracks seen on other standards of turbine blades.

Nonetheless, given the location of the initiation, it was determined by the manufacturer that the phenomenon could start because of the presence of a DML. This evidence of improvable design led the manufacturer to modify the IPT blades of the Trent 1000 by completely encapsulating the blade in a different coating (chromium and platinum instead of platinum only, figure 12) in addition to changing the base material alloy.

The manufacturer has launched an in-depth scientific research campaign when the issue was first identified in order to evaluate how exactly the mechanism initiate and what is the effect the different routes and airport in terms of contaminants. The research is still on-going at the time this report is published.

Of the remaining IPT blades of ESN 10166, further 84 showed the presence of a crack.

1.16.3. Right engine borescope inspection

Borescope inspection of the right engine showed no damage. Some signs of erosion (photo 39) were found in the high pressure turbine blades within acceptable limits for continued operation. Signs of rework were also found on the LPT blades (photo 40) carried out in a previous shop visit at the manufacturer and authorized by technical variance.

Photo 39: erosion on the HPT blades.

Photo 40: rework on LPT blades.

1.16.4. ESN 10140 (right engine) IPT blades

The IPT blades of the ESN 10140 after being removed from the disc were subjected to visual inspection and eddy currents to check for cracks. A total of 92 blades with cracks were identified. These were subjected to fractographic observation. The deepest crack was measured to be approximately 3,47 mm. Some of the cracks had single point origins, and others were multi-origin.

1.16.5. Details on the previously detached IPT blades in service

Evidence similar to that of the IPT 79 blade of ESN 10166 in terms of the failure mechanism was found on the previous IPT blades that released in service. Details in terms of crack depth and area of progression for each of the previous events are provided below. The areas quoted for these fractures are only for the regions of Corrosion Fatigue and do not include the planar area of Progressive Overload. However the maximum crack depths are for both areas.

#	Event Date	ESN	Maximum crack depth (mm)	Crack area (% of total surface)
1	21st Oct 2015	10159	5,71	45
2	22nd Feb 2016	10079	7,14	39
3	3rd Mar 2016	10072	5,84	42
4	18th Mar 2016	10179	7,25	45
5	20th Aug 2016	10176	6,52	34
6	11th Feb 2017	10209	4,84	41
7	5th Dec 2017	10231	6,20	48
8	6th Dec 2017	10227	5,93	43
9	6th Jul 2018	10086	4,88	37
10	15th May 2019	10202 #15	6,1	39
		10202 #15	5,2	43,5
11	10th Aug 2019	10166	6,03	37

1.16.6. IPT blade stress analysis

Numerical assessments were requested to verify the stresses acting on the IPT blade at Maximum Take-Off (MTO), Climb and Cruise. The results in terms of temperatures and stress levels show how these reach modest values with respect to the characteristics of the used material, specifically in the area where typically the cracks of a progressive nature were found to initiate.

1.17. ORGANISATIONAL AND MANAGEMENT INFORMATION

1.17.1. Airworthiness and certification principles

In the framework of the event under discussion, it is appropriate to recall below the main concepts of continuous airworthiness for EASA certified products. These are mainly described in the Annex I of EU regulation 748/2012[6] (Part-21 continuous airworthiness, CAW), as well as for certain topics in the CS-E and CS25 (Large Aeroplanes), including relevant AMC & GM.

The parts of the aforementioned regulations that were considered useful for the purpose of analyzing the event will be cited below.

The following concepts are therefore recalled [AMC & GM for Part 21 Section A Subpart A GM 21.A.3B(d)(4), 2.1 and 2.2]:

«Over the years, target airworthiness risk levels underlying airworthiness requirements have developed on the basis of traditional qualitative airworthiness approaches; they have been given more precision in recent years by being compared with achieved airworthiness levels (judged from accident statistics) and by the general deliberations and discussions which accompanied the introduction of rational performance requirements, and more recently, the Safety Assessment approach in requirements. Although the target airworthiness risk level tends to be discussed as a single figure (a fatal accident rate for airworthiness reasons of not more than 1 in 10,000,000 flights / flying hours for large aeroplanes) it has to be recognized that the requirements when applied to particular aircraft types will result in achieved airworthiness levels at certification lying within a band around the target level and that thereafter, for particular aircraft types and for particular aircraft, the achieved level will vary within that band from time to time.
The achieved airworthiness risk levels can vary so as to be below the target levels, because it is difficult if not impossible to design to the minimum requirements without being in excess of requirements in many areas; also because aircraft are not always operated at the critical conditions (e.g., aircraft weight, cg position and operational speeds; environmental conditions - temperature, humidity, degree of turbulence). The achieved level may vary so as to be above the target level because of undetected variations in material standards or build standards, because of design deficiencies, because of encountering unforeseen combinations of failures and / or combinations of events, and because of unanticipated operating conditions or environmental conditions.».

The concepts set out above and currently in force, are therefore based on:

«accident statistics) and by the general deliberations and discussions which accompanied the introduction of rational performance requirements, and more recently, the Safety Assessment approach in requirements.»

leading to consider valid at aircraft level, the definition of a

«fatal accident rate for airworthiness reasons of not more than 1 in 10,000,000 flights / flying hours for large airplanes».

The same text can be found in the Airworthiness Information Leaflet AD/IL/0092/1-7 of the CAA dated November 19, 1982 (Attachment "A").

[6] Commission regulation EU 748/2012 of 3 August 2012 laying down implementing rules for the airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as for the certification of design and production organisations.

In any case, in the light of the above it is hypothesized that situations of decreased safety levels can occur about 10 times in the life of an aircraft that has a typical life of 60,000 flight hours and, assuming these numbers, it is provided as guideline the possibility of going in decreased levels of safety in proportion to the total aircraft life as indicated below [AMC & GM for Part 21 Section A Subpart A GM 21.A.3B(d)(4), 3.7]:

«Using these criteria, there could then be during each of these emergency periods (assumed to be ten in number) a risk allowance contributed by the campaign alone of:
1×10^{-7} for 2.5% of the aircraft's life; or
5×10^{-7} for 0.5% of the aircraft's life; or
1×10^{-6} for 0.25% of the aircraft's life; or
1×10^{-5} for 0.025% of the aircraft's life, etc.».

All the aforementioned provisions are in force today. They were identically reported, using the same numerical values, in the Airworthiness Information Leaflet AD/IL/0092/1-7 of the CAA dated November 19, 1982.

Reaction times are also provided to restore safety levels according to the following table [AMC & GM for Part 21 Section A Subpart A GM 21.A.3B(d)(4), 3.8]:

Estimated catastrophe rate to aircraft due to the defect under consideration (per a/c hour)	Average reaction time for aircraft at risk (hours)	On a calendar basis
4×10^{-8}	3750	15 months
5×10^{-8}	3000	12 months
1×10^{-7}	1500	6 months
2×10^{-7}	750	3 months
5×10^{-7}	300	6 weeks
1×10^{-6}	150	3 weeks
1×10^{-5}	15	Return to base

The GM 21.A.3B(d)(4), 4.4 also states:

«It is not intended that the method should be used to avoid quicker reaction times where these can be accommodated without high expense or disruption of services.».

Also in this case, a similar table and same text was already present in the Airworthiness Information Leaflet AD/IL/0092/1-7 of the CAA dated November 19, 1982.

In detail, further statistical evaluations must be put in place for the evaluation of the CAW. To avoid risk peaks, even if for a very short time, the probability for each aircraft is limited to 20 times the average value [AMC & GM for PART 21, GM 21.A.3B(d)(4), 3.10]:

«There is one further constraint. However little effect a situation may have on the 'whole life' risk of an aircraft, the risk should not be allowed to reach too high a level for any given flight. Thus while a very high risk could be tolerated for a very short period without unacceptable degradation of the overall airworthiness target, the few flights involved would be exposed to a quite unacceptable level of risk. It is therefore proposed that the Table 1 should have a cut-off at the 2×10^{-6} level so that no flight carries a risk greater than 20 times the target.».

The same approach is assumed for hazardous events whose probability of occurrence can reach 2×10^{-5} per single aircraft.

Furthermore, for large fleets it is also considered appropriate to define a cutoff value in terms of probability of catastrophic event and hazardous [AMC & GM for PART 21, GM 21.A.3B (d)(4), 3.15][7]:

«In addition, in order to take into account large fleet size effect, the expected probability of the catastrophic event during the rectification period on the affected fleet shall not exceed 0.1.
In addition, in order to take into account large fleet size effect, the expected probability of the hazardous event during the rectification period on the affected fleet shall not exceed 0.5.».

The latter values are used to determine the PNE during the emergency campaigns.

What has just been said applies at aircraft level and for fleet. However, it is clear that any increase in the failure rate of the individual component has to be considered to evaluate overall risk.

In this framework, the unsafe conditions are defined [AMC & GM for PART 21, AMC 21.A.3B(b)]:

«An unsafe condition exists if there is factual evidence (from service experience, analysis or tests) that:
(a) An event may occur that would result in fatalities, usually with the loss of the aircraft, or reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be:

(i) A large reduction in safety margins or functional capabilities, or (ii) Physical distress or excessive workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely, or [*omissis*]

(iii) Serious or fatal injury to one or more occupants unless it is shown that the probability of such an event is within the limit defined by the applicable airworthiness requirements, or

(b) There is an unacceptable risk of serious or fatal injury to persons other than occupants, or
(c) Design features intended to minimise the effects of survivable accidents are not performing their intended function.».

The AMC & GM for PART 21 also establish how it is necessary to conduct an event analysis to determine if an unsafe condition actually occurs.

In particular, GM 21A.3B(b) paragraph 2.1, states:

«2.1.2 Events involving an aircraft, engines, system, propeller or part or appliance failure, malfunction or defect

The general approach for analysis of in service events caused by malfunctions, failures or defects will be to analyse the actual failure effects, taking into account previously unforeseen failure modes or improper or unforeseen operating conditions revealed by service experience.
These events may have occurred in service, or have been identified during maintenance, or been identified as a result of subsequent tests, analyses, or quality control."
These may result from a design deficiency or a production deficiency (non conformity with the type design), or from improper maintenance.».

Specifically, for engines [GM 21A.3B(b), paragraph 2.2]:

«The consequences and probabilities of engine failures have to be assessed at the aircraft level in accordance with paragraph 2.1, and also at the engine level for those failures considered as Hazardous in CS E-510.

The latter will be assumed to constitute unsafe conditions, unless it can be shown that the consequences at the aircraft level do not constitute an unsafe condition for a particular aircraft installation.».

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[7] FAA AC 39-8 contain similar concept but setting at the value 1 the probability of hazardous occurrence.

The definition of hazardous is precisely provided in the CS E-510 (g)(2) by the following events[8]:

«(i) Non-containment of high-energy debris;
(ii) Concentration of toxic products in the Engine bleed air for the cabin sufficient to incapacitate crew or passengers;
(iii) Significant thrust in the opposite direction to that commanded by the pilot;
(iv) Uncontrolled fire;
(v) Failure of the Engine mount system leading to inadvertent Engine separation;
(vi) Release of the Propeller by the Engine, if applicable;
(vii) Complete inability to shut the Engine down.».

Although the text of the CS-E does not explicitly define the high-energy debris, on this topic there is the following text [AMC E 510 Safety Analysis (d)(iii)]:

«Uncontained debris cover a large spectrum of energy levels due to the various sizes and velocities of parts released in an Engine Failure. The Engine has a containment structure which is designed to withstand the consequences of the release of a single blade (see CS-E 810(a)), and which is often adequate to contain additional released blades and static parts. The Engine containment structure is not expected to contain major rotating parts should they fracture. Discs, hubs, impellers, large rotating seals, and other similar large rotating components should therefore always be considered to represent potential high-energy debris.
Service experience has shown that, depending on their size and the internal pressures, the fracture of the high-pressure casings can generate high-energy debris. Casings may therefore need to be considered as a potential for high-energy debris.».

Therefore, discs, hubs, impellers, large rotating seals, and other similar large rotating components should certainly be considered potential high-energy debris. However, different possibilities are not excluded, being the energy level that characterizes a high-energy debris undefined.

Furthermore, on one hand it is clear that the engine is required to contain potential radial projections of blades, on the other hand it is not excluded that the definition of uncontained can be applied to axially projected components.

In this framework, there is a discrepancy with the United States legislation (AC33.75), which, although has similar guidelines for the definition of high energy debris, it also adds:

«Uncontained blades from a multiple blade release are typically considered low energy fragments because their energy has been significantly reduced in defeating the containment structure. These events may typically be considered major engine effects.
However, the release of significant numbers of blades (for example, corn-cobbed rotors) will likely include fragments exiting with high energy, and would therefore result in a hazardous engine effect.».

Regarding the acceptability of the Hazardous Engine Effects, there is basically reference to a failure rate as can be seen below [CS-E 510 (a).(3)]:

«It must be shown that Hazardous Engine Effects are predicted to occur at a rate not in excess of that defined as Extremely Remote (probability less than 10^{-7} per Engine flight hour).».

The CS-E also provides a failure rate applicable to events classified as major engine effects [CS-E 510 (a).(4)]:

[8]FAR 33.75 – Safety Analysis has an equivalent text to the CS-E 510.

«It must be shown that Major Engine Effects are predicted to occur at a rate not in excess of that defined as Remote (probability less than 10^{-5} per Engine flight hour).».

Regarding major engine effects, more details are provided in the AMC 510 (3)(e):

«Major Engine Effects
Compliance with CS-E 510(a)(4) can be shown if the individual Failures or combinations of Failures resulting in Major Engine Effects have probabilities not greater than 10–5 per Engine flight hour. No summation of probabilities of Failure modes resulting in the same Major Engine Effect is required to show compliance with this rule.
Major Engine Effects are likely to significantly increase crew workload, or reduce the safety margins. Not all the effects listed below may be applicable to all engines or installation, owing to different design features, and the list is not intended to be exhaustive.
Typically, the following may be considered as Major Engine Effects:
— Controlled fires (i.e. those brought under control by shutting down the Engine or by on-board extinguishing systems).
— Case burn-through where it can be shown that there is no propagation to Hazardous Engine Effects.
— Release of low-energy parts where it can be shown that there is no propagation to Hazardous Engine Effects.
— Vibration levels that result in crew discomfort.
— Concentration of toxic products in the Engine bleed air for the cabin sufficient to degrade crew performance.
— Thrust in the opposite direction to that commanded by the pilot, below the level defined as hazardous.
— Loss of integrity of the load path of the Engine supporting system without actual Engine separation.
— Generation of thrust greater than maximum rated thrust.
— Significant uncontrollable thrust oscillation.».

Regarding minor engine effects, following the definition as per CS-E 510 (g)(1):

«An Engine Failure in which the only consequence is partial or complete loss of thrust or power (and associated Engine services) from the Engine must be regarded as a Minor Engine Effect.».

The definition of the aforementioned failure rates derives from the definition valid at aircraft level about the possibility of a catastrophic event set at 10^{-9} [CS 25 AMC 25.1309 (6)]:

«For a number of years aeroplane systems were evaluated to specific requirements, to the "single fault" criterion, or to the fail-safe design concept. As later-generation aeroplanes developed, more safety critical functions were required to be performed, which generally resulted in an increase in the complexity of the systems designed to perform these functions. The potential hazards to the aeroplane and its occupants which could arise in the event of loss of one or more functions provided by a system or that system's malfunction had to be considered, as also did the interaction between systems performing different functions. This has led to the general principle that an inverse relationship should exist between the probability of a Failure Condition and its effect on the aeroplane and/or its occupants (see Figure 1). In assessing the acceptability of a design it was recognised that rational probability values would have to be established. Historical evidence indicated that the probability of a serious accident due to operational and airframe-related causes was approximately one per million hours of flight. Furthermore, about 10 percent of the total were attributed to Failure Conditions caused by the aeroplane's systems. It seems reasonable that serious accidents caused by systems should not be allowed a higher probability than this in new aeroplane designs. It is reasonable to expect that the probability of a serious accident from all such Failure Conditions be not greater than one per ten million flight hours or 1×10^{-7} per flight hour for a newly designed aeroplane. The difficulty with this is that it is not possible to say whether the target has been met until all the systems on the aeroplane are collectively analysed numerically. For this reason it was assumed, arbitrarily, that there are about one hundred potential Failure Conditions in an aeroplane, which could be Catastrophic. The target allowable Average Probability per Flight Hour of 1×10^{-7} was thus apportioned equally among these Failure Conditions, resulting in an allocation of not greater than 1×10^{-9} to each. The upper limit for the Average Probability per Flight Hour for Catastrophic Failure Conditions would be 1×10^{-9}, which establishes an approximate probability value for the term "Extremely Improbable". Failure Conditions having less severe effects could be relatively more likely to occur.».

In this framework, more schematically, the following table is reported [CS 25 AMC 25.1309 (8)][9]:

Classification of Failure Conditions	No Safety Effect	Minor	Major	Hazardous	Catastrophic
Allowable Qualitative Probability	No Probability Requirement	<-Probable->	<--Remote-->	Extremely <---------------> Remote	Extremely Improbable
Allowable Quantitative Probability: Average Probability per Flight Hour on the Order of:	No Probability Requirement	<---------------> $<10^{-3}$ Note 1	<---------------> $<10^{-5}$	<---------------> $<10^{-7}$	$<10^{-9}$
Note 1: A numerical probability range is provided here as a reference. The applicant is not required to perform a quantitative analysis, nor substantiate by such an analysis, that this numerical criteria has been met for Minor Failure Conditions. Current transport category aeroplane products are regarded as meeting this standard simply by using current commonly-accepted industry practice.					

From the in-depth analysis carried out during the investigation process, it emerges that the concepts expressed above together with the same numerical values were conceived by the industrial world in the 1950s, only to be considered usable in the 1960s. British Civil Airworthiness Requirements (BCARs) were the first to establish acceptable quantitative probability values or transport aircraft systems.

The definition for continuous airworthiness was substantially based on accident statistics together with the introduction of rational performance requirements. This originated the prescription of the maximum allowable probabilities of occurrence at aircraft and system level that remained unaltered up today.

It was ascertained that, for engines, the probabilities of occurrence as discussed above were already present in the AMC of the 1981 JAR-E revision 6: they are unchanged since at least 40 years. It was also verified that there is currently no project in Europe aimed at verifying/re-evaluating these probabilities of occurrence in the light of updated accident/incident statistics and actual volume of traffic.

It is important to note that minimum Safety objectives allocated to a systems and equipment defined in the AMC 25.1309 are composed of several elements. The probabilities are one of them. The AMC 25.1309 was updated 13 times since 1988. Each update introduced new safety relevant considerations.

In the framework of this report it is also important to highlight also the following provision for turbine engines: AMC E 810:

[9] Same numbers are associated to the qualitative definitions of minor, major and catastrophic are reported in the AC 25.1309 1A dated 21-06-1988.

«(c) Condition after Tests . On completion of the tests, a complete power Failure is acceptable, but there should be -
(i) containment by the Engine without causing significant rupture or hazardous distortion of the Engine outer casing or the expulsion of blades through the Engine casing or shield;
NOTE: If debris is ejected from the Engine intake or exhaust, the approximate size and weight of the debris should be reported with an estimate of its trajectory and velocity, so that the effect upon the aircraft can be assessed».

This AMC-E takes into consideration in the design and testing phase the trajectories and speeds of the parts to consider the effect on the airplane.
However, more attention to people on ground is given in the CM-21.A-A-001 Issue 01 dated 29th of November 2018 (Attachment "B"): the document deals specifically with Parts Detached from Aeroplanes (PDA), taking into account the following main variables:

- population density;
- size and weight of the PDAs;

these variables are used to calculate in terms of probability of occurrence per flight hour:

- the likelihood of a PDA event occurring;
- the likelihood that a person will be affected by a PDA;
- the probability that a person, if hit by a PDA, will suffer fatal injuries (conservatively assumed to be 100%).

These probabilities are compared to the probabilities of occurrences used in the CS25 in order to estimate the above mentioned risks.
The CM concludes that on the basis of the statistical study, there are currently no long-term unsafe conditions for the people on ground. This determination was supported by the absence of cases of death or serious injuries due to PDA. However, the study does not take into account the specific risk for people living nearby airports. In this context, it should be highlighted that, taking European Union alone into consideration, the population has grown by about 93 million people from 1960 to 2020 (figure 34) [10], creating higher concentration in urban areas.

