국토교통부
Ministry of Land, Infrastructure and Transport

ARAIB/AIR 1101

Aircraft Serious Incident Report

In-Flight Engine Shutdown
Korean Air
A330-300, HL7553
Approximately 20 km South of Incheon Int'l Airport
26 May 2011

June 2014

AVIATION AND RAILWAY ACCIDENT INVESTIGATION BOARD

This aircraft incident report has been prepared in accordance with the Article 25 of the Aviation and Railway Accident Investigation Act of the Republic of Korea.

According to the provisions of the Article 30 of the Aviation and Railway Accident Investigation Act, it is stipulated;

"The accident investigation shall be conducted separately from any judicial, administrative disposition or administrative lawsuit proceedings associated with civil or criminal liability."

And in the Annex 13 to the Convention on International Civil Aviation, Paragraphs 3.1 and 5.4.1, it is stipulated as follows:

"The sole objective of the investigation of an accident or incident shall be the prevention of accidents and incidents. It is not the purpose of the activity to apportion blame or liability. Any investigation conducted in accordance with the provision of this Annex shall be separate from any judicial or administrative proceedings to apportion blame or liability."

Therefore, this investigation report may not be used for purposes other than to improve aviation safety.

In case of divergent interpretation of this report between the Korean and English languages, the Korean text shall prevail.

Aircraft Serious Incident Report

Aviation and Railway Accident Investigation Board. ***In-Flight Engine Shutdown, Korean Air, A330-300, HL7553, Approximately 20 km South of Incheon International Airport, 26 May 2011.*** **Aircraft Serious Incident Report ARAIB/AAR-1101. Sejong Special Self-Governing City, Republic of Korea.**

The Aviation and Railway Accident Investigation Board (ARAIB), Republic of Korea, is a government organization established for independent investigation of aviation and railway accident, and the ARAIB conducts accident investigation in accordance with the provisions of the Aviation and Railway Accident Investigation Act of the Republic of Korea and Annex 13 to the Convention on International Civil Aviation.

The objective of the investigation by the ARAIB is not to apportion blame or liability but to prevent accidents and incidents.

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Contents

In-Flight Engine Shutdown

- ○ Operator: Korean Air
- ○ Manufacturer: Airbus Industrie, France
- ○ Type: A330-300
- ○ Registration Mark: HL7553
- ○ Location: Approximately 20 km south of Incheon Int'l Airport
  (Latitude: N 37°13'33", Longitude: E 126°23'35")
- ○ Date & Time: 26 May 2011, approximately 14:23 KST (05:23 UTC[1])

Synopsis

On 26 May 2011, approximately 14:23, Korean Air flight 935, which took off from Incheon International Airport, Republic of Korea, bound for Ruzyne International Airport, Czech Republic, experienced an uncommanded right roll with a sudden bang while passing through 11,900 ft during its climb out and observed a No. 2 engine fire warning message displayed, followed by a continuous repetitive chime sound and a fire warning light. The flight crew shut down the No. 2 engine through related emergency procedures, declared an emergency, and returned to Incheon International Airport.

Aboard the aircraft were 3 flight crew, 11 cabin crew, and 281 passengers. There was no personal injury.

The Aviation and Railway Accident Investigation Board (ARAIB) determines the probable cause of this serious incident to be one liberated 4th-stage low pressure turbine (LPT) vane cluster of the No. 2 engine, which successively damaged later stages of blades and vanes, thereby resulting in an engine failure.

1) Unless otherwise indicated, all times stated in this report are Korean Standard Time (KST, UTC +9).

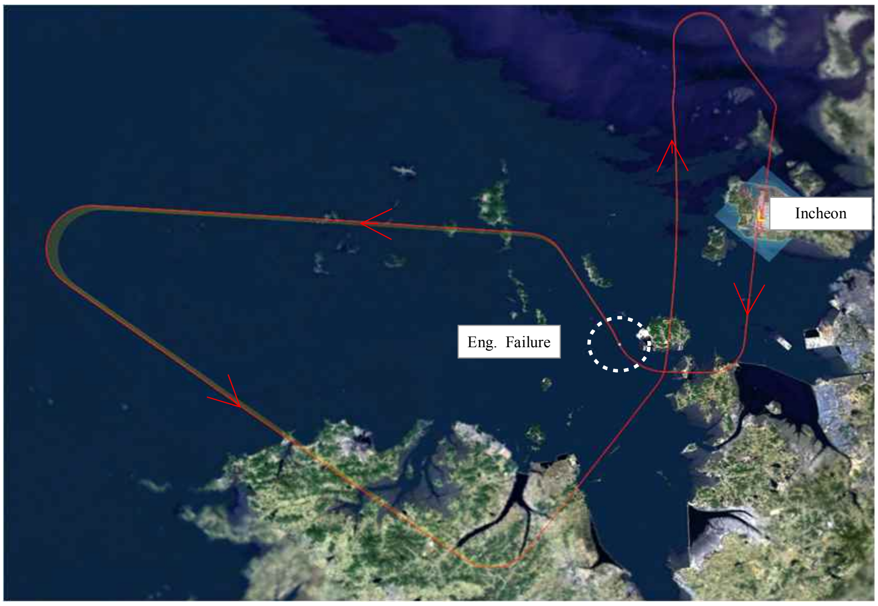
Contributing to the serious incident was excessive wear to the 4th-stage LPT vane cluster's C-channel caused by abnormal 2E excitation, which had resulted from the aerodynamic pattern of the 2nd-stage high pressure turbine (HPT) rotor.

As a result of this serious incident investigation, the ARAIB addresses two safety recommendations to Korean Air and one safety recommendation to Pratt & Whitney.

1. Factual Information

1.1 History of the Flight

On 26 May 2011, approximately 13:58, Korean Air flight 935 (hereafter referred to as HL7553) with 14 crew members and 281 passengers aboard, took off from runway 16 at Incheon International Airport (hereafter referred to as Incheon Airport) and climbed as per the NOPIK 1U SID[2]. The aircraft experienced an uncommanded right roll with a sudden bang while passing through 11,900 ft during its climb out and observed a No. 2 engine fire warning message displayed, followed by a continuous repetitive chime sound and a fire warning light. N1 vibration and EGT[3] over limit messages were also displayed on the cockpit instrument panel.



[Figure 1] Flight Path of HL7553

At the time, the captain was the pilot flying (PF), and the first officer (FO) was the pilot monitoring (PM). Immediately after the engine failure, the flight

2) Standard Instrument Departure.
3) Exhaust Gas Temperature.

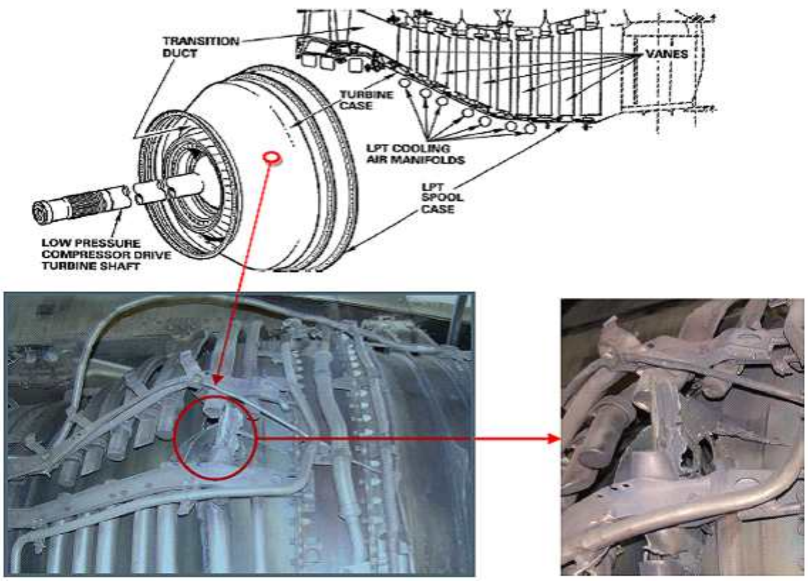
crew stopped climbing and, in accordance with ECAM[4] procedures, extinguished a No.2 engine fire by discharging a No.1 fire bottle and stopped the engine. Also, the flight crew who confirmed the disappearance of the fire warning message declared an emergency to the applicable ATCs and performed air turn back (ATB) to Incheon, then auto-landed using the ILS approach in accordance with ILSDME RWY16 procedures of Incheon Airport.

1.2 Injuries to Persons

Injuries	Crew	Passenger	Others	Total
Fatal	0	0	0	0
Serious	0	0	0	0
Minor	0	0	0	0
None	14	281	0	295
Total	14	281	0	295

[Table 1] Personal Injuries

1.3 Damage to Aircraft



[Figure 2] LPT Case

4) Electronic Centralized Aircraft Monitoring.

As shown in [Figure 2], the aircraft sustained a hole puncture damage to the low pressure turbine (LPT) case at the 9 o'clock position. The fragments of airfoils, which damaged inside the engine, were caught in cracks, whereas some of them fell out to the ground when the engine cowl was open.

As shown in [Figure 3], all 7th-stage LPT blades and vanes were damaged.

[Figure 3] 7th-Stage LPT

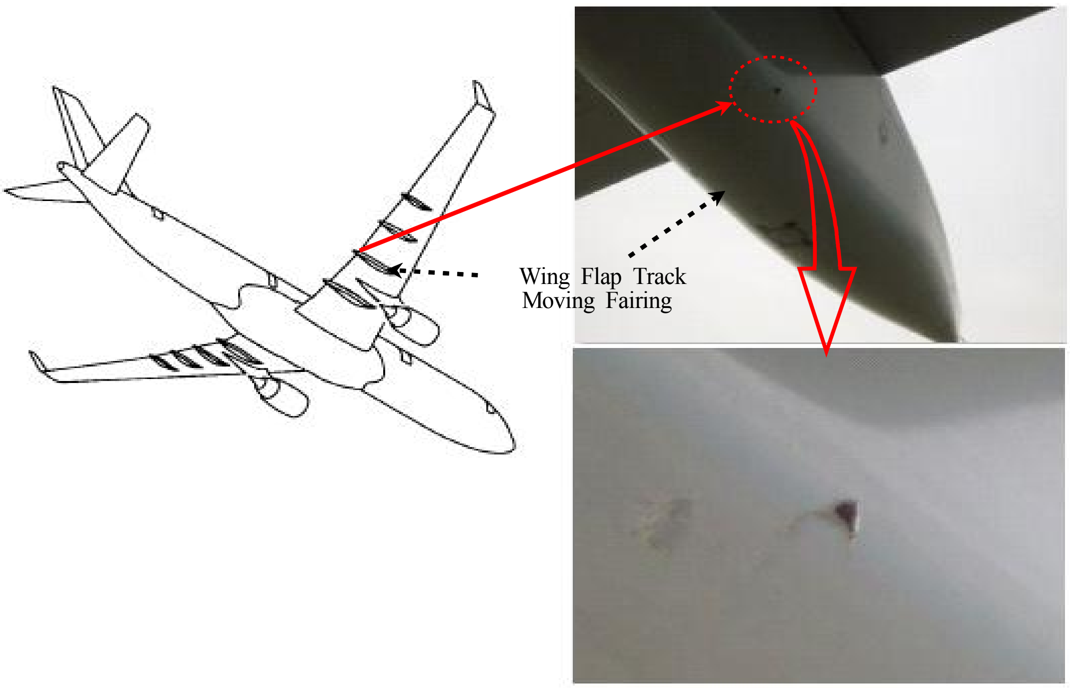
As shown in [Figure 4], metal fragments were found near the exhaust nozzle, but the air inlet sustained no damage.

[Figure 4] Metal Fragments near the Exhaust Nozzle

As shown in [Figure 5], engine debris, which penetrated the LPT case, all remained in the engine cowl, but there was no sign that the debris passed through the cowl.

