AA2018-5

AIRCRAFT ACCIDENT INVESTIGATION REPORT

KOREAN AIR LINES CO., LTD.
H L 7 5 3 4

July 26, 2018

Japan Transport Safety Board

The objective of the investigation conducted by the Japan Transport Safety Board in accordance with the Act for Establishment of the Japan Transport Safety Board and with Annex 13 to the Convention on International Civil Aviation is to determine the causes of an accident and damage incidental to such an accident, thereby preventing future accidents and reducing damage. It is not the purpose of the investigation to apportion blame or liability.

Kazuhiro Nakahashi
Chairman
Japan Transport Safety Board

Note:

This report is a translation of the Japanese original investigation report. The text in Japanese shall prevail in the interpretation of the report.

AIRCRAFT ACCIDENT INVESTIGATION REPORT

ENGINE FIRE DURINING TAKE-OFF ROLL
KOREAN AIR LINES CO., LTD.
BOEING 777-300, HL7534

ON RUNWAY 34R
AT TOKYO INTERNATIONAL AIRPORT
AT AROUND 12:38 JST, MAY 27, 2016

July 6, 2018

Adapted by the Japan Transport Safety Board

Chairman	Kazuhiro Nakahashi
Member	Toru Miyashita
Member	Toshiyuki Ishikawa
Member	Yuichi Marui
Member	Keiji Tanaka
Member	Miwa Nakanishi

SYNOPSIS

Summary of the Accident

On Friday, May 27, 2016, a Boeing 777-300, registered HL7534, operated by Korean Airlines Co.,Ltd, as the scheduled Flight 2708 of the company, flight crew had a rejected takeoff on runway 34R at the Tokyo International Airport during a takeoff roll to Gimpo International Airport, because there was a warning to indicate a fire from the No.1 (left-side) engine activated at around 12:38, the flight crew stopped the aircraft on the runway, and conducted an emergency evacuation. There were 319 people in total on board, consisting of the PIC, sixteen other crew members, and 302 passengers. Among them, 40 passengers were slightly injured.

Probable Causes

It is highly probable that the causes of this accident were the fracture of the high pressure turbine (HPT) disk of the No.1 (left-side) engine during the takeoff ground roll of the HL7534, the penetration of the fragment through the engine case and the occurrence of subsequent fires.

Regarding the cause for the 1st stage HPT disk to be fractured, it is probable that a step was machined exceeding the allowable limit when machining U-shaped groove on the aft side of the 1st stage HPT disk to manufacture the engine and from this step the low-cycle fatigue cracks were initiated and propagated during running of engine.

Regarding why the step could not be found, it is somewhat likely that defects failed to be detected at the time of the inspection by the manufacturer during the production process. And as for the cracks that were not found, it is somewhat likely that those cracks failed to be detected at non-destructive inspection on the disk by the Korean Airlines Co., Ltd , at the time of maintenance of the engine in use.

Regarding the fire breakout from the No.1 engine, it is probable that due to the impact forces generated by the release of the fragment from the ruptured rim part of the 1st stage HPT disk through the engine case and the engine rundown loads generated when the engine stopped suddenly, the cracks were developed in the outer case of the Fuel Oil Heat Exchanger and the fuel and engine oil leaking through these cracks contacted the hot area of engine case of the No.1 engine to be ignited.

Abbreviations used in this report are as follows:

AC :	Advisory Circular
AD :	Airworthiness Directive
APU:	Auxiliary Power Unit
ARAIB :	Aviation and Railway Accident Investigation Board（Korea）
ATC :	Air Traffic Control
ATSM :	Automatic Society for Testing and Materials
CA:	Cabin Attendant
CAPT :	Captain
CAT :	Category
CCM :	Cabin Crew Manual
CMM :	Coordinate Measuring Machine
COM :	Cabin Operations Manual
CSN :	Cycle Since New
CVR :	Cockpit Voice Recorder
ENG :	Engine
EVAC :	Evacuation
EFB :	Electronic Flight Bag
EGT:	Exhaust Gas Temperature
EICAS :	Engine Indicating and Crew Alerting System
FAA :	Federal Aviation Administration
FCOM :	Flight Crew Operations Manual
FCTM :	Flight Crew Training Manual
FDR :	Flight Data Recorder
FOM :	Flight Operations Manual
FPI :	Fluorescent Penetrant Inspection
GND :	Ground
HPC :	High Pressure Compressor
HPT :	High Pressure Turbine
IAS:	Indicated Air Speed
ICAO :	International Civil Aviation Organization
JST :	Japan Standard Time
LCF:	Low Cycle Fatigue
LPC :	Low Pressure Compressor
LPT :	Low Pressure Turbine

MIL :	Military
MOLIT:	Ministry Of Land Infrastructure and Transport
MRE :	Material Review Engineer
NAS :	National Aerospace Standard
NDI :	Non Destructive Inspection
NTSB :	National Transportation Safety Board (U.S.A.)
PA:	Public Address
PF :	Pilot Flying
PFD :	Primary Flight Display
PIC :	Pilot In Command
PM :	Pilot Monitoring
POM :	Pilot Operating Manual
QA	Quality Assurance
QAR :	Quick Access Recorder
QN:	Quality Notification
RTO :	Rejected Take Off
RWY :	Runway
RPM :	Revolutions Per Minute
SEM :	Scanning Electron Microscope
SB :	Service Bulletin
SDS :	System Description Section
SPEC:	Specification
TO/GA	Take Off / Go Around

Unit Conversion Table

1 ft:	0.3048 m
1 kt:	1.852 km/h（0.5144 m/s）
1 nm:	1,852 m
1 in:	25.40 ㎜
1 µm :	Micro meter (10^{-6} m)
1 psi:	6.895kPa

CONTENT

1. PROCESS AND PROGRESS OF INVESTIGATION

1.1 Summary of the Accident

On Friday, May 27, 2016, a Boeing 777-300, registered HL7534, operated by Korean Airlines Co.,Ltd, as the scheduled Flight 2708 of the company, flight crew had a rejected takeoff on runway 34R at the Tokyo International Airport(Haneda) during a takeoff roll to Gimpo International Airport, Seoul, Republic of Korea because there was a warning to indicate a fire from the No.1 (left) engine activated at around 12:38, the flight crew stopped the aircraft on the runway, and conducted an emergency evacuation. There were 319 people in total on board, consisting of the PIC, sixteen other crew members, and 302 passengers. Among them, 40 passengers in total, were slightly injured.

1.2 Outline of the Accident Investigation

1.2.1 Investigation Organization

The Japan Transport Safety Board (JTSB) designated an investigator-in-charge and three investigators on May 27, 2016 to investigate the accident.

1.2.2 Representatives of the Relevant States

An accredited representative and advisers of Republic of Korea, as the State of the Registry and the Operator of the aircraft involved in the accident, and an accredited representative and advisers of the United States of America, as the State of Design and Manufacture of the Aircraft and Engines involved in the accident, participated in the investigation.

1.2.3 Implementation of the Investigation

May 27 to June 1, 2016	Site investigation, aircraft and engine examinations and interviews
June 4 to 7, 2016	Engine teardown investigation at a repair shop of the engine manufacture
June 9, 2016	Interviews
June 13 to 16, 2016	Turbine disk Inspection at the laboratory of NTSB of the United States of America
June 16, 2016	Interviews
June 22 to June 24, 2016	Turbine disk Inspection at a facility of the Engine

	manufacturer
July 19 to July 22, 2016	Investigation on a manufacturing process of the turbine disk and interviews
August 24, 2016	Interviews
October 10 to 14, 2016	Interviews, Investigation of the Engine repair shop and Aircraft maintenance factory

1.2.4 Provision of Factual Information to the Civil Aviation Bureau

Based on the engine teardown investigation at the repair shop of the engine manufacturer, because of evidence that a 1st stage high pressure turbine disk was fractured and pieces penetrated through an engine case, on June 18, 2016, to the Civil Aviation Bureau and the users of the same type of engines, the information was provided concerning the issuance of the recommendations to inspect the 1st stage high pressure turbine disk. Furthermore, the later investigation revealed that during the takeoff roll, because the 1st stage high pressure turbine disk had a partial rim separation, the case and an engine cover were damaged and at the same time as cracks were initiated at engine parts (fuel-oil heat exchanger) by the impact due to the partial rim separation of the 1st stage high pressure turbine disk, it was confirmed that the fuel and engine oil leaked from the location including the engine cover caused fire at outside of the fire zone, the JTSB provided this information to the Civil Aviation Bureau on November 8, 2017.

1.2.5 Comments from the Parties Relevant to the Cause of the Accident

Comments were invited from parties relevant to the cause of the accident.

1.2.6 Comments from the Relevant States

Comments were invited from the relevant States.

2. FACTUAL INFORMATION

2.1 History of the Flight

On Friday, May 27, 2016, an Boeing 777-300, registered HL7534 (hereinafter referred to as "the Aircraft"), operated by Korean Air Lines Co.,Ltd (hereinafter referred to as "the Company") was scheduled to fly to Gimpo International Airport Seoul, Republic of Korea from Tokyo International Airport(Haneda) as a scheduled Flight 2708 of the Company.

There were 319 people in total on board, consisting of the Pilot-in-Command (hereinafter referred to as "the PIC"), sixteen other crew members, and 302 passengers. The PIC sat in the left seat as PM[1]*1 and the First Officer (hereinafter referred to as "the FO") in the right seat as PF*1 in the cockpit.

According to the records of the flight data recorder (hereinafter referred to as "FDR"), the air traffic control (hereinafter referred to as "ATC") communication and the cockpit voice recorder (hereinafter referred to as "CVR"), and the statements of crew members, a local controller of Tokyo airport traffic control tower (hereinafter referred to as "the Tower") and others, the history of the flight up to the accident was summarized as below.