[10] Source https://ec.europa.eu/eurostat/statistics-explained/index.php/Population_and_population_change_statistics#EU-27_population_continues_to_grow

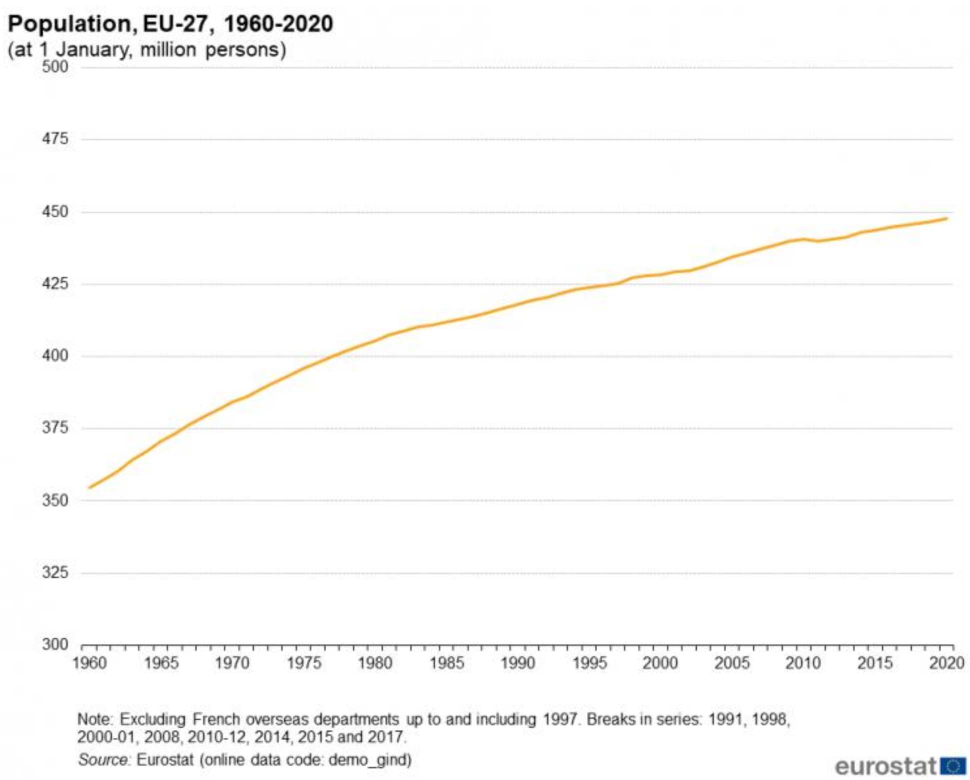


Figure 34: EU population growth over the past 60 years.

Furthermore, with particular reference to the reliability of the engines, the CM under discussion seems not to consider that in the take-off phases and climb engines are more stressed than in other phases of flight. This occurs regardless of the duration of the flight (probabilities of occurrence are defined only in terms of flight hours). In this framework, it should be noted that the manufacturer for the Service Management of these blades had to consider the life of the engine in cycles rather than in terms of flight hours, since this choice gave a better correlation with the crack depth data than the hourly lives. Moreover, the CM does not attribute value in the risk assessment to the temperature that the PDA may have. In this case, the TGT was 876 °C at the time of the failure.

Finally, in this context it also is necessary to consider the ETOPS certification. The Trent 1000 maximum approved diversion time is 330 minutes as stated on the Type Certificate. An operator can choose to use a level of ETOPS lower than that which has been certified because it suits their operation, but this does not affect the original certification of the engine. Indeed, the B787 marks LN-LND was limited to 180 minutes. However, it is also important to note that ETOPS is an aircraft-level consideration. As this airframe is certified by the FAA, the applicable target reliability[11] is 0.01 per thousand hours for all diversions 180 minutes or greater.

1.17.2. Application of the certification principles and of CAW to the specific case

In the framework of this report, the 10 cases preceding the one under discussion were classified as minor, as the most serious consequence of the IPTB releases was an IFSD (in 8 out of the 10 cases; there was no IFSD in the other 2). During the investigation on ESN 10231 (event occurred 5th December 2017), it was identified that the damage found on the LPT1-2 drive arm had the potential to have progressed and resulted in separation of the LPT Stage 1 disc, which may have then overspeed and burst. This sequence of events did not actually occur on ESN 10231, but the potential for it to happen in the future and result in a hazardous outcome was the reason a change in service management approach was needed. This induced more effective actions and quicker reaction times consistent with the provisions of the CAW principles set out in the previous paragraph, which, as mentioned, are substantially based on the CS failure rates. The management of the reliability level of the engines was in compliance with the applicable provisions and within two limits:

1) the certification principles (set out in the previous paragraph, based on hazardous probabilities of occurrence), below those no action is required;
2) principles of CAW (set out in the previous paragraph, derived and proportional to maximum allowable probabilities of occurrence), above those the fleet equipped with that type of engine would have been grounded.

Within these two limits, the mitigating actions resulted in the determination of a maximum admitted Predicted Number of Events (PNE) for the pre-modification engines to remain airworthy, based on the fleet size of 180 affected engines. Figure 35 schematically illustrates what was assessed by the manufacturer when the NMSB 72-AK186 was issued, as a result of the findings from the investigation of the 7th event, after the ninth case of IPTB release. In particular, although all the 10 previous events of IPTB release were classified as minor, after the ESN 10231 investigation, the fleet was conservatively managed to prevent the possible hazardous event of the overspeed and burst of the LPT Stage 1 disc. Considering the fleet of the 180 potentially affected engines, the Hazardous PNE was 0.27, equal to about 4 cases of IPT blade release admissible. In more detail, the whole Trent 1000 pre-modification fleet was divided in operators sub-fleet; relevant failure rates were retrieved in order to impose a conservative hard life for each ESN.

[11] Federal Register Vol. 72, No. 9

Considering the ETOPS requirements, the statistical evaluation made by the manufacturer led to categorizing the risk of a hazardous failure more arduous than DIFSD, which would generate a total loss of thrust.

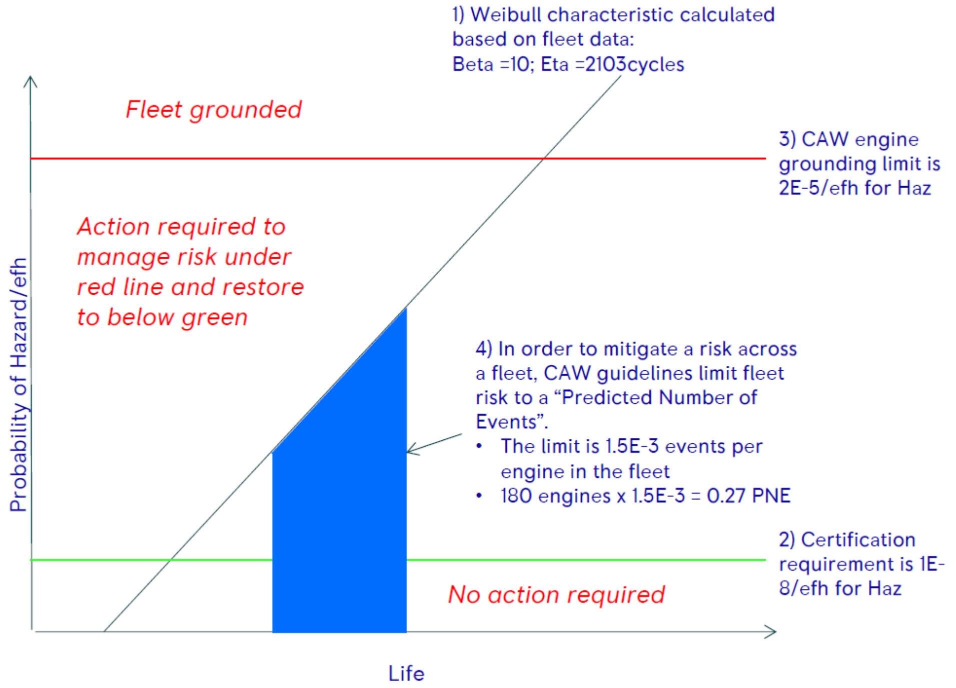


Figure 35: application of the certification principles and CAW to the specific case (property diagram of Rolls-Royce).

1.17.3. Commercial aviation, current statistics

In order to analyze the above-mentioned principles of CAW and certification, some statistics related to commercial aviation are shown below.

Figure 36 shows[12] the number of kilometers traveled per passenger by CAT in the years 2010-2019. There is a steady growth trend. This translates into an increase in the use of aircraft for travel.

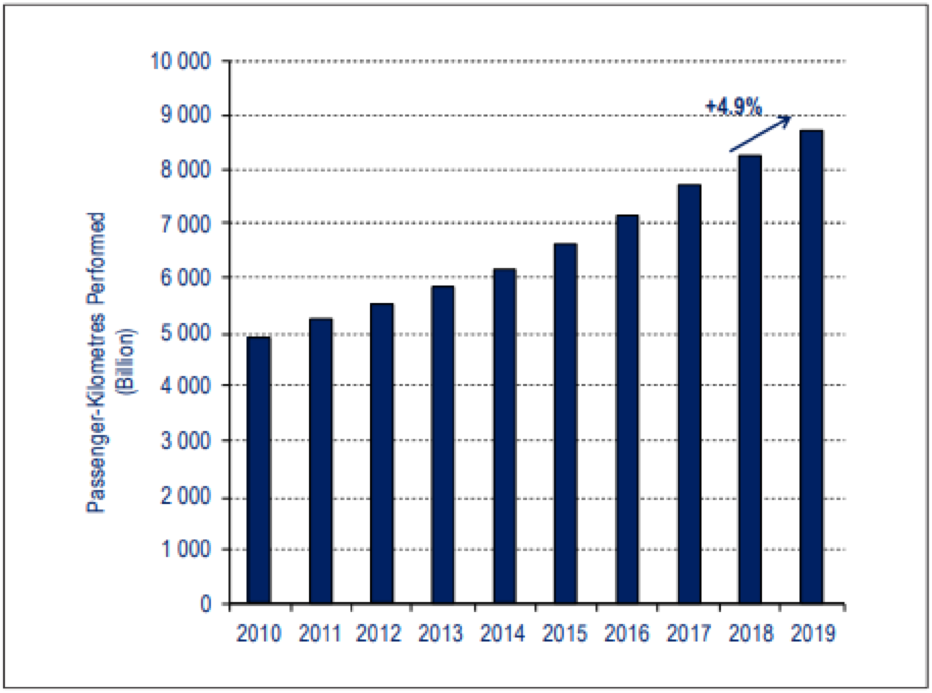


Figure 36: kilometers traveled per passenger in CAT, 2010-2019.

Before 2020, when the COVID-19 pandemic led to a dramatic contraction in air traffic, this trend was expected to increase further in the next 20 years. In this regard figure 37, IFR traffic in Europe[13], is shown.

[12] Source https://www.icao.int/annual-report-2019/Pages/the-world-of-air-transport-in-2019.aspx

[13] EUROCONTROL, European Aviation in 2040. Challenges of Growth, Annex 1, 2018, available at the following link: https://www.eurocontrol.int/publication/challenges-growth-2018

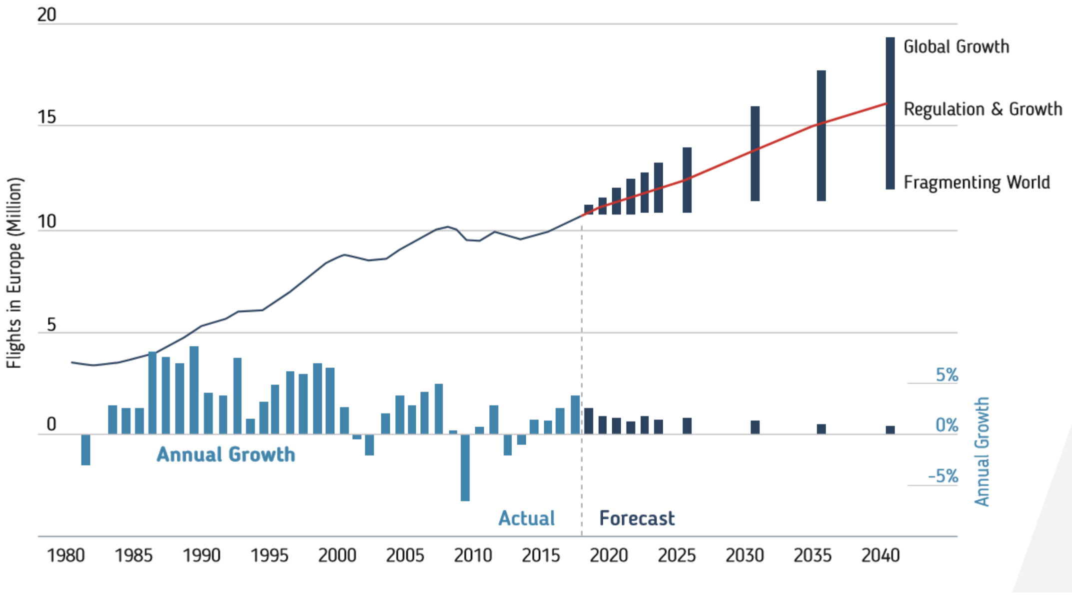


Figure 37: IFR traffic in Europe 1980-2018 and forecast up to 2040.

Nonetheless, the forecasts for the future are gradual return to the 2019 levels and above, according to the different hypothesized scenarios, based mainly on the efficacy and availability of vaccines[14] (figure 38).

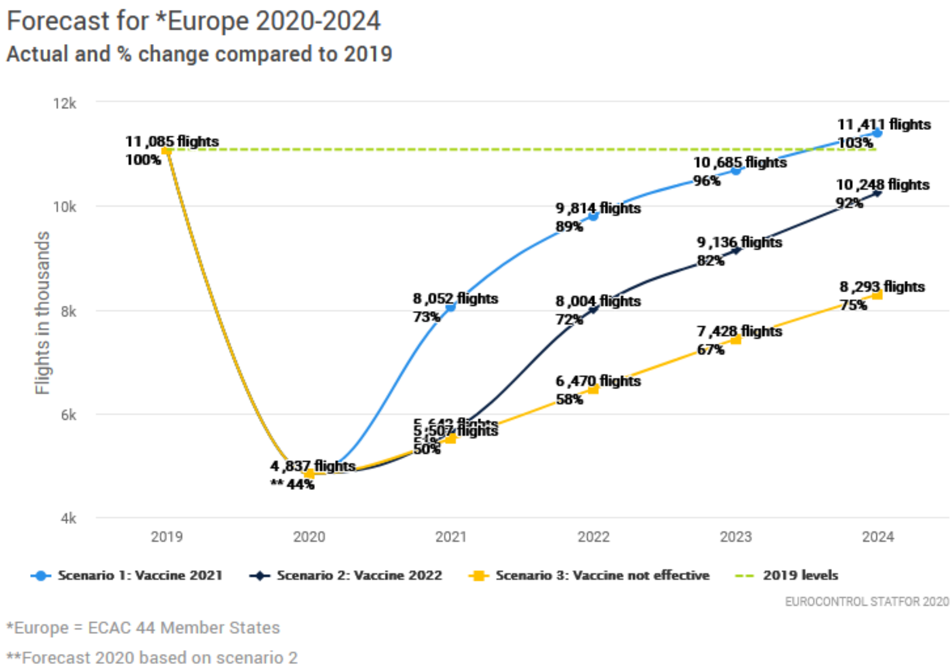


Figure 38: CAT traffic projection in Europe 2019-2024.

At the same time, it should be noted that from the origin of commercial aviation up to 2019[15] there has been a decrease of fatal accidents over the years (figure 39).

[14] Source https://www.eurocontrol.int/publication/eurocontrol-five-year-forecast-2020-2024
[15] Source https://cdn.aviation-safety.net/asnnews/wp-content/uploads/2020/01/ASN_infographic_2019.jpg

On the other hand, a focus on Europe over the last ten years shows a less clear[16] overall trend of improvement in safety (figure 40).

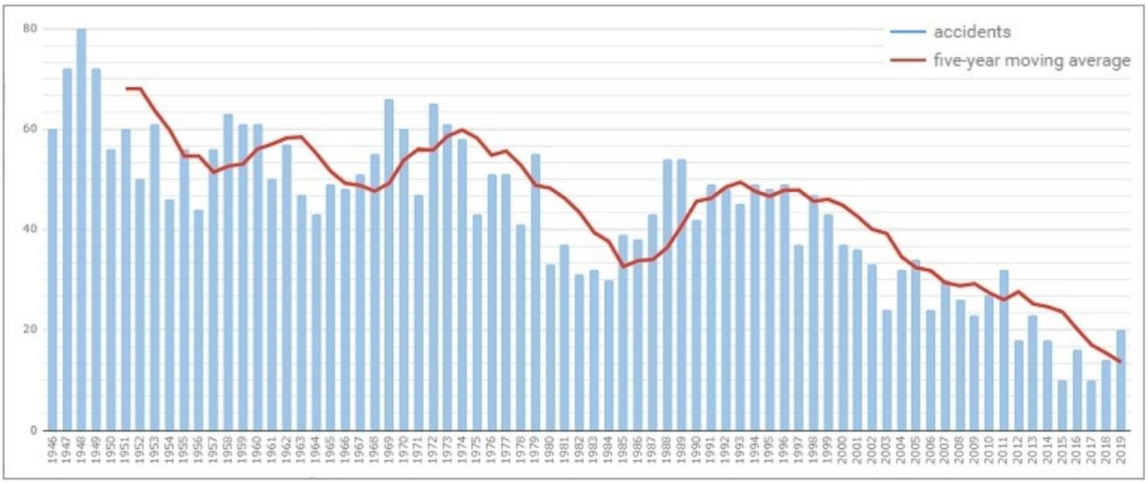
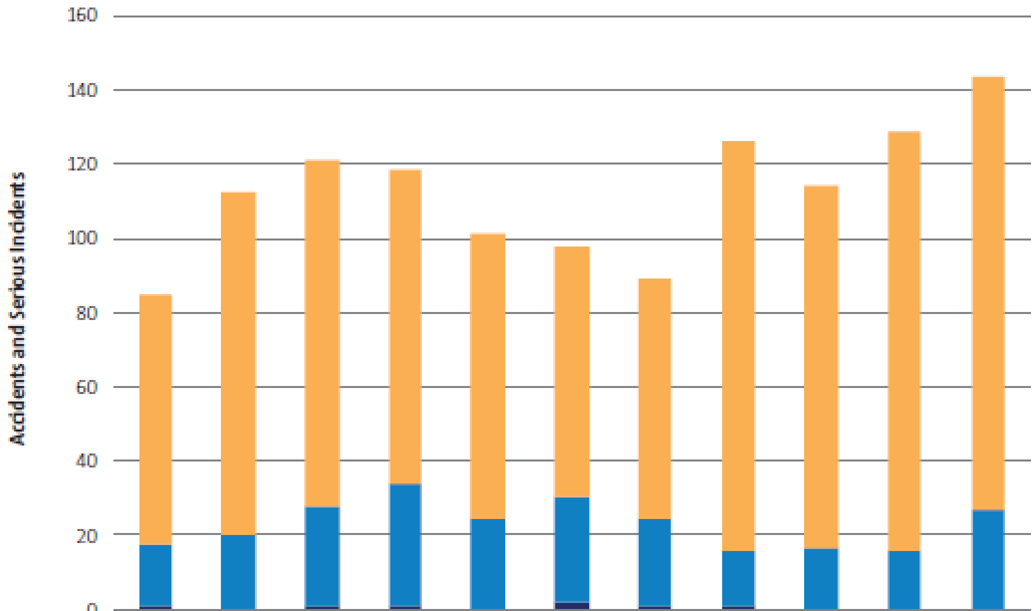


Figure 39: Number of CAT fatal accidents in the world 1946-2019.



	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Serious Incidents	67	93	93	85	76	67	64	110	97	113	117
Non-Fatal Accidents	17	20	27	33	25	29	24	15	17	16	27
Fatal Accidents	1	0	1	1	0	2	1	1	0	0	0

Figure 40: Number of CAT accidents and serious incidents in Europe 2009-2019.