[Figure 5] Interior and Exterior of the Engine Cowl (9 o'clock position)

As shown in [Figure 6], a puncture with a diameter of 5 cm was found at the bottom surface of the right-hand wing flap moving track fairing.



[Figure 6] Wing Flap Track Moving Fairing Damage

1.4 Other Damage

None

1.5 Personnel Information

1.5.1 The Captain

The captain (male, age 56) held a valid air transport pilot license[5], A330 type rating, a first-class airman medical certificate[6], an aeronautical radio operator license[7], and level 4 ICAO English Proficiency Certificate.

The captain had accumulated 16,779 total flight hours, including 5,656 hours as pilot-in-command in A330 airplanes. He had flown 143 and 54 hours in the last 90 and 30 days, respectively. He passed his line check in October 2010 and proficiency check in February 2011.

For the last 24 hours before the event, the captain took a day off, so he took a walk, went to market, and watched TV at home, then slept for about 9 hours, which was enough sleep for him.

1.5.2 The First Officer

The FO (male, age 41, US national) held a valid air transport pilot license[8], A330 type rating, a first-class airman medical certificate,[9] an aeronautical radio operator license[10], and level 4 ICAO English Proficiency Certificate.

5) License No.: 866 (24 Oct. 1992).
6) Expiry Date: 30 Sep. 2011.
7) License No.: 903400484.
8) License No. : 3880 (7 Oct. 2009).
9) Expiry Date: 30 Sep. 2011.
10) License No.: 103410508.

The FO had accumulated 8,345 total flight hours, including 935 hours in A330 airplanes. He had flown 165 and 34 hours in the last 90 and 30 days, respectively. He passed his line check in October 2010 and proficiency check in April 2011.

For the last 24 hours before the event, the FO arrived at Incheon Airport on an extra flight in the afternoon, then took a rest at the hotel and slept for about 8 hours.

1.6 Aircraft Information

1.6.1 Aircraft History

HL7553 was manufactured[11] by Airbus in April 1999, and purchased and registered by Korean Air on 4 June 1999. The aircraft held a valid airworthiness certificate, logging 40,393 flight hours and 15,681 cycles. C check and A check on the affected airplane were carried out in May 2010 and April 2011, respectively.

1.6.2 Engine History

As shown in [Table 2], HL7553 was equipped with two PW4168A engines manufactured by Pratt & Whitney.

Category	Manufacture No.	TSN/CSN[12]	TSO/CSO[13]	Installation Date
No. 1 Engine	P733521	34,356/6,557	897/251	19 Mar. 2011
No. 2 Engine	P733445	36,534/12,387	12,167/3,599	13 Jun. 2008

[Table 2] Engine

11) Manufacture No.: 267.
12) Time/Cycle Since New.

1.6.3 Weight and Balance

The weight and balance data of HL7553 is as follows:

- Zero Fuel Weight (ZFW)....................... 343,938 lbs (Max. 381,396 lbs)
- Takeoff Fuel (TOF)............................ 162,600 lbs
- Takeoff Weight (TOW).......................... 506,538 lbs (Max. 507,001 lbs)
- Trip Fuel (TIF)............................. 142,000 lbs
- Landing Weight (LDW)................. 364,538 lbs (Max. 407,851 lbs)
- Takeoff Weight Center of Gravity (TOW C.G % MAC) : 30.2 % MAC

1.7 Meteorological Information

Not applicable.

1.8 Aids to Navigation

Not applicable.

1.9 Communications

There was no trouble with communications during HL7553's operation.

1.10 Aerodrome Information

Not applicable.

1.11 Flight Recorders

13) Time/Cycle Since Overhaul.

1.11.1 Cockpit Voice Recorder[14)]

HL7553 was equipped with L3-Communications' cockpit voice recorder (CVR) with 120-minute recording time, but no CVR data for the serious incident was available since it was overwritten 120 minutes after the event.

1.11.2 Flight Data Recorder[15)]

HL7553 was equipped with the solid-state flight data recorder (FDR) manufactured by Honeywell, with 25-hour recording time.

As shown in [Table 3], the ARAIB retrieved, from the FDR, main engine parameters at the time of the No. 2 engine failure.

14) Part No.: 2100-1020-02, Serial No.: 167232.
15) Part No.: 980-4700-042, Serial No.: 13026.

Subframe	UTC	ALT	EPR		N1 RPM		N2 RPM		N1 VIB		N2 VIB		EGT		ENG FIRE		TRA		FUEL FLOW		Fuel Valve	
			No.1	No.2	No.1	No.2	No.1	No.2	No.1	No.2	No.1	No.2	No.1	No.2	No.1	No.2	No.1	No.2	No.1	No.2	No.1	No.2
		ft	ratio		% rpm		% rpm		units		units		degC				deg		PPH			
46623-4	5:22:57	11536	1.598	1.598	95.3	94.6	94.9	95.3	0.4	7.5	0.5	1.0	542	576	NO FIRE	NO FIRE	64.7	64.7	20136	20592	OPEN	OPEN
46624-1		11604	1.594	1.598	95.3	94.6	94.8	95.3	0.3	7.5	0.4	1.0	542	576	NO FIRE	NO FIRE	64.7	64.7	20168	20508	OPEN	OPEN
46624-2		11676	1.598	1.594	95.3	94.6	94.9	95.3	0.3	7.5	0.4	0.8	542	576	NO FIRE	NO FIRE	64.7	64.7	20164	20436	OPEN	OPEN
46624-3		11748	1.602	1.598	95.5	94.6	94.8	95.4	0.3	7.5	0.4	0.7	542	576	NO FIRE	NO FIRE	64.7	64.7	20188	20440	OPEN	OPEN
46624-4	5:23:01	11816	1.598	1.602	95.5	94.8	94.6	95.4	0.3	7.5	0.4	0.7	542	576	NO FIRE	NO FIRE	64.7	64.7	20132	20444	OPEN	OPEN
46625-1		11884	1.602	1.598	95.4	89.4	94.6	95.4	0.3	7.6	0.5	0.7	542	576	NO FIRE	NO FIRE	64.7	64.7	20064	20400	OPEN	OPEN
46625-2		11960	1.602	1.016	95.4	61.4	94.6	93.6	0.4	8.9	0.5	1.8	542	596	NO FIRE	NO FIRE	64.7	64.7	20012	20100	OPEN	OPEN
46625-3		12036	1.602	0.883	95.4	55.9	94.6	97.5	0.3	7.4	0.4	1.4	542	628	NO FIRE	NO FIRE	64.7	64.7	19936	17392	OPEN	OPEN
46625-4	5:23:05	12104	1.602	0.879	95.4	54.4	94.6	98.9	0.3	7.6	0.5	0.8	542	664	NO FIRE	NO FIRE	64.7	64.7	19896	30828	OPEN	OPEN
46626-1		12168	1.602	0.883	95.4	54.5	94.6	99.3	0.3	7.7	0.5	0.5	542	686	NO FIRE	FIRE	64.7	64.7	19800	11632	OPEN	OPEN
46626-2		12228	1.602	0.887	95.3	54.5	94.6	99.6	0.3	7.7	0.5	0.4	542	704	NO FIRE	FIRE	64.7	64.7	19712	11312	OPEN	OPEN
46626-3		12276	1.602	0.887	95.3	54.5	94.6	99.6	0.3	7.6	0.4	0.0	542	712	NO FIRE	FIRE	64.7	64.7	19660	11312	OPEN	OPEN
46626-4	5:23:09	12328	1.602	0.883	95.3	54.5	94.5	99.5	0.3	7.6	0.5	0.0	542	718	NO FIRE	FIRE	64.7	64.7	19656	11312	OPEN	OPEN
46627-1		12376	1.602	0.879	95.1	54.6	94.5	99.6	0.3	7.7	0.5	0.0	542	724	NO FIRE	FIRE	64.7	64.7	19500	11256	OPEN	OPEN
46627-2		12420	1.602	0.879	95.1	54.6	94.5	99.6	0.3	7.8	0.4	0.0	540	726	NO FIRE	FIRE	64.7	64.7	19388	11272	OPEN	OPEN
46627-3		12464	1.598	0.883	95.0	54.6	94.4	99.6	0.3	7.8	0.5	0.0	540	728	NO FIRE	FIRE	64.7	64.7	19212	11260	OPEN	OPEN
46627-4	5:23:13	12500	1.602	0.898	95.0	54.6	94.4	99.6	0.3	7.9	0.5	0.0	540	746	NO FIRE	FIRE	64.7	64.7	19176	11272	OPEN	OPEN
46628-1		12536	1.602	0.898	95.0	54.8	94.4	99.6	0.3	7.9	0.4	0.1	540	734	NO FIRE	FIRE	64.7	64.7	19156	11244	OPEN	OPEN
46628-2		12568	1.602	0.895	94.9	54.9	94.4	99.8	0.3	7.9	0.4	0.1	540	770	NO FIRE	FIRE	64.7	64.7	19096	11280	OPEN	OPEN
46628-3		12596	1.598	0.891	94.9	54.9	94.4	99.9	0.3	7.9	0.3	0.1	540	770	NO FIRE	FIRE	64.7	64.7	19040	11324	OPEN	OPEN
46628-4	5:23:17	12624	1.574	0.891	94.9	54.9	94.8	99.9	0.3	7.9	0.3	0.1	540	774	NO FIRE	FIRE	64.7	45.0	18980	11364	OPEN	OPEN
46629-1		12644	1.582	0.895	94.4	54.6	95.5	99.9	0.3	7.9	0.3	0.7	540	778	NO FIRE	FIRE	64.7	25.3	18996	11356	OPEN	OPEN
46629-2		12664	1.594	0.879	94.6	53.8	95.6	98.8	0.3	7.9	0.4	0.5	544	776	NO FIRE	FIRE	64.7	0.0	19076	11044	OPEN	OPEN
46629-3		12680	1.594	0.875	94.9	53.1	95.5	97.8	0.3	8.3	0.4	0.3	546	770	NO FIRE	FIRE	64.7	-2.8	19180	10456	OPEN	OPEN
46629-4	5:23:21	12692	1.598	0.871	95.0	52.9	95.6	97.4	0.3	8.6	0.5	0.2	548	764	NO FIRE	FIRE	64.7	-2.8	19272	10008	OPEN	OPEN
46630-1		12704	1.598	0.871	95.0	52.8	95.5	96.9	0.3	8.7	0.5	0.1	550	762	NO FIRE	FIRE	64.7	-2.8	19284	9552	OPEN	OPEN
46630-2		12712	1.598	0.871	95.0	52.8	95.5	96.8	0.3	8.6	0.5	0.0	550	760	NO FIRE	FIRE	64.7	-2.8	19276	9544	OPEN	OPEN
46630-3		12716	1.605	0.852	95.1	40.4	95.4	75.5	0.3	7.6	0.5	0.0	550	664	NO FIRE	FIRE	64.7	0.0	19220	0	OPEN	CLOSED
46630-4	5:23:25	12720	1.609	0.867	95.3	33.6	95.1	68.0	0.3	7.6	0.4	0.0	550	646	NO FIRE	FIRE	64.7	0.0	19208	0	OPEN	CLOSED
46631-1		12724	1.609	0.871	95.3	28.8	94.9	64.0	0.3	6.3	0.4	0.0	550	628	NO FIRE	FIRE	64.7	0.0	19164	0	OPEN	CLOSED
46631-2		12728	1.609	0.875	95.3	25.6	94.8	60.8	0.3	4.1	0.5	0.0	548	616	NO FIRE	FIRE	64.7	0.0	19180	0	OPEN	CLOSED
46631-3		12732	1.613	0.875	95.1	23.5	94.5	58.1	0.3	3.1	0.5	0.0	546	610	NO FIRE	FIRE	64.7	0.0	19100	0	OPEN	CLOSED
46631-4	5:23:29	12736	1.605	0.875	95.1	22.0	94.3	55.5	0.3	2.4	0.4	0.0	546	606	NO FIRE	FIRE	64.7	0.0	19052	0	OPEN	CLOSED
46633-1		12740	1.605	0.875	95.0	20.6	94.1	53.0	0.3	2.4	0.4	0.0	544	602	NO FIRE	FIRE	64.7	0.0	18960	0	OPEN	CLOSED
46633-2		12744	1.602	0.875	94.9	19.8	94.1	51.1	0.3	1.6	0.4	0.0	542	596	NO FIRE	FIRE	64.7	0.0	18924	0	OPEN	CLOSED
46633-3		12748	1.602	0.875	94.9	19.1	94.3	49.4	0.3	0.9	0.5	0.0	542	596	NO FIRE	FIRE	64.7	0.0	18920	0	OPEN	CLOSED
46633-4	5:23:33	12752	1.602	0.875	94.9	18.6	94.3	47.8	0.3	0.5	0.5	0.0	542	594	NO FIRE	FIRE	64.7	0.0	18968	0	OPEN	CLOSED
46634-1		12756	1.602	0.875	94.9	18.3	94.3	46.3	0.3	0.5	0.5	0.0	540	592	NO FIRE	FIRE	64.7	0.0	18952	0	OPEN	CLOSED
46634-2		12760	1.605	0.875	94.9	18.0	94.4	44.9	0.3	0.3	0.5	0.0	540	590	NO FIRE	FIRE	64.7	0.0	18964	0	OPEN	CLOSED
46634-3		12764	1.605	0.875	95.0	17.8	94.4	43.6	0.3	0.3	0.5	0.0	540	590	NO FIRE	FIRE	64.7	0.0	19000	0	OPEN	CLOSED
46634-4	5:23:37	12772	1.605	0.875	95.0	17.6	94.4	42.4	0.3	0.0	0.6	0.0	542	588	NO FIRE	FIRE	64.7	0.0	19044	0	OPEN	CLOSED
46635-1		12776	1.602	0.871	95.0	17.4	94.4	41.1	0.3	0.0	0.5	0.0	542	586	NO FIRE	FIRE	64.7	0.0	19012	0	OPEN	CLOSED
46635-2		12776	1.602	0.871	95.0	17.3	94.4	40.0	0.3	0.0	0.5	0.0	542	584	NO FIRE	FIRE	64.7	-2.8	19040	0	OPEN	CLOSED
46635-3		12784	1.605	0.871	95.0	17.3	94.5	38.9	0.3	0.0	0.6	0.0	542	582	NO FIRE	FIRE	64.7	0.0	19044	0	OPEN	CLOSED
46635-4	5:23:41	12784	1.605	0.871	95.1	17.1	94.5	37.9	0.3	0.0	0.6	0.0	542	580	NO FIRE	FIRE	64.7	-2.8	19096	0	OPEN	CLOSED
46636-1		12792	1.605	0.871	95.1	17.0	94.5	37.0	0.3	0.0	0.6	0.0	542	576	NO FIRE	FIRE	64.7	-2.8	19164	0	OPEN	CLOSED
46636-2		12792	1.605	0.871	95.1	17.0	94.5	36.1	0.3	0.0	0.5	0.0	542	574	NO FIRE	FIRE	64.7	0.0	19180	0	OPEN	CLOSED
46636-3		12796	1.605	0.871	95.3	16.9	94.5	35.3	0.3	0.0	0.4	0.0	542	572	NO FIRE	FIRE	64.7	0.0	19164	0	OPEN	CLOSED
46636-4	5:23:45	12804	1.605	0.871	95.3	16.9	94.5	34.4	0.3	0.0	0.4	0.0	542	570	NO FIRE	FIRE	64.7	0.0	19128	0	OPEN	CLOSED
46637-1		12808	1.609	0.871	95.3	16.9	94.5	33.6	0.4	0.0	0.4	0.0	542	566	NO FIRE	FIRE	64.7	0.0	19140	0	OPEN	CLOSED
46637-2		12808	1.609	0.871	95.3	16.9	94.5	33.0	0.4	0.0	0.4	0.0	542	564	NO FIRE	NO FIRE	64.7	0.0	19204	0	OPEN	CLOSED
46637-3		12812	1.609	0.871	95.3	16.8	94.5	32.3	0.3	0.0	0.3	0.0	542	562	NO FIRE	NO FIRE	64.7	0.0	19280	0	OPEN	CLOSED
46637-4	5:23:49	12820	1.609	0.871	95.4	16.8	94.5	31.6	0.3	0.0	0.3	0.0	542	560	NO FIRE	NO FIRE	64.7	0.0	19264	0	OPEN	CLOSED
46638-1		12824	1.609	0.871	95.4	16.8	94.5	30.9	0.3	0.0	0.3	0.0	542	558	NO FIRE	NO FIRE	64.7	0.0	19212	0	OPEN	CLOSED
46638-2		12828	1.609	0.871	95.4	16.8	94.5	30.4	0.3	0.0	0.4	0.0	544	556	NO FIRE	NO FIRE	64.7	0.0	19188	0	OPEN	CLOSED
46638-3		12836	1.609	0.867	95.4	16.8	94.5	29.8	0.3	0.0	0.4	0.0	544	552	NO FIRE	NO FIRE	64.7	0.0	19168	0	OPEN	CLOSED
46638-4	5:23:53	12840	1.609	0.867	95.3	16.6	94.6	29.1	0.3	0.0	0.5	0.0	544	550	NO FIRE	NO FIRE	64.7	0.0	19188	0	OPEN	CLOSED

