Statens haverikommission
Swedish Accident Investigation Authority

ISSN 1400-5719

Final report RL 2012:21e

Serious incident on 16 of January 2010 to aircraft EP-IBB at Stockholm/Arlanda Airport, Stockholm county, Sweden

Ref.no. L-02/10

2012-12-28

The report is also available on our web site: www.havkom.se

This document is a translation of the original Swedish report. In case of discrepancies between this translation and the Swedish original text, the Swedish text shall prevail in the interpretation of the report.

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Statens haverikommission
Swedish Accident Investigation Authority

1. The Swedish Transport Agency, Civil Aviation Department
2. International Civil Aviation Organization (ICAO)
3. U.S. Federal Aviation Administration (FAA)
4. European Aviation Safety Agency (EASA)

Final report RL 2012:21e

The Swedish Accident Investigation Authority (Statens haverikommission, SHK) has investigated a serious incident that occurred on 16 January 2010 in Stockholm County, involving an aircraft with the registration EP-IBB.

In accordance with Regulation (EU) No 996/2010 on the investigation and prevention of accidents and incidents in civil aviation, SHK hereby submits a final report on the investigation.

SHK respectfully requests to receive, by 1 April 2013 at the latest, information regarding measures taken in response to the recommendations included in this report.

On behalf of the SHK investigation team,

Hans Ytterberg   Stefan Christensen

APPENDICES:

1. Transcript of radio communications.
2. Analysis of the aircraft's yaw stability.
3. Expert opinion from the Swedish National Laboratory of Forensic Science. (Swedish only).
4. Report from Lufthansa Technik.
5. Report from Volvo Aero Corporation.
6. Comments from Bureau d'Enquêtes et d'Analyses (BEA).

Final report RL 2012:21e

Aircraft; registration and model	EB-IBB, Airbus A300 B4-605ER
Class/Airworthiness	Normal, Certificate of Airworthiness and Valid Airworthiness Review Certificate (ARC)
Owner/Operator	Iran Air No.221, Second Floor, Public Relations, Support Services BLd, Iran Air H.Q, Mehrabad Airport, Tehran, Iran
Time of occurrence	16-01-2010, 12.38 hours, in daylight Note: All times are given in Swedish standard time (UTC[1] + 1 hr), unless otherwise stated
Location	Stockholm/Arlanda Airport, Stockholm county, (pos. 59° 39.7' N 017° 55.4' E, 17 m above sea level)
Type of flight	Commercial air transport
Weather	METAR ESSA at 12.20 hrs: Wind 140°/5 kts, visibility 8000 m, snow grains, scattered clouds with base at 1500 ft, temp./dp -1/-3 °C, QNH[2] 1035 hPa.
Passengers:	149
Injuries to persons	None
Damage to aircraft	Limited
Other damage	Minor ground damage
Commander:	
Age, licence	59 years, ATPL[3] 709
Total flying hours	22,300 hours, of which 10,230 hours on type
Flying hours last 90 days	100 hours, all on type
Number of landings last 90 days	30
Co-pilot:	
Age, licence	29 years, CPL[4]
Total flying hours	5,067 hours, of which 1,693 hours on type
Flying hours last 90 days	141 hours, all on type
Number of landings last 90 days	21
Cabin crew members	15 cabin crew members and 4 flight security officers

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[1] Universal Time Co-ordinated (UTC) is a reference for exact time the world over.

[2] QNH indicates barometric pressure adjusted to sea level.

[3] ATPL (Airline Transport Pilot License), licence with commander competence.

[4] CPL (Commercial Pilot License).

Summary

Operational

The incident occurred in connection with a commercial air transport with the airline Iran Air. The aircraft in question, an Airbus A300-600 with the registration EP-IBB, was to commence a flight from Stockholm/Arlanda Airport to Tehran in Iran. Following normal preparations, the aircraft was taxied out to runway 19R for take-off.
The runway conditions were reported as good, with some patches of ice along the runway. The investigation has however revealed that the runway was contaminated and likely had coefficients of friction which fell short of the reported values.

After taxiing out, the crew began routine take-off procedures by increasing engine thrust during acceleration on the runway. After just over 10 seconds, one or more of the edges in a repaired section of the engine – the diffuser aft air seal – separated, thereby triggering a sequence which led to a sudden engine failure.

No warning messages were announced in the cockpit at the time of the failure; the pilots only noticed the engine failure through a muffled bang at the same time as the aircraft began to veer to the left. The initial veer, immediately after the engine seizure, was a result of the nose wheel being unable to gain sufficient force against the contaminated surface to counteract the moment which arose when the right engine – for a duration of approximately 1.5 seconds – supplied full thrust at the same time as the left engine rapidly lost thrust. The highest speed registered during the sequence was 59 knots (110 km/h).

Despite the co-pilot's reactions – retarding the thrust levers after just over a second, at the same time as steering and opposite rudder were applied – the veer could not be corrected and the aircraft ran off the runway, mainly caused by the forces from the moment in combination with the slippery surface. The chances of stopping the continued veer were probably reduced by the fact that the pilots did not apply any differential braking in the opposite direction.

The investigation also showed that the pilots' braking was unintentionally asymmetrical, with a higher brake pressure on the "wrong side", i.e., in the direction in which the aircraft ran off the runway. Even if this fact may have affected the aircraft's movement pattern, such an impact has, however, not been possible to determine with any reasonable degree of certainty. It is, nevertheless, noteworthy that analyzed data from the FDR show that the recorded brake angles (asymmetric braking) were not accompanied or followed by any corresponding change in the rate of heading change.

There are no specific certification requirements for aircraft design organization to show that the aircraft is manoeuvrable in the event of a sudden loss of engine thrust during the initial stage of the take-off sequence. There are also no mandatory requirements for training regarding how to handle sudden losses of engine thrust during the initial stage of the take-off sequence for pilots in training or recurrent training for this class of aircraft.

Technical

Following the event, the engine was sent for examination to Lufthansa Technik (LHT) in Hamburg on behalf of SHK. Following a completed damage analysis, LHT provided a report on the examination. In addition to an analysis of the sequence and the damage, the report also contained an opinion on the probable cause of the engine failure.

According to LHT, it is likely that the diffuser aft air seal had come loose due to micro cracks in the nine attachment lugs that hold the seal against the diffuser.

Neither General Electric Aircraft Engines (GE) nor SHK were in agreement with the LHT's assessment of the recovered hardware for which reason the decision was made for further analysis of the recovered parts of the failed engine at the Volvo Aero Corporation metallurgical labs.

The analysis carried out by Volvo Aero Corporation indicated that the engine failure that occurred – and which was the primary reason for the incident – had probably been caused by fatigue damage in a different part of the diffuser aft air seal.

The engine failure started once the aft air seal separated from the diffuser assembly. Seal fragments began increasing the amount of debris when seal material fractured a six bolt section of the stage 1 HPT[5] blade retainer,
liberating pieces of bolt threads, nuts and retainer material. This debris quickly got into the engine gaspath resulting in downstream damage from the HPT Rotor aft causing an engine stall.

The engine stall is clearly visible in the films taken by onlookers from the station building. As the liberated debris travelled aft down the engine's gaspath, low pressure turbine blades were being broken / separated. With the amount of LPT[6] blade damage, fan speed (N1) began to decrease since the LPT didn't have enough blade airfoils to drive the fan.

The overall assessment of the investigation results suggests that the fatigue had started in the repaired seam at the diffuser aft air seal teeth. All documented cases of CF6-80C2 diffuser aft air seal failures have been seals that had been previously repaired.

The incident that occurred was caused by the following factors:

Operational

- Deficiencies in the certification process for large aircraft with wing-mounted engines with regard to requirements for yaw stability in the event of sudden loss of engine power in the speed range below V_{MCG}.
- Deficiencies in pilot training with regard to training for sudden losses of engine thrust in the speed range below V_{MCG}.

Technical

- Deficiencies in the approval and follow-up of the Dabbler TIG Weld repair on the engine's diffuser aft air seal.

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[5] HPT - High Pressure Turbine.

[6] LPT - Low Pressure Turbine.

Recommendations

ICAO is recommended to:

- Take measures in order for authorities that issue certification directives – the FAA and EASA – to adopt the safety requirements issued by ICAO in Annex 8 concerning safety in large aircraft, so that these are applied during the entire take-off sequence of a flight. *(RL 2012: 21 R1).*

The FAA is recommended to:

- Investigate, in consultation with EASA, the prerequisites for introducing requirements concerning yaw stability in large aircraft in the event of sudden loss of engine thrust below V_{MCG} under the anticipated operating conditions. *(RL 2012: 21 R2).*
- Review and revise processes and permissions issued for the Dabber TIG Weld repair method regarding concerned parts in engines that have FAA type certification. *(RL 2012: 21 R3).*
- Improve processes to expedite safety of flight considerations in granting export licenses and waivers so that political sanctions do not unnecessarily delay civil aviation safety investigations concerning aircraft – or parts thereof – which are manufactured in the USA. *(RL 2012: 21 R4).*

EASA is recommended to:

- Investigate, in consultation with the FAA, the prerequisites for introducing requirements concerning yaw stability in large aircraft in the event of sudden loss of engine thrust below V_{MCG} under the anticipated operating conditions. *(RL 2012: 21 R5).*
- Ensure that initial and recurrent pilot training includes mandatory rejected takeoff exercises that cover events of a sudden loss of engine thrust below V_{MCG}. *(RL 2012: 21 R6).*

General observations

The Swedish Accident Investigation Authority (Statens haverikommission – SHK) is a state authority with the task of investigating accidents and incidents with the aim of improving safety. SHK accident investigations are intended to clarify, as far as possible, the sequence of events and their causes, as well as damages and other consequences. The results of an investigation shall provide the basis for decisions aiming at preventing a similar event from occurring again, or limiting the effects of such an event. The investigation shall also provide a basis for assessment of the performance of rescue services and, when appropriate, for improvements to these rescue services.

SHK accident investigations thus aim at answering three questions: What happened? Why did it happen? How can a similar event be avoided in the future?

SHK does not have any supervisory role and its investigations do not deal with issues of guilt, blame or liability for damages. Therefore, accidents and incidents are neither investigated nor described in the report from any such perspective. These issues are, when appropriate, dealt with by judicial authorities or e.g. by insurance companies. The task of SHK also does not include investigating how persons affected by an accident or incident have been cared for by hospital services, once an emergency operation has been concluded. Measures in support of such individuals by the social services, for example in the form of post crisis management, also are not the subject of the investigation.

Investigations of aviation incidents are governed mainly by Regulation (EU) No 996/2010 on the investigation and prevention of accidents and incidents in civil aviation. The investigation is carried out in accordance with Annex 13 of the Chicago Convention.

The investigation

On 16 January 2010, SHK was informed that a serious incident involving an aircraft with the registration EP-IBB had occurred at Stockholm/Arlanda Airport, Stockholm county, at 12:38 hrs on the same day.

The incident has been investigated by SHK, represented by the following investigators:

- Ms Åsa Kastman Heuman, Chairperson until 1 December 2010,
- Mr Göran Rosvall, Chairperson from 2 December 2010 to 25 January 2012,
- Mr Hans Ytterberg, Chairperson from 26 January 2012,
- Mr Jonas Bäckstrand, Deputy Chairperson from 6 February 2012,
- Mr Stefan Chistensen, Investigator in Charge,
- Mr Roland Karlsson, Operational Investigator until 31 December 2010,
- Mr Nicolas Seger, Operational Investigator from 1 January 2011,
- Mr Henrik Elinder, Technical Investigator until 31 December 2010,
- Mr Staffan Jönsson, Technical Investigator from 1 October 2010,
- Mr Kristoffer Danél, Technical Investigator from 1 January 2011,
- Mr Urban Kjellberg, Investigator on Fire and Rescue Services.

SHK was assisted by KTH/Proffessor Ulf Ringertz on aero-mechanical matters, and Mr Christer Magnusson on CVR/FDR[7] analyses.

The investigation has been followed by Ms Britt-Marie Kärlin until 15 August 2010, and Mr Ola Johansson thereafter, of the Swedish Transport Agency.

Accredited representatives: from Iran's aviation authority Mr Mehdi Aliasgari, from the accident investigation authorities BFU (Germany) Mr Thomas Karge, BEA (France) Mr Gérard Legauffre, NTSB (USA) Mr Jean-Pierre Scarfo and from AAIB (UK) Mr Adrian Burrows and Mr Richard James.

The report on this serious incident deals with in principle two separate events, where the second event is a consequence of the first. The first event is the engine failure in the left engine during the take-off sequence and the second event is the course deviation upon the engine failure, causing the aircraft to run off the runway.

The report will therefore include separate cause analyses of both events in this serious incident.

The investigation process

A meeting was held in Stockholm on 7 June 2011 of around 30 invited parties with an interest in the incident that had occurred. At the meeting, SHK presented the facts available at the time.

Prior to the publication of the final report, all interested parties were offered the opportunity to comment on a draft proposal for the final report.

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[7] Cockpit Voice Recorder/Flight Data Recorder.

1 FACTUAL INFORMATION

1.1 History of the flight

1.1.1 Circumstances

The incident occurred in connection with a commercial air transport with the airline Iran Air. The aircraft in question, an Airbus A300-600 with the registration EP-IBB, had earlier the same day been operated from Tehran with flight number IRA 763 and destination Stockholm/Arlanda.

After a short ground stop in Stockholm, EP-IBB was planned to return to Tehran as flight number IRA 762. At the time of the incident there were 149 passengers and 23 crew members onboard the aircraft.

1.1.2 Flight preparations

The airline operates the route between Tehran and Stockholm with a double augmented cockpit crew, meaning that one crew flies the first sector and is then replaced by the second crew which flies the next sector.

The flight is normally planned by the company's flight operations department in Tehran, which sends operational data to the handling agent at the relevant airport. Any corrections or changes are made by the crew going on duty prior to departure. In connection with this, the crew also receives current Notam[8] and weather information for the route as well as for destination and alternate airports.

At the time of the incident, the company had a local office in Stockholm and a representative at Arlanda. The representative at the airport has roles including coordinator between the company and the other service providers contracted for operations.

The checking in of passengers and luggage and ramp services such as loading and unloading were carried out by the ground handling company Menzies at Arlanda. The aforementioned operational service was attended to by the ground handling company, which also performed calculations of the load sheet and loading instructions.

Runway 08 was in use for take-off on the day in question. For performance purposes, however, the pilots requested clearance to use runway 19R since this runway offers a longer available distance for take-off. No other aircraft had used this runway for take-off previously that day.

Performance calculations and other operational calculations were performed by the pilots prior to departure. The aircraft's take-off mass on departure had been calculated at 148.4 tonnes, and due to the prevailing conditions on the runway, it was decided that the maximum take-off thrust of the engines (TOGA[9]) would be used at take-off.

1.1.3 Taxiing out

The runway which came to be used was 19R, meaning take-off in a southerly direction on Arlanda's main runway with an available runway length of 3,300 me-

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[8] Notam - Notices to Airmen. Short-term aeronautical information.

[9] TOGA - Take Off Go Around (Thrust).

tres. IRA 762 was cleared to taxi to holding point runway 19R. It had been agreed that the co-pilot would be the "Pilot Flying" (PF) and fly the forthcoming sector to Tehran.

The Airbus A300 can be manoeuvred by both pilots during taxiing, which meant that the co-pilot was in control of the aircraft throughout the course of taxiing from the gate until take-off was aborted. The prevailing weather conditions at the airport indicated that friction on aprons and taxiways were reduced. According to the automatic terminal information service, ATIS[10], the braking action was "poor" on aprons and taxiways and "good" on runway 19R where the take-off was to occur.

The taxiing commenced in accordance with standard procedures after the push-back from gate 18 and along taxiway Y. While taxiing out, according to the tape recording from the cockpit, the commander is heard drawing the co-pilot's attention to the slippery conditions (*"Pay attention, it is a little slippery"*).

Fig. 1. Arlanda Airport. Source: Google Earth.

The pilots had decided to execute a rolling take-off, i.e., the aircraft would not be stopped once it had been taxied out to the take-off position at the runway end, but take-off thrust would be applied to the engines while rolling. Before the take-off, flaps and slats 15°/15° had been selected by the pilots. When IRA 762 approached the take-off position at the runway end, take-off clearance was received from the tower.

As the aircraft was in the final left turn at the runway end, the commander indicated that the co-pilot should not initiate the take-off sequence before they had lined up on the runway. Otherwise the aircraft could skid off the runway. (*"Don't start rolling from here. You must first line up before you go, otherwise you may skid off the runway."*).

1.1.4 *The take-off*

IRA 762 was taxied out towards the take-off position at the same time as the pilots carried out the final checks in accordance with the before take-off checklist. At 12.38:10 hrs, take-off thrust was applied (the autothrottle was activated) for take-off and the aircraft began to roll along the runway. Approximately 11 seconds later, a muffled bang was heard from the left side of the aircraft. The pilots retarded both

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[10] ATIS - Automatic Terminal Information Service.

thrust levers just over one second after the bang at the same time as the aircraft had begun to veer to the left.

Fig. 2. Image from video. Photo: Saeid Cedighi Chafjiri.

The speed when the engine failure occurred was approximately 54 knots, but the aircraft continued to accelerate to approximately 59 knots (110 km/h). The incident occurred after rolling approximately 250 metres along the runway. The image in Figure 2 above has been obtained from a private video taken from the viewing terrace at Arlanda Airport during the sequence of events. The engine failure started with a puff of smoke and was quickly followed by three flames of varying size within the space of 0.77 seconds.

The pilots were unable to correct the veer that had arisen and the aircraft ran off the runway approximately 400 metres from the runway 19R threshold. The time from the bang until the aircraft ran off the runway, 12.38.29, was just over 7 seconds. The nose wheel dug into the ground and the aircraft came to a stop after a severe retardation. The distance which the aircraft rolled on the ground outside the runway was approximately 200 metres, and the final stop was approximately 40 metres from the edge of the runway.

The airport rescue services were activated, but could later be recalled as no fire – or risk of fire – had been detected and it was deemed that no other interventions were necessary. Upon investigation of the accident site, a large number of small metal parts were found in the exhaust section of the left engine and on the ground behind the aircraft. The damage to the aircraft – apart from the left engine – were limited to the landing gear and light fittings.

The passengers left the aircraft in the normal manner via external stairs which had been brought to the incident site by the airport staff. No injuries to persons occurred during the incident.

The incident occurred at the location: 59° 39.7' N, 017° 55.4 E, 17m above sea level.

1.1.5 Interview with the commander

The information from the commander is based partly on an interview in connection with the incident and partly on the supplementary written answers submitted to SHK on a later occasion. The commander stated that the flight preparations followed the company's standard procedures and that the crew did not perceive that any difficulties or deviations affected the flight planning.

The taxiing out for take-off took place with the co-pilot at the controls, and the commander recalled pointing out the slippery conditions that prevailed (on aprons and taxiways, SHK's note) and thereby instructed his colleague to taxi slowly. When the aircraft lined up on the runway, the commander assessed the braking action to be medium (medium braking action). The take-off took place rolling, with the co-pilot as PF, and was according to the commander executed in accordance with the operator's established procedures. The commander stated that the centre of the runway seemed to be free from contamination/covering, but that there was visible contamination further out from the centre of the runway.

The first stage of the take-off sequence was normal, with a synchronous acceleration rate of the engines. When the engine power had reached the set values (approximately 103%), a muffled bang was heard. According to the commander, the aircraft began to veer to the left, more or less immediately after the bang. Neither of the pilots had at this stage understood what had happened, but thought that the aircraft had collided with something or that a tyre explosion had occurred.

Fig. 3. The aircraft after the excursion. Photo: Swedavia.

According to the commander, it was the co-pilot who aborted the take-off sequence by retarding both thrust levers. In the interview, the commander explains that he then immediately took over the controls and simultaneously applied full right rudder and activated the brakes. He had no recollection of whether or not full brake pressure had been applied, but maintained that the pilot seat and pedal set were set so that simultaneous application of full rudder and maximum brake pressure were possible.

The take-off was aborted without any commands or instructions being articulated by the commander. No warning signals were announced – or heard – via the aircraft's warning system ECAM in connection with the bang and the subsequent veer (see 1.6b.5). According to the commander, the first warning that was announced came around the time that the aircraft passed the edge of the runway and out onto the snow-covered grass area.

According to the commander, the nose wheel steering via the steering wheel was activated more or less immediately when the aircraft began to veer to the left, but the sequence could not be corrected and the aircraft ran off the runway. The commander has not provided any explanation as to why thrust reversal of the engines was not used during the sequence of events. He also stated that the contamination on the runway had contributed to the fact that the aircraft could not be controlled. When the aircraft veered, he was also aware that the nose wheel was "skidding".

The commander also considered the cooperation in the cockpit to be satisfactory during the incident sequence and that the co-pilot's action to himself abort the take-off had been instinctive. In addition, the commander had no experience of training for engine loss in these speed ranges and also pointed out that this could not be found in Airbus manuals. He also considered the checklists and procedures used during – and after – the incident to have been sufficient.

When the aircraft had come to a final stop, the commander made the decision not to initiate an emergency evacuation after the excursion. The decision was based on the fact that no fire was indicated in the cockpit and that air traffic control reported that no fire was visible from the tower. Nor was there any reason in this situation, according to the commander, to perform all the measures on the "on ground emergency" checklist.

1.1.6 Interview with the co-pilot

The information from the co-pilot is based partly on interviews on the occasion of the incident and partly on a filmed interview on a later occasion in the cockpit of the very same aircraft. The co-pilot's statement concerning the initial stage of the take-off sequence is essentially consistent with the commander's statement. The normal take-off sequence was commenced and the co-pilot – who was PF – pushed forward the thrust levers to approximately 40%. When the engine values were stabilized, the autothrottle system was activated and the thrust was increased towards the set TOGA value. The co-pilot remembers waiting for the confirmation "thrust set" from the commander (also announced in blue on the PFD[11]) when the incident occurred.

The co-pilot remembers the commander reporting "thrust set" at an N1[12] just below the set TOGA value, after which the engine failure occurred. When the crew heard the bang, the co-pilot still had his hand on the thrust lever controls. As there was no reaction – or any command – from the commander, and as the aircraft was perceived to begin to veer to the left immediately, the co-pilot retarded both thrust levers to the ground idle position. At the same time he applied full rudder in the opposite direction (right) and initiated braking.

According to the co-pilot, the commander reacted when the initial measures had been performed and took over the manoeuvring of the aircraft. The co-pilot remembered removing his hand from the thrust levers when he had retarded and saw that the commander took over. He had no recollection of having used the steering

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[11] PFD - Primary Flight Display (Central display showing flight status and system information).

[12] N1- rpm of the engine's fan.

wheel for the nose wheel steering, but noted that he had seen the commander's hand on the steering wheel during parts of the sequence of events. However, it was unclear to him when the commander activated the nose wheel steering.

During the first seconds of the sequence, the co-pilot noticed that no messages were announced on the screen where warnings are announced (ECAM). The first ECAM message – which was accompanied by an audio signal – came a number of seconds later when "*Eng no 1 shut down*" was announced on the screen. He also recollected that further warnings were displayed on the screen, but could not say what these were.

After the aircraft had come to a stop, the co-pilot assisted the commander with checklists and other measures. He also confirmed that neither of the pilots was entirely sure of what had happened and that they thought that a tyre explosion (or something similar) had occurred.

1.1.7 Graphical overview of the sequence of events

Description of the presentation of FDR data[13].

A software tool has been developed in Matlab®. The software tool facilitates the reading and presentation of FDR data, among other data types. The intention has been to present the sequence of events and the registered data in a graphical environment. A number of axes in a graphic user interface can be chosen to present selected data. In this case, the trajectory of the aircraft's movement at ground level is presented.

The trajectory has been integrated from the speed over the ground (GS - Ground Speed) registered by the FDR and the Magnetic Heading. Also presented among other things are the heading and heading display instruments, the engines' rpm, pedal position for right and left brake pedals, and rudder position. Graphs of the selected variables are displayed as a function of UTC time. See Figs. 4 - 7.

The cycle time for the FDR in question is 1/64 s. The parameters saved on the FDR are registered with different cycle times depending on which unit they come from. This means that data from different units will be mutually asynchronous. In order to obtain a time synchronous depiction of data, piecewise cubic polynomials (splines) have been adapted to FDR data, (ref. de Boor, C., *A Practical Guide to Splines*, Springer-Verlag, 1978).

An adaptation of this nature provides a reasonable picture of the behaviour of a sluggish analogue system and takes into account trends in the data. From these splines, data points have been produced for each cycle for which the FDR registers data, in order to obtain time synchronous data.

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[13] Information from the aircraft's Flight Data Recorder.

The graphs and data presented in figs. 4 – 7 are based on the retrieved FDR data.

+ BRKPDL [°]	Left brake pedal position.
○ BRKPDR [°]	Right brake pedal position.
✱ GS [KT]	Ground Speed.
× MHDG [°]	Magnetic Heading.
□ N1A1 [%]	Rpm fan 1 engine 1 actual value.
● N1A2 [%]	Rpm fan 1 engine 2 actual value
△ N1C1 [%]	Rpm fan 1 engine 1 reference value.
▽ N1C2 [%]	Rpm fan 1 engine 2 reference value.
▷ RUDD [°]	Rudder angle.
◁ EGT1G [DC]	Initial low pressure turbine temperature, engine 1
★ EGT2G [DC]	Initial low pressure turbine temperature, engine 2

Fig. 3. Legend describing the graphs in Figs. 4-7.

The presentation, integrated with the video taken from the terminal building, can be downloaded at http://www.havkom.se

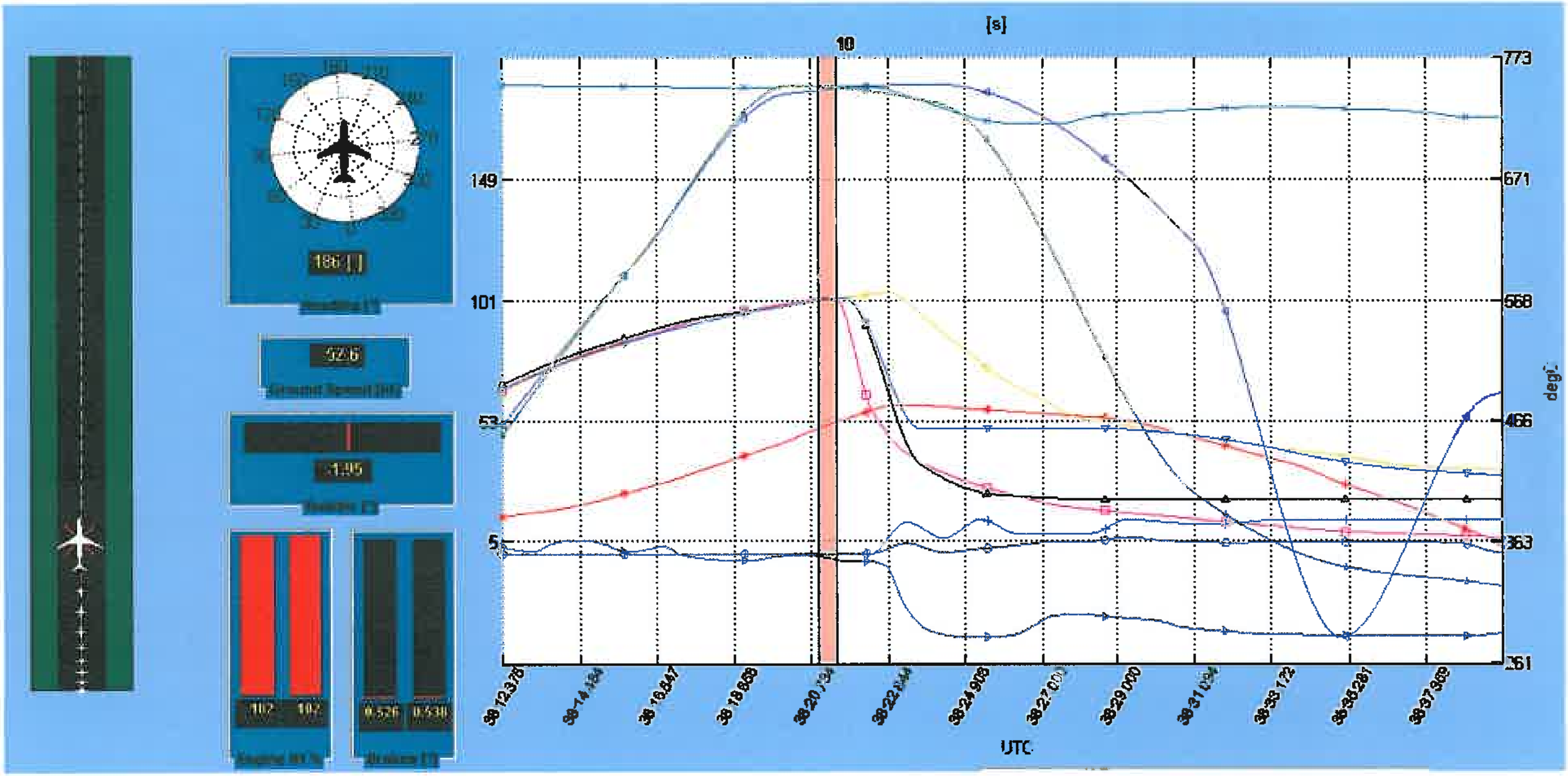

Fig. 4. Point of time for loss of engine power. Based on FDR data.

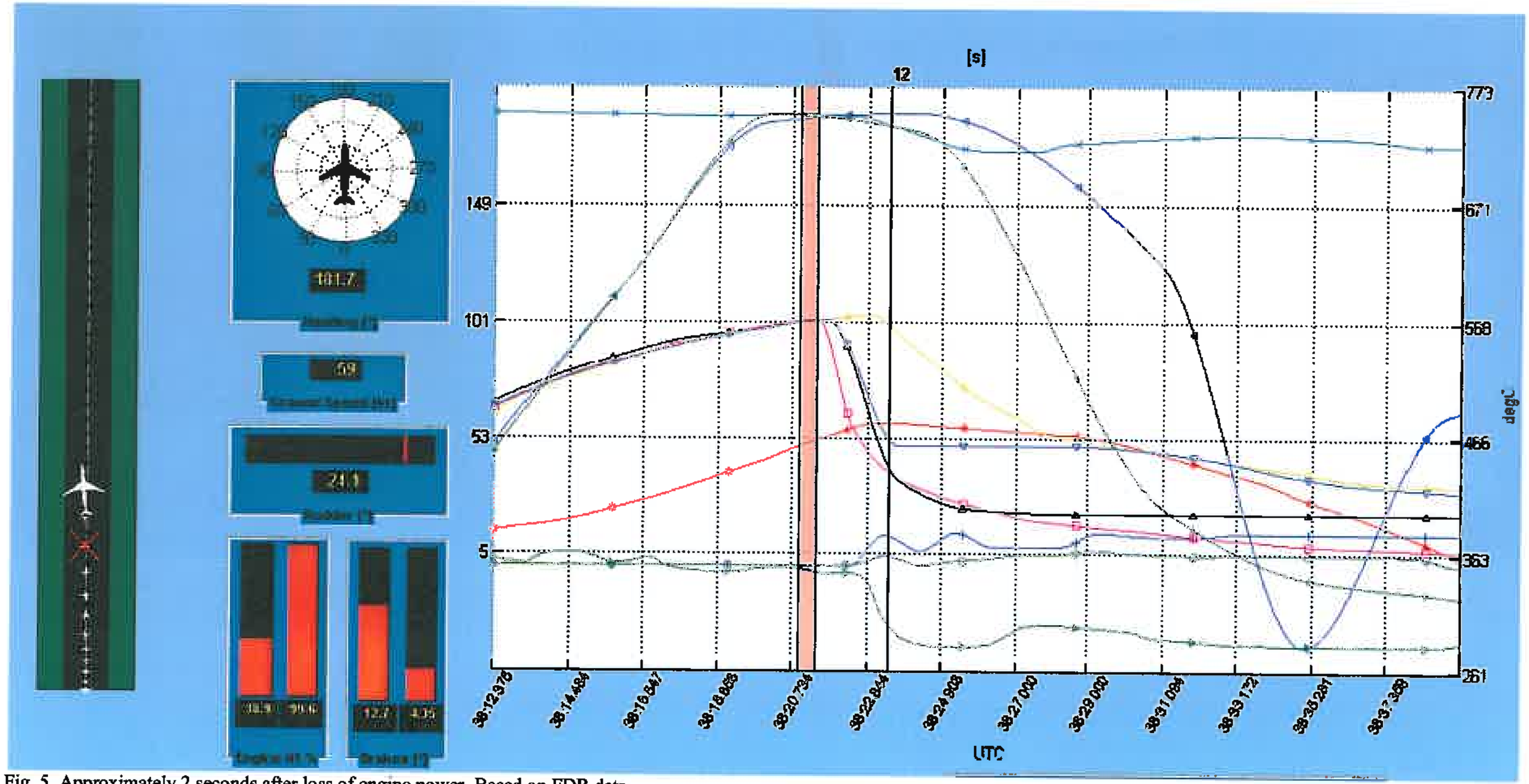

Fig. 5. Approximately 2 seconds after loss of engine power. Based on FDR data.

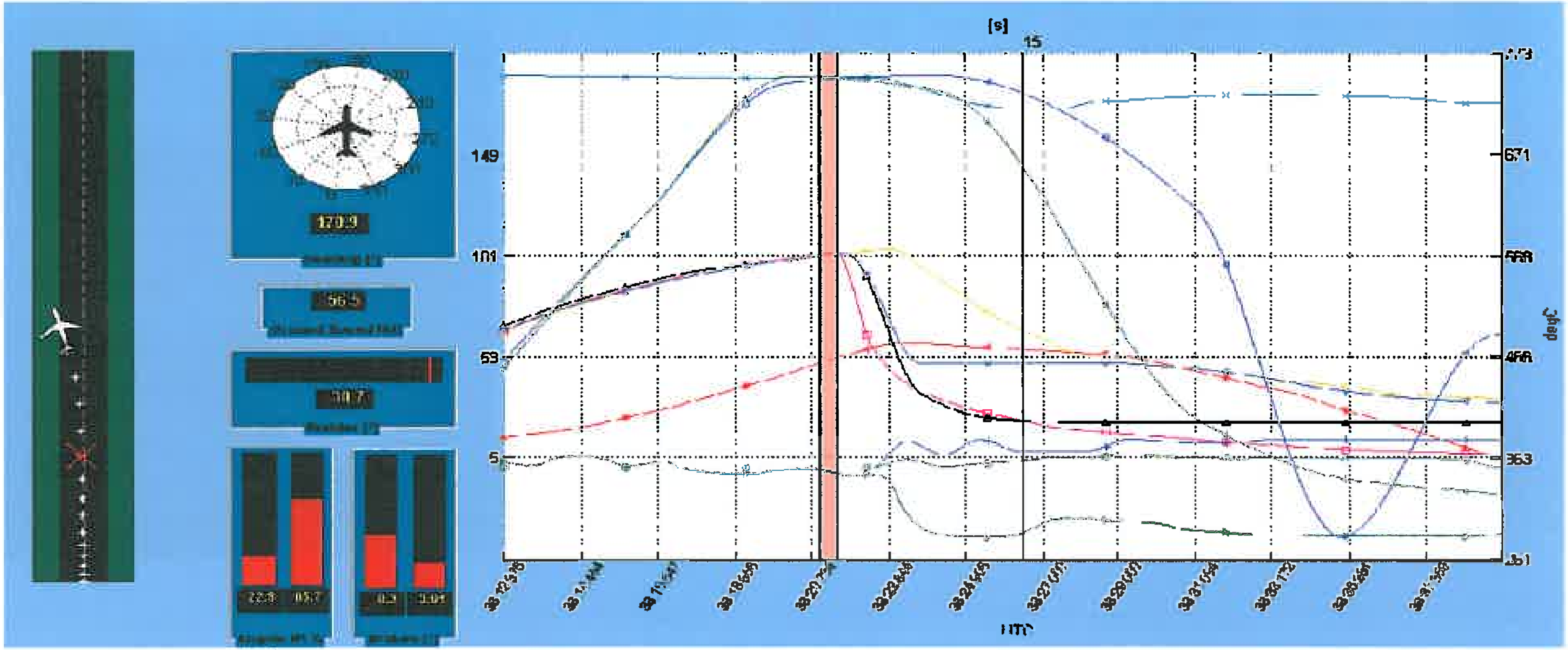

Fig. 6. Approximately 5 seconds after loss of engine power. Based on FDR data.

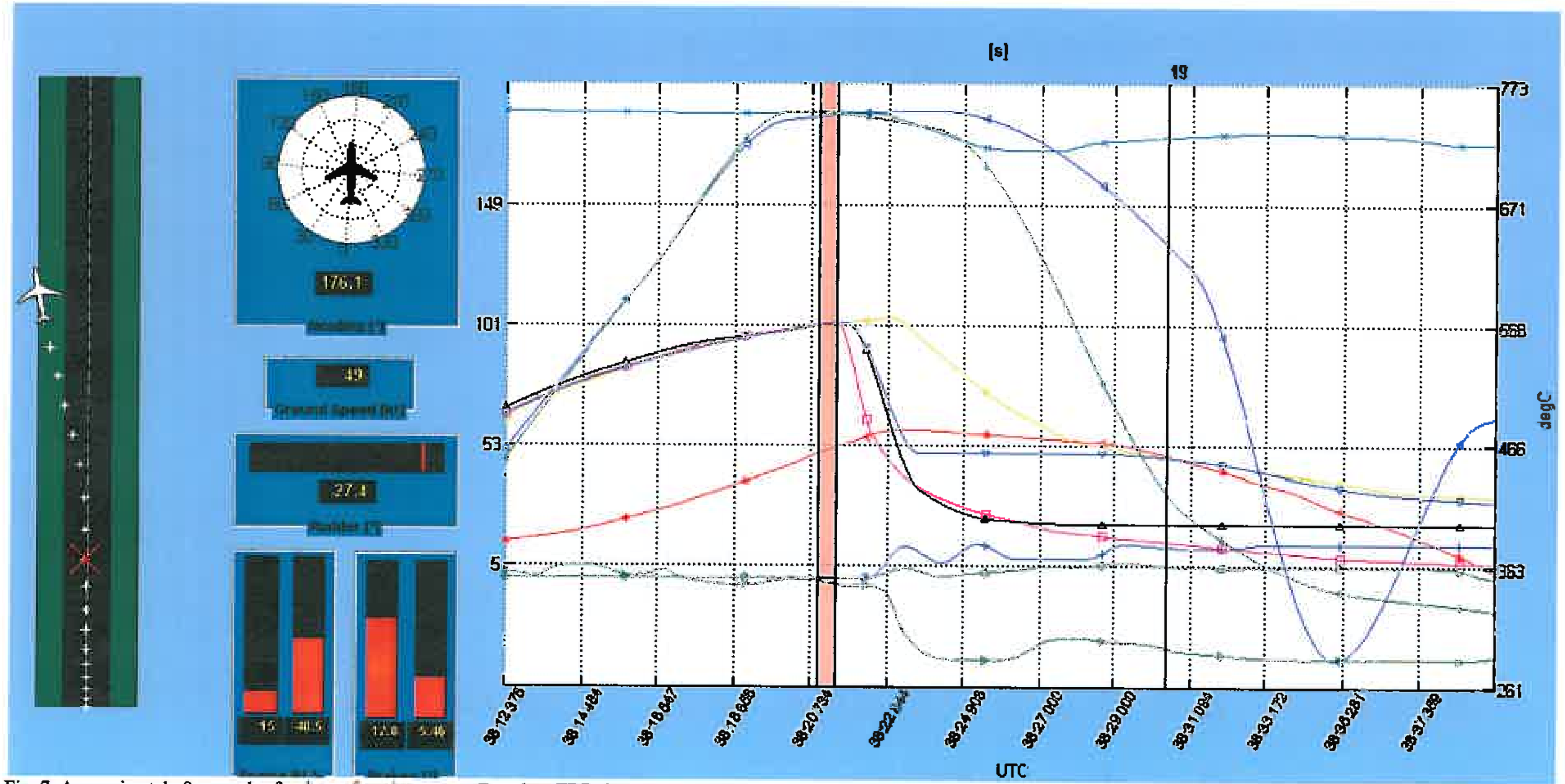

Fig. 7. Approximately 8 seconds after loss of engine power. Based on FDR data

1.2 Injuries to persons

	Crew members	Passengers	Others	Total
Fatal	–	–	–	–
Serious	–	–	–	–
Minor	–	–	–	–
None	23	149	–	172
Total	23	149	–	172

1.3 Damage to the aircraft

Limited.

1.4 Other damage

Minor damage to the ground surface beside the runway.

1.5 Personnel information

1.5.1 Commander

The commander was 59 years old at the time and had a valid ATPL.

Flying hours			
Last	24 hours	90 days	Total
All types	0	100	22,300
This type	0	100	10,230

Number of landings this type last 90 days: 30.
Type rating concluded on 23 September 1995.
Latest PC (proficiency check) carried out on 13 January 2010 on A300.

1.5.2 Co-pilot

Co-pilot was 29 years old at the time and had a valid CPL.

Flying hours			
Last	24 hours	90 days	Total
All types	0	141	5,067
This type	0	141	1,693

Number of landings this type last 90 days: 21.
Type rating concluded on 12 March 2007.
Latest PC (proficiency check) carried out on 5 July 2009 on A300.

1.5.3 The pilots' duty schedule

The planned aircraft rotation on the day in question was constituted by the flight Tehran – Stockholm – Tehran with the flights IRA 763 and IRA 762. The departure time from Tehran was 08:00 hrs LT[14], with a check-in time of 06:30 hrs established by the operator. Arrival to Tehran was 20:45 hrs LT according to the schedule, with 21:15 hrs LT as the planned check-out time. The rotation involves a planned duty time of 14 hours and 45 minutes. On the basis of this long duty time, the operator had augmented the cockpit crew with two additional pilots (double augmented crew).

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[14] Local time.

According to international flight duty time limitations, the flight time/duty time may in such a case be extended to 18 and 24 hours, respectively.

The intention was for the first two pilots to fly the first sector to Stockholm and the second flight crew to fly the concluding return sector to Tehran.

1.5.4 Cabin crew members

The crew on the aircraft consisted of 23 persons, of which four were cockpit crew (see 1.5.3), 15 cabin crew as well as an additional four persons, designated by the company as security staff (Flight Security Officers).

Individual cabin crew members were interviewed by SHK in connection with the incident. No panic or other problems had arisen among the 149 passengers during the incident. The evacuation had taken place in a calm and organized manner via the external stairs which had been brought out to the aircraft by airport staff.

One cabin crew member had heard the "bang" and thereafter observed smoke from the left engine. No views were expressed on the commander's information to the passengers after the incident. The cabin crew members who were interviewed had no critical views – or differing opinions on the handling of the situation – concerning the communication between cabin and cockpit after the incident.

1.6a Aircraft information – general

1.6a.1 General

Aircraft		
TC-holder	Airbus	
Type	A300 Model B4-605 ER	
Serial number	727	
Year of manufacture	1994	
Gross mass	Max authorized take-off/landing mass 170,500/140,000 kg, actual 148,375 kg	
Centre of gravity	CG/I 26.3%	
Total flying time	36,565 hrs	
Number of cycles	9,568	
Flying time since latest inspection	197 hrs (A-check)	
Fuel loaded before event	JET A1	
Engine		
TC-holder	General Electric	
Model	CF6-80C2A5F	
Number of engines	2	
Engine	*No 1*	*No 2*
S/N	705207	705205
Total operating time, hrs	32,684	20,480
Operating time since overhaul	5,998	7,120
Cycles after overhaul	1,491	1,829

The aircraft type is a twin-engine jet aircraft with a capacity of approximately 300 passengers.

The aircraft had a Certificate of Airworthiness and a valid Airworthiness Review Certificate.

1.6b Aircraft information - operational

1.6b.1 Operational documentation

The pilots' general documentation consisted of manuals from Jeppesen relating to route and airport information adapted to the company's route network.
The aircraft-specific operational documentation for the aircraft which SHK retrieved consisted of FCOM[15], divided into two volumes, and QRH[16].

Volume one contained a description of the aircraft and its systems and part two information on operational handling, performance conditions and loading instructions. QRH contained information which supplemented the electronic warning system ECAM which is described in a later section of this report.

It can also be mentioned that regardless of warnings on screens and/or in QRH, the type certificate holder (TC) has left an opening for alternative actions in emergency situations when there is a lack of time for additional support. Below is an excerpt from the QRH valid at the time in FCOM2:

"Referring to the FCOM1 and/or FCOM2 is not required for the short term handling of any emergency procedure but may be considered when convenient if so desired".

1.6b.2 Standard procedures for take-off up to V_1[17] according to FCOM

The text in 1.16b.2 and 1.16b.3 refers to Iranair FCOM, which, according to the operator is identical to the FCOM issued by the TC holder.

Take-off is normally executed with PMC[18] and A/THR[19] engaged. Two types of take-off procedure can be applied; "static" take-off, meaning that the aircraft is held on the brakes until 40 % N1 is reached, or a rolling take-off, where the engine thrust is applied while rolling. The commander decides whether a rolling take-off is to be performed. Irrespective of which method of take-off is used, "TAKEOFF" shall be called out at the same time as the clock is started. If a static take-off has been used, the brakes are released at this moment.

The desired engine thrust is selected with consideration of the current mass and prevailing external conditions. If reduced engine thrust – FLEX – is to be used, this value is set and the thrust levers are pushed forward to this position during take-off, whereby the selected thrust is obtained automatically. If maximum take-off thrust – TOGA – is to be used, the thrust levers are instead set to this position.

The pilot flying (PF) increases the engine thrust to approximately 40% N1, checks that the engines are accelerating symmetrically and then sets the thrust levers to the take-off position.

CM1 (Crew Member 1, the pilot in the left seat, normally the commander) is tasked with holding his/her hand over the thrust levers until V1, without interfering with the lever's movement. If the thrust levers move asymmetrically, CM1 must be prepared to adjust this or disengage A/THR.

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[15] FCOM – Flight Crew Operating Manual (flight manual).

[16] QRH – Quick Reference Handbook (emergency checklist).

[17] V_1 is the speed at which a decision must be made at the latest about whether the take-off is to be completed or aborted.

[18] PMC - Power Management Control, a system that adjusts the fuel flow when take-off thrust is applied.

[19] A/THR - Autothrottle, automatic setting of the engine thrust.

The PF pushes the control column forward to the appropriate extent until approximately 80 knots and then reverts gradually to once again reach the neutral position at 100 knots. The purpose of this is to counteract the nose-up moment caused by the engine thrust and to increase the pressure on the nose wheel against the runway.