[16] EASA, Annual Safety Review 2020, available at the following link: https://www.easa.europa.eu/sites/default/files/dfu/easa_asr_2020.pdf
Statistics in figure 40 are for EASA Member State Operators of airline passenger/cargo and Air-Taxi with aeroplanes that have a maximum take-off weight above 5700 kg, and as such may not be directly comparable to figure 39 which covers aircraft with a minimum capacity of 14 passengers. Considering the data for the period 2015-2019, figure 40 shows that there were only 2 fatal accidents in Europe out of a total of about 70 shown worldwide in figure 39.

1.17.4. Operator

The aircraft operator at the time of the event was Norwegian Air Shuttle ASA, holder of the AOC issued by the Norwegian Civil Aviation Authority on the 28.10.2014. As indicated in the operations specification issued on the 11.03.2019 the company operated the Boeing 787-8 marks LN-LND for CAT worldwide.

1.18. ADDITIONAL INFORMATION

1.18.1. Statements

Following the written report from the crew. Some aspects of the flight were also discussed during the interview to the flight crew held at the ANSV premises.

Captain

«Shortly after gear up I noticed unusual noises I could not identify. This was followed by an EEC MODE L message and loss of TPR L indication. Vibrations were felt and engine problems reported to ATC. As we had already started a turn on SID, I requested a HDG out to the sea. ENG LIMIT EXCEED L followed and the EGT was full red, combined with more and stronger vibrations. L ENG was shut down. MAYDAY declared and vectors for relanding requested. Meanwhile cabin crew called and informed about engine problems and to stand by. Flight leveled at 3000 ft. 2 circles flown as delay vectors to gain time for landing prep. NITS briefing performed with a normal landing announced. Overweight landing checklist performed as decision was made not to expose the aircraft to more single engine time than necessary. This resulted in a F20 landing which was carried out without further incident. RWY 16R vacated. Acft stopped on Twy AH for tow. During wait 2 tires deflated due to hot brakes.».

First Officer

«After a normal preflight and taxi we took off from runway 16R at time 14:45 UTC. Less than two minutes after departure at approximately 400 ft we simultaneously felt airframe vibrations, felt loss of power on the left side indicated by yaw, and had EICAS messages start to appear. At this point I as pilot flying was flying manually and I initiated a turn to the right as per SID despite the engine issues as they were simultaneous with the turn and it brought us over the ocean where we wanted to be to troubleshoot. Once the turn was completed we identified the problem as severe damage. The EICAS indications we had were ENG EEC

MODE L, OVERHEAT ENG L and I believe one or two others which at this time I do not recall. We observed that TPR indication was gone, the EGT was red and exceeded, thrust was fluctuating on the left engine, vibrations at 99 and OIL TEMP rapidly rising. We completed memory items for severe damage and asked for a vector over the ocean. We were cleared to climb 3000 ft on initial heading 240. Once a few miles were done we requested to stay in the area as we were turning back and were given heading 340. At the time of the engine shutdown we declared Mayday. We then continued to clean up the aircraft retracting the flaps. Once level we initiated all the non-normal and normal checklists including the overweight landing checklist. We then proceeded to inform the cabin crew first, then the passengers. During the next period of time we prepared the ILS approach for runway 16R including landing performance which was done with actual conditions. The landing phase proceeded with no further incident. We decided to vacate the runway and then stop as we could not do a single engine taxi as per procedure and we had very hot brakes which we wanted inspected.

Some minutes after we stopped on taxiway AH we had fire services, engineers and police on the scene. We then had the external tires on the left main gear, which were the hottest, deflate suspecting the fuse plugs had melted. The fire brigade proceeded to cool our brakes. The cabin was given the call “situation under control” which allowed everyone in the cabin to remain calm.

Once satisfied with the situation we disembarked the passengers on the taxiway by stairs in to busses with no issues. The engineers proceeded to change the 2 flat tyres in order to tow the aircraft. While this was happening the police came on board and started asking us questions which we cooperated with as best we could. The crew disembarked and there were no further incidents.».

Relief captain

«At appr. 600 to 800 ft above MSL EEC L EICAS MSG appeared, followed by high EGT on ENG 1. PM reduced thrust on effected engine. After a very short time strong vibration of airframe occurred with indication of vibration level 99, crew decided to shut down the associated ENG because of suspected severe damage. ENG shutdown stopped the vibration. Declared MAYDAY, informed ATC, cabin chief and pax of situation and intentions. Requested latest weather and confirmed landing performance calculations for return to RWY 16R. Prepared overweight landing (which had already been briefed on ground in case of ENG fail). PIC became PF to perform the landing. Normal ILS 16R approach was performed with an uneventful flaps 20 landing and full Reverse Thrust on remaining Engine. Vacated RWY 16R and stopped airplane on TWY. Firefighters and engineer approached the aircraft and direct communication with engineer was established via headset in the nose wheel well. After crew checked break temperatures and noticed high values on all main wheels we requested firefighters to check, report and possibly cool effected wheel breaks. ATC suddenly informed us about smoke and fire in the nose (!) wheel. Contacted ground engineer immediately, who had visual contact with all wheels and did not confirm any fire. Only fumes from cooling agent used by fire fighters at the left main (!) gear had been confirmed by him. I was on the jump seat and left immediately to check for any smoke or visual evidence in and out of the cabin from a window next to the engine inlet to gain as much information as possible for judgment of the situation after having been informed by cabin crew that some passengers reported white smoke below the left hand wing. No smoke or fire was visible to me at any time, which I reported to the PIC when I returned after one minute. However, tire 1 and 5 fusible plug melted later, so that the airplane couldn't be towed to a parking position. Pax left the airplane via air bridges and busses towards the terminal. Total air time was 25 minutes.».

Senior cabin crew member

«We started the day as usual and normal flight. We've arrived to the AC and did a briefing as per SOP. At FD briefing as procedures they inform us about AC issues as mentioned at the tech/logbook and AC info. They mentioned issues about air-conditioning system/pressurization and other minor issues (coffee makers, etc). So we (the crew and me) were already aware to be extra vigilant during our long flight ahead and specially over high terrain areas. We did our checks as SOP. We had the AC been searched by the Italian police department with dogs, the crew at that time had to be outside the AC (FD remain on board). After they police left because everything was right we started boarding on a remote stand. We TOOK OFF. It was a regular TO. Nothing out of normal or different during TO. Few minutes after the TO 1R and me 1L we started to feel strong sounds and strong vibrations from specially my door side. It was approximately 3-5 minutes after TO. We stared to share our perceptions. At that time I've receive a call from 3L. Telling me he heard strong sounds and felt strong vibrations on his for area as well. Asked me if he should inform the FD directly or if I'll do it, because the seat belt sign was still on and we were still climbing and gaining altitude (and was not long after TO). I told him I'll call/inform the FD. I've called all the crew to know as well if it was all around the AC or just left side and if they heard or felt the same. Right after I've called the FD. Informed then about our perception and the situation at the cabin. They answered they had a situation they were dealing with so I'll receive NITS briefing shortly. When FD mentioned NITS I knew we could have an emergency or abnormal situation and that it could upgrade or downgrade. I called all attendant and informed then about the situation to be aware and ready to hear an emergency call from FD. Asked how they were and how were the passenger, because they were as well hearing the inter phone calls in the cabin. Some pats were showing and feeling noises and vibrations too. The passenger were calm but looking at us at all time. We received the emergency call from FD: “Senior to FD, Senior to FD” around 5 minutes after our call approximately (10-15) minutes after TO. Without delay I’ve grabbed a pen, piece of paper and my file and proceed/report to the FD. Once entered to FD I’ve received NITS briefing from Cpt. He was calm and so clear with the briefing and further instructions to be followed. I’ve repeated the NITS to him as per SOP.

Nits were:

N: LHS engine failure.

I: to land at FCO airport.

T: 15-10 min.

S: No specials, just NORMAL LANDING PROCEDURE so secure the cabin, but not a prepared EMERGENCY LANDING , he’ll do the PA to paxs and the inform us when 10min to land.

When I left the FD as per SOP 1R, 2L and 2R were outside with their CEC and ready to receive NITS briefing. I called 4R and gave him NITS briefing, he repeated to me. I’ve gave NITS to the fwd crew and they repeated back to me. I’ got 4R confirmation NITS were completed.

At the same time the Cpt. did a PA to all paxs informing that due to technical issues we were going back to FCO airport. We’ve secured the cabin, as we were doing a NORMAL LANDING. We knew we have an abnormal situation and that we have to be extra vigilant during landing and right after. We were aware that will be an overweight landing and with very fast speed due to the engine failure.

The crew were calm and following SOP and their duties, calming passengers at all time. I called all crew to receive the cabin report and gave the cabin secure to pilots. Those minutes before the landing were feeling so long, but we had the time to think about all our Emergency procedures.

LANDED. It wasn’t that hard landing as I thought it would be. Paxs were still calm and clamping for the great and safe landing. We waited seated meanwhile decreasing the speed at the runway and looking outside and inside conditions, waiting for further instruction or Emergency call or Evacuation if required. Few minutes after we heard “Cabin crew remain seated, situation under control”. Even though we were still vigilant to cabin and passenger. I’ve call all the crew to know if they were ok and how were the paxs at the areas I couldn’t see.

FD was at all time letting the passenger know about the situation and asking them to remain calm and seated, informing them that they will see fire department approaching us and that was a normal. Told again to remain seated and following crew instructions. The passenger after landing were calm, few of them just curious and looking through the windows and taking pictures or videos of the fire department and all the display of ground staff around the AC.

The crew were reassuring passenger at all time, very professional and calm. Knowing their duties and communicating with each other constantly.

Few minutes after and when it was safe and sure the FD made the PA: “Cabin crew disarm Doors”. It is usually made by de Senior crew, but as we were communicating and they were very busy receiving all the info about the emergency landing we decided that the will let us know when to disarm doors.

After the FD PA Cabin crew you may open doors. We waited for a while and were in constant communication between crew and FD to be sure that when we opened the door was safe to do it.

Once we received the OK from FD and Ground staff we started to disembark. When disembarking paxs were so grateful and complimenting the FD and all crew. Just a few were asking what’s next.

When all the paxs were disembarked the italian police came on board and wanted to talk first with the CMDR, I told that he was still busy (he really was). So they started to question me about everything that was happening. The needed information. I’ve told them just flight number, AC registration how many crew. The asked me for the Passenger list. I asked the Capt first because I know we can’t give any information in this case of situation without company permission. The police told us that some parts/pieces of the AC had fallen over Fiumicino town, cars and houses. That maybe a person was injured and at the hospital. We were so concern about that because we didn’t know about this fact. Nor crew neither pats knew or saw any pieces were falling from the AC. Half an hour later they confirm us there were

no injured people. With was such a relief for FD and cabin crew.

They finally managed to talk to the FD, authorities, airport emergency management, etc. The police needed constantly help with english, asked for translation from the crew, FO and myself (even if I’m still improving Italian) so we managed to communicate.

The CCMs, myself and the FD We were so long waiting to disembark on board the AC, we left the AC around 19:45 or 20:00 local time. Meanwhile FD and me talked and discussed what to do after, but still in the meantime the Cpt. was at the phone and very very busy. I had

little debriefing on board with the cabin crew, to know how they were feeling and make sure they were ok.
The Cpt. and the FO (he was the official translator to the italian policemen), when we finally were able to leave the AC, had to go with the Italian police to do an statement. RC at Jump Seat went with them as well.
CCM and me went to the crew room to be all together and wait for a debriefing from the FD. We decided to get change to civilian clothes in case we needed to be at the terminal so the passengers won't be recognising us that easily. In case they were around without knowing the next steps after the incident.
I took around 4h to the FD to reach the FCO crew room. They've arrived at FCO crew room around midnight. We finally managed to get a proper debriefing. We shared the experience and got more clear information about everything that happened. We've had at all time a great support from the FD and the company. Our team work was from the beginning AWESOME!!! The crew calmness and professionalism in my opinion were outstanding. They were prepared for the unprepared and amazingly well trained to know what to do at all time. I can say without doubts how lucky I felt to be part of that amazing crew. We went home around 1am local time.».

Cabin crew "3 right door"

«Yesterday 10/08/2019, I was onboard the flight DY7115 that took off from FCO heading towards LAX. Shortly after takeoff, I experienced very strong vibrations and then a loss of power coming from the left engine.
The colleague at the door 3L immediately called the Senior Cabin Crew at door 1L asking if they were feeling the same strange things in the front. The SCCM confirmed that and also doors 2 and doors 4. Than we received an all attendant call from the SCCM informing us that soon we were going to receive NITS from the flight deck. After that there was "Senior to flight deck; Senior to flight deck". We followed all our procedures; I took the emergency checklist and I went to the aft galley and everyone was ready to receive NITS. The commander did the announcement to inform passengers about what was going on and let me say that his tone of voice was so calm and he definitely reassured us and all the cabin. After that we secured the cabin and we were ready to land in FCO airport. Aircraft landed safely, however with two flat tires due to an overweight. Situations like this are not what we are used to in our daily work onboard, but let me say that thanks to an amazing team work and all the training that Norwegian provides us, we were able to sort out everything with professionalism, confidence and calmness.».

Cabin crew "3 left door"

«Just after take off we faced unusual strong vibrations within the cabin and suddenly seemed like there was a power loss from one of the engines, afterwards more vibrations occurred. For that reason I decided – at the time we were all fastened pax/crew – to call the SCCM to inform her whether the situation was the same at the door 1L. SCCM confirmed that. She contacted directly the flight deck. Then I called 3R to ensure the strong vibrations were heard as well. Confirmed from 3R. All Attendant call was initiated from SCCM to inform the crew that in a few minutes NITS would be provided. CMDR announced "SENIOR TO FLIGHT DECK, SENIOR TO FLIGHT DECK'. At that stage I took the emergency check list and I went straight in AFT galley. NITS were provided from SCCM to 4R and then 4R to the rest of the crew. CMDR announced the intention to return to FCO airport explaining the reasons why of this decision. Crew secured the cabin. Safely landed in FCO however with two flat tires. At complete stop of CMDR announced "Cabin Crew Situation is under control". SCCM announced "Cabin Crew disarm slide and cross check". CMDR announced "Cabin crew you may open the doors". All passenger disembarked safely from 1L door via stairs.».

1.18.2. Take-off performance[17]

To evaluate the take-off performance that motivated the choice of RWY 16R instead of RWY 25 (preferential), the data reported on the load sheet and the meteorological conditions were used for the calculation:

- TOW: 225.800 KG; ZFW: 152.100 KG; CG: 19.9%;
- LIRF 101450Z 28012KT CAVOK 30/21 Q1015 NOSIG.

The software Boeing OPT, was used. When considering the maximum take-off weight for RWY 25, the Boeing OPT system indicated a weight of 227.354 kg. This value, however, with a calculation carried out without considering the headwind component (wind 0), the maximum take-off weight allowed dropped to 223.799 kg. Analyzing the take-off performance and runway selection it can be seen that the use of RWY 25 was very dependent on the benefit of the wind component and also the maximum allowable take-off weight value was very close to the actual take-off weight. Indeed, FDR data show that the actual take-off weight was 225.369 kg. The take-off weight of the load sheet was 225.771 kg.

[17] Source of the images of this paragraph is Boeing OPT software.

Therefore, take-off from RWY 25 (figure 41-42) would have been allowed only if full take-off thrust and flaps at 15 would have been used. In order to take-off from RWY 25 at least 6 kt headwind was required.

For RWY 25 (shorter) the following data was used:

- TORA: 3307 m takeoff analysis result (weight of 225.800 kg);
- TODA: 3367 m engine-inop go distance 2641 m (Max THR Not applicable);
- ASDA: 3307 m accelerate-stop distance 2780 m (Max THR Not Applicable); Slope: 0,01%;
- All engine go distance: 2531 m (Max THR Not applicable); LDA: 3307 m.

Figure 41: take-off performance RWY 25.

Figure 42: take-off performance RWY 25.

On the other hand the following data were considered for runway 16 R (longer, figure 43-44):

- TORA: 3902 m take-off analysis result (weight of 225.800 kg);
- TODA: 3962 m engine-inop go distance 3256 m (Max THR), 3479 m (Reduced THR);
- ASDA: 3902 m accelerate-stop distance 3279 m (Max THR), 3830 m (Reduced THR); Slope: 0,01%;
- All engine go distance: 3011 m (Max THR), 3400m (Reduced THR) LDA: 3902 m.

Figure 43: take-off performance RWY 16R.

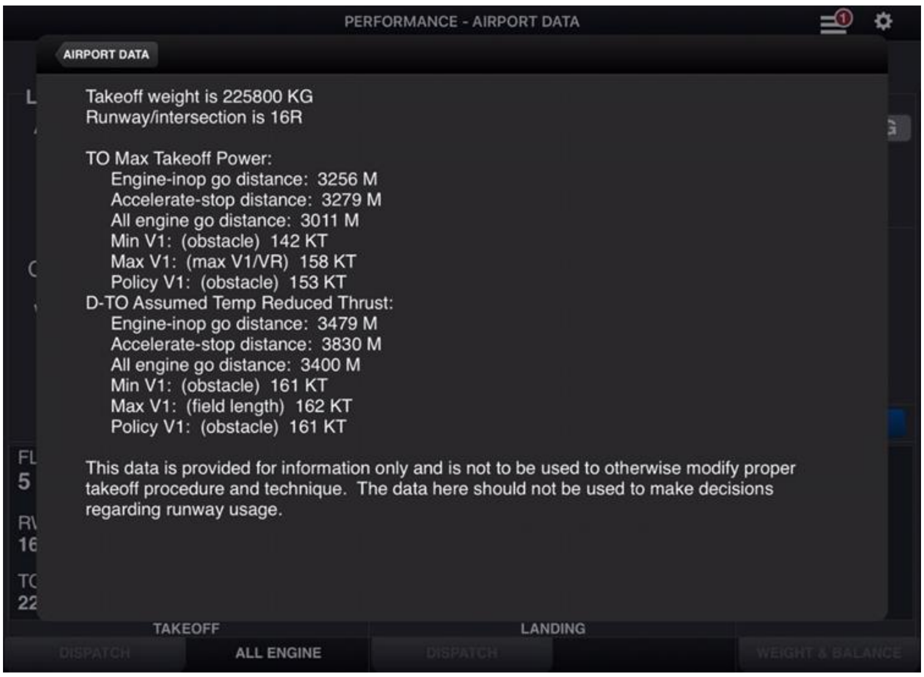
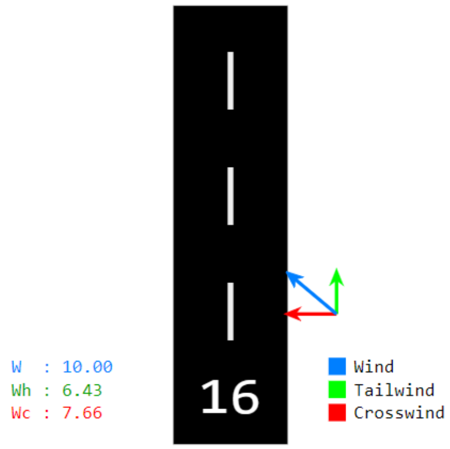


Figure 44: take-off performance RWY 16R.

1.18.3. Landing performance[18]

At the time of the landing performance calculations there was at the RWY 16R (LDA of 3902 m) 10 kt wind coming from 290°, resulting in a tailwind component of 6,43 kt. The resulting operational landing distances were as follows:

- Max manual braking 1795 m;
- Auto Brake 1 4004 m;
- Auto Brake 2 3540 m;
- Auto Brake 3 3133 m;
- Auto Brake 4 2700 m;
- Max Auto 2203 m.