2.1.1 History of the Flight Based on ATC Communication Records, FDR Records and CVR records

Around 12:36:40	The Aircraft entered Runway 34R.
Around 36:53	The Tower cleared the Aircraft for takeoff.
Around 37:04	The Aircraft had its thrust levers advanced forward and commenced a takeoff roll as N1[2] increased.
Around 37:34	Along with a decrease of N1 of the No.1 engine, the warning for malfunction of the No.1 engine was activated.
Around 37:35	The Aircraft reached 119 kt.
Around 37:35	Thrust levers were moved backward.
Around 37:36	Pressure for brake of the Aircraft started to increase.
Around 37:37	The Tower reported a fire breakout from the No.1 engine and order an emergency stop.
Around 37:38	The first FIRE BELL from the No.1 engine was activated.

[1] "PF (Pilot-Flying) and PM (Pilot-Monitoring)" are the terms to identify pilots on the basis of role sharing when operating an aircraft by two pilots: The PF is mainly in charge of aircraft control and the PM is mainly in charge of monitoring of the aircraft in flying status, cross-checking of PF's operations and performing tasks other than flying.

[2] "N1" indicates RPM of fan and low pressure compressor at dual-spool jet engine. In addition, N is a symbol to indicate rpm.

Around 37:39	The FO called-out "SPEED BRAKE up, the No.2 engine reverse".
Around 37:45	The Aircraft reported to reject a takeoff (RTO) to the Tower.
Around 37:50	The Tower requested a dispatch of fire engines via crash-phone at Airport office.
Around 37:51	The ground speed of the Aircraft became 0.
Around 37:59	The PIC ordered cabin attendants "Crew at the station".
Around 38:01	The PIC and the FO commenced the checklist for the engine stop.
Around 38:13	Cut off fuel to the No.1 engine.
Around 38:20	ENGINE FIRE BOTTLE No.1 – OPEN to extinguish the No.1 engine fire.
Around 38:27	The fire warning from the No.1 engine was released.
Around 38:51	Two chemical fire engines were dispatched from the Fire Department East Building.
Around 38:51	The Aircraft reported that the fire was contained.
Around 40:40	The second FIRE BELL from the No.1 engine was sounded.
Around 40:52	The Aircraft reported to the Tower that there was a message of fire breakout displayed on the No.1 engine. At this time, the first two fire engines had arrived at the scene and had commenced the fire-fighting operation.
Around 40:59	Firefighting for the No.1 engine (the second time).
Around 41:11	Fire warning for the No.1 engine was released. The FO reported to the PIC that the fire was out, again.
Around 42:07	The third FIRE BELL from the No.1 engine was activated.
Around 42:13	The Aircraft reported to the Tower that because the message of fire breakout from the No.1 engine was on and the message did stayed on, the emergency evacuation from the right hand side of the Aircraft would be required.
Around 42:37	The PIC called for the emergency evacuation checklist of the FO.
Around 42:51	The PIC activated the emergency evacuation signal switch ON.
Around 43:03	The PIC addressed the emergency evacuation to cabin via PA[3].
Around 43:14	The PIC called for the checklist of the FO, again.
Around 43:25	The FO commenced to perform emergency evacuation the checklist.
Around 43:45	Cut off fuel to the No.2 engine was operated.
Around 43:48	FDR stopped to record.
Around 43:50	The Aircraft reported to the Tower to execute an emergency evacuation.

(See Appended Figure 1. Recordings of FDR and Attachment 1.Recordings of CVR,

3 "PA" is an abbreviation of Public Address and means a broadcasting system.

FDR and Video.)

2.1.2 History of Evacuation based on Video Records

Around 43:17	L1 and R1 door opened and the slide deployed normally and took upright positions.
Around 43:22	R5 door opened and the slide deployed but did not take upright position.
Around 43:25	R3 door opened and the slide deployed normally and took upright position.
Around 43:27	R4 door opened and the slide deployed but did not take upright position.
Around 43:29	R2 door opened and the slide deployed normally and took upright position.
Around 43:50	The first passengers evacuated via R3 door.
Around 44:04	The slide at R4 door re-positioned forward.
Around 44:06	Passengers commenced the evacuation from R4 door.
Around 47:04	The last passenger evacuated via the R2 door.

It took three minutes and 47 seconds, since when L1 door had been opened first to the time when passenger who was thought to be the last had evacuated via R2 door. Thereafter, the PIC had evacuated via R1 as the last of all, but because the video could not confirm this situation, the time to have completed the evacuation of all people was not verified.

Time correction for Video was performed by matching the estimated ground speed of the Aircraft based on the analysis of Video with the ground speed in FDR. The time in Video may contain an error of approximately 2 seconds as maximum.

(See Attachment 1. Recordings of CVR, FDR and Video.)

2.1.3 Statements of the Crew Members, Air Traffic Controllers and others

(1) The PIC

At around 12:20, the PIC started the engine and taxied the Aircraft to Runway 34R. During this time, the engine, instruments and others had no trouble, the PIC did not feel any vibration, odd sound or odd smell.

The FO was PF and the PIC was PM. The Tower cleared the Aircraft for takeoff, therefore, the PIC placed his hand over thrust levers as preparing Reject Takeoff (hereinafter referred to as "RTO"). The PIC called "80 kt Hold".

When the airspeed was at approximately 100 kt, “bang “ sound was heard, and because the Aircraft drifted to left slightly, the PIC decided RTO, exchanged the roles with the FO to take a control and immediately moved the thrust levers to idle position. The V1[4] of the Aircraft at that day was 122 kt, the speed when moving the thrust levers at idle position was approximately 110 kt, therefore, there were margin in speed by approximately 10 kt till the V1 speed.

During the time to stop the Aircraft, lights were on the fire warning and the sound of warning was confirmed. Furthermore, the EICAS[5] message of “FIRE ENG L (fire on the left engine)” was also confirmed. As the Aircraft stopped, the PIC had checked the left thrust lever of being at the idle position and cut off the left side fuel control switch. At this time, the FO pulled the fire handle, but still the message of “FIRE ENG L (fire on the left engine)” was displayed, therefore, discharged the first fire extinguisher bottle and did the time check. After a short time, the message went out. As the FO reported the Tower “RTO on Runway 34R”, the Tower replied that the fire engines were dispatched to the Aircraft. After the message went out, the PIC instructed the FO to set the parking brake and told him “Fire was gone. That’s OK.” Considering the possibilities of emergency evacuation, the PIC made PA to cabin attendants “Crew at the Station”, then performed the memory item[6]. The fire warning went out temporarily, but because after ten seconds, the light was turned on again, he discharged the second fire extinguisher bottle. The fire warning went out once, but immediately the light was turned on again, therefore, he decided to perform the emergency evacuation. When discharging the fire extinguisher bottle twice, the PIC saw the fire engines ahead, but since it was still further away, he felt that the emergency evacuation must be carried out in a hurry. The PIC called for the emergency evacuation checklist of the FO to hurry, but the checklist was not found at the specified location, he could not read out the checklist, immediately.

While the FO was looking for the checklist, the PIC thought that the emergency evacuation should be carried out in a hurry, therefore, he performed the engine shut down procedure from his memory.

After the PIC completed the engine shut down procedure, he made PA to evacuate via right hand side slides. And then, the FO completed the emergency evacuation checklist by reading out the tablet (hereinafter referred to as “the

---

4 “V1” is the maximum speed that an operator is able to start RTO operation at serious events on an engine or others affecting the continuous safe flight.

5 “EICAS” is the system to display the condition of engine and aircraft in integrated manner, and various troubles by the messages on a display

6 Performing “the Memory Item” means to carry out prompt countermeasures based on the memory in an emergency situation without seeing checklist.

Tablet") and evacuated to the cabin.

More than a half of passengers still could not be evacuated and their movement were slow, then the PIC urged them to evacuate from the right hand side following the cabin attendants' instruction to stay calm in order not to be panic because the fire were suppressed completely and it was all right.

After receiving the report from the purser that all passengers were evacuated, first the FO evacuated, then after checking that no one remained in the Aircraft, the PIC evacuated from R1 slide. After the evacuation, following the instruction by the firefighter, the PIC left the vicinity of the Aircraft and moved to the direction of the sea.

(2) The FO

When entering the runway, everything was normal. The FO was PF. The PIC was PM and communicated with ATC (Air Traffic Control). According to the regulation of the Company, the PIC should take the thrust levers up to the V1, after the FO pushing the TO/GA[7] switch, the PIC took over the charge of thrust levers.

Ten to fifteen seconds after hearing the call "80 kt, Hold" by the PIC, the PIC took over the control due to the trouble and stopped the Aircraft, then I saw the EICAS message of "FIRE ENGINE L". The PIC stopped the No.1 engine, set the parking brake and declared "Crew at the station".

The PIC and the FO performed the memory item. After three to five seconds from the discharge of the first fire extinguisher bottle, the message "FIRE ENG L" went out. Reported to the Tower that the fire was out. Then, after five to ten seconds, the same message was reappeared, therefore the second fire extinguisher bottle was discharged, and three to five seconds later, again the message was out. But, again five to ten seconds later, the same message was reappeared, therefore the PIC decided to evacuate from the right hand side.

Because the FO was called for the emergency evacuation checklist of the QRH[8], he looked in the box at right side where QRH is normally stored but could not find, then looking through the box at left side and the FO's flight bag, but there were no finding again and the FO was confused. Later on, he recalled the tablet had the checklist and read out the emergency evacuation checklist in the tablet. The PIC told the Tower to evacuate at Runway 34R. The PIC clearly instructed to evacuate

[7] "TO/GA switch" means the switch attached to thrust lever and relating to an auto-throttle. When pressing at the time of takeoff, it transits to "N1 mode", the thrust lever is advanced to takeoff thrust, when pressing during the approach, it transits to "GA" mode, and then "go around N1" thrust is set.