The rudder pedals are used to maintain the heading, the instruments are checked and the PM[20] calls out "THRUST SET" in order to confirm that the take-off value for N1 is reached before 80 knots. When the decided take-off thrust is set the pilot's attention will be concentrated on the "look out" along the runway and to monitor the speed via the flight instruments.

Note

The procedure described above was valid at the time of the incident. After the incident, a revision was introduced which entailed that when CM1 is PM, he/she is to take control of the thrust levers when CM2 has activated the take-off procedure and set the thrust levers in the selected take-off position – which in the present case was TOGA.

1.6b.3 Published procedures upon of loss of engine thrust at low speeds according to FCOM

According to the normal procedures, the commander shall always be the one to make the decision to abort or continue a take-off. It is therefore recommended that the commander keeps a hand on the thrust levers until the speed V_1, regardless of which of the pilots executes the take-off.

The measures which, in accordance with the manuals used, shall follow a decision to abort a take-off (at speeds below 100 knots) can be summarized according to the following:

Commander

- Calls out "STOP" and takes over the controls as well as initiates measures according to the items:
- Brakes manually (at speeds below 85 knots).
- Retards engine thrust to ground idle and disengages A/THR.
- Reverses the engines' thrust.

Co-pilot

- Monitors the braking.
- Monitors the thrust reversal.
- Acknowledges any audio warnings.

However, another paragraph in the same manual states that at speeds below 100 knots, the above-mentioned general instructions that the commander *shall* always make the decision to abort a take-off have been modified so that the commander *should* make the decision in this speed range.

In the present case, the co-pilot was PF and – in the absence of commands and/or interventions from the commander – himself made the decision to abort the take-off.

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[20] PM - Pilot Monitoring (the pilot who assists the PF)

1.6b.4 Steering on the ground and during take-off

It is the operator's normal procedure that the pilot who is to be PF also manoeuvres the aircraft on the ground during taxiing[21] and take-off acceleration. The PF can either be the pilot in the left seat or the pilot in the right seat, depending on what has been agreed by the crew prior to take-off. During taxiing, the aircraft is mainly manoeuvred with the use of the nose wheel steering via a tiller on the side panels at the respective pilot's seat.

The nose wheel can be steered in two ways: by means of steering wheels (tillers) on the pilots' respective side consoles and with the use of the rudder pedals. The nose wheel can be turned ± 65° by means of the steering wheels and ± 6° by means of the pedals.

Where required, differentiated braking or engine thrust can be used to reduce the turn radius during taxiing. During take-off, only the rudder pedals shall be used to control the heading of the aircraft.

1.6b.5 Warning system

The aircraft is equipped with a central monitoring system, ECAM[22], which in various ways attracts the crew's attention by means of audio and light warnings. When the system has detected a fault, three different types of signals are generated simultaneously:

	Type of warning	**Where**
1	**Audio signal:** CRC[23], continuously repeated audio signal for emergency faults SC[24] single audio signal for other faults	Speaker in cockpit Speaker in cockpit
2	**CRT[25] information:** List of necessary measures System presentation	Left ECAM CRT Right ECAM CRT
3	**Visual warnings:**	Primary warning light (Master Warning – red) Secondary warning light (Master Caution – amber)

Fig. 8. Warning system.

The warning system is intended to draw the pilots' attention to malfunctions and/or deviations from normal values in the aircraft's various systems. Some of the warning messages announced via ECAM require follow-up and measures by means of the emergency checklist in the QRH.

1.6b.6 Secondary warnings activated by loss of engine thrust

During the incident, 7 single audio signals (SC) for secondary warnings were registered. No emergency fault warnings (CRC) were registered during the incident. It cannot be established which warnings were announced because only the existence of announced messages are found on the parameter list on the aircraft's FDR, not their origin.

During certain predetermined critical flight phases, certain parts of the warning system are supressed. In the present incident, the loss of engine thrust occurred at a speed of ap-

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[21] Taxiing - All manoeuvring on the ground other than the take-off and landing sequences.

[22] ECAM - Electronic Centralized Aircraft Monitor – Viewing screen for electronic central monitoring of aircraft systems.

[23] CRC – Continuous Repetitive Chime – A continuous, repeated signal.

[24] SC – Single Chime – A single signal.

[25] CRT – Cathode Ray Tube – An electronic viewing screen in the cockpit.

proximately 54 knots. In this flight phase, the following engine-related secondary warnings were possible:

- Loss of engine thrust (ENG FAIL)
- Engine shut down (ENG SHUT DOWN)
- Generator failure
- Low oil pressure
- Overspeed
- Overtemperature (EGT[26])

During the interviews, the co-pilot has stated that "ENGINE (1) SHUT DOWN" has been announced on ECAM at a late stage in the sequence of events. According to information from the type certificate holder, this warning is announced when the fuel supply is activated (fuel condition lever ON), and when engine speed and oil pressure simultaneously drop below predetermined values. The warning can also be activated by a detected air pressure fault in the compressor section of the engine.

1.6b.7 Operations on contaminated runways – type certificate holder

Winter operations with aircraft are largely associated with contaminated surfaces. Operational limitations most often arise as a consequence of the relationships between current mass, runway length and crosswind during variable runway conditions, where the aircraft's steering and braking capabilities are largely dependent on the prevailing friction coefficient and any contamination on the runway.

The TC carries out tests in connection with the certification of the aircraft, which then constitute the basis for the operators' performance data. The tests are limited to dry and wet runway conditions. As an information basis for the operators, the type certificate holder Airbus has also published (non-certified) recommendations concerning conditions and definitions for operations on contaminated runways.

These recommendations do not contain any limitations regarding a minimum friction coefficient for take-off. There is however a recommendation that take-off should not take place on "icy runways", which are defined as surfaces with a friction coefficient of 0.05 and below (see 1.16a.10).

1.6b.8 Operations on contaminated runways - operator

With the certified data as a basis, the operator develops performance tables for maximum permitted aircraft mass for take-off and landing with different friction coefficients and contamination types, as well as the maximum permitted crosswind component in relation to the friction coefficient. Normally, the operator also states the lowest permitted friction coefficient for operations with the aircraft type in question.

The operator in the present case, Iran Air, follows the operational recommendations issued by the TC concerning operations on contaminated runways. With regard to friction coefficients, the operator's operations manual, OM, states that take-off (and landing) may not be performed if the friction coefficient is below 0.30.

1.6c Aircraft information - technical

1.6c.1 Engine type

The engine type is a two-spool axial-flow turbofan engine with a high bypass ratio[27], certified in 1993. The engine of model CF6-80C2A5F is intended for Airbus A300 B4-

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[26] EGT – Exhaust Gas Temperature.

[27] Bypass flow – The ratio between the flow through the fan in relation to the engine.

605ER and is divided into five main sections; fan/low pressure compressor (Fan Section), high pressure compressor (Compressor Section), combustion chamber section (Combustion Section), turbine section (Turbine Section) and gearbox (Accessory Drive Section), see Fig. 9. Nominal rpm on the low-pressure spool is N1 = 3,320 and on the high pressure spool N2 = 10,070 rpm.

The 14-stage high pressure compressor is driven by a two-stage high pressure turbine. The integrated fan and low pressure compressor are driven by a five-stage low pressure turbine. The engine is equipped with FADEC[28] for fuel distribution control and monitoring engine parameters.

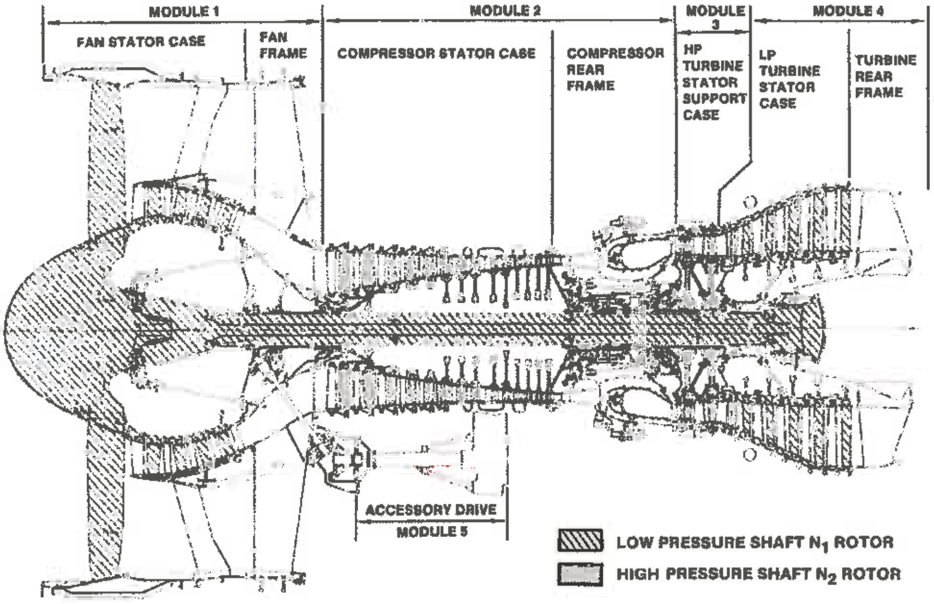

Fig. 9. Engine CF6-80C2A5F.

1.6c.2 *Thrust reversal*

The aircraft is equipped with a system for reversing the engines' thrust (Thrust Reverser System). The system is designed so that the flow of air from the fan is turned by means of doors in the rear section of the engine cowling. The thrust reversal creates a forward-directed thrust which is used for deceleration of the aircraft. The time for thrust reverser deployment and engine acceleration from take off thrust to full reverse thrust is up to five seconds.

Thrust reversal can only be used when the aircraft is on the ground and is activated by means of a control located on the thrust levers in the cockpit. According to MMEL[29], the aircraft may be operated with the thrust reversal system inoperative on one or two engines. When flying with the thrust reversal fully or partially inoperative, certain restrictions of both a technical and operational nature apply. The operational restrictions encompass performance adjustments in respect of the required runway length for take-off and landing.

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[28] FADEC – Full Authority Digital Engine Control (Unit for electronic engine control).

[29] MMEL – Master Minimum Equipment List (A list of when – and how – the aircraft can be operated when certain systems are inoperative).

1.6c.3 *Braking system*

The braking system on the aircraft consists of multi-disc brakes positioned on the eight wheels of the main landing gear. The brakes are operated by two sets of pistons which are independent of each other. One set is supplied with pressure from the green hydraulic system and the other through the yellow hydraulic system. The system is secured through two brake accumulators.

The wheel brakes are operated with toe pedals which are hinged and located above the rudder pedals. The entire pedal unit is adjustable lengthwise in order to give full displacement and is interconnected between the left and right pilot seats. When the heels are placed on the rudder pedals, the blade of the foot is used to depress the brake pedals.

There is no point on the aircraft's checklist which prescribes that the pilots shall check that full brake pedal displacement can be applied at the same time as full rudder displacement to the same side is applied. Information on this check of the pedal setting is only found in the training manual for the aircraft which not was available to the pilots at the time of the incident.

The left brake pedal for each pilot seat activates the brakes on the pair of wheels of the left main landing gear and the right pedal activates in a corresponding manner those on the right. It is therefore possible for either one of the pilots to increase the brake pressure on one side independently of the other pilot's pedal displacement. The wheel brake system can be activated when the green hydraulic system is pressurized, the anti-skid circuit breaker is on and the parking brake is disengaged.

The aircraft brakes are equipped with an anti-skid system which compares the rotation speeds of the nose wheel and main wheels. The system ensures maximum braking action through counteracting incipient wheel locking and is activated at a speed of approximately 20 knots. The aircraft is also equipped with an automatic braking system (auto brake system) which is activated if both thrust levers are retarded to ground idle when the speed passes 85 knots during the take-off acceleration. If the take off is aborted below this speed, braking must be done manually.

1.6c.4 *Types of loss of engine thrust*

Losses of engine thrust can be divided into the categories occurred during flight (Inflight Shut Down, IFSD) or occurred on the ground, e.g., excursions (RE, Runway Excursion and RTO, Rejected Take-Off). Both main categories can in turn be divided into the subcategories caused by the engine or related to the engine (engine caused or related). Henceforth, only the category of losses of engine thrust occurring on the ground is discussed.

Most common for large fan engines is that the engine's monitoring system reacts because one of the monitored engine parameters such as temperature, pressure, rpm, flow, etc. is outside a permitted value. A special alternative is a fault in the control system due either to a fault or incorrect input data from the control system's sensors. Modern engines have a logic which compares expected control parameters with the measured parameters and if this value is unreasonable, an error message is displayed, but the engine continues to generate thrust with limitation of turbine temperature or thrust.

The category of loss of engine power which is most relevant in this incident is *Uncontained turbine failure*, i.e. turbine failure with penetration of the turbine housing. In this incident, this damage is secondary. There are many subcategories and the mildest case is penetration of the turbine housing where the fragments remain inside the engine cowling.

In the next subcategory, the turbine blades leave the engine casing and penetrate the fuselage. The worst case is when one or more turbine discs separate from the engine and penetrate the turbine housing, engine casing and cabin or other primary structure. The latter case is however extremely rare.

In cases where the loss of engine power is caused by the physical action of water, ice or foreign objects such as birds etc., it is common for the sequence of events to be relatively quick. If the fan blades are seriously damaged, there is a risk that the entire engine will separate from the aircraft due to extreme vibrations.

The certification rules have for a long time been becoming stricter in order to withstand the effect of foreign objects that can be ingested into the engine. For example, more and heavier birds are to be able to pass the fan without generating consequential damage or increased risk of engine damage.

1.6c.5 Asymmetric thrust upon loss of engine thrust

The case which has occurred, in which the entire high and low pressure turbines are damaged as a result of foreign metal fragments in the gas stream, is extremely unusual. Fragments from the knife-edge seal (mass 9.1 kg) are flung out into the gas stream and then destroy everything in their path backwards in the engine. The vast amount of energy stored in the engine's rotating parts, and especially the fan with its large diameter, means that the engine rotates for a relatively long time despite the braking moment from the turbine being great.

If it is assumed that the majority of the static thrust during the present engine failure came from the engine fan, it is clear that the difference in thrust between the right and left engines became great during the period before the right engine had spooled down – see Fig. 56 for a graphical presentation. In this connection, it should also be taken into account that the reaction time of the PF was slightly over a second before taking measures to reduce the thrust of the engines.

Engine section	Time for thrust reduction 102-50% (s)	Time for thrust reduction 102-10% (s)
Left fan, N1	2	4
Right fan, N1	8	>30

Fig. 10 Approximate times for rpm reduction on left and right fan stages during the incident.

If the asymmetric thrust is compared with the change in magnetic heading, it is clear that the aircraft veered sharply to the left during the initial phase of the sequence.

1.6c.6 Engine modules

The engine consists of a number of modules as is shown in the drawing in Fig. 11. The modules, which are joined together by bolted joints, have individual flying time limitations and can be overhauled separately. Monitoring of the modules' flying times and the number of cycles takes place individually for each module.

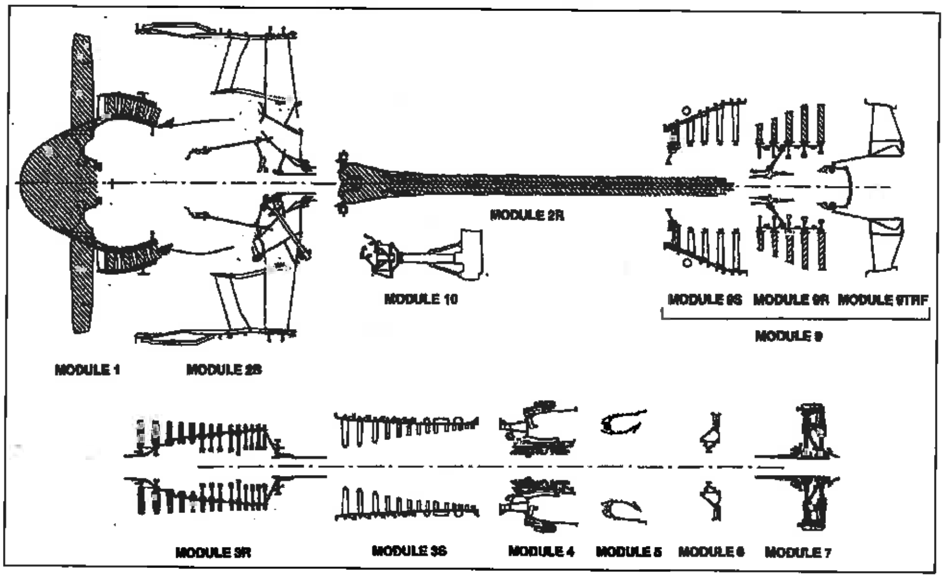


Fig. 11. Composition of the engine in modules.

The parts of the engine which are primarily discussed henceforth are the combustion chamber section (Combustion Chamber, Module 5) and the high pressure turbine stage one (HPT Nozzle STG1, Module 6), which is mounted on the rear section of the compressor (Compressor Rear Frame, Module 4), which in turn is mounted on the high pressure turbine (High Pressure Turbine, Module 7) and the low pressure turbine (Low Pressure Turbine, Module 9).

1.6c.7 *Diffuser Assembly*

A small quantity of the air from the high pressure compressor stage 14 is used to cool hot parts of the engine and to control the axial pressure balance in the rotor system. See module 7.

In order to control and regulate this air, there is an air distributor with seal parts (Diffuser Assembly) between the rear section of the high pressure compressor and the high pressure turbine. This consists of three sections with the disc-shaped air distributor and two air seals, the Diffuser Front Air Seal and the Diffuser Aft Air Seal, which are all rabbeted together and held in an axial clamp with nine bolts and nuts.

The rotating diffuser assembly has three functions. First, the diffuser vane ring takes the compressor discharge air which is metered by the stationary mini nozzle seal support and pumps that air into the High Pressure Turbine Rotor structure for structure and blade cooling.

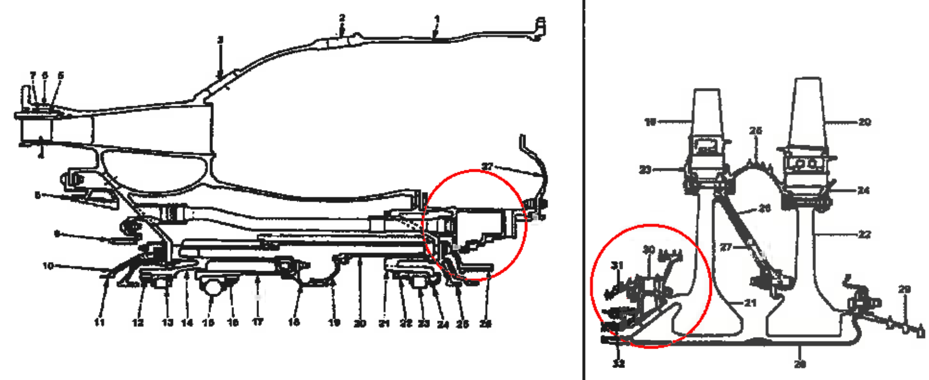
Second, the high pressure compressor discharge air which leaks past the diffuser vane ring aft across the rotating aft air seal, is used to pressurize the air cavity in front of the stage 1 High Pressure Turbine disk face, thus applying an aftward force which assists in pressure balancing the core rotor system. This air is also used to cool the forward side of the High Pressure Turbine stage 1 disk.

Third, the high pressure compressor discharge air which leaks past the diffuser vane ring forward across the rotating forward air seals, makes up the High Pressure Recoup air which is used for Low Pressure Turbine stage 1 nozzle cooling.
The diffuser assembly is installed to the stage 1 HPT forward shaft with an interference fit, with circumferential alignment provided by the nine tangs on the aft air seal flange which aligns with the nine slots on the stage 1 HPT disk forward shaft cone. The diffuser

assembly is retained axially by the number 5R inner race and rotating air / oil seal stack clamp.

If the aft air seal separates, seal debris which enters the core flowpath in addition to the loss of pressure balance will result in an engine stall event by the result of the disruptive core airflow. In the investigated incident, the separated debris which entered the core flowpath resulted in significant downstream damage which resulted in high exhaust gas temperature (EGT) and loss of fan speed (N1 system) from the LPT blade damage.

In the drawing below, a red circle marks the static seal surfaces on the Compressor Rear Frame and the rotating Diffuser Assembly on the High Pressure Turbine.



Seal surfaces on the Compressor Rear Frame

Diffuser assembly

Fig.12. Diffusor Assembly and Compressor Rear Frame.

1.6c.8 *Repair of the Diffuser Aft Air Seal*

The seal teeth on the air distributor's aft seal (Diffuser Aft Air Seal), termed Pressure Balance Air Seals (see Fig. 13.), become worn and can in some cases be repaired. Engine Manual section 72-53-07, repair 003, provides a Dabber TIG Weld Repair of the aft seal teeth which adds material to the teeth edges in the form of weld beads on the flange, which are then turned down on a lathe to the correct tooth dimensions. Section 1.18.1 describes the procedure schematically.

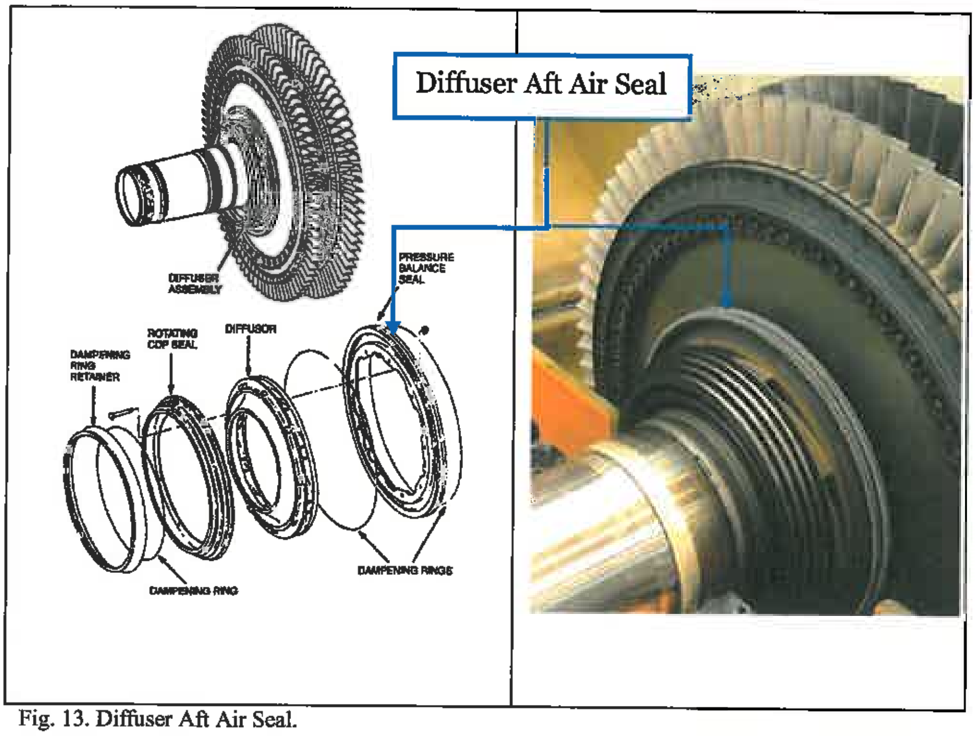


Fig. 13. Diffuser Aft Air Seal.

1.6c.9 *Repair of the Stationary Seal Support*

The stationary section which seals against both the forward and aft seal teeth consists of a honeycomb with a cell size of about a millimetre. In connection with the repair of the seal teeth on the forward and aft rotating air seals, the static honeycomb seal is also replaced.

1.6c.10 *Remaining technical remarks*

According to the technical logs viewed by SHK, there were no remaining technical remarks concerning the aircraft which could have had an effect on the sequence of events during the incident.

SHK has also asked the operator in question about reported faults – or malfunctions – pertaining to the aircraft's brake or ground steering systems. No information has come to light on notable faults whether before or after the present incident at Stockholm/Arlanda.

1.7 Meteorological information

METAR ESSA 161220Z: wind 14005KT, visibility 8000 km - Snow Grains (SG) Scattered Clouds (SCT) 1500 feet, Broken Clouds (BKN) 2200 feet, temperature/dew point - 01/-03, QNH 1035 hPa. Runway conditions: R01L/710152 R08/710156 R01R///99// - in plain text: Runway 01L, ice, 10% or less, 1 mm, friction coefficient 52/ Runway 08: ice, 10% or less, 1 mm, friction coefficient 56/ Runway 01R: figures unreliable. No significant change expected within the next two hours (NOSIG).

The recorded radio communication indicates that wind was calm just before the incident. It was daylight at the time of the incident.

1.8 Aids to navigation

The runway was equipped with daylight markings and centreline lights in accordance with international standards. The lighting was off at the time of the incident.

1.9 Radio communications

The radio communication between the aircraft and air traffic control was recorded and secured, as was the internal communication in the cockpit. The table below contains excerpts, selected by SHK, from the communication between air traffic control and the crew as well as excerpts from the communication in the cockpit.

The table contains summaries of the communication during the sequence of time from around +40 seconds before the engine failure to -20 seconds afterwards. Parts of the internal communication in the cockpit take place in Persian, but for practical reasons have only been reproduced in English in this table. Text in brackets represents SHK's comments – or clarification – in connection with an established event.

Appendix 1 to the report is a printout of the entire communication, which also presents the part in Persian which has not been translated here.

Time	Message origin	Message
11.37:41 hrs	Commander	*Take-off issued?* (Here, the commander wants confirmation from the co-pilot that take-off clearance has been obtained from air traffic control.)
11.37:44 hrs	Co-pilot	*Yes.*
11.37:46 hrs	Commander	(In Persian) *Don't start rolling from here. You must first line up before you go, otherwise you may skid off the runway.*
11.37:50 hrs	Co-pilot	(In Persian) *Yes, sir.*
11.37:51 hrs	Commander	*Iran Air 762 rolling 19.*
11.37:53 hrs	Air traffic control	*Iran Air 762.*
11.38:05 hrs	Commander	*Stabilized.*
11.38:10 hrs	Commander	*Thrust, SRS, heading, time.* (SRS = Speed Reference Setting. An increase in engine speed can be heard on the recording).
11.38:19 hrs	Commander	*Power set.* (According to the co-pilot, the engine speed is here around 5 % below the desired rpm)
11.38:22 hrs		(A loud bang is heard, followed by a reduction in engine speed and a rattling sound. The rattling sound commences around 4 seconds after the bang).

11.38:29 hrs		(A chime is heard from the ECAM system. The sound is heard 3 times, frequency 985 Hz, around 0.5 seconds in duration each time).
11.38:36 hrs	Commander	(In Persian) *What happened?*
11.38:38 hrs	Co-pilot	(In Persian) *Tire was blown.*
11.38:40 hrs		(The rattling sound ceases).
11.38:42 hrs		(A chime is heard, frequency 985 Hz, around 0.5 seconds in duration.)
11.38:42 hrs	Commander	(In Persian) *What?*
11.38:43 hrs	Co-pilot	*Set parking brake.*
11.38:45 hrs	Air traffic control	*Iran Air 762, report persons on board.*
11.38:49 hrs	Commander (via radio)	*We aborted take-off, Iran Air 762. 149.*
11.38:53 hrs	Air traffic control	*149 POB. Roger.* (POB = Persons On Board.)
11.38:56 hrs	Commander (via radio)	*Thank you, and we are in …?*
11.38:58 hrs	Co-pilot	(In Persian) *I don't know what happened.*
11.39:00 hrs	Air traffic control	*Yeah, we are ... fire engine standing by shortly.*
11.39:04 hrs	Commander (via radio)	*Roger.*
11.39:05 hrs	Air traffic control	*Will you evacuate passengers?*
11.39:08 hrs	Commander (via radio)	*It is not necessary. We don't have any fire.*
11.39:12 hrs	Air traffic control	*It's up to you if you want to evacuate. Stand by and report new intention.*
11.39:19 hrs	Commander	*Have you any visible fire on this side?*
11.39:22 hrs	Air traffic control	*No fire visible from the tower.*
11.39:25 hrs	Commander	*Okay.*

Fig.14. Excerpt from communications summary. Times in UTC.

1.10 Aerodrome information

Stockholm/Arlanda runway 19R had runway code 4E, according to the Swedish AIP[30]. The airport operational status was in accordance with the Swedish AIP.

1.11 Flight recorders

1.11.1 Flight Data Recorder (FDR, QAR)

The FDR has been secured and data extracted. The equipment was a digital recording device manufactured by Honeywell. See Fig. 15. It has the capacity to record over 300 parameters for more than 50 hours. The FDR was transported by a representative of SHK to the UK accident investigation authority, the AAIB (Air Accidents Investigation Branch), where the data were compiled and stored on a computer memory.

The data files were stored in Microsoft Excel format. The information was then further processed and interpreted by an engaged expert and examined by SHK. More information can be found in chapter 1.16.

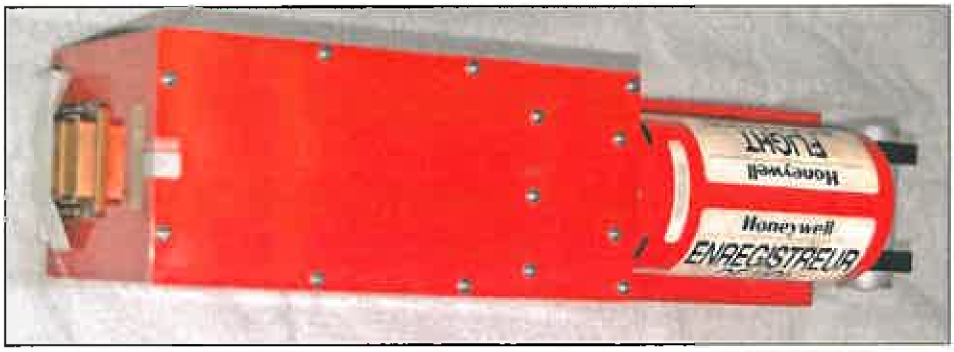


Fig. 15. Digital FDR.

1.11.2 Cockpit Voice Recorder (CVR)

The CVR has been secured and analysed. The equipment was an analogue recording device manufactured by Fairchild, model 93-A100A. See Fig. 16.The examination of the CVR is presented in chapter 1.16.2. The equipment was transported together with the FDR to the UK accident investigation authority (AAIB). Extraction of the audio was done by the AAIB under the supervision of a representative for the Swedish accident investigation authority. The audio was played back from the analogue equipment and was transferred to digital audio files.

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[30] AIP – Aeronautical Information Publication.

Fig. 16. CVR of analogue type.

1.11.3 *Video recordings*

Two amateur video recordings by private persons have been placed at SHK's disposal. One of the videos was recorded by a passenger seated in the aircraft in question, on the left side above the wing. The video is of a view through a passenger window where the failed engine can be glimpsed. The second video was recorded from the terminal building, and shows the aircraft in question as it commences take-off. It can also be seen when the engine fails and how the aircraft runs off the runway.

The video taken from the terminal building, intergrated with the graphics from chapter 1.1.7, can be downloaded from SHK's website, http://www.havkom.se/.

1.12 Site of occurrence and aircraft damage

1.12.1 *Site of occurrence*

The aircraft initially rolled along the centre line on runway 19R during the acceleration for take-off. After a rolling distance of approximately 250 metres, the aircraft veered to the left and rolled off the left runway edge, approximately 400 metres from the runway threshold. Off the runway, the aircraft rolled approximately a further 200 metres before stopping about 40 metres from the runway's asphalt surface.

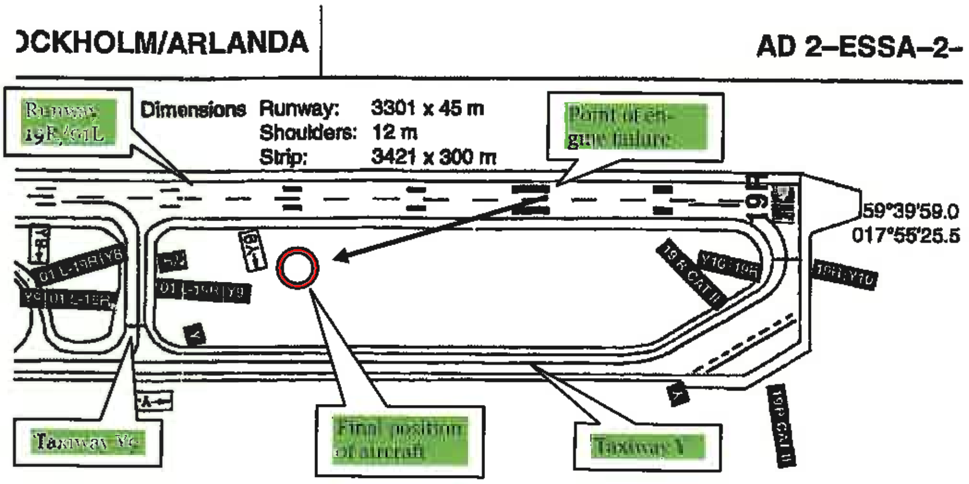

Fig.17. Plan view from AIP of the incident area at the airport.

The area outside of the runway consists of a level, grass-covered area which at the time of the incident was frozen and covered with an approximately 20 cm thick covering of snow. At the end of the ground roll, the skewed nose wheel ploughed an approximately 50 cm wide and 50 cm deep track in the frozen area of ground.

The aircraft stopped approximately 200 metres from taxiway Y9. This taxiway is used frequently as an intersection to runway 19R for aircraft taking off from runway 19R that do not use the full length of the runway. In a given period of time, just over 40% of aircraft taking off from runway 19R use the intersection at Y9.

1.12.2 Aircraft damage

Other than damage to the left engine, the aircraft sustained only minor damage during the incident, including to the light fittings. The nose gear, which was angled at approximately 65° to the right, was after the incident partly packed in dammed up masses of snow and dirt.

Following an engine replacement and technical inspections of the concerned parts, the aircraft was able to be ferried[31] to Tehran and eventually put back into service.

Fig.18. The cabin crew leaves the aircraft after the incident. Photo: SHK.

1.12.3 Runway conditions

At the time of departure, runway 08 was in use for take-off, but for performance reasons the pilots requested to take off from runway 19R. However, during the same period of time as the departure of IRA762, air traffic control changed so that runway 19R should be used for all take-offs.

Runway 19R was at the time damp but cleared of snow and water. The runway temperature has been estimated to be below the freezing temperature of water. The last measurement of runway friction prior to the incident was carried out between 04.15 hrs and 04.25 hrs. The measurement was carried out in the form of two measurement runs in both runway directions on each side of, and approximately 7,5 m from, the centreline. The aver-

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[31] Ferrying – Delivery flight without passengers.

age runway friction for the respective thirds of the track – A, B and C – was recorded at 69, 62 and 65, with a total mean value of 65.

The first third of runway 19R, and the part of the runway on which the incident took place, is defined in this context as runway section C. At 10.30 hrs, the runway friction was deemed to be unchanged and no new measurement was taken, but the entire runway was at that point sprayed with Formiate.[32]

At 13.20 hrs, approximately 35 minutes after the incident, a check was made of the runway friction in the form of a measurement in a southerly direction. The runway friction was then recorded at 75, 71 and 73 respectively for runway sections A, B and C, with a total mean value of 73. See the separate examination of this area in chapter 1.16.

1.13 Medical information

Nothing indicates that the mental or physical condition of the pilots had been impaired before or during the flight. The cockpit crew was double augumented, which means that the crew on duty at the time of the incident had not been on active duty during the earlier flight from Tehran to Stockholm Arlanda airport.

1.14 Fire

There was no fire.

1.15 Survival aspects

1.15.1 General

The Emergency Locator Transmitter (ELT) of type A06V2 was not activated in the incident.

1.15.2 The rescue operation

The accident alarm from Arlanda Airport was received by the SOS Alarm Centre in Stockholm at 12:38 hrs. The airport rescue services were alerted at the same time and the first of their vehicles arrived at the aircraft approximately one minute later. The rescue leader from the airport rescue and fire fighting services arrived at 12:41 hrs. It was established that the aircraft had slid off the runway and stopped on the strip outside of the runway. A reassuring report was received from the commander on the situation on board.

JRCC[33] received information on the incident at 12:41 hrs from the control tower via the SOS Alarm Centre.

From the SOS Alarm Centre, the appropriate emergency service and command centres for the rescue services were alerted, and from there, the fire stations in Märsta and Upplands Väsby were alerted at 12:40 hrs, at the same time as the police command centre was informed.

The SOS Alarm Centre alerted the first ambulance and two medical care teams at 12:44 hrs. Transport for the medical care teams was called in one minute later. An ambulance emergency response vehicle, an emergency physician car, an air ambulance and two additional ambulances were alerted, as well as the concerned officials on call (TIB). The last ambulance was alerted at 13:01 hrs, which is approximately 23 minutes after the accident alarm and around the same time as units from Uppsala fire department received instructions that they could return to their fire station as there was no need for intervention on their part.

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[32] Formiate – Chemical used for anti-skid treatment on runways.

[33] JRCC – Joint Rescue Coordination Centre / Coordinated rescue centre.

The ambulance from Märsta and the municipal rescue services' first vehicle from Märsta fire station reported that they arrived at 12:51 hrs, which is approximately 13 minutes after the accident alarm. The fire officer from Märsta and the incident commander from the airport rescue services assessed that no other resources from the rescue services were required. Buses, stairs and ploughing equipment for clearing the snow were ordered from the airport authorities.

The passengers were then able to leave the aircraft without assistance via the external stairs that had been driven up and were then taken out to the buses under supervision of, among others, the medical personnel from the air ambulance. The aircraft was evacuated of passengers at 13:32 hrs, which is around one hour after the accident alarm. After this, the rescue services and medical care operations were ceased.

A medical team was alerted at the Danderyd hospital and was ready for departure at around 13:15 hrs. Another transport vehicle was directed to the Norrtälje hospital to pick up a medical team, but the medical actions were discontinued, at 13:23 hrs, before the vehicle arrived in Norrtälje.

None of the persons on board were injured during the incident.

1.16a Tests and research - operational

1.16a.1 Examination of the FDR

The information from the FDR has been visualized by means of animation software and presented in the form of curves: see example in Fig. 19 below. The figures below show data in unprocessed form, where the times in the diagrams are displayed in UTC. Times are otherwise reported with the hour number omitted.

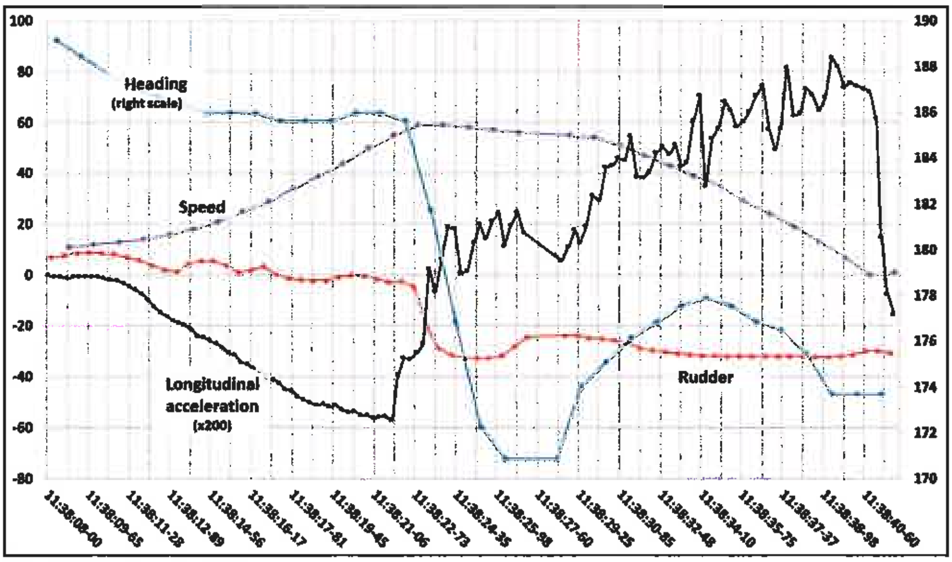

Fig. 19 Data from the FDR.

The parameters primarily investigated are the engine parameters and the parameters which describe the aircraft's movement, position, brake pedal angular positions and rudder angle. The nose wheel turn angle has not been registered, but has been calculated based on the rudder position, which was recorded. The rudder is controlled from the pedals, and at full rudder deflection, the nose wheel turn angle is 6°. This means that the nose wheel can be turned a maximum of ± 6° by means of the pedals. The full nose wheel turn angle (± 65°) is attained by the turning of two steering wheels in the cockpit, one on each side.

In the figure above, it is seen that the heading changed to the left (decreasing number of degrees) at the same time as the rudder, and thereby the nose wheel, were turned to the right. This means that the nose wheel lost its grip against the runway and skidded to the left. After the heading angle began to change, the aircraft's rate of heading change was almost unchanged, i.e., it turns to the left with an almost constant rate of turn.

The following data has been obtained from the FDR:

- Autothrottle was engaged from 38:10 hrs to 38:23 hrs.
- Ground spoiler was armed at 30:35 hrs and disarmed at 42:30 hrs.
- The aircraft's take-off mass was 148,4 tonnes.
- Thrust reversal was not used.

In connection with the loss of engine power, a number of parameters changed abruptly. The table below shows the recording frequency, time and value before the loss of engine power, and the time and value after the abrupt change.

Parameter	**Freq (Hz)**	**Before**	**Value**	**Value**	**After**
Longitudinal acceleration	4	38:21.79	-0.28	-0.20	38:22.04
Fuel flow left engine (1)	1	38:21.96	9109	8081	38:22.96
N1 left engine (1)	1	38:21.34	102	57	38:22.34
N1 right engine (2)	1	38:22.84	104	93	38:23.84
N2 vibration left engine (1)	0.25	38:21.14	0.6	3.8	38:25.14
Throttle control angle	1	38:22.46	78°	67°	38:23.46
Brake pedal position (left pedal)	1	38:22.25	0.3	12.9	38:23.25
Rudder position	2	38:22.18	-2.5	-4.3	38:22.68
Elevator position right side	4	38:22.07	5.6	4.5	38:22.34

Fig. 20. Table of FDR data.

The recording of the brake pedal angles has been secured, for the right and left pedals, respectively. The pedals for right and left pilot are mechanically interconnected, which means that it is not possible to determine which one of the pilots has pressed down any of the brake pedals. Only the joint brake angle has been recorded. The brake pedal angles are presented in Fig. 21 below. A value of 14 represents the maximum displacement.

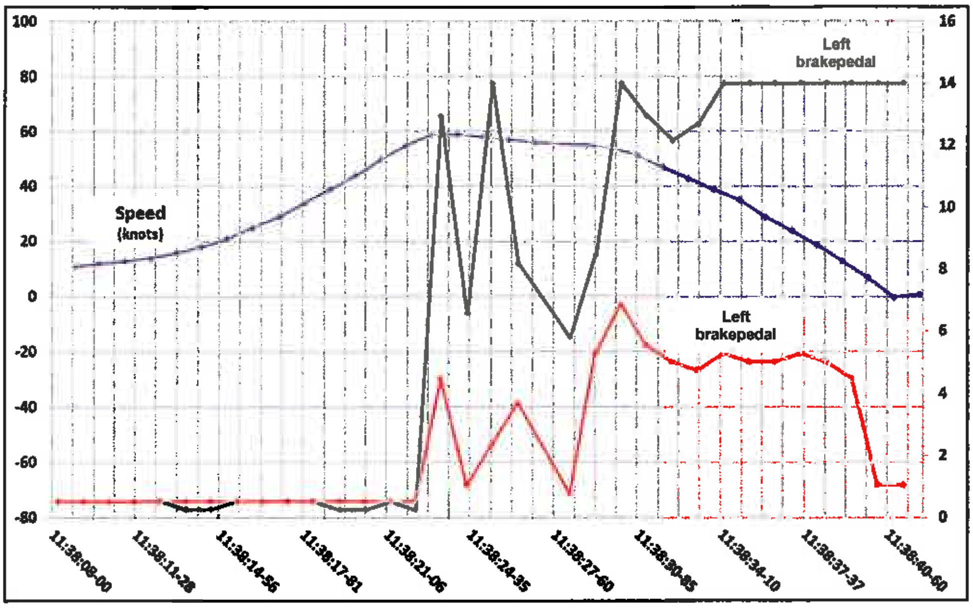

Fig. 21. Brake pedal angles.

From the diagram in Fig. 21, it can be noted that the recorded pedal displacements follow each other at different levels during the sequence, where the right pedal has been recorded with values corresponding to around half of the value for the left pedal.

Maximum displacement has been recorded from the left brake pedal during the final phase until the point when the aircraft stops. During this phase, the value from the right pedal decreases and approaches zero when the aircraft stops.

The engines' rpm N1, thrust lever angle, and the speed of the aircraft are presented in Fig. 22 below. The red line represents the left engine, i.e., the engine that failed.

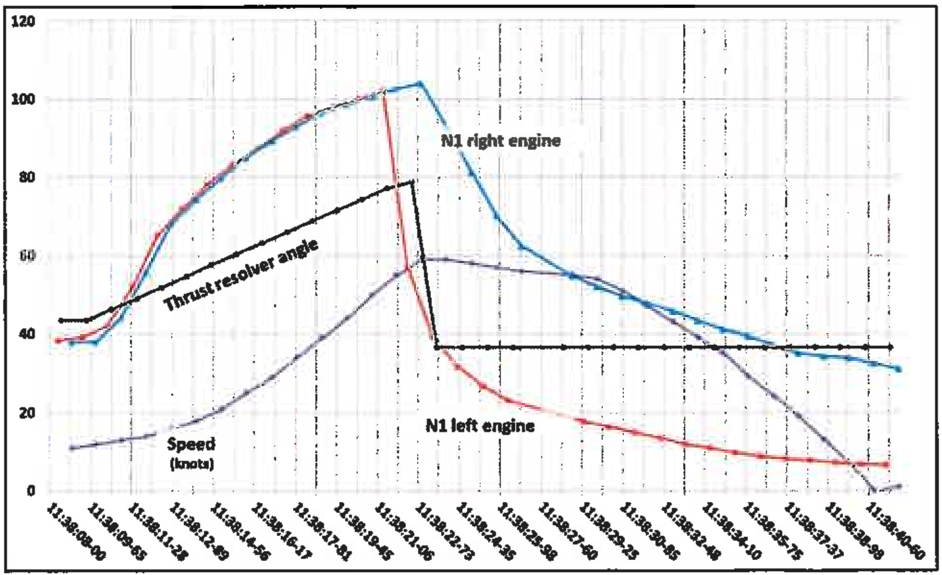

Fig. 22 Rpm N1, throttle angle, aircraft speed.

Fig. 23 also shows N1 for the left and right engines, though it is the square of N1 that is presented as this better represents the amount of energy developed by the engines. The red area represents the energy output of the left engine from the loss of engine power until the aircraft was close to a standstill. The blue area represents the energy output of the right engine over and above that of the left engine, i.e., the energy which contributed to the yawing moment of the aircraft.