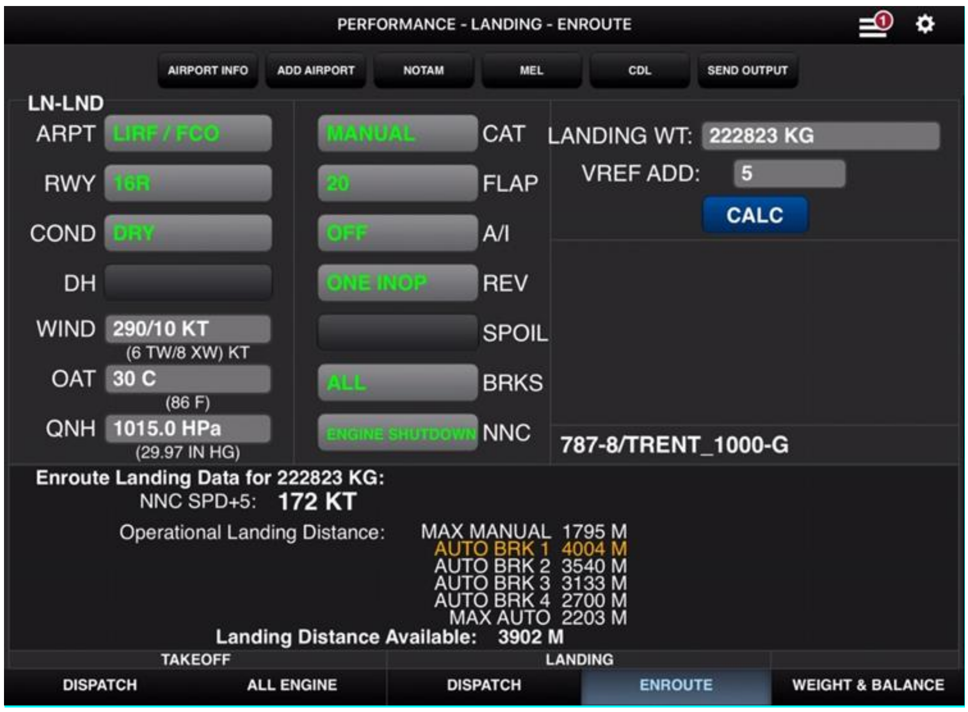


Figure 45 landing performance RWY 16R.

[18] Source of the images of this paragraph is Boeing OPT software.

Following same calculation for landing on RWY 34L and 25.

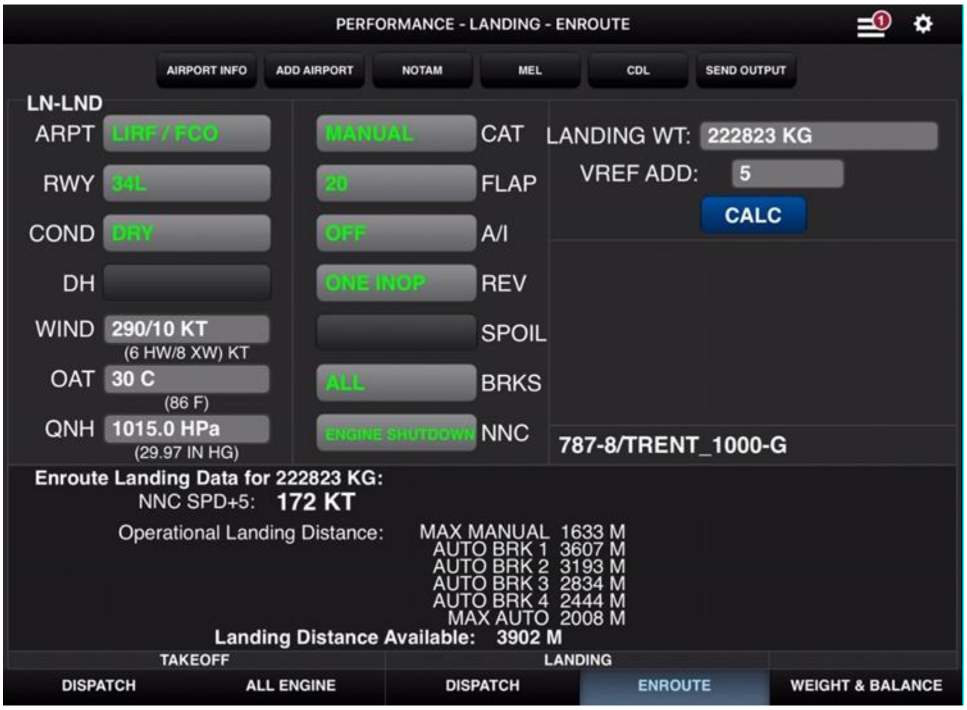


Figure 46: landing performance RWY 34L.

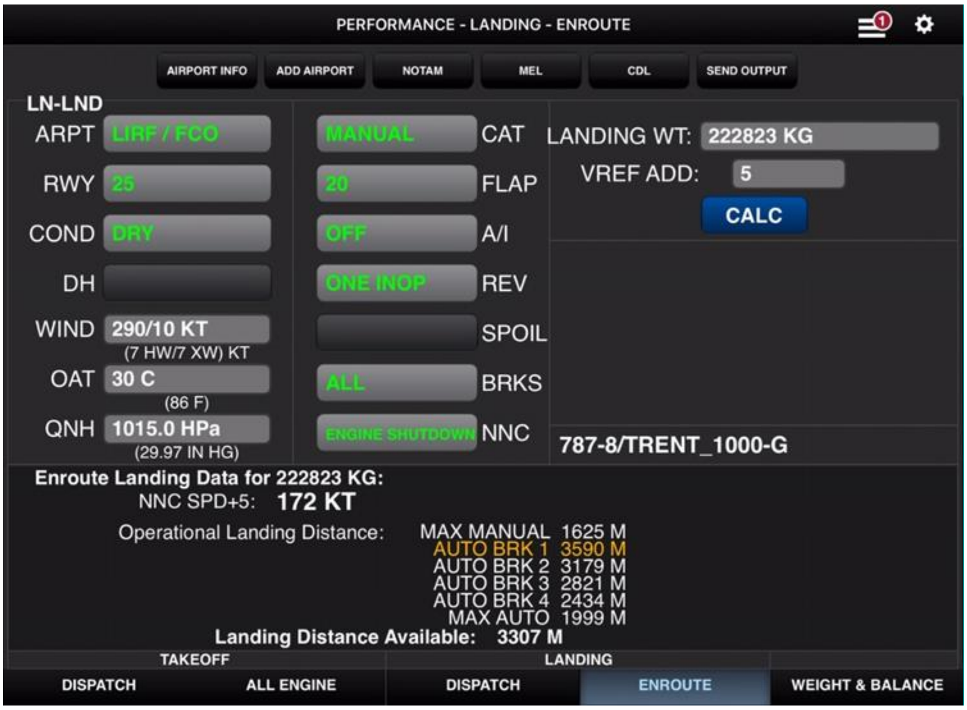


Figure 47: landing performance RWY 25.

1.18.4. Emergency procedures

Considering the EICAS indications and perceived vibrations, the crew applied the "Engine severe damage/Separation" (figure 48) procedure. In addition, when returning to the departure airport with a weight greater than the maximum expected for landing, the "Overweight landing" (figure 49) procedure was used.

The "Engine failure" procedure (figure 50, only initial part) is also reported in order make comparisons to the abovementioned procedures.

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Eng Svr Damage/Sep L, R

Condition: One or more of these occur:
- Airframe vibrations with abnormal engine indications
- Engine separation

1 A/T ARM switch
(affected side) . . . . Confirm . . . . . . OFF

2 Thrust lever
(affected side) . . . . Confirm . . . . . . Idle

3 FUEL CONTROL switch
(affected side) . . . . Confirm . . . CUTOFF

4 Engine fire switch
(affected side) . . . . Confirm . . . . . . Pull

5 **If** high airframe vibration occurs and continues after engine shutdown:

Without delay, reduce airspeed and descend to a safe altitude which results in an acceptable vibration level.

If high vibration returns and further airspeed reduction and descent are not practical, increasing the airspeed may reduce the vibration.

6 APU selector
(if APU available) . . . . START, then ON

7 TRANSPONDER MODE selector . . . . TA ONLY

8 Plan to land at the nearest suitable airport.

▼ Continued on next page ▼

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▼Eng Svr Damage/Sep L, R continued▼

9 Do **not** accomplish the following checklists:

AUTOTHROTTLE

ENG FAIL

10 Choose one:

◆Landing using flaps **20**:

Tuning and control panel
GPWS FLAP OVRD . . . . .OVRD

Note: Use flaps 20 and VREF 20 for landing and flaps 5 for go-around. Buffet may be felt with flaps extended.

Check the Non-Normal Configuration Landing Distance tables for ENG SHUTDOWN L, R in the Performance Inflight-QRH chapter or other approved source.

►►**Go to step 11**

◆Landing using flaps **30 (if performance allows)**:

Note: Use flaps 30 and VREF 30 for landing and flaps 20 for go-around. Buffet may be felt with flaps extended.

Check the Non-Normal Configuration Landing Distance tables for ENG SHUTDOWN L, R in the Performance Inflight-QRH chapter or other approved source.

■ ■ ■ ■

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▼Eng Svr Damage/Sep L, R continued▼

11 **Checklist Complete Except Deferred Items**

Deferred Items

Descent Checklist

Recall . . . . Checked
Notes . . . . Checked
Autobrake . . . . ___
Landing data . . . . . . **VREF 20___, Minimums___**
Approach briefing . . . . Completed

Approach Checklist

Altimeters . . . . ___

Landing Checklist

Cabin call. . . . . Given
Speedbrake . . . . ARMED
Landing gear . . . . DOWN
Flaps. **20**

■ ■ ■ ■

Figure 48: Engine severe damage/Separation.

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Overweight Landing

Condition: A landing at greater than maximum landing weight is needed.

1 Choose one:

◆**One engine is inoperative:**

Tuning and control panel
GPWS FLAP OVRD . . . . OVRD

Note: Use flaps 20 and VREF 20 for landing and flaps 5 for go-around. This provides greater climb capability.

►►**Go to step 4**

◆**Both engines are running** normally:

Note: Refer to the Landing Climb Limit Weight (landing with flaps 25) table in the Performance Inflight chapter.

ZA576 - ZA652
►►**Go to step 2**
ZB251 - ZB841
►►**Go to step 3**

▼ Continued on next page ▼

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▼Overweight Landing continued▼

ZA576 - ZA652

2 Choose one:

◆Landing gross weight is **greater than** the Landing Climb Limit Weight:

Tuning and control panel
GPWS FLAP OVRD . . . . OVRD

Note: Use flaps 20 and VREF 20 for landing and flaps 5 for go-around. This provides greater climb capability.

►►**Go to step 4**

◆Landing gross weight is **less than or equal to** the Landing Climb Limit Weight:

Note: Use flaps 25 and VREF 25 for landing and flaps 20 for go-around.

Limit the additives for wind and gusts such that the approach speed does not exceed 175 knots.

►►**Go to step 4**

▼ Continued on next page ▼

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4 **Checklist Complete Except Deferred Items**

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▼Overweight Landing continued▼

Deferred Items

Descent Checklist

Recall . . . . Checked
Notes . . . . Checked
Autobrake . . . . ___
Landing data . . . . . **VREF 20___ or VREF 25___, Minimums___**
Approach briefing . . . . Completed

Approach Checklist

Altimeters . . . . ___

Landing Checklist

Cabin call. . . . . Given
Speedbrake . . . . ARMED
Landing gear . . . . DOWN
Flaps. . . . . **20 or 25**

■ ■ ■ ■

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March 16, 2015 D615Z003-NLH(NLH) 0.7

Figure 49: Overweight landing.

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[] ENG FAIL L, R

Condition: Engine speed is below idle.

Objective: To restart the engine if needed, or configure for single engine operation.

1 **If** thrust is lost on **both** engines:

►►Go to the Dual Eng Fail/Stall checklist on page 7.2

■ ■ ■ ■

2 **If** airframe vibrations with abnormal engine indications exist:

►►Go to the Eng Svr Damage/Sep L, R checklist on page 7.11

■ ■ ■ ■

3 **If** an engine has separated:

►►Go to the Eng Svr Damage/Sep L, R checklist on page 7.11

■ ■ ■ ■

Figure 50: Engine failure.

1.19. USEFUL OR EFFECTIVE INVESTIGATION TECHNIQUES

Not applicable.

CHAPTER II
ANALYSIS

2. GENERAL

The evidence acquired during the investigation, described in the previous chapter, are analyzed below.

The goal of the analysis is to establish a logical link between the evidence acquired and the conclusions.

2.1. CONDUCT OF THE FLIGHT

According to what was ascertained during the investigation, the flight preparation, briefing and ground procedures took place regularly.

The Captain sat in place CM-1, the FO who sat in place CM-2. This latter was the PF in the first phase of the flight. The relief captain was on the folding seat.

The choice to take-off for RWY 16R, longer than the RWY 25 normally used for departures, was more appropriate: according to the calculations made with the Boeing OPT software: considering that the take-off weight from the load sheet, 225.771 kg, take-off of runway 25 would only be allowed with full take-off thrust, flaps at 15 and with a headwind component of at least 6 kt.

The flight was authorized by ATC to take-off for RWY 16R, SID SOSIV 6B with SOVAN 6A transition and initial climb at 4000 ft. The SID foresees, upon reaching point RF601 (located on the radial 168° at 2 NM from the VOR OST), the turn to the right until reaching the heading 310°.

The FO carried out the SID briefing, also specifying the possible route to follow in case of emergency: «Straight ahead… 6000 ft essentially, but visual today». The captain confirmed: «Anything happen before the turn, we go straight», and then added «We can continue outbound to the sea, if you want».

The start-up and taxiing procedures were carried out without any problem and in agreement with the SOPs.

Once the aircraft was aligned on the RWY 16R and the take-off clearance was received, the captain handed over control of the aircraft to the FO.

At 14.45’35”, after a regular take-off run, the flight took place.

The engine failure occurred at 14.46’07”, 32” after take-off and at 1028 ft radio altitude, while the FO was manually piloting the aircraft in the initial climb phase in VMC weather conditions: the CVR in fact recorded the astonished question of the captain who, immediately after the communication with the ATC for the change of frequency, asked what was happening to the aircraft.

Indeed, from the FDR analysis it emerges that, starting from 14.46’05” there was a sharp decrease in the N1 value of the left engine (from 90% to less than 60%), with a slight increase in the N2 values and N3 of the left engine, in addition to those of the oil temperature and pressure.

At 14.46’11”, the captain, when analyzing the behavior of the left engine, commented the anomalous indications “Engine EEC mode left” and “EGT”.

At 14.46’16” the acoustic signal of the master caution was recorded following the activation of the message “Eng1 Vib Warn” linked to the strong vibrations of the engine.

The reaction of the crew in this situation was to order the FO verbally, in two times, to reduce the power of the left engine. The FO also disengaged the autothrottle.

At 14.46’23”, about 18” from the manifestation of the engine problem, the relief captain suggested carrying out the memory items. The captain, however, ordered to wait and stated “Identify the problem” to indicate that the failure and the consequent procedure to be applied had not yet been established.

At 14.46’31” the captain made the radio call communicating to the ATC the presence of an engine problem and the intention to turn right and continue on 240° heading in a sort of counterbase. After the call at 14.46’58”, crossing 1800 ft, the captain handed over the radio communications to the FO. In this phase the autopilot was activated.

At 14.47’13”, the captain, continuing with the identification of the problem, commented on how the indications of N1 appeared normal but that vibrations were felt. The observation by the captain of the indications of the vibratory level confirmed this feeling, therefore at 14.47’28” the captain confirmed the need to further reduce the engine.

At 14.47’32” there was a variation in the background noise of the engine with roughness and blows. At this point the captain commented «engine failure» and at 14.47’38” added «regular engine failure».

At 14.47’51” the relief captain suggested turning off the engine and the captain confirmed, announcing the need to carry out the memory items without specifying the failure.

Starting at 14.47’55” the captain announced and confirmed the selection of the autothrottle switch for the left engine - OFF, «Left engine idle» and «Fuel control switch left OFF», all actions confirmed by the acknowledgment of the FO.

At 14.48’06”, after 1’59” from the detection of the failure, 2’01” from the occurrence of the anomaly, the left engine was turned off and the captain at 14.48’13” commented «No damage, no fire».

The procedure initially applied was the “Eng fail” which is substantially the same as the “Engine Svr Damage/Sep” except the latter also provides for the activation of the engine fire switch.
Both procedures are outlined in the 787 Quick Reference Handbook and listed on the Quick Action Index; they are defined as unannunciated checklists as they do not automatically appear on EICAS. The “Engine Svr Damage/Sep L, R” procedure must be applied in the conditions of “airframe vibrations with abnormal engine indications” and/or in the case of “engine separation”. Once the engine is off and safe, it provides “deferred items” to be completed for the descent, approach and landing phases.
The “Eng fail L, R” procedure, on the other hand, is applicable when the following conditions occur: engine speed is below idle.
The “Eng fail L, R checklist”, in the case of vibrations with abnormal engine indications, refers to the “Engine Svr Damage/Sep L, R” procedure.
At 14.48’24” the captain announced the need to carry out the «non normal checklist for engine failure» checklist. At the same time, the cabin crew made a call via the intercom and the captain asked the relief captain to answer the call.
At 14.48’38” the captain communicated the need to proceed with the deconfiguration of the aircraft.
At 14.49’15” the captain declared “Mayday” communicating the nature of the problem and requesting directions for landing. The flight was instructed to turn right on a 320° heading.
14.49’36” the captain announced the execution of the checklist “Engine failure” and then corrected immediately “Severe damage checklist” that was actually the right one (“unannaunced non normal checklist menu, engines, severe damage checklist”).
At 14.50’30” while leveling at 3000 ft and continuing the checklist, the captain said «Left engine switch confirm pull ... confirm?» (after confirmation by the FO, «Pull»). Then, he continued to read the “Engine severe damage checklist page 2” with the ignition of the APU, the selection of the GPWS on FLAPS OVERRIDE and the calculation for landing using flaps at 20°. At 14.53’48” the relief captain, communicated to the ATC the need to carry out a 360°.
14.54’33”: the captain announced the execution of the “after take-off checklist”, “the overweight checklist”, with the preparation of on-board avionics for the approach. Then, the NITS briefing to the cabin crew took place, notifying the “one engine out” condition, the return to Fiumicino airport for a normal landing with arrival time estimation, and the need to tow once on ground. Then, the passenger announcement took place.
After carrying out two 360° orbits north-west of the airport in order to get sufficient time to entry of the data for the approach and landing, together with the completion of the checklists

and with the cabin preparation, the captain requested the ATC vectoring for a long straight in approach at 20 NM. The ILS Y RWY 16R approach took place with an overweight procedure and one engine out without recording any significant events.
The captain, due to the anomalous situation, took control of the aircraft for landing and the autopilot was deactivated at 15.08’30”. At 15.09’08”, about 1000 ft height (FDR radio altitude 993 ft), the aircraft was stable on the approach path, IAS 172 kt, Flaps 20, LG down, ENG 2 62% N1.
The landing took place in flaps 20 configuration, approach speed of 167 kt and autobrake selected at level “4”.
The fuel dumping option was not considered by the captain, as it would have required to significantly extend the flight time in one engine out conditions. However, the length of the runway and the performance of the aircraft together with the weight of the aircraft were taken into account to take this decision.

After the landing, the aircraft cleared the runway at taxiway “AH”. In this position, having received the brake overheating indication, the captain requested the intervention of the Fire Brigade for a check. Engine No. 2 was switched off at 15.13’11” and passengers normally disembarked by ladder trucks and then they were taken to the terminal by bus.

2.2. TECHNICAL FACTOR

2.2.1. ESN 10166, left engine

The maintenance history of the engine has not revealed details that would have prevented the blade from being released in flight. The FDR and EMU data showed that the crew could not realize in advance that there was an anomaly in the engine until the moment the failure occurred. Furthermore, the data recorded together with borescope inspections correctly identified immediately after the event the primary damage: the detachment of the IPT No. 79 blade due to a progressive failure.
The subsequent investigation of the engine made possible to ascertain the sequence of damage. The failure analysis of the IPT 79 blade confirmed the corrosion-fatigue progressive phenomenon. The initiation was favored by the methodology and type of coating in addition to the base material composition constituting the IPT blades. The absence of cases of IPT blade detachment in service in post-SB 72-H818 engine fleets supports this thesis. The corrosion-fatigue mechanism identified was the same already observed in the previous 10 cases of IPT blade detachment. These occurred in flight on aircraft flying different routes.

Therefore it is reasonable to attribute the cause of the technical issue to an improvable design, indeed, improved over the course of subsequent modification.

Typical fatigue striations were clearly visible at the crack tip, whose spacing, varying greatly from area to area. However, this feature was not observed in the bulk propagation. The understanding of the progressive phenomenon in the area dominated by the morphological characteristic called "fingers" is not completely clear.