[8] "QRH" is a booklet in checklist styles publishing Normal Operation and Abnormal / Emergency Operation from FCOM (Flight Crew Operation Manual).

from the right hand side. However, after exiting from the cockpit, the FO was confused that the L1 slide was deployed, but the FO confirmed that no one evacuated from there.

(3) Chief Purser and Cabin Attendants

Chief Purser felt sure that there would be emergency evacuation to be carried out based on the report of a cabin attendant in charge of L3 who found the smoke at outside of the Aircraft, and she judged that an evacuation from R1 slide would cause no problem because no smoke was seen there as checking outside through the window at Door L1 and the passengers were almost to its capacity of the cabin, prior to the emergency evacuation signal from the PIC and the announcement to "Evacuate form the right hand side" via PA.

Based on the emergency evacuation signal from the PIC, L1 slide deployed, but as seeing outside through the window of L1 Door, because the fire from the No.1 engine was quite obvious and there were fire engines parking at the exit of L1 slide, the L1 slide was not used as the result. As announcement of not carrying baggage and evacuating from the right side were made and cabin attendants kept shouting at the passengers that do not carry baggage and take off the high heel, but many passengers evacuated with their carry-on baggage.

Because the personnel in charge of R5 operated the slide manually but it did not deploy normally, she blocked R5 and guided passengers to R4 to evacuate. Personnel in charge of R4 tried to stop passengers to evacuate because the R4 slide was blown by the wind at first, but as the slide re-positioned itself, the personnel started the evacuation using this slide. Furthermore, because R5 could not be used therefore passengers gathered to R4, the passengers in the rear were instructed to use the left side aisle to evacuate from the right front side door.

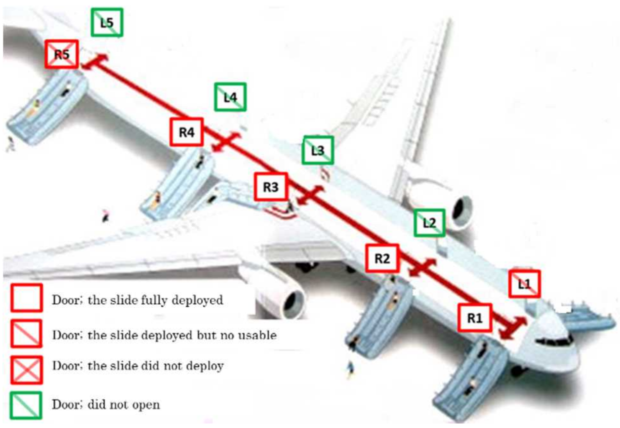


Figure 1. Door Layout for Emergency Evacuation

(4) Air Traffic Controller

The ATC cleared the Aircraft for takeoff from Runway 34R. Until then, the ATC did not feel any abnormality. As the Aircraft commenced the takeoff ground roll, because a fire from the No.1 engine near Taxiway C3 was seen, the ATC reported to the Aircraft about the fire broke out from the No.1 engine and ordered to reject the takeoff.

The ATC requested fire engines to be dispatched via crash phone. Before the full stop as the ATC thought, we received the report from the Aircraft about their RTO. At the time, a smoke was coming out of the Aircraft but not seeing fire. Later on, the pilot reported that the fire message was displayed, so we reported back to them that the fire engines were already dispatched. Then, the Aircraft reported that the fire was out. And soon, the Aircraft reported that the No.1 engine fire message had annunciated. At this time, already the first fire engine arrived at the site and started to fight fire.

After one to two minutes, the Aircraft reported that "the fire message had annunciated again (third time), we require the emergency evacuation from the right hand side". About 10 seconds after this, the slide was deployed. Shortly, the pilot reported that "MAYDAY, we evacuate" and at the same time we saw the passengers starting the evacuation. After this, as trying to confirm whether the Aircraft shut down the right engine or not, but there was no response and we could not confirm that there were any pilot left in the cockpit.

(5) Passenger A

According to the Passenger A who sat near the rear of the right wing, the male cabin attendant shouted in Korean "run, pronto" and the door opened suddenly. Hearing this, the passenger were getting into panic. As soon as the door opened, the passengers were rushing to evacuate. There were no cabin attendant at the R3 door near the right wing. The Passenger A went R3 and had companion escape ahead, but the companion had leaped out to the runway because there were no one to assist at the bottom of the slide. As following, the Passenger A was evacuated as being pushed from the behind, hit his right knee onto the runway and suffered a bruise.

(6) Airport Firefighter (Airport Security Section and Disaster Prevention and Air Safety Foundation)

According to an airport firefighter who worked at the east fire station, when the Aircraft departed, as confirming the sound of "bang " to know something abnormal event occurred, the firefighter started to prepare for the dispatch prior to the crash phone ringing. When entering the runway, the flame from the No.1 engine was confirmed. Within about two minutes since the dispatch, the firefighter arrived at the site. Judging that the water could be discharged from downwind side, deployed the fifth truck at the left wing tip and the third truck at the rear of the No.1 engine to start to discharge water. There were smoke coming out of the No.1 engine, the flame could be seen at the engine cowling. Later on, the forth fire engine from the west fire station started to discharge water from forward of the No.1 engine, and the third and fifth truck stated to extinguish the fire by using dry chemical which could reach the inside of the engine. After the fire engines from the Tokyo Metropolitan Fire Department arrived, we reported the situation and then dealt with logistics support (be on guard).

According to the station firefighter who guided the evacuation, immediately after the initial firefighting activities were started, the emergency evacuation was commenced, but there were no passenger to assist at the bottom of the slide, the firefighters took the charge of assisting the passenger at the bottom of R1, R2 and R4 slides. There were none to assist at the R3 slide. After the evacuation, as the passengers were shooting pictures near the Aircraft and making telephone calls, they did not respond to the guide or instruction given by the airport firefighters, therefore, they were guided by the guide-pointing rod to the perimeter road at sea side. Many of passengers were carrying their baggage, and some of them carried large suitcases.

This accident occurred on Runway 34R of Tokyo International Airport (N35°32', E139°48') and at around 12:28 on May 27, 2016.
(See Appended Figure 2. Estimated Taxiing Route Map)

2.2 Injuries to Persons

40 of passengers suffered minor injuries like bruises, scratches and others.

2.3 Damage to the Aircraft

2.3.1 Extent of Damage

Slightly Damaged

2.3.2 Damage to the Aircraft Components

(1) The No.1 engine: Damaged (See Attachment 3. Condition of the No.1 engine)
(2) The left wing Flaps: Penetrating marks

2.4 Information Relevant to Damaged Properties other than the Aircraft

None

2.5 Personnel Information

(1) PIC: Male, Age 49

Airline Transport pilot certificate (Airplane)	January 3, 2002
Type rating for Boeing 777	November 24, 2009
Class 1 aviation medical certificate	
Validity	July 31, 2016
Total flight time	10, 410 hours and 05 minutes
Flight time in the last 30 days	32 hours and 00 minutes
Total flight time on the type of the aircraft	3, 205 hours and 22 minutes
Flight time in the last 30 days	32 hours and 00 minutes

(2) FO: Male, Age 41

Commercial pilot certificate (Airplane)	April 30,1999
Type rating for Boeing 777	July 7, 2016
Instrument flight certificate	April 30, 1999
Class 1 aviation medical certificate	
Validity	May 13, 2017
Total flight time	5, 788 hours 16 minutes
Flight time in the last 30 days	40 hours 00 minutes
Total flight time on the type of the aircraft	2, 531 hours 18 minutes
Flight time in the last 30 days	40 hours 00 minutes

2.6 Information Relevant to the Aircraft

2.6.1 Aircraft

Type	Boeing 777-300
Serial number	27950
Date of manufacture	January 4, 1998
Certificate of airworthiness	AS071213
Validity	Since September 21, 2012 until discontinued/limited
Category of airworthiness	Aircraft Transport T
Total flight time	64, 028 hours 00 minutes
Flight time since IAA (every 500 hours, performed on April 12, 2016)	412 hours 00 minutes

(See Appended Figure 3.: Three-view drawing of Boeing 777-300)

2.6.2 Engine

Location to be worked	No1 (Left)	No2(Right)
Type	PW4090	

Serial number	P222221	P222017
Date of manufacture	October 23,2004	February 5, 1997
Total flight times	41,594 hours	70,660 hours
Total number of use time	9,832 cycles	11,059 cycles

2.6.2.1 The Structure of the Engine

The engine installed on the aircraft is a dual-spool turbofan engine consisting of a low pressure compressor and turbine (expressed in blue at Figure 2) and high pressure compressor and turbine (expressed in red at Figure 2). From the front of the engine, the structure consists of a 112-inch diameter fan, six-stage low pressure compressor (hereinafter referred to as "LPC"), 11-stage high pressure compressor (hereinafter referred to as "HPC"), annular combustor, two-stage high pressure turbine (hereinafter referred to as "HPT"), and seven-stage low pressure turbine (hereinafter referred to as "LPT"). (See Figure 2. Engine Structure (Schematic))