The greatest yawing moment was at the time when the right engine's rpm was at its highest, i.e., when the thrust lever angle was reduced to minimum and the right engine's rpm began to decrease. Between 38:22.34 hrs and 38:23.84 hrs, the yawing moment was greatest, followed by a rapid decrease as the right engine's rpm decreased. This area is marked as a checked area in Fig. 23 below.

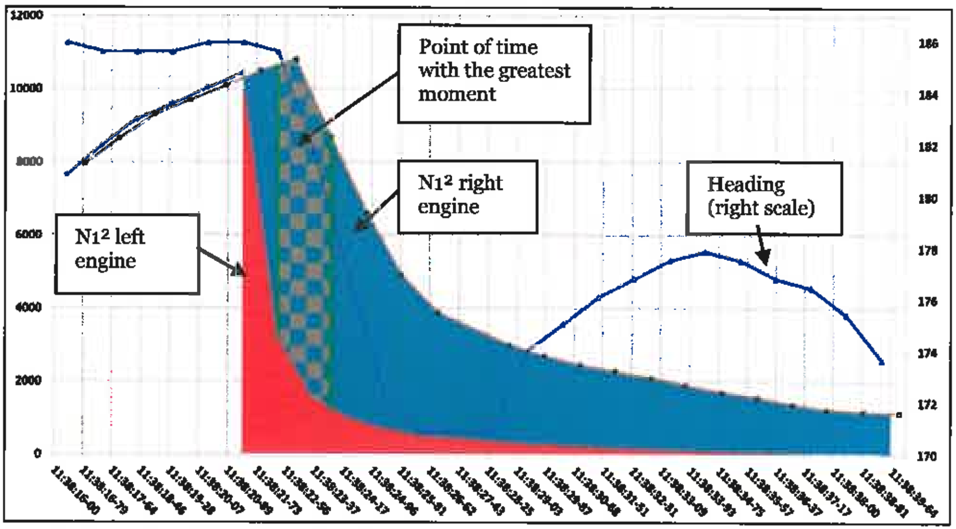

Fig. 23. Illustration of the energy from the engines.

The point of time for the loss of engine power can be determined by means of the parameters for the aircraft's acceleration, engine speed and fuel flow. As the longitudinal acceleration is recorded at the highest frequency (4 Hz), this parameter provides the best means to establish the point of time. Between 38:21.79 hrs and 38:22.04 hrs, a decrease in the acceleration takes place, i.e., the loss of engine power begins at 38:21.79 hrs at the earliest and at 38:22.04 hrs at the latest.

The pilots' reaction to the loss of engine thrust can be seen in the thrust lever angle, rudder and the brake pedal angles. The pilots' reaction begins at 38:22.18 hrs at the earliest (rudder) and at 38:22.68 at the latest (rudder position recorded at 2 Hz, i.e., two times per second). At 38:22.18 hrs, the rudder passes -20° (turn right). The first value recorded when the brake pedals had begun to be used is at 38:23.25 hrs (they are recorded at 1 Hz). The left brake pedal was at that point depressed at around 92% of maximum displacement, and the right pedal at around 29%. The thrust lever angle is recorded at 1 Hz, and at 38:22.46 hrs, the thrust lever positions were still unchanged. At 38:23.46 hrs, the thrust levers had been retarded down to ground idle. The sequence can be seen in Fig. 25.

With the above times, the pilots' reaction time is at most the difference between 38:21.79 hrs (the earliest recording of the loss of engine thrust) and 38:22.68 hrs (rudder), i.e., 0.49 seconds. At its shortest, the reaction time is 0.12 seconds. These figures assume that the rudder angle is used as an indication of the pilots' reaction. If the thrust cut off (thrust lever angle) is used, the time is at most 1.67 seconds and at least 0.42 seconds.

The enlarged diagram overleaf – Fig. 24 – illustrates the times with raw data from the FDR at the time of the loss of engine thrust itself, from 38:21 to 38:25. The first point on the N1 line is also the highest point (102.25%).
Among other parameters which could be noted from the FDR readouts, it can be seen that aileron was applied (the steering wheel on the steering column was moved to the right),

and that the steering column was pulled back a little. These actions were initiated when the aircraft had already begun the veer to the left.

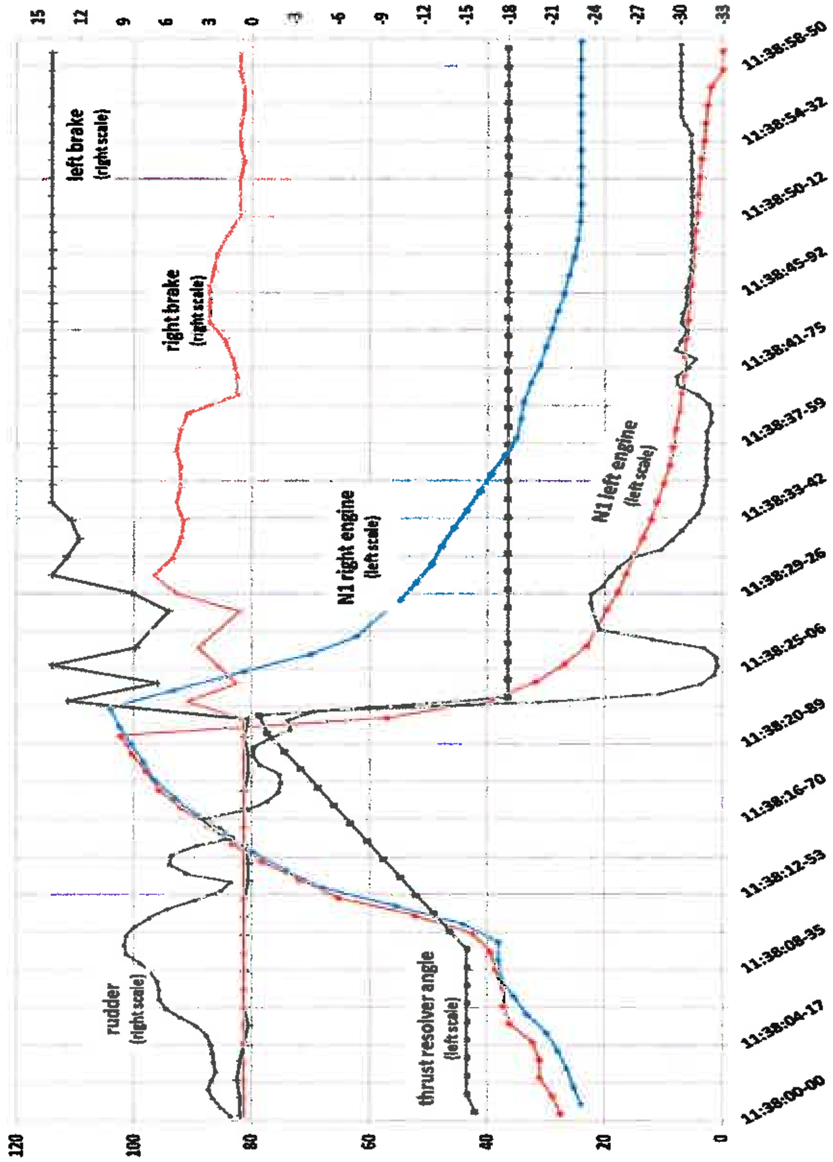

Fig. 24. Data from the FDR.

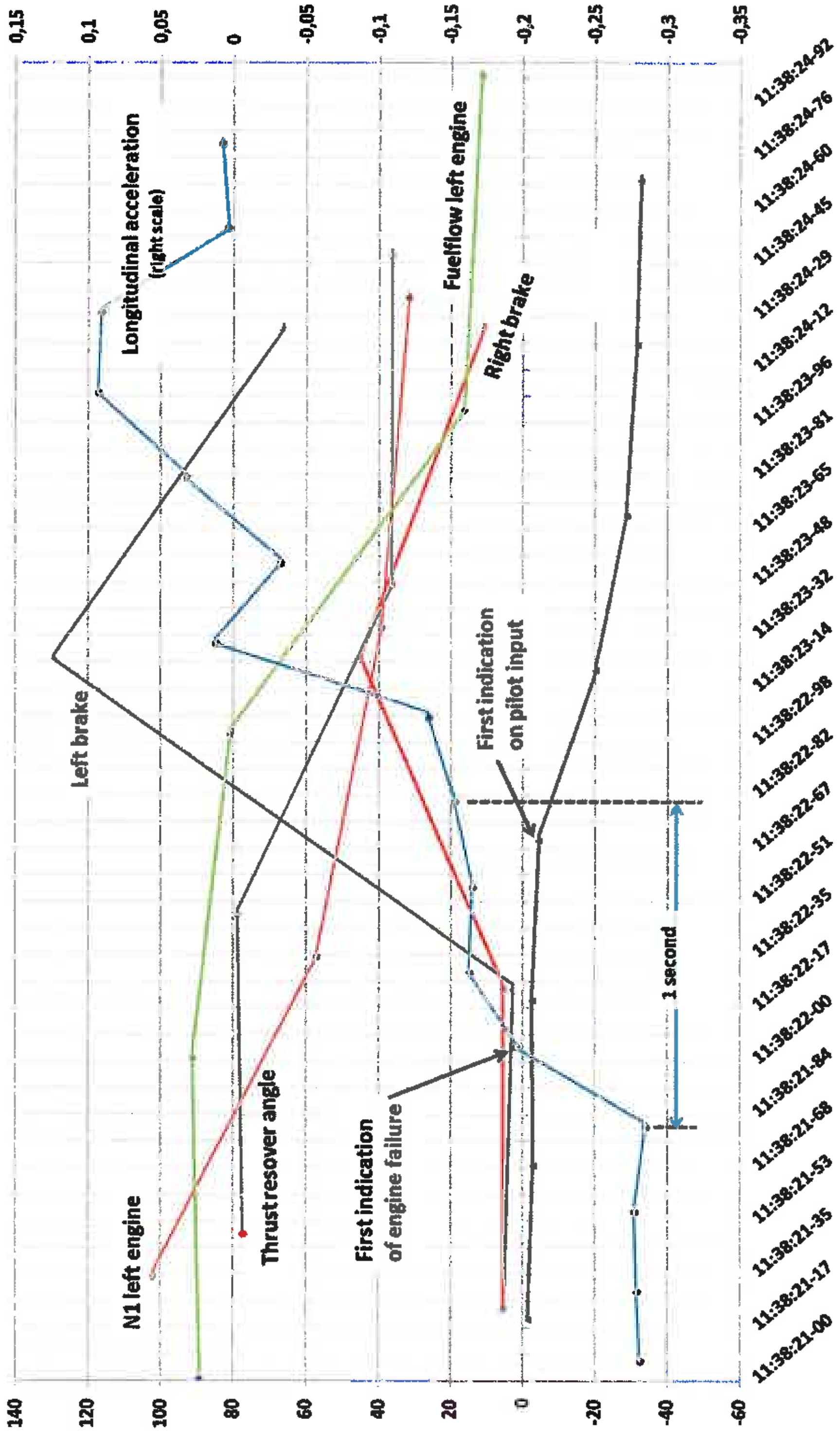

Fig. 25. Data from the FDR.

1.16a.2 Additional testing of the FDR data

Conditions

Data recorded in the FDR during the incident did not correspond in all respects with the statements submitted by the pilots at their interviews. The analyses of FDR data that were performed indicated values that could not be deemed to be entirely compatible with other recordings, as the right brake pressure was recorded on the "wrong side", i.e., in the opposite direction compared with rudder deflection and nose wheel steering.

In consequence of this, SHK made the decision to supplement the examination of the FDR with additional tests. The remaining tests deemed necessary consisted of the examination and verification of recorded FDR parameters regarding values for brake angles. During these tests, the FDR unit in question had to be installed in the aircraft EP-IBB.

Due to stricter sanctions for member states of the European Union concerning trade with Iran, the examination could not for formal reasons be carried out in Sweden. The examination therefore took place in Iran in the presence of representatives of SHK.

Procedure and result

Schedule and protocol regarding the process and documentation had been sent to the operator in advance. At the time of testing, the FDR unit in question had been installed in the aircraft EP-IBB. The purpose of the test was to check the reliability of the values for both left and right brakes that had been recorded during the incident.

The test was conducted in accordance with the schedule drawn up by SHK, in which the company's chief pilot performed manoeuvres on the command of a representative of SHK. Put simply, varied braking manoeuvres were performed in parallel with other manoeuvres with the aim of verifying and identifying certain positions and displacements. All test manoeuvres were carried out from the right pilot position. The tests were documented in writing and on video film.

The FDR unit was then removed from the aircraft and taken to the company's "avionics shop" (avionics workshop) for extraction and processing. The recorded data was presented in the form of numerical values and in the form of graphs in which a number of parameters had been selected for analysis. See Fig. 26.

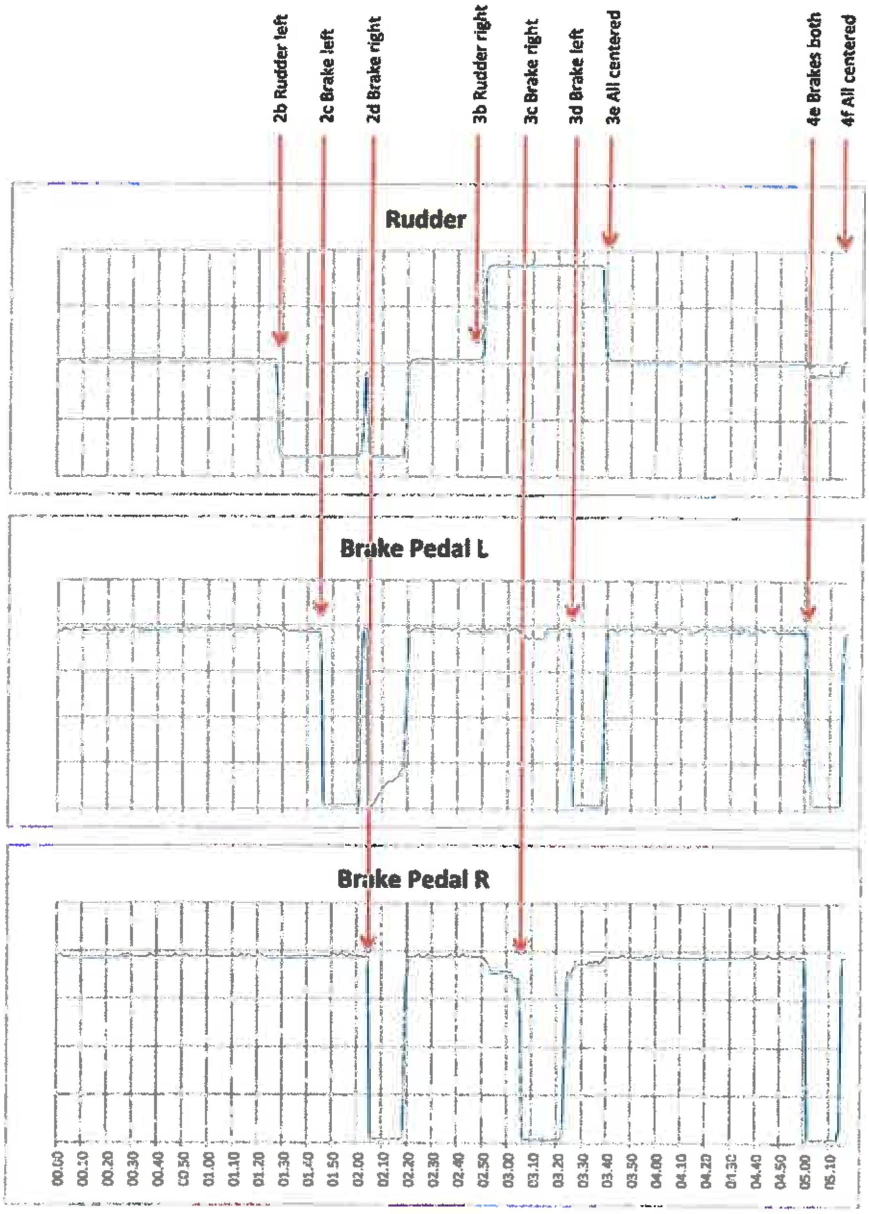

Fig. 26. Section of a graphical presentation of the data recorded during testing. Terms on the upper edge refer to SHK's test schedule. The bottom scale represents a time axis.

When the recorded data were extracted, it was established that there were no malfunctions or deviations, compared with the original recordings from the incident. Upon full displacement of left and right brakes, the corresponding maximum values had been recorded in the FDR. In the illustration above, it can also be understood that full brake displacements were registered irrespective of whether the rudder pedals were in left, right or neutral position. All recorded values corresponded fully to the movements and manoeuvres carried out by the test persons in the cockpit.

SHK was able to establish that the FDR values from the incident which were previously assessed to be dubious could now be considered accurate and therefore be added to the factual base in the investigation.

1.16a.3 Examination of the CVR

The CVR recorded the final 30 minutes on four channels: left pilot, right pilot, interphone communication and sound from a microphone positioned on the overhead panel in the cockpit (area microphone). The sounds have been transferred to digital audio files by the AAIB. These audio files have then been processed with sound analysis software.

The recording started 10 minutes before pushback and stopped when the crew pulled the circuit breaker to the CVR around 8 minutes after the loss of engine thrust.

At 38:29 hrs, the first ping signal (chime) is heard on the CVR. It is an audio signal which indicates that the ECAM has sent some form of warning. There is no recording that specifies which warning was announced.

The sounds from the CVR have been synchronized with times from the FDR where the points of time for radio transmission have been recorded. Further synchronization with the sound recording of air traffic control's traffic has been carried out. The accuracy of the time indications is within ± 1 second after adjustments of the recording speed and absolute time differences between different sources.

When interpreting the sounds from the CVR, it was noted that parts of the crew communication was in Persian. These parts of the communication was translated into English with the aid of an independent interpreter with expertise in the field of aviation, the co-pilot present during the incident and the Fleet Director of Iran Air.

The quality of the audio recordings from the CVR was low and certain sections have been difficult to interpret. The co-pilot's sound level was set low and the recording of the commander was frequently interrupted by cabin announcements and radio traffic. The area microphone was unusable and recorded only a 400 Hz tone until the left engine failed. After the engine failure, the sound recording from the area microphone functioned normally.

SHK has produced a sonogram (frequency diagram) and audiogram from channel 2 (right pilot) which provides a graphical representation of parts of the recorded acoustic image. See figs. 27 and 54.

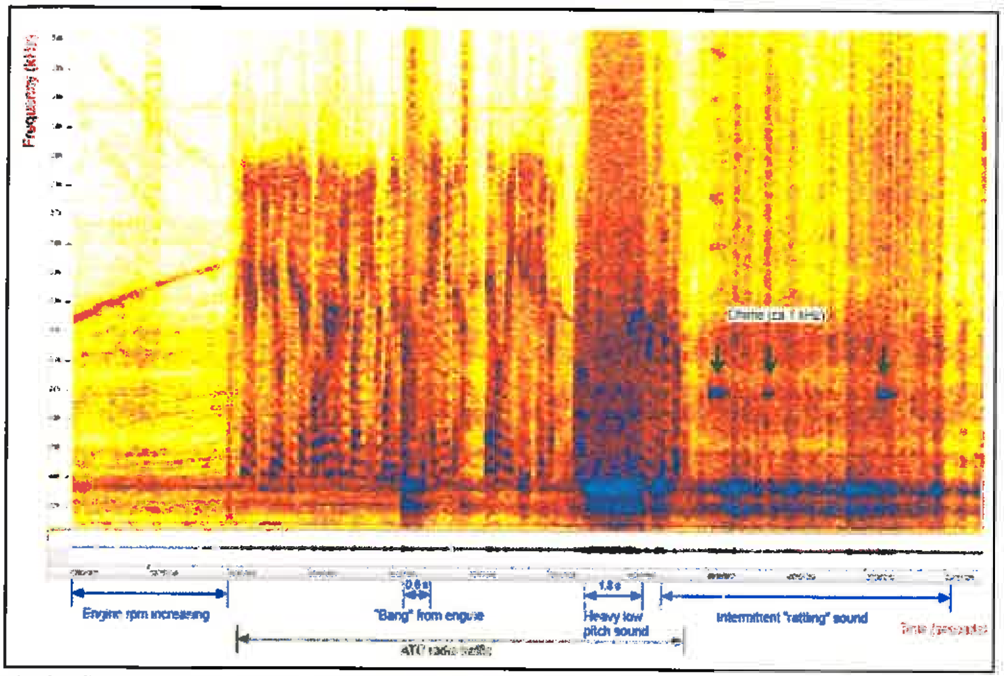

Fig. 27. Sonogram from channel 2 of the CVR. Graphics: Magnic AB.

The sonogram describes how sound can be visualized in the frequency plane, with time on the horizontal axis, where in addition to the "bang", the low-frequency sound recorded approximately 4.5 seconds after the engine failure can also be noted.

The radio traffic between the rescue personnel and the tower was in Swedish and has also been reproduced in Swedish in the transcript in Appendix 1.

Immediately after the aircraft had come to a stop off the runway, the commander asked the tower if they could see any fire. As no fire could be seen, the commander decided not to evacuate the passengers. The tower alerted the rescue personnel, who established contact with the crew on a separate frequency. The crew asked the rescue personnel to check whether there was visible damage or fires anywhere.

However no signs of a remaining fire could be discovered, and it was also reported that all of the aircraft's landing gear was ploughed deep into the ground. At this point, the crew was still not clear on what had caused the incident and why the aircraft had slid off the runway.

1.16a.4 Simulator test 1

An initial series of simulator tests was carried out on an A300-600 simulator at Airbus in Toulouse. In addition to SHK, personnel from the French accident investigation authority (BEA) also participated. Participants from Airbus included Flight Test Pilot, Handling Qualities Engineer, Chief Engineer, Safety Advisor and a Flight Safety Technical Advisor.

The purpose was to emulate, as far as possible, the present incident based on the FDR data, weather conditions, brake values and what came to light through the pilots' statements.

Before the tests, a detailed programme was presented which took into consideration the differences between the aircraft and the simulator and which involved the following:

- The simulator was programmed to resemble 25 % ice patches on the runway to simulate the runway status at the incident.
- Loss of engine thrust was initiated at a lower speed than the actual speed, as the simulator could not be programmed for sudden engine failure, but only for slow engine failure, known as flame out.
- Immediate retardation of both thrust levers.
- Full displacement of the rudder pedal against the running engine within one second.
- Asymmetric braking with the left pedal half a second after loss of engine power as well as no braking at all.
- No engine thrust reversal, alternatively full engine thrust reversal.

The tests were documented by means of video recording and meticulous note taking. Adjustments regarding the set values in order to emulate the sudden loss of engine power in the incident are based on calculations made by the type certificate holder, Airbus Industries.

In total, 26 take-off sequences were carried out, in which the runway friction was varied between a dry, wet and patchily ice-covered runway. Asymmetric braking was used in 19 test take-offs and resulted in excursions in 17 of the cases. In the two other tests, where engine thrust reversal was also used, the aircraft was successfully stopped within the runway width. Seven take-off sequences were executed without application of brakes, and these also resulted in the aircraft remaining on the runway.

However, it has not been possible to establish any details on how the simulator models reduced friction in connection with different runway surface conditions. SHK has not been given satisfactory details on how friction reduction is applied to nose and main gear wheels in the simulator model and how the side force depends on the nose wheel steering angle and vertical load. Further, the TC holder has not presented sufficient documentation on the experiments and testing performed in order to establish the accuracy of the models used in the simulator.

At a late stage in the investigation the TC holder added information regarding the simulator model, stating that the model is accurate in lateral directional control for the four runway conditions (dry, wet, snowy and icy). In braking performance the model is however only accurate down to wet conditions, and do not degrade performance further for snowy and icy conditions.

1.16a.5 Simulator test 2

A second series of simulator tests was carried out on an A330-200 simulator at Oxford Aviation Academy (OAA) at Stockholm/Arlanda Airport. In addition to SHK staff, a simulator technician from OAA participated.

The purpose of these tests was primarily to assess the ergonomics in the use of the rudder and brake pedals.

- The simulator was set to values which, as far as possible, emulated the present incident.

- Loss of engine thrust was initiated at the actual speed of the aircraft at the time of the incident, as it was possible to simulate sudden loss of engine thrust on the simulator model in question.

- Immediate retardation of both thrust levers.

- Full displacement of the rudder pedal against the running engine within one second.

- Maximum symmetric braking, asymmetric braking with the left pedal half a second after loss of engine thrust as well as no braking at all.

- No engine thrust reversal, alternatively full engine thrust reversal.

The tests were documented by means of video recording, printout of track lines and meticulous note taking.

Assessment of rudder and brake pedal ergonomics

Tests were carried out in order to assess the ergonomics in the handling of the rudder and brake pedals with different settings on the pedal set, from the forward position to the rear position. With maintained full displacement of the right rudder pedal, two different brake pedal combinations were tested:

1. Full displacement of the right brake pedal without displacement of the left brake pedal.

2. Full displacement of the left brake pedal without displacement of the right brake pedal.

The test persons assessed that it was easier to brake fully with the right pedal compared with the left pedal, i.e., combination 1 above was perceived somewhat easier to perform than combination 2. The perceived muscle strain was higher in combination 2. The opposite situation with full displacement on the left rudder pedal was tested with the same result, i.e., it was perceived easier to brake in the same direction as the rudder displacement in question.

It should however be noted that the simulator used on the test occasion cannot be considered to be entirely representative for recreating the conditions during the incident. Aside from the fact that it is a different and considerably more modern model, there are significant differences in the cockpit design. In the model A330, the steering column at the pilot seat has been replaced with a joystick at each pilot's side panels. However, the pedal set for operating rudder and brakes are of a similar design and construction.

1.16a.6 Applicable regulations/performance requirements at take-off

The fundamental principle is that a twin-engine aircraft in the category of transport aircraft shall either be able to abort the take-off at the decision speed V_1 and stop on the runway or be able to complete the take-off, climb and maintain an established margin to underlying obstacles, both with one and two engines running.

According to the regulations in the design requirements in FAR 25/CS-25 for twin-engine aircraft in the category of transport aircraft and applications in EU-OPS 1, the runway length for take-off shall be calculated as the longest of:

a) the distance for acceleration to V_1, climb to 35 ft on two engines + 15%,
b) the distance for acceleration to V_{EF}, acceleration to V_R on one engine and climb to 35 ft over the runway end,
c) the distance for acceleration to V_{EF}, acceleration to V_1 on one engine, reaction time with constant speed + braking distance.

V_1 is the speed at which the procedure for aborted take-off must be initiated at the latest. V_{EF} is the speed at which loss of engine power is expected to occur, based on performance calculations. V_R is the speed at which elevator operation for take-off shall take place and V_2 is the speed which shall be maintained during the first part of the outbound flight. When calculating the points in time for pilot reactions, a one-second delay is added for identification and decision on measures to be taken.

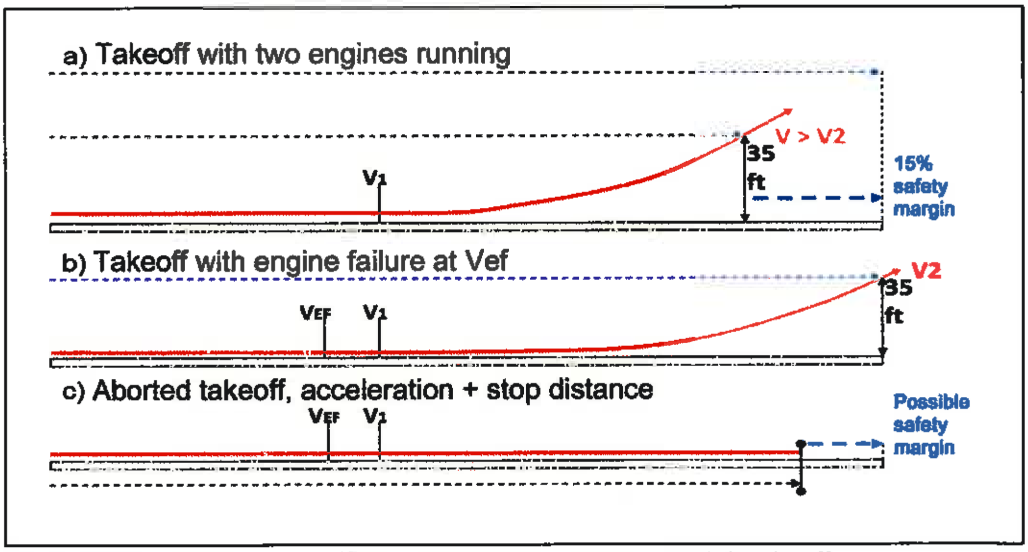

Fig. 28. Criteria according to FAR 25/CS-25 for calculation of runway length for take-off.

In order to fulfil the requirements, the aircraft's mass must not be higher than the longest distance of a, b and c is accommodated within the available runway length at the airport. See Fig. 28. For every take-off, the runway length according to a, b and c shall be calculated with consideration of prevailing meteorological conditions and current runway conditions. In the event of a "balanced take-off", the safety margin for aborted take-off may be zero. Consideration must also be given to the fact that the aircraft's maximum permitted structural take-off mass may not be exceeded.

The definition of V_{MCG} can be found in Airworthiness Standards: Transport Category Airplanes, FAR § 25.149 (e), valid at the time of certification of the Airbus A300:

> *"V_{MCG} is the calibrated airspeed during takeoff run at which, when the critical engine is suddenly made inoperative, it is possible to recover control of the airplane with the use of primary aerodynamic controls alone (without use of nosewheel steering) to enable the takeoff to be safely continued using normal piloting skill and rudder control forces not exceeding 150 pounds".*

The descision speed for take off ,V_1, must be higher than $V_{MCG.}$ Correspondingly, there is a speed, V_{MCA}, which denotes the lowest speed at which the aircraft can be manoeuvred when it is in the air when the "critical engine" has ceased to function.

1.16a.7 Certification requirements for loss of engine thrust before V_{MCG}

The general requirements regarding controllability of the aircraft during the take-off phase in the case of an engine failure are covered in CS25.143 (a1) and (b1). See fig. 29. These requirements assume however that the aircraft can be stopped/controlled with the combined use of brakes, steering and rudder and reverse thrust (only above 80 KIAS).

There are no specific certification requirements concerning manoeuvrability or other factors upon sudden loss of engine power if the speed is below V_{MCG}.
When the speed is higher than V_{MCG}, the aircraft shall be controllable by means of aerodynamic controls. In the certification requirements, "controlable" means that the aircraft may not deviate by more than 30 ft (9.1 metres) from the runway's centre line upon loss of engine power (the most critical engine). The consequence of this is that upon loss of engine power below V_{MCG}, the take-off must be aborted immediately. In the present case, V_{MCG} was around 113 knots, i.e., significantly higher than the speed of the aircraft at the engine failure.

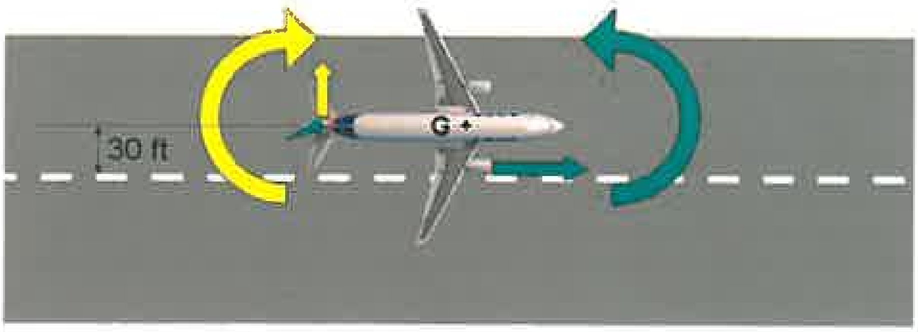

Fig. 29. Forces on the aircraft upon loss of engine power.

1.16a.8 Analysis of the aircraft's yaw stability on the runway during take-off with only one functioning engine

As there are no certification requirements for the speed range in question – from start of the take off to V_{MCG} – SHK decided to carry out certain studies concerning the conditions for the aircraft's yaw stability with only one functioning engine.
The task of carrying out the study was given to Professor Ulf Ringertz at Royal Institute of Technology (KTH) in Stockholm.

The result of these studies can be assumed to correspond to the situation during the incident and describes the conditions which the pilots had in the initial part of the sequence with an immediate loss of thrust on one engine and maximum take-off thrust on the other engine.

The study focused on the aircraft's stability without the effect of brakes and engine thrust reversal. The constituent parameters used in the study are nose wheel steering and rudder. Certain sections of the study are based on estimations as it has not been possible to obtain the necessary data from the type certificate holder.

The result of the study shows that the aircraft's yaw stability is limited on contaminated surfaces unless differential braking is used. In low speed ranges, the rudder cannot generate sufficient aerodynamic moment to counteract the forces caused by the unbalanced thrust produced by one engine only. The unbalance in thrust requires a large side force to be supported by the nose wheel in order to maintain directional stability and control. The efficiency of the rudder increases by the square of the speed, but only attains full authority at around 100 knots.

It should also be mentioned that although this study has been carried out on the basis of data from the aircraft in question, the results can in significant respects be considered to apply in general to twin-engine aircraft with wing-mounted engines. The study can be found in its entirety as Appendix 2 to this report.

1.16a.9 Condition and friction status of the runway

SHK has chosen to carry out a relatively in-depth investigation of the characteristics of the runway during the incident. It is known that both the prevailing temperature and contamination conditions on the runway add further complexity to the relevant friction measurement, while the correlation with an aircraft's ability to stop is particularly difficult in these conditions.

The UK accident investigation authority (AAIB[34]) has recently examined a number of cases where the correlation between friction measurement on a damp or wet runway and an aircraft's directional control has been questioned. The report[35] states, among other things, that there can be large differences between the expected runway friction, based on measurements, and an aircraft's actual directional control and braking capacity on a wet runway. The texture of the runway also has great importance for directional control and braking capacity, and the report demonstrates the benefit of a grooved surface on the runway.

The pilots on IRA 762 stated that they attempted to steer the aircraft both with the rudder pedals and with the nose wheel steering when the engine failure occurred. The nose wheel's position after the incident indicates that the steering wheel for the nose wheel steering had been used in order to increase the steering angle in addition to what can be achieved with the rudder pedals.

Furthermore, a rattling sound can be heard on the cockpit sound recording which may come from the nose wheels which, instead of rolling in the direction of travel, may have vibrated against the runway surface in a transverse position. However, the aircraft's heading was not affected by the fact that the nose wheel's steering displacement had increased from the six degrees maximum displacement angle achievable by means of the rudder pedals to the nose wheel position which was noted after the incident.

1.16a.10 Applicable BCL-F[36], Runway maintenance at approved airports

The Swedish Transport Agency's regulations on runway maintenance at airports are based on Standards And Recommended Practices (SARP) in Annex 14 of the Chicago Convention[37] – Aerodromes. Sweden has informed ICAO[38] of certain deviations from SARP in Annex 14, including friction measurement and reporting of braking action. In Sweden, this takes place with standardized measuring equipment for continous measuring and the statement of a friction coefficient as a measure of braking action.

Responsibility for operation and runway maintenance lies with the airport manager, and measures to be taken for winter runway maintenance are described in BCL-F 3.2, Subsection 8.1.1, which was applicable during the incident:

a) Inspection of the movement area including measurement of precipitation depth and braking action on the runway system.

b) Reporting of conditions in the movement area to air traffic control or to the airport manager where there is no such entity.

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[34] Air Accidents Investigation Branch.

[35] AAIB –, 1-2009 G-XLAC.

[36] BCL – Bestämmelser för Civil Luftfart (Regulations for Civil Aviation).

[37] The Chicago Convention of 1944 concerning international civil aviation.

[38] ICAO – International Civil Aviation Organization is a specialized agency within the UN.

c) Measures for improvement of such a scope that the goals which apply to each section of the facility are achieved.

When measuring braking action, standardized measuring equipment shall be used and current information on the runway condition and on the winter runway maintenance be available at the airport's air traffic control.

At commercial airports with code number 3 or 4, measurement of braking action shall take place at least four times per day, except for where the friction coefficient can with certainty be considered to have a value of 0.40 or better. The first measurement shall be made in the morning before the first known take-off or landing and other measurements thereafter shall be distributed evenly across operating hours. In addition, measurement of braking action must be taken as soon as there is reason to assume that a measured value of the braking action upon a new measurement would deviate from the applicable value within one of the sections by 0.05 units or more.

The relation between the measured value for the friction coefficient and braking action and the published phraseology for reporting from air traffic control to aircraft and the MOTNE[39] code for telex are given in the table below (BCL-F 3.2. Subsection 8.2.8):

Braking action, measured value	**Braking action, phraseology**	**Braking action, MOTNE code**
0.40 and above	Good	5
0.39 to 0.36	Good to Medium	4
0.35 to 0.30	Medium	3
0.29 to 0.26	Medium to Poor	2
0.25 and below	Poor	1
Unreliable	Unreliable	0

Fig. 30. Table of calculation methods for braking values.

Measures for improvement of braking action shall encompass the entire length of the runway and at least 4/5 of its width; however, at least on 40 m width for runways wider than 40 m. If improvement of the braking action is temporarily not possible for the entire length of the runway and 4/5 of the runway's width, this shall be reported, upon which the braking action on an untreated area is stated.

When improving the braking action, the aim shall be to achieve conditions which are as even as possible on the entire improved surface. Special chemical preparations may be used for improvement of braking action in the movement area.

1.16a.11 Standardized measurement equipment for friction measurement on runways

Friction measurement at Arlanda and other large Swedish airports are performed routinely with what is known as an Airport Surface Friction Tester (ASFT), previously SAAB Friction Tester, a method for "continuous friction measurement" which has been used in Sweden since the mid-1970s. The system has been developed from an earlier system, the Bromsvagn BV:11, which in terms of system engineering is very similar to ASFT but is installed on a trailer which is towed by a passenger car.

The ASFT system consists of a car with a fifth wheel which can be lowered to the ground with a certain force and braked separately from the car's other braking system. The measurement principle is based on the skiddometer principle, i.e., the measurement wheel is

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[39] MOTNE – Meteorological Operational Teletype Network Europe – European network for standardized reporting of weather and operational conditions at airports.

forced to rotate by means of a gearing, with a periphery speed which is slower than that of the reference wheels.

The fifth wheel will thereby be braked and rotate with approximately 15% skidding, which at normal speeds has proven capable of providing maximum friction. The extra wheel has a type of tyre which emulates the friction characteristics of an aircraft tyre as closely as possible. Normally, a tyre with a tyre pressure of 700 kPa is used and whose performance resembles the characteristics of an aircraft tyre. The pressure in the tyres of the aircraft in question (A300-600) should be 194 psi (approximately 1.35 MPa) for the main wheels and 144 psi (approximately 993 kPa) for the nose wheels[40].

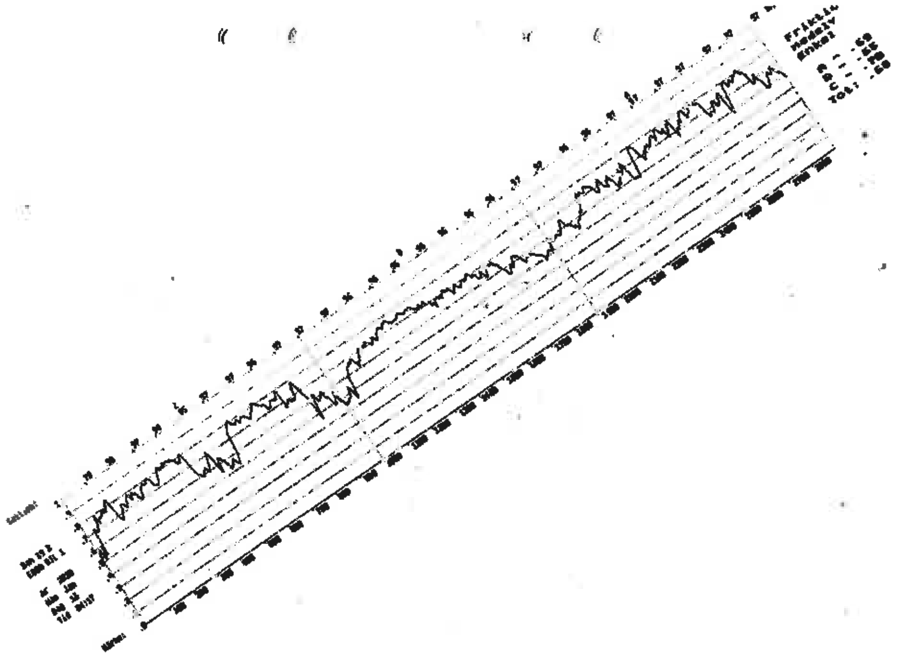

Fig. 31. Friction measurement at 04.17 hrs on runway 19R.

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[40] Airbus A300-600 Airplane Characteristics for Airport Planning.

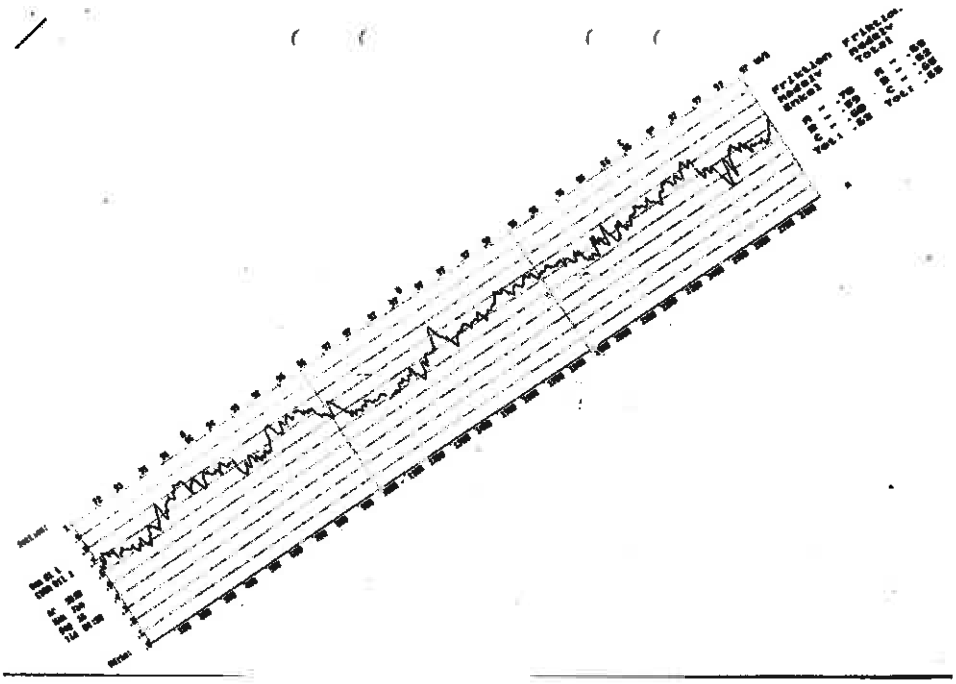

Fig. 32. Friction measurement at 04.20 hrs on runway 01L.

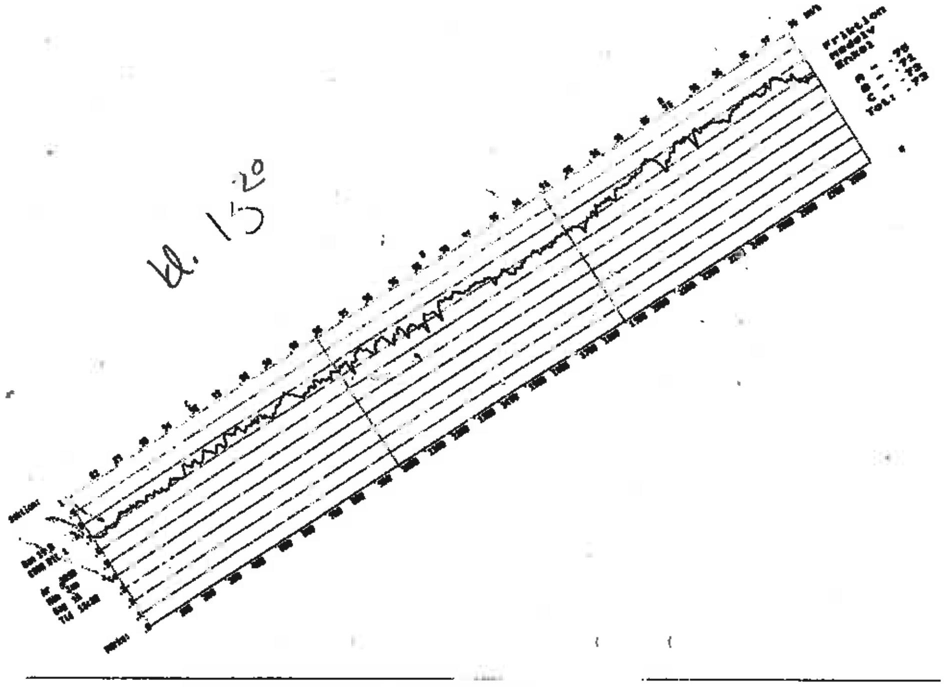

Fig. 33. Friction measurement at 13.20 hrs on runway 19R.

The measurement wheel is braked until skidding arises and the braking force is recorded digitally and printed in a diagram in the vehicle. The measurement takes place continuously and at a speed of approximately 95 km/h and is performed approximately 7,5 metres on both sides from the runway's centre line. The measurements begin and end approximately 300 m from the ends of the runway, in order to facilitate acceleration and braking of the measuring vehicle.

According to ICAO annex 14, (aerodrome standards), such measurements of runway friction shall take place 3-5 meters from the runway centreline, on both sides. The Swedish AIP prescribes that the measuring shall be performed at a distance of 5-10 meters. This difference from ICAO annex 14 is not published neither in annex 14 nor in the Swedish AIP.