Nevertheless, 10 of 11 cases of detachment of the blades occurred at take-off or during climb, leading to the belief that the final overload occurs at the greatest engine stress.

The detachment of the IPT 79 blade caused the trailing blade to break too and, as a consequence, all the other damages listed in paragraph 1.16.

In one of the 10 previous IPT blade detachment events, in addition to the IFSD, damage to the LPT1-2 drive-arm occurred, although its structure did not result to be compromised. The failure of this component could have induced an uncontained failure with radial projection of parts.

In none of the IPTB release events on the Trent 1000, including the event discussed in this report, the damage did not induce the radial projection of parts outside the engine, but only axial ejection from the exhaust cone.

At the time the crew felt the first vibrations (14.46'07"), the aircraft had 1028 ft radio altitude. The larger parts found on ground weighted about 100 g. The projection caused damage to cars and housings on ground and to the aircraft structure.

The TGT recorded at the time of the failure was 876 °C. Therefore, the fragments that fell at high velocity down on the city of Fiumicino were still at very high temperature and potentially capable of causing burns and injuries to the people on ground. The failure of the IPT 79 blade occurred at 1210 cycles compared to the 1410 established by the service management, therefore 200 cycles before the limit established for that ESN. This showed that the hard life imposed was not sufficient to avoid harmful effects on safety.

For this reason, the ANSV in the course of its investigation, on the 29th of August 2019, issued two safety recommendations, listed below.

Type of recommendation: SRGC / SRUR.

Motivation: the borescope inspection of the engine Trent 1000 G/01A SN 10166, performed after the IFSD event occurred to the B787-8 registration marks LN-LND, highlighted the fracture of two IPT blades. One of these is attributable to the same corrosion fatigue fracture mechanism that was responsible for ten previous cases of IFSD in the Trent 1000 fleet. In one of those cases, in addition to IFSD the blade release also caused damage on the LPT drive-arm, proving further negative effects on safety could be possible as a consequence of an IPT blade fracture beside what happened in the B787-8 marks LN-LND event, in which damages to the aircraft and to objects on the ground were recorded. Indeed, for this matter EASA has already recognized the need to maintain fleet safety and has mandated several Rolls-Royce recommended safety actions in the last two years through 6 ADs, the latest and only live action being issued in NMSB 72-AK186, which instructs a hard life for pre-modification blades and is mandated by EASA AD 2019-0135. However, the in-flight IPT blade failure of the

Trent 1000 G/01A SN 10166 happened 200 flight cycles before the hard life limit, demonstrating this not sufficient to avoid detrimental effects on safety.

Recipient: EASA.

Safety Recommendation ANSV-9/1147-19/1/I/19.
To take immediate actions to achieve an higher level of safety, also taking in consideration, but not limiting EASA initiatives to, defining different and more stringent time limits for the Trent 1000 pre-mod 72-H818 IPT blades.

Safety Recommendation ANSV-10/1147-19/2/I/19.
To re-evaluate the whole validity of the service management adopted by the manufacturer for the Trent 1000 pre-mod 72-H818 IPT blades, endorsed by the AD 2019-0135.

2.2.2. ESN 10140, right engine

After the IFSD commanded by the crew on the left engine, the B787 marks LN-LND was in OEI. When in such conditions the engine that remains in service undergoes overall higher stresses. This would make less improbable a DIFSD. Furthermore, in OEI conditions the controllability of the aircraft is reduced.

The right engine of the B787-8 marks LN-LND, the Rolls-Royce Trent 1000 G/01A ESN 10140, like the ESN 10166, was also pre-mod 72-H818, with fewer life cycles remaining (103 FC) than the left engine.

The investigation carried out on the right engine ESN 10140 highlighted 92 IPT cracked blades. Among these, the largest one had a crack depth of about 3,47 mm.

The statistics of the 10 previous cases of IPTB detached in flight showed that the blade that broke with a smaller crack depth reached about 4,8 mm. This brought to believe that the ESN 10140, had sufficient safety margins during the flight of the event considering a possible the detachment of an IPT blade. The aforementioned considerations are in any case the result of the evidence collected in the investigative process and could not be confirmed without tearing down the engine. Not being available non-destructive test that allowed an evaluation in service of the crack size in the root shank of the IPT blades. Therefore, the ANSV deemed necessary to issue on the 29th of August 2019 also the following safety recommendation during the investigation addressed to EASA (info FAA).

Type of safety recommendation: SRGC/SRUR.

Motivation: the borescope inspection of the engine Trent 1000 G/01A SN 10166, performed after the IFSD event occurred to the B787-8 registration marks LN-LND, highlighted the fracture of two IPT blades. One of these is attributable to the same corrosion fatigue fracture mechanism that was responsible for ten previous cases of IFSD in the Trent 1000 fleet. In one of those cases, in addition to IFSD the blade release also caused damage on the LPT drive arm, proving further negative effects on safety could be possible as a consequence of a IPT blade fracture beside what happened in the B787-8 marks LN-LND event, in which damages to the aircraft and to objects on the ground were recorded. Indeed, for this matter, EASA has already recognized the need to maintain fleet safety and has mandated several Rolls-Royce recommended safety actions in the last two years through 6 ADs, the latest and only live action being issued in NMSB 72-AK186, which instructs a hard life for pre-modification blades and is mandated by EASA AD 2019-0135. The in-flight IPT blade failure of the Trent

1000 G/01A SN 10166 happened 200 flight cycles before the hard life limit, demonstrating this not sufficient to avoid detrimental effects on safety. The right engine of the B787-8 marks LN-LND Trent 1000 G/01A SN 10140, was also a pre-mod 72-H818, having less flight cycles remaining than the left engine (103 FCs remaining).
Since the life limit imposed has been proved to be not adequate to prevent the left engine Trent 1000 G/01A S/N 10166 to fail, as well as the engine S/N 10202 to fail (15th of May 2019 (see table 1) and at the time this ANSV document is issued, there is no requirement for de-pairing pre-mod 72-H818 engines, there was the possibility also that the right engine could have failed. In addition, in case of one engine inoperative the engine that remains operative undergoes overall higher solicitations. This would increase the probability of a DIFSD.

Recipient: EASA.

Safety Recommendation ANSV-11/1147-19/3/I/19.
To evaluate provisions relevant to the de-pairing of pre-mod 72-H818 engines, avoiding two engines of the same pre-mod status being installed on the same aircraft, thus further lessening the possibility of a DIFSD.

2.2.3. Outcome of the safety recommendations issued during the investigation

The aforementioned safety recommendations issued by the ANSV during the investigation led to coordination between EASA (recipient of the safety recommendations) and the manufacturer of the Trent 1000 (Rolls-Royce).
On the 19th September 2019 the Rolls-Royce company issued the Alert NMSB TRENT 1000 72-AK186 rev. 3, which contains a review of the hard life and a consequent definition of the new limits for certain serial numbers of the Trent 1000 pre-mod 72-H818 engines.
On the 18th of October 2019, EASA made mandatory the content of this document by means of the AD 2019-0261 (Attachment “C”).
On the 19th of November 2019 EASA formally replied to the ANSV recommendations issued during the investigation, declaring agreement and making reference to the action already put in place in the meantime: the SR ANSV-9/1147-19/1/I/19 and ANSV-10/1147-19/2/I/19 were in fact been implemented through EASA AD 2019-0261 (figure 51 and 52).

Reply to Safety Recommendation ITAL-2019-004 received on 29/08/2019

Safety Recommendation:	To take immediate actions to achieve a higher level of safety, also taking in consideration, but not limiting EASA initiatives to, defining different and more stringent time limits for the Trent 1000 pre-mod 72-H818 IPT blades.
Final response:	To achieve a higher level of safety, Rolls-Royce updated the Service Bulletin Trent 1000 72-AK186 to revision 3. This revision reduces the time limits of the Trent 1000 pre-mod 72-H818 IPT blades. The European Union Aviation Safety Agency (EASA) published Proposed Airworthiness Directive (PAD) 19-180 on the 25th September 2019 to mandate this service bulletin. The final Airworthiness Directive (AD) 2019-0261 was published 18 October 2019 and will be effective 01 November 2019. This AD sets the manufacturer's stringent time limits for the replacement of affected IPT blades.
EASA Status:	Closed – Agreement

Figure 51: EASA reply to the SR ANSV-9/1147-19/1/I/19.

Reply to Safety Recommendation ITAL-2019-005 received on 29/08/2019

Safety Recommendation:	To re-evaluate the whole validity of the service management adopted by the manufacturer for the Trent 1000 pre-mod 72-H818 IPT blades, endorsed by the AD 2019-0135.
Final response:	The European Union Aviation Safety Agency (EASA) has re-evaluated the validity of the service management adopted by the manufacturer for the Trent 1000 pre-mod 72-H818 IPT blades, and endorsed by EASA Airworthiness Directive (AD) 2019-0135. The results of the evaluation confirmed that the adopted method is valid, but could be reinforced by reducing the blade life limits. This resulted in the publication, by Rolls-Royce, of Service Bulletin Trent 1000 72-AK186 revision 3, and the supersession of AD 2019-0135 by AD 2019-0261 (effective 01 November 2019), which requires the remaining "pre-mod 72-H818" engines (3%) to be modified.
EASA Status:	Closed – Agreement

Figure 52: EASA reply to the SR ANSV-10/1147-19/2/I/19.

About the SR ANSV-11/1147-19/3/I/19 received the following answer (figure 53).

Reply to Safety Recommendation ITAL-2019-006 received on 29/08/2019

Safety Recommendation:	To evaluate provisions relevant to the de-pairing of pre-mod 72-H818 engines, avoiding two engines of the same pre-mod status being installed on the same aircraft, thus further lessening the possibility of a DIFSD
Final response:	The European Union Aviation Safety Agency has evaluated the proposed solution of mandating the de-pairing of pre-mod 72-H818 engines. This evaluation showed that the event involving B787 registration LN-LND on 10th August 2019 did not significantly change the statistical evaluation of the dual in-flight shut down (IFSD) risk. This dual IFSD risk is sufficiently low to obviate mandatory action. Nevertheless, Rolls-Royce has taken the decision to ensure the de-pairing of pre-mod 72-H818 engines with more than 500 cycles. This de-pairing exercise has been completed.
EASA Status:	Closed – Agreement

Figura 53: EASA reply to the SR ANSV-11/1147-19/3/I/19.

2.3. HUMAN FACTOR

In the framework of the safety investigation the human factor aspects was taken into consideration with particular reference to the management of the emergency and the interaction between the crew and CRM aspects in the presence of a relief captain in the cockpit.

During the ANSV interview it was discussed together with the crew how failures occurs in the reality; indeed, it can significantly differ from the way in which it occurs during simulator sessions. These, because of the need for standardization, although realistic, may result stereotyped: for example, a mechanical engine failure in which the engine RPM quickly drop to zero or repeated blows are simulated to indicate a mechanical malfunction.

The identification of the emergency, therefore, especially if the latter is not limited to a single indication on the EICAS, requires an analysis of several indications.

Nonetheless, the actions taken by the crew were substantially correct. In this context, a further consideration is to be referred to the interaction of the flight crew in augmented configuration. In fact, the Operating Manual provided for long-haul flights the possibility of augmented flight crew (additional crew over the minimum required). This allows crew members to take rest shifts in flight and, if necessary, to be replaced by qualified personnel. Indeed, during the flight of the event there was also a relief captain in the flight deck during take-off operations. This crew configuration, at the onset of the failure, made it possible to have more resources in the management of the emergency with the possibility of lessening the workload (already high due the specific phase of flight and increased due to the failure onset).

This resource therefore certainly had a positive impact on the event: the captain managed the situation in a non-standard way, interacting with two other pilots instead of one. It is precisely this aspect that makes the operator's indications in the OM particularly valuable together with the specific training for Relief Captain in which aspects of CRM and MCC are addressed and deepened with augmented crew scenarios.

2.4. ORGANISATIONAL FACTOR

2.4.1. Uncontained High Energy Debris

In the flight of the event ejection of fragments from one engine occurred. In detail, the radial projection of the parts was contained within the engine while the axial projection was not contained. Radially projected fragments are certainly to be considered high-energy. However, the CS-E (excerpts reported in paragraph 1.17.1.), while clarifying that large rotating parts are to be considered high-energy fragments, at the same time does not exclude that there may be other types. In fact, in the case under discussion, the axially projected parts have resulted in damage to the aircraft, requiring extensive maintenance interventions and various inspections. In addition, the fragments, certainly at a high temperature and capable of causing burns (at the time of the failure, the TGT recorded was 876 °C), precipitated on an inhabited area, causing damage to vehicles and houses. Therefore, only by chance there were no injuries. This situation could be defined as an unsafe condition, induced by a hazardous engine effects (concepts presented in paragraph 1.17.1 in the extracts of CS-E), for which the probability of occurrence, failure rate, should be below 10^{-7}.

However, there is no clear definition of hazardous engine effects in the CS-E. There is only a list of what should be considered as such [CS-E 510 (g)(2)]:

«(i) Non-containment of high-energy debris;
(ii) Concentration of toxic products in the Engine bleed air for the cabin sufficient to incapacitate crew or passengers;
(iii) Significant thrust in the opposite direction to that commanded by the pilot;
(iv) Uncontrolled fire;
(v) Failure of the Engine mount system leading to inadvertent Engine separation;
(vi) Release of the Propeller by the Engine, if applicable;
(vii) Complete inability to shut the Engine down.».

The event under investigation in which the axial projection of fragments at high temperature took place could be included in point (i). However, this is traditionally associated only to radially ejected parts: this is made possible by the fact that there is no clear definition of high energy debris in the CS-E. In fact, in AMC E 510 (d)(iii):

«Uncontained debris cover a large spectrum of energy levels due to the various sizes and velocities of parts released in an Engine Failure. The Engine has a containment structure which is designed to withstand the consequences of the release of a single blade (see CS-E 810(a)), and which is often adequate to contain additional released blades and static parts. The Engine containment structure is not expected to contain major rotating parts should they fracture. Discs, hubs, impellers, large rotating seals, and other similar large rotating components should therefore always be considered to represent potential high-energy debris.
Service experience has shown that, depending on their size and the internal pressures, the rupture of the high-pressure casings can generate high-energy debris. Casings may therefore need to be considered as a potential for high-energy debris.».

Thus, it is clear what is always to be considered as high energy debris, while is not excluded the possibility high temperature parts ejected axially could be high energy debris.

In this framework, there is a discrepancy with the United States legislation (AC33.75), which, although has similar guidelines for the definition of high energy debris, it also adds:

«Uncontained blades from a multiple blade release are typically considered low energy fragments because their energy has been significantly reduced in defeating the containment structure. These events may typically be considered major engine effects.
However, the release of significant numbers of blades (for example, corn-cobbed rotors) will likely include fragments exiting with high energy, and would therefore result in a hazardous engine effect.».

Regarding minor engine effects, following the definition as per CS-E 510 (g)(1):

«An Engine Failure in which the only consequence is partial or complete loss of thrust or power (and associated Engine services) from the Engine must be regarded as a Minor Engine Effect.».

Based on the above excerpts, all 10 of the cases preceding the one under discussion were classified as minor. The risks posed for the population below hit by fragments, as well as causing damage to the aircraft, were not directly assessed by the engine manufacturer, nor were they required to be. This situation was most likely made possible by the absence of a clear definition of high energy debris and hence management of events potentially considering a lower than real risk. In this framework it is important to highlight that the 11th case of IPTB release occurred after the manufacturer applied more stringent provisions. In more detail, after the ESN 10231 investigation, the fleet was managed to protect the possible hazardous event of the overspeed and burst of the LPT Stage 1 disc (see paragraph 1.17.2.). Despite this, as a result of the event, the manufacturer and EASA took the actions in paragraph 2.2.3.

Thus it seems to be necessary to provide a clear and complete definition of high energy debris, allowing a more immediate assessment of the severity of the events, which must be analyzed according to the actual/potential damage to the aircraft, but also to the actual/potential risk for people on ground. Apparently this latter aspect is not fully developed in the CS-E. It is instead detailed in CM-21.A-A-001 of 29th November 2018. This document discuss the exposure for people on ground to PDAs. In the following paragraph, the analysis on this matter.

2.4.2. PDA

In the event discussed in this report, the ejection of fragments from one engine occurred. In more detail, the radial projection of the parts was contained within the engine, while the axial projection occurred allowing about 38 kg of parts to fall over the city of Fiumicino, several hundred of fragments, at high temperature (TGT was 876 °C at the time of the failure of the n° 79 IPTB). These may represent an example of what is defined as PDA in the CM-21.A-A-001 dated 29th of November 2018.

With regard to PDAs, the CM addresses the problem in detail with particular reference to the people on ground. The study takes into account numerous factors and the maximum allowable probabilities of occurrence assumed for the certification criteria, which are assumed as a safety objectives to be achieved within the definition of what is meant as hazardous. The CM concludes there are no unsafe conditions currently and in the long-term for the population on ground. This determination was supported by the absence of cases of death or serious injuries due to PDA.

The review of the CM carried out by ANSV after the event discussed in this report, highlighted how the exposure for people on ground is related to the probabilities of occurrence assumed for the certification purposes; these, being based hourly failure rates, are fundamentally proportional to the duration of the flights. This appears highly questionable as the exposure to PDA risk for populations living near airports cannot be a function of the duration of flights, but should be assessed by the number of take-offs. Furthermore, the CM considers an average population density, not taking into account that the exposure to risk for PDA of those who live near an airport is reasonably higher, especially in the light of the engines stress that is typically higher during take-off and initial climb. This is true without considering that the European population tend to increase by agglomerating around urban centers. These aspects make the CM evaluations non-exhaustive of the risk for the population on the ground and make it worthy of further study aimed to take into consideration most conservative exposures depending on the possible types of event.

2.4.3. Reliability

In the event discussed in this report, the ejection of fragments from one engine occurred. This was the result of a corrosion-fatigue phenomenon, made possible by an improvable design in terms of method and type of coating in addition to base material composition of the IPT blades. The radial projection of the parts was contained within the engine while the axial projection was not contained. As discussed in paragraph 2.4.1., the CAW guidelines are based on failure rates compared to maximum allowable probabilities of occurrence and corrective measures, balanced according to the severity of the issue and the effective life of the equipment (see also paragraph 1.17.1.). However, the maximum allowable probabilities of occurrence currently used in the certification and a CAW have remained unchanged for many years; for engines they were defined more than 40 years ago.

Taking into consideration the statistics concerning accidents and incidents, it should be pointed out that while maintaining the probabilities of occurrence unchanged, overall the trend of air accidents in CAT has decreased over time: in particular, compared to the early days of aviation, the technical factor is less and less the root cause of a serious incident or accident. The reason for that, regardless of the prescribed probabilities of occurrence, is the industrial practice in general improved anyway, leading to more reliable components: in fact, they usually exceed the requirements of the CSs.

Nevertheless, aiming to continuous improvement, other further aspects should be also considered.

a) There may be the case in which, due to a design or production defect, the reliability of a component is lower than the actual expected industrial standard. The same component could guarantee a failure rates in compliance with the maximum allowable probabilities of occurrence prescribed by the CSs and the CAW guidelines. The result would be an airworthy component, having level of reliability whose suitability was established using an obsolete standard (in the case of engines at least 40 years ago); this reliability would not be in line with the average standards that is realistically possible to produce today, given the technological progress that has occurred in the meantime (introduction of rational performance requirements[19]).

At the time of the ninth IPT blade release event, the PNE was equal to possible further 4 cases of blade release.

b) Technical factor is often cause of events or contributing factor; therefore, a more reliable component, could stop the chain of events before other factors may occur. For example, it could happen that on a twin-engine aircraft, in case of failure of one of the two engines, the crew erroneously performs the IFSD of the only functioning engine. This would result in human factor (IFSD of the running engine instead of the faulty one). Nevertheless, if the engine that fails would have been more reliable, it would also have prevented the event. Therefore, greater reliability of components would lead to an increase in safety even in accidents/incidents in which the technical factor is present in the chain of events although not being the main causal factor.

c) Air transportation volume generally decreased in 2020 and early 2021 due to the COVID-19 pandemic. However, it can reasonably be assumed that air traffic will increase again in the future. This means that, keeping unchanged the maximum allowable probabilities of occurrence used as certification baseline, the reliability of the components may not improve as it may be required to balance the increase in volume of traffic. If this were to happen, it would allow for a greater number of accidents/incidents to occur in which the technical factor is the cause or contributing factor.

d) Since the time when the maximum allowable probabilities of occurrence were established, the population, in particular the European, has increased: this makes greater the risk people on ground being hit by a PDA than it originally was.

e) Regardless of points a, b, c, d, it seems clear that after such a long time it is possible to require technological standards in terms of minimum reliability higher than those requested by the CSs; specifically for engines, these standards have remained unchanged in terms of maximum allowable probabilities of occurrence for at least 40 years.