[Table 3] Main Engine Parameters

1.12 Wreckage and Impact Information

Not applicable.

1.13 Medical and Pathological Information

The flight crew of HL7553 held a valid first-class airman medical certificate. According to their statements, they did not drink any alcohol or take any illegal medication before flight.

1.14 Fire

Not applicable.

1.15 Survival Aspects

Not applicable.

1.16 Tests and Research

1.16.1 General

The No. 2 engine removed from the aircraft was transported to the Korean Air engine overhaul facility in Bucheon, Korea. The engine was disassembled and examined with investigators from the ARAIB and NTSB[16], and experts from Korean Air and Pratt & Whitney in attendance.

Engine disassembly revealed extensive mechanical damage in the LPT module, but examination revealed no significant mechanical damage in the HPT module and other upstream engine modules.

Major findings from the engine teardown examination are as follows:

1.16.2 Engine Teardown Examination

1.16.2.1 HPT Module

As shown in [Figure 7], visual examination from aft of the HPT module revealed no apparent damage to the 1st- and 2nd-stage HPT blades. Although

16) National Transportation Safety Board.

rubbing damage was observed in the blade outer airseal (BOAS), their conditions are considered to be typical from service.

[Figure 7] 2nd-Stage HPT Blades and BOAS

1.16.2.2 LPT Case

As shown in [Figure 8], the LPT case was torn open circumferentially between 8:00[17] and 9:30 o'clock positions in the plane of the 5th-stage LPT rotor, approximately 57 cm in length by 7 cm in width. Partial cracks were also found at the 11:00, 11:30, and 12:00 o'clock positions.

[Figure 8] Before & After the Removal of LPT Case Wrapping Components

17) All radial position descriptions are given as clock hours viewed from the rear of the engine, looking forward.

As shown in [Figure 9], the LPT case exhibited local bulges at the 6:00, 7:00, and 9:30 o'clock positions in the plane of the 4th-stage LPT rotor. Apparent bulge was also found along the full circumference of the N1 flange.

[Figure 9] Upper Surface of LPT Case and Turbine Exhaust Case

1.16.2.3 Turbine Exhaust Case

As shown in [Figure 10], the turbine exhaust case (TEC) exhibited bulges along the circumference of the P-flange. One hole and one small crack/tearing were found at the 11:00 and 2:30 o'clock positions, respectively.

The TEC exhibited local tearing at the strut leading edge positions of the No. 1, 2, 13, 14, and 15 struts.

[Figure 10] TEC Struts and P-flange

1.16.2.4 LPT Shaft

The LPT shaft exhibited relatively light rubbing marks at multiple circumferential locations and axially in the plane of the HPT shaft.

1.16.2.5 Turbine Transition Duct

All turbine transition ducts were intact, sustaining no damage. There are multiple outer transition ducts seal plates exhibiting missing rivets or missing material from wear, cracking, and fracture.

1.16.2.6 LPT Module

1.16.2.6.1 3rd-Stage LPT Vane

There were no anomalies.

1.16.2.6.2 3rd-Stage LPT Rotor

All 3rd-stage LPT (T3) blades were intact, but all T3 blade BOAS exhibited contact marks and material loss due to wear by contacting the 4th-stage LPT (T4) vane outer shrouds, except at the location of missing No. 27 T4 vane cluster[18] which showed a partial contact pattern.

1.16.2.6.3 4th-Stage LPT Vane

During the engine assembly, a total of 44 T4 vane clusters were installed, but as shown in [Figure 11], the No. 27 vane cluster was missing from the assembled position and was not recovered from the disassembly.

18) A total of 44 T4 vane clusters are installed, and the numbers of the vane clusters in this report were assigned, for convenience, to distinguish their positions.

[Figure 11] Missing No. 27 T4 Vane Cluster

The C-channel in the T4 BOAS for the aft outboard foot of T4 vane clusters exhibited significant wear at multiple locations. Partial C-channel wear-through was observed at 10 T4 vane clusters. The C-channel material that was in contact with the No. 27 T4 vane cluster was all missing.

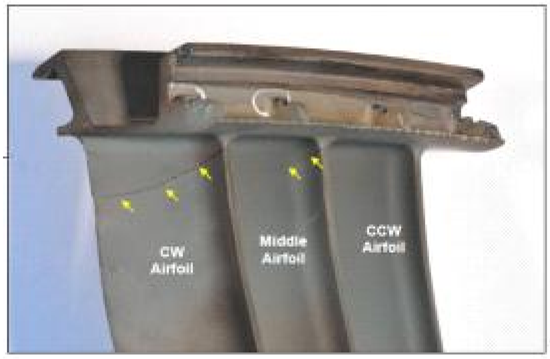
Multiple T4 vane clusters exhibited missing material and wear-through at the pin-pocket at the inboard shroud. A total of 16 T4 vane clusters out of 44 exhibited wear-through.

Also, multiple T4 vane clusters exhibited forward inboard shroud displacement along the full circumference.

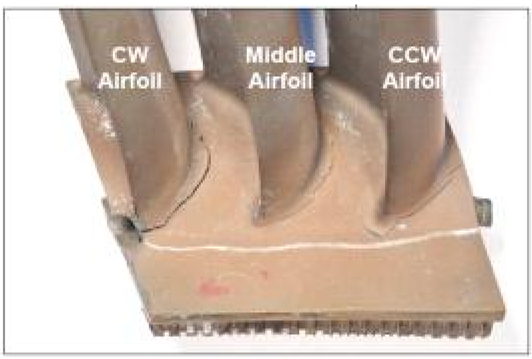
As shown in [Figure 12], the outboard insulation blanket of the No. 27 vane cluster was missing. Impact marks due to the part debris were found on the interior surface of the LPT case. The insulation blanket of the adjoining No. 28 vane cluster was wrinkled, whereas that of the No. 26 shortened, with no damage.

[Figure 12] Insulation Blankets of Vane Clusters

As shown in [Figure 13], the No. 25 vane cluster exhibited cracks in the clockwise (CW) side and middle airfoils, adjacent to the outboard shroud. The middle airfoil showed a crack running from the leading edge to the middle section.