The system is calibrated to reassemble the braking action values given in the table in Fig. 30 above. The runway is divided into three sections, A, B and C, and the mean value for the measurements within each section is presented, as is any prevailing contamination on the runway. The result of the friction measurement is presented in code form in METAR and Met Report, and via ATIS[41] transmission. Experiences of friction measurements and correlation with braking action with the ASFT system in Sweden have been generally good.

```
ARLANDA DEPARTURE ATIS VICTOR.
TIME 1120.
RUNWAY 19 RIGHT.
BRAKING ACTION GOOD TIME 0910 CONTAMINATION DAMP RIME OR FROST
COVERED WITH AND ICE 1 MILLIMETRES 10 PERCENT ANTIFREEZE.
ARRIVAL RUNWAY 26 BRAKING ACTION TAXIWAYS MEDIUM TO POOR
BRAKING ACTION APRON POOR.
MET REPORT WIND 160 DEGREES 5 KNOTS.
VISIBILITY 10 KILOMETRES.
CLOUD BROKEN 1 THOUSAND 8 HUNDRED FEET.
TEMPERATURE MINUS 1.
DEWPOINT MINUS 3.
QNH 1035 HECTOPASCAL.
ARLANDA DEPARTURE ATIS VICTOR.
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Fig. 34. Printout of the most recently available ATIS transmission prior to the incident. Times given in UTC.

The system does, however, have certain limitations in temperature conditions around zero degrees and with the presence of contamination on the runway, such as water or slush. It is common practice for operators to have special education and training programmes for take-off and landing on runways in winter conditions, where attention is paid to limitations and risks.

A Communication from the Swedish Civil Aviation Safety Authority (MFL) no. F 3/84, 8 NOV states:

> Experience has shown that braking values measured with BV:11 or the Airport Surface Friction Tester (ASFT) fitted with low-pressure tyres can yield misleadingly low values for Aircraft when the runway is covered with slush or wet snow, even if the layers are negligible.

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[41] ATIS – Automatic Terminal Information Service – automatic radio transmission of weather and other important conditions at the airport.

The same MFL notes:

> If the temperature falls below 0°C, the use of urea can lead to the formation of slush also at lower temperatures.

It is also stated in MFL F 3/84 that: the runway temperature can be 5 - 10°C lower than the measured air temperature and ice can therefore form despite the fact that the stated air temperature can be several degrees above freezing point. In such conditions, the measurement must be accompanied by a special code which indicates that the measurement is unreliable.

Urea, which is a carbamide, has been replaced as a chemical anti-skid treatment agent at Swedish airports with a formiate, which has a superior melting effect on ice compared to urea, according to the report "Nya avisningsmedel och asfaltbeläggningar"[42] (New de-icing agents and asphalt surfaces).

1.16a.12 Reporting the results of the friction measurement

The conditions in the movement area were reported by runway maintenance staff to the air traffic control on a designated form, Protocol for brake testing. The following information shall be included: Braking value/Conditions on runways, taxiways and aprons. There is a special column for Remarks on the form.

1.16a.13 Friction measurements on the day in question at Arlanda Airport

Prior to the departure time for IRA 762, runway 08 was in use for take-off and runway 19R for landing. For performance reasons, the crew requested to use the longer runway 19R for take-off. IRA 762's take-off was the first of the day on this runway.

Braking tests had been carried out with ASFT on runway 01L/19R prior to the incident, between approximately 04.15 and 04:20 hrs and at around 10:30 hrs – see protocol in Fig 35 a. The mean value from the measurement in a northerly direction was 63,[43] in a southerly direction 68, and the total mean value was 65. The difference between the highest and lowest friction measurements for each direction was 44 and 39 respectively. For the area between 300 and 350 m from the beginning of runway 19R, the measured friction value was between 40 and 55.

In the protocol the friction is stated as 69, 62 and 65 respectively for the three sections on runway 01L/19R, beginning from runway 01L, and the presence of a 10% covering in the form of 1 mm damp, rime and ice – see Fig. 35a. In the remarks field of the report, it is also stated that friction improvement with formiate had been carried out on runway 01L + runway 08 + exits.

This protocol also seems to have been used to report measurements carried out at around 10:30 hrs with seemingly identical results, the only difference being that the time 04:15 hrs has been crossed out and changed to 10:30 hrs.

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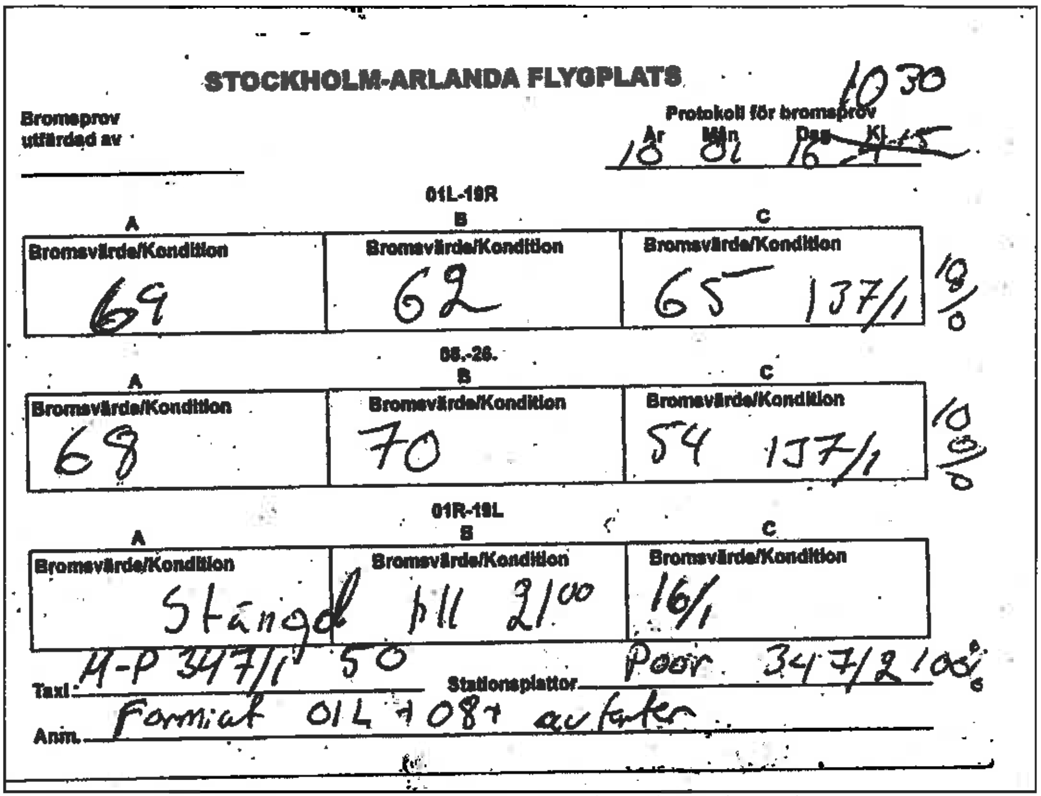
[42] NVF 33 FoU Uppsala 19.6.2006. Tekniska Högskolan, Väglaboratoriet i Finland. (Helsinki University of Technology's Road Laboratory).

[43] The measurement value for the braking action according to BCL-F is the measurement value from the measurement with SFT divided by 100.



STOCKHOLM-ARLANDA FLYGPLATS 10 30

Bromsprov utfärdad av

Protokoll för bromsprov
År Mån Dag Kl.
10 02 16 ~~4.15~~

01L-19R

A	B	C	
Bromsvärde/Kondition 69	Bromsvärde/Kondition 62	Bromsvärde/Kondition 65 137/1	10/9/0

08.-26.

A	B	C	
Bromsvärde/Kondition 68	Bromsvärde/Kondition 70	Bromsvärde/Kondition 54 137/1	10/9/0

01R-19L

A	B	C
Bromsvärde/Kondition Stängd till 21^{00}	Bromsvärde/Kondition	Bromsvärde/Kondition 16/1

Taxi: M-P 347/1 50 Stationsplattor: Poor. 347/2 100%

Anm. Formiat 01L + 08 + avfarter

Fig. 35a. Protocol from friction measurements, 04.17 hrs, 04.20 hrs and around 10.30 hrs.

[text in figure 35a:]
STOCKHOLM-ARLANDA FLYGPLATS = STOCKHOLM-ARLANDA AIRPORT
Bromsprov utfärdad av = Braking test executed by
Protokoll för bromsprov År Mån Dag Kl. = Protocol for braking test Year Month Day Time
Bromsvärde/Kondition = Braking value/Condition
Taxi = taxi
Stationsplattor = Aprons
Anm. = Remarks
[handwritten text]
Stängd till 21.00 16/1 = Closed until 21.00 hrs 16/1
Formiat 01L + 08 + avfarter = Formiate 01L + 08 + exits

The airport has confirmed that formiate was already spread on the day before the incident and that the runway was swept the following morning.

Approximately 35 minutes after the incident, a new friction measurement was carried out on runway 01L/19R, Fig. 33. This friction measurement shows generally higher values, 75, 71 and 73 for the respective sections and a mean value of 73. The difference between the highest and lowest friction values was on that occasion approximately 19.

The runway surface temperature was not measured on any of the measurement occasions.

The pilots' latest available data for the runway conditions was reported in the ATIS transmission (Victor) at 1120 hrs (UTC), Fig. 34. For runway 19R, the braking action was stated as "Good", with a covering of damp, rime and frost as well as a 1 mm covering of ice on 10% of the runway surface. It was also stated that antifreeze had been applied. For the taxiways, the braking action was stated as "Medium to Poor" and for the aprons "Poor".

The actual friction values for the runway were not stated in the ATIS transmission which the pilots noted. The reason for this is that values ≥ 0.40 are only presented as "GOOD" in the ATIS transmission. The runway conditions that the pilots would expect for the impending take-off were therefore a runway friction of 0.40 or higher and 10% contamination from patches of ice and other degrading contaminants.

1.16a.14 Morning and afternoon weather conditions

SHK has analyzed METARs from the day in question. For interpretation of the video recordings made before and after the incident as well as still images taken after the incident, weather data from after the incident has also been included. Between 1050 hrs and 1150 hrs there was snowfall, with a visibility distance of 7-, >10- and >10 km respectively for the three observations. For a period of three hours after the incident, there was precipitation in the form of snow or snow grains and 8 km visibility in four out of eight reported METARs.

SHK has received an analysis of the weather conditions at the time of the incident from SMHI. SMHI states that there were periods of light snow between 1000 hrs and 1500 hrs. Freezing rain was not reported in METAR, but according to SMHI there was a small possibility that there may have been some freezing rain between the observations.

The runway conditions for runway 01L were stated for the period 0720 hrs to 1050 hrs in code form as – R01L/710152, for METARs at 1120 hrs and 1150 hrs as R01L/710156 and at 1320 hrs once more as R01L/710152. In plain language, this means 10 % ice covering with a depth of 1 mm. The friction coefficient was 0.52 for the first and last periods and 0.56 for the intermediate period.

1.16a.15 Other observations of runway conditions

On the cockpit recording from the aircraft, the commander is heard warning the co-pilot, who was maneuvering the aircraft, to be careful with engine thrust before the aircraft had been aligned in the take-off direction in order to avoid sliding off the runway.

The co-pilot told SHK that the runway surface had a different appearance along an area of approximately 15 m around the centre line compared with the runway's outer parts. The middle part was said to be damp while the surface outside of this area had a different quality.

The video recording taken from the cabin during the aircraft's way to the runway shows that the runway was mostly greyish-black and smooth with areas of a more greyish colour towards the edges. Around 5 m from the left edge of the runway, a greyish longitudinal strip is seen, and at the runway's outer edges, a wavy edge in the transition between the runway and the snow-covered area outside of the runway is seen.

In the video recording taken from the viewing point on the ground, certain observations can be made concerning the aircraft's movement and the condition of the runway. Immediately after the flame's emergence, the aircraft seems to slide sideways somewhat at the same time as the aircraft yaws to the left. It looks as though the aircraft skids for a brief moment. The flame from the left engine is reflected in the runway surface. See Fig. 2. When the aircraft approaches the edge of the runway, the reflection of the landing lights is also visible in the runway surface. When the aircraft approaches the runway edge, a white splash is seen to arise around the landing gear.

SHK has had the Swedish National Laboratory of Forensic Science (SKL) examine the video recordings taken from the viewing point on the ground and from inside the aircraft cabin, including Fig. 2, and still images taken after the incident, including Fig. 2. The question was whether there had been a contamination on the runway at take-off and whether the white splash around the landing gear had arisen while the aircraft was on the runway or whether it arose outside of the runway.

SKL has come to the following conclusion:

"The results suggest that there is contamination in the form of snow, ice or slush on the runway and that it is not free from contamination".

SKL could however not conclude on the matter of the white splash arising around the landing gear. The expert opinion from SKL is found in Appendix 3 to this report.

Both SHK and the airport staff have photographed the runway and the aircraft after the incident, see figs. 35b and 50. Judging by the images, the runway seems to have been covered with a grey contamination, in contrast to the appearance of the runway in the video recordings. Tracks from the aircraft's wheels are clearly seen in the contamination on the runway and in the snow outside of the runway. The landing gear is fitted with wheels mounted in pairs with a common axle and the main landing gear each has two pairs of wheels mounted in tandem. Double wheel tracks from main landing gear and nose landing gear can be seen on the runway surface in the images.

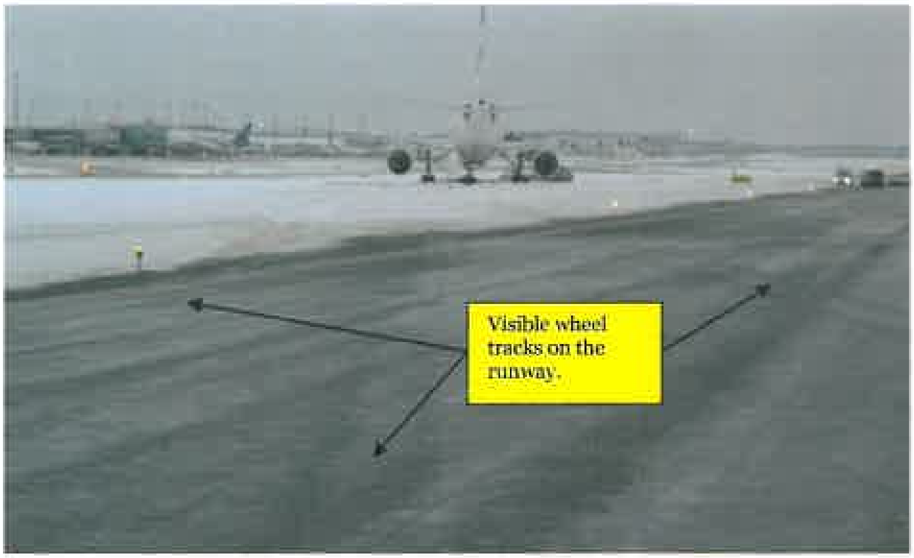


Fig. 35b. Tracks on the contaminated runway surface. Photo: Swedavia.

It can also be mentioned that the friction at the beginning of the runway on an otherwise contaminated runway which is used for frequent take-offs can be affected positively on account of the hot exhaust gases from the engines of aircraft taking off. However, no other aircraft had taken off from runway 19R on the day in question.

1.16a.16 Aquaplaning

Aquaplaning can impair both the braking capacity and directional control of an aircraft on the ground. Important factors for the emergence of aquaplaning are speed, gas pressure in the tyre and the texture of the runway surface. Three types of aquaplaning (hydroplaning) can occur; viscous, dynamic and aquaplaning as a result of viscous or dynamic aquaplaning if a film of water vapour arises under a stationary tyre.

Viscous aquaplaning can arise with a depth of water less than 0.025 mm, while dynamic aquaplaning can arise with a minimum water depth of 0.25 – 0.76 mm, depending on whether the tyres are worn or new. An empirically based formula for calculation of the speed at which dynamic aquaplaning arises for a stationary wheel has been developed by the UK accident investigation authority AAIB, among others. The formula is expressed as

$9\sqrt{p}$, where p is the gas pressure in the tyre expressed in psi (pounds per square inch). With values for the model of aircraft in question, the range in which dynamic aquaplaning arises is approximately 108-125 knots.

1.16b Tests and research - technical

1.16b.1 Technical inspection of the aircraft

A preliminary inspection of the aircraft was conducted at the site of the excursion. Apart from a quantity of metal fragments found in the exhaust section of the left engine, only minor damage to the aircraft was established. Metal fragments could also be recovered on the ground outside of the runway, along the path the aircraft took.

After the aircraft had been checked and the landing gear inspected by the operator's technicians, it was salvaged from the site and brought into the hangar for continued technical inspection.

1.16b.2 Initial technical inspection of the left engine S/N 705207

Before the left engine was replaced, a further inspection of the engine was performed, including a limited boroscope inspection of the combustion chamber and turbine sections.

During the boroscope inspection, extensive thermal damage was established, as well as mechanical damage to the inlet guide vanes and to blades and guide vanes in the high pressure turbine (HPT) and in the low pressure turbine (LPT). In the low pressure turbine front stage, several turbine blades were missing. A closer examination of the turbine housing of the low pressure turbine stages one and two revealed two small holes around five by five millimetres. It has not been possible to conclude if material passed through them.

1.16b.3 Decision concerning the inspection at Lufthansa Technik

SHK decided to commission Lufthansa Technik (LHT) and its engine overhaul shop in Hamburg which holds an LBA[44] and FAA repair and overhaul authorization certificate, allowing them to repair and return to service General Electric Company Aircraft Engines (GEAE) CF6-80. The decision was based on the fact that the workshop had previously carried out maintenance on engine modules for the operator and that previous inspection documents were available.

1.16b.4 Handling and inspection of the engine outside of SHK's control

Following the initial examination at Arlanda, the engine was transported to Germany for technical examination at LHT. The operator carried out the engine shipment on behalf of SHK. Due to various circumstances outside of SHK's control, the engine was at a later stage transported from Germany to Tehran without any qualified examination having been carried out.

Without authorization from SHK, the operator on its own initiative in Tehran removed the HPT and LPT from the engine. With no third party oversight during the engine disassembly in Tehran there's the possibility that not all of the diffuser aft air seal debris was captured for metallurgical evaluation. The HPT was partly removed and inspected on site by the airline's technicians. The airline has authorization to replace modules on this engine type but does not have permission to repair or overhaul turbine modules.

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[44] LBA – Luftfahrt-Bundesamt – The German CAA.

During the inspection, extensive damage to blades and guide vanes was discovered in both HPT and LPT, which was documented with photos. No written report of the examination has been presented.

Following the inspection of the HPT and LPT modules by the operator, the engine modules were mounted back into the engine and transported to LHT in Hamburg where it arrived approximately eight months after the accident.

1.16b.5 Technical inspection of the left engine at LHT

After a substantial delay, (see 1.18.2), technical inspection of engine CF6-80C2A5 with serial number 705207 was carried out by LHT. Participating in the investigation were - apart from SHK - the accredited representative from the German accident investigation authority BFU,[45] a representative from the engine type certificate holder (GE) and airline representatives. Decisions concerning the scope and execution of the inspection were made by the Swedish accident investigation authority following consultation with the participating parties. The result of the examination has been compiled by LHT in a separate report. The objects found to be of interest for detailed analysis were examined by LHT's materials laboratory and have been presented in a separate report, see Appendix 4.

An initial meeting with all concerned parties was held in Hamburg on 27 October 2010. SHK's proposed planning of the work was approved with virtually no changes. The changes which were made were related to discoveries during the course of the work and access to resources during removal. A status meeting was held before the end of the working day in order to clarify the results that had been achieved and further work. A number of issues were conveyed to GE during the initial work, but most of the questions were not answered until several weeks later.

The following presents a summary of the preliminary result of the examination.

Fan, compressors and combustion chamber
No fault or anything abnormal was ascertained which is assessed to have been able to influence the sequence of damage.

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[45] BFU – Bundesstelle für Flugunfalluntersuchung – The German aviation accident investigation authority.

High Pressure Turbine, HPT Nozzle STG1

All HPT nozzle guide vanes had extensive impact damage from the "turbine side". Its rear edges were severely mangled and partly torn away. Extensive mechanical impact damage was also found on the sheet-metal windage covers, which cover the guide vanes' mounting bolts and hold them in place. Section 1.16b.9 discusses the parts of the diffuser aft air seal that were originally located between HPT stage one, guide vanes and turbine.

Fig. 36. HPT guide vanes stage one. Photo: SHK.

The compressor's rear support, Compressor Rear Frame/ (Stationary Seal Support)

Sealing surfaces for the diffuser's forward seal (Diffuser Front Seal) were intact and had normal wear. Sealing surfaces in the form of the stationary honeycomb for the diffuser's aft seal (Diffuser Aft Air Seal) were torn away. The bolts which hold together the forward and aft seals against the diffuser were overstressed and sheared off. The edge of the seal normally lies parallel with the engine's longitudinal axis, but in this case it was angled outwards at 45°. Extensive impact damage was ascertained on the parts of the module that were directed towards the HPT disc stage one.

Fig. 37. Stationary seal, forward and aft (honeycomb completely torn away). Photo: SHK.

High Pressure Turbine, HPT

All blades were damaged through mechanical impact. The tops of the blades were entirely or partly torn away.

Fig. 38. HPT disc and turbine stage one with Diffuser Front Seal.
Photo: SHK.

Impact damage was found on the forward side (Aft Looking Forward) of the HPT stage one disk.

Seven of the eighty bolts which axially secures the stage 1 HPT Blade retainer to the stage 1 disk, also known as the 1st stage HPT blade retainer "Hook Bolts", were found broken just under their windage cups. Six of these seven bolts were adjacent to each other. One broken bolt was located 12 bolt holes beyond the others.

Fig. 39. HPT stage two. Photo: SHK.

Five of the severed bolt parts, with their locknuts, were found in the space between the compressor's rear support, Compressor Rear Frame and HPT.

The diffuser's aft seal, Diffuser Aft Air Seal, was missing from the diffuser's part assembly, Diffuser Assy. Parts of the seal were found in the space between the compressor's rear support, Compressor Rear Frame and the high pressure turbine, HPT. Some of these had become wedged in the guide vanes for high pressure turbine stage one.

Low Pressure Turbine, LPT

All five stages of the turbine, both blades and guide vanes had extensive damage. The damage decreased the further back in the engine the stages were examined (higher number of turbine stage). The turbine housing was also severely damaged with two penetrations and a number of considerable deformations in a radial direction.

Throughout all five stages of the low pressure turbine, impact damage to both the low pressure turbine blades and guide vanes were observed. The amount of damage decreased further back in the low pressure turbine module. The low pressure turbine case was examined and found to have penetrations measuring around five by five millimeters. It has not been possible to conclude if debris passed through the holes. The LPT case was also observed with a number of case deformations in the radial direction.

Fig. 40. LPT guide vanes and turbine blades stage two. Photo: SHK.

Presence of impurities in the oil system

Initially, before the sequence of the engine failure was clarified, impurities in the oil system were a lead in the investigation. Inspection of the chip plugs[46] gave a clear indication that the oil system was not contaminated and that no bearing race was on the way to being damaged.

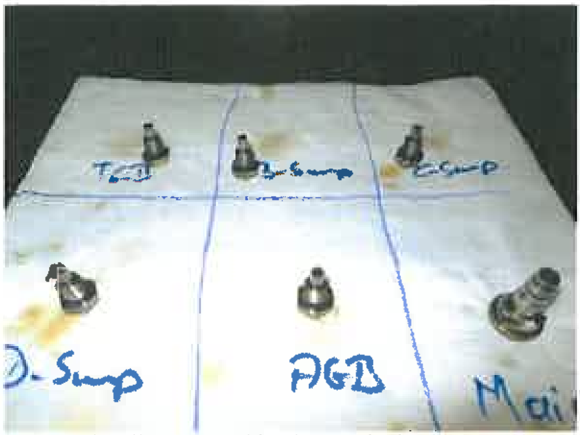

Fig. 41. The oil system's chip plugs; only the D sump (LPT) plug had traces of magnetic material. The number of chips was normal for the operating time. Photo: SHK.

1.16b.6 *Metallurgic examination of critical engine components*

After the engine components behind the high pressure turbine's guide vanes had been removed, a number of issues arose. Apart from the diffuser aft air seal, see Fig. 42, there was a need to analyse the sequence of failure on the high pressure turbine blade bolts in stage one (Hook bolts), the high pressure turbine stage one (3 blades were inspected), the bolts which hold the aft and forward diffuser seals and a number of fragments from the oil system's D sump.

Of the parts analysed, it was discovered that the majority had secondary damage and that the sequence of failure on the diffuser aft air seal was the primary damage in a sequence of failure that is unknown at this time. LHT concluded that the seal came loose due to micro cracks in the nine attachment lugs that hold the seal against the diffuser. The attachment lugs are to have come loose, and the ring to have expanded radially outwards and come into contact with the stationary honeycomb seal. See Fig. 42.

Neither GE, SHK nor Volvo Aero (VAC) were in agreement with the LHT's conclusions in this regard.

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[46] Chip plug – Strategically placed magnetic detectors in the oil system.

Fig. 42. Fragments of the diffuser aft seal analysed by LHT.
Photo: LHT.

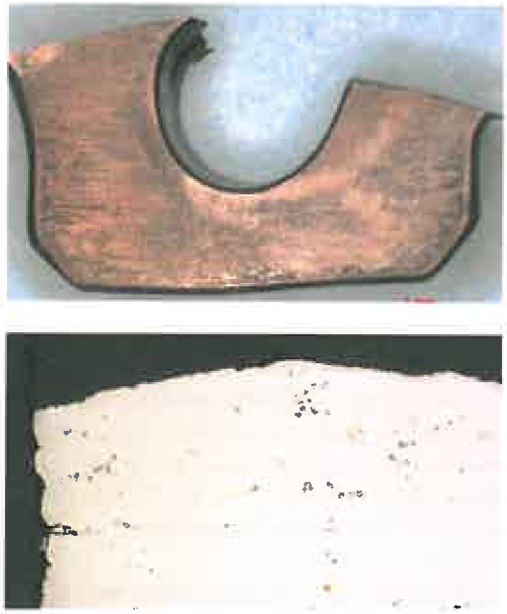

Fig. 43. Cross sections of the attachment lug with micro cracks, diffuser aft air seal. Photo: LHT.

It could also be established that LHT's laboratory examination did not encompass all fragments which have been deemed to be of interest. Some of the fragments found at the very rear of the low pressure turbine had not been analysed.

1.16b.7 Volvo Aero Corporation laboratory

After summarizing the results of LHT's laboratory report HAM TQ/M Report 2010 611, SHK and GE agreed that the sequence of failure reported was less probable. SHK therefore contacted Volvo Aero Corporation (VAC) and received confirmation that the company had specialist knowledge of the alloy from which the diffuser aft air seal was manufactured. VAC was therefore commissioned to perform an in-depth analysis of the concerned parts from the engine and the diffuser aft air seal.

A crucial question was whether GE would be able to accept VAC's access to the information in the case on account of the American trade embargo against Iran. After a short time, it was established that VAC could start its work and that GE Aviation was of the opinion that VAC's participation was within the area of application (scope) of "Export License IA-13352", see 1.18.2.

1.16b.8 VAC's analysis

VAC was given access to the same material analysed by LHT's laboratory. In some cases, the objects were embedded in test blocks for test preparation in optical microscopes.

Fig. 44. Fragments analysed by Volvo Aero Corporation. The piece marked in red is a piece of the edge of the diffuser aft air seal. Photo: SHK.

VAC's review soon revealed that the remaining parts of the diffuser aft airseal checked by LHT did not include any parts with areas where the fatigue cracks which later resulted in the final fracture would have started. The encircled area marked in red in Fig. 44 proved to be the only fragment of the fragments provided by Iran Air and LHT where both the parent material and the machined Dabber TIG Weld material remained.

Other parts were thrown out on to the runway and the area between the runway and the taxiway during the engine failure. At the time of the incident, this area was covered in snow. VAC's report is reproduced in Appendix 5.

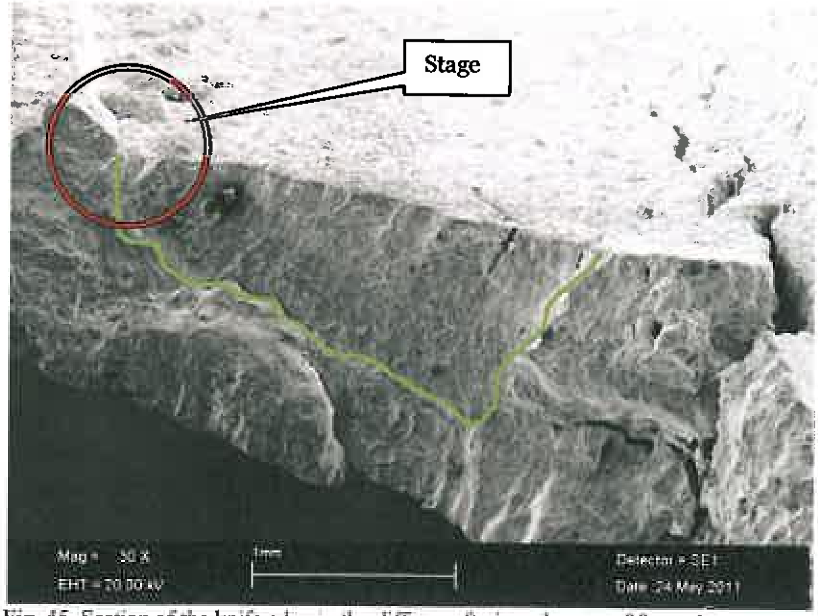

Fig. 45. Section of the knife edge in the diffuser aft air seal – one of four edges. Fatigue zone with crack initiation. Photo: VAC.

Fig. 45 also shows that the crack initiation of the secondary crack has occurred in the parent material. Note the stage between the parent and weld material. The stage is within the machining tolerance of 0.2 mm, but generates a stress concentration factor of 2.5 when bent in the plane of the figure. The retrieved piece of the seal teeth does however not have crack initiation.

Conclusions of the Volvo Aero Report:

1. The small area of fatigue observed on one of the seal teeth remnants appears to be secondary and not related to the primary fracture initiation.
2. The seal teeth were dabber TIG weld repaired.
3. The primary fracture was not found or was consumed during the event.

1.16b.9 Engine flight time status and cycle status

According to the aircraft's technical documentation, the left engine with serial number 705207 was installed on 31 August 2007. The work was carried out in Tehran by the operator's own technical personnel. The engine accumulated 5998 hours and 1491 cycles "on wing" prior to the incident. During this period until the incident, no modules were overhauled.

The main engine modules have no limitation as regards flight hours, only cycles (number of flights). The limitation with regard to cycles per component in each module is stated in the section of the engine's maintenance manual that deals with airworthiness. If the trend monitoring shows that the engine's performance lies within prescribed values, operation continues until a cycle-limited component falls due. The table in Fig. 46 is a summary of the status of the modules at the time of the incident.

Module no.	Name	Cycles since overhaul CSO	LLC[47] Limiting component for this individual	Remaining cycles
1	Fan	8784	15000	6216
2	LPC	8640	19600	10960
3	HPC	1491	3371	1886
5	Flame tube	1614	No limit	No limit
6	Inlet guide vanes	1491	No limit	No limit
7	HPT	5385	9000	3615
9	LPT	8640	17400	8760

Fig. 46. Engine module status with regard to cycles; for module four, see Fig. 47.

1.16b.10 History of Module 04, serial number 5206

Diffuser Aft Air Seal
Part number: 9272M20P10, serial number: BTABR518.
The seal was originally mounted in the engine with serial number 705206 and was removed on 10 October 2002 for overhaul. On this occasion, the edges of the seal were repaired for the first time. The seal was released to service on 28 November 2002.

The seal was reinstalled in the engine with serial number 705205 and removed once again on 5 January 2007. Measurements indicated that the edges of the seal teeth were below permissible nominal dimensions and that certain measures were necessary. No welding was required, so the seal was only repaired by means of surface treatment. The seal was released to service on 2 March 2007 and installed in the engine with serial number 705205. After a few months, the engine sustained FOD[48] and the aft air seal was removed for inspection.

On 31 August 2007, the operator's workshop installed module number four, which included the diffuser aft air seal with serial number 705207. The module was installed on this engine until the incident with the aircraft at Arlanda on 16 January 2010.

Event	TSO[49]	CSO[50]	TTH[51]	TTC[52]
Installation Engine 705206	0	0	0	0
Operation	12 992	3 771	12 992	3 771
Overhaul/Repair	0	0	12 992	3 771
Installation Engine 705205	0	0	12 992	3 771
Operation	467	123	13 459	3 894
Overhaul/Inspection	467	123	13 459	3 894
Installation Engine 705207	467	123	13 459	3 894
Operation	5 998	1 491	19 864	5 508

Fig. 47. Operational data diffuser aft air seal P/N 9272M20P10,
S/N BTABR 518

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[47] LLC – Life Limit Cycle, limiting the number of cycles.

[48] FOD – Foreign Object Damage, damage caused by foreign objects.

[49] TSO – Time Since Overhaul.

[50] CSO – Cycles Since Overhaul.

[51] TTH – Total Time Hours.

[52] TTC – Total Time Cycles.

1.16b.11 Analysis of the engine's performance in operation

According to the operator, the engine performance is recorded during every flight. The recording is performed manually by the pilots. The recorded engine data is processed continuously in a data system called SAGE which is supplied by the engine type certificate holder GE.

From SAGE, different types of trends – and performance curves – can be extracted which can be used to assess the condition of the engines and to identify any abnormal changes in performance and vibrations. Such analyses are performed continuously for all engines in operation.

The pilots are also instructed to report any abnormal engine events, such as overtemperature.

According to the operator, there is nothing in the monitoring of the engine's performance which indicates that the engine in question had been subject to anything abnormal in operation. During the period the engine was installed in the aircraft, it has functioned with no remarks.

1.16b.12 The engine TC holder's analysis of available performance information

The available performance information has been submitted to SHK and forwarded to the engine type certificate holder for analysis.

According to the type certificate holder, the operator's method for performance monitoring is standard for the engine type. The performance trends produced indicated that the engine has undergone a normal performance degradation during the time it has been installed in the aircraft. There is nothing in the performance information to suggest that the engine has been subjected to anything in excess of the monitored standard parameters or any other abnormal event.

1.17 Organizational and management information

1.17.1 General

Iran Air was established in 1961 through a merger of two smaller companies. The company, which is state-owned, operates a fleet of around 50 aircraft, including the types Airbus, Boeing and Fokker. Its route network stretches over the Middle East, Europe and Asia. The base of operations and head office is located in Tehran.

The company has its own organizations for training, engineering and operational handling, but has difficulties with parts supply and technical maintenance due to the prevailing political situation with an embargo on goods and services.

On 6 July 2010, the European Union announced in a legal notice that Iran Air was no longer permitted to operate to EU airspace with the aircraft types Boeing 747 (all models), Airbus A320 or Boeing 727. The decision was based on deficiencies found during SAFA inspections and an audit performed at the company's base in Tehran.

The company was however given permission to continue limited traffic – with the volume of operations (frequencies and destinations) prevalent at the time of the decision – within the EU with the aircraft types Airbus A300, A310 and Boeing 737. The restrictions are stated in reason 69, article 1 and Appendix B in Commission Regulation (EU) No 590/2010, OJ L 170, 6.7.2010, p.15.

1.17.2 *The pilots' education and training*

According to an interview with the company's chief pilot, all type education and training of the pilots on Airbus A300 have taken place in accordance with the manuals and training syllabi issued by the type certificate holder. The theoretical part of the training – "ground training" – is conducted at the company's training centre in Tehran.

The practical part of the training has been conducted by the company's own flight instructors and took place at Lufthansa's training centre in Frankfurt and/or Emirates training centre in Dubai, where simulator training and associated training have taken place. According to the chief pilot, engine failure at low speeds was included as part of the simulator training on the type. The Airbus FCTP (Flight Crew Training Program) for flight crew transition includes low speed rejected take-off scenarios. An animation of a previous incident in Munich in 2005 was used as an example of the consequences of differentiated engine power at low speeds. See chapter 1.18.5.

The company's own instructors are also used for recurrent training of the pilots. Following the incident, the recurrent simulator training has been supplemented with a scenario similar to the incident at Arlanda, which is now a mandatory part of the training.

According to information from the company's chief pilot, only some 50% of the pilots – on the first attempt – were able to keep the aircraft on the runway in a simulated sudden loss of engine power at the speed that applied when the incident occurred. It should be noted that the pilots were informed that a sudden engine failure would be simulated. The runway conditions were programmed to correspond to MEDIUM/POOR braking action.

Upon repeated training of the scenario, there was a marked increase in the number of pilots that were able to keep the aircraft on the runway.

The current FCL[53] rules in JAR[54]-FCL/Part FCL, with regard to mandatory "Rejected take-off" training is covered in Part-FCL appendix 9 / JAR-FCL 1.240 and 1.295. Both documents require training and checking of "*rejected take-off at a reasonable speed before reaching* V_1". The requirements do however not specify type of engine failures or at what speeds they should occur.

1.18 Additional information

1.18.1 *Information from the engine type certificate holder*

Previous Diffuser Aft Air Seal failures

A technical representative from the type certificate holder (TC) participated, during the disassembly in LHT's engine shop, in the work meetings which were held daily for management of the disassembly work and analysis of the findings made. Initially, no information was received from GE that the CF6-80C2A5 Diffuser Aft Air Seal had caused any known operational problems.