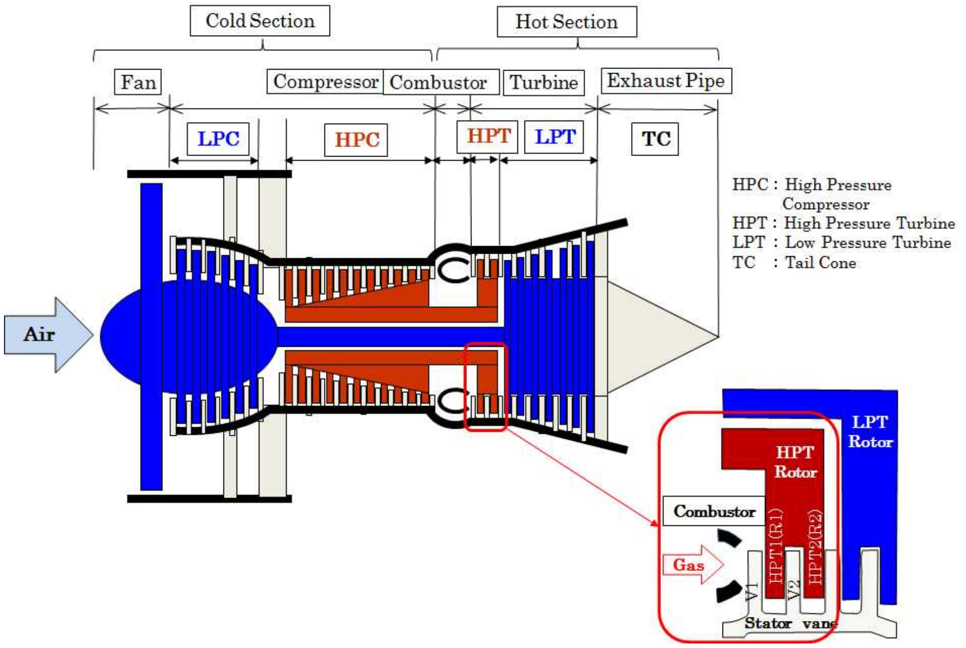


Figure 2. Engine Structure (Schematic)

2.6.2.2 HPT (high pressure turbine)

The parts of the engine structure are distinguishing by calling the parts where is exposed to high temperature and pressure combustion gas (Figure 2 Combustor, Turbine and Exhaust Pipe) as hot section and calling the other parts as cold section. Especially because HPT of the hot section operates under a high temperature, rotor blades, stator vanes, disks and other of HPT's components are made of a heat resistant alloy having excellent heat resisting properties.

HPT is a component of engine driving HPC through a high pressure shaft as converting the high temperature and pressure combustion gas from the combustor to rotating movement by expanding via two-staged turbine and it consists of the 1st stage stator vane (V1), the HPT1 rotor blade (R1), the second stage stator vane (V2) and the HPT 2 rotor blade (R2). Each HPT rotor is a disk-shaped disk with dozens of airfoil rotor blade installed on outer periphery of the disk.

HPT rotor is installed on a shaft (axis) and rotating in high speed between stator vanes. During its operation, the HPT rotor receives thermal stresses caused by the high temperature and pressure combustion gas, and centrifugal forces due to the high speed rotation. Per the Type Certificate Data Sheet (TCDS), the maximum exhaust gas temperature (EGT) is 675°C and the maximum HPT rpm is 10,850 RPM.

Furthermore, when starting an engine and making the engine the maximum thrust to takeoff, the outer diameter of the disk near the blades are heated rapidly and it expands as the result, but because inner diameter of the disk (hub) does not become high temperature, tensile force would be generated between outer diameter (rim) and inner diameter. As operating for some time, the heat transmits to the inner diameter, the temperature difference would be gone. And at next, when the engine stops, the outer diameter of disk would be shrink rapidly due to the cooling, but the inner diameter would not be cooled so easily, therefore, the compressive stress would be generated between the outer and inner diameter of the disk.

As these samples, the disk receives a set of tensile stress and compressive stress per one cycle due to difference in temperature, which generated one cycle per one flight (start – takeoff – climb – cruise – descent – landing – stop). Count this one set of stresses as one cycle. The one cycle time varies depending on the operating route distance, but it should be about one to 14 hours in general.

Comparing to fatigue accumulated within a short time like vibration, the metal fatigue caused by receiving repeatedly sets of low cycle stresses as above mentioned is called as a low cycle fatigue (hereinafter referred to as "LCF"). Almost all disks installed in the engine have the fatigue life limit by LCF. Therefore, the engine manufacturer set a fatigue life for the 1st stage HPT disk of the engine installed on the Aircraft as 13,300 cycles for its use limit.

2.6.2.3 Processing and Inspecting when manufacturing the HPT Disk

The 1st stage HPT disk has the structure with machined grooves to install the air seal (hereinafter referred to as "U-shaped grooves") to suppress a leak of cooling air or the grooves to install rotor blades on the perimeter as machined. (See Photo 1. the HPT Disk)

Furthermore, since large stress would act on the HPT disk repeatedly, if mere scratch or step exceeding the manufacturing allowance exists, because of notch effect[9], it could be an originating point for stress to concentrate or fatigue crack, the machining and inspecting at the manufacturing have being controlled strictly.

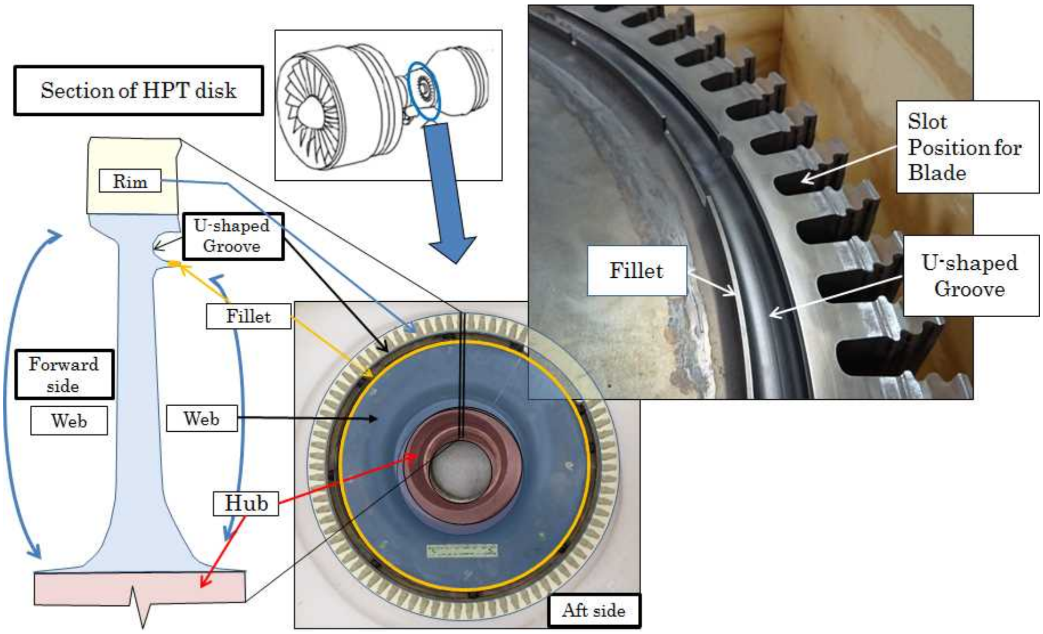


Photo 1. HPT Disk

U-shaped grooves are machined for cutting and processing by vertical and horizontal movements of the tip of the machining tool while the 1st stage HPT disk which is a workpiece is mounted and turned on the turn-table of the vertical milling machine. The vertical milling machine is processing automatically by computer program control. Machine Operator (worker) monitors the status of positioning of a workpiece, fixing, setting the machining tool and automatic processing.

Because U-shaped groove are cut from both sides of groove from the outer side and the inner side, a machined resultant step-like trace would be initiated at the seams from both sides. The Machine Operator, in order to remove this mismatch step at the seams when processing final finishing of U-shaped groove, inserts 0.010 inches shim stock into a clearance between the tip on the machining tool and the bottom of U-shaped groove while checking the situation by a fingertip touches and visual examination, controls the manual feeder installed on the vertical automatic

[9] "Notch Effect" is the phenomena that the surface of object with a notch could be initiated far bigger stress than a flat smooth surface, when an external force works.

lathe for a precision finish, and sets the final processing position by adjusting the clearance between tip of machining tool and the bottom of U-shaped groove. This adjustment is to compensate the wear occurred at the tip of machining tool, and the value (Z axis; vertical feeding) of the final machining position would be displayed on the manual feeder counter for precision finishes. Inputting this value from keyboard to vertical automatic lathe, automatic machining would be executed, but the real final machining position is programmed to send the tip of machining tool at the 0.010 inches lower than this value in order to compensate the shim stock thickness.

According to the investigation by recreating the processing as the final processing position without using the 0.010 inches thick shim stock and investigating by recreating the machining by setting the condition without no gap at the bottom of U-shaped groove initiated by the tip of the machining tool had resulted in 0.010 inches deep step at the bottom of U-shaped groove. (See Figure 3. Processing the HPT Disk with use of a vertical milling machine.)