[Figure 13] No. 25 Vane Cluster



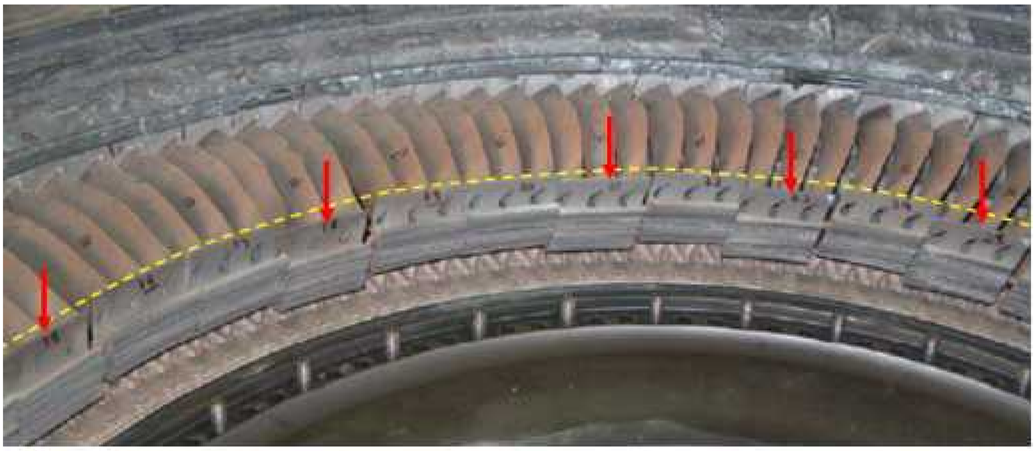
[Figure 14] No. 26 Vane Cluster

As shown in [Figure 14], the No. 26 cluster immediately adjacent to the No. 27 exhibited through-thickness cracks in the inboard shroud at the transition radius runout of each airfoil. Wear was found at the pin-pocket which was in contact with the No. 27 vane cluster pin.

As shown in [Figure 15], the inboard shroud of the No. 28 T4 vane cluster, which was immediately adjacent to the missing No. 27 cluster, showed missing honeycomb material of the inner airseal, and contact marks.

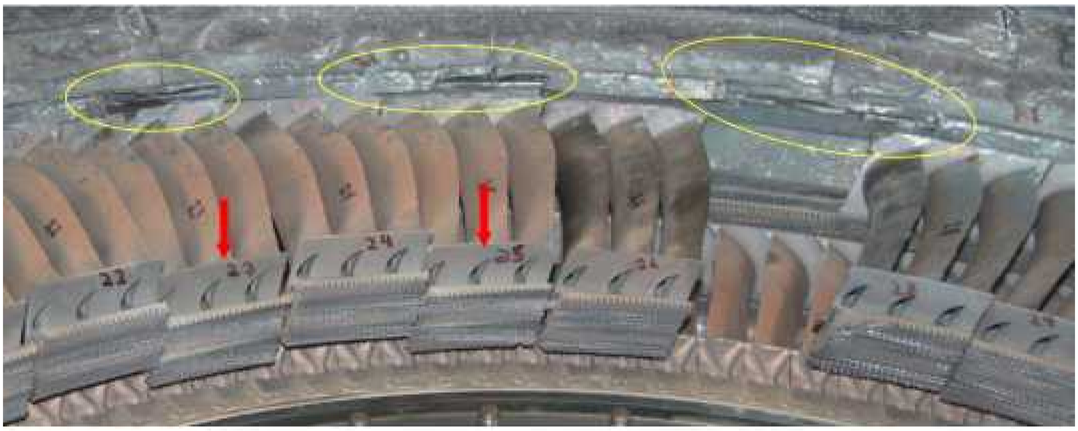
[Figure 15] Inboard Shroud of the No. 28 T4 Vane Cluster

As shown in [Figure 16], the inboard view of the T4 vanes showed that multiple cluster inner shrouds were displaced axially forward relative to others. The honeycomb of the inner airseal exhibited wide or multiple grooves.



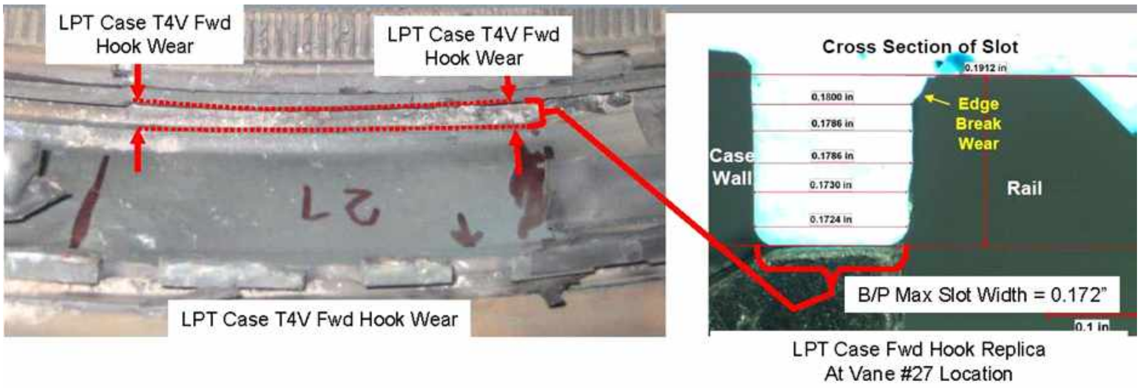
[Figure 16] Interior of the T4 Vane Clusters

As shown in [Figure 17], the overall inboard view of the T4 vane clusters adjacent to the missing No. 27 cluster showed the missing aft outboard locking feature C-channel at the location of the missing No. 27 cluster. Parts of the C-channels for clusters No. 23 and 25 were also missing. Clusters No. 23 and 25 appeared to be displaced forward at the inner shroud.



[Figure 17] T4 Vane Cluster C-channel

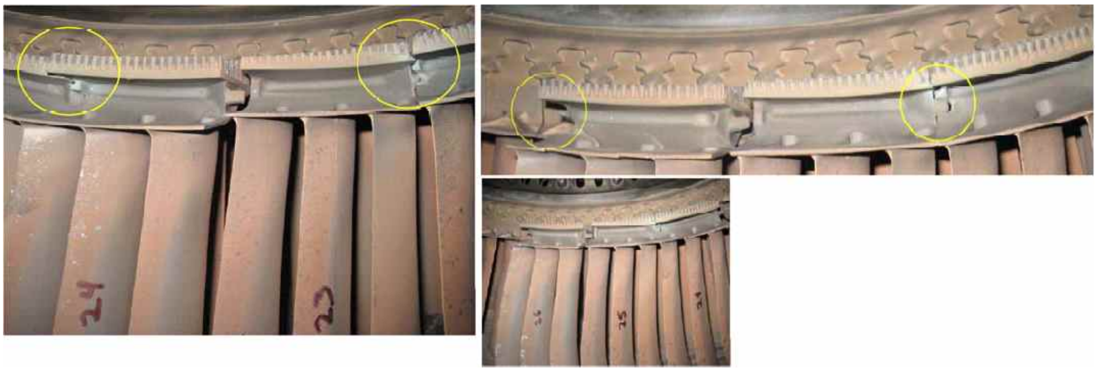
As shown in [Figure 18], the LPT case forward hook at the location of the No. 27 cluster exhibited material loss, without apparent deformation. The forward and rear hooks together showed wear, and in particular, the LPT case forward hook slot has worn down approximately 1.5 mm over the max. B/P dimension.



[Figure 18] LPT Case Forward Hook Wear

As shown in [Figure 19], the pin-pocket has worn through[19] in the vane clusters No. 22, 24, and 26 which were adjacent to the missing No. 27 cluster.

19) The pin-pocket develops a hole through contact wear between the pin and the pin-pocket.



[Figure 19] T4 Vane Cluster Pin-Pocket Wear

1.16.2.6.4 4th-Stage LPT Rotor

All 130 T4 blades were inside the disk blade slots, but five T4 blades within 90 degrees exhibited airfoil fractures at mid-span, between 50% to 80% of airfoil length from the platform. Other blades showed material loss mainly along the outboard circumference. The T4 disk was intact.

[Figure 20] 4th-Stage LPT Rotor

1.16.2.6.5 5th-Stage LPT Vane

Three adjacent 5th-stage LPT (T5) vane clusters, No. 29, 30, and 31, were liberated from their assembly positions, which were directly adjacent to the largest LPT case breach location. The fragments of the two liberated clusters were recovered from the large torn area of the LPT case.

[Figure 21] 5th-Stage LPT Vanes

1.16.2.6.6 5th-Stage LPT Rotor

All 118 T5 blade airfoils fractured adjacent to the platform. All blade roots remained in the disk blade slots. The T5 disk was intact.

[Figure 22] 5th-Stage LPT Rotor and Vanes

1.16.2.6.7 6th-Stage LPT Vane

Three adjacent 6th-stage LPT (T6) vane clusters, No. 21, 22, and 23, were liberated from their assembled positions, and were recovered from the debris trapped forward of the 7th-stage LPT (T7) vanes. The front outboard hook in the outer shroud of all liberated T6 vane clusters was fractured, and the fragments were recovered from the debris that trapped before the T7 vanes.

Multiple T6 vane airfoils were fractured and missing as follows: two vane airfoils from cluster No. 6; one vane airfoil from cluster No. 9; two adjacent vane airfoils from cluster No. 10; one adjacent airfoil from cluster No. 23; and all three airfoils and inner shrouds from clusters No. 21 and 22.

[Figure 23] 6th-Stage LPT Vanes

1.16.2.6.8 6th-Stage LPT Rotor

All 128 6th-stage LPT (T6) blade airfoils were fractured outboard of the platform within 20% of airfoil length. All blade roots remained in the disk blade slots. The T6 disk was intact.

[Figure 24] 6th-Stage LPT Rotor

1.16.2.6.9 7th-Stage LPT Vane

Multiple 7th-stage LPT (T7) vane airfoils were fractured and missing. Single airfoils were fractured and missing in clusters No. 24, 34, and 37. All three airfoils were fractured and missing in cluster No. 8, with the inner shroud section missing and the outer shroud still in the assembled position.

[Figure 25] 7th-Stage LPT Vanes

1.16.2.6.10 7th-Stage LPT Rotor

All 102 T7 blade airfoils were fractured and missing outboard of the platform within 20% of spanwise length from platform. All blade roots remained in the disk blade slots. The T7 disk was intact.

[Figure 26] 7th-Stage LPT Rotor

1.16.2.6.11 Engine Teardown Examination Summary

Engine examination revealed that significant mechanical damage was limited within the LPT/TEC module in the engine. Upstream engine modules exhibited no significant damage that might have caused the mechanical damage in the LPT module. The T4 vane was the most forward stage in the LPT that exhibited damage that might have caused downstream damage and the engine event.

The No. 27 T4 vane cluster was missing and was not recovered during the engine disassembly. The remaining T4 vane clusters exhibited damage but were intact.

The outboard shroud locking features for the missing No. 27 T4 vane cluster were defeated and missing, including the forward hook in the case and the aft locking feature C-channel in the T4 BOAS. The pin-pocket at the inner shroud of the No. 26 T4 vane cluster was worn through, which was in contact with the No. 27 cluster.

Multiple remaining T4 vane clusters also exhibited the worn-through pin-pockets, partially worn-through C-channels, and the inner shrouds which were displaced axially forward relative to other clusters.

The No. 27 T4 vane cluster likely defeated locking features and was liberated into the gas path, thereby causing the engine event.

1.16.3 FDR Data Review

1.16.3.1. FDR Data Analysis

The data showed that the mechanical failure and surge[20] occurred during climb at an altitude of 11,900 ft and 260 kts CAS when the airplane was approximately 5 minutes after takeoff from Incheon Airport. As shown in [Figure 27], about 100 seconds prior to the mechanical failure and surge, N1 vibration increased significantly to above the AMM[21] N1 vibration advisory level, 5.2 cockpit units.

This N1 vibration increase occurred 10 seconds after both throttles were

20) Surge occurring generally in the combustor indicates a phenomenon where the air flow in the compressor abnormally collapses as a stall of the air into the combustor is not relieved and spread throughout the all stages of the compressor. In this case, speed of the air flow decreases, and pressure significantly increases.
21) Aircraft Maintenance Manual.

advanced from the Maximum Climb throttle detent to the Maximum Continuous throttle detent, apparently to increase the rate of climb.