[19] UK CAA Airworthiness Information Leaflet AD /IL/0092/1-7 dated 19th November 1982 and same text in the latest version of AMC & GM for Part 21 Section A Subpart A GM 21.A.3B(d)(4), paragraphs 2.1 e 2.2 applicable nowadays.

Based on the above considerations, taking into account the statistics of accidents and incidents, the actual air traffic and technological limits based on the state of the art, it seems appropriate to periodically review the validity of the maximum allowable probabilities of occurrence. This should be done setting achievable standard level of reliability, compatible with the actual state of the art. This would have a direct positive impact in terms of preventing all those events in which technical factor is causal or contributing.

2.4.4. ETOPS requirements

The aircraft involved in the event was limited ETOPS 180 minutes. This type of certification includes reliability requirements aimed to prevent, in twin-engine aircraft, cases of total loss of thrust. This is done by trying to keep the IFSD rate for independent reasons below a certain threshold, which precisely determines the ETOPS time limitation.

In this case, it was verified that the IFSD rate due to the IPT blade release did not invalidate the ETOPS 180 certification. Moreover, the circumstances of the failure, which ten cases out of eleven occurred at take-off or climb phase, made it reasonable to address the reliability problem in terms of general risks rather than specific capability to reach an alternate airport (diversion) within a predetermined time: the failure of a single engine at take-off/climb allows returning to departure airport in a short time.

2.5. ENVIRONMENTAL FACTOR

From the meteorological information available, it is believed that this factor had no effect on the occurrence.

2.6. SURVIVAL ASPECTS

As reported by the pilots once the aircraft was stopped and after having cleared the runway, the flight crew noticed the increase in temperature of the brakes due to the overheating generated during deceleration. Therefore, the captain asked the control tower for the assistance of the Fire Brigade in order to monitor and possibly cool down the brake assembly. At this point a sort of misunderstanding took place as the control tower communicated by radio to the crew the presence of smoke and fire from the nose wheel. However, the technical staff on the ground did not confirm the presence of fire, but only the presence of the smoke generated by the liquid sprayed by the Fire Brigade to cool the down brakes of the main landing gear. The relief captain then leaned forward to rule out any evidence of fire. Shortly after, the tires of wheels 1 and 5 deflated, thus preventing the aircraft from being towed to the parking lot.

During the ANSV interview the crew reported basically two factors in the management of the brake assembly problem:

- lack of clarity in the communications from/to of the ATC: the crew was alerted about the presence of fire from the nose gear;
- impossibility for the crew to communicate directly to the Fire Brigade.

The momentary and slight sense of confusion, however, had no further effects and the subsequent disembarking operations were uneventful.

CHAPTER III
CONCLUSIONS

3. GENERAL

This chapter reports the main evidence ascertained during the investigation and the causes of the event.

3.1. FINDINGS

- The flight crew held the necessary aeronautical qualifications to carry out the flight.
- The weather conditions were not a relevant factor in the event.
- The aircraft and the engines were properly maintained.
- The data from FDR and EMU showed that before the detachment of the IPT blade position 79, ESN 10166 showed no signs of abnormal behavior.
- The detachment of the IPT blade position 79 resulted in all the other damage to the engine, those to the aircraft and on ground.
- Damage to the ESN 10166 engine induced vibrations and the activation of numerous EICAS messages.
- The ESN 10166 engine was shut down by the crew after 2’01” from the onset of abnormal engine operation.
- The ESN 10166 was a Trent 1000 package “B” with pre-mod SB 72-H818 IPT blades.
- The metallurgical analyses following the event showed that the ESN 10166 IPT blade number 79 failed due to a progressive corrosion-fatigue mechanism.
- The initiation of the phenomenon was inhibit in the post-modification blades by changing methodology and type of coating in addition to the base material composition of the IPTB.
- In order to verify the effectiveness of this modification, the Manufacturer is pro-actively removing blade from service examining for them for cracks to verify the effectiveness of this modification. At the time this report is published, the post-modification blades have not shown any defects associated with those discussed in this report.
- The maximum crack depth in ESN 10166 was 6,03 mm in the detached n.79 blade.
- The analysis of the other IPT blades of ESN 10166 showed that further 84 blades that were cracked.
- Prior to the case under discussion in this report, there have been other 10 similar cases of IPTB detachment since 2015 due to a progressive corrosion-fatigue phenomenon.
- The analysis of the IPT of ESN 10140 showed that 92 blades of this module were affected by cracks. The maximum depth was 3,47 mm.

- Hard life limits was a change to the previous service management and were mandated (NMSB 72-AK186) for the IPT blades of the Trent 1000 packages “B” and “C” only after the seventh case of IPTB release, since in this event the secondary damage to the LPT1-2 drive-arm allowed to envisage possible hazardous engine effect.
- Management of the IPTB releases using the CAW guidelines allowed further detachment events.
- The IPT n. 79 blade failure from ESN 10166 occurred 200 cycles before the limit of 1410 set by NMSB 72-AK186.
- The ESN 10140, was also a Trent 1000 package “B” and its hard life defined by the NMSB 72-AK186 had 103 IPTB cycles left.
- Following the event, also according to the ANSV recommendations issued during the investigation, actions were taken by the manufacturer to further limit the life of the pre-modification engines and to de-pair the pre-modification engines. The aforementioned actions were implemented by EASA.
- The phasing out of pre-modification blades started over two and a half years before the event of the 10th of August 2019 and the plan for removal of the remaining number of engines with pre-modification blades was accelerated as a result of this event.
- From the date of the event up to date, there have been no further blades breaking events of the Trent 1000 engine.
- There is no clear definition of high energy debris in the CS-E.
- The certification of aeronautical components and their continuous airworthiness is based on the prescription of maximum allowable probabilities of occurrence.
- The rationale behind these CAW concepts these were discussed many years ago: the oldest document that the investigation was able to find on the subject is the Airworthiness Information Leaflet AD/IL/0092/1-7 of the 19th November 1982. These concepts have remained unchanged and are nowadays applicable as per AMC & GM for Part 21 Section A Subpart A GM 21.A.3B(d)(4), paragraphs 2.1 and 2.2. Enormous changes occurred since 1982, these are in terms of technology, volume of air traffic, population quantity and density. All of these factors will change further in the future (technology, organisations, air traffic volume, population in terms of quantity and density).
- The specific maximum allowable probabilities of occurrence used in the CS-E currently applicable have also remained unchanged for about 40 years (older source JAR-E change 6 of 1981).
- The CAW requirements led to a PNE of 4 further cases at the time of the ninth IPT blade release event.

- The FAA regulation has the same maximum allowable probabilities of occurrence than EASA regulation.
- The risk for people on ground is discussed in the CM-21.A-A-001 dated 29th November 2018. This document deals with the issue of PDA assuming the safety objective to be below the maximum allowable probabilities of hazardous occurrence of the CSs. The probabilities of occurrence, in addition to being defined a long time ago, represent a defect rate per flight hour.
- 10 of the 11 IPTB events occurred at take-off or during climb.
- In the take-off and climb phases, some components in the engines are more stressed: this increases the risk that the PDAs such as turbine blade fragments can be released onto the population in these flight phases.
- The timing of peak stress suffered by aircraft engines in take-off phases is not dependent on the overall flight duration.

3.2. CAUSES

The serious incident of the Boeing B787-8 marks LN-LND occurred due to a technical factor. Specifically, the failure of the IPTB n. 79 was induced by a progressive corrosion-fatigue phenomenon made possible by an improvable the blade design.

The detachment of the IPTB n. 79 induced damage to other parts of the engine, to the aircraft and on ground in the city of Fiumicino.

Organisational aspects, in terms of regulatory framework, probably contributed the event to occur, although 10 previous similar cases were already occurred starting from October 2015:

- the risk assessment for people on ground due to PDA, discussed in CM-21.A-A-001;
- the absence of a clear and more comprehensive definition of high energy debris;
- the absence of any project of revision of the maximum allowable probabilities of occurrence used in the CSs and for the Part 21.

CHAPTER IV
SAFETY RECOMMENDATIONS

4. RECOMMENDATIONS

In light of the evidence collected and the analyses carried out, ANSV deems necessary to issue the following additional safety recommendations.

4.1. RECOMMENDATION ANSV-10/1147-19/4/I/21

Type of recommendation: SRUR/SRGC.

Motivation: in the event discussed in this report, the ejection of fragments from one engine occurred. In more detail, the radial projection of the parts was contained within the engine, while the axial projection occurred allowing about 38,2 kg of parts to fall over the city of Fiumicino, several hundred of fragments, at high temperature (TGT at the time of the failure 876 °C): these fragments may represent an example of what is defined as PDA in the CM-21.A-A-001 dated 29th November 2018.

With regard to PDAs, the CM addresses the problem in detail with particular reference to the people on ground. The study takes into account numerous factors and the maximum allowable probabilities of occurrence assumed for the certification criteria, which are assumed as a safety objective to be achieved within the definition of what is meant as hazardous. The CM concludes there are currently no long-term unsafe conditions for the population on ground. This determination was supported by the absence of cases of death or serious injuries due to PDA.

The review of the CM carried out by ANSV after the event discussed in this report, highlighted how the exposure for people on ground is related to the maximum allowable probabilities of occurrence assumed for the certification purposes; these, being based hourly failure rates, are fundamentally proportional to the duration of the flights. This appears highly questionable as the exposure to PDA risk for populations living near airports cannot be a function of the duration of flights, but should be assessed by the number of take-offs. Furthermore, the CM considers an average population density, not taking into account that the exposure to risk for PDA of those who live near an airport is reasonably higher, especially in the light of the engines stress that is typically higher during take-off and initial climb. This is true without considering that the European population tend to increase by agglomerating around urban centers. These aspects make the CM evaluations non-exhaustive of the risk for the population on the ground and make it worthy of further study aimed to take into consideration most conservative exposures depending on the possible types of event.

Addressee: EASA.

Text: it is recommended to evaluate the opportunity of revising the risk assessment related to people on ground being hit by PDA, considering in the most conservative way the different specific scenarios for each phase of flight for the improvement of safety. Special attention should be given to people living nearby the airports.

The results should be taken into account for the next certification requirements.

4.2. RECOMMENDATIONS ANSV-11/1147-19/5/I/21 and ANSV-11/1147-19/6/I/21

Type of recommendation: SRUR/SRGC.

Motivation: in the event discussed in this report, the ejection of fragments from one engine occurred. In detail, the radial projection of the parts was contained within the engine while the axial projection was not contained. Radially projected fragments are certainly to be considered high-energy. However, the CS-E, while clarifying that large rotating parts are to be considered high-energy fragments, at the same time does not exclude that there may be other types. In fact, in the case under discussion, the axially projected parts have resulted in damage to the aircraft, following requiring extensive maintenance interventions and various inspections. In addition, the fragments, certainly at a high temperature and capable of causing burns (at the time of the failure, the TGT recorded was 876 °C), precipitated on an inhabited area, causing damage to vehicles and houses. Therefore, only by chance there were no injuries. This would lead to define this situation as an unsafe condition, induced by a hazardous engine effects for which the probability of occurrence should be below 10^{-7}. However, there is no clear definition of hazardous engine effects in the CS-E. There is a list of what should necessarily be considered as such [CS-E 510 (g)(2)]:

«(i) Non-containment of high-energy debris;
(ii) Concentration of toxic products in the Engine bleed air for the cabin sufficient to incapacitate crew or passengers;
(iii) Significant thrust in the opposite direction to that commanded by the pilot;
(iv) Uncontrolled fire;
(v) Failure of the Engine mount system leading to inadvertent Engine separation;
(vi) Release of the Propeller by the Engine, if applicable;
(vii) Complete inability to shut the Engine down.».

The event under investigation in which the axial projection of fragments at high temperature took place could be included in point (i). However, this is traditionally associated only to radially ejected parts: this is made possible by the fact that there is no clear definition of high energy debris in the CS-E. In fact, in AMC E 510 (d)(iii):

«Uncontained debris cover a large spectrum of energy levels due to the various sizes and velocities of parts released in an Engine Failure. The Engine has a containment structure which is designed to withstand the consequences of the release of a single blade (see CS-E 810(a)), and which is often adequate to contain additional released blades and static parts. The Engine containment structure is not expected to contain major rotating parts should they fracture. Discs, hubs, impellers, large rotating seals, and other similar large rotating components should therefore always be considered to represent potential high-energy debris.».

Thus, it is clear what is always to be considered as high energy debris, while is not excluded the possibility high temperature parts ejected axially could be high energy debris.

Furthermore, on the one hand it is clear that the engine is required to contain potential radial projections of blades, on the other hand it is not excluded that the definition of uncontained can be applied to axially projected parts.

In this framework, there is a discrepancy with the United States legislation (AC33.75), which, although has similar guidelines for the definition of high energy debris, it also adds:

«Uncontained blades from a multiple blade release are typically considered low energy fragments because their energy has been significantly reduced in defeating the containment structure. These events may typically be considered major engine effects.
However, the release of significant numbers of blades (for example, corn-cobbed rotors) will likely include fragments exiting with high energy, and would therefore result in a hazardous engine effect.».

Regarding minor engine effects, following the definition as per CS-E 510 (g)(1):

«An Engine Failure in which the only consequence is partial or complete loss of thrust or power (and associated Engine services) from the Engine must be regarded as a Minor Engine Effect.».

Based on the above excerpts all 10 of the cases preceding the one under discussion were classified as minor. This classification was most likely made possible by the absence of a clear definition of high energy debris and hence management of events potentially considering a lower than real risk. In this framework it is important to highlight that the 11th case of IPTB release occurred after the manufacturer applied more stringent provisions. In more detail, after the ESN 10231 investigation, the fleet was managed to protect the possible hazardous event of the overspeed and burst of the LPT Stage 1 disc. Despite this, as a result of the event, the manufacturer issued the Alert NMSB TRENT 1000 72-AK186 rev. 3 and EASA made mandatory the content of this document by means of the AD 2019-0261.

Thus it seems to be necessary to provide a clear and complete definition of high energy debris, allowing a more immediate assessment of the severity of the events, which must be analyzed not only according to the actual/potential damage to the aircraft, but also to the actual/potential risk for people on ground.

Addressees: EASA **(ANSV-11/1147-19/5/I/21)**, FAA **(ANSV-11/1147-19/6/I/21)**.

Text: it is recommended to evaluate a revision of the CS-E and AC33.75 in order to provide a clear definition of high energy debris including what constitute a risk for the aircraft and people on board, but also for people on the ground in the framework of the different phases of flight. Special attention should be given to people living nearby the airports.

4.3. RECOMMENDATIONS ANSV-12/1147-19/7/I/21 and ANSV-12/1147-19/8/I/21

Type of recommendation: SRUR/SRGC.

Motivation: in the event discussed in this report, the ejection of fragments from one engine occurred. This was the result of a corrosion-fatigue phenomenon, made possible by an improvable design in terms of methodology and type of coating in addition to base material composition of the IPT blades.

The radial projection of the parts was contained within the engine while the axial projection was not contained. The CAW guidelines are based on failure rates compared to maximum allowable probabilities of occurrence and corrective measures, balanced according to the severity of the issue and the effective life of the equipment. However, the maximum allowable probabilities of occurrence currently used in the certification and a CAW have remained unchanged for many years; for engines they were defined more than 40 years ago.

Taking into consideration the statistics concerning accidents and incidents, it should be pointed out that while maintaining the maximum allowable probabilities of occurrence unchanged, overall the trend of air accidents in CAT has decreased over time: in particular, compared to the early days of aviation, the technical factor is less and less the root cause of a serious incident or accident. The reason for that, regardless of the prescribed maximum allowable probabilities of occurrence, is the industrial practice in general improved anyway, leading to more reliable components: in fact, they usually exceed the requirements of the CSs. Nevertheless, aiming to continuous improvement, other aspects should be also considered.

a) There may be the case in which, due to a design or production defect, the reliability of a component is lower than the actual expected industrial standard. The same component could guarantee a failure rates in compliance with the maximum allowable probabilities of occurrence prescribed by the CSs and the CAW guidelines. The result would be an airworthy component, having level of reliability whose suitability was established using an obsolete standard (in the case of engines at least 40 years ago); this reliability would not be in line with the average standards that is realistically possible to produce today, given the technological progress that has occurred in the meantime (introduction of rational performance requirements[20]). At the time of the ninth IPT blade release event, the PNE was equal to possible further 4 cases of blade release.

b) Technical factor is often cause of events or contributing factor; therefore, a more reliable component, could stop the chain of events before other factors may occur. For example, it could happen that on a twin-engine aircraft, in case of failure of one of the two engines, the crew erroneously performs the IFSD of the only functioning engine. This would result in human factor (IFSD of the running engine instead of the faulty one). Nonetheless, if the engine that fails would have been more reliable, it would also have prevented the event. Therefore, greater reliability of components would lead to an increase in safety even in accidents/incidents in which the technical factor is present in the chain of events although not being the main causal factor.

c) Air traffic generally decreased in 2020 and early 2021 due to the COVID-19 pandemic. However, it can reasonably be assumed that air traffic will increase again in the future. This means that, keeping the maximum allowable probabilities of occurrence used as certification baseline unchanged, the reliability of the components may not improve as it may be required to balance the increase in air traffic. If this were to happen, it would allow for a greater number of accidents/incidents to occur in which the technical factor is the cause or contributing factor.

d) Since the time when the maximum allowable probabilities of occurrence were established, the population, in particular the European, has increased: this makes the risk that the people on ground being hit by a PDA greater than it originally was.

e) Regardless of points a, b, c, d, it seems clear that after such a long time it is technologically possible to require technological standards in terms of minimum reliability higher than those requested by the CSs; specifically for engines these standards have remained unchanged in terms of maximum allowable probabilities of occurrence for at least 40 years.

Based on the above considerations, taking into account the statistics of accidents and incidents, the actual air traffic and technological limits based on the state of the art, it seems appropriate to periodically review the validity of the maximum allowable probabilities of occurrence. This should be done setting achievable standard levels of reliability, compatible with the actual state of the art. This would have a direct positive impact in terms of preventing all those events in which technical factor is causal or contributing.

[20] UK CAA Airworthiness Information Leaflet AD /IL/0092/1-7 dated 19th November 1982 and same text in the latest version of AMC & GM for Part 21 Section A Subpart A GM 21.A.3B(d)(4), paragraphs 2.1 e 2.2 nowadays applicable.

Addressees: EASA **(ANSV-12/1147-19/7/I/21)**, FAA **(ANSV-12/1147-19/8/I/21)**.

Text: taking into account the actual accident and incident statistics, the actual volume of traffic of the commercial transportation and the actual technology state of the art, it is recommended to evaluate a periodic revision of the maximum allowable probabilities of occurrence used in the CSs and Part21 (FAA regulation: AC25 25.1309-1A, AC33-75, AC39-08), establishing clear calculation methods. This has the aim to improve the safety, setting achievable standard levels of reliability, compatible with the actual state of the art.

ATTACHMENTS

Attachment "A": CAA, Airworthiness Information Leaflet AD/IL/0092/1-7 19 November 1982.

Attachment "B": CM-21.A-A-001 Issue 01 of 29 November 2018.

Attachment "C": EASA, AD 2019-0261.

In the attached reproduced documents the anonymity of the persons involved is safeguarded, according to current dispositions regarding safety investigations.

Civil Aviation Authority

Airworthiness Division

AIRWORTHINESS INFORMATION LEAFLET

Ref AD/IL/0092/1-7

Date 19th November 1982

Author's Initials LJWH/GLG

This Leaflet will not necessarily be kept up to date by reissues

SUBJECT TITLE DEFECT CORRECTION - SUFFICIENCY OF PROPOSED CORRECTIVE ACTION

PURPOSE This Leaflet provides guidelines to assist in establishing rectification campaigns to remedy discovered defects.