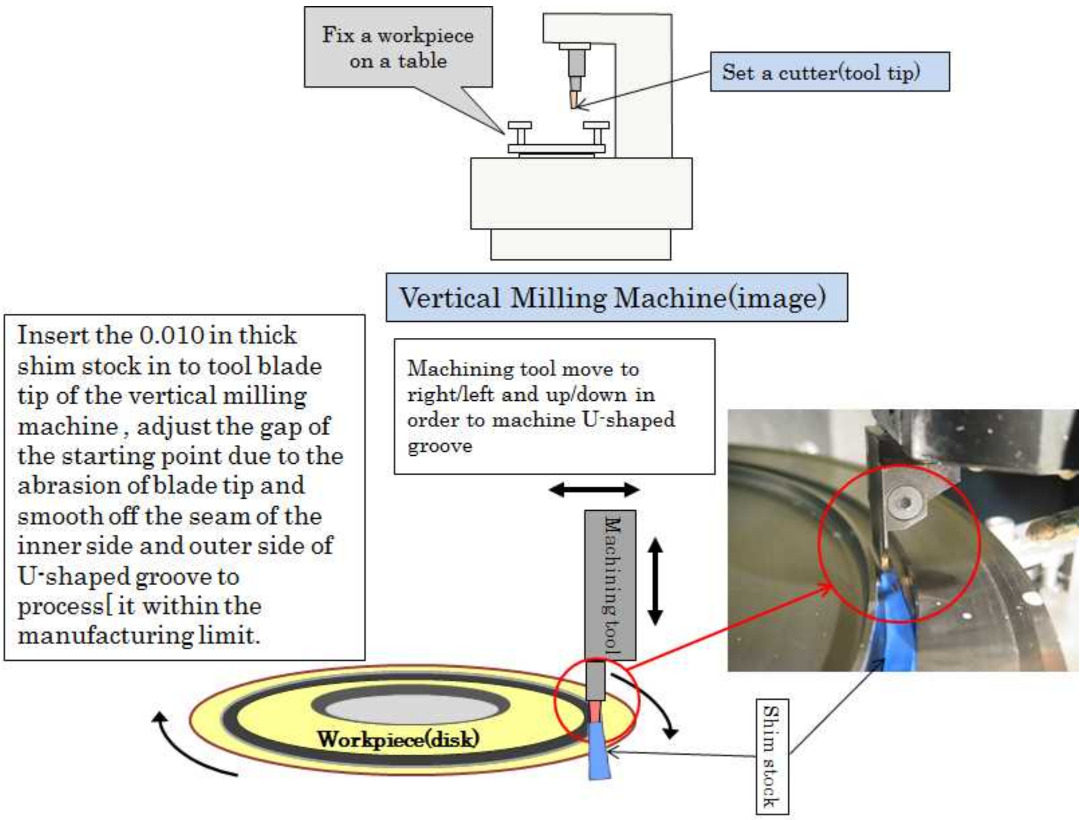


Figure 3. Processing the HPT Disk with use of a vertical milling machine

After the manufacturing, a machine operator confirms that the HPT disk are within its allowable range for manufacturing by visual inspection, touch examination and measurement by instruments (Product Inspection). Subsequently, an inspector (Inspector) confirms that the product is machined according to the manufacturing instruction, and confirms that an inspection itself is carried out correctly based on a work order and manufacturing drawing (Quality Inspection).

Work order and manufacturing drawing which used for inspection are managed by the computer at technical section and the latest version are constantly delivered to the workplace through the in-house Intranet.

The inspection method used by an inspector are specified depending on the location of inspection such as visual inspection, touch examination, measuring by measurement instrument and CMM (Coordinate Measuring Machine; three dimensional measuring device). Furthermore, when the inspector judges that it is necessary for checking the machined step, making a replica using thermosetting rubber compound to measure the mismatch between the two machined radii in the groove by the optical comparator. Manufacturing allowable limit is shown in manufacturing drawings. Because the locations of U-shaped groove are not specified as the critical inspection points (blade mounting slot, installing grooves for hub shaft and others which possess the highly critical situation), standard manufacturing allowable limits of 0.002 inches is applied for the 1st stage HPT disk.

Furthermore, regarding the critical inspection points, the manufacturing drawing has the note concerning the detailed inspection, in the records column in the work order had the records of the measured values of the product inspection and quality inspection, but other that, the manufacturing drawing does not have note and only to pass or fail as the result of inspection are recorded in the work order. In addition, U-shaped groove of the 1st stage HPT disk of the No.1 engine of the Aircraft had not been processed at the repair work after the manufacture.

2.6.2.4 Records of manufacturing the HPT disk

At the engine manufacturer, the 1st stage HPT disk receives a product inspection by machine operator at the time of manufacturing and a quality control by inspector as described in 2.6.2.3. According to the manufacturing records (Inspection results recorded in the work order) of the 1st stage HPT disk of the engine, there were no entry of measurement data and likes since U-shaped groove is not an critical inspection point for the quality control, but there was a description that the inspection result was approved.

2.6.2.5 Quality Control System of the Engine Manufacturer

The engine manufacturer holds Production Certification from FAA of the

United States of America which is the State of Manufacture. On-site inspections were carried out regarding the facilities, the equipment, the organizations, the personnel and the quality management system relating to the manufacture of the engine along with confirmation of the records of the manufacturing the 1st stage HPT disk of the Engine and as interviewing the machine-operator and the inspector who had worked to manufacture the engine, however, the facts to be the cause of this incident was not found. When a malfunction of being out of the allowable limit and others is found at the quality management inspection, QN (Quality Notification) will be issued and there is a system to make up decision to rework or to reject by the MRE (Material Review Engineer) who is an engineer of the technical section and in charge of quality control, however, QN was not issued for the 1st stage HPT disk of the engine.

2.6.2.6 Non-destructive Inspection of the HPT disk

Regarding the HPT disk in order to find out signs of either damage or cracking in advance due to the LCF described in 2.6.2.2, the engine manufacturer is requesting users to carry out Non Destructive Inspection (NDI) when disassemble the HPT at an engine maintenance work and to carry out Fluorescent Penetration Inspection (hereinafter referred to as "FPI") which is one of NDI, to the 1st stage HPT disk. It is difficult for regular visual inspection to detect a discontinuous damage which opens up to a surface, but this FPI is an inspection to detect the damage using penetrant containing fluoresce. Besides, regarding the requirement to implement FPI, well-known standard (MIL SPEC, MIL STD, NAS410, ASTM-STD-1595 and others) or aircraft manufacturers' engineering data specify facilities, equipment, operator and working method relating this NDI strictly and require to carry out as following these. The Company implements FPI as following the specified procedure by the engine manufacturer. Outline of FPI procedure to detect cracks is as follows;

① Apply the fluorescent penetrant to the inspection surface or soak in it, then because of capillary phenomenon the penetrant liquid penetrates into cracks.

(Penetration Processing)

② Remove an excess of penetrant remaining on a surface.

(Removal process and Pre-Rinse)

③ After in the emulsifier to remove the penetrant from the surface of the part to allow the penetrant to remain in the crack, rinse and dry the part.

(Emulsification apply)

④ Spray developer and suck up the penetrant from cracks. (Developing processing)

⑤ When illuminate with Ultra-Violet Light,the cracks emit fluorescence. (Inspection)

(See “Attachment No.2. FPI manual of the Company” for the detailed procedure of FPI.)

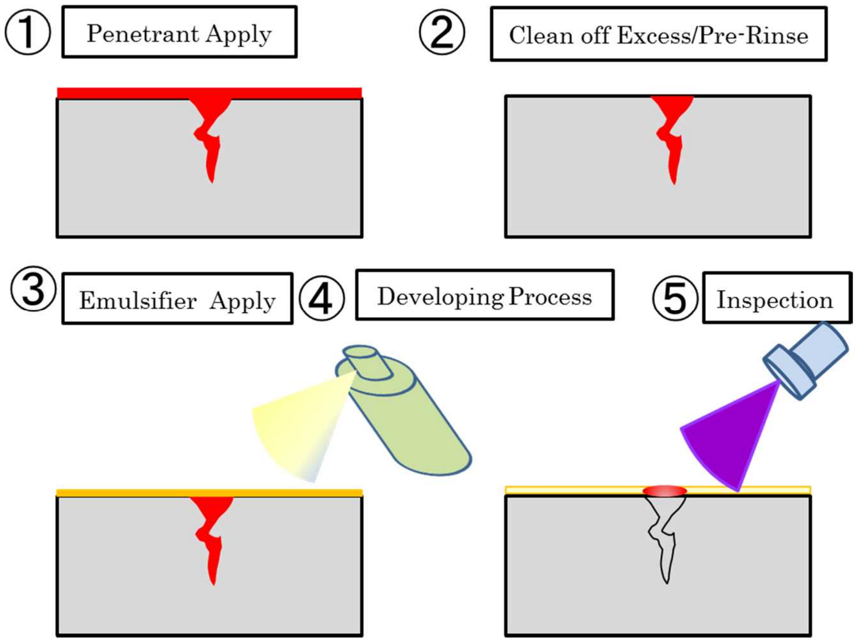


Figure 4. Outlined procedure to detect surface flaws by FPI

According to the FAA advisory circular (AC43-3 “Nondestructive Testing Aircraft”), FPI is effective to detect flaws at surfaces of non-magnetic metal, ferromagnetic metal and non-metallic materials.

2.6.2.7 Major Operating History of the No. 1 engine and 1st stage HPT disk

According to the maintenance records of the engine, the major history of the No.1 engine and the 1st stage turbine disk after their manufacturing are as shown in Table 1. The 1st stage HPT disk of the engine was manufactured on October 28, 2004 and has a life limit of 13,300 cycles. It remained with the engine since then.

The part number was 53L121-001, SN CKLBHE5552. According to the maintenance records, the 1st stage HPT disk had accumulated 9,832 cycles and 41,594 hours since new and the time and cycles since new of the engine and 1st stage turbine disk are the same.

FPI for the 1st stage HPT disk was implemented at the times of manufacturing the engine ①, and of disassembling HPT module[10] ②, ⑥ and ⑧. Besides, the 1st stage HPT disk of the engine was installed from the time of manufacturing the engine, and number of cycles and use hours up to the time of accident were 9,832 cycles and 41,594 hours as the same for the both engines. In addition, when disassembling the HPT module at the delivery to the engine repair shop, FPI on the 1st stage HPT disk for each time was implemented as specified by the engine manufacturer.