When the throttles were increased, all engine parameters reflected the increase in engine power, and N1 vibration began a gradual increase before the sharp, significant increase that reflected the onset of engine damage. Afterward, N1 vibration maintained a level of at least 6.6 cockpit units, then showed another step increase just before the final mechanical failure and surge.

As shown in [Figure 22], after the mechanical failure and surge on the engine, the exhaust gas temperature (EGT) rapidly increased beyond the Maximum Continuous EGT Limit of 600℃.

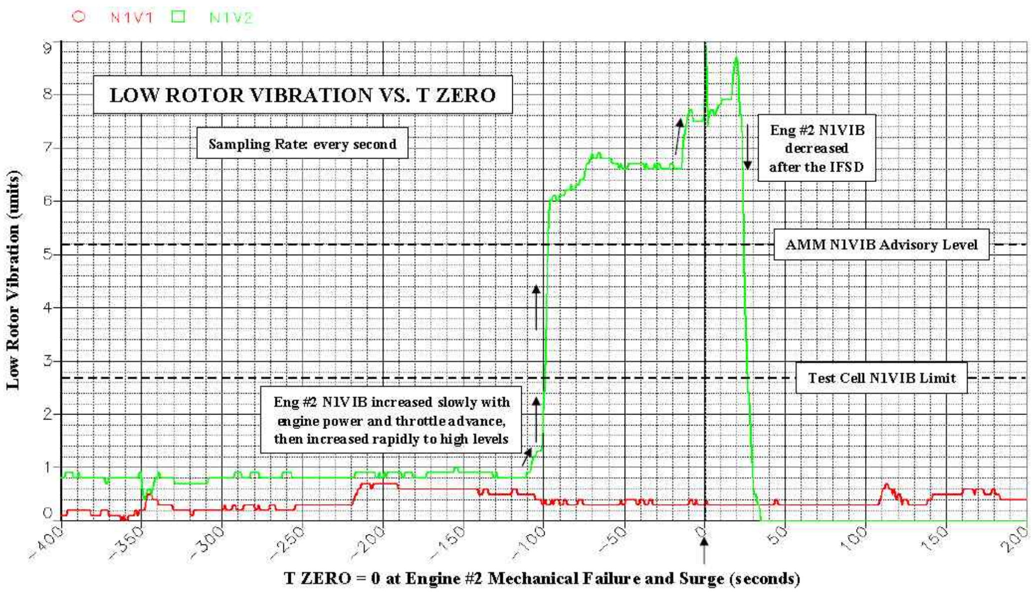
As shown in [Figure 23] and [Figure 24], the Fire Discrete was triggered, N1 RPM rapidly decreased significantly, and N2 RPM increased to near the N2 Redline of 100%N2.

Beginning approximately 14 seconds after the mechanical failure and surge, the throttle for the engine was rapidly reduced to the idle throttle stop. At approximately 21 seconds after the mechanical failure and surge, the flight crew shut down the engine when N1 vibration was at 8.7 cockpit units and EGT increased to 778℃.

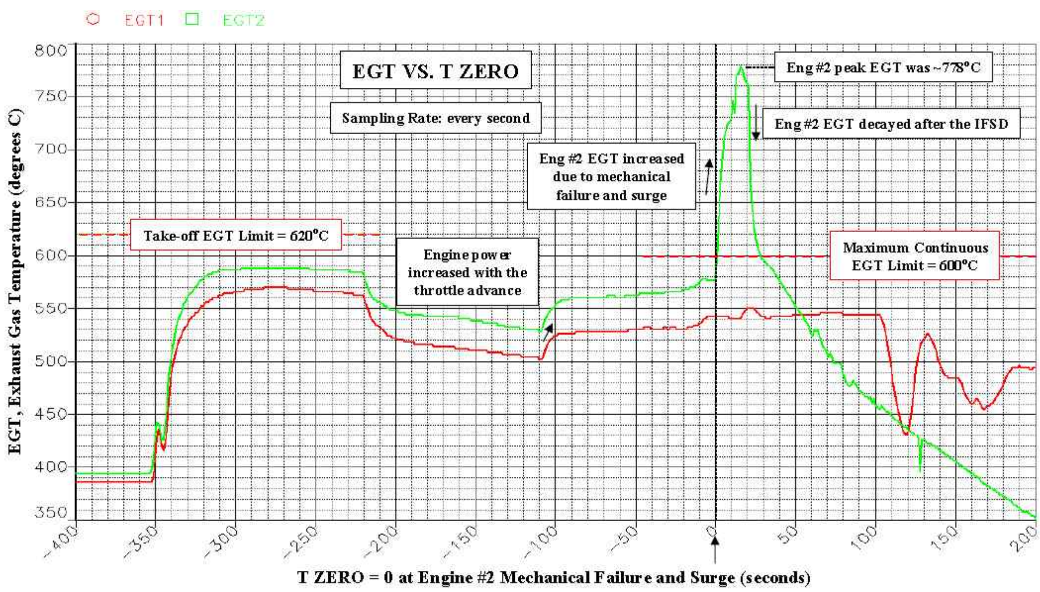
After the in-flight shutdown (IFSD) on the engine, N1 vibration and EGT immediately decreased, and both rotor speeds on the engine decreased sub-idle to windmill speeds. The data indicated that both rotors on the engine continued to windmill for the 32 minutes between the IFSD and the landing.

N2 vibration on the engine remained well-behaved throughout this event. The total flight time was approximately 38 minutes.

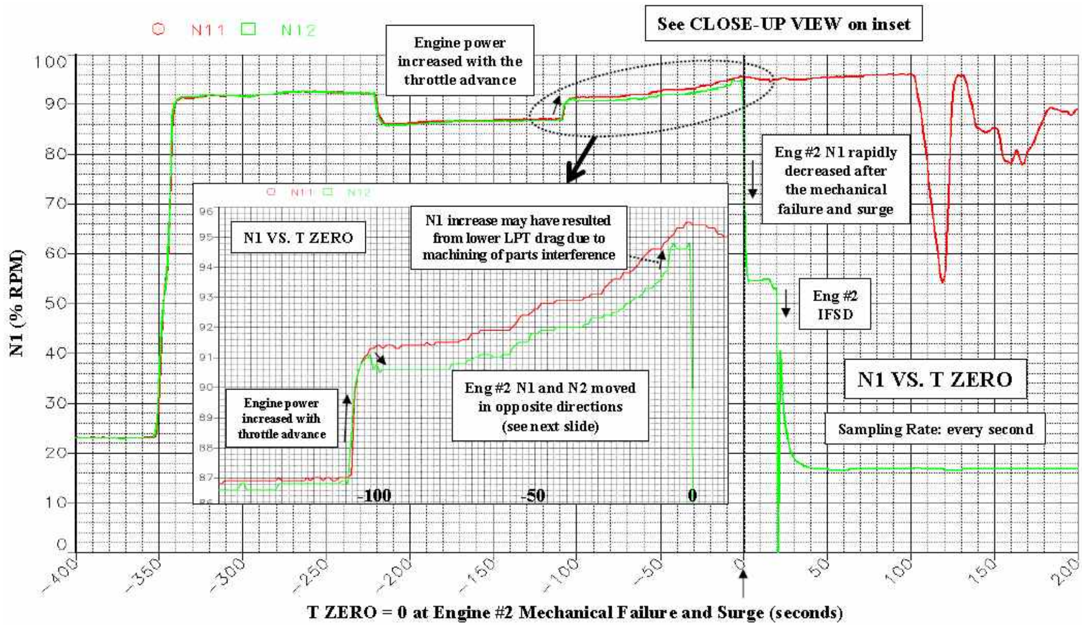
Except for the significant N1 vibration increase that occurred approximately 100 seconds before the mechanical failure and surge on the engine, there did not appear to be any other precursor to the LPT failure based on the FDR data parameters that were available.



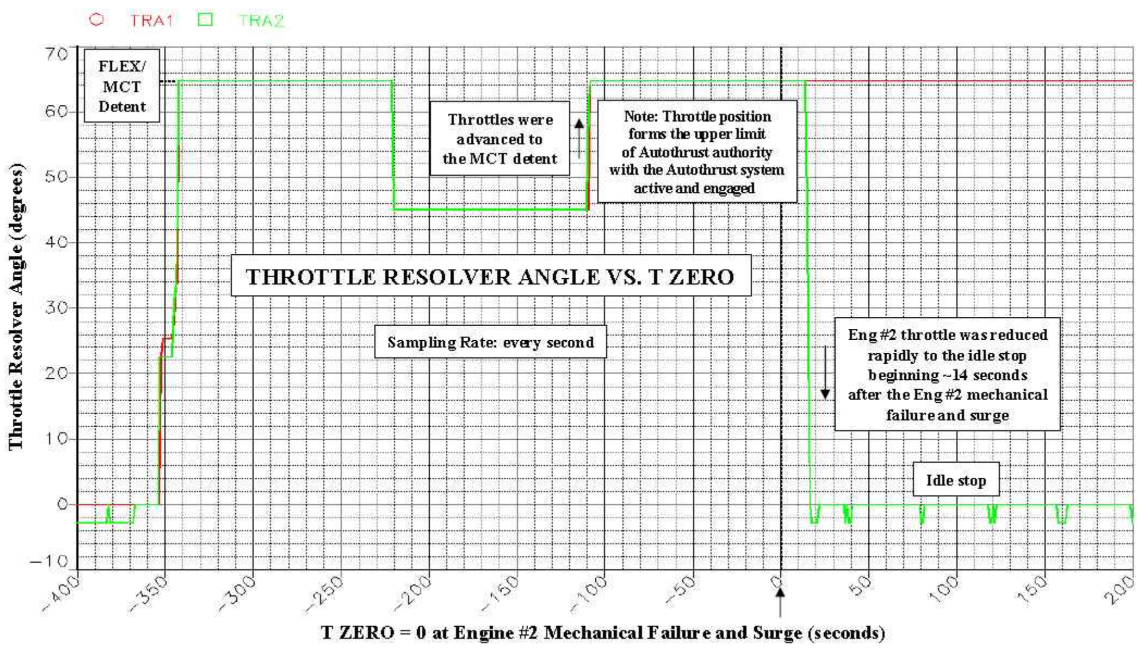
[Figure 27] N1 Vibration



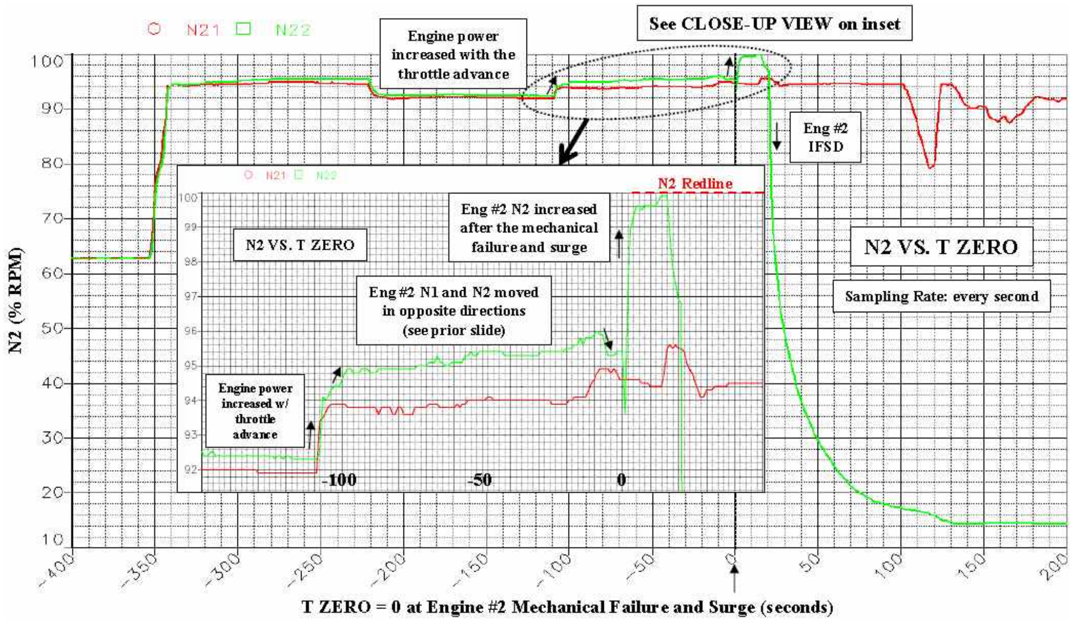
[Figure 28] EGT



[Figure 29] N1 RPM



[Figure 30] N2 RPM



[Figure 31] Throttle Lever Angle

1.16.3.2 QAR[22] Data Analysis

The QAR data from the affected engine has been processed and time history plots were generated. A quick comparison of the QAR and FDR data found good agreement except for the fuel flow (FF) parameters, which shows that the QAR FF data was 2,000 - 2,500 pph higher than the FDR FF data. The FADEC FF data recorded when the mechanical failure and surge occurred were consistent with the FDR FF data.