In November 2010, some days after the disassembly of the turbine at LHT was completed, a conference call was scheduled with the involved parties. At the conference, SHK was presented with previously completely unknown information on failures resulting directly from fatigue fractures in the diffuser aft air seal. At the time, a total of four cases were known, Iran Air being number three.

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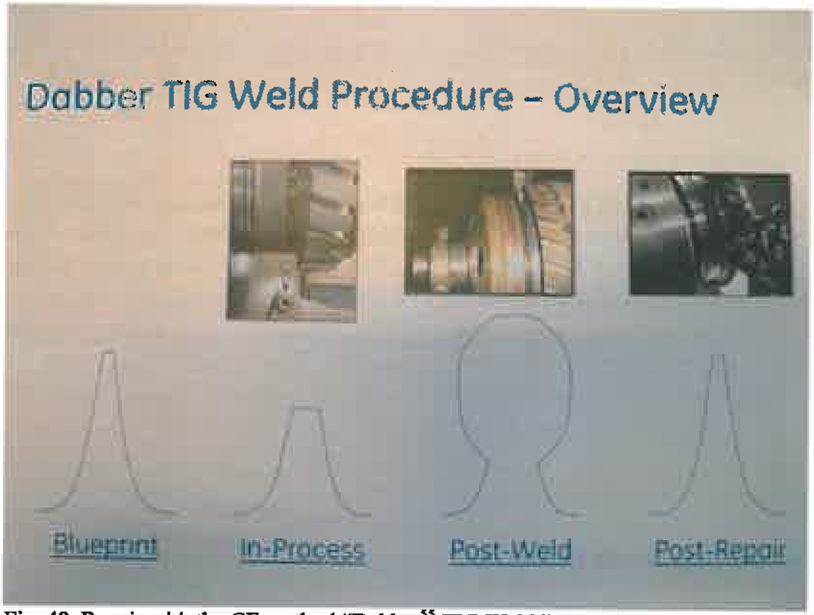
[53] FCL – Flight Crew Licencing.

[54] JAR – Joint Aviation Regulations.

A thoroughly prepared presentation with images of failed diffuser aft air seals was presented with operational data. A common factor was that all parts had been repaired with a method approved by GE known as the "Dabber TIG-Weld repair".

The method involves the application of a pulsed TIG weld in a machine, where the part to be repaired is rotated as in a lathe. Surplus material is machined by means of cutting, subsequent heat treatment, and finally a protective thermal barrier coating is applied to the entire seal area. Fig. 48 shows a schematic sequence of how the stages of the processing are carried out in principle.

The seal material is Inconel 718. During a repair, the seal edges are dabber-welded in an age-hardened state (aged). The risk for crack formation is thereby greater in weld and heat-affected zones. For newly manufactured engine parts using TIG Weld operations, however, Inconel 718 is always welded in a solution-heated state. The material is then more ductile and has lower hardness.



Dabber TIG Weld Procedure – Overview

Fig. 48. Repair with the GE method "Dabber[55] TIG Weld ".

In spring 2011, an operators' conference on CF6-80C engines was held. It emerged that there had been two further failures of the Diffuser Aft Air Seal which were unknown to GE. In the summer of 2011, additional information was compiled. In September 2011, the following six cases had been identified, see Fig. 49

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[55] As in "dabbing"; indicative of the technique.

Date	Operator	A/C	Incident	Seal TSN	Seal CSN	Comment
9 Jan 2002	A	B747-400	Overhaul	36 396	4 497	Unknown no. of repairs
15 Mar 2004	B	B747-400	IFSD[56]	38 376	8 447	3 Repairs
31 Mar 2009	C	MD-11	IFSD	60 965	10 618	2 Repairs
4 Sep 2009	D	B747-400	RTO[57]	80 419	10 628	3 Repairs
16 Jan 2010	E	A300-605ER	RTO	19 864	5 508	1 Repair
23 Jul 2010	F	A300-600	IFSD	32 885	17 329	3 Repairs

Fig. 49. GE compilation of known failures of the Diffuser Aft Air Seal. The investigated incident is marked in light green colour.

It is worth noting that all the seals have been repaired, one or more times. The fracture has taken place after relatively few engine cycles (1,500 – 3,000) since the repair. CF6-80C2 Engine Manual Dabber TIG Weld Repair (72-53-07, repair 003), is a substantiated repair which requires any maintenance provider to have their repair process reviewed and approved by GE Aviation. GE has examined the qualifications for performing the repair and did not identify any deficiency in the repair procedure which could explain the known failures. The repair documentation has remained unchanged since 6 March 2005.

Operational statistics

The number of units replaced with new parts during maintenance is relatively small.

Of all engines in operation of model CF6-80C, an average of 600 high pressure turbine units are overhauled in engine shops each year. By the middle of 2011, this group of engines had together produced $172.5*10^6$ flight hours.

Part sales of part numbers 9272M21P01 to P07 have at most been five units per year, with an average of 2.42 units per year calculated over a period of twelve years ending in September 2011.

From this it is clear that a large number of seals have been repaired with the Dabber TIG Weld method. It is not possible to establish with reasonable certainty the number of repaired units as there are currently nine workshops/locations approved for this method of repair. It should be observed that the six known failures with diffuser aft air seals have together undergone at least 13 repairs.

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[56] IFSD – In Flight Shut Down, the engine shuts down during flight.

[57] RTO – Rejected Take Off, aborted take-off.

1.18.2 *Political issues*

Background

After the failed engine had been removed from the aircraft in Stockholm, contact was made with Lufthansa Technik (LHT) concerning inspection and examination of the damaged engine. LHT is an authorized engine shop with permission to perform maintenance and overhaul on the engine type in question, GE CF6-80C2A5F.

As it was not practically feasible to initiate the inspection immediately, it was decided in consultation with the operator that the engine would be flown to Frankfurt for storage pending a "time slot" for the inspection at LHT. It was most probable that the work would be carried out at the workshops in Hamburg, though support would be required by resources and expert knowledge from the engine type certificate holder in the USA.

Meanwhile, the accredited representative from the USA's accident investigation authority, NTSB, had notified SHK that U.S. sanctions against Iran would require that a licence be granted before U.S. support could be provided by the NTSB or GE.

This requirement also affected LHT. LHT offered assistance but would only participate pending approval of the GE export license with them as a party.This was necessary because of the potential transfer and thus export of technical data to the Iranian entities as part of the investigation.

Preparation

In cooperation with the NTSB, GE applied for an export license in order to legally participate in the investigation. In the application, GE included the NTSB and Lufthansa Technik as participating parties within the scope of the requested export license.

The first contacts concerning application for exemption from the embargo were made at the end of January 2010. Three U.S. Government agencies were involved in reviewing and approving the license application.

The final permission, issued by the Department of the Treasury, Washington, was addressed to General Electric Aviation for participation in the investigation of the failed engine. The permission took the form of a licence (No. IA-13352) with departure from the otherwise applicable American trade embargo (*Iranian Transactions Regulation, 31 C:F:R part 560*), and contained an approval for the TC Holder to participate in the work with a view to facilitating examination and analysis of the engine failure.

The licence was issued on 21 June 2010 and sent to SHK on 6 July the same year. The handling led to the investigation being delayed by approximately five months partly caused by the prevailing political situation. After the formal go-ahead had been obtained, contract negotiations concerning the inspection could be commenced with Lufthansa Technik in August 2010.

1.18.3 *Gender equality issues*

No circumstances have been observed that indicate that the present incident or its effects were caused or affected by the men and women involved not having the same opportunities, rights or obligations in different respects.

1.18.4 *Environmental aspects*

The incident has had no known environmental consequences.

1.18.5 Similar incidents – operational

Excursion as a result of asymmetric thrust has occurred previously with a similar Airbus aircraft. The incident occurred in Munich in 2005 with an Airbus A310-300. The friction coefficient on the runway was stated as 30 (medium). When take-off thrust was initiated, the engines accelerated at different rates. The thrust levers were therefore retarded, to just a few seconds later be increased again.

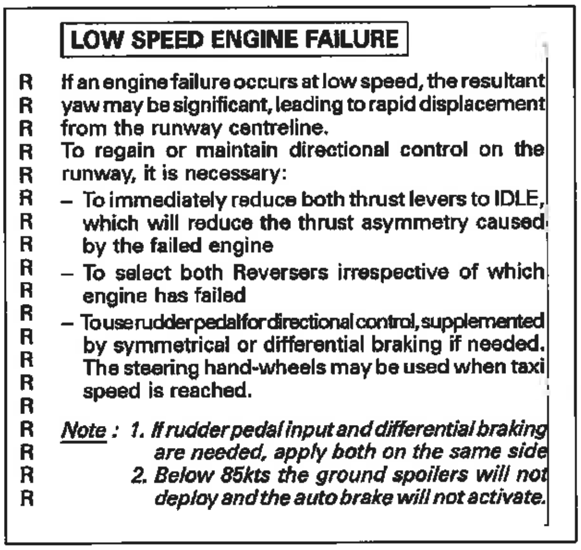
The engines also responded asymmetrically at this point – left engine 96% and right engine 56% N1. Despite the fact that the crew immediately retarded both thrust levers, the aircraft could not be prevented from yawing and running off the runway. The incident did however occur at a very low speed and therefore did not lead to any significant damage.

1.18.6 Measures taken

Following the incident, the operator Iran Air has requested that Airbus supplement the training manual with training for sudden loss of engine power at low speeds (engine seizure/low speed).

The operator has also included the scenario of the incident at Stockholm/Arlanda Airport in the simulator training of the company's pilots on the aircraft.

After the serious incident in Stockholm the TC holder released the FCTM (Flight Crew Training Manual) to all operators. The recommended procedure for engine failures at low speeds has also been revised. The valid revision (July 2012, REV34) is presented in fig. 49b below.



LOW SPEED ENGINE FAILURE

If an engine failure occurs at low speed, the resultant yaw may be significant, leading to rapid displacement from the runway centreline.
To regain or maintain directional control on the runway, it is necessary:

- To immediately reduce both thrust levers to IDLE, which will reduce the thrust asymmetry caused by the failed engine
- To select both Reversers irrespective of which engine has failed
- To use rudder pedal for directional control, supplemented by symmetrical or differential braking if needed. The steering hand-wheels may be used when taxi speed is reached.

Note : *1. If rudder pedal input and differential braking are needed, apply both on the same side*
2. Below 85kts the ground spoilers will not deploy and the auto brake will not activate.

Fig. 49b. Valid procedure in A300 FCTM.

1.18.7 The concept of safety in civil aviation

According to the manual issued by ICAO – the Safety Management Manual or SMM – the concept of safety can be defined as follows:

"The state in which the possibility of harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level through a continuing process of hazard identification and safety risk management".

In the development of safety for commercial aviation, this concept has come to be a cornerstone of the network of global strategies concerning increased aviation safety which over the years has been developed by ICAO. The areas which encompass certification and airworthiness are described in Annex 8 of the Chicago Convention, where general guidelines are found in Chapter 1.2: *"Design aspects of the appropriate airworthiness requirements".*

In this chapter, ICAO has formulated the safety requirements relating to the design of aircraft in accordance with the following:

"The design shall not have any features or characteristics that render it unsafe under the anticipated operating conditions".

Details in the safety and performance requirements for aircraft are regulated by the American and European authorities in charge of matters of airworthiness, i.e., the Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA).

2. ANALYSIS

2.0 Safety

In practice, the application of ICAO's definition of safety (see 1.18.7) presupposes a holistic view of commercial air transportation. It is SHK's view that, the safety requirements for a flight must be maintained at the highest level reasonably possible during all elements of a flight, i.e. from the moment a person enters the aircraft with the intent of flying until the last person has left the aircraft. This approach will primarily govern the analyses presented in this report and the recommendations which these lead to.

2.1 General assessment of the incident

2.1.1 General

Operational

The fact that an aircraft in the transport category was not able to be kept on the runway after an engine failure leads SHK to categorize the incident as very serious. Malfunctions of engines constitute a clearly dominant category among the technical faults and deviations which may occur with multi-engine aircraft.

Engine failures (of various natures) therefore constitute a fundamental – and thereby limiting/determining – part of the safety-based performance requirements when certifying an aircraft. A clear focus has therefore also been placed on the training of pilots and crews with regard to engine failures at critical points of a flight. The training for engine failures has been focused on being able to make decisions on measures in an incident and thereafter continue to handle the aircraft while maintaining the level of safety.

In terms of certification and training, however, the above principles have mainly come to be applied in the speed range which starts at the decision speed V_1. The serious incident which occurred at Stockholm/Arlanda shows, however, that the aircraft – and thereby the passengers – were exposed to risks also during the lower speed range of the take-off phase. For the relatively large speed range during the take-off phase which is critical from a control perspective, present regulations pertaining to yaw stability when certifying an aircraft will probably need to be revised and supplemented.

Technical

The engine failure that occurred – and which was the primary reason for the incident – was probably caused by fatigue cracks originating in the Diffuser Assembly Aft Air Seal teeth parent metal to dabber TIG weld interface. The engine event occurred when the nine bolts which secure the rotating diffuser assembly sheared. This allowed the rotating aft air seal to separate and travel radially outward into the CDP nozzle support, which fragmented the liberated aft air seal, which in turn resulted in seal debris moving into the cavity forward of the stage 1 HPT disk.

Liberated aft airseal debris impacted the forward face of the stage 1 HPT disk and the aft side of the stage 1 HPT Nozzle support and Toroid cover. Liberated aft air seal debris also impacted and liberated seven stage 1 HPT Disk bolts and pieces of the stage 1 HPT blade retainer. Liberated debris entered the engine's gaspath resulting in downstream damage to all hot section (HPT and LPT) airfoils, which resulted in a disruption of gaspath airflow and an engine stall.

The overall assessment of the investigation results suggests that the fatigue had started in the Dabber TIG Weld repaired aft air seal tooth, at the interface of the seal parent metal to weld material. The known cases of engine failure caused by the separation of the diffuser aft air seal have all shared the common factor of having been Dabber TIG Weld repaired on one or more occasions. In an engine event which results in liberated debris entering the engine gaspath, consequences in the form of additional downstream damages are great.

In light of what has been reported, SHK draws the conclusion that the current procedure for repairs of the engine part in question should be called into question.

2.1.2 *The incident*

The engine failure at Arlanda occurred within a speed range which was unfavourable in terms of manoeuvrability, where the speed was relatively low, just under 60 knots, but at the same time not high enough to activate the automatic braking system. The majority of the resulting moment at this speed is compensated by frictional forces at the nose wheel. In this speed range, the fin and rudder do not contribute enough to be able to generate forces which can compensate for a veer.

In the present case, the pilots' actions may be attributed to the fact that their training did not sufficiently cover scenarios like this one. The measures recommended by the type certificate holder have not been followed in all respects during the incident, e.g. no differential braking in the "right direction" was applied. Instead, the pilots attempted to manage the situation by means of measures which could be better described as instinctive countermeasures rather than trained emergency procedures.

SHK considers this incident as an opportunity to draw attention to the need for changes with regard to certification requirements and the training of flight crews.

2.2 Operational

2.2.1 *Runway conditions*

The friction measurements on runway 01L/19R were performed in accordance with the regulations for such measurements, both in terms of scope and time interval. The only deviation found was regarding the measuring distance from the centreline, see 1.16a.11. The report on the runway conditions was also done in accordance with the regulations.

The diagrams from 04:20 hrs and 13:20 hrs indicate that the lowest friction values were found in the same area of the airport in which the aircraft's engine failure and runway excursion occurred. However, the measurement values for the runway friction have not been below what corresponds to "Good" braking action in any of the reports.

However, the air temperature varied between -1 and -2 °C in the hours before the incident. The METAR's in the morning report the runway as being, at least in part, covered by water and ice in the area of the incident, and that there had been precipitation that morning. This is also supported by the photographs taken after the incident, see fig. 3. The wheel tracks visible in the images indicate that there was contamination on the runway when the aircraft veered off, and this irrespective of the fact that there had been precipitation also after the incident.

The co-pilot's statement that the middle part of the runway and the area outside of this looked different indicates the presence of contamination on the runway on both sides of the centreline. It is also clear in the video film taken from the cabin that the runway surface has, in patches, varied blackening, which also indicates an uneven distribution of the contamination on the runway. The fact that both the flame and the landing lights are seen reflected on the ground in the video taken from the terminal building supports SHK´s opinion that the runway was wet and the colour of the surface may indicate that slush was also present. Furthermore, it seems that the reported 10 % amount of contamination is an underestimate.

The weather conditions at the time of the incident correspond well with the kind of conditions that may lead to misleading results of friction measurements with the Airport Surface Friction Tester (see section 1.16a.10).

SHK therefore concludes that there was contamination on the runway in the area of the incident, and that the friction conditions on the runway were uneven and probably worse in the area where the incident occurred, than stated in reports. The SMHI analysis also indicates that there may have been freezing drizzle during the period before the incident.

The friction measurements in the morning show that there were areas of 50 – 150 m in length where the friction properties deviated considerably from the mean value. Since the report submitted at 10:30 hrs was identical to that of the morning measurements, it is not likely that snow sweeping had taken place between these measurements. Sweeping of the runway would have evened out the large differences in the measured friction. When measuring after the incident at 13:20 hrs, the runway friction was varying significantly less along the runway, and the mean value was 8 units higher and corresponding to what is known as "summer conditions". This may indicate that the runway had been swept, or that chemical anti-skid treatment had been used and that this had taken place at some point between 10:30 hrs and 13:20 hrs.

The contaminated surface must be concluded to have affected the friction negatively, however not to the extent of causing aquaplaning since the aircraft speed was too low for that.

Fig. 50. (See also fig. 35b). Tracks on the contaminated runway surface. Photo: Swedavia.

It should also be mentioned that the area in which the engine failure occurred lies outside the boundary of the area where the friction measurements were performed. The engine failure occurred after rolling approximately 250 metres while the measurements begin only about 300 metres from the runway threshold. The friction at the beginning of the runway had also not been improved by continuous take-offs, as the take-off of IRA 762 was the first of the day on that runway.

2.2.2 *The pilots' planning with regard to weather and runway conditions*

The pilots' decision to use maximum engine thrust (TOGA) for take-off is an indication that they were aware of the conditions on the runway with contamination and patches of ice. The commander stated that he had drawn the attention of the co-pilot – who was to be PF for the flight – to the prevailing conditions on aprons and taxiways and on the runway which would be used for take-off.

The fact that the pilots requested the longer runway 19R for take-off may be seen as a standard measure for an aircraft in this category in the case of a long haul flight and contaminated runway conditions.

2.2.3 *Taxiing out*

When the aircraft was taxied towards the take-off position on runway 19R, both pilots stated that this was executed very slowly in consideration of the surface and the prevailing conditions. At the end of the runway, the commander pointed out to the co-pilot that he should not increase power before they had lined up on the runway because they could otherwise "slide off".

During the interviews, it also emerged that the crew had estimated the braking action to be medium at the beginning of the runway and that visible contamination outside of the runway's centre line had been observed.

With regard to the crew's actions, it can be established overall that they were probably well aware of the conditions and acted appropriately in consideration of the prevailing –

and anticipated – conditions on taxiways and on the runway that would be used for take-off.

2.2.4 *The take-off*

The pilots had decided to perform a rolling take-off; i.e. the aircraft would not be stopped but take-off thrust would be applied while rolling. It is the commander who is responsible for the decision as to which take-off method shall be used. In the present case, with friction values down to 0.40 on a runway with patches of ice, it can be difficult to execute anything other than a rolling take-off as the aircraft may begin to slide if take-off thrust is applied with brakes activated. The commander's decision to execute a rolling take-off may therefore be considered as justified.

The initial stage of the take-off sequence was then carried out in accordance with the company's current procedures with the co-pilot as PF. When the engine failure subsequently occurred, at a speed just under 60 knots, the co-pilot still had his hand on the thrust levers. The procedure for control of the thrust levers during the initial stage of the take-off sequence had previously been a subject of discussion, as the type certificate holder's manual used by the company contained certain ambiguities.

Following the incident, the manual has been revised so that when CM1, (Crew Member 1, the pilot in the left seat, normally the commander), is PM, he or she shall take over the thrust levers when these have been set in the position for take-off. After analysis of data from the FDR, SHK can however establish that the changes would probably not have had any significant effect on the time factor in the sequence of events with regard to the handling of the thrust levers in the present case. The commander would probably not have retarded the levers any quicker than was done by the co-pilot.

It can be noted from interviews and CVR recordings that the commander did not call out any commands upon the engine failure, and only took control of the aircraft after the co-pilot had retarded the thrust levers. This is a deviation from the procedure published in the company's manuals.

Both pilots have stated that full rudder was then applied at the same time as braking was initiated. The recommended procedure to use full thrust reversal, as per the manual, was not used during the incident. Neither of the pilots has been able to provide an explanation for this.

It cannot be said with sufficient certainty whether thrust reversal would have changed the development of the incident, but SHK's assessment is that it would probably not have meant any notable change in the sequence of events. With an estimated reaction time of approximately 1.4 seconds (see 2.3.6) and 2-3 seconds' time taken to operate the controls and for adjustment of the engines' thrust reversal equipment, the thrust reversal would have taken effect when the aircraft's course had already changed by approximately 15° and at a position only just over two seconds from the point at which it passed over the runway edge.

According to the information obtained during the interviews, neither of the pilots has any recollection of having used differentiated braking; they just wanted to reduce the speed of the aircraft. However, the values from the FDR readouts, where the angles of the brake pedals have been converted to pressure, indicate that higher braking pressure was registered on the left side. This issue is discussed further in section 2.3.7.

Activation and use of the nose wheel steering has no separate parameter registered in the FDR. As a result of the activation of full rudder deflection by the rudder pedals, the nose wheel was simultaneously yawed to the right by 6 degrees. The co-pilot has later stated that the commander, at some time during the sequence, also activated the steering via the steering wheel (tiller) in the cockpit. These facts are supported by the fact that the aircraft – after having stopped – was found with the nose wheel at an angle fully to the right.

Fig. 51. The nose wheel angled to the right. Photo: Swedavia.

2.2.5 *The runway excursion*

When the engine failure occurred, neither of the pilots was aware of what had happened. During the interviews following the incident, both pilots stated that they suspected that a tyre explosion had occurred or that they had collided with something on the runway.

The first warning which was announced (probably "*eng no 1 shut down*") came at a late stage when the aircraft had already left the runway. It must be considered as a flaw in the design that such an extensive engine failure does not render an immediate warning via the aircraft's warning system in the cockpit.

The pilots could certainly have read the engine instruments and thus been able to establish that the left engine had stopped. However, the design of the ergonomically located warning lights and accompanying audible signals has been developed in order that the pilots' attention is not required to be turned to e.g. the engine instruments in suddenly arising and critical situations.

Pilots are also generally trained not to pay too much attention to the engine instruments after the required thrust is set, but more to the flight instruments, e.g. speed, and to keep an outside look for obstructions and remaining runway length. It is therefore understandable that the pilots on IRA 762 not immediately recognized the failure.

During the final stage of the aircraft's path, the nose wheel buried itself approximately half a metre into the ground, partly due to the nose wheel being maximally angled to the right. The steering wheel for the nose wheel steering is not intended for use during the take-off sequence as steering via the rudder pedals is considered to be sufficient. However, when an aircraft is about to run off the runway,
it is fully understandable that all means are used by the pilots in attempt to prevent an accident.

Fig. 52. The aircraft after evacuation. Photo: SHK.

When the aircraft came to a stop, the commander made the decision not to carry out all measures according to the "*on ground emergency*" checklist. According to the interview, the commander did not anticipate that there was need for additional measures and also decided, following dialogue with air traffic control, not to initiate an emergency evacuation of the aircraft. The basis of the decision was that no fire – or risk of fire – was imminent.

The engine seizure did not cause any external damage like separated doors or ruptured casings or uncontainments. With no engine fire warning – or other indications of fire – the decision by the commander not to order an emergency evacuation of the aircraft must be assessed as correct.

2.3 Analysis of the FDR

2.3.1 General

The data used in this report is based on the extraction of recorded FDR parameters carried out by the UK accident investigation authority, AAIB. Decoding of the recorded values is based on parameter lists provided by the type certificate holder. In some of the graphical presentations included in this report, the recorded values have been concatenated into curves. In other cases, a time interval is presented – which is dependent on the quantity of recorded data per time unit – where the time of a specific event within the interval cannot always be precisely determined.

In the analysis, SHK has chosen to use the recorded values which can either be verified by means of two or more parameters or which have been verified via other data. For example, the video film taken during the incident (see 1.1.4) has been used in the analysis to ensure the accuracy of certain values recorded in the FDR.

As previously mentioned, the recorded values for the braking did not seem reasonable or expected. Due to this – and the fact that these parameters cannot be verified via other media – a separate test of these recordings was carried out (see chapter 1.16a.2).

2.3.2 The engine failure

Apart from the remaining kinetic energy in the engine's rotating fan, the loss of power took place extremely fast. In the space of only two seconds, the thrust was reduced to approximately 50% and after a further two seconds to approximately 10%. This has been able to be established through a total appraisal of the recorded parameters concerning acceleration, fan rpm (N1) and fuel flow.

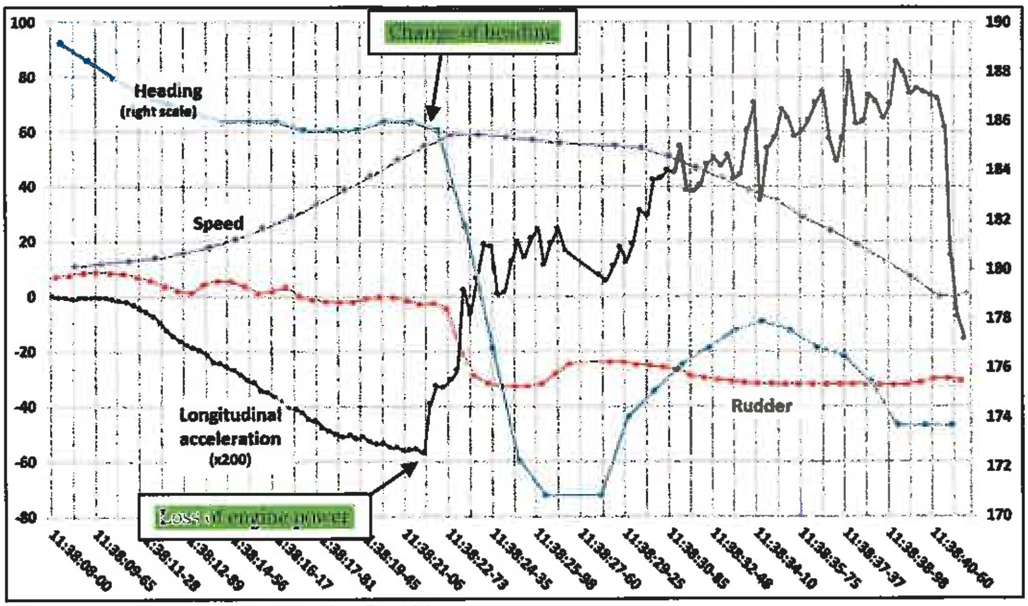


Fig. 53. Data from the FDR. (See also fig. 19.)

Following evaluation of the available parameters, SHK has chosen to use the decreasing acceleration as an indicator of the point in time of the engine failure. According to this parameter, the point in time of the engine failure can be established at 38:21.9 (± 0.12 seconds). Apart from the higher frequency at which the values were recorded, this parameter can be verified in comparison with other data from the engine. In other words, the time of the engine failure has been determined as the point in time when the acceleration decreases due to reduced thrust from the left engine.

Note that in the following time references, hours, and in some sections hundreds of seconds, have been omitted.

2.3.3 *The change of heading*

Data from the FDR has been compared with the measured times from the video film taken during the incident. The time interval when the change of heading of approximately 4° took place to a lower heading is between 22.46 and 23.46.
However, because the rudder deflection (see Fig. 53) is a pilot induced reaction to the change of heading, the latest point in time for the change of heading cannot be after the latest time of the rudder deflection. This reduces the possible interval for the change of heading to have taken place to between 22.46 and 22.68.

An analysis of the video film, in which the initial puff of smoke from the engine has been taken to constitute a time reference point, indicates that the first change of heading can be observed approximately half a second after the engine failure. The time of the change of heading – where the rate of change was initially 4°/sec. – can thereby with high probability be established at 22.5.

Note that in terms of time, the reference point in the video film (the first puff of smoke) has been considered to coincide with the point in time of the engine deceleration.

2.3.4 Rudder deflection

The use of the rudder during the sequence of events can be verified – in addition to by means of recorded data – via the video film and the pilots' witness statements. The values recorded on the FDR concerning the initial rudder deflection should however not be viewed as a reaction to the loss of engine thrust, but rather as a normal reflex reaction from a pilot to a change of heading.

The recorded time for the rudder deflection lies in a time interval between 22.18 and 22.68. However, this interval can be considerably limited because the rudder deflection cannot have occurred before the point in time of the change in heading, which is why the earliest possible point in time can be established at 22.5. From the measurements made on the video film, it can be established that rudder deflection is also noticeable within a second after the engine failure.

As the pilots' concentration during a take-off sequence is largely occupied by maintaining the aircraft's heading, it is reasonable to assume that the reactions to changes of heading are virtually immediate. SHK has therefore assessed the reaction time of the first corrective rudder displacement at 0.1 seconds after the change of heading occurred. This means that the first rudder deflection should have occurred at 22.6.

2.3.5 Nose wheel steering

The yaw angle of the nose wheel is not recorded as a parameter in the FDR. There are however other facts which facilitate analysis of the changes in the nose wheel's angle during the sequence of events. At the initial change of heading (22.5), the direction of the nose wheel was in line with the aircraft's longitudinal axis as the nose wheel steering via the rudder was not yet activated.

When the rudder deflection followed, the nose wheel angle also increased to at least 6 degrees and when tiller was also applied the angle could have been significantly higher giving a very limited nose wheel side force.

As the facts surrounding the nose wheel – and the nose wheel steering – can only be verified indirectly by other FDR parameters, the continued analysis must be supplemented by data from the CVR. It is not likely that the difference in angle during the initial phase of the incident – between 22.6 and 26.5 – caused any measurable sound.

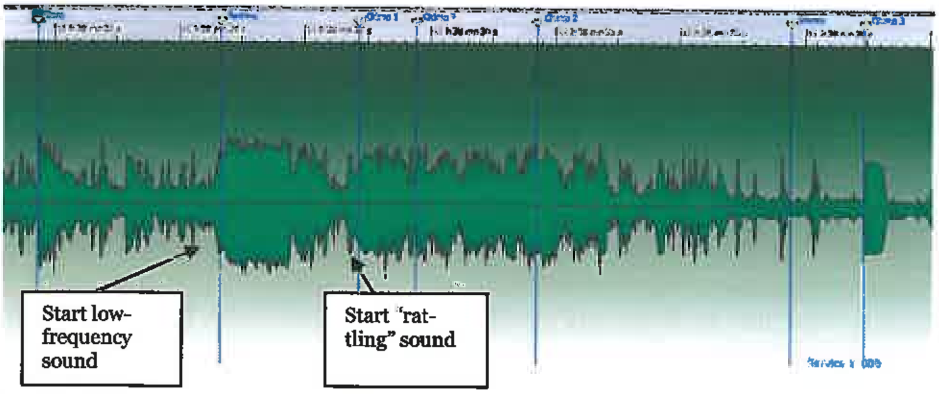


Fig. 54. Audiogram of parts of the incident. Graphics: Magnic AB.

At 26.5, a loud, low-frequency sound is recorded, which continues until 28.3. This sound is probably caused by the commander activating the nose wheel steering via the steering wheel at this point in time and turning the nose wheel to its maximum displacement angle. The increasing angle results in the nose wheel being more or less transverse against the aircraft trajectory, which can be assumed to have generated the sound recorded on the CVR.

The recorded sound of the nose wheel skidding against the surface ceased before the point in time at which the aircraft's nose wheel passed over the edge of the runway. An explanation for this may be that the nose wheel enters the area at the outside edges of the runway where visible contamination has been ascertained, which means that the friction significantly decreases.

The rattling sound – which begins at 29.5 – is most likely attributable to the point in time at which the nose wheel meets the snow-covered area of grass outside of the runway edge.

2.3.6 *Pilot reaction*

According to consistent reports from the pilots' interviews, it was the co-pilot who had his hand on the thrust levers when the engine failure occurred and also retarded the levers after the failure. When the reference point for reduced acceleration is compared with the thrust levers (angle of the thrust lever control), the point in time of the cut off thrust can be established within the time interval between 0.42 seconds and 1.67 seconds after the engine failure.