REFERENCES

1 STATUS OF LEAFLET

This Information Leaflet contains guidance material of a general nature, not intended to be regarded as binding in specific cases, but, by being used in conjunction with engineering judgement, to aid airworthiness engineers in reaching decisions in the state of technology at the material time.

2 INTRODUCTION

2.1 Over the years, target airworthiness risk levels underlying airworthiness requirements have developed on the basis of traditional qualitative airworthiness approaches; they have been given more precision in recent years by being compared with achieved airworthiness levels (judged from accident statistics) and by the general deliberations and discussions which accompanied the introduction of rational performance requirements, and more recently, the Safety Assessment approach in requirements. Although the target airworthiness risk level tends to be discussed as a single figure (a fatal accident rate for airworthiness reasons of not more than 1 in 10,000,000 flights/flying hours for large aeroplanes) it has to be recognised that the requirements when applied to particular aircraft types will result in achieved airworthiness levels at certification lying within a band around the target level and that thereafter, for particular aircraft types and for particular aircraft, the achieved level will vary within that band from time to time.

2.2 The achieved airworthiness risk levels can vary so as to be below the target levels, because it is difficult if not impossible to design to the minimum requirements without being in excess of requirements in many areas; also because aircraft are not always operated at the critical conditions (e.g. aircraft weight, eg position and operational speeds; environmental conditions - temperature, humidity, degree of turbulence). The achieved level may vary so as to be above the target level because of undetected variations in material standards or build standards, because of design deficiencies, because of encountering unforseen combinations of failures and/or combinations of events, and because of unanticipated operating conditions or environmental conditions.

2.3 There is now a recognition of the need to attempt to monitor the conditions which tend to increase the level and to take appropriate corrective action when the monitoring indicates the need to do so in order to prevent the level rising above a predetermined “ceiling”.

2.4 Equally the CAA has a duty in terms of providing the public with aviation services and therefore must balance the acceptability of any potential. variation in airworthiness level against the penalties associated with curtailment or even removal (by “grounding”) of aviation services.

2.5 Thus, the purpose of this Leaflet is:-

(a) to postulate basic principles which should be used to guide the course of actions to be followed so as to maintain an adequate level of airworthiness rink after a defect has occurred which, if uncorrected, would involve a potential significant increase of the level of risk for an aircraft type.

(b) for those cases where it is not possible fully and immediately to restore the normal level of airworthiness risk by any possible alleviating action such as an inspection or limitation, to state the criteria which should be used in order to assess the residual increase in risk and to limit it to an appropriate small fraction of the mean airworthiness through life risk.

3 DISCUSSION

3.1 Several parameters are involved in decisions on safety matters. In the past the cost of proposed action has often been compared with the notional ‘risk cost’, i.e. the cost of a catastrophe multiplied by its probability of occurrence.

3.2 This can be a useful exercise, but it must be held within the constraint of acceptable airworthiness risk levels, i.e. within airworthiness risk targets which represent the maximum levels of risk with which an aircraft design must comply i.e. in the upper part of the ‘band'. Currently for large aeroplanes the mean airworthiness risk level is set at a catastrophe rate for air-worthiness reasons of not more than one in every ten million flights/flying hours. The constraint is overriding in that any option which could be permitted on risk cost considerations, or other grounds, is unacceptable if it leads to significant long-term violation of this safety requirement.

3.3 While it should clearly be the objective of all to react to and eliminate emergency situations i.e. those involving a potentially significant increase of airworthiness risk levels, without un-reasonable delay, an Authority must be able finally to rule on what is a minimum acceptable campaign programme. It has therefore seemed desirable to devise guidelines to be used in judging whether a proposed campaign of corrective actions is sufficient in airworthiness terms, and clearly this ought to be based on determining the estimation of the achieved airworthiness risk levels for the aircraft and passengers during any periods of corrective action and comparing them with some agreed target.

3.4 Obviously during periods of corrective action, not being instan-taneous (unless by grounding), there must be potentially an in-crease in the achieved airworthiness risk level possibly to and, without controls, even above the higher part of the ‘band’, and the amount by which the level is above the mean target figure, and the period for which it should be allowed to continue, has been a matter of some arbitrary judgement.

3.5 It would appear desirable to try to rationalise this judgement. For example, if an aircraft were to spend 10% of its life at a level such that the risk of catastrophe was increased by an order of magnitude, the average rate over its whole life would be doubled. It is suggested this would offend the public intent. A more suitable criterion is perhaps one which would allow an average increase in risk of, say one third on top of the basic design risk when spread over the whole life of the aircraft an amount which would probably be acceptable within the concept (See Figure 1). It would then be possible to regard the ‘through life' risk to an aircraft — e.g. a mean airworthiness target of not more than one airworthiness catastrophe per 10^7 hours *, as made up of two parts, the first being ¾ of the total and catering for the basic design risks and the other being ¼ of the total, forming an allowance to be used during the individual aircraft's whole life for unforseen campaign situations such as described above.

3.6 It is suggested that it would be prudent to plan as if a total of ten such occasions might arise during the life of the aircraft.

3.? Using these criteria, there could then be during each of these emergency periods (assumed to be ten in number) a risk allowance, contributed by the campaign alone of:

1×10^{-7} for 2.5% of the aircraft's life; or

5×10^{-7} for 0.5% of the aircraft's life; or

10×10^{-7} for 0.25% of the aircraft's life; or

100×10^{-7} for 0.025% of the aircraft's life etc.

without exceeding the agreed 'allowance' set aside for this purpose.

3.8 Thus a 'reaction table' can be created as indicated in Table 1 (the last column assuming an aircraft life of 40,000 hours and an annual utilisation of 3000 hours per annum) showing the flying or calendar time within which a defect must be corrected if the suggested targets are to be met.

Table 1

Estimated catastrophe rate to aircraft due to the defect under consideration (per a/c hour)	Necessary reaction time for each air-craft at risk (hours)	On a calendar basis
10^{-7}	1000	4 months
5×10^{-7}	200	1 month
10×10^{-7}	100	1 Week
100×10^{-7}	10	Return to base

* While the main principles of this Information Leaflet could be applied to small private aeroplanes, helicopters, etc. the numerical Values chosen for illustration are appropriate to large aeroplanes for public transport.

3.9 These principles may be applied to a single aircraft or a number of aircraft of a fleet but in calculating risk, all the risk must be attributed to those aircraft which may carry it, and must not be diluted by including other aircraft in the fleet which are known to be free of risk. (it is permissible to spread the risk over the whole fleet when a source is known to exist without knowing where). Where a fleet of aircraft is involved Column 2 may be interpreted as the <u>mean</u> time to rectification and not the time to the last one.

3.10 There is one further constraint. However little effect a situation may have on the 'whole life' risk of an aircraft, the risk must not be allowed to reach too high a level for any given flight. Thus while a very high risk could be tolerated for a very short period without unacceptable degradation of the overall airworthiness target, the few flights involved would be exposed to a quite unacceptable level of risk. It is therefore proposed that Table 1 should have a cut-off at the 20×10^{-7} level so that no flight carries a risk greater than 20 times the target. At this level the defect is beginning to contribute a greater likelihood of catastrophe than that from all other causes, including non-airworthiness causes, put together. If the situation is worse than this, grounding appears to be the only alternative with possibly specially authorised high risk ferry flights to allow the aircraft to return to base empty.

3.11 It will be seen that the above suggestions imply a probability of catastrophe from the campaign alone of 1/10,000 per aircraft during each separate campaign period.

3.12 It should also be noted that in assessing campaign risks against the 'design risk', an element of conservatism is introduced, since the passenger knows only 'total risk' (i.e. airworthiness plus operations risks) and the fatal accident rate for all reasons is an order of magnitude greater than that for airworthiness reasons only (i.e. 10^{-6} as against 10^{-7}). The summated campaign risk allowance as proposed by this Information Leaflet is therefore quite a small proportion of the total risk to which a passenger is subject. When operating for short periods at the limit of risk proposed (20×10^{-7}) the defect is however contributing more risk than <u>all</u> other causes added together.

4 <u>GUIDELINES</u>

4.1 The above would lead to the following guidelines for a rectification campaign to remedy a discovered defect without grounding the aircraft -

(i) Establish all possible alleviating action such as inspections, crew drills, route restrictions, other limitations.

(ii) Identify those individual aircraft which are exposed to the residual risk, after compliance has been established with (i).

(iii) Using reasonably cautious assumptions, calculate the likely catastrophic rate for each aircraft carrying the risk.

(iv) Compare the speed with which any suggested campaign will correct the deficiency with the time suggested in Table 1. The Table must not be used beyond the 20×10^{-7} level, except for specially authorised flights.

4.2 It must be stressed that the benefit of these guidelines will be to form a datum for what is considered to be the theoretically maximum reaction time. A considerable amount of judgement will still be necessary in establishing many of the input factors and the final decision may still need to be tempered by non-numerical considerations, but the method proposed will at least provide a rational 'departure point' for any exercise of such judgement.

4.3 It is not intended that the method should be used to avoid quicker reaction times where these can be accommodated without high expense or disruption of services.

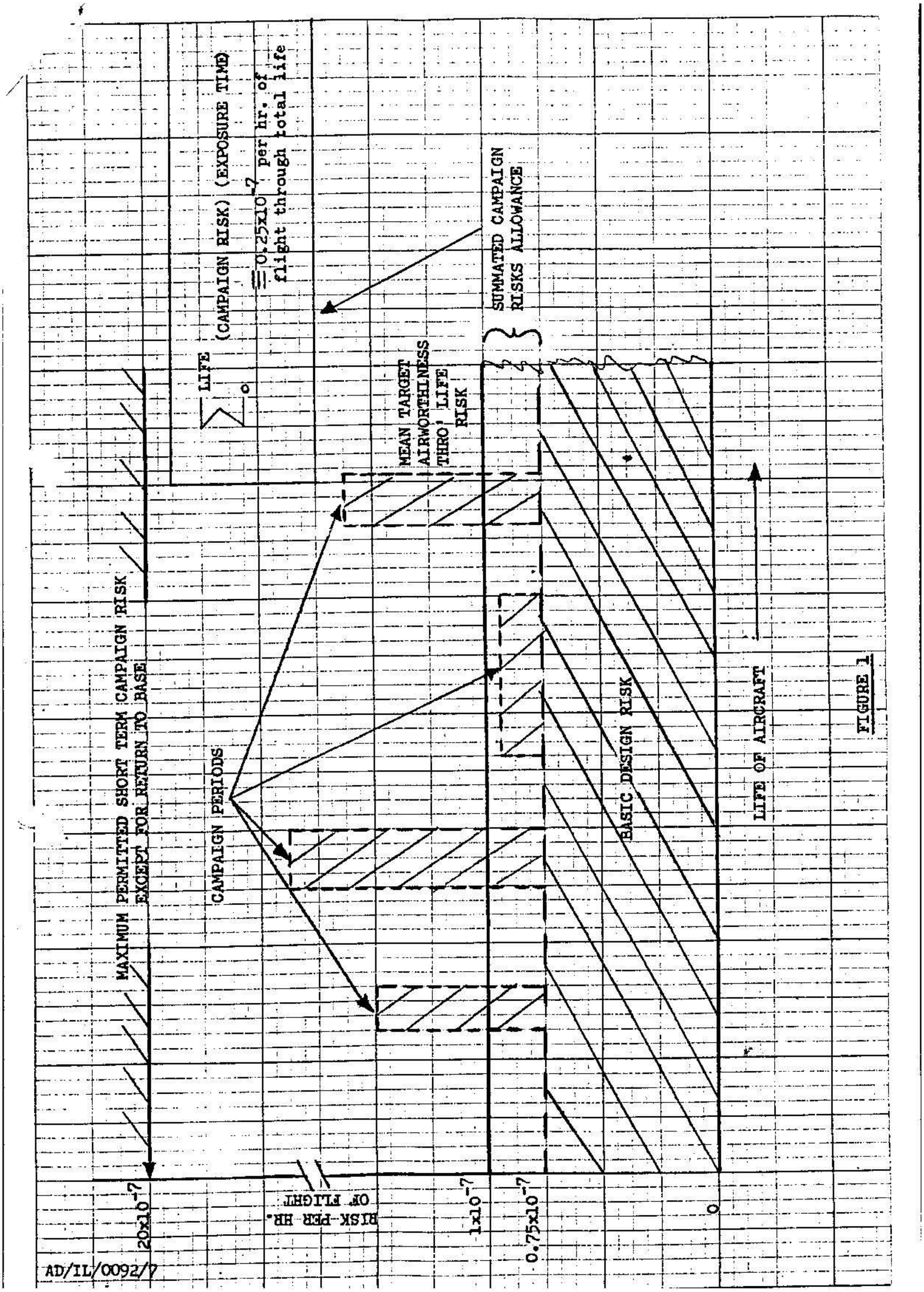
MAXIMUM PERMITTED SHORT TERM CAMPAIGN RISK EXCEPT FOR RETURN TO BASE
CAMPAIGN PERIODS
$\sum_{0}^{LIFE}$ (CAMPAIGN RISK) (EXPOSURE TIME) $\equiv 0.25x10^{-7}$ per hr. of flight through total life
SUMMATED CAMPAIGN RISKS ALLOWANCE
MEAN TARGET AIRWORTHINESS THRO' LIFE RISK
BASIC DESIGN RISK
LIFE OF AIRCRAFT
RISK PER HR. OF FLIGHT
$20x10^{-7}$
$1x10^{-7}$
$0.75x10^{-7}$
0
AD/IL/0092/7

FIGURE 1

Certification Memorandum

PARTS DETACHED FROM AEROPLANES

EASA CM No.: CM–21.A-A-001 Issue 01 issued 29 November 2018

Regulatory requirement(s): 21.A.3B(b), AMC& GM 21.A.3B(b)

In accordance with the EASA Certification Memorandum procedural guideline, the European Aviation Safety Agency proposes to issue an EASA Certification Memorandum (CM) on the subject identified above.
All interested persons may send their comments, referencing the EASA Proposed CM Number above, to the e-mail address specified in the “Remarks” section, prior to the indicated closing date for consultation.

EASA Certification Memoranda are intended to provide guidance on a particular subject and, as non-binding material, may provide interpretative material. Certification Memoranda are provided for information purposes only and must not be misconstrued as formally adopted Acceptable Means of Compliance (AMC) or as Guidance Material (GM). Certification Memoranda are not intended to introduce new certification requirements or to modify existing certification requirements and do not constitute any legal obligation.

Log of issues

Issue	Issue date	Change description
01	29.11.2018	First issue

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1. Introduction

1.1. Purpose and scope

The purpose of this Certification Memorandum is to provide specific guidelines, limited to large aeroplanes, for evaluating whether an unsafe condition exists in Parts Departed from Aeroplanes events, hereafter referred to as 'PDA'. These guidelines can be applied by European DA holders.

This CM attempts to clarify how the Part 21 AMC that provides the definition of unsafe conditions should be interpreted when a case of PDA occurs.

Additionally, this CM provides harmonisation with the FAA on their draft policy PS-ANM-25-23 'Risk to Persons on the Ground from Objects Falling off Transport Category Airplanes' published by the FAA for comments in 2017.

1.2. Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
AIA	Aerospace Industries Association
AMC	Acceptable Means of Compliance
CAAM	Continued Airworthiness Assessment Methodologies
CAT	Catastrophic
CM	Certification Memorandum
CS	Certification Specification
CVR	Cockpit Voice Recorder
DA	Design Approval
DFDR	Digital Flight Data Recorder
EASA	European Aviation Safety Agency
ELT	Emergency Locator Transmitter
FAA	Federal Aviation Administration
FH	Flight Hours
FOD	Foreign Object Damage
GM	Guidance Material
HAZ	Hazardous
PDA	Parts Departed from Aeroplanes

1.3. Definitions

PDA	In the context of this certification memorandum, parts detached from the aeroplane with no or low initial relative speed to the aeroplane.

2. Background

EASA shall issue airworthiness directives to correct any unsafe condition that is likely to exist, in accordance with Part 21.A.3B(b).

In the framework of Continued Airworthiness, PDA represent recurrent events whose consequences may lead to unsafe conditions.

The objective of the CM is to provide criteria to determine whether each potential PDA identified for an aeroplane model is an unsafe condition or not.

As per AMC 21.A.3B(b), an unsafe condition exists if there is factual evidence [...] that:

(a) An event may occur that would result in fatalities, usually with the loss of the aeroplane(s), or reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be:

(i) A large reduction in safety margins or functional capabilities, or
(ii) Physical distress or excessive workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely, or
(iii) Serious or fatal injury to one or more occupants

unless it is shown that the probability of such an event is within the limit defined by the applicable certification specifications, or

(b) *There is an unacceptable risk of serious or fatal injury to persons other than occupants, or* [...]

PDA can be very different in their nature and location: doors, access panels, fairings, engine cowlings, fasteners, lights etc. may be involved, therefore determining whether an unsafe condition exists is not always straightforward. There are three main categories of potential consequences following PDA events that can be foreseen:

1. Damage and/or reduced functionality of the aeroplane (wing, fuselage, horizontal or vertical stabilizer structures, engine ingestion, control and other systems) potentially causing injuries to its occupants.
2. Injuries to people on the ground.
3. Damage to other aeroplane(s) (e.g. PDA encountered on runways) potentially causing injuries to its occupants.

As quoted above, the risk to the aeroplane and its occupants is covered by AMC 21.A.3B(b), paragraph (a), and further guidance is provided in GM 21.A.3B(b). The risk of injuring people on the ground or in other aeroplane(s) is addressed by AMC 21.A.3B(b), paragraph (b), according to which an unsafe condition exists when there is an ‘unacceptable risk’ of serious or fatal injury to persons other than occupants.

However, the word ‘unacceptable’ does not bound specific scenarios, and is open to interpretation, as no further guidance is provided in the AMC or GM to Part 21.

3. EASA Certification Policy

3.1. Objective

The objective of this CM is to provide guidance, limited to large aeroplanes, for evaluating whether each potential PDA event identified for an aeroplane model is, or is not, an unsafe condition.

The three main potential consequences of a PDA event, identified in Section 2, have been analysed in terms of their severity and probability of occurrence following a 'CS 25.1309-like' approach. They are assessed in Sections 3.2 to 3.4, and the conclusion is provided in Section 4.

This CM may be used only to assess PDA events in the framework of Continued Airworthiness. Although some PDA scenarios mentioned in this CM could be acceptable based on the observed rate of parts loss per FH, in general, the loss of parts should be prevented as much as possible.

This CM does not contradict certain accepted Initial Airworthiness requirements that address scenarios in which parts are assumed to fail and to depart from the aeroplane (e.g. fan blade loss, landing gear separation).

This CM covers the cases of parts that become detached from the aeroplane with no or low initial relative speed to the aeroplane.

Cases such as high energy rotating parts departing from the engine, or the inadvertent ejection of an ELT, or a DFDR/CVR, are therefore outside the scope of this CM.

3.2. SCENARIO 1: Damage to the aeroplane itself

In the case of a PDA, an unsafe condition can be caused by a direct effect of the detached part on the aeroplane, i.e. the loss of the function that this part provides; or by an indirect effect on the aeroplane, i.e. an impact on other zones of the aeroplane.

Concerning the direct effects of the PDA on the aeroplane itself, an assessment must show that the aeroplane functions compromised by the missing PDA, and the occupants of the aeroplane, are not adversely affected up to the point of experiencing an unsafe condition due to the loss of the part, following the guidance of GM 21.A.3B(b).

Similarly, concerning the indirect effects of the PDA on the aeroplane itself, an assessment must show that the potential impact of the part on other parts of the aeroplane does not cause an unsafe condition for the aeroplane.

In order to conclude that a potential unsafe condition, based on the hazard, is not unsafe based on the level of risk, it has to be shown, for both effects, that they meet the proper associated safety objectives. As per AMC 25.1309, any failure condition that would result in multiple fatalities, usually with the loss of the aeroplane, is classified as catastrophic (CAT). In addition, as per AMC 25.1309, any failure condition that would result in serious or fatal injury to a relatively small number of the occupants other than flight crew, is classified as Hazardous (HAZ). The safety objective associated with a CAT event is satisfied if the probability of occurrence per FH is less than 1E-9. The safety objective associated with a HAZ event is satisfied if the probability of occurrence per FH is less than 1E-7. There are other cases for which the severity of the event can be different.