Table 1. Major History of the No.1 Engine

No.	Date	Equipped Machine Number Location	Reason to Overhaul	Delivery Destination	FPI on disk Yes; ○, No; ×	Use hours / number of cycles since its manufacture
①	October 28, 2004	HL7573 right (New Machine)			○(when inspecting the product as newly manufactured)	0 hour 0 cycles
②	August 13, 2007		EGT*; High temperature	Engine Manufacturer Repair Shop	○(when disassembling HPT module)	11,168 hours 3,043 cycles
③	March 5, 2008	HL7531 right				
④	June 17, 2008		Internal damage	Engine Manufacturer Repair Shop	×(not disassembling of HPT module)	12,691 hours 3,262 cycles
⑤	November 18, 2008	HL7573 left				
⑥	March 31, 2011		Internal corrosion	The Company's Repair shop	○(when disassembling HPT module)	22,120 hours 6,050 cycles
⑦	September 6, 2011	HL7734 left				
⑧	June 29, 2014		EGT; High Temperature	The Company's Repair shop	○(when disassembling HPT module)	36,825 hours 8,023 cycles
⑨	November 12, 2014	HL7534 left				
⑩	May 27, 2016		This Accident May 27, 2016			41,594 hours 9,832 cycles

2.6.2.8 The Engine Repair Shop of the Company

The Company has received the approval for the maintenance work from MOLIT of Republic of Korean as the State of Registry. Upon implementing the on-site investigation concerning facilities, equipment, organization, personnel, and the

[10]"Module" is maintenance units which forms the engine structure parts in order to improve the maintainability.

quality management system relating to the FPI at the engine repair shop of the Company, we had checked the maintenance records at the time to carry out FPI on the 1st stage HPT disk of the engine, but we could not find any fact to be the cause of this accident.

The FPI at the Company was provided exactly as the method specified by the Engine Manufacturer and the FPI is implemented by an operator and an inspector who hold the qualification and capabilities required for FPI.

Operator carries out the inspection (NDI inspection) following the work order. Inspector carries out QA inspection to guarantee the quality of inspected product by confirming the inspection carried out properly by the operator following the procedure and work process specified at the last.

On June 29, 2014 (hereinafter referred to as "at that time"), the inspector (hereinafter referred to as "the Inspector") who carried out FPI inspection on the last of the 1st stage HPT disk of the engine was working as an inspector for about 25 years after working as operator at the Company for about 10 years. At that time, the Inspector had accumulated about 27 years of experience at the Company. Then, the Inspector was retired and is now working as cleaning aircraft parts at a company relating to the Company. The Inspector made a statement concerning FPI at that time of the investigation of this accident.

At that time, an operator (hereinafter referred to as "the Operator") who carried out the last FPI inspection on the 1st stage HPT disk of the engine was working for cleaning aircraft parts at the Company for three years and then became the Operator at the engine shop of the Company. At that time, the years of experience at the Company was about 19 years. When investigating, the Operator became an inspector working for the Company and he was the personnel who had executed FPI in real at the time of investigating the FPI implementing system of the Company as described later in 2.14.12, . At that time, the inspector and the operator held the appropriate qualifications (FPI level[11] Ⅱ) and passed the annual Eyesight test provided by the Company.

According to the Operator, at first confirming the work order and executing the visual checking a workpiece for its part number and its serial number, and then the operator would carry out the work as following the work procedure (the

[11] "FPI level" is an inspection qualification level that is specified by nation's regulatory standard authorized depending on an experience time and a degree of difficulty per the type of NDI and Level 1 becomes to Level 2 then Level 3 as the highest. After the qualification authorized, in order to maintain the competence, it is necessary to have experience times more than specified inspecting time and pass an Eyesight test, and others. With being qualified more than level 2, one can inspect alone.

procedure specified by the engine manufacturer).

According to the engine manufacturer, the inspection in a dark room, as an inspector would take a few minutes to adjust to the darkness prior to the work, the Inspector had been taking for about two to five minutes and the Operator for about ten minutes.

The Operator had an experience to find out a crack at the cooling hole of the 2^{nd} stage HPT disk of the same type engine in a past. The Inspector had no experience to find out any crack at his inspecting turbine disk of the engine.

Furthermore, since the Operator became the Inspector of the Company at the time of investigation who carried out FPI in real at the time of investigating the FPI system of the Company, and made an statement described in 2.14.1.2, the following are based on the statement of the Operator;

① When carrying out inspection, an inspector could inspect turbine disk done alone, but depending work load, he/she would inspect it with other parts as combination. Turbine disk inspection is done on the disk suspended from the belt traveling while rotating the disk, and at first the whole disk is seen from the front. These are done because the forward side of disk has higher level of critical. Time duration to inspect a disk is about 30 minutes but it could be about one hour to inspect when taking a longer time.

② When we differed in our opinion with the Technical section, we discuss with other inspector and carry out the inspection all over again if required. Prior to the final inspection done by the inspector, operator carries out inspection as following the manual.

③ Regarding the inspection results, the differences in opinion do not occur that many, up to now, but we had a cleaning section to re-clean because of insufficient cleaning.

④ From 2004 to the present, there are no changes in work environment concerning work quality or measures on malfunction.

⑤ The human factors training is carried out periodically for all member in the engine shop as the subject. As the training is targeting for foreseeing operational errors, restraining over-confidence and others, it is very useful for everyday operations.

⑥ Regarding points to inspect at FPI of the engine with care, there is nothing particular, but it is important to see the points where need cautions with care at the inspection by confirming this according to the manual. We have not questioned the engine manufacturer and others regarding manual, till now.

2.6.2.9 Records of FPI on the 1st stage HPT Disk

As described in 2.6.2.5, the 1st stage HPT disk of the engine after its manufacturing had received FPI four times in total, which were implemented at the time of engine manufacturing, at the engine manufacturer repair shop and the engine repair shop of the Company, but any of these records did not contain descriptions regarding any malfunction such as cracks and others.

2.6.3 Fuel and Lubricating Oil

The fuel and the lubricating oil used for the Aircraft were Jet A-1 and Mobil Jet Oil II, respectively. The spontaneous ignition temperature of Jet A-1 is approximately 210 °C and the flash point is approximately 40 °C.

2.7 Meteorological Information

Aeronautical weather observations for the Airport around the time of the accident were as follows:

(1) METAR (Aerodrome routine meteorological report)

12:30 ; Wind direction: 060°, wind speed: 20 kt, visibility: more than 10 km
Cloud Amount: 1/8-2/8, Type Cumulus, Cloud base: 800 ft
Amount: 3/8-4/8, Type Cumulus, Cloud base: 1,300 f
Amount: 5/8-7/8, Type Cumulus, Cloud base: 1, 800 ft
Temperature 19℃; Dew point 18 ℃; Altimeter setting (QNH) 29.80 inHg

(2) SPECI (Aerodrome special meteorological report)

12:52 ; Wind direction: 060°, wind speed: 18 kt, visibility: 25 km
Cloud Amount: 1/8-2/8, Type Cumulus, Cloud base: 800 ft
Amount: 3/8-4/8, Type Cumulus, Cloud base: 2,000 f
Amount: 5/8-7/8, Type Cumulus, Cloud base: 4, 000 ft
Temperature 19℃; Dew point 17℃; Altimeter setting (QNH) 29.80 inHg

2.8 Runway Information

Tokyo International Airport has four runways as Runway A (16R/34L, 3,000m by 60 m in width), Runway B (04/22, 2,500 m by 60 m in width), Runway C (16L/34R. 3,360 m by 60 m in width), and Runway D (05/23, 2,500 m by 60 m in width), and this accident occurred at Runway C. (See Appended Figure 2. Estimated Taxiing Route)

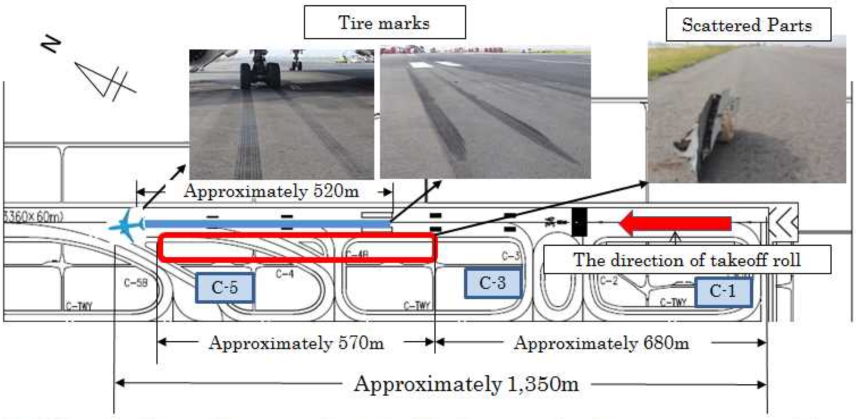
The runway had received the periodic runway inspection from 11:00 to 11:10, however, no anomaly to cause obstacle to its operation was found.

2.9 FDR and other Information

The Aircraft was equipped with a FDR capable of recording for a duration of about 25 hours and a CVR capable of recording for a duration of about two hours, manufactured by Honeywell, U.S.A. The records concerning this accident were retained in both recorders. The time data on the FDR and CVR were corrected by correlating the time signals on the ATC communication records with the VHF transmission keying signals in the FDR and ATC communication records in the CVR.

2.10 Accident Site Information

The Aircraft entered to Runway 34R from the approach taxiway C1 and commenced the takeoff roll. At some time later, the Aircraft rejected the takeoff and stopped on the runway at short of Taxiway C5 with heading direction of 335 ° (magnetic direction). During this time, the Aircraft run approximately 1,350 m. tire marks due to the heavy brakes were confirmed from the stop position to approximately 520 m south along the runway centerline and at the both sides of the centerline. Besides, there were many rejected fragment and parts relating to the engine found and collected over the runway originating the point about 680 m from inside of the runway threshold to approximately 570 m north, the taxiway and the grass land of the perimeter road. (See Figure5.Tire Marks and Scattering range of fractured Parts.)



Red frame indicates the range of scattered broken parts in the grass area around the runway.

Figure 5. Tire Marks and Scattering range of Fractured Parts

2.11 Details of Damage of the Airframe and Engine

The on-scene examination at Tokyo International Airport revealed the following details of damage of the airframe and engine. In addition, within the following sentence, all references to position or directions, as referenced to the clock, will be as viewed from the rear, looking forward, unless otherwise specified. Besides, "Photo # X" means the number of photos shown in the Attachment 3.