To facilitate a realistic calculation of when the thrust levers were retarded, one second should initially be counted for the time it takes to make the decision to retard the thrust levers (in accordance with performance calculations at V_1). Other time factors must also be added to this second. The co-pilot was not trained to make decisions that involve aborting a take-off sequence with the subsequent procedure, including cut down of thrust among other measures. Further factors which probably also influenced the time were that neither of the pilots was aware of what had happened and that no warnings were announced in the cockpit.

An assessment of when the thrust levers were retarded therefore places this in the time interval between 1.0 and 1.67 seconds after the engine failure. It is logical to assume that the brakes were not activated before the thrust levers were retarded. On the basis of both instinctive reactions and trained procedures, it can probably rather be assumed that retarding thrust levers and brake activation were initiated simultaneously. With the point in time for brake activation as a comparison (23.25 rounded to 23.3), the point in time when the thrust levers were retarded may be established at 23.3.

This point in time provides a time between engine failure and retarding of thrust levers of 1.4 seconds, which may be seen as a reasonable time in consideration of the conditions described. The time corresponds well with the time interval according to the FDR, which shows that the thrust levers had been retarded to flight idle at 23.46.

2.3.7 *Brakes - general*

After the initial evaluation of the available FDR data concerning the use of brakes, SHK made the assessment that the brake data recorded could not immediately be considered to fulfil accuracy requirements.

There are a number of reasons for taking this position. The first reason is of course the absence of logic with regard to the recorded values, where braking would have been performed in the "wrong direction", i.e., to the left. If an aircraft is found with its nose wheel buried half a metre in the ground on account of the wheel being maximally angled to the right, at the same time as two sources that are independent of each other indicate that the rudder has full deflection to the right, there must be compelling reasons for accepting the braking data recorded in the FDR without question.

In light of the above, SHK decided to conduct supplementary tests of the FDR unit installed in the incident aircraft. As can be seen from the examination results in 1.16a.2, no malfunctions or deviations could be established with regard to the relationship between the manoeuvres carried out in the aircraft and the corresponding recordings in the FDR. The parameters recorded during the incident must therefore be assumed to be accurate.

These facts presented SHK with two questions:

- Why did the pilots apply the brakes asymmetrically and in the wrong direction?
- What effect did this have on the development of the incident?

2.3.8 *Causes of the asymmetric braking*

The natural point of departure for SHK's continued analysis is that the established asymmetry was not the result of intentional action. It is likely that both pilots recounted an accurate recollection when stating that the braking was performed with the intention of stopping the aircraft – not steering it – and that this was perceived to have taken place symmetrically.

The asymmetry which nevertheless arose must therefore, according to SHK, have arisen as a consequence of an unintentional action. It has not been possible to establish with certainty the reason for this, but certain elements can provide interesting contributions to the discussion concerning the cause:

Ergonomic causes

- The simulator tests that were carried out in order to ascertain whether the ergonomic conditions can be assumed to have affected the possibility of symmetric braking did not yield conclusive results. The test persons did not perceive having applied a higher brake pedal pressure on the opposite side to the rudder displacement in a test with symmetric braking, nor that the ergonomic conditions made it easier to brake to the "wrong" side.

  The simulator used for these tests did however have certain dissimilarities with the actual aircraft in question. The steering column with a steering wheel for elevator and aileron control was in this model replaced with joysticks on the side panels.

  When analysing the FDR data, it was revealed that a right bank was performed at the same time as the steering wheel was pulled back somewhat during the initial stage of the sequence of events. SHK does not consider these displacements to have affected the aircraft's conditions or movement patterns because the speed was too low to generate sufficient flight control forces, but leaves the question open as to whether these manoeuvres had any ergonomic side effect on the pilots' movement patterns in the cockpit – for example in the form of asymmetric brake angles.

Operational causes

- Activation of the aircraft's braking system takes place through depressing the blade of the rudder pedals. The pair of brake pedals can be adjusted longitudinally to fit pilots of different hights. If the pedal set is not adjusted to the correct distance, this can entail that full brake displacement cannot be achieved on the side where the pedal is in the position for maximum rudder deflection. In the present case, it was established that there was maximum rudder deflection to the right for almost the entire sequence of events.

It is not unlikely that the pilots' setting of the pedals had been made with a focus on being able to provide full rudder deflection, but that no check was performed to determine whether full brake angle could be achieved at the same time as full rudder deflection. This check is not stated in the aircraft's standard – or expanded – checklists in the operational manual SOP (Standard Operating Procedures). The check was however described in the aircraft's FCTM (Flight Crew Training Manual) which was not, however, available to the pilots at the time of the incident.

SHK considers it likely that the cause of the recorded asymmetric braking values was that the pedal setting was not correctly executed, which meant that full brake displacement on the right side could not be applied at the same time as the right rudder pedal was in the position for maximum displacement.

2.3.9 *Consequences of the asymmetric braking*

From the FDR data, it can be ascertained that braking was applied on both the right and left sides, but that the braking values had been higher on the left side. The tests carried out on the simulator in Toulouse indicated that braking may have been a contributing factor to the aircraft running off the runway. As is detailed in 2.6.3, however, SHK cannot attach full factual status to these tests.

The higher braking pressure generated on the left side would in normal friction conditions contribute to the turning moment caused by the asymmetric thrust of the engines. In the present case, however, friction was reduced, and was probably worse on the left side of the aircraft during most of the time of the incident. Any additional moment caused by a higher braking pressure on the left side could therefore to some extent have been balanced by the inferior friction on the same side.

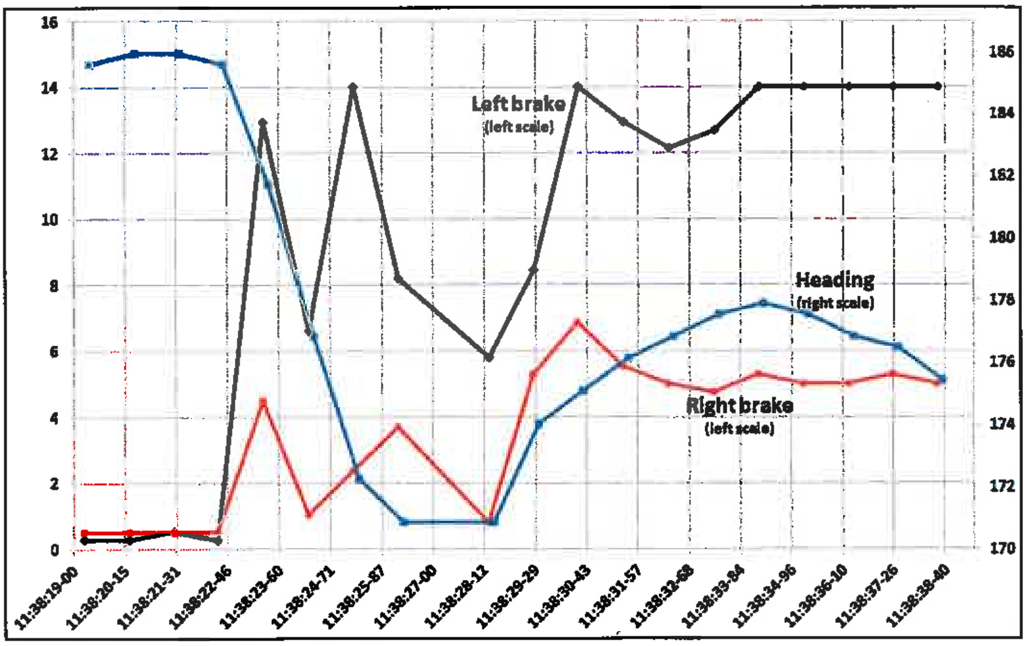


Fig. 55. Brake angles vs change of heading.

As can be seen from the graphical presentation in Fig. 55 above, the main change of heading – and the rate of the change of heading of approximately 4° per second – has not changed discernibly compared with the asymmetric braking values recorded during the same period. The first recorded change of heading began before the first recorded brake angle increases. After this first heading change, the heading follows an almost linear change to a lower heading, reaching its lowest value approximately 15° to the left of the take-off direction of 186°.

The overall conclusion is that no measurable variation of the heading change rate is observable in connection with the recorded brake values. Even though the possibility that the asymmetric braking had a certain effect on the turning moment cannot be excluded, such an impact has, however, not been possible to determine with any reasonable degree of certainty.

2.3.10 *Graphical summary*

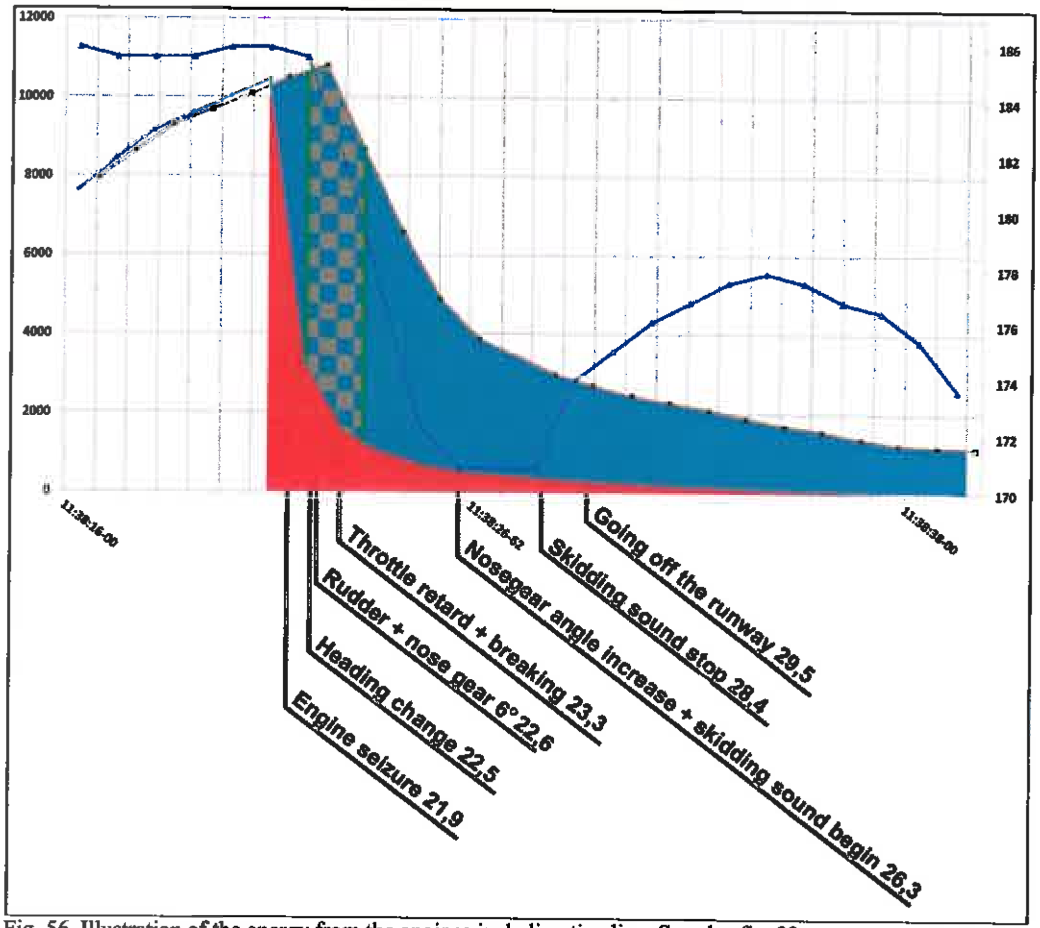


Fig. 56. Illustration of the energy from the engines including timeline. See also fig. 23.

In the diagram in Fig. 56, relevant data from the FDR, with the area of high yawing moment inserted, has been combined with the analysed timeline of the incident. The diagram shows clearly that the force from the excess moment from the situation of asymmetric thrust almost immediately produced the veer.

The measures taken by the pilots – in combination with a possible but undetermined negative impact from the differential braking - could not generate the counter forces required to stop the motion of the aircraft on the remaining runway width with the partly contaminated surface.

2.4 Technical

2.4.1 Iran Air's engine shop

The engine installed in the aircraft in position one (left side) had been assembled by Iran Air's engine shop. At this time, the shop had the capacity/competence to overhaul modules on this engine model. The modules that the engine consisted of had different backgrounds, where module four had previously been installed in an engine with the serial number 705206.

The modules assembled for the engine with the serial number 705207 met the airworthiness requirements with regard to flying time and cycles and complied with the introduced Airworthiness Directives (AD) which applied on 31 August 2007. It has not been possible to monitor to what extent the AD of the type certificate holder's country had been introduced after this date.

2.4.2 Engine operating data

The printouts of operating data inspected by SHK and which Lufthansa Technik examined for the period from 10 October 2009 until the day of the incident did not contain any deviating information which could have given advance notice that the installed engine would perform in a deviating manner. The trends generated by General Electrics' software SAGE did not contain any information which gave advance warning that any of the parameters was on the way to falling outside of permissible limits. The trends were generated by week provided that input data were available.

2.4.3 Diffuser aft air seal

The inspection of the engine reveals that the diffuser aft air seal had completely separated from the diffuser assembly which is mounted on the stage 1 HPT Disk forward shaft. The sequence of failure started when one or more of the four teeth in the seal moved radially outwards due to low cycle fatigue (LCF) and came in contact with the stationary honeycomb seal. A crack originating at the Dabber TIG Weld seal/parent metal interface propagated radially with stable crack growth. The tangential stress reached its maximum on the inside of the rabbet causing an actual rupture when the crack growth changed into being unstable. Stresses then increased on the diffuser vane ring aft rabbet and low cycle fatigue cracking occurred.

Once the crack was long enough in one or more of the four teeth in the air seal, the loads were transferred to the nine rotating diffuser assembly bolts. Bolts sheared which liberated the aft air seal radially outward contacting the nozzle support structure with debris fragments entering the cavity forward of the stage 1 HPT disk and aft of the stage 1 HPT nozzle. At the time of the aft air seal separation, the HPT rotor speed was approximately 10,000 RPM.

Fig. 57. HPT guide vanes stage one with fragments of the diffuser aft air seal. Photo: SHK.

Parts of the diffuser aft air seal were subjected to high temperature when it started to wobble between the stationary seal and the HPT's stage one disc. The normal operating temperature in this area is 600°C. Parts of the aft air seal were flung out radially between the stage one guide vanes and the stage one turbine (disc and blades) and were limited radially by the turbine housing. The gas stream through the turbine had a high pressure (27 bar) and when the movement was limited radially, the smaller fragments (around one cm) of the diffuser aft air seal could not continue radially, but instead remained in the gas stream which hit the stage turbine blades, continued backwards and progressively destroyed both the HPT and the LPT.

The larger parts of the diffuser aft air seal were found in the space between the compressor rear frame and the HPT's stage one disc. It can be seen in Fig. 57 that fragments can become wedged in the sheet metal windage covers, which are positioned radially just inside the stage one guide vanes.

Only one fragment of the seal teeth repaired with the Dabber TIG Weld method has been recovered. One explanation for this is that the majority of the knife edges were ground down upon contact with the static honeycomb seal. The fragments which had come loose from the diffuser aft air seal disappeared at an early stage of the failure through the turbine out into the gas stream and then exited the engine via the exhaust pipe and were thrown out behind the aircraft.

In Tehran there was no external supervision when the HPT module was exposed and SHK does not know if all fragments found were handed over to LHT together with the assembled engine.

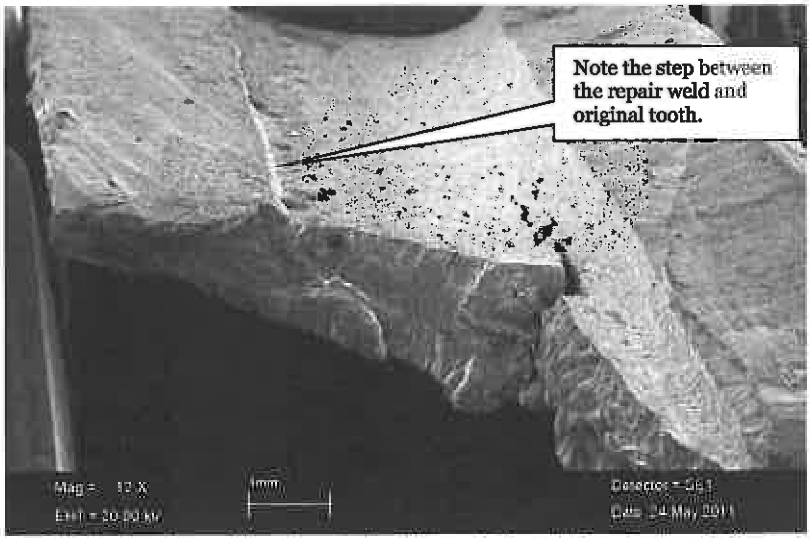


Fig. 58. Section of one of the edges in the diffuser aft air seal. See also fig. 45. Photo: VAC.

Only around 65% of the aft air seal including screws and dampening rings were found. The missing fragments had probably been left on the runway and been sucked up by the snow removal vehicles located at Arlanda. Since so few fragments have been found, a major part of the knife-edge seals must have left the engine at an early stage.

Once the aft air seal separated from the diffuser assembly, seal material fractured a six bolt section of the stage 1 HPT blade retainer, liberating pieces of bolt threads, nuts and retainer material. Thus, the increased amount of debris quickly got into the engine gaspath resulting in downstream damage from the HPT Rotor aft causing an engine stall.

The engine stall is clearly visible in the films taken by onlookers from the station building. As the liberated debris travelled aft down the engine's gaspath, low pressure turbine blades were being broken / separated. With the amount of LPT blade damage fan speed (N1) began to decrease since the LPT didn't have enough blade airfoils to drive the fan.

The damage in the rear sections of the engine decreased gradually as the rpm of the fan decreased. The engine parts found at the very back were primarily turbine blades and a smaller quantity of guide vanes from the previous turbine stages. The guide vanes in LPT stages two to five largely remained in their positions, but with decreasing levels of damage further back in the engine.

2.4.4 *Similar incidents with the diffuser aft air seal*

During the dismantling of the engine's damaged modules at LHT in Hamburg, there was no unequivocal explanation for the engine's sequence of failure. Several different clues were studied where the incident could have started, inter alia, the blade bolts on the stage one turbine (Hook bolts), failure of turbine blades in stage one, failure of the nine bolts on the forward and aft seals of the diffuser and variants of fatigue cracking in the diffuser aft air seal. Only the last of these could have generated the forces necessary to shear off all nine bolts which held the diffuser aft air seal.

When General Electric reported in November 2010 that there were four verified known cases of failure of the diffuser aft air seal with part number 9272M20P10, the entire sequence became clear. During spring 2011, 2 further known cases of failure of the same part number were reported.

During autumn 2011, General Electric has gathered facts and analysed the six known incidents, but has been unable to identify a single common parameter which controlled the incident sequences. However, there is a lot to suggest that the number of repairs per unit could be just such a common factor that affects the mechanical qualities of the seal and thus leads to fatigue fractures.

2.4.5 *Measures to avoid similar engine damage*

The studied cases mentioned in section 1.18 suggest, the likelihood of an aft diffuser that has been repaired several times failing. However, the number of incidents of this nature that have occurred is low compared with the total number of operating hours in this group of engines. Based on a strict certification perspective, it is therefore difficult to justify doing away completely with Dabber TIG Weld repairs on diffuser aft air seals.

The six cases in which the diffuser aft air seal failed featured different models of CF6-80C2. The engines were installed on B747, MD-11 and A300. It is therefore difficult to see type-related deviations dependent on the specific aircraft model or types of operation. Common to these engine models is that they have a high static thrust.

A reasonable balance to avoid taking unnecessary risks is to rule out repeated Dabber TIG Weld repairs to the seal teeth on the diffuser aft air seal. If the change in grain size is examined after a TIG weld, a clear growth in grain size is visible. With the heat treatment sequence after a weld, as specified by General Electric, there is a significant difference to be seen between the parent material, the heat-affected zone and the applied weld.

2.5 Training

The commander stated during the interview that he could not remember any training for loss of engine power at low speeds during the simulator sessions he participated in. The company's chief pilot (Fleet Director) was of a different opinion and stated that training of similar situations had been carried out in the simulator during further training with the company's pilots. Training of low speed rejected take-off scenarios is however also a part of the initial crew transition program issued by the TC holder.

Regardless of the different views on this training issue, it is clear that this element of specific training of "worst case" scenarios during take-off are not included as a mandatory part of neither the basic training nor further training of pilots on this category of aircraft.

In this respect, Airbus A300 is not unique in terms of risk factor and yaw stability during losses of engine power in the lower speed range. Most large aircraft with wing-mounted engines are subject to powerful yaw moments if the thrust rapidly becomes asymmetric.

As previously mentioned, traditionally there is focus on the training of pilots in terms of handling losses of engine thrust in the speed range around V1. This is naturally both beneficial and necessary. However, the purpose of this report is also to shed light on risks in the flight phase from just before take-off power is applied up until the speed (V_{MCG}) at which the aircraft can be controlled with rudder.

Risk factors within this speed range are probably underestimated and often not included in education and recurrent training programs. Apart from the direct increase in risk entailed by the lack of training, indirect consequences in the form of insufficient risk awareness among pilots should also be taken into consideration. Thus, elements that do not need to be trained are not perceived as a risk.

The current requirements in JAR/FCL state that training of rejected take-off at *"reasonable speed before V1"* shall be performed. This requirement leaves however room for interpretation as it does not specify any "worst case" scenario for the aircraft type in question. This could include engine seizure, specified speeds, contaminated surface etc.

SHK therefore recommends that relevant authorities introduce training for sudden loss of engine power at specific low speeds as a mandatory element of the simulator training for pilots on transport category airplanes.

2.6 Operational conditions

2.6.1 Theoretical yaw stability

As is clear from the investigation carried out by KTH (Appendix 2), the yaw stability of the aircraft type upon loss of engine thrust in the lower speed range is largely due to the forces which can be generated through the nose wheel's friction against the surface. The investigation did not include the possible effects of braking or thrust reversal of the engines.

With the calculation methods used, it is clear that the means of counteracting the yaw moment which arises with a sudden loss of engine thrust are limited when the surface is wet and/or friction is reduced. The efficiency of the rudder increases by the square of the speed, and attains the necessary authority from around 100 knots.

The conclusions that can be drawn from the investigation are that sufficient frictional forces at the nose wheel cannot be generated in the lower speed range on a runway with reduced friction. In the event of a loss of engine thrust on a wet or contaminated runway, a yaw moment will turn the aircraft towards the side of the malfunctioning engine. The nose wheel will – irrespective of the displacement angle – skid, i.e, slide over the surface with a direction that deviates from the aircraft's longitudinal axis.

In the present case, it is probably this skidding that can be heard on the CVR recordings and also observed on the audiogram of the acoustic image of the incident. At the same time as the skidding can be heard, a phase begins in which the aircraft has fully opposite rudder deflection and an angle increase of the nose wheel from 6° to the maximum deflection of 65°.

SHK considers the results reported by KTH in its investigation to be in line with the actual course of events. It can thereby also be considered to be proven that the runway was to some extent contaminated, and in any case wet.

2.6.2 The type certificate holder's recommended measures

The type certificate holder's (TC) Flight Crew Operating Manual, FCOM, (see section 1.6b.3) – had as points in its list of actions upon loss of engine power at low speeds that asymmetric braking and thrust reversal shall be carried out.

SHK understands that the TC proposes these measures in order to keep an aircraft on the runway, as both theory and the actual sequence of events show that the other measures which can be applied – use of rudder and nose wheel steering – are not always sufficient.

However, objections can also be raised against the measures proposed by the TC. SHK is of the opinion that the safety concept used by the ICAO, according to which the design shall not have any features or characteristics that render it unsafe under the anticipated operating conditions, should be applied in the present case.Thus, the aircraft type has no limitations issued by the TC regarding the friction coefficient – only a recommendation not to operate under 0.05. In order to be in line with ICAO's definition of safety, the TC should also expound upon how the effect of braking is to be calculated in the event of sudden loss of engine power during operations with low friction coefficients.

The above reasoning is also applicable with regard to the second measure recommended by the TC, namely thrust reversal. According to MMEL (see footnote 27), it is allowed to dispatch the aircraft without the thrust reversal system being operable. However, it is difficult to reconcile ICAO's safety concept with the fact that a system which does not need to be functioning is nevertheless included in a recommended procedure for sudden losses of engine power.

2.6.3 *Evaluation of simulator tests*

Just as training programmes, flight simulators have their primary focus – and thereby their greatest system accuracy – on speed ranges from V_{MCG} and upwards.

The tests carried out in Toulouse on an A300 simulator have certain deficiencies with regard to the capacity to emulate the incident at Stockholm/Arlanda. The sudden engine failure (engine seizure) that occurred could not be programmed in, a deficiency which had to be compensated with a calculated speed reduction.

Nor was it possible to fully substantiate the accuracy of the models used in the simulator for main and nose wheel tire forces and how these forces depended on steering angles and runway surface conditions. A particularly problematic factor for the assessment of the simulator tests has been the fact that the model used was accurate in lateral direction control (nose wheel) for runway conditions down to *icy* runway conditions, while the braking performance (main wheels) not was possible to degrade below *wet* runway conditions.

During the tests, a number of take-off sequences were carried out without the use of brakes. In all of these, it was possible to keep the aircraft on the runway, though this was not in line with the actual sequence of events. When differential braking (to the "wrong" side) was added to the test programme the number of runway excursions increased. The different programming of the wheels has however reduced the possibility to consider the tests as fully reliable for this investigation.

SHK views the simulator tests as very interesting from a broad perspective, but considers at the same time that in the present case it has not been possible to recreate the actual sequence of events with sufficient accuracy. Probably the only way to achieve this would be to carry out all testing "for real" in an aircraft.

2.7 Aircraft certification

The ultimate responsibility for approval and certification of an aircraft lies with the relevant authority of the country that designs an aircraft. However, this process is based on partly shared guidelines, issued by EASA in Europe (CS 25) and by the FAA in the USA (FAR 25).

Requirements for the directional stability of an aircraft during the take-off sequence are not clear until the speed range starting with V_{MCG}, i.e. the lowest speed at which the aircraft's course can be controlled with the use of rudder alone. Before V_{MCG} there are no specific requirements concerning directional stability.

In consideration of the incident in question, there is cause to question the absence of certification requirements in the speed range below V_{MCG}. As V_{MCG} is the lowest speed at which an aircraft can be controlled with rudder alone in the event of sudden loss of engine power on the most critical engine, a natural consequence is that the crew must resort to other methods in order to maintain control – with reasonable, established deviations – within the speed range from application of take off thrust up to V_{MCG}.

The engine failure which occurred during the present incident represents the most difficult – and most dramatic – form of malfunction in an engine, where the consequence is a rapid sequence with a more or less immediate loss of power. The risk of such an engine failure occurring during the take-off sequence is however not in any way negligible, as the take-off is the very phase of flight in which maximum power is used and the load on the engines is at its greatest.

As previously mentioned, a considerable proportion of the certification requirements focuses on the speed range between V_{MCG} (V_1) and V_R, where pilot training pertaining to loss of engine thrust is also frequent and constitutes a mandatory part of both initial and recurrent training. Translated into terms such as "risk time", however, the take-off acceleration from application of take off thrust up to V_{MCG} constitutes a significantly longer risk phase compared with the phase between V_{MCG} and V_R.

Failure to set requirements concerning requirements for the manoeuvrability of aircraft in the event of a sudden loss of engine power for the entire take-off sequence, including the most critical stage, is to accept a risk which according to SHK is not in line with reasonable safety requirements for commercial aviation.

It should be emphasized that these problems are general and not limited to the aircraft type in this incident. They also occur in many other types of aircraft where, naturally, designs with wing-mounted engines constitute the highest risk category in terms of incidents such as the one in question.

SHK will however not submit any detailed proposals for requirement specifications or practices concerning manoeuvrability during the phase in question. On the other hand, it is a natural consequence of the incident that the certification requirements are supplemented with the requirement to demonstrate the aircraft's manoeuvrability during all phases of the take-off sequence.

The requirements should include all phases of the aircraft's planned field of application, i.e. if a design organization intends to certify an aircraft which is also to be used on surfaces with reduced friction, there should be evidence that it is also possible to manoeuvre the aircraft in a safe manner under such conditions in the case of unforeseen events such as sudden loss of engine thrust.

Where any of the aircraft's systems other than the rudder (e.g. thrust reversal) are intended to be used to control manoeuvrability, it should also be demonstrated how the aircraft can be controlled during the take-off sequence with this system inoperable.

This report also raises certain issues concerning the tests carried out during certification of the aircraft's performance limitations in connection with take-off and landing. The design organization needs only to report values for the aircraft's characteristics and performance on dry and wet runways. When the aircraft is to be operated on surfaces which are contaminated and where the friction is reduced, it is the operator's responsibility to perform calculations – and establish limits – under the operating conditions which can be anticipated within the operator's field of activity.

SHK is of the opinion that the lack of governance from authorities in this area may lead to different interpretations with regard to performance and operational limitations, which in turn can have an adverse effect on aviation safety.

2.8 Performance of rescue and medical services

The first ambulance was alerted approximately 6 minutes after the accident alarm and the air ambulance after approximately 10 minutes. An ambulance emergency response vehicle and an emergency physician car were alerted in the intervening period. The final two ambulances were alerted approximately 22 minutes after the accident alarm. From the reported elapsed times, the conclusion can be drawn that the alarm procedure should be made more efficient and quick.

The first medical team's transport departed from the hospital 35-40 minutes after the accident alarm and the second group did not leave the hospital before it was recalled. The transport of medical teams was initiated by means of a call to a transport company to ask whether it could carry out the transport. More detailed planning should be able to result in no unnecessary waiting for the medical personnel to be collected and taken to the site of an accident at which the need for medical care is assessed as acute.

To a certain extent, the reported times can be explained by the fact that the description of the conditions at the accident site contained reassuring reports of the situation on board the aircraft. At the same time, the planning for an accident with a large aircraft at Sweden's largest airport should include an effective procedure for alerting predetermined resources without delay.

2.9 General risk assessment

An excursion of an aircraft during take-off can at first sight seem a relatively trivial incident from a general aviation safety perspective. International regulations govern requirements for both obstacle clearance and design of the surfaces at an airport e.g. a runway.

Excursions often end in the aircraft being quickly slowed once it has passed the runway edge and runs onto a surface with lower surface bearing characteristics. In most cases, the aircraft speed is also relatively low, which means that the risk of serious consequences is reduced. It should however be noted that the speed range in question – and where no guarantees can be made as to the level of control – covers the range from application of take off power to V_{MCG}. For the aircraft type in question, this speed is 113 knots, or just under 210 km/h.

In the incident, the excursion took place at a speed of approximately 60 knots, i.e. just over 110 km/h. There is a considerable build-up of kinetic energy when a mass of 148 tonnes is travelling, out of control, at a speed of 110 km/h. In this case, there were no serious consequences, but with just marginal displacements of the time, the incident could have had much more serious consequences.

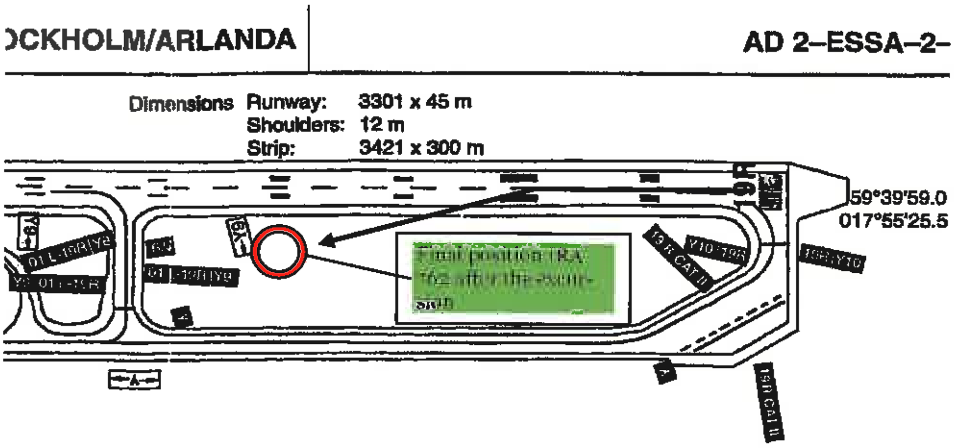


Fig. 59. Overview of the incident area at the airport.

Had the incident occurred just a few seconds later, the aircraft would most probably have run onto taxiway Y9. At the holding point on this taxiway, aircraft are often lined up awaiting take-off. On average, 40% of all take-offs from runway 19R are carried out from the intersection at taxiway Y9.

In the event of collisions between aircraft on the ground, the consequences are incalculable, but statistics on similar accidents suggest that these often end badly. In addition, aircraft about to take off have vast quantities of fuel on board, which increases the risk of fire with even worse consequences.

2.10 Overview of the incident

After normal preparations for flight in anticipated winter conditions, the crew of IRA 762 began a routine take-off procedure with increasing engine thrust during acceleration on the runway. After just over 10 seconds, at a speed of approxmatly 54 knots, one or more edges in the repaired diffuser aft air seal separated, and was triggering a sequence of events that led to a sudden engine failure and loss of thrust.

No warning message of the failure was announced in the cockpit; the pilots only noticed the engine failure through a muffled bang at the same time as the aircraft began to veer to the left. The initial veer, immediately after the engine seizure, was caused by the nose wheel not being able to generate enough force against the contaminated surface in order to counteract the yaw which arose when the right engine – for a duration of approximately 1.5 seconds – supplied full take-off thrust at the same time as the left engine immediately lost thrust, together with the pilot's not applying any differential braking in the correct direction.

Despite the co-pilot's reactions, retarding the thrust levers after just over a second at the same time as applying braking and opposite rudder, the veer could not be corrected and the aircraft ran off the runway. Even if the pilots had used thrust reversal (as recommended by the TC), it is the opinion of SHK that the aircraft may well still have run off the runway.

The forces from the moment in combination with the partly contaminated and slippery surface, probably meant that the pilots had little chance of altering the sequence of events in any decisive manner without the contribution of forces from asymmetric braking in the opposite direction. The moment from the asymmetric braking in the "wrong" direction has probably also contributed to the excursion to a degree, which has not been possible to determine.

In the investigation of this incident, a number of deficiencies and problem areas have been identified:

- Fatigue cracks have very probably developed in a repaired engine part.
- There are no specific certification requirements to demonstrate the manoeuvrability of an aircraft in the event of sudden loss of engine power in the speed range below VMC_G.
- Training for sudden loss of engine power in speed ranges before V_{MCG} is included in the TC holders transition training manual but is not a mandatory element of initial and recurrent training of pilots in general.