The probability of a PDA impacting the aeroplane(s) depends on the trajectory that the released part follows, and the potential damage that a PDA impacting the aeroplane can cause depends on the force with which it may impact the aeroplane. The trajectories cannot be easily predicted, whereas the impact energy may be conservatively estimated.

For this potential risk, engineering judgement represents the most reasonable approach to be adopted. The location of the part in the aeroplane, its weight, size, and shape, and the configuration of the aeroplane are important parameters in order to identify the existence or not of an unsafe condition.

The combination of the trajectory of the part, the orientation of the part, and its impact energy should therefore be considered when assessing the side effects of PDA. The following aspects may be taken into account:

A. Trajectory of the detached part. Predicting the exact trajectories of detached parts is not generally possible, however some acceptable assumptions are that:

   — relatively light parts that do not behave as lifting surfaces may follow trajectories similar to the streamlines along the aeroplane;

   — parts that behave as lifting surfaces (like panels or undercarriage doors) will not follow the streamlines along the aeroplane;

   — non-lifting high-mass lost parts may not present a risk of hitting the aeroplane if the trajectory is mainly determined by gravity, or if the starting location on the aeroplane is such that the detached part is unlikely to impact the aeroplane;

   — the results of a statistical analysis of existing in-service data may be acceptable.

B. Damage to the impacted area. The potential damage depends on the energy of the detached part, the impact angle, the geometrical and material properties of the detached part, and on the characteristics of the impacted area itself. Conventional analysis is sufficient in most cases. Detailed dynamic modelling may not be required. The following steps may be accepted:

   — An estimation of the impact energy based on the mass and the maximum relative impact speed of the detached part;

   — An estimation of the impact angle and the worst orientation of the part;

   — An estimation of the worst possible extent of the damage;

   — Statistical analysis or in-service data used to substantiate the likelihood of a certain level of damage.

In general, the maximum energy of impact of a detached part can be conservatively estimated by considering the maximum estimated relative speed of the part and its mass. This is a conservative estimation, since the relative speed of the part is dependent on the drag coefficient of the PDA during its travel from the departure point to the impact point.

In-service experience: the results of a search into historical data going back to 1990, available at EASA, show that all the occurrences involving PDA have always been completed with uneventful landings and without any serious or fatal injuries for the occupants.

Note: some approval holders may wish to use existing bird strike compliance demonstrations as part of their assessment. As the impact dynamics for a bird versus a part impacting an aeroplane are generally different in terms of their densities, body shapes and consistencies, only a simple comparison of the energy level involved in the PDA event with the one defined in the bird strike requirements is not considered to be a sufficient substantiation for assuring that the impact will not prevent continued safe flight and landing.

3.3. SCENARIO 2: People on ground

PDA could produce serious or fatal injuries to people on the ground. The typical number of people hit by a part detached from an aeroplane can be assumed to be a small number. In the context of this CM, serious or fatal injuries to a person or a small number of people on the ground are considered to be events with hazardous consequences, extrapolating the severity definitions, as per AMC 25.1309, for people on the aeroplane to people who were not travelling on the aeroplane. Having a probability of occurrence that is lower than 1E-7/FH would therefore meet the safety objectives for a HAZ event, and hence, no unsafe condition would exist, as explained later in the text. This numerical threshold is in line with the EASA AMC 25.1309 safety objective associated with a Hazardous failure condition, which includes the possibility of 'serious or fatal injuries to a relatively small number of people'.

Several methods can be adopted in order to quantify the likelihood of causing fatal injuries to the people on the ground associated with PDA, however for all of them, the variables to be adopted are generally common:

— The density of population, with reasonable correction factors related to time exposure and shielding such as being indoors and shielded by, for example, buildings, or being on a means of transportation;

— The size and weight of the aeroplane(s) part concerned.

The likelihood/probability of causing a fatal injury is expressed as the combination of:

— The likelihood of a PDA event;

— The likelihood of a person being hit by the PDA;

— The likelihood that, if hit by the PDA, there will be fatal consequences.

The probability of a person being fatally injured when hit by PDA is set to 1, as a conservative assumption.

The probability of a person being hit by PDA (where PDA is considered to be large debris) is strictly connected to the time exposure calculated using the density of the population and factors such as the exposed area per person during both day and night.

The aforementioned evaluation could be made less conservative by refining the analysis and considering the size/weight criteria.

Following the different methods, the result is that the probability of fatally hitting people is in the order of magnitude of 1E-3 and, therefore, in order to meet a target of 1E-7 occurrences-per-FH, the probability of losing a single part per FH would need to be less than 1E-4.

Data retrieved from several large aeroplane manufacturers have been analysed. These data show a rate of loss of parts that is between 1E-6/FH and 1E-5/FH, resulting in an overall risk to people on the ground that is substantially lower than the proposed objective. The analysed data comprise different types of large aeroplane (long range, regional and business jets), which represent more than 90% of the EASA certified flying fleet. These data show a level of homogeneity, suggesting that the results that were obtained can be representative of an average large aeroplane design and fleet.

The conclusion is that the likelihood of fatally injuring people on the ground due to a PDA event is conservatively estimated to be close to the objective set in CS 25.1309 for system failures with a catastrophic effect, i.e. 1E-9/FH, and can therefore be considered to be acceptable regarding the probability objective of 1E-7/FH for impacting people on the ground. Furthermore, this is supported by the absence of any in-service events of people who were fatally injured as a consequence of PDA.

As a result, no unsafe condition has been identified for people on the ground from a quantitative point of view, or for the purpose of evaluating the need for mandatory corrective action.

In addition, an extrapolation of the parameters used in the assessment, together with the conservatism of some of the assumptions, confirms that this estimate will be valid in the mid and long-term.

A reassessment by the DA holder of a specific PDA case for a potential unsafe condition is expected when the loss of a specific part has a probability rate per FH that is significantly higher than the average probability rate, which is between 1E-6/FH and 1E-5/FH, as currently observed in the field.

3.4. SCENARIO 3: Damage to other aeroplanes/parts on the runway

A PDA, if lost on the runway, on a taxiway or in the airport area, may represent a threat to other aeroplanes (i.e. due to Foreign Object Damage - FOD). Statistics from field experience show that typically the areas that are most likely to be potentially damaged are aeroplane engines, tyres and wheels, causing economic impacts on maintenance costs, but usually with no significant impact on safety.

Nevertheless, depending on the damage that can be caused to another aeroplane, the severity may rise to CAT, and therefore the safety objective may be as low as 1E-9 occurrences per FH. As mentioned in Scenario #2, EASA has retrieved information from some European manufacturers on the parts lost, obtaining a rate of detached parts that is between 1E-6/FH and 1E-5/FH. Furthermore, considering the exposure time of the take-off and landing runs, the probability per FH of losing a part on the runway might be estimated to be about two orders of magnitude lower, i.e. between 1E-8 and 1E-7. This would mean hazardous outcomes would not be considered unsafe, but it is not possible to evaluate a priori the frequency of impacts on aeroplane of runway debris comprising PDA or the proportion of those events that may be catastrophic.

As a result, for this scenario, field experience remains the most valuable data on which to base a risk assessment.

In the recent history of European commercial air transport with aeroplanes that were certified under FAR/JAR/CS25, there have been non-catastrophic events that were caused by parts on the runway. For aeroplanes certified to earlier requirements, there is one record of an accident in which a part departed from an aeroplane with catastrophic results for a following aeroplane, although in that particular case it cannot be concluded that PDA was the sole contributor to the accident.

As a result of a quantitative assessment based on the above history, it can be concluded that the risk that PDA causes an accident to another aeroplane does not meet the criteria for an unsafe condition as defined in AMC 21.A.3B(b).

In terms of actions to address the threat from runway debris, in 2013, EASA published NPA 2013/02[1] that considered the need for new certification standards for protection of large aeroplanes against certain categories of threats, i.e. tyre and wheel failure, small engine debris and runway debris.

The Working Group involved in the preparation of the NPA reviewed existing threat models, outcomes of studies and in-service occurrences. With specific reference to runway debris (which may include PDA), the most frequent risk identified was damage to tyres and engines, the consequences of which were considered in the NPA to be adequately addressed by the proposed requirements to consider tyre, wheel and engine debris threats; subsequently introduced under CS 25.734 in CS-25 Amdt. 14. Of the other risks presented to aeroplanes by runway debris, no events were identified that caused injury. The working group considered that the protection afforded against tyre and wheel debris by the proposed requirements would also indirectly provide robustness and protection against runway debris thrown up by contact with the tyres. However, notwithstanding the potential safety benefits of the proposed threat models for wheel and tyre debris and engine debris, the NPA also recommended that airports improve FOD prevention as a complement to their current disposition of ICAO Annex 14.

As a result, in order to support the current satisfactory safety record and although the above assessments indicate an unsafe condition will not usually result from runway debris consisting of PDA, it is recommended

[1] https://www.easa.europa.eu/document-library/notices-of-proposed-amendments/npa-2013-02

that DA holders pay particular attention to preventing occurrences of PDA when the parts are prone to loss in the take-off and landing phases and of a nature that could cause tyre or engine damage.

A reassessment by the DA holder of a specific PDA case for a potential unsafe condition is expected when the loss of a specific part has a probability rate per FH that is significantly higher than the average probability rate, which is between 1E-6/FH and 1E-5/FH, as currently observed in the field.

4. Conclusion

In PDA events, given the current observed rates of loss of parts per FH, the risk of injuries to persons on the ground or damage to other aeroplanes, under the assumptions taken for this analysis, do not constitute an unsafe condition as per 21.A.3B(b). No specific assessment for a potential unsafe condition is expected for these scenarios unless a specific part shows a rate of loss per FH that is significantly higher than the average PDA rate that is currently observed in the field. In this latter case, the DA holder is expected to reassess the situation and to report to EASA if it is considered to be potentially unsafe (i.e. if the rate of loss per FH of this individual part is such that the conclusions of this CM, in terms of the existence or not of a potential unsafe condition, are invalidated).

As a consequence, the main scenario that a DA holder is expected to address is the possibility of the existence of an unsafe condition as per AMC 21.A.3B(b), paragraph (a), i.e. the possibility that a part detached from an in-service aeroplane creates an unsafe condition for the aeroplane itself. For this, the guidelines provided in Section 3.2 of this text and GM 21.A.3B(b) are expected to be followed.

5. Remarks

1. Comments or suggestions regarding this EASA Proposed Certification Memorandum should be referred to the Certification Policy and Safety Information Department, Certification Directorate, EASA. E-mail CM@easa.europa.eu.
2. For any question concerning the technical content of this EASA Proposed Certification Memorandum, please contact:

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European Union Aviation Safety Agency

Airworthiness Directive

AD No.: 2019-0261

Issued: 18 October 2019

Note: This Airworthiness Directive (AD) is issued by EASA, acting in accordance with Regulation (EU) 2018/1139 on behalf of the European Union, its Member States and of the European third countries that participate in the activities of EASA under Article 129 of that Regulation.

This AD is issued in accordance with Regulation (EU) 748/2012, Part 21.A.3B. In accordance with Regulation (EU) 1321/2014 Annex I, Part M.A.301, the continuing airworthiness of an aircraft shall be ensured by accomplishing any applicable ADs. Consequently, no person may operate an aircraft to which an AD applies, except in accordance with the requirements of that AD, unless otherwise specified by the Agency [Regulation (EU) 1321/2014 Annex I, Part M.A.303] or agreed with the Authority of the State of Registry [Regulation (EU) 2018/1139, Article 71 exemption].

Design Approval Holder's Name:
ROLLS-ROYCE DEUTSCHLAND Ltd & Co KG

Type/Model designation(s):
Trent 1000 engines

Effective Date:	01 November 2019
TCDS Number(s):	EASA.E.036
Foreign AD:	Not applicable
Supersedure:	This AD supersedes EASA AD 2019-0135 dated 11 June 2019.

ATA 72 – Engine – Intermediate Pressure Turbine Blades – Replacement

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Manufacturer(s):
Rolls-Royce plc

Applicability:
Trent 1000-A, Trent 1000-A2, Trent 1000-AE, Trent 1000-AE2, Trent 1000-AE3, Trent 1000-C, Trent 1000-C2, Trent 1000-CE, Trent 1000-CE2, Trent 1000-CE3, Trent 1000-D, Trent 1000-D2, Trent 1000-D3, Trent 1000-E, Trent 1000-E2, Trent 1000-G, Trent 1000-G2, Trent 1000-G3, Trent 1000-H, Trent 1000-H2, Trent 1000-H3, Trent 1000-J2, Trent 1000-J3, Trent 1000-K2, Trent 1000-K3, Trent 1000-L2, Trent 1000-L3, Trent 1000-M3, Trent 1000-N3, Trent 1000-P3, Trent 1000-Q3 and Trent 1000-R3 engines, serial numbers (ESN) as listed in Appendix 1 and 2 of the NMSB, except those that have embodied Rolls-Royce modification (mod) 72-H818 or mod 72-J559 in production, or have embodied the applicable SB in service.

These engines are known to be installed on, but not limited to, Boeing 787 aeroplanes.

Definitions:
For the purpose of this AD, the following definitions apply:

Where, in this AD, reference is made to a Rolls-Royce mod, Service Bulletin (SB) or Non-Modification SB (NMSB) with an 'A' (Alert) in the number, it should be recognised that an earlier or later revision may not have that 'A'. This kind of change does not effectively alter the publication references for the purpose of this AD.

The NMSB: Rolls-Royce Alert NMSB TRENT 1000 72-AK186 Revision 3. Appendix 1 of the NMSB contains the applicable time limit of each ESN for removal from service and replacement of intermediate pressure turbine blades (IPTB). Appendix 2 contains a list of ESN that, at the time of NMSB issuance, were known to be either stored, in-shop, or otherwise not operational.

Affected IPTB: IPTB, having Part Number (P/N) KH30773 or P/N KH44898.

The applicable SB: Rolls-Royce SB TRENT 1000 72-H818, introducing IPTB P/N KH11808; or SB TRENT 1000 72-J559, introducing IPTB P/N KH71526, as applicable.

Groups: Group 1 engines are those that are in operational use, which includes those engines identified by ESN in Appendix 1 of the NMSB.
Group 2 engines are those that are either stored, in-shop, or otherwise not in operational use, which includes those identified by ESN in Appendix 2 of the NMSB.

Reason:
Occurrences were reported of IPTB shank cracking. Analysis shows that this kind of failure is due to sulphidation corrosion.

This condition, if not corrected, could lead to IPTB shank release, possibly resulting in engine in-flight shut-down (IFSD) and consequent reduced control of the aeroplane.

Prompted by these events, Rolls-Royce identified engines with a high level of sulphidation exposure using a corrosion fatigue life (CFL) model. Consequently, EASA issued AD 2017-0056 to require removal from service of certain engines, to be corrected in shop. In addition, to reduce the risk of dual IFSD, it was decided to introduce a new cyclic life limit to certain engines, determining when an engine can no longer be installed on an aeroplane in combination with certain other engines. Consequently, EASA issued Emergency AD 2017-0253-E, AD 2018-0086, and finally AD 2018-0139, each next AD superseding the previous one, to require de-pairing of the affected engines.

After EASA AD 2018-0139 was issued, prompted by further analyses of data provided by operators, Rolls-Royce developed an updated service management approach to minimise the risk of IPTB release and issued the NMSB, identifying those ESN at highest risk, and providing the corresponding cyclic limits for in-shop IPTB replacement. Consequently, EASA issued AD 2018-0257, superseding EASA AD 2017-0056 and AD 2018-0139, removing the de-pairing requirements, to require removal from service of certain engines, to be corrected in shop. The AD also retained the optional terminating action as previously provided by EASA AD 2018-0139. For engines having service-used material (SUM) IPTB installed, that AD required introduction of IPTB cyclic limits.

After EASA AD 2018-0257 was issued, it was determined that, unless mod/SB 72-H818 or mod/SB 72-J559 is embodied, each engine must remain subject to service management to minimise the risk of IPTB release. Rolls-Royce mod/SB 72-J559 applies to the Trent 1000 TEN engine standard, introducing IPTB P/N KH71526 and additional IPTB coating. Consequently, EASA issued AD 2019-0135, retaining the requirements of EASA AD 2018-0257, which was superseded, expanded the Applicability by including Trent 1000 TEN engine models, and included reference to NMSB TRENT 1000 72-AK186 Revision 2.

Since that AD was issued, it has been decided to reduce the IPTB life limits for the remaining in-service pre-mod engines. It was also determined that installation of affected SUM IPTB is no longer allowed. Rolls-Royce issued the NMSB, as defined in this AD, accordingly, to provide the new limits and instructions.

For the reason described above, this AD retains the requirements of EASA AD 2019-0135, which is superseded, but reduces the IPTB life limits. For engines that are not operational, this AD requires replacement of the affected IPTB before release to service of the engine. This AD also prohibits installation of affected SUM IPTB on any engine.

Required Action(s) and Compliance Time(s):

Required as indicated, unless accomplished previously:

Removal from Service:

(1) For Group 1 engines: Within the applicable flight cycle (FC) limit as specified in Table 1 of this AD, remove the affected engine from service.

Table 1 – Engine Removal from Service (see Notes 1 and 2 of this AD)

FC Accumulated	Compliance Time
More than 140 FC over the limit, and those engines not listed in Appendix 1 of the NMSB	Within 25 FC after the effective date of this AD
Between 50 FC below the limit and not more than 140 FC over the limit	Within 50 FC after the effective date of this AD
More than 50 FC below the limit	Before exceeding the affected IPTB FC limit as specified in Appendix 1 of the NMSB, as applicable to ESN

Note 1: Unless indicated otherwise, the number of FC specified in Table 1 of this AD are those which an engine has accumulated, on the effective date of this AD, in relation to the FC limit as specified in Appendix 1 of the NMSB, as applicable to ESN.

Note 2: Where the NMSB refers to the date of 05 September 2019 to determine the FC accumulated by the engine, this AD requires the use of the effective date for that purpose.

Replacement:

(2) After removing a Group 1 engine from service as required by paragraph (1) of this AD, before release to service of that engine, replace the affected IPTB in accordance with the instructions of the applicable SB, as defined in this AD.

(3) For Group 2 engines: Before release or return to service of the engine, replace the affected IPTB in accordance with the instructions of the applicable SB, as defined in this AD.

Parts Installation:

(4) Do not install on any engine affected IPTB, as defined in this AD, as required by paragraph (4.1) or (4.2) of this AD, as applicable.

(4.1) For Group 1 engines: After replacement of the affected IPTB as required by paragraph (2) of this AD.

(4.2) For Group 2 engines: From the effective date of this AD.

Ref. Publications:

Rolls-Royce Alert NMSB TRENT 1000 72-AK186 Revision 3 dated 19 September 2019.

Rolls-Royce SB TRENT 1000 72-H818 original issue dated 14 November 2016.

Rolls-Royce SB TRENT 1000 72-J559 original issue dated 27 November 2017.

The use of later approved revisions of the above-mentioned documents is acceptable for compliance with the requirements of this AD.

Remarks:

1. If requested and appropriately substantiated, EASA can approve Alternative Methods of Compliance for this AD.

2. This AD was posted as PAD 19-180 on 25 September 2019 for consultation until 09 October 2019. The Comment Response Document can be found in the EASA Safety Publications Tool, in the compressed (zipped) file attached to the record for this AD.

3. Enquiries regarding this AD should be referred to the EASA Programming and Continued Airworthiness Information Section, Certification Directorate. E-mail: ADs@easa.europa.eu.

4. Information about any failures, malfunctions, defects or other occurrences, which may be similar to the unsafe condition addressed by this AD, and which may occur, or have occurred on a product, part or appliance not affected by this AD, can be reported to the EU aviation safety reporting system.

5. For any question concerning the technical content of the requirements in this AD, please contact your designated Rolls-Royce representative, or download the publication from your Rolls Royce Care account at https://customers.rolls-royce.com.

   If you do not have a designated representative or Rolls Royce Care account, please contact **Corporate Communications** at **Rolls-Royce plc**, P.O. Box 31, Derby, DE24 8BJ, United Kingdom Telephone +44 (0)1332 242424,

   or send an email through http://www.rolls-royce.com/contact/civil_team.jsp identifying the correspondence as being related to **Airworthiness Directives**.