Gas Path Advisory Report that was triggered by the Surge Flag from the affected engine contained the FF that was consistent with the FF in both the FADEC fault memory files and with the FDR data. Therefore, since only the QAR data FF disagrees with the other sources of the FF, it is determined that the QAR data decoding must have had an erroneous scale factor applied during the conversion. Therefore, the FDR FF data regarded as the correct level was used for the failure investigation.

22) Quick Access Recorder.

1.16.3.3 FADEC Fault Data Analysis

The FADEC[23] fault data showed that both channels stored an Engine Stall Message (Surge Flag) during the event flight with no other faults. This dual channel Surge Flag was written to fault memory on 26 May 2011 at 05:23:00 (UTC).

In addition, there were 5 "nuisance" Surge Flags stored in Channel A and 7 "nuisance" Surge Flags in Channel B. Four of these "nuisance" Surge Flags were stored in both channels, while the remainder occurred only in a single channel. These "nuisance" Surge Flags sometimes occur when the engine is shutdown from a normal idle. The cause for occasional "nuisance" Surge Flags is a known issue, and these are not an indication of actual engine surges.

Nuisance Surge Flags can occasionally be generated when the reset discrete from the airplane to the FADEC is slightly delayed so that the control software detects the Pb decay at fuel cut-off as a "surge" before the control is reset, even though it was a normal engine shutdown.

Selected parameters that were stored with the actual Surge Flag were associated with the LPT mechanical failure and surge. They were also consistent with the FDR data. Some parameters recorded on the FADEC before surge are as follows:

May 26, 2011 Engine Stall (Surge Flag)
Ch A: Press. Alt = 11832 ft., Mn = 0.48, TRA = 66.08 deg., N1 = 2914.25 RPM (80.95%N1), N2 = 9830 RPM (94.1%N2), EEC Run Time = 26878.64 hrs.
Ch B: Press. Alt = 11842 ft., Mn = 0.48, TRA = 66.08 deg., N1 = 2914.25 RPM (80.95%N1), N2 = 9830 RPM (94.1%N2), EEC Run Time = 26878.64 hrs.

23) Serial No. 4171-0498.

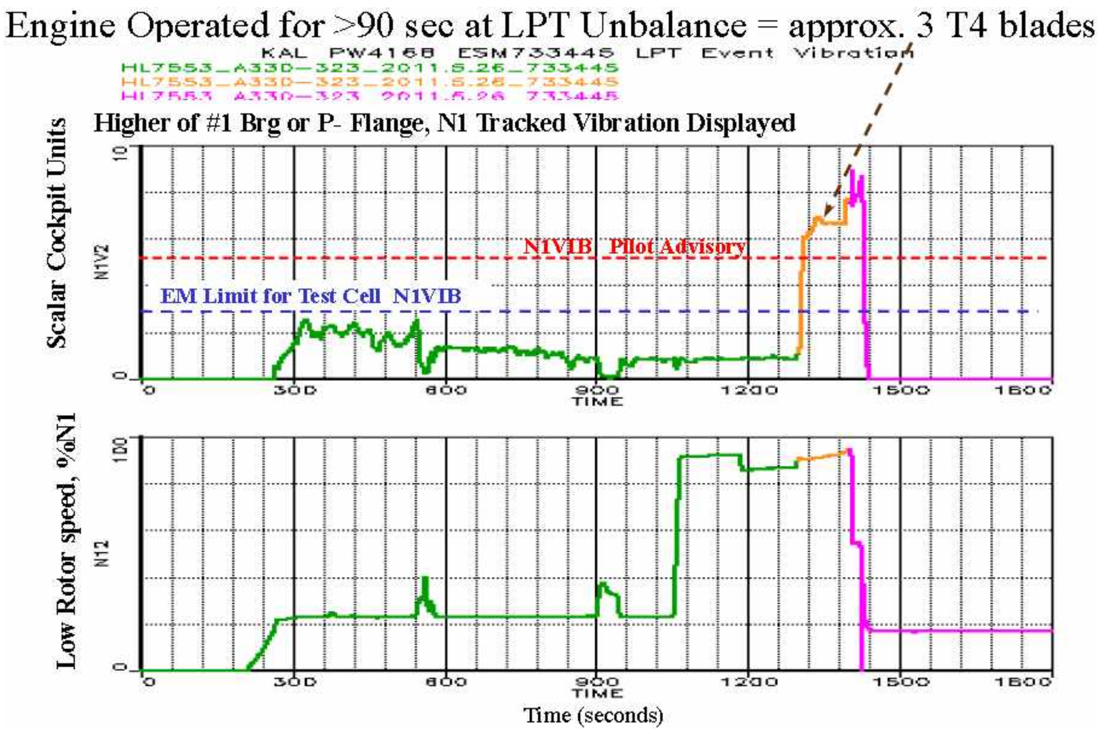
1.16.3.4 Engine Vibration Analysis

Engine vibration from the FDR and prior flights' QAR were analyzed, and the summary of key observations is shown in [Figure 32].

During the two prior flights, there was no precursor of vibration change by N1 or N2 rotors' unbalanced revolutions.

There was no precursor in rotor-tracked vibrations on the event flight until 98 seconds from the surge when N1 vibration increased substantially.

Only "precursor" vibration observed was the Takeoff Report snapshot, where elevated P flange broadband vibration of 3.66 IPS suggested that vanes had rubbed on blades inside the LPT.



[Figure 32] Engine Vibration Analysis

1.16.4 Hardware Examination

Engine teardown examination identified the liberation of a single T4 vane cluster by worn-through retaining features (C-channel in T4 BOAS and pin-pocket in the adjacent vane cluster). One known cause of excessive wear in the LPT module is the 2E excitation[24)] from the HPT module, which caused abnormal vibration in the LPT module in an engine test. After the examination, T1 and T2 rotors, and the LPT case were sent to the Pratt &Whitney's facility in East Hartford, Connecticut, US for further examination.

1.16.4.1 2nd-Stage HPT Rotor

The HPT module was last assembled by the KAL engine shop in 2008. The last overhaul record indicates that the T2 blades were 50-50 split of new and used blades, which were assembled by following the instruction in the EM[25)], the "Indian Trail" method[26)].

The T2 rotor was inspected by the coordinate measuring machine (CMM). Measuring results indicated significant differences between "larger" areas with refurbished blades and relatively "smaller" areas with new blades.

The measured flow area pattern is likely a result of the use of the “Indian Trail” assembly method at the previous overhaul. The “Indian Trail” method results in the heavy blades being 180° apart to balance the rotor from a rotor dynamics standpoint. The area pattern is generated because new blades typically have higher mass than used blades, and a more closed flow area. Used blades

24) When the T2 blades are 50-50 split of new and used blades, significant differences are made to the aerodynamic pattern aft of the blades, thereby causing the aerodynamic excitation and affecting the T4 vane clusters most.

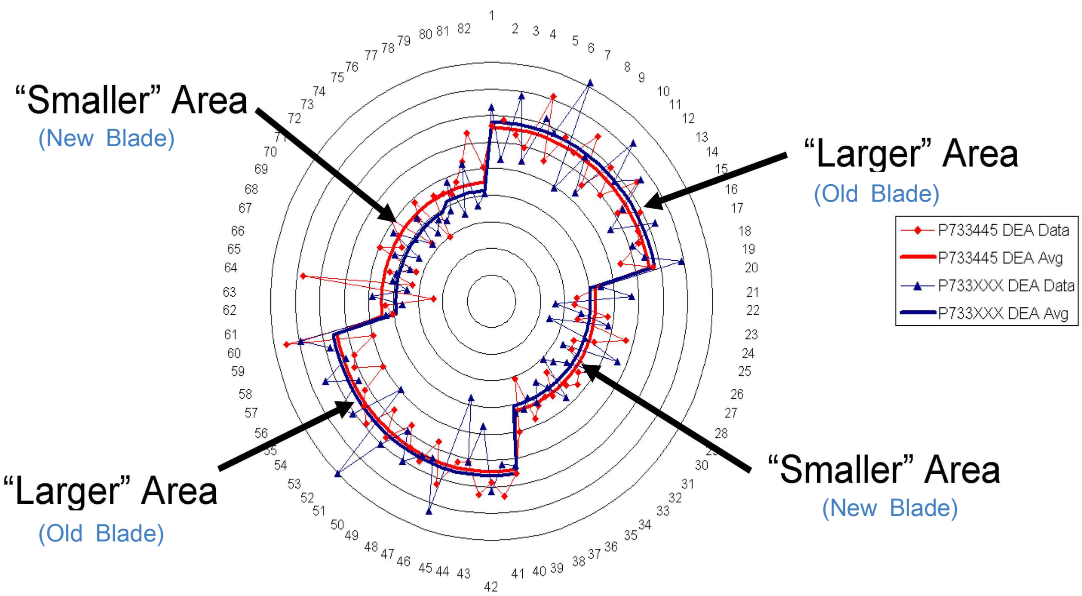
25) EM Task 72-52-01 Assy-01, 15 Dec. 2004.

26) After the blades are weighed, they are numbered from No. 1 to No. 82 in order of decreasing weight from heaviest to lightest. Then, the blades are installed clockwise in order of 1, 3, 5... 79, 81; 2, 4, 6... 80, 82.

typically have lower mass and a more open flow area as a result of tip rub from previous engine runs, creep/untwist as well as material removal from coating strip and re-coat operation.

Although this method result in a balanced rotor for rotor dynamics, it has been found to result in an aerodynamic pattern where a twice per revolution (2E) pressure pulses exit the rotor due to the area variation. This 2E pressure pulse has been found to result in excitation of LPT hardware which can increase wear and vibratory stresses. Previously an engine was tested at P&W with a 2E pattern and test data confirmed wear and vibrations in the LPT.

A comparison of the flow areas from the previously tested P&W engine to the P733445 event engine is shown in [Figure 33].

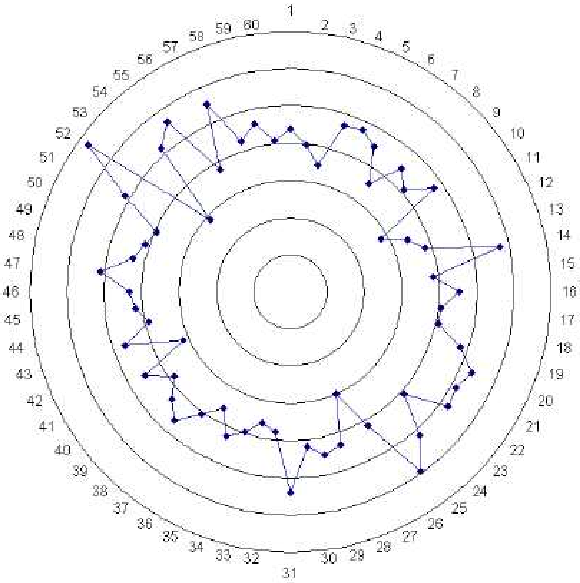


[Figure 33] T2 Blade Aerodynamic Pattern

1.16.4.2 1st-Stage HPT Rotor

The HPT module was last assembled by the KAL engine shop in 2008. The last overhaul record indicates that the T1 blades were all new blades.