The points briefly summarized above constitute deficiencies, each of which has contributed to the present incident, and its consequences. The incident with IRA 762 at Stockholm/Arlanda Airport led to no serious consequences in terms of personal injury. SHK has however highlighted in this report the potential risks of more severe accidents upon this type of event.

With reference to the safety concepts defined in the manual issued by ICAO, SHK emphasizes the following. It is fully possible – and also likely – that all the above points have previously been viewed to be in line with the risk levels associated with continuous commercial aviation safety levels described in the manual.

However, this incident has provided new grounds for assessment for the "continuously ongoing" process concerning risk assessment and risk management that is part of ICAO's definition of safety. It should also serve as an incentive to revise the appropriate regulations in the process to continuously improve aviation safety.

3 CONCLUSIONS

3.1 Findings

a) The crew members were qualified to perform the flight.
b) The aircraft had a valid certificate of airworthiness.
c) FAA Airwortiness Directives adopted until 31 August 2007 had been implemented on the engine.
d) The trends generated by General Electrics' software SAGE for engine one contained no advance warning that any of the analysed parameters might be outside of the permissible interval.
e) The diffuser aft air seal came in contact with the honeycomb seal and parts of it continued out in the gas stream.
f) The diffuser aft air seal was repaired using the Dabber TIG Weld method.
g) Analysis of the materials from the diffuser aft air seal teeth shows that it is likely that the crack was formed in the heat-affected zone adjacent to the repair weld.
h) The pilots were prepared for operations with reduced friction on taxiways and runway.
i) This present take-off was the first of the day on runway 19R.
j) Friction measurements had been performed at 10:30 hrs and the values reported were good.
k) Analysis shows that the friction may have been lower than that stated, and that patches of ice and slush may have been present on a larger section of the runway than stated.
l) Measurement of friction is only carried out on the runway's centreline and approximately 7,5 metres on either side of the same.
m) The change of heading occurred more or less immediately after the engine failure, when the yaw moment was greater than the forces which the nose wheel's friction against the ground could create.
n) The co-pilot was PF and executed the retardation of the thrust levers 1.4 seconds after the engine failure.
o) The aircraft's operating manual contained ambiguous procedures concerning aborted take-off.
p) When certifying large aircraft, no requirements are specified for yaw stability at speeds before the speed V_{MCG}.
q) Training for sudden loss of engine power at low speeds is not a mandatory element in the education and recurrent training of pilots.
r) The investigation was delayed by five months owing to the processing of applications, which was caused by politically determined sanctions.
s) The alerting of medical units was spread out over an extended period of time.
t) According to ICAO annex 14, (aerodrome standards), measurements of runway friction shall be carried out 3-5 meters on both sides of the runway centreline. The Swedish AIP prescribes that the measuring shall be performed at a distance of 5-10 meters. This difference from ICAO annex 14 is not published either in annex 14 or in the Swedish AIP.

3.2 Causes

The following causal factors were identified:

3.2.1 Operational

- Deficiencies in the certification process for large aircraft with wing-mounted engines with regard to requirements for yaw stability in the event of sudden loss of engine power in the speed range below V_{MCG}.

- Deficiencies in the pilot training with regard to training for sudden losses of engine thrust in the speed range below V_{MCG}.

3.2.2 Technical

- Deficiencies in the approval and follow-up of the Dabbler TIG Weld repair on the engine's diffuser aft air seal.

4 RECOMMENDATIONS

ICAO is recommended to:

- Take measures in order for authorities that issue certification directives – the FAA and EASA – to adopt the safety requirements issued by ICAO in Annex 8 concerning safety in large aircraft, so that these are applied during the entire take-off sequence of a flight. *(RL 2012: 21 R1).*

The FAA is recommended to:

- Investigate, in consultation with EASA, the prerequisites for introducing requirements concerning yaw stability in large aircraft in the event of sudden loss of engine thrust below V_{MCG} under the anticipated operating conditions. *(RL 2012: 21 R2).*

- Review and revise processes and permissions issued for the Dabber TIG Weld repair method regarding concerned parts in engines that have FAA type certification. *(RL 2012: 21 R3).*

- Improve processes to expedite safety of flight considerations in granting export licenses and waivers so that political sanctions do not unnecessarily delay civil aviation safety investigations concerning aircraft – or parts thereof – which are manufactured in the USA. *(RL 2012: 21 R4).*

EASA is recommended to:

- Investigate, in consultation with the FAA, the prerequisites for introducing requirements concerning yaw stability in large aircraft in the event of sudden loss of engine thrust below V_{MCG} under the anticipated operating conditions. *(RL 2012: 21 R5).*

- Ensure that initial and recurrent pilot training includes mandatory rejected takeoff exercises that cover events of a sudden loss of engine thrust below V_{MCG}. *(RL 2012: 21 R6).*

EP-IBB CVR Transcript

Irrelevant messages/ information have not been transcribed.

Time:	**Universal Time Coordinated (UTC).** Local Time = UTC + 1 hour.

Src:	**Source of message**
CDR	Commander (Left Pilot)
2CDR	Relief captain (comes into cockpit after aircraft stopped)
FO	First Officer (Right Pilot).
HC	Handling Coordinator
CA	Cabin Attendant/ Purser
Push	Person handling pushback on ground
GND	Arlanda Ground
TWR	Arlanda Tower
R	Rescue personnel

Rem:	**Remark**
P	Persian *(also In Italic)*
A	Cabin announcement
#	Radio communication

Information:	**Message transcribed.**
Text in Italic	*Text translated from Persian to English.* ***Please observe that this is not a certified translation.***
??	Denotes information that has not been possible to interpret, due to disturbances or for other reasons.
?	Either means a question is asked or that the information is uncertain.
( )	Brackets surround information that is uncertain.
[ ]	Brackets surround comments about CVR content.

UTC Time	Src	Rem	Information	Farsi original
11:18:15	CDR	P	*Why don't we go.* [Discussion in Persian about missing passengers. A woman with a child are late but on their way.]	چرا نمیریم پس؟ ...خوب.
11:18:21	CA	P	*Mr. [passenger name] is kindly requested to get in touch with forward cabin. Mr. [passenger name].*	از جناب آقای [نام] خواهش میکنم با قسمت جلوی هواپیما تماس بگیرند. متشکرم. آقای [نام].
11:18:29	SM	P	*Hello Captain, Everyone is onboard, only two passengers were missing, but we have just been informed that they are at the check-in counter and they have 3 pieces of luggage.*	سلام کاپیتان خسته نباشید، همه سوار شدن، فقط دو تا مسافر موندن که سه تا بسته هم بار دارند، به ما اطلاع دادن همین الان دم چکینگ تازه رویت شدن .
11:18:41	CDR	P	*Oooh, They are far away.*	اوه...، خیلی فاصله هست تا اینجا!
11:18:55		P	*Why do you want to get onboard one who is so careless. If I were you I had not taken them to give them a lesson.*	اینها که اینقدر بی خیال و بی غم اند .... من اگر جای شما بودم سوارشون نمی کردم تا یه درسی بهشون بدم.
11:19:05	HC	P	*Captain! It is a lady with a child.... [discussion continues about the not boarded passengers]*	کاپیتان، یک زن و یک بچه هستند.
11:21:36	HC		Hello, load sheet.	
11:21:38	CDR		Is all on board?	
11:21:40	HC		All on board, (we are trying to locate the two missing passengers we will let you know when we have found them).	
11:22:35	CDR	P	*Insert ZFW 117.*	بزن *زیرو فیول ویتو* ۱۱۷ تا.
11:22:42	FO	P	*153 and 800* Sir. [TOW]	۱۵۳ و ۸۰۰ سر.
11:22:46	CDR	P	*No 112* [laughing], *It must be 149.*	نه... ۱۱۲ تا بزن [با خنده] ! ۱۴۹ تا باید بشه .
11:22:56	FO		Almost 149.	*آلموست* ۱۴۹ .
11:22:58	CDR	P	*Yes, insert Zero Fuel Weight 25.4.*	آره. *زیرو فیول ویتم* بزنش ۲۵،۴ .
11:23:09	FO	P	*25.4 Zero Fuel Weight CG (you mean)!*	۲۵،۴ *زیرو فیول ویت* CG (منظورتونه)؟
11:23:17	CDR		[Listens to the onboard music for a few seconds]	
11:23:23	FO	P	*25.8 takeoff CG.*	۲۵،۸ *تیک آف* CG.
11:23:44	FO	P	*152, 162, 164 (after application of wet runway corrections)*	۱۵۲ ، ۱۶۲ ، ۱۶۴ (با *کرکشن*).
11:24:46	CDR		Ground!	
11:24:48	Push		Go ahead Sir.	
11:24:56	Push		Go ahead Captain.	
11:25:08	CDR		OK, would you disconnect the ground power please and the air condition unit.	
11:25:03	Push		OK, disconnecting, thank you.	

11:25:05	CDR		Thank you.	
11:25:15	HC?		[Knocking twice] Now the passengers are on board so everything is okay.	
11:25:19	CDR		What about this one?	
11:25:43	HC?		(That one) okay.	
11:25:45	HC?		[Very weak discussion in the the background].	
11:25:44	CDR		Okay.	
11:25:50	HC?		Thank you very much. Bye bye now.	
11:25:51	FO		Bye.	
11:26:01	CDR	#	Ground ... Arlanda Ground, Iran Air 762 requesting push.	
11:26:07	GND	#	Iran Air 762 pushback approved. Caution push from stand 16.	
11:26:12	CDR	#	Confirm up to stand 16?	
11:26:16	GND	#	Iran Air 762 we are pushing from stand 16 simultaneously.	
11:26:20	FO	P	*(He says that there is a simultaneous pushback).*	(میگه با هم همزمان یکی داره باهامون پوش میشه).
11:26:22	CDR	#	Okay we understand (18) and cleared for push, Iran Air 762.	
11:26:26	GND	#	Scandinavian 1421, due to push from 18, expect to exit apron via ZL via left turn.	
11:26:29	CDR		Ground!	
11:26:30	Push		Go ahead Sir.	
11:26:33	CDR		(Requesting) push?	
11:26:35	CDR		We are ready for push.	
11:26:36	Push		Okay, release brakes and we will commence pushback.	
11:26:38	CDR		Brake release.	
11:26:38	FO	P	*The forward door is still open!*	درجلو را هنوز نبستند !!!
11:26:42	CDR	P	*Yes, close the door.*	در را ببند آره ..!
11:26:44	Push		Negative Sir, the passenger door is still open.	
11:26:47	CDR		Okay, stand by one.	
11:26:54	CDR	P	*It is a pity we have a delay.*	تاخیر خورد ها...
11:27:05			[Cabin chime]	
11:27:06	CA	P	*Can I have the information?* [Flight information]	اطلاعات را میتو نم داشته باشم؟ [اطلات پرواز]
11:27:07		P	*Information.* [To the First officer]	اطلاعات. [خطاب به کمک خلبان].
11:27:10	FO	P	*35000 feet, 5 hours.*	۵ ساعت، سی و پنج هزار پا.
11:27:13	CDR	P	*[Name of First Officer]! Read below the line.*[In the check list].	[نام]، *بیلو ده لاین* رو بخون. *بیلو ده لاین* آره.
11:27:15	FO		Windows and doors.	
11:27:16	CDR		Closed!	

11:27:17	FO		(Beacon).	
11:27:18	CDR		On.	
11:27:19	FO		Parking brake.	
11:27:20	CDR		Released for push.	
11:27:21	CDR		Ready for push.	
11:27:22	FO		Transponder.	
11:27:23	Push		Okay, release brakes.	
11:27:24	CDR		Brake release.	
11:27:26	FO		Transponder mode Sierra. Before start and push complete.	
11:27:28	CDR		(Roger).	
11:27:34	CDR	P	*Push!* [and more comments in Persian to CA].	هول بده ...
11:27:59	CDR		Anytime for engine start number two and one.	
11:28:02	Push		Aah, stand by for engine start due to slippery ...	
11:28:03	CA	A	[Cabin announcement starts]	
11:28:07	CDR		Okay.	
11:28:23	Push		Sir, you are all clear for engine start, 2 and 1.	
11:28:25	CDR		Okay, take 2.	
11:28:27	Push		Go for 2.	
11:28:52	CDR	P	*It is getting sunny.*	داره آفتاب میشه.
11:28:54	??		??	
11:29:06	CA	A	Cabin crew, doors on flight position. Check the doors on flight position.	
11:29:22	Push		Pushback ready, set brakes Sir.	
11:29:24	CDR		Set brakes on. Number 1.	
11:29:27	Push		Go for 1.	
11:29:29	CDR		Okay, turning 1.	
11:29:32	FO		Valve open.	
11:29:46	?		(Ignition).	
11:30:09	FO		Valve closed.	
11:30:11	CDR		45	
11:30:14	CDR		Ground!	
11:30:15	Push		Go ahead Sir.	
11:30:16	CDR		Thanks, you disconnect and signal on the left.	
11:30:19	Push		Okay disconnecting. Have a nice flight Sir. Bye.	
11:30:21	CDR		Thank you very much, hejdå.	
11:30:29		A	[Prerecorded safety briefing starts. Also heard on CDR channel. Setting of switches are heard on FO and CDR channels].	

11:30:39	CDR		After the start …	
11:30:40	FO		Trims.	
11:30:41	CDR	P	*Zero, zero how much is it? 1.7 nose up.*	زیرو، زیرو، چقده..؟ ۱,۷ *نوز آپ*.
11:30:46	FO		Slats, flaps.	
11:30:50	CDR		15 ??	
11:30:52	FO		Spoilers.	
11:30:53	CDR		Armed.	
11:30:54	FO		Anti-ice.	
11:30:55	CDR		Off.	
11:30:56	FO		ECAM status	
11:30:57	CDR		Auto trim tank inop manually.	
11:30:59	FO		Slides.	
11:31:00	CDR		Armed.	
11:31:01	FO		Ground signal.	
11:31:02	CDR		Received.	
11:31:03	FO		After start checklist is completed.	
11:31:05	CDR		Thank you.	
11:31:10	FO	#	Ground Iran Air 762 request taxi.	
11:31:13	GND	#	Iran Air 762 taxi to holding point 19R, hold short of PA.	
11:31:21	FO	#	Taxi to holding point 19R, hold short of PA, Iran Air 762.	
11:31:28	FO		Clear right.	
11:31:49	CDR	P	*We should go to Yankee, right? [Y taxiway].*	باید بریم تو *یانکی*, نه؟ [تاکسی وی Y].
11:31:51	FO		(Yes Sir).	
11:32:01	FO		Yes Sir, second to the right.	
11:32:04	CDR	P	*No! Do you really mean that.*	برو! جدی میگی؟
11:32:06	CDR		Left, right.	
11:32:09	FO	P	*Turkish is in sight but he does not have anything to do with us.*	ترکیش *این سایته* ولی کاری به ما نداره.
11:32:11	CDR	P	*Does he dare to come forward (joking)*	جرات داره بیاد جلو...
11:32:31	CDR		To the right here.	
11:32:32	FO		Yes Sir.	
11:32:37	CDR	P	*Look how it is skidding* [laughing]. [The aircraft is skidding].	به به به، چه سری هم می خوره! [با خنده] خیلی عالیه.
11:32:50	CDR	P	*[Name of First Officer], you have it.* [FO takes the controls]	[نام] بیا بگیر، دیگه مال تو. [کمک خلبان کنترل را به دست میگیرد].
11:32:52	FO		Yes Sir.	

11:32:54	CDR		?? [Completely masked by radio transmissions].	
11:33:05	CDR		Control checks Sir, elevat ...	
11:33:08	GND	#	Iran Air 762, continue to holding point 19R.	
11:33:11	CDR	#	762 hold ... Roger, holding point runway 19R.	
11:33:16	FO		Control check, please.	
11:33:23	CDR		Full down, neutral,elevator up, full up, (spoiler) left, right,(neutral), full left, neutral, full right. [checking flight controls]	
11:33:46	CDR		Before takeoff checklist.	
11:33:47	CDR	P	*Don't get too close to her [Name of First Officer]! Don't let the speed be more than 10 knots.*	زیاد به اون [نام] نزدیک نشو. *اسپدت* هم بیشتر از ۱۰ *نات* نزار بشه تو این یارو.
11:33:55	CDR		Flight Controls.	
11:33:56	FO		Checked.	
11:33:57	CDR		Checked left. Flight instruments.	
11:33:58	FO		Checked.	
11:33:59	CDR		Checked left. FCU/FMA.	
11:34:01	FO		Set, checked.	
11:34:03	CDR		Set and checked. Briefing.	
11:34:04	FO		Completed.	
11:34:06	CDR		Complete left.	
11:34:07	CDR		Slat and flaps.	
11:34:08	FO		15, 15.	
11:34:09	CDR		Confirm, 15, 15. V_1, V_r, V_2 flex temperature.	
11:34:16	FO		152, 162, 164, TOGA.	
11:34:18	GND	#	Iran Air 762, in sequence line up runway 19R.	
11:34:22	CDR	#	Roger, in sequence line up runway 19R, Iran Air 762.	
11:34:29	CDR		Okay briefing completed ... V1, Vr, V2, flex temperature.	
11:34:34	FO		152, 162, 164, TOGA.	
11:34:37	CDR		152, 162, (16 and) TOGA set checked.	
11:34:42	CDR		Takeoff configuration.	
11:34:46	FO		Normal for takeoff.	
11:34:47	CDR		Before takeoff checklist complete below the line.	
11:34:53	CDR	P	*Pay attention, It is a little slippery.*	یک کمی لیزه گوش دادی؟
11:34:55	FO	P	*Yes.*	بله.
11:34:56	CDR	P	*Don't drag the brakes!*	رو ترمز ها درگ نکن ها.
11:35:00	CDR	P	*Just don't drag.*	درگ نکن فقط!

11:35:13			[Three chimes from safety movie in cabin].	
11:35:33	CDR	P	*Since it is uphill give it a little [power] … or it will stop.*	این جا سر بالاییه، باید یه خورده بهش بدی [*پاور*] … می مونه.
11:36:13			[Two chimes from safety movie in cabin].	
11:36:31			[One chime from safety movie in cabin].	
11:36:35	CDR	A	Good afternoon cabin, at your stations for take off shortly. Thank you.	
11:36:48	TWR	#	Iran Air 762, runway 19R, cleared for takeoff.	
11:36:56	CDR	#	Roger Iran Air 762 lineup and takeoff runway 19R.	
11:37:01	CDR	P	*… Why did you turn this [brake cooling fan] on? You did it as a habit didn't you? [Masked by radio traffic]*	… اینو چرا ON کردی [*بریک فن*] ؟؟؟ از *هبیته* ، هان؟
11:37:06	FO	P	*The book says to turn it on anyway. [Commenting on the checklist. Masked by radio traffic]*	(پروسیجر) میگه بکنین کاریتون نباشه.
11:37:09	CDR	P	*No, it freezes here.*	نه… ایجا یخ می زنه.
11:37:12	CDR		Cabin crew.	
11:37:13	FO		Advised.	
11:37:14	CDR		Transponder.	
11:37:15	FO		Mode Charlie.	
11:37:16	CDR	P	*Mode Charlie! Don't take your hands off in this freezing weather. [Keep hands on the throttle!]*	مود چارلی ،،، دستتو بر ندار دیگه تو این هوای یخی [دستت را روی تراتل نگه دار]
11:37:19	CDR	P	*From now on control it with brakes.*	با ترمز بگیرش از حالا.
11:37:24	CDR		Auto-brake. [Masked by radio traffic]	
11:37:25	FO		Max. [Masked by radio traffic]	
11:37:27	CDR		Pardon me, transponder mode C. [Masked by radio traffic]	
11:37:29	CDR		Auto-brake. [Masked by radio traffic]	
11:37:30	CDR		Terrain. [Masked by radio traffic]	
11:37:31	CDR		Stay on radar, both sides, hah? [Masked by radio traffic]	
11:37:35	FO		Yes.	
11:37:36	CDR		Okay. Ignition.	
11:37:37	FO		On.	
11:37:38	CDR		Packs.	
11:37:39	FO		On APU.	
11:37:40	CDR		APU.	
11:37:41	CDR	P	*Takeoff issued?* [Wants F/O to confirm T/O clearance given].	*تیک آف* هم داد؟!
11:37:44	FO	P	*Yes Sir.*	بله سر.

11:37:46	CDR	P	*Don't start rolling from here. You must first line up before you go, otherwise you may skid off the runway.*	از الان *رول* نکنی ها، باید بری *لاین آپ* شی، بعد بری. برای اینکه میری بعد بیرون!
11:37:50	FO	P	*Yes Sir.*	بله سر.
11:37:51	CDR	#	Iran Air 76(2) rolling 19.	
11:37:53	TWR	#	Iran Air 762.	
11:38:05	CDR		Stabilized.	
11:38:10	CDR		Thrust, SRS, heading, time [SRS= Speed Reference System. Engine rpm increasing can be heard].	
11:38:19	CDR		Power set. [According F/O rpm is about 5% below TOGA thrust at this point]	
11:38:22			[Loud bang is heard followed by decreasing engine rpm and a rattling sound (starting 4 seconds after bang)].	
11:38:29			[Chime from ECAM system. Heard 3 times, 7.7, 11.9 and 19.8 sec after bang. Frequency 985 Hz, ca 0,5 seconds each. There is also a possible 4th Chime (weaker) 9.3 sec after bang].	
11:38:36	CDR	P	*What happened?*	چی شد؟؟؟
11:38:38	FO	P	*Tire was blown.*	تایر ترکید!
11:38:40			[Rattling sound stops].	
11:38:42	CDR	P	*What?*	چی؟
11:38:43	FO		Set parking brake. [To the captain]	
11:38:45	TWR	#	Iran Air 762, report persons on board.	
11:38:49	CDR	#	We aborted takeoff, (Iran Air 762) 149.	
11:38:53	TWR	#	149 POB, Roger.	
11:38:56	CDR	#	Thank you, and we are in a ...??	
11:38:58	FO	P	*I don't know what happened.*	نمیدونم چی شد!
11:39:00	TWR	#	Yeah, we are ... Fire engine standing by shortly.	
11:39:04	CDR	#	Roger.	
11:39:05	TWR	#	Will you evacuate your passenger?	
11:39:08	CDR	#	It is not necessary! We don't have any fire!	
11:39:12	TWR	#	It's up to you if you want to evacuate. Stand by and report new intention.	
11:39:19	CDR	#	Have you any visible fire on this (side of us)?	
11:39:20			[Chime (from ECAM?)]	
11:39:22	TWR	#	No fire visible from the tower.	
11:39:25	CDR	#	Okay.	

11:39:29	FO	P	*The problem was not a failure. Something detached.*	نه اصلاً مشکل *فیلییر* نبود، یه چیزی در رفت!
11:39:33	CDR	P	*Yes, something detached.*	آره یه چیزی در رفت.
11:39:35	CDR	P	*What?*	چی ؟
11:39:37	CA	P	*Dear passengers, please remain seated with seat belts fastened. Dear lady! Please sit down. Lady please sit down and fasten your seatbelt.*	مسافرین محترم تقاضا می کنیم همچنان روی صندلی های خود قرار گرفته و کمربندهای مخصوص پرواز را ببندید. خانم بفرمایید خواهش می کنم! سرکار خانم بفرمایید بشینید و کمربندتونو ببندید!
11:39:38	FO	P	*… Yes, but first it was a bang sound and then something detached . Probably a tire has exploded.*	… آره ولی اصلاً صدای تقّی اومد، یه چیزی در رفت. تایر احتمالاً ترکیده.
11:39:52	FO	P	*Ask them to be calm until someone has checked it from the outside. [Asking the captain to make a Passenger announcement]*	بگو اونها آروم باشن [مسافرها]، حالا تا بیان از بیرون ببینند چه خبره.
11:39:56	CDR	P	*Yes.*	آره.
11:40:00	CDR	P	*Good afternoon. This is your captain. We have got a certain problem which is not clear yet. We will give you information later on.* [Passenger announcement].	بعد از ظهر بخیر مسافرین عزیز ، خلبان پرواز هستم. جهت اطلاعتون، مشکل خاصی پیش اومده که هنوز مشخص نیست چی هستش اینه که بعداً به اطلاعتون می رسونیم.
11:40:03	TWR	#	Iran Air 762, what is your opinion about the situation now?	
11:40:10	FO	#	Sir, at this time we are uncertain the reason of the aircraft veering to the left. We do not have any indications in the cockpit at this time. We would appreciate if someone could look from the outside what has happened.	
11:40:25	TWR	#	Iran Air 762, for your information we have sent out the rescue vehicles, they will assist you.	
11:40:30	FO	#	Thank you.	
11:40:35	CDR	P	*What?*	چی ؟
11:40:42	CDR	P	*??*	
11:40:49	FO	P	*We have the APU, if you want you can shut down the engine.*	*ای پی یو* داریم اگه می خواین می تونین *انجین* رو *شات دان* کنین.
11:40:52	CDR	P	*Engine is already shut down.*	*شات دانه* انجین!
11:40:54	FO	P	*Number 2 as well.*	شماره دو هم …
11:40:57	CDR	P	*Something detached. Did you notice?*	یه چیز در رفت، دیدی؟
11:41:01	TWR	#	Iran Air 762, the reason for your aborted take(off) was it because the head gear or the steering gear (geared) to the left?	

11:41:13	FO	#	The aircraft has steered to the left on its own and we are not certain at this point what was the problem.	
11:41:21	TWR	#	Roger. Does it feel like your landing gear is operative or inoperative?	
11:41:23			[Chime (ECAM?)]	
11:41:28	FO	#	It feels like it is not.	
11:41:30	TWR	#	Okay.	
11:41:41	CDR	P	*What is your time?*	یه چیز کنده شده...
11:41:48	FO	P	*Thank God that we don't have fire.*	*فایر* خدا رو شکر که نداریم.
11:41:57	FO	P	*Engine until ...*	*انجین* ، تا...
11:42:00	CDR	P	*You mean the fire handle?*	*فایر هندلو* ؟
11:42:03	FO	P	*Number one. [The left fire handle was pulled].*	یکو ... [*فایر هندل* سمت چپ کشیده شد].
11:42:03			[Click from fire handle and a chime from the ECAM]	
11:42:10	CDR	P	*We don't have any fire!*	*فایر* نداریم که !
11:42:15	TWR	#	Iran Air 762 have you turned off your engines?	
11:42:19	CDR	#	Affirmative.	
11:42:19	FO		Affirmative.	
11:42:21	TWR	#	Thank you for that information.	
11:42:22	FO	#	No worries.	
11:42:41	CDR	P	*Something has detached.*	یه چیز کنده شده.
11:42:43	FO	#	Do you have any information about our main landing gear, probably the left main landing gear, if they can see from the outside.	
11:42:52	TWR	#	Yeah, stand by.	
11:43:08	CDR	P	*He does not speak at all. [Commenting on the TWR delay].*	هوم؟ حرف نمی زنه اصلاً! [تاخیر برج مراقبت در جواب دهی].
11:43:10	TWR	#	Iran Air 762, the rescue vehicles would like to talk to you on frequency 123,1.	
11:43:19	FO	#	Okay, 123,1.	
11:43:30	FO	#	Hello this is Iran Air 762.	
11:43:34	R	#	Yeah I hear you. Is this Irian Air?	
11:43:37	FO	#	That is correct, yes.	
11:43:40	R	#	Okay, I go check your plane now. Every engine is off, yes?	
11:43:47	CDR	#	Yeah is off!	
11:43:47	FO	#	Affirmative, all engines are off, except the APU is on.	
11:43:52	R	#	Okay.	
11:44:08	R	#	Okay I see you have ... What I can see now, you have no real damage, that you are real, you have make it real deep in the ground.	

11:44:21	FO	#	Okay, can you see the main landing gears? They are deep inside the ground?	
11:44:29	R	#	Just a minute I check it out.	
11:44:31	FO	#	Thank you.	
11:44:36	CDR	P	*Now we have a problem.*	گرفتار شدیم حالا!
11:44:37	FO	P	*I believe that a tire has come off or the left main landing gear has collapsed or a tire or something has come off. Because …*	من میگم اصلاً تایر در رفت، یا * مین لندینگ گیر *لفت* کولپس * کرد یا اینکه یه تایری چیزی در رفت، چون قشنگ...
11:44:45	R	#	Yes they are deep inside in the ground, about a half meter.	
11:44:52	FO	#	Okay, there is no apparent indication of any of them being broken or anything?	
11:45:02	R	#	Do you have a indication where I can see it?	
11:45:06	FO	#	Negative.	
11:45:08	FO	P	*He says that nothing can be seen.*	میگه چیزی دیده نمیشه!
11:45:09	R	#	Okay. I do my best to check it out.	
11:45:12	FO	#	We appreciate.	
11:45:24	FO	P	*EGT has stayed up there. [Referring to Engine No.1 EGT]*	*ای جی تی* این بالا مونده. [اشاره به EGT موتور یک].
11:45:29	FO	P	*But Captain! Before the engine shut down we had no indications. First it was a bang, then it started veering to the left, then the "engine shut down" message came on. [To relief captain coming into cockpit. ECAM shows "Engine shut down"]*	... منتها کاپیتان قبل از اینکه *شات دان* بشه، هیچ *ایندیکیشنی* نبود، یه صدای تقّی اومد، شروع کرد به لفت *ویر* کردن، بعد [پیغام] *انجین شات دان* داد. [توضیح به کاپیتان دوم پرواز که به کاکپیت آمده، در مورد پیغام روی ECAM].
11:45:37	CDR	P	*Yes. It went quickly.*	آره سریع رفت.
11:45:40	2CDR	P	*(This happens when an engine explodes in an Airbus).*	(این هواپیمای ایرباس وقتی موتورش میترکه همینطوری میشه).
11:45:45	CDR	P	*Yes here it is.*	آره ایناها.
11:46:07	FO	P	*Now normally they should be evacuated, nothing else can be done.*	حالا *نرمالی* باید اینها *ایوکوویت* بشن،،، دیگه کاری نمی شه کرد!
11:46:15	CDR	P	*Evacuate them? If we throw them out, they will all break their legs and arms!*	*ایوکوویت* اینها، اگه بریزیم پایین که همش دستو پاشون میشکنه که!
11:46:16	FO	P	*Not in that way.*	نه اون شکلی که ...
11:46:32			[CVR stop].	

ON THE DIRECTIONAL CONTROL OF AN AIRBUS A300 IN TAKEOFF WITH ONLY ONE ENGINE OPERATING

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Report, SHK case L-02/10, February 14, 2011

Abstract

The purpose of the present study is to estimate the directional control performance of an Airbus A300 in take-off with only one engine at full throttle. The aerodynamic data for yaw moment and side force in side-slip and with rudder deflected is estimated using a potential flow model of the aircraft. The forces on the nose and main landing gears are estimated using models derived using established testing procedures. It is found that directional control should be possible at all airspeeds on a dry runway but directional control is questionable at low speed on a slippery runway.

1. Introduction

The author was asked to analyze the stability and control of an Airbus A300 during take-off with only one engine operating at full thrust. The motivation for the analysis was a recent incident at the Stockholm Arlanda airport when an aircraft of this type departed from the runway when one engine lost all thrust during the take-off acceleration. The aircraft departed from the runway after approximately 10 seconds when the ground speed had reached approximately 60 knots.

The following data was provided or obtained for the analysis:

1. Flight manual, B4.605 R
2. Weight and balance manual, Dec 1987
3. Flight data recorder information
4. Video sequences

1.1. The Airbus A300 aircraft

The aircraft is a twin engine wide body transport of conventional design and configuration and the most important characteristics are listed in Table 1.1. The coordinate axis along the fuselage (x) is defined with origin at the nose of the aircraft. The aircraft individual involved in the incident has serial number 727 and is equipped with two General Electric CF6-80C2A5 with a rated output of 267 kN according to the ICAO data sheet [1].

2. Aerodynamics

In order to estimate the basic aerodynamic coefficients for the aircraft, the geometry was first defined in the *sumo* modeling tool [2]. The geometry is then used to define a triangular mesh

Span	b	44.84	m
Wing area	S_{ref}	260	m^2
Reference chord	$\bar{c}$	6.6	m
Aspect ratio	AR	4.132	
Distance centerline to thrust line	l_T	7.94	m
Wheel track	l_{wt}	9.6	m
Distance nose to nose gear	x_{ng}	6.671	m
Wheel base	l_{wb}	18.6039	m
Distance nose to main gear	x_{mg}	25.275	m
Aerodynamic reference point	x_{ref}	23.6325	m
Maximum rudder deflection	$\delta_{r\max}$	30	degrees

Table 1.1: Basic aircraft data.

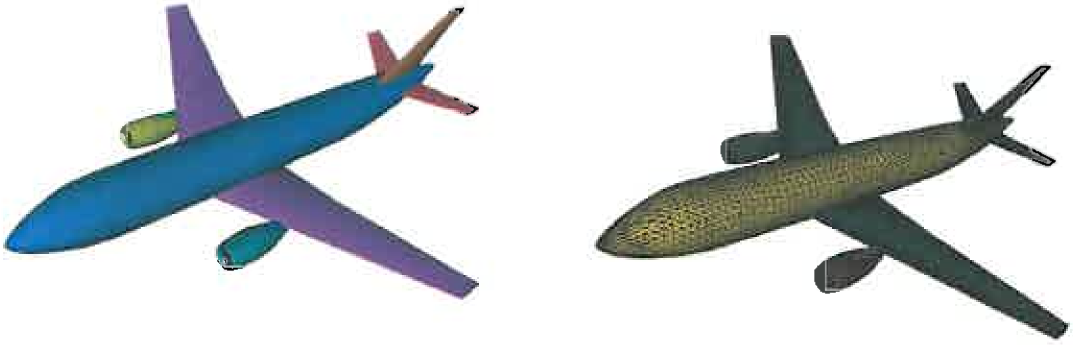

Figure 2.1: Geometry definition and grid for analysis.

which is used for the analysis using a potential flow solver. The geometry and mesh used is shown in Figure 2.1.

Based on the reference aircraft data listed in Table 1.1, the analysis gives the aerodynamic derivatives listed in Table 2.1 where moments are defined around the aerodynamic reference point x_{ref}.

Yaw moment for side-slip	$C_{n\beta}$	0.0165	1/rad
Yaw moment for rudder	$C_{n\delta_r}$	0.144	1/rad
Side force for side-slip	$C_{y\beta}$	-0.83	1/rad
Side force for rudder	$C_{y\delta_r}$	-0.258	1/rad

Table 2.1: Aerodynamic derivatives.

3. Estimating performance in take-off

The rated output of the engines is most likely an overestimate of the actual thrust that drives the aircraft forward due to for example installation losses and bleed air. In order to estimate the actual thrust, the following model of the excess thrust given by

$$T_{ex} = T - qS_{ref}C_{D0} \tag{3.1}$$

is used, where q denotes the dynamic pressure, T the unknown thrust and C_{D0} the unknown drag coefficient. Assuming standard sea-level conditions and using the measured ground speed V and longitudinal nondimensional acceleration n_x which are given on the flight data recorder, it is possible to rewrite (3.1) as

$$T - \frac{1}{2}\rho V^2 S_{ref}C_{D0} = -n_x mg, \tag{3.2}$$

where ρ denotes the standard sea-level air density, m the mass of the aircraft and g the gravitational acceleration. Using the data from the flight data recorder for a previous take-off, the unknown actual thrust T and drag coefficient C_{D0} can be estimated by solving a linear least-squares problem. The solution to the least-squares problem gives T/mg=0.2232 and C_{D0}=0.0701. Integration of the equations of motion based on this model of the excess thrust gives the acceleration shown in Figure 3.1. The actual acceleration for the accident flight as well as a previous successful flight are shown for comparison demonstrating the accuracy of the modeling. The actual thrust is most likely somewhat larger since rolling resistance is part of the estimated thrust. A reasonable estimate of the rolling resistance is $0.015mg$ [3]. The actual thrust for each of the two engines is thus given by

$$T_{eng} = (T + 0.015mg)/2. \tag{3.3}$$

This gives the estimate $T_{eng} \approx 0.12mg$ or 175 kN which is significantly less than the rated 267 kN. The lower, possibly more realistic value, of T_{eng} is used in the following analysis.

4. Modeling of landing gear and tires

The modeling of tire performance under different conditions involves many complex issues. However, several studies performed at the NASA Langley Research Center Aircraft Landing Dynamics Facility (ALDF) [4, 5] provide many useful models for aircraft tire performance. A comprehensive study of modern aircraft tires is given by Daugherty [4] involving the nose and main gear tires of the Boeing 737 and 777. The Airbus 300 tires are similar in type but with different size and rated load. However, Daugherty gives support that some basic characteristics can be made nondimensional with respect to the rated load of the tire. This assumption is used to model the nose wheel tires of the Airbus A300.

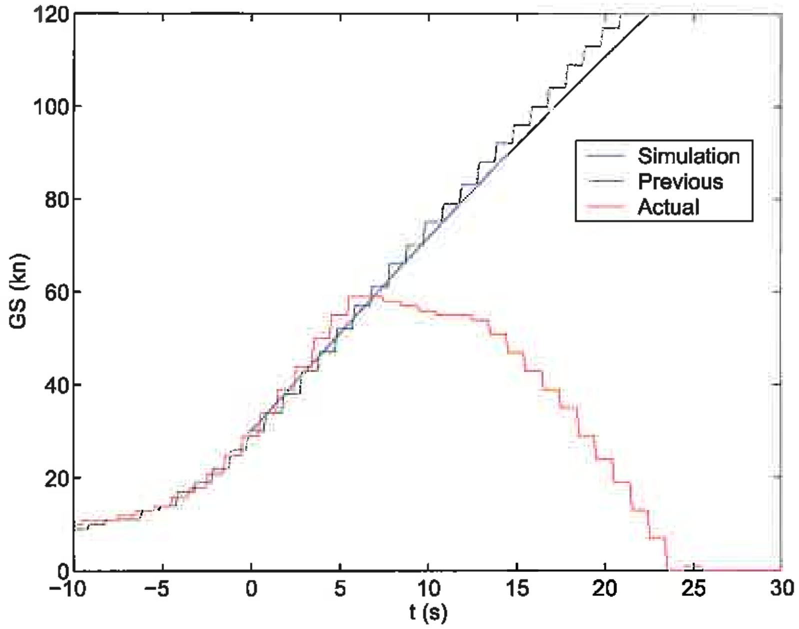

Figure 3.1: Actual and simulated take-off performance.

The side force coefficient is defined as

$$\mu_s = S/F_z, \tag{4.1}$$

where S denotes the side force and F_z the vertical load on the landing gear. For dry concrete, Daugherty [4] suggests to model the side force coefficient μ_s as

$$\mu_s = \beta_0 + \beta_1 R^2 + \beta_3 R^3 + \beta_4 \psi + \beta_5 \psi^2 + \beta_6 \psi^3 + \beta_7 R\psi + \beta_8 R\psi^2 + \beta_9 R^2 \psi, \tag{4.2}$$

where R denotes the ratio of the vertical force to the rated maximum load of the tire and ψ the yaw angle of the tire to the direction of motion. The nondimensional coefficients of the model were obtained by Daugherty [4] using a curve fitting technique on a large set of experimental data and are listed in Table 4.1. The model for the side force coefficient is shown in Figure 4.1 for three different values of the load ratio. Clearly, the side force coefficient reaches its maximum

Coefficient	Value
β_0	0.1952
β_1	-0.5224
β_2	0.4329
β_3	-0.1140
β_4	0.1273
β_5	-0.0027
β_6	-0.0002
β_7	-0.058
β_8	0.0023
β_9	0.0051

Table 4.1: Nondimensional coefficients of the tire model.

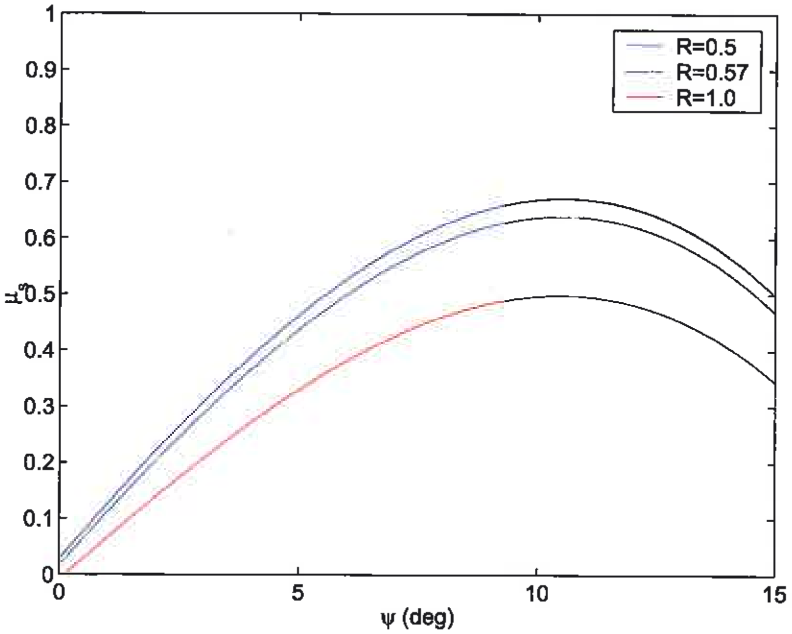

Figure 4.1: Side force coefficient on dry concrete.

of about 0.7 at 10 degrees yaw angle and is reduced to 0.5 when the vertical force reaches the maximum rated load. In more slippery conditions, such as a wet runway, the side force coefficient is significantly reduced [4] by about 25% at low speed and up to 40% when the ground speed approaches 100 knots.

According to Airbus [6], the nose landing gear of the aircraft in question was equipped with the Bridgestone 40x14 tire [7] with a rated maximum load of 25000 lbs or approximately 11000 kg. With two wheels on the nose landing gear the maximum rated vertical force is thus 22000 kg. The accident aircraft had a mass of approximately m =148000 kg and according to Airbus [6] the static load on the nose gear would be about 8.5% of m or 12700 kg. This nose gear load is thus in the lower range of the 8-15% of m suggested as typical [3]. With this nose landing gear load, the force ratio R becomes approximately 0.57.

Consequently, on dry concrete the maximum side force coefficient can be expected to be about 0.6 with a significant reduction in slippery conditions.

5. Static equilibrium

Assuming a point of rotation between the main landing gears, the required side force to be carried by the nose landing gear is given by

$$S = T_{eng}\frac{l_T}{l_{wb}}. \tag{5.1}$$

Using the data from Table 1.1 and the estimated actual thrust for one engine gives $S = 75$ kN. With a nose gear vertical load in the range 8-9% of mg the required side force coefficient is in the range 0.57-0.65 clearly very close to critical.

The required side force coefficient computed for different nose load factors is shown in Table 5.1. The maximum available side force coefficients according to the tire model given by (4.2) are given for comparison.

Nose gear load (% of mg)	R	Required μ_s	Max μ_s	0.75(Max μ_s)
8.0	0.54	0.65	0.65	0.49
8.5	0.57	0.61	0.64	0.48
9.0	0.61	0.57	0.62	0.47

Table 5.1: Required and available side force coefficient.

Consequently, on a dry runway the nose gear tires can only barely balance the unsymmetric thrust for the case with low nose gear vertical load. Applying a 25% reduction in maximum side force coefficient gives an unstable condition.

The rudder efficiency increases with the square of the airspeed while the available maximum side force coefficient in slippery conditions goes down with ground speed. Daugherty [4] suggests a reduction of 25% at low speed and 40% at 100 knots. In order to estimate the required side force coefficient as a function of speed, the following moment balance is considered

$$Sl_{wb} + qS_{\text{ref}}bC_{n\delta_r}\delta_{r\max} = T_{eng}l_T, \tag{5.2}$$

where q denotes the dynamic pressure. The required side force is then given by

$$S = (T_{eng}l_T - qS_{\text{ref}}bC_{n\delta_r}\delta_{r\max})/l_{wb}, \tag{5.3}$$

and the corresponding side force coefficient is then obtained by dividing S with the vertical load F_z on the nose landing gear.

The required side force coefficient for different speeds are shown for a nose-gear vertical load of 8.5% of mg in Figure 5.1. The maximum available side force coefficient is also shown assuming a 25% reduction from the dry runway value at low speed and a 40% reduction at 100 knots ground speed.

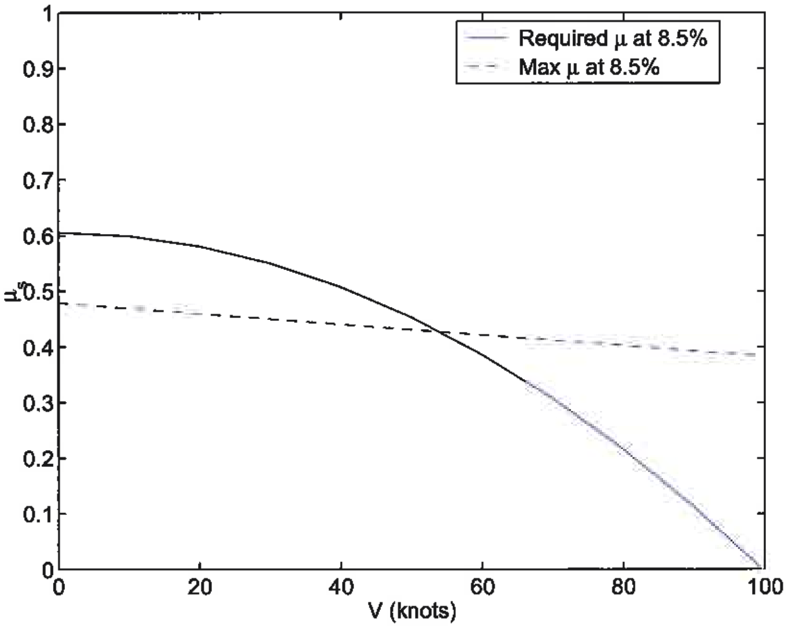

Figure 5.1: Required and available μ_s at different speed.

At low speed directional stability appears not to be possible in slippery conditions. But as speed increases, the yaw moment induced by the maximum deflected rudder starts to help and at 100 knots there is no side force on the nose landing gear.

6. Conclusions