(1) Damage of the No1 Engine were as follows;

① The left side of the engine and the external accessories were burned and sooted. (Photo #1)

② The rear flange of the diffuser[12] case at the position from about 5:30 to 6:30 o'clock was bent radially outward. The inner diffuser case had cracks between the aft flange and the center part of the case and at about 12 o'clock, there was a piece missing from the case.

③ The HPT case between the position of 7:30 and 9:00 along the periphery was bent radially outward and twisted, exposing the 1st stage turbine disk and blades and the 2nd stage turbine stator inner support.

All of the visible 1st stage turbine blades were in place in the disk were fractured transversely across the airfoil adjacent to the blade root platform. There were no 2nd stage turbine stator vanes visible through the hole in the HPT case. (See Photo #7.)

④ Air Starter valve had a hole. (Photo #8)

⑤ A piece was missing from the rim of the 1st stage HPT disk.(See Photo #10.)

The missing pieces are found among the scattered debris at grassland near Runway C.

⑥ On the body case of fuel-oil heat exchanger[13], cracks and soot due to fire damage were confirmed.

⑦ Pieces are missing along the periphery of cowling from the left rear frame of the translating cowl along the periphery of cowling to front. (See Photo #11.)

(See Attachment 3. Status of the No.1 engine)

(2) Outboard Flap

The outboard flap had an 8-inches (20cm) long crack in the trailing edge at 48 inches (120cm) length to outboard from the inboard edge. (See Photo 2. Outboard

[12] "Diffuser" is located at the aft side of compressor and is the device convert high velocity, lower pressure airflow from the high pressure compressor to lower velocity, higher pressure airflow prior to entering the combustor.

[13] "Fuel-oil heat exchanger" is a system to warm fuel in order to prevent freezing of water in fuel and cool the engine oil by exchanging heat between fuel and oil.

flap showing the cracks.)

Photo 2. Outboard flap showing the cracks

(Note: The flap position shown in this photo is differed from the takeoff flap position at the time of accident.)

2.12 Information of Firefighting

2.12.1 Emergency System at Airport when Aircraft Accident occurred

(1) Tokyo International Airport Emergency Plan

Tokyo Airport Office has Tokyo International Airport Emergency Plan established in compliance with ICAO Annex 14 (Aerodrome) and stipulating the counteractions when an Aircraft accident occurs. According to the Emergency Plan, when the accident occurs, the Airport office shall report to the relevant authorities using emergency contact table, and request a firefighting operation, a medical rescue operation and others, and this plan includes the training and others, too.

(2) Dispatching Airport Firefighter and Stationed Emergency Vehicle

Five chemical fire engines, one command vehicle, one water truck, one rescue lighting vehicle and one medical transport vehicle shall be assigned at the Airport. At the time of this accident, eleven Airport Firefighters shall ride separately on five chemical fire engines and one medical transport vehicle and shall be dispatched.

(3) Dispatch Situation at Tokyo Fire Department

Tokyo Fire Department shall dispatch 48 fire engines in total and 14 ambulance to the site and 239 firefighters in total shall carry out firefighting operation and emergency medical aid operations.

2.12.2 History of Firefighting

Regarding the response taken by the Airport Fire Station Staff when this accident occurred, according to the records of the airport office, the summary was as follows;

12:38 Fire station received the dispatch request through Crash Phone from the Tower.

12:39 Two chemical fire engines (the third car and the fifth car) were dispatched.

12:41 The engines arrived at the site from the rear of the Aircraft and started to fight fire.

12:42 The forth fire engine arrived at the site from the front of the Aircraft and started to discharge water.

13:03 Airport fire station staff finished the initial firefighting operation, handed over the firefighting operation to Tokyo Fire Department and dealt with logistics support.

According to the records of Tokyo Fire Department, a fire suppressed[14] was at 14:21 and a confirmation of fire extinguished was at 15:09.

2.13 Information on Rescue and Evacuation Guidance

2.13.1 Rescue and Evacuation Guidance By Airport Fire Station Staff

At 12:42,the eighth Fire Engine arrived at the site from the front of the Aircraft and dealt with the Evacuation guidance for crew and passengers. At 12:43, the ninth Fire engine arrived at the site from the Aircraft and dealt with the Evacuation guidance. Airport Fire Station Staff assigned at the base of the emergency evacuation slide R1,R2 and R4(hereinafter referred to as “the Slide”) and following the confirmation of all passengers evacuation, guided the crew and passengers to a perimeter road at the side of Runway C.

At 12:51, the twelfth fire engine (ambulance) arrived at the site and provided the medical care to the injured people near the edge at east side of Runway C.

[14] “Fire Suppressed” and “Fire Extinguished” are terms used for Firefighting, “Fire Suppressed” means that a force of fire is lost by firefighting, and “Fire Extinguished” means that the fire is out and the condition of no more firefighting required by the firefighter.

2.14 Information on Tests and Researches

2.14.1 Investigation of the Engine

2.14.1.1 Analysis of fractured surface

After disassembling the No.1 engine of the Aircraft at the engine overhaul facility, a metallurgical examination of the damaged 1st stage HPT hub (disk) and the ejected disk fragment from the body was carried out by the NTSB and the engine manufacturer. The findings as the results of this investigation are as follows;

The 1st stage turbine disk was complete except for a section of the rim that was missing and the disk's material conformed to the requirements. The missing piece of the disk's rim, that was about 19.68 cm (7.75 inch) as measured along the snap inner diameter, was recovered from along the edge of the runway. The complete fracture surface on the disk corresponded to the complete fracture surface on the piece of the rim. The fracture surface on the disk and the recovered piece of the rim and elliptical-shaped patterns. There were 73 blade slots in the disk and 9 blade slots in the recovered piece of the rim. The 1st stage turbine disk has 82 blade slots. 0.010 inches (0.25 mm) deep step was confirmed all over periphery of U-shaped groove at the aft side rim of the 1st stage HPT disk. Maximum allowable limit for machining mismatch when manufacturing was 0.002 in (0.05 mm) as described in 2.6.2.3. As the result of the detailed investigation around the step, it was confirmed that several cracks were dotted along the left and right step around where the 1st stage HPT disk was fractured. A detailed visual inspection could confirm the size of opening were about 1 mm to 4 mm respectively. (See Photo 3-1. Fractured Rim, Photo 3-2. U-shaped Groove and Crack 1, Photo 3-3. U-shaped Groove and Crack 2, and Photo 4. Created Replica of the Step)

Regarding the fracture surface of the ejected fragment, cracks were originating at the machined step in U-shaped groove and was propagating from the aft side of the 1st stage HPT disk to the front side. The fracture surface exhibited severe damage due to the impact and others, but the beachmark[15] of a typical characteristic of the fatigue crack fracture surface was confirmed of its initiating along with the propagating area on crack. The size of the three thumbnail cracks were as follows;

① large; approximately 0.608 inches deep, approximately 2.358 inches long
(15.44mm x 59.89 mm)

② medium; approximately 0.282 inches deep, approximately 1.000 inches long

---

[15] "Beach mark" is half circle pattern like shell to be seen at a macro-observation of fatigue crack surface.

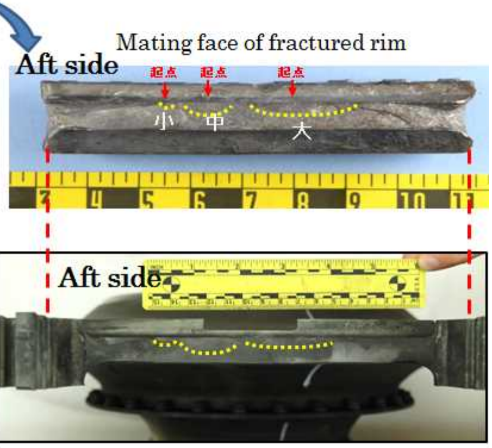
(7.163 mm x 25.40 mm)

③ small; approximately 0.088 inches deep, approximately 0.489 inches long

(2.235 mm x 12.42 mm)

(See Attachment 4. Photo of fracture face)

To investigate, divided the rim into eight parts and assign number to parts in a clockwise direction from the fractured parts. (Slot① to Slot ⑧) There were 73 blade slots in the disk and 9 blade slots in the recovered piece of the rim. The 1st stage turbine disk has 82 blade slots.



Abutting surface of fractured rim

Trace of crack propagations (beach mark) in size of large; approximately 0.608 inches deep, approximately 2.358 inches long, medium; approximately 0.282 inches deep, approximately 1.000 inches long, and small; approximately 0.088 inches deep, approximately 0.489 inches long, which was originating at the aft side of disk, were confirmed.