Although the same Indian Trail method as the T2 blades was used to assemble the T1 blades, inspection revealed no apparent variations that would have caused aerodynamic vibration excitation since all new blades were installed, as shown in [Figure 34].



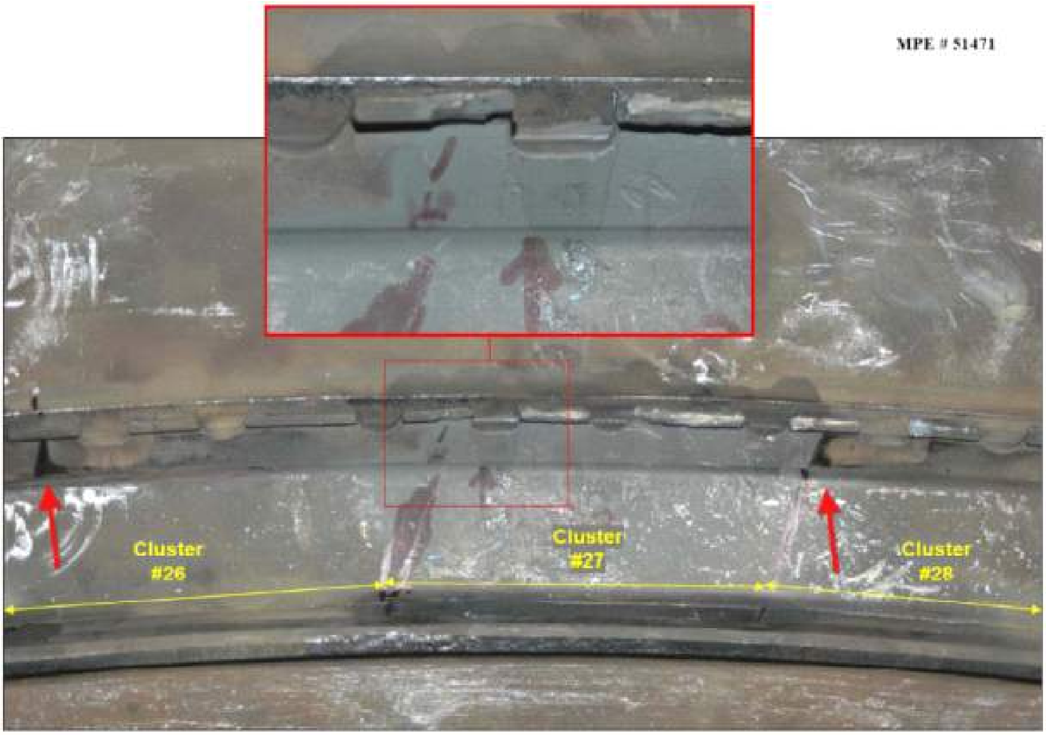
[Figure 34] T1 Blade Aerodynamic Pattern

1.16.4.3 LPT Case Dimensional and Metallurgical Property Evaluation

The forward hook of the LPT case for the T4 vane clusters exhibited wear. The case breach along the plane of the T5 rotor was caused by overload tearing.

Dimensional examination revealed material loss due to wear in the contact surfaces between T4 vane clusters and LPT case.

As shown in [Figure 35], it was observed that there were T4 vane cluster contact marks (red arrows) on the radial surface in the LPT case just forward of the aft rail at all T4 vane clusters locations except at the location of the missing No. 27 T4 vane cluster.

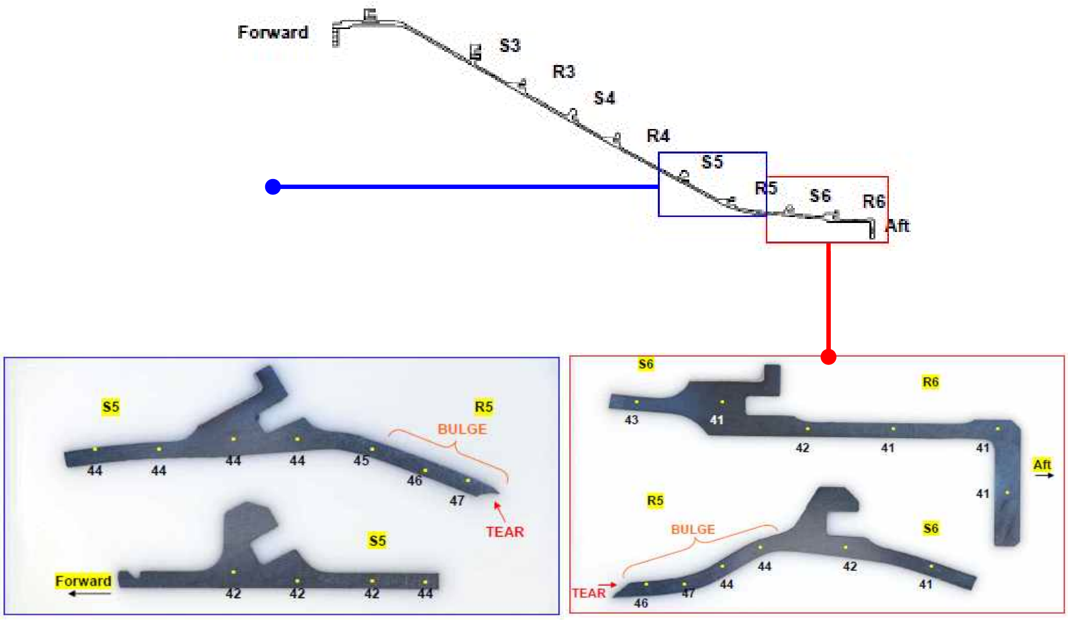


[Figure 35] LPT Case at T4 Vane Clusters Locations

Point micrometer measurements of the wall thickness at several locations around the tear revealed it conformed to the drawing requirements of 2.184 mm - 2.438 mm.

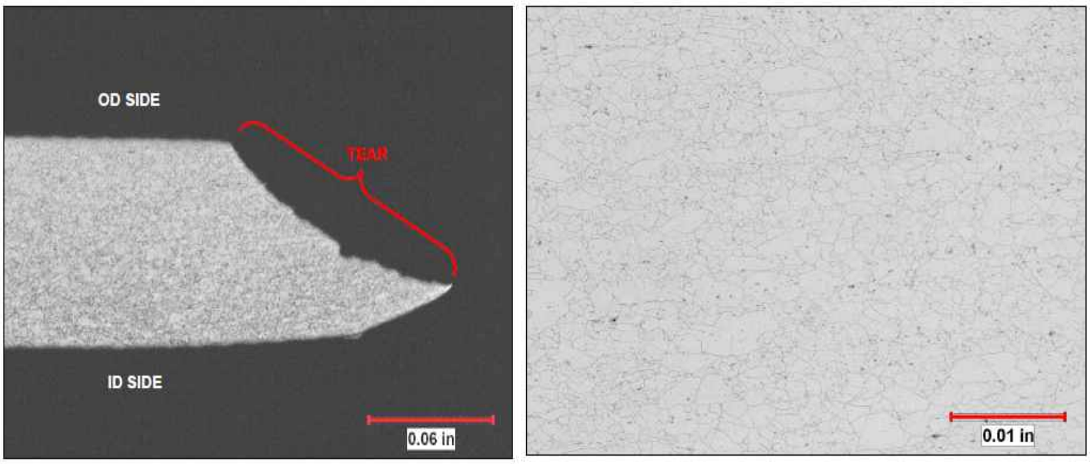
As shown in [Figure 36], hardness measurement of the 5th- and 6th-stages of the LPT case, and the aft flange revealed that it ranged between 41 - 47 HRC, which met the AMS 5707 specification requirement[27]. Hardness was at the higher end of the range within the bulge, which was, however, within the allowable range.

27) Between 35 - 47 HRC.



[Figure 36] Hardness Values of the LPT Case (No.: HRC Value)

Microstructure of the case wall at the tear appeared typical of properly processed AMS 5707 material. Grain size at the tear met the drawing requirement. Energy Dispersive Spectrometer (EDS) analysis of the section revealed a composition consistent with Waspalloy.



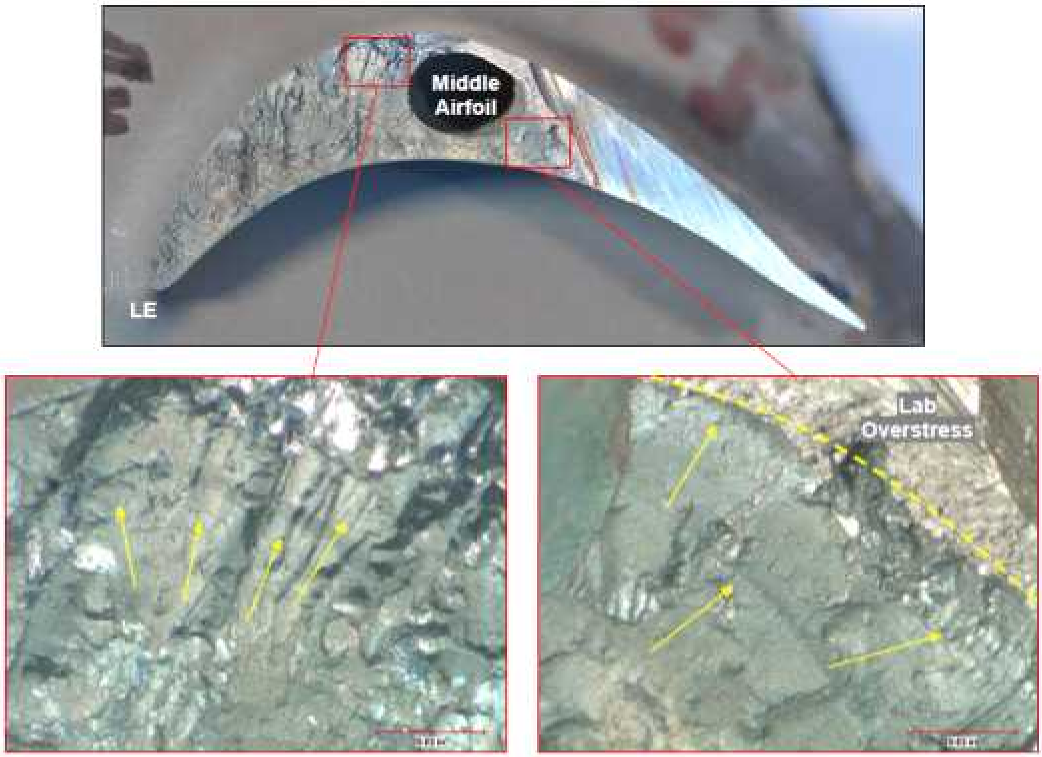
[Figure 37] Microstructure of the LPT Case

1.16.4.4 4th-Stage LPT Vane Cluster Examination

Five T4 Vane Clusters (No. 2, 7, 17, 25, and 26) were selected for examination of various conditions.