Although the data made available for this investigation is very limited, it is still possible to demonstrate that directional stability of a large twin engine transport with only one engine at full thrust is questionable on a slippery runway. Even though the available side force from the nose landing gear is reduced as speed increases, the effect of the rudder increases more quickly. Consequently, the directional stability appears to be most problematic at low speed.

The analysis of this report suggests that directional stability and control could be possible at all speeds on a dry runway even if only one engine is running at full thrust. However, the analysis also suggests that directional stability and control is not possible if the runway is wet and slippery. Even a moderate reduction of the maximum available side force coefficient makes stability and control questionable. Further, the analysis assumes that the pilot is able to apply maximum rudder while simultaneously adjusting the hand steering wheel to achieve the optimal nose gear steering angle (about 10 degrees) to achieve the best possible side force coefficient. According to the flight manual, the nose wheel steering is connected to the rudder pedals in a way that maximizes the steering angle to 6 degrees but higher angles are available by simultaneously using the hand steering wheel.

The analysis is questionable in many ways because of limited data but still confirms that runway directional stability and control is questionable below 100 knots if only one engine is running at full thrust. It would be most appropriate if the manufacturer performs a more detailed investigation and then presents the important conclusions in the flight manual so that pilots can be better prepared on what to expect in a similar situation.

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Sakkunnigutlåtande

Datum	Vårt diarienummer
2010-07-14	2010008248
Ert datum	**Er beteckning**
2010-06-08	-

Statens haverikommission
Roland Karlsson
Box 12538
10229 Stockholm

STATENS HAVERIKOMMISSION
Ink 2010 -07- 14
Dnr L-02/10
Aktbil nr 173

Uppdragsgivare

Statens haverikommission.Stockholm

Allmän information om SKL:s sakkunnigutlåtanden

Återgivande av sakkunnigutlåtande

Vid återgivande av denna redovisning ska detta i normalfallet göras i sin helhet. Om utdrag ur redovisningen återges i annat dokument ska detta följas av en tydlig hänvisning till ursprungsdokumentet.

Standardförfarande och metoder

Standardförfarande (SF) och metoder (M) markerade med asterisk * ingår i laboratoriets ackreditering enligt ISO/IEC 17025. För förklaring av kortkoderna för använda standardförfaranden och metoder hänvisas till laboratoriets hemsida på IntraPolis eller Internet. Önskas mer information kontakta ärendeansvarig.

Utlåtandeskala

För information om utlåtandeskalan, se sista sidan.

Material, metodik och materialhantering

Beteckning	Undersökningsmaterial
Video takeoff.mp4	**Ett digitalt videoklipp** Beslagsnr: - Uppdragsgivarens beteckning: Video takeoff.mp4 SKL:s materialnr: 201000824801 Materialhantering: Materialet återgår Metodik: Do-SF101
Video takeoff ny.mov	**Ett digitalt videoklipp** Beslagsnr: - Uppdragsgivarens beteckning: Video takeoff ny.mov SKL:s materialnr: 201000824802 Materialhantering: Materialet återgår Metodik: Do-SF101
DSC01793.JPG	**Ett digitalt fotografi** Beslagsnr: - Uppdragsgivarens beteckning: DSC01793.JPG SKL:s materialnr: 201000824803 Materialhantering: Digital arkivering Metodik: Do-SF101
DSC01834.JPG	**Ett digitalt fotografi** Beslagsnr: - Uppdragsgivarens beteckning: DSC01834.JPG SKL:s materialnr: 201000824804 Materialhantering: Digital arkivering Metodik: Do-SF101
DSC01835.JPG	**Ett digitalt fotografi** Beslagsnr: - Uppdragsgivarens beteckning: DSC01835.JPG SKL:s materialnr: 201000824805 Materialhantering: Digital arkivering Metodik: Do-SF101
P1020238.JPG	**Ett digitalt fotografi** Beslagsnr: - Uppdragsgivarens beteckning: P1020238.JPG SKL:s materialnr: 201000824806 Materialhantering: Digital arkivering Metodik: Do-SF101

Ändamål

Ändamålet är att undersöka om det från de fyra digitala fotografierna går att avgöra om det förekommer beläggning i form av snö, is eller slask på rullbanan, samt

att undersöka om snömolnet som uppstår när planet lämnar rullbanan på filmerna "Video takeoff ny.mov" och "Video takeoff.mp4" uppstår innan planets hjul lämnar rullbanan.

Undersökning

Beläggning på rullbanan

Bilderna DSC01834.JPG och DSC01835.JPG visar rullbana som mörkare än på bilden P1020238.JPG. Detta skulle kunna bero på att bilderna är tagna med olika kameror som exponerat bilderna olika. På bilderna iakttogs vita molnliknande områden på asfalten samt mörka hjulspår i dessa, se figur 1. Även ljusa hjulspår har iakttagits i de mörkare områdena på körbanan. Dessa observationer förväntas i större utsträckning om det är snö, is eller slask på rullbanan än om rullbanan är fri från beläggningar.

DSC01793.JPG **DSC01834.JPG**

DSC01835.JPG **P1020238.JPG**

Figur 1. De fyra digitala fotografierna.

Avkörning från rullbanan

För att det ska vara möjligt att bedöma om snömolnet uppstår innan flygplanets hjul lämnar banan krävs det att båda banan och planets hjul är tydligt synliga i filmerna. I detta fall är filmernas kvalitet av sådant slag att laboratoriet inte kan uttala sig i frågan.

Figur 2. Bild från "Video takeoff.mp4" när planet lämnar banan.

Slutsats

Resultaten talar för att det förekommer beläggning i form av snö, is eller slask på rullbanan, och inte för att den är fri från beläggning (*Grad* +2).

Det har inte varit möjligt att undersöka om snömolnet som uppstår när planet lämnar banan på filmerna "Video takeoff ny.mov" och "Video takeoff.mp4" uppstår innan planets hjul lämnar banan.

Handläggning

Undersökning	Handläggare
Bild	forensikern Tobias Höglund (ansvarig handläggare) förste forensikern Fredrik Eklöf

Frågor riktas i första hand till forensikern Tobias Höglund (ärendeansvarig), direkttelefon 013-24 16 49. Eventuell kallelse till rättegång ställs till den ansvarige handläggaren för berörd undersökningstyp.

Tobias Höglund
Forensiker

Utlåtandeskala

Ett sakkunnigutlåtande från SKL är en redovisning av de resultat som erhålls vid en undersökning. Resultaten har prövats dels gentemot den hypotes (antagande) som ligger till grund för frågeställningen under rubriken "Ändamål ", dels gentemot andra aktuella hypoteser. Undersökarnas värdering av dessa resultat redovisas som graderade slutsatser enligt nedanstående utlåtandeskala. Utlåtandeskalan är utarbetad för och kopplad till SKL:s resultatvärdering som baseras på det logiska synsättet, för mer information se https://www.skl.polisen.se/For-rattsvasendet/Utlatandeskala/Sa-nar-vi-slutsatserna/.

I de fall undersökarna kan fastställa ett faktum används andra uttryckssätt såsom "är", "är inte" eller "kan uteslutas att".

Grad +4	Resultaten talar med visshet för att... *Möjligheten att erhålla dessa resultat om någon annan hypotes är sann bedöms i praktiken som utesluten.*
Grad +3	Resultaten talar starkt för att... *Möjligheten att erhålla dessa resultat om någon annan hypotes är sann bedöms som mycket liten.*
Grad +2	Resultaten talar för att... *Möjligheten att erhålla dessa resultat om någon annan hypotes är sann bedöms som liten.*
Grad +1	Resultaten talar i någon mån för att... *De erhållna resultaten ger ett något större stöd för den uppställda hypotesen än för andra aktuella hypoteser.*
Grad 0	Frågan om ... lämnas öppen *De erhållna resultaten ger inte mer stöd åt vare sig den uppställda hypotesen eller andra aktuella hypoteser.*
Grad -1	Resultaten talar i någon mån för att ...inte... *De erhållna resultaten ger ett något mindre stöd för den uppställda hypotesen än för andra aktuella hypoteser.*
Grad -2	Resultaten talar för att...inte... *Möjligheten att erhålla dessa resultat om den uppställda hypotesen är sann bedöms som liten.*
Grad -3	Resultaten talar starkt för att...inte... *Möjligheten att erhålla dessa resultat om den uppställda hypotesen är sann bedöms som mycket liten.*
Grad -4	Resultaten talar med visshet för att...inte... *Möjligheten att erhålla dessa resultat om den uppställda hypotesen är sann bedöms i praktiken som utesluten.*

Appendix 4

HAM TQ/M Report 2010 611 — Lufthansa Technik AG

Subject: **Failure investigation on HPT Parts of a CF6-80C23A5F**

Date: 20.01.11

Operator	**A/C**	**A/C Registration**	**Engine Type**	**Engine No.**
IRA	A300	EP-IBB	CF6-80C2A2F	705207
Part	**P/N**	**S/N**	**Originator**	**Material**
HPT Parts (see list below)	div.		GE	div.

Ordering Dept. WP 311

Distribution WP 311, WP 15, TQ 2-I, WR 123; SHK, Assist.nu and IRA via WP 15

History

During T/O a Turbine Failure occurrd on L/H engine. The A/C yawed to the left and run off the runway.
Laboratory analysis should be performed to determine the failure mode on following parts:

1. Fragments of HPT Diffuser Aft Seal (PN 9272M20P10 / SN BTABR518).
2. Fracture surface of several Hookbolts (PN: VCW0097P03).
3. 3ea HPT Blades #35 #36 #37 (PN:BLC1538M90P12).
4. Fracture surface of Vane Ring bolts (PN:VCA0023P03).
5. Metal chips taken from D-sump chip detector.
6. Traces taken from the observed metal build up on 1st STg HPT Disk web.
7. Traces taken from Toroid Seal (metal build up).

Results

1. HPT Diffuser Aft Seal P/N 9272M20P10
Material: Inconel 718.
The seal was fractured in a large number of single pieces. About two third of the seal could be put together from segments found within the failed engine. The remaining seal parts are missing or could not been identified as seal parts. Most of the fracture faces were post fracture damaged by rubbing. On this fractures no original fracture structures were visible. On some of the remaining lugs typical indications of fatigue could be recognized. Scanning electron microscopical (SEM) investigation could confirm the fatigue fracture mode. Typical striation formation could be observed on fracture faces. Intergranular fracture structures were visible on the remaining fracture force zones. Most likely this intergranular structure is due to material overheating during seal rubbing.
Microscopical investigation of the fracture origins exhibited an oxidized fracture face. Next to the fracture origin several further thermal fatigue cracks were visible.
The general microstructure corresponded with the expected Inconel 718 structure.
Material and / or manufacturing defects could not be discovered on the remaining parts of the seal.

The findings of the seal investigation indicate that thermal fatigue is the root cause of the HPT diffuser aft seal lug failure.

The results of the complete investigation indicate that the HPT diffuser aft seal fracture is the primary source of the engine failure.

2. Hookbolt P/N VCW0097P03
Material: Inconel 718
Some bolts were found fractured next to each other in a row while a single bolt had fractured separately away from these bolts. The fracture faces of the bolts in a row exhibited a granular structure indicating a shear fracture mode. The single bolt exhibited a darkish fracture surface with no clear structure. Due to the dark coloration indicating oxidation / corrosion this bolt first was believed to be a primary source of failure. Further investigation of the fracture face by stereo- and scanning electron microscope indicated that a sprayed layer of foreign material covered fracture face and remaining thread area of the bolt with foreign material. Remaining fracture structure indicated a shear fracture as on the other fractured bolts.

Investigated bolt threads on non fractured bolts indicated no discrepancies like older cracks or material anomalies.

The results of investigations on subject hookbolts indicate that the hookbolt failures are secondary.

3. Stg. 1 HPT Blade P/N BLC1538M90P12
Material: DSR 142
Three fractured stg. 1 HPT blades, numbers 35, 36 and 37, were selected from the set for evaluation. The blades exhibited separations of about half of the airfoils. Fracture faces exhibited some sulfidation as well as foreign material residuals. Also the blade airfoils exhibited post fracture damages / deformations. The SEM investigation revealed only forced fracture propagation features.
Metallographic evaluation revealed a number of oxidized / sulfidized cracks within the blade airfoils some of these cracks had already run through the coating and reached the blade base material. The nature of this cracks indicates that they were present prior to engine failure. Overheated microstructures of the blade material were not discovered.

The results of investigations on subject stg. 1 HPT blades indicate that the blade failures are secondary.
Note: Obviously the blades were in bad service conditions with airfoil base material cracks before the engine failure occurred.

4. Ring Bolt P/N VCA0023P03
Material: Inconel 718
The subject ring bolts exhibited fracture structures indicating a shear fracture mode. The bolts revealed no damages or faulty material.

It is likely that the failure of the bolts is secondary

5. Metal chips, D-Sump Detector
The metal chips collected from the D-sump chip detector were of Ni-layer remains.

6. Metal build up on Stg. 1 HPT Disk web
The metal build up was analyzed to be Ni-base material, likely of Inconel 718 or similar.

7. Metal build up on Toroid Seal

The metal build up was analyzed to be Ni-base material, likely of Inconel 718 or similar.

Documentation attached to the report.

Conclusions

The investigation on subject engine parts could not completely ascertain the cause of engine failure.
Due to the findings of the laboratory investigation, it is most likely that increased stresses / vibrations were implemented on the HPT diffuser aft seal. Due to these vibratory stresses thermal fatigue fractures could develop and propagate from the HPT diffuser aft seal lugs.

It is most likely that the HPT diffuser aft seal fracture is the primary source of the engine failure. All additional parts investigated only exhibited secondary fracture indications.

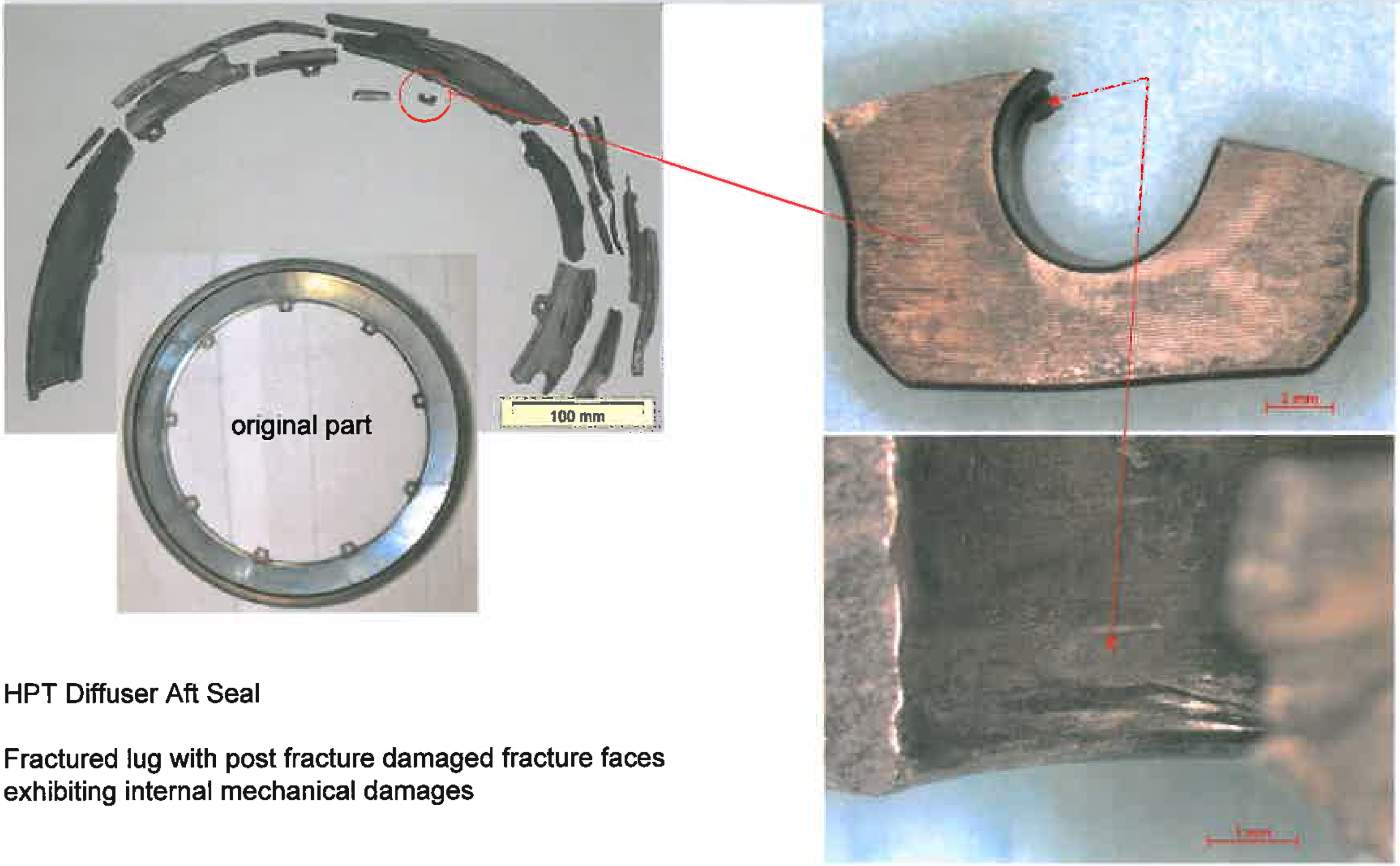
Best Regards

Lufthansa Technik AG
Dept. HAM TQ/M

Dr. Siry

Person in charge: Detlef Warmbold

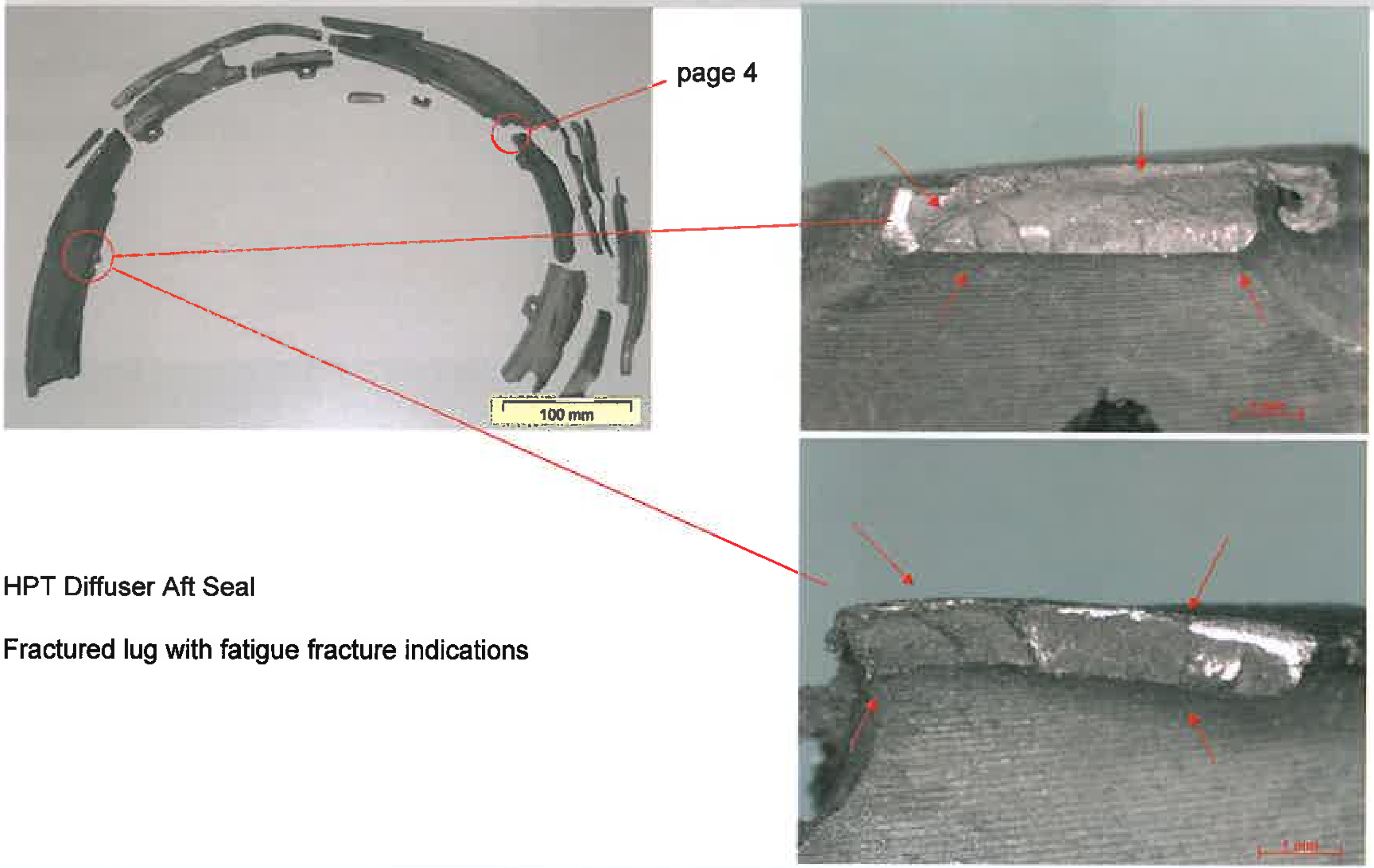
Investigation into the cause of failure CF6-80C2A5F, Eng. no. 705207



HPT Diffuser Aft Seal

Fractured lug with post fracture damaged fracture faces exhibiting internal mechanical damages

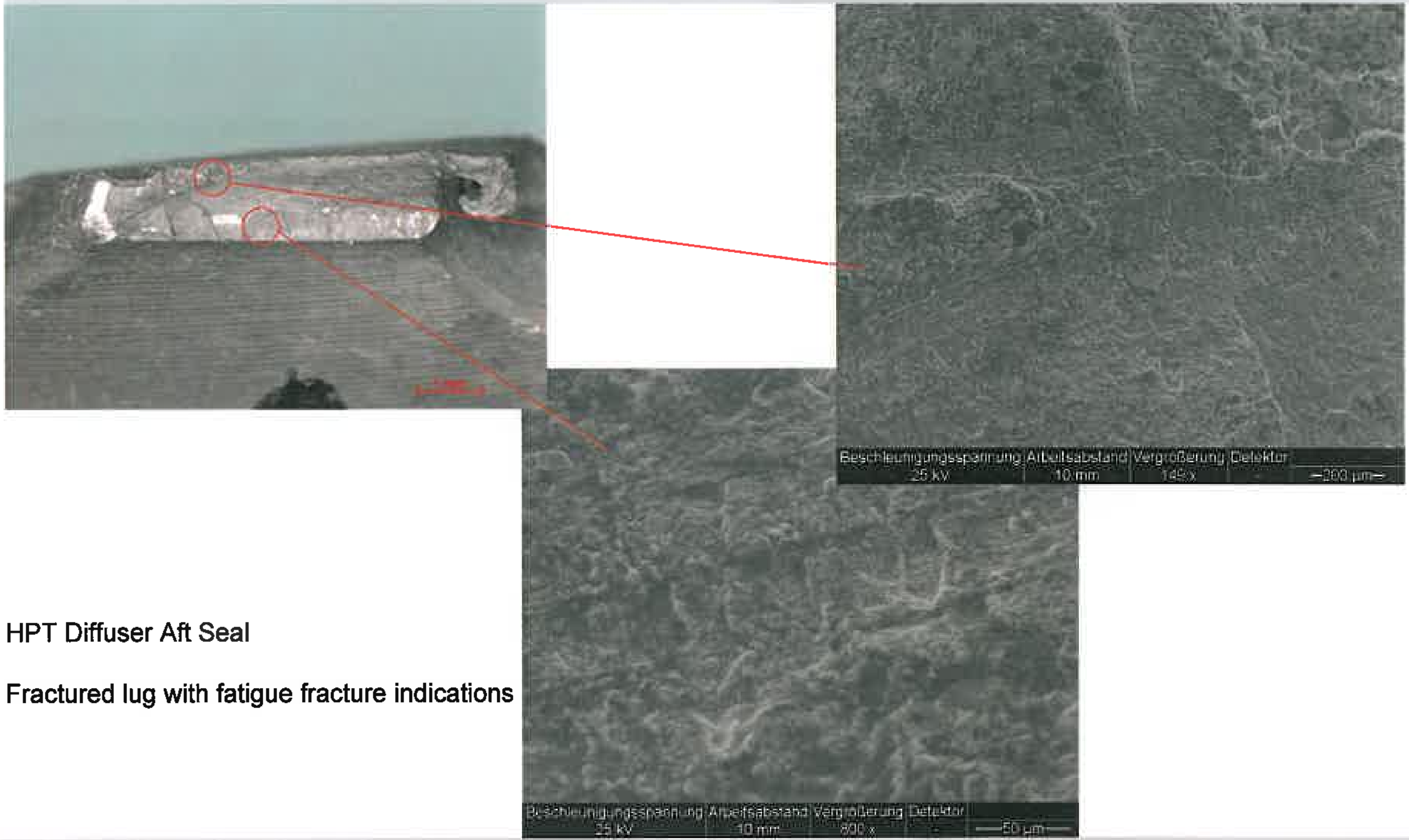
Investigation into the cause of failure CF6-80C2A5F, Eng. no. 705207



HPT Diffuser Aft Seal

Fractured lug with fatigue fracture indications

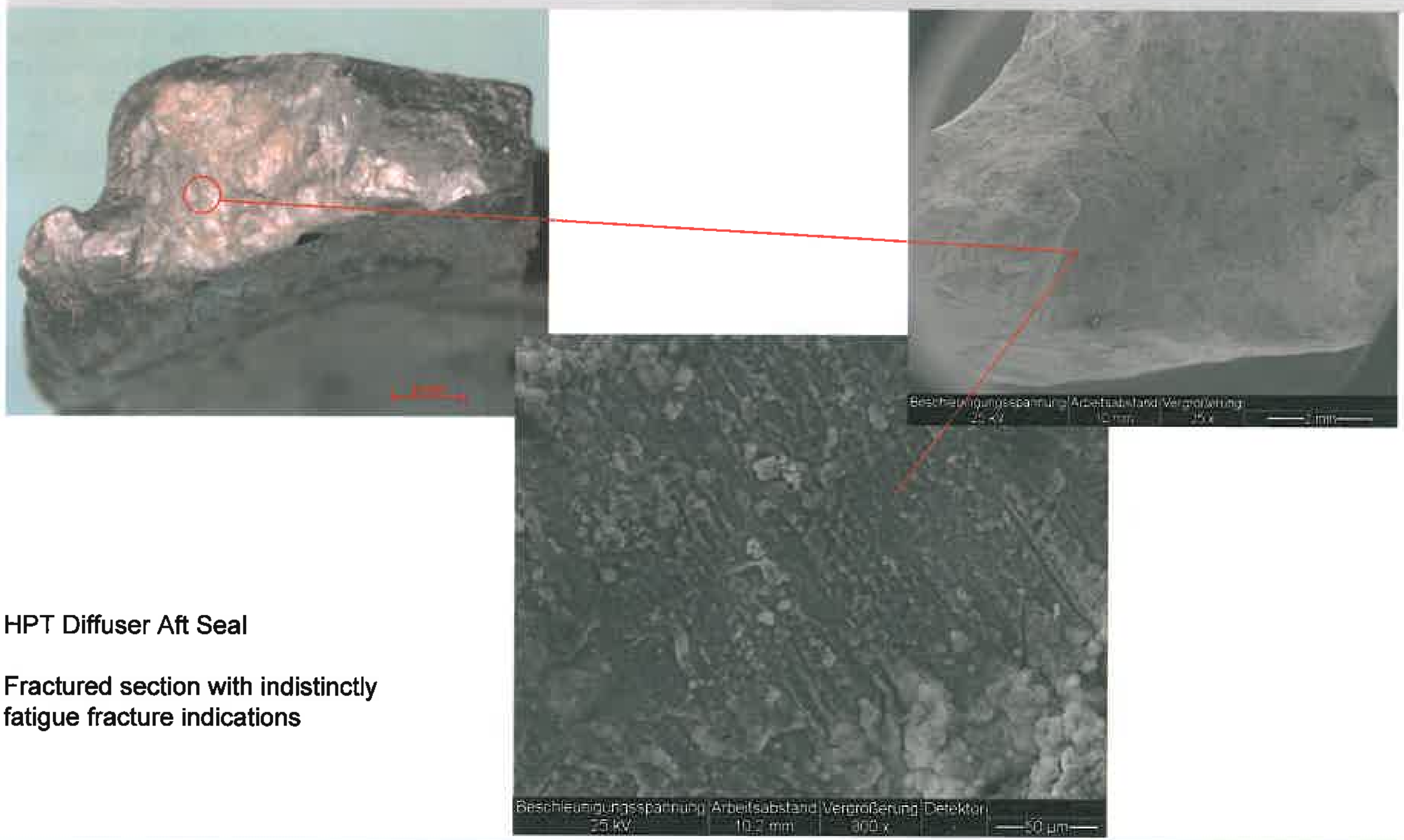
Investigation into the cause of failure CF6-80C2A5F, Eng. no. 705207



HPT Diffuser Aft Seal

Fractured lug with fatigue fracture indications

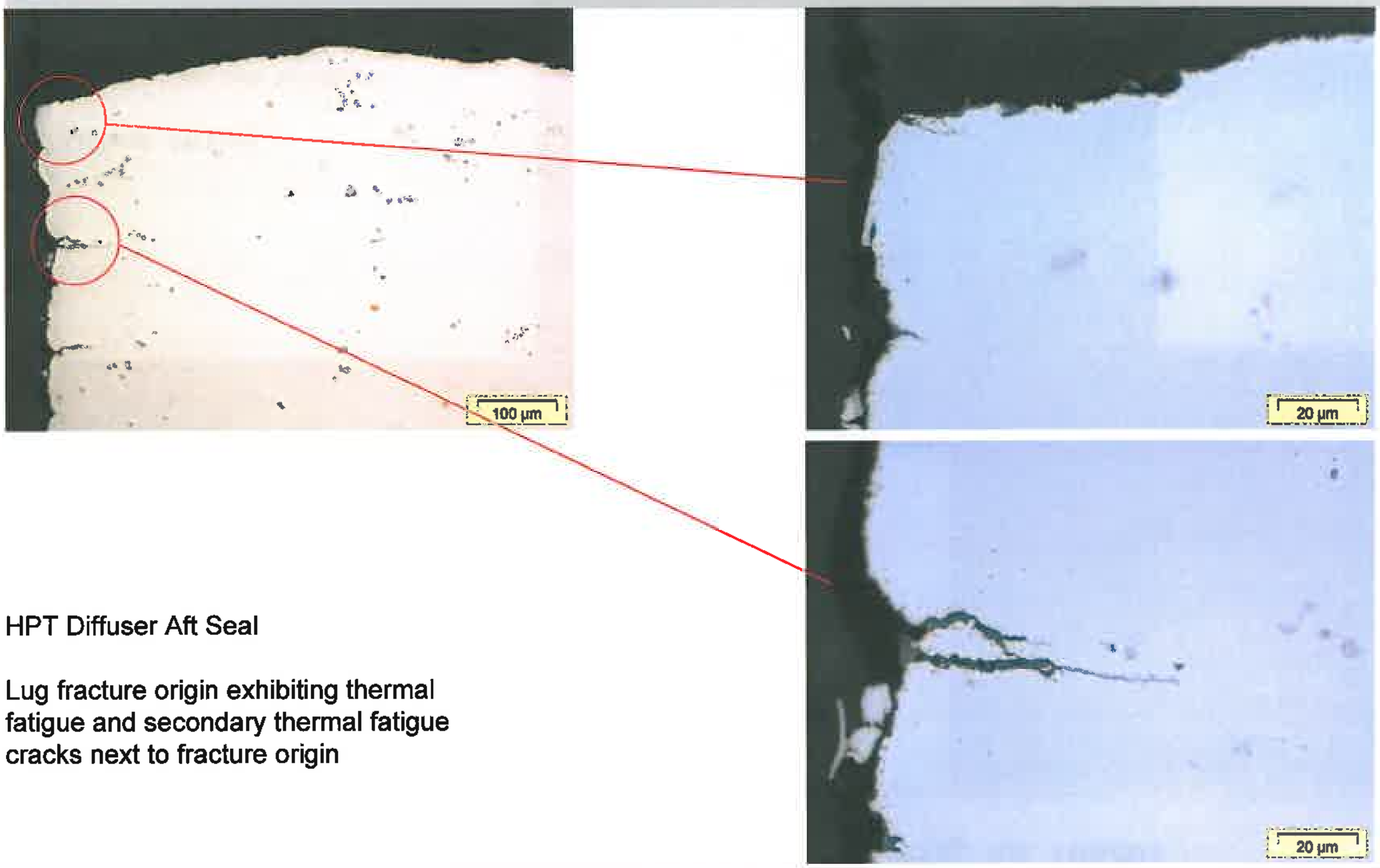
Investigation into the cause of failure CF6-80C2A5F, Eng. no. 705207



HPT Diffuser Aft Seal

Fractured section with indistinctly fatigue fracture indications

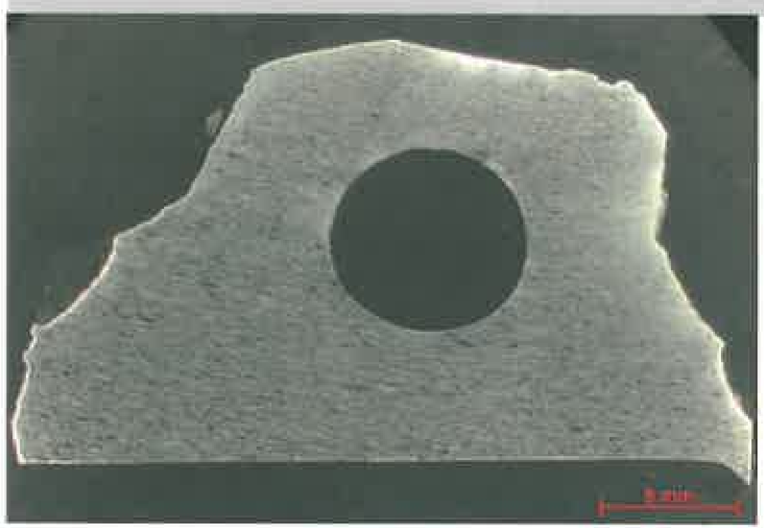
Investigation into the cause of failure CF6-80C2A5F, Eng. no. 705207

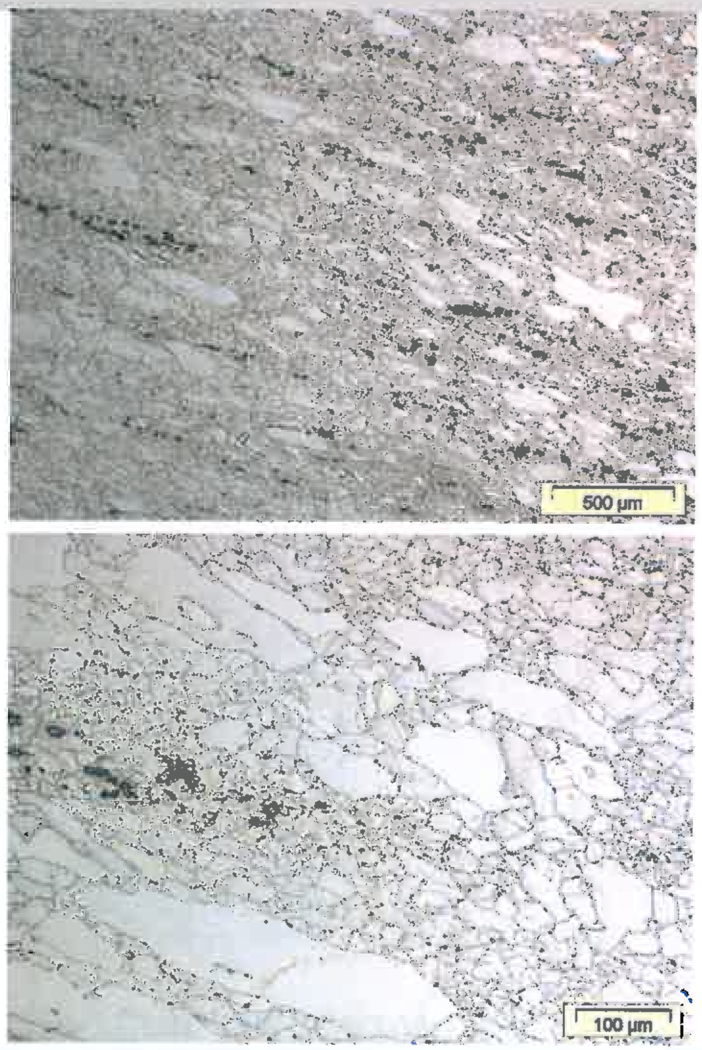


HPT Diffuser Aft Seal

Lug fracture origin exhibiting thermal fatigue and secondary thermal fatigue cracks next to fracture origin

Investigation into the cause of failure CF6-80C2A5F, Eng. no. 705207

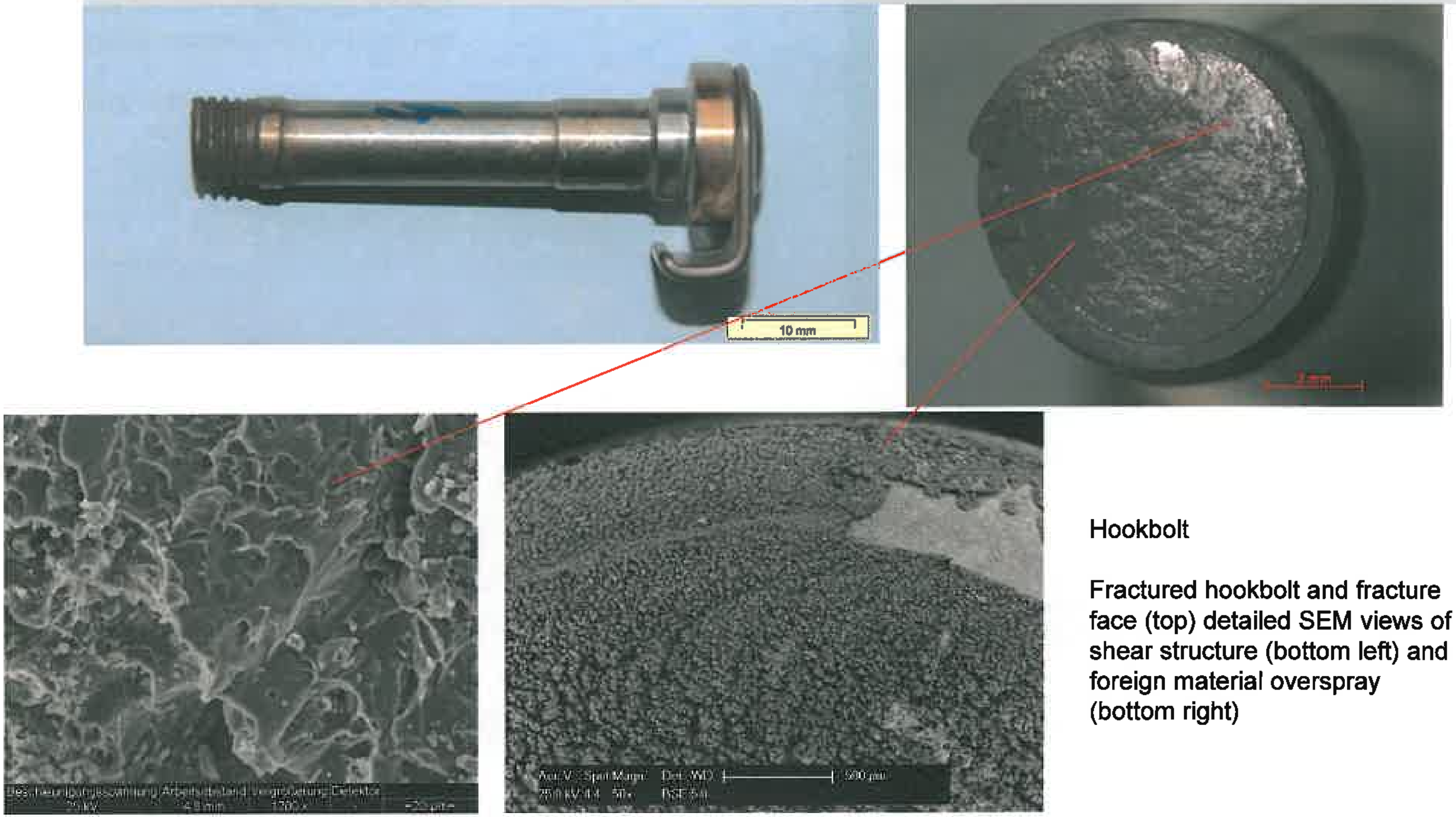




HPT Diffuser Aft Seal

Slightly ovalized seal lug (top left)
and general microstructure (right)

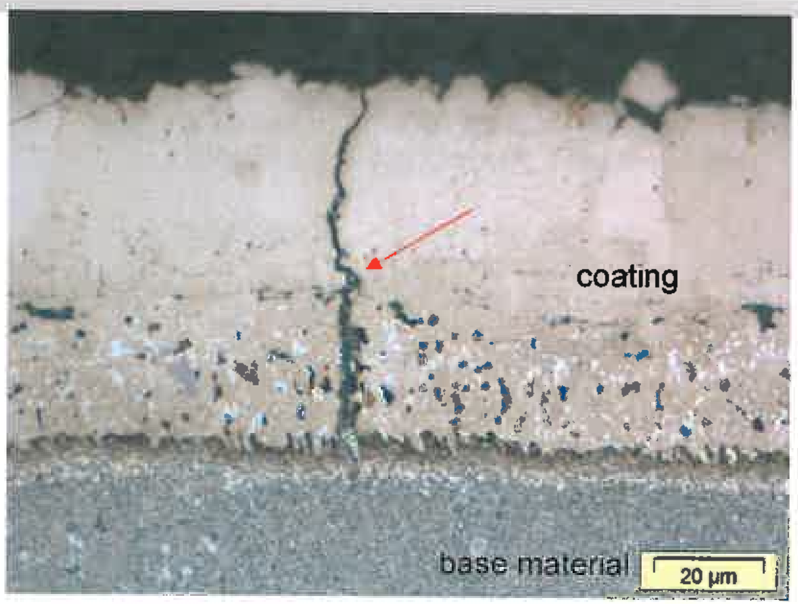
Investigation into the cause of failure CF6-80C2A5F, Eng. no. 705207



Hookbolt

Fractured hookbolt and fracture face (top) detailed SEM views of shear structure (bottom left) and foreign material overspray (bottom right)

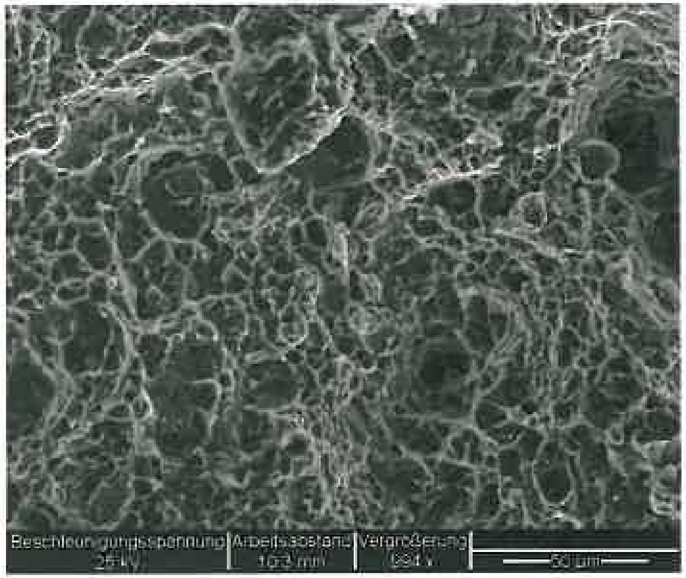
Investigation into the cause of failure CF6-80C2A5F, Eng. no. 705207



HPT Blade

Fractured blades (top left), fracture face of blade airfoil (bottom left) and oxidized / sulfidized crack through the airfoil coating (top right)

Investigation into the cause of failure CF6-80C2A5F, Eng. no. 705207



Ring Bolt

Fractured ring bolts (top), typical fracture face (top right) and SEM view depicting the ductile structure of the fracture (bottom left)

VOLVO AERO

Materials Laboratory **Volvo Aero Corporation** **Trollhättan - Sweden**	Dokumenttyp/Document type Laboratory report		Sida/Page 1 (14)
	Reg. nr/Reg No. VOLS:10137936	Utgåva/Issue 01	Dokdel. Part no.
	Extern identitet/External identity	Bilaga/Appendix	Datum/Date 2011-05-24
Utfärdad av/Issued by 9653KA Kenneth Andersson	Affär, Process, Funktion/Business, Process, Function		
Granskad av/Checked by 9653BK Björn Karlsson	Projekt (eller motsvarande)/Project (or equivalent)		
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SHK Staffan Jönsson

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Dokumenttitel/Document title

CF6-80C2A2F, ESN 705207. Hardware Metallurgical Investigation.

Summary

An Iran Airlines CF6-80C2A2F engine had a turbine failure during takeoff from the Arlanda airport in Sweden, January 2010..
Failure investigation of the engine was performed by Lufthansa Technik AG (HAM TQ/M Report 2010 611).
The Swedish Accident Investigation Board (SHK) has requested a second opinion of the available HPT Diffuser Aft Seal hardware, received from Lufthansa.

The investigation of the Diffuser Aft Seal pieces and fragments received from Lufthansa Technik AG (LHT) showed no presence of fractures or fatigue cracks which are believed to be evidences of the primary cause to the failure.
A secondary fatigue crack was found in an aft tooth fragment from the Diffuser Aft Seal.
This tooth fragment has also a machining step on the FWD surface, between the repair weld and the original tooth, with a geometry which gives a stress concentration factor of about 2.5 for radial and bending stresses in this area.
This machining step may have contributed to initiate a fatigue crack in the seal tooth.

Keywords

Referens/Reference	Job No 11-0584
Motortyp/Engine model	CF6-80C2A2F
Engine Serial No	705207
Part name)	HPT Diffuser Aft Seal, S/N BTABR518
Leverantör/Vendor	
Tillverkare/Manufacturer	
Verkstadsorder/Production order	
Satsnummer/Batch number	
Kontrollparti/Inspection lot	
Materialbenämning/Material description	Inco 718 premium quality forging (GE spec C50TF37 CL-B)
Materialspecifikation/Material specification	

Revision record

Issue	Date	Change
01	2011-05-27	Initial

1 Background

An Iran Airlines CF6-80C2A2F engine had a turbine failure during takeoff from the Arlanda airport in Sweden, January 2010..
Failure investigation of the engine was performed by Lufthansa Technik AG (HAM TQ/M Report 2010 611).
The Swedish Accident Investigation Board (SHK) has requested a second opinion of the available HPT Diffuser Aft Seal hardware, received from Lufthansa.

2 Result

Volvo Aero received not only the Diffuser Aft Seal fragments investigated by Lufthansa (photo No 2) but also a plastic bag with the fragments, which were not investigated by LHT, shown in photo No 1 below.

Photo No 1. Content of the plastic bag. The pieces within the red marking are not believed to be from the Diffuser Aft Seal based upon visual appearance and geometry. The piece marked "A" is from the aft tooth of the seal.
Every piece was inspected for evidences of fatigue fracture but such features were only found on piece "A".

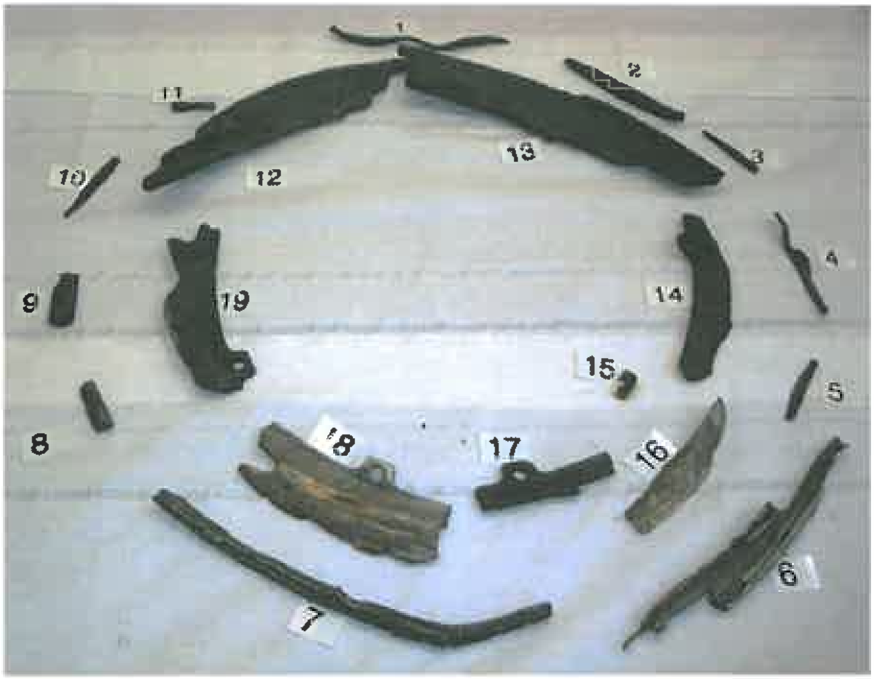


Photo No 2. LHT photo showing Diffuser Aft Seal fragments.

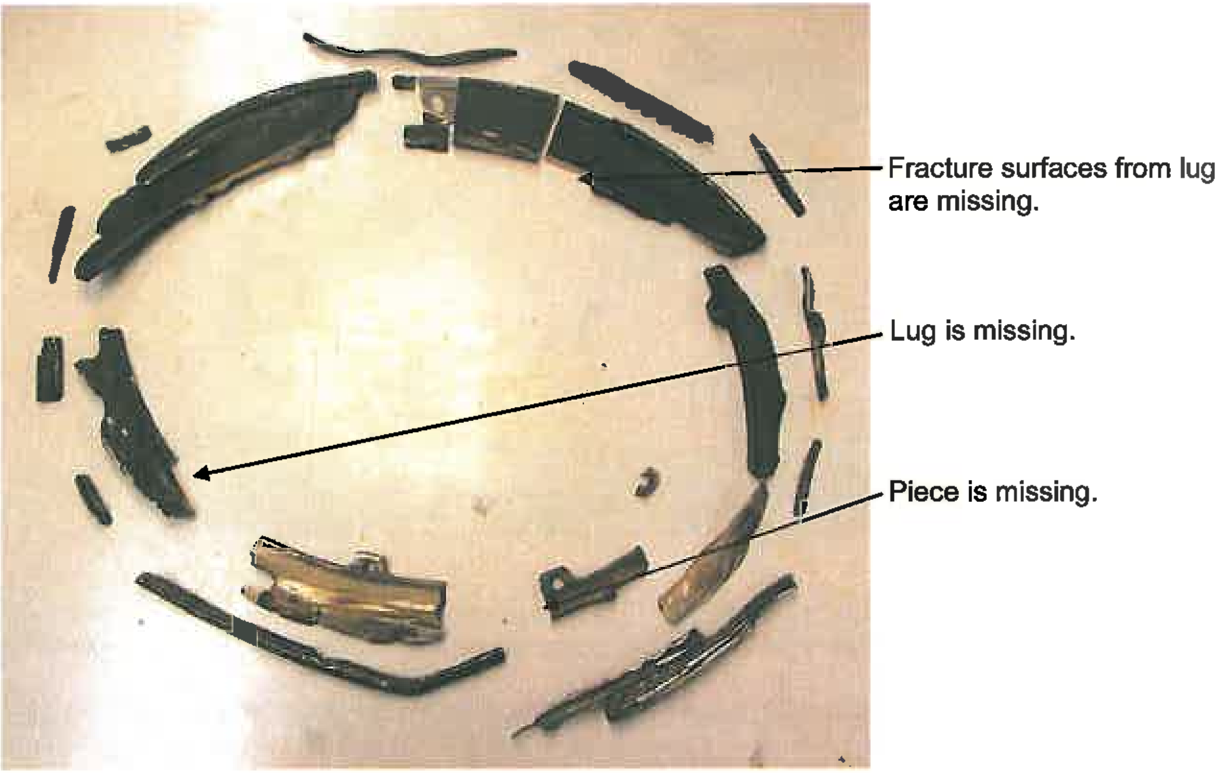


Photo No 3. All of the fragments were received. LHT have cut sections from No 13, 17 and 19.

Some of the missing pieces were received as molded sections.
The fracture surfaces from the lug of fragment 13 are available as molded sections.
Pieces 4, 5, 9, 10 and 11, on photo no 2, are not believed to come from the Diffuser Aft Seal, based upon visual appearance and geometry.
Piece No 9 is confirmed by GE Aviation to be a HPT Stage 1 Nozzle air cover baffle.

Photo No 4. Piece no 9, HPT Stage 1 Nozzle air cover baffle.

The weight of a HPT Diffuser Aft Seal is 2295g.
Total weight of received fragments from the Seal is 1224g, which means that 45% is missing.

Photo No 5. Piece No 6 is the only fragment with the four seal teeth in the same piece.

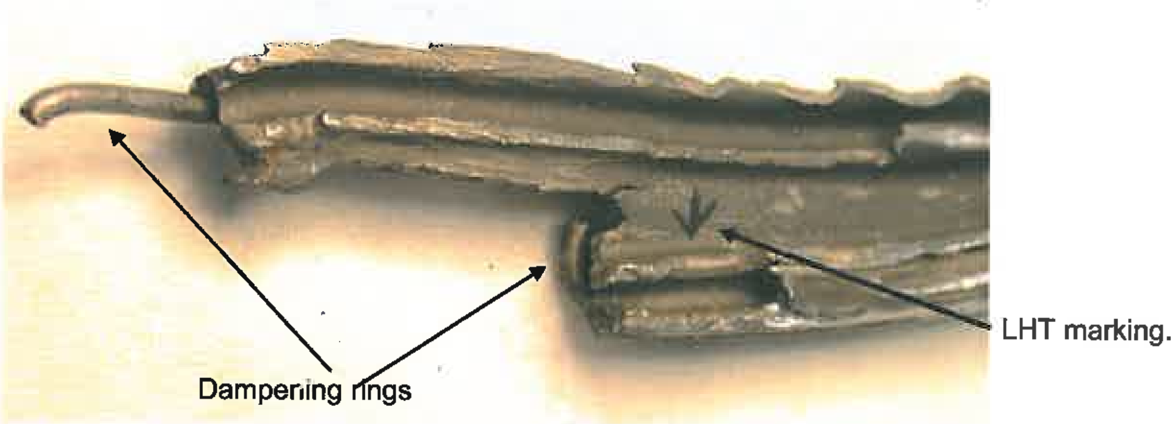
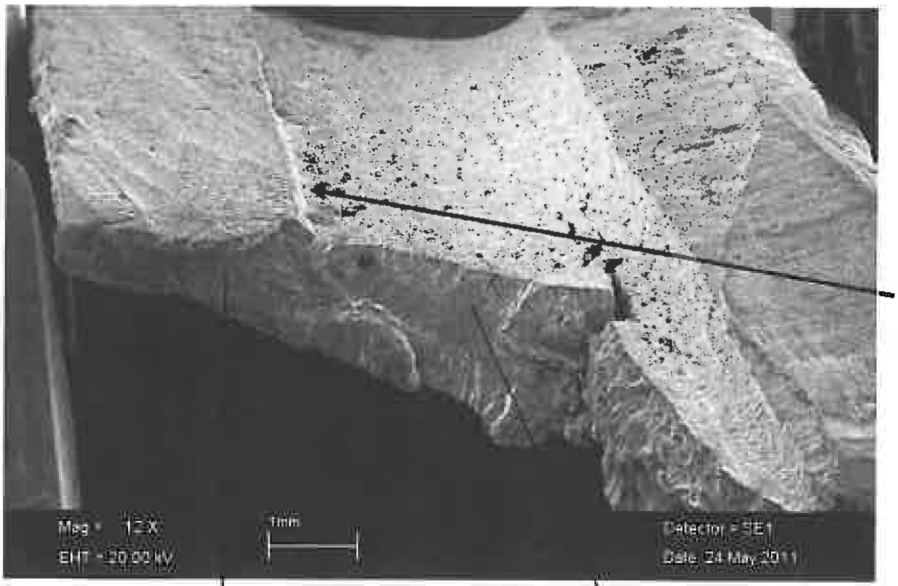


Photo No 6. Both dampening rings were in place at the failure.

Photo No 7. The most interesting piece of the ones in photo No 1 is this 30 mm long fragment (labeled A) of the aft tooth of the seal (FWD surface shown on photo). This is the only piece of a seal tooth which is rather undamaged.
The line shows where a metallographic section was cut.

Photo No 8. The left end of the tooth in photo no 7 shows a fatigue crack (arrow). The bright appearance of the crack surface suggests it to be a secondary crack, developed during the engine break down.



Note the step between the repair weld and original tooth.

Photo No 9. SEM-photo of the fracture surface in photo no 8.

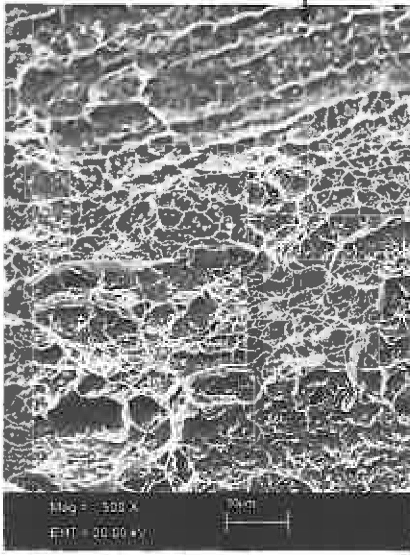


Photo No 10. Tensile overload (weld) structure.

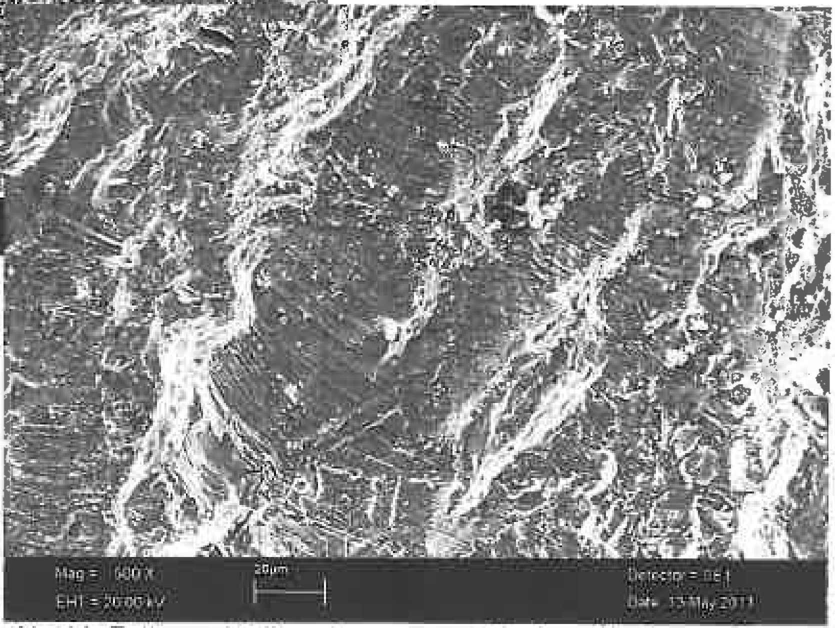


Photo No 11. Fatigue striations in a comparatively oxide free surface.

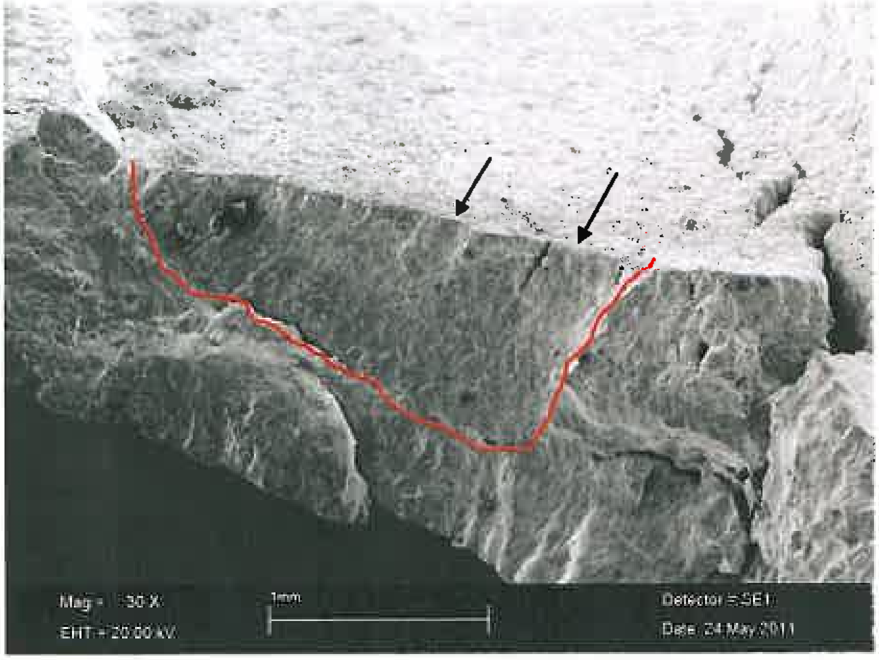


Photo No 12. Fatigue surface outlined with red. Arrows show two crack initiation points.

Metallography.

A cross section was cut through the seal tooth and prepared for metallographic evaluation.

Photo No 13. Cross section, in etched condition, shows the seal tooth with the dabber weld repair.

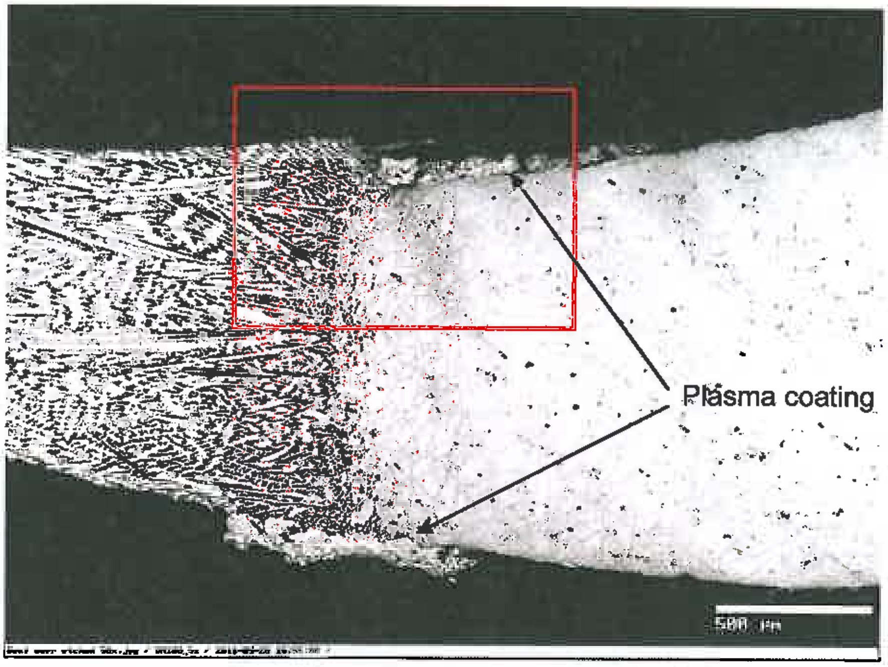


Photo No 14. Higher magnification of the dabber weld interface.

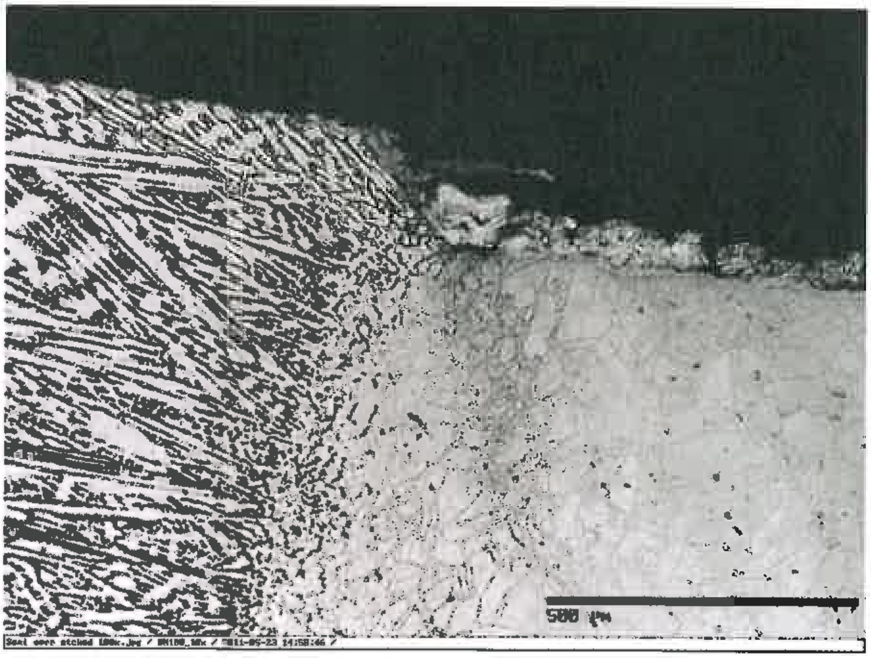


Photo No 15. Higher magnification of the area in the red rectangle in previous figure shows the machining step between the original seal and the repair weld.

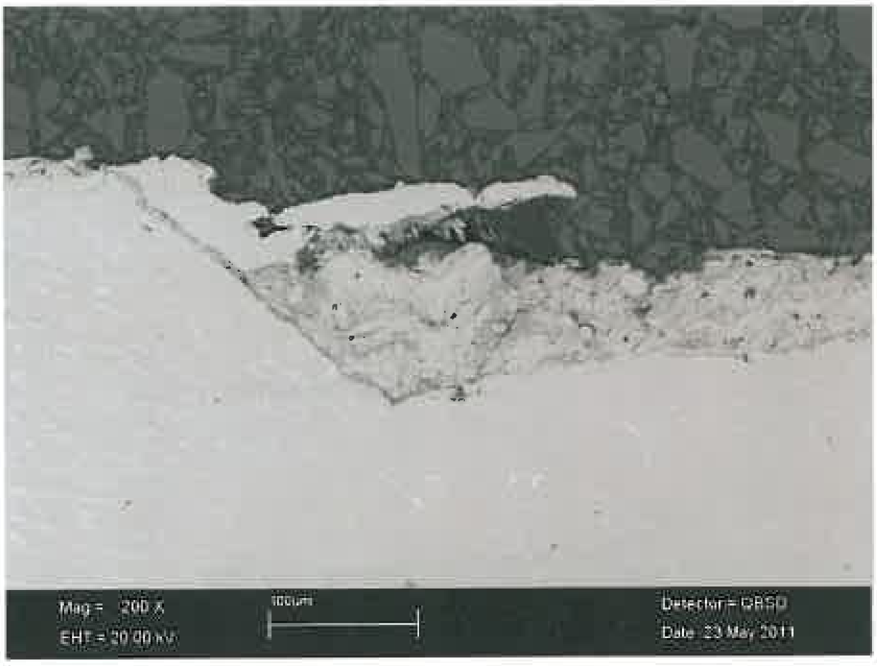


Photo No 16. SEM-photo in 200X shows that the bottom of the machining step between the original seal and the repair weld is considered to be a sharp corner.

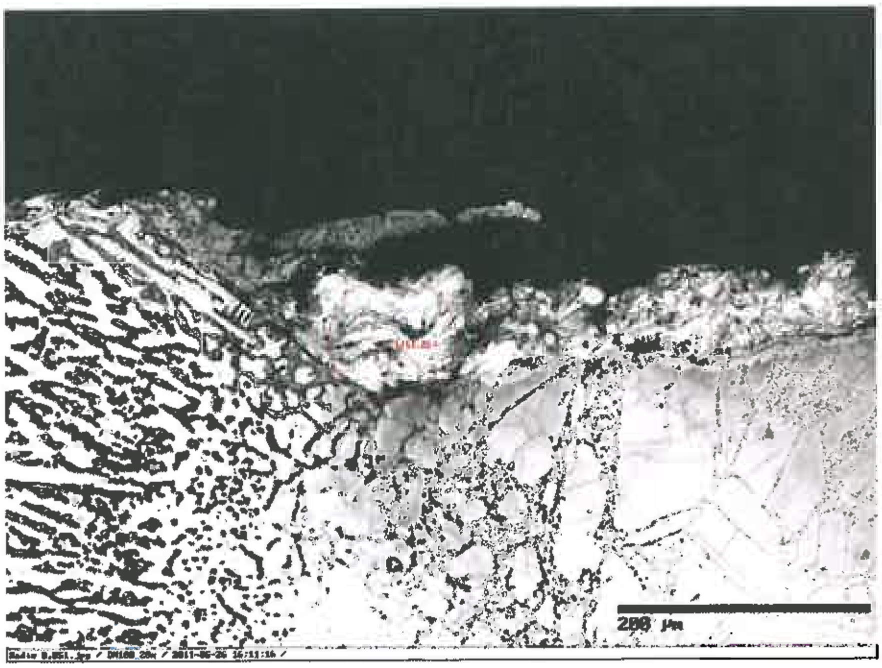


Photo No 17. The radius of the machining step is measured to be 0.05mm.

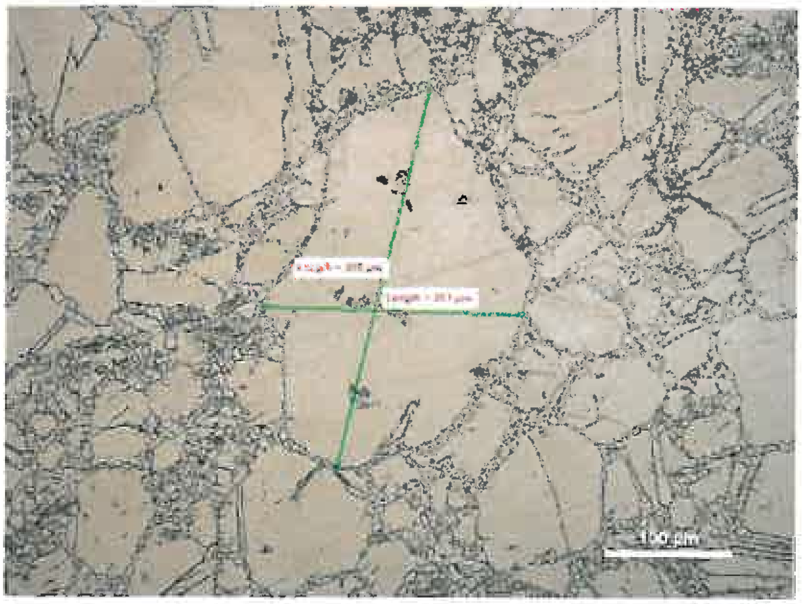


Photo No 18. The grain size of the seal tooth base material, about 3 mm from the weld interface, was evaluated per GE C50TF37 CL B per ASTM E 112.

Requirements: Forgings shall have an average size of ASTM No 4 or finer, with occasional grains as large as 0.18 mm permissible. Grain size shall be predominantly uniform without pronounced segregation of fine and coarse grained areas.
All requirements per GE C50TF37 CL B rev. S29.

Result:

-Duplex, necklace grain size with 50% fine grains.
-GS fine: ASTM 13
-GS coarse: ASTM 5.5
- ALA ASTM 1.5.

Duplex, necklace structure is not permitted according to the requirements.
The largest grain in photo No 18 is 0.30 x 0.20 mm which is not permitted.

Carbide segregation check shows that the amount and distribution of particles do not exceed the extent shown i GEAE photo 317164, although the amount of particles is considered to be high for a premium quality In 718.

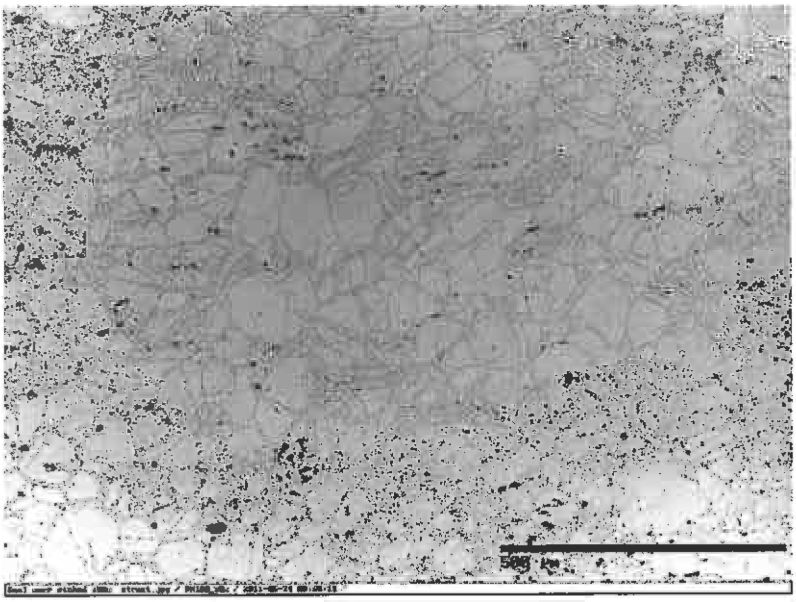


Photo No 19. Microstructure of the seal tooth, about 3 mm from the weld interface.

Analysis of the chemical composition of the dabber weld and the seal base material was performed using the SEM/EDS.
Both results show the chemical composition for Inconel 718.

Elmt	Spect.	Element	Atomic	
	Type	%	%	
Al K	ED	0.52	1.10	
Si K	ED	0.02*	0.04*	
Ti K	ED	0.86	1.04	
V K	ED	0.02*	0.02*	
Cr K	ED	19.06	21.20	
Mn K	ED	0.08*	0.08*	**Weld**
Fe K	ED	19.15	19.84	
Ni K	ED	52.89	52.12	
Cu K	ED	0.17*	0.16*	
Nb L	ED	4.03	2.51	
Mo L	ED	3.01	1.82	
Ta M	ED	0.18*	0.06*	
Total		100.00	100.00	
* = <2	Sigma			

Elmt	Spect.	Element	Atomic		
	Type	%	%		
Al K	ED	0.55	1.18		
Si K	ED	0.11*	0.22*		
Ti K	ED	1.01	1.22		
V K	ED	0.11*	0.13*		
Cr K	ED	19.26	21.44		
Mn K	ED	0.00*	0.00*	**Base metal**	
Fe K	ED	19.21	19.91		
Ni K	ED	51.83	51.10		
Cu K	ED	-0.03*	-0.02*		
Nb L	ED	4.49	2.80		
Mo L	ED	3.27	1.97		
Ta M	ED	0.17*	0.05*		
Total		100.00	100.00		
* = <2	Sigma				

3 Discussion

Among the pieces received from LHT, which were not included in the LHT report, was a 30 mm long comparatively undamaged fragment of the aft tooth of the Diffuser Aft Seal.
One end of this tooth fragment showed a fatigue crack which was considered to be secondary based upon its appearance, i.e. a grey, comparatively oxide free surface, multiple origins and a large tensile overload area, indicating high stresses.
In order to evaluate the repair weld a cross section was cut from the tooth fragment. The cross section showed a 0.2 mm high machining step with a sharp bottom (radius about 0.05 mm) between the repair weld and the original seal tooth surface.
The shape of the machining step will give a stress concentration factor of about 2.5 for radial and bending stresses in this area. The stress concentration factor has been estimated with an ANSYS 2D FE analysis, using a radius of 0.05 mm, height of the step of 0.2 mm and an angle of 128 degrees.

The weld and the post stress relief heat treatment (760 C for 2 hours, furnace cooling to 621 C and hold time for 4 hours at 621 C) will give a residual stress of about 300 MPa in the weld area.
The residual stress, thermal stresses and possible stresses from vibrations in combination with the stress concentration factor of 2.5 caused by the machining step appears to be possible causes for that a crack could initiate and grow.

4 Conclusion

The investigation of the Diffuser Aft Seal pieces and fragments received from Lufthansa Technik AG (LHT) showed no presence of fractures or fatigue cracks which are believed to be evidences of the primary cause to the failure.
A secondary fatigue crack was found in an aft tooth fragment from the Diffuser Aft Seal.
This tooth fragment has also a machining step with a geometry which gives a stress concentration factor of about 2.5 for radial and bending stresses.
This machining step may have contributed to initiate a fatigue crack in the seal tooth.

Appendix 6

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RÉPUBLIQUE FRANÇAISE

Ministère de l'Ecologie,
du Développement durable
et de l'Energie

BEA
Bureau d'Enquêtes et d'Analyses
pour la sécurité de l'aviation civile

Le Bourget, 13 August 2012

Stephan Christensen
Staten
Haveri Kommission
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12538
SE-102
29 Stockholm
Sweden

N° 00772/BEA/INV
Subject: EP-IBB BEA comments
Your Ref: Draft report L-02/10 related to the incident which occurred in Stockholm/Arlanda on 16 January 2010
Attachment: 1 appendix

Dear Mr Christensen,

Thank you for having associated the BEA (Bureau d'Enquêtes et d'Analyses pour la sécurité de l'Aviation Civile) with the investigation into the accident to the Airbus A300-600, registered EP-IBB, and for the opportunity to make comments on the Draft Final Report. I would also like to reiterate our great appreciation for the spirit of cooperation that has permeated this investigation.

It is in this same spirit, and with the interests of civil aviation safety in mind, that we hereby present you with the following observations. I hope that they will appear to you to improve the overall comprehension of the accident and that you will accept that they be included into your report. If this is not the case, I would be obliged if you would append these observations to the report, in accordance with the provisions of Annex 13.
As you requested directly Airbus' comments, this document does not take into account their observations.

The BEA remains at your disposal for any further information that you may wish to obtain.

Yours sincerely.

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APPENDIX

Generals

The BEA does not totally support the draft report. The most important is that SHK rules out the influence of asymmetric braking action on the veer off. We consider that the crew actions on the brakes have contributed to the movement of the aircraft to the left as well as the asymmetric thrust. Then, because of the contaminated pavement and the low speed, the use of tiller and rudder could not prevent the aircraft from exiting the runway. .

This position is supported by the simulator runs that were carried out on the Airbus A300-600 simulator, which has been certified by the French DGAC. Even if the accident scenario cannot be accurately reproduced, the various simulator runs give a good qualitative representation of the factors that contributed to the aircraft veer off and those that had little or no influence.

The appliance of the approved procedure could have helped maintaining the aircraft on the runway. The report neither presents the crew training (generally speaking and for this procedure) nor the crew work and CRM. However, SHK issues a recommendation within this domain.

The analysis repeats some paragraphs of the factual report. In addition, some new factual information, is presented in this chapter (i.e crew reaction times - 2.2.4, 2.3.6, audiogram -2.3.5,..). This data could better be included in 1.16.

Text in blue colour is added by SHK as comments to the BEA letter.

The results from the simulator tests are described in the report. As the accuracy, among other items, regarding friction modulation possibilities for the different wheels (main and nose gear wheels) are rather uncertain, the tests will remain "informative", but not regarded as facts.

The crew transition training program from Airbus has been added to the report. The recommendation concerns mandatory simulator programs issued by authorities.

The crew reaction times shall not be regarded as "facts". These issues are calculated and analyzed from available facts and should therefore remain in the analysis part of the report.

Modifications

Section	**Draft text**	**Change proposals from BEA**	**Comments SHK**
Summary §4	"The veer was a result of the nose wheel being unable to gain sufficient force against the contaminated surface to counter-act the moment which arose when the right engine –	The veer was the result of the yawing moment created by a brief thrust asymmetry and by the differential braking applied by the crew. Then, crew inputs on rudder pedals and control wheel could not prevent the aircraft from running off the	Text in report changed to: "The initial veer, immediately after the engine seizure, was a result of the nose wheel being unable to gain sufficient force against the

	for a duration of approximately 1.5 seconds – supplied full power at the same time as the left engine lost power."	runway.	contaminated surface to counteract the moment which arose when the right engine – for a duration of approximately 1.5 seconds – supplied full thrust at the same time as the left engine rapidly lost thrust".
1.History of flight		Some additional time references such as the time of the runway excursion would help the understanding of the sequence of events. A trajectory with a legend indicating the main events might also help.	Time for runway excursion added in 1.1.4.
1.1.2 Flight Preparation, §6	"T.O.W 148.4 tonnes"	We have 148,980 in 1.16a.1	Corrected in the report.
1.6b.2	"The PF pushes the throttle lever forward"	"The PF pushes the control column forward"	Corrected in the report.
1.6c.4, §3	"The category of loss of engine power which is most relevant in this incident is Uncontained turbine failure"	Disagree with the definition Uncontained turbine failure is when parts of the turbine go out of the engine cooling. To be confirmed.	Text in the technical chapters adjusted. The definition is however difficult as small holes in the turbine housing were discovered.
1.6c.5	"This rotation is a consequence of the resulting turning moment caused by the engines"	"This rotation is a consequence of the resulting turning moment caused by the engines and asymmetrical braking"	The entire sentence is removed from the report.
1.16a.4	"It has however not been possible to establish how the simulator has been programmed with regard to reduced friction in connection with varying surfaces."	The simulator used was a training simulator. It does not represent the "true" aircraft in all the domains. Even if we don't know its programs for the contaminated runway, it gives good trends. The various tests result in a lateral runway excursion when there is an asymmetric braking action. This has to be taken into account as a contributive or aggravating factor.	The text in the report is changed and in some parts completed. — See also text above.
1.16a.5	Sim 2	This test is irrelevant. The aircraft is not the same, positions, angles, settings are different from the accident model.	Text will not be changed. The reason for these tests was ergonomical.
1.16a.9,§3	"The British	The study in the AAIB	Text will not be

	accident investigation authority (AAIB33) has recently examined a number of cases where the correlation between friction measurement on a damp or wet runway and an aircraft's directional control has been questioned."	bulletin does not address the correlation between friction and aircraft directional but between measured friction and calculated breaking performances. These references are irrelevant.	changed. The report is interesting as it is addressing the problems between runway surface status and aircraft controllability.
2.3.9	"The overall conclusion is that no measurable change of heading – or of change of heading – is observable in connection with the recorded brake values. Even though the possibility that the braking had a certain effect on the turning moment cannot be excluded, it is SHK's understanding that the asymmetry had not been of crucial significance for the development of the incident."	Due to the sampling rate, interpretation of FDR data is limited. When the heading began to change significantly, between 11:38:22 and 11:38:23, both the braking action and the rudder deflection started. So the resulting heading rate is the consequence of the combined effects of thrust and braking asymmetry and rudder deflection. To the BEA's point of view, FDR data does not allow quantifying in any manner the effect of these contributory factors nor does it allow asserting that asymmetrical braking had no influence on the development of this event.	Text in report will be adjusted. It is SHK:s opinion that the differential braking may have had influence on the event. It is however not possible to conclude that this had any crucial significance to the occurrence. The variation of heading change rate, as seen in fig 55 in the report, does not reveal any measurable heading rate changes in connection with the braking.
2.10	"The veer was caused by the nose wheel not being able to generate enough force against the contaminated surface in order to counteract the moment which arose when the right engine – for a duration of approximately 1.5 seconds – supplied full power at the same time as the left engine immediately lost power."	Same comment as for summary	Text in the report will be changed to: The initial veer, immediately after the engine seizure, was caused by the nose wheel not being able to generate enough force against the contaminated surface in order to counteract the moment which arose when the right engine – for a duration of approximately 1.5 seconds – supplied full thrust at the same time as the left engine immediately lost

			thrust, together with the pilot's not applying any differential braking in the correct direction.
Findings 3.1.m)	"The change of heading occurred more or less immediately after the engine failure, when the moment was greater than the forces which the nose wheel's friction could create."	"The change of heading occurred more or less immediately after the engine failure, due to the yawing moment created by asymmetrical thrust and differential braking applied unintentionally by the crew. The crew inputs on rudder and tiller could not prevent the aircraft from veering of the runway."	Text will not be changed. The heading change occurred instantly after the engine failure. Braking was initiated later. See fig 56 in the report.