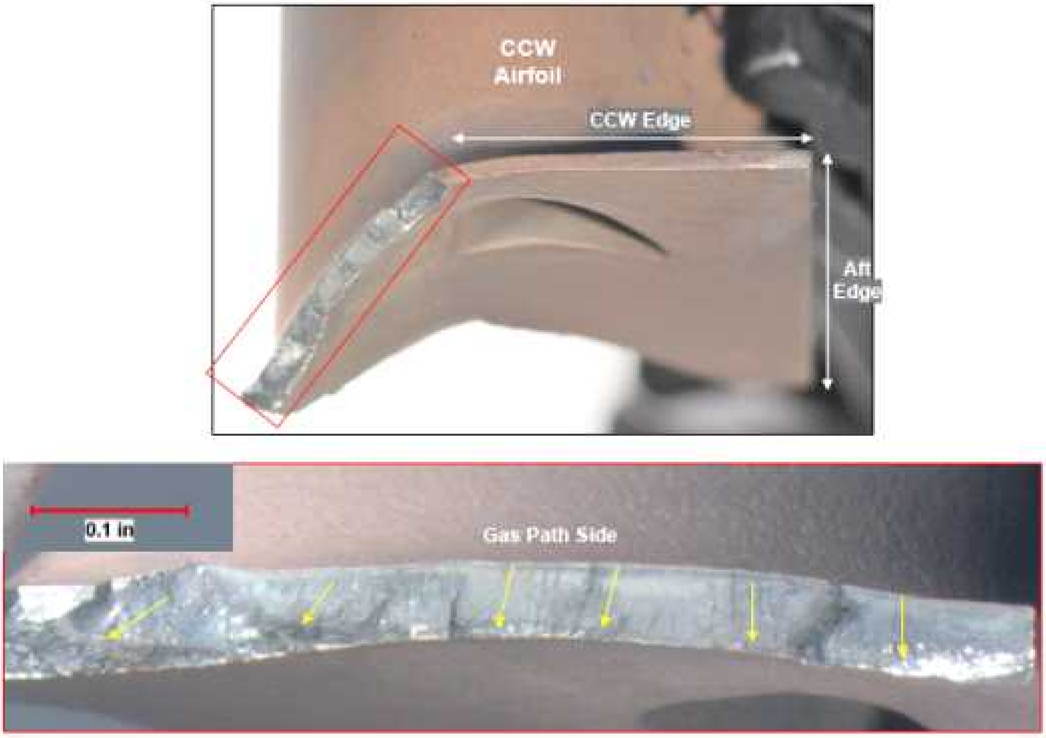
Examination of clusters No. 2 and 25 revealed that inner radius at the cluster rear outboard foot conformed to the drawing requirements as well as wear in both front hook and rear outboard foot.

As shown by the yellow arrows in [Figure 38], examination of the middle airfoil's chordwise crack in the No. 25 cluster revealed fatigue which progressed from the airfoil leading edge. Also, the fracture surface was heavily oxidized.



[Figure 38] Middle Airfoil's Crack in the No. 25 Cluster

Examination of the inner shroud cracks in the No. 26 cluster revealed fatigue, which progressed primarily from multiple origins along the gas path surface of the inner shroud.



[Figure 39] Inner Shroud Cracks in the No. 26 Cluster

Examination revealed no material or processing anomalies in those T4 vane clusters.

1.17 Organizational and Management Information

Not applicable.

1.18 Additional Information

Not applicable.

2. Analysis

2.1 General

The flight crew of HL7553 held qualification certificates suitable for the applicable flight and took the required rest before flight. Also, no medical factors that could have affected the flight were found.

The aircraft held a valid airworthiness certificate, and the flight concerned was carried out within the allowable limits of weight and balance. Any maintenance factors that could have directly contributed to this serious incident were not found.

2.2 Engine Teardown Examination Results

2.2.1 Hardware Examination Summary

Detailed examination of the hardware revealed an aerodynamic pattern in the T2 rotor that can introduce 2E excitation in the LPT module, which had been previously found out in the P&W test.

Examination of the LPT case and five T4 vane clusters showed wear in the retaining features for the T4 vane clusters, but no material or processing anomalies in either the LPT case or the T4 vane clusters were found.

The LPT case exhibited no noticeable contact marks from the missing T4 vane cluster just forward of the aft rail, unlike the rest of the T4 vane cluster locations.

2.2.2 Engine Analysis

The liberation of the No. 27 T4 vane cluster was most likely the initiation of the engine event, evidenced by the following observations:

① The T4 vane was the most forward engine stage which exhibited mechanical damage that might have caused the downstream damage.

② Retaining features that interacted with the No. 27 T4 vane cluster exhibited excessive wear, especially at the forward hook in the LPT case and C-channel in the T4 BOAS.

③ Heat shield missing/damage at/adjacent to the location of the missing No. 27 T4 cluster, and impact marks from lacking of shielding on the adjacent T4 vane airfoils and on the LPT case inboard surface indicate that the No. 27 T4 cluster had left the assembled position either as the initiator of the engine event or occurred in the early stage of the engine event.

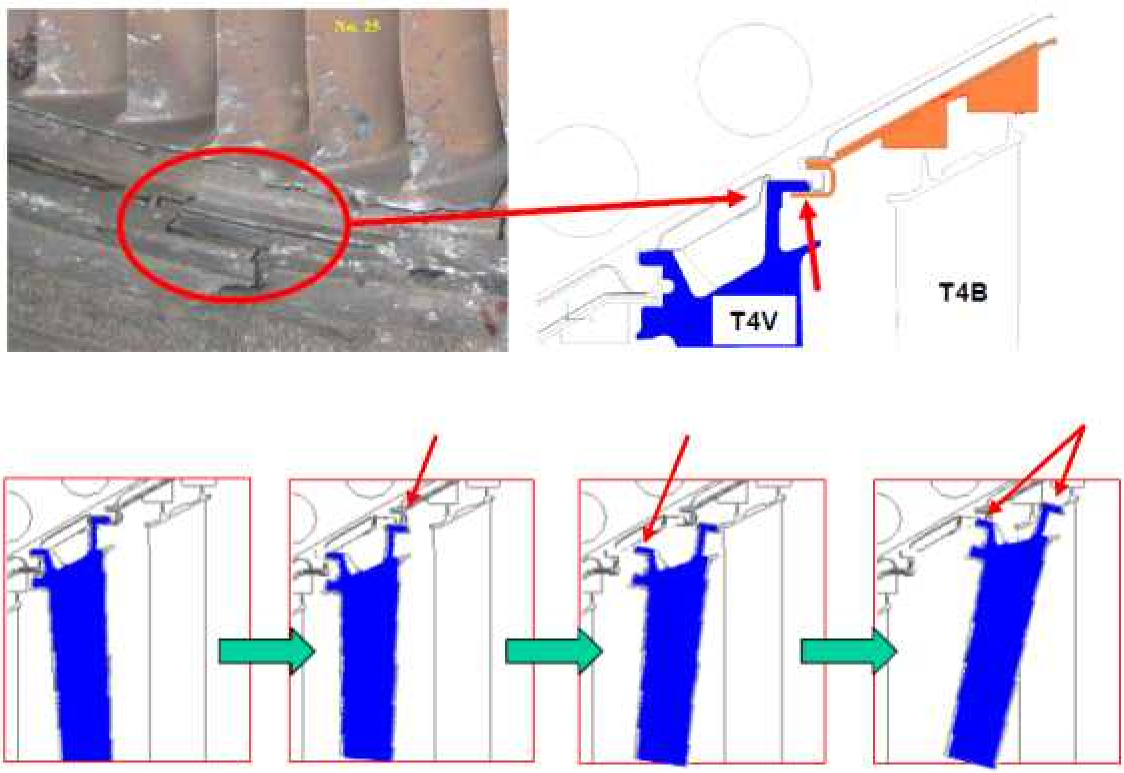
2.2.3 No. 27 T4 Vane Cluster Liberation Scenario

It is assumed that the liberation of the No. 27 T4 vane cluster was most likely a result of defeating retaining features by excessive wear, which was induced by excessive excitation from the aerodynamic pattern of the T2 rotor. The assumption was based on the following findings:

① The retaining feature for the rear outboard foot of the No. 27 T4 vane cluster was worn through and defeated. In addition, the pin-pocket was worn through at the inboard shroud, and the material was missing by wear in the retaining feature for the forward outboard hook of the No. 27 T4 vane cluster. As a result of that wear in the retaining features, the No. 27 T4 cluster could rotate out of the forward outboard hook in the LPT case by moving the inner shroud forward.

② Multiple other T4 vane clusters also exhibited pin-pocket wear-through, rear outboard foot wear, and cracking in the airfoil and inner shrouds. Those are indicative of excessive vibration in the T4 vane clusters.

③ According to the data previously generated from P&W's engine test, an aerodynamic pattern in the T2 rotor that could introduce significantly high 2E excitation in the LPT module was found.



[Figure 40] T4 Vane Cluster Liberation Process

3. Conclusions

3.1 Findings

1. The flight crew of HL7553 held qualification certificates suitable for the applicable flight and took the required rest before flight. Also, no medical factors that could have affected the flight were found.

2. The aircraft held a valid airworthiness certificate, and the flight concerned was carried out within the allowable limits of weight and balance. Any maintenance factors that could have directly contributed to this serious incident were not found.

3. Engine teardown examination at the KAL engine shop in Bucheon, Korea revealed that the engine failure occurred primarily within the LPT/TEC module. One T4 vane cluster was liberated from the assembled position and was not recovered, which was the most forward engine location that exhibited significant damage. Further hardware examination was carried out at Pratt & Whitney's facility.

4. The engine manufacturer's examination revealed excessive wear in the retaining features that interacted with the T4 vane clusters, especially at the location of the No. 27 cluster which aft outboard foot retaining feature (C-channel in the T4 BOAS) had been worn through completely and defeated.

5. The pin-pocket feature in the adjacent T4 vane cluster that constrained the inner shroud axial movement of the No. 27 T4 vane cluster was also worn through.

6. As a result of wear damage in the retaining features, the No. 27 T4

vane cluster could rotate out of the forward outboard hook slot in the LPT case by moving the inner shroud forward, and then was liberated into the gas path.

7. It is observed that the LPT case had no noticeable contact marks from the missing T4 vane cluster just forward of the aft rail, which was different from the rest of T4 vane cluster locations.

8. Examination revealed the presence of a strong aerodynamic pattern in the T2 rotor as a result of the assembly method and 50-50 mix between new and refurnished T2 blades. The previous engine test of P&W revealed an aerodynamic pattern in the T2 rotor that can introduce high 2E excitation induced vibration in the LPT module.

9. Excessive wear and cracking in other T4 vane clusters were indications of abnormal vibration in T4 vane clusters.

10. The engine event was most likely caused by the liberation of the No. 27 T4 vane cluster, which was most likely a result of defeating retaining features by excessive wear caused by abnormal vibration. The abnormal vibration in the T4 vane clusters were likely induced by the high 2E excitation from the aerodynamic pattern of the T2 rotor.

11. The fragments of the damaged LPT blades and vanes mostly remained in the LPT case, but some of them penetrated it or were discharged overboard along with exhaust gas.

12. The fragments that penetrated the LPT case were contained by the engine cowl, but some of them that had passed through the exhaust nozzle were dispersed by exhaust gas blast, thereby damaging the wing flap track fairing made of composite materials.

3.2 Causes

The ARAIB determines the probable cause of this serious incident as follows:

1. One liberated 4th-stage LPT vane cluster of the No. 2 engine (serial No. P733445) damaged the interior of the engine by impacting later stages of blades and vanes, thereby resulting in an engine failure.

Contributing to this serious incident is as follows:

1. The 4th-stage LPT vane cluster's C-channel and pin-pocket sustained excessive wear caused by abnormal 2E excitation, which had resulted from the aerodynamic pattern of the 2nd-stage HPT rotor.

4. Safety Recommendations

As a result of the serious incident that occurred to HL7553 on 26 May 2011, the ARAIB issues the following safety recommendations.

To Korean Air

1. Include the following in its maintenance program.
   Strengthen inspection of the wear status of the pin-pocket at the inner shroud of 4th-stage LPT vane clusters in the case of the A330 engines (PW4168) on which 2nd-stage HPT blades are installed according to the unrevised assembly procedures. (AAR1101-1)

2. Implement actively the engine manufacturer's measures to enhance the reliability of 4th-stage LPT vane clusters of the PW4168 engine when they are prepared. (AAR1101-2)

To Pratt & Whitney

1. Take improvement measures to prevent 4th-stage LPT vane clusters of the PW4168 engine from being liberated. (AAR1101-3)