Photo 3-1. Fractured Rim

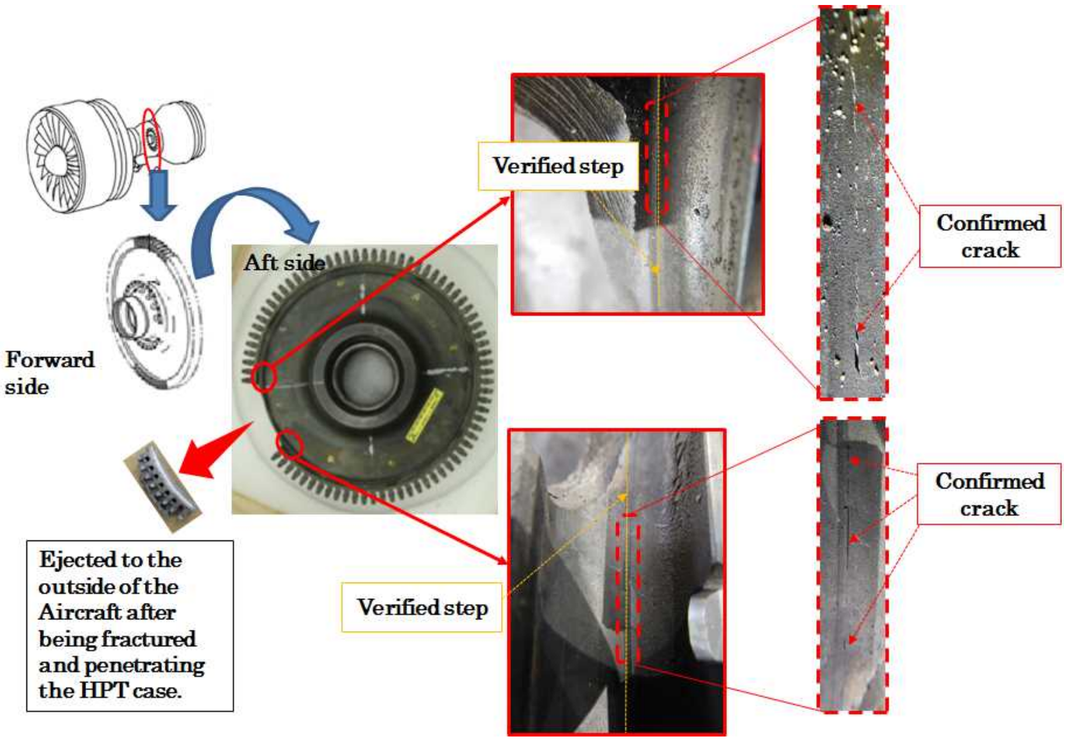
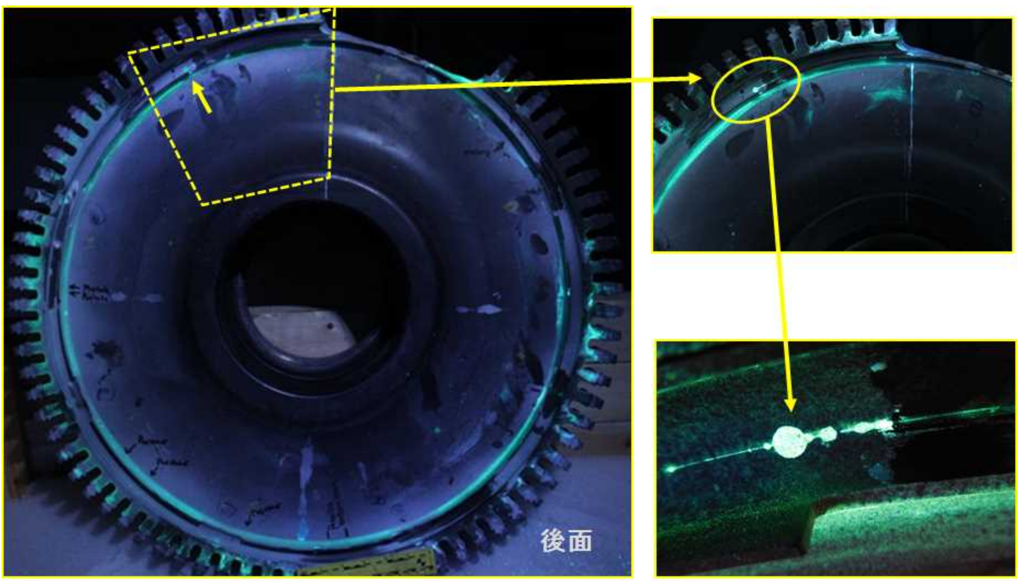
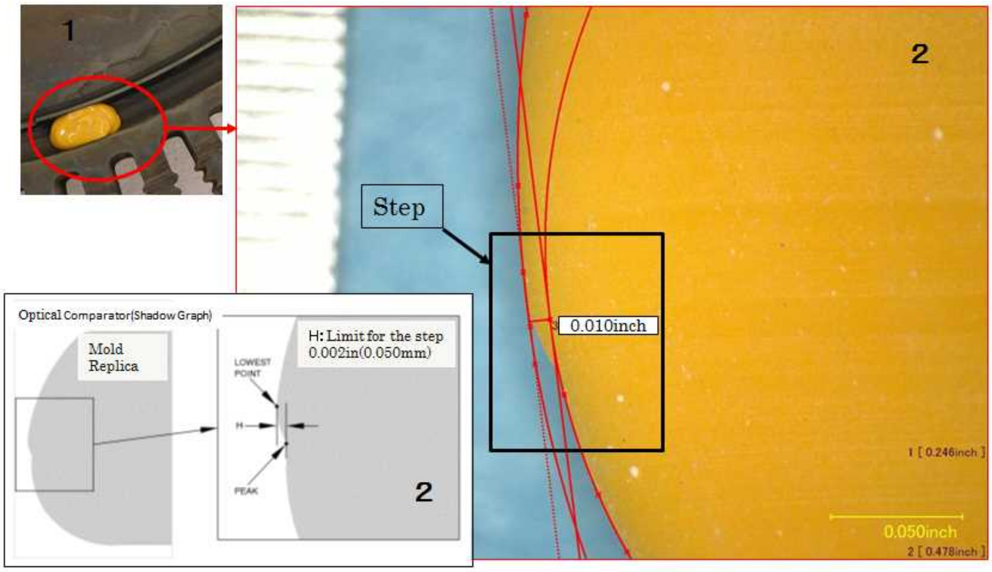


Photo 3-2. U-shaped groove and crack 1



FPI at the aft side of the disk
(Clear Crack was confirmed at the left side slot⑧of the fractured part)

Photo 3-3. U-shaped groove and crack 2



1．The U-shaped groove was used to make multiple replicas using a thermosetting rubber compound.
2．Setting the replica on an optical comparator, measure the machined step (mismatch) based on two machine radii. The step is 0.010 inch （0.25mm） *(Limit for the step is 0.002inch(0.050mm).

Photo 4. Created Replica of the Step

The fractured surface of the ejected piece of the 1st stage HPT disk was damaged, however, stable striations could be counted at a part of the section with the scanning electron microscope (SEM). The fractured surface on the disk was unreadable because of oxidation from the fire extinguishing agent used by the fire department. Furthermore, open the crack which was cut out a part from the disk which had clear cracks from the remaining aft side of the disk, and analyzed the crack surface. (See Attachment 5. Striations at the crack on the test piece)

The striation count analysis completed on the fracture surface and crack surface estimated 2,130 cycles and 2,868 cycles of repeated stress respectively. Why these two numbers differed from each other were because the time period to initiate cracks were differed and cracks initiated at the initial crack propagation stage was damaged by corrosion, heat and others. As shown in Figure 5, at the time of accident, the disk had 9,832 cycles as the total number of cycles since the manufacturing the disk, subtracting 2,130 cycles from these number became 7,702 cycles and subtracting 2,868 cycles from these became 6,964 cycles. Besides, the total number of use cycles of the disk at the time of the previous inspection was 8,023 cycles. Based on these numbers, it is possible that the 1st stage HPT disk had cracks when it delivered to the engine shop of the Company to have the previous inspection (November 12, 2014). (See Figure 6. Number of Cycles of the

Disk estimated from the analysis of the fracture surface of rejected fragment)

Furthermore, from the numerical analysis based on the counting at the crack surface, values of 0.088 to 0.176 inches (2.24 mm to 4.47 mm) along the surface were obtained on the cracks at the latest inspection at the engine repair shop of the Company.

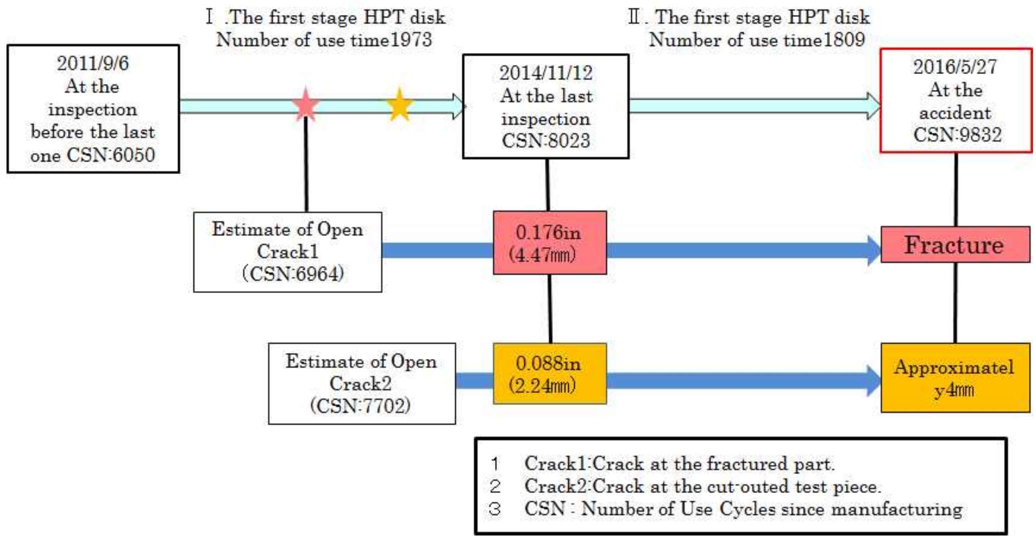


Figure 6. Number of Cycles of the Disk estimated from the analysis of the fracture surface of rejected fragment

2.14.1.2 Investigation of FPI implementing system by using sister disk at the Company

For the so-called sister disk of the 1st stage HPT disk of the same engine which was manufactured and inspected by the same operator and the same inspector, at the engine repair shop of the Company, the status of following inspection and others carried out by the same operator were checked and the FPI implementing system of the Company was investigated.

(1) Inspection of the disk based on the PW Service Bulletin (SB) PW4G-112-72-342 (issued on September 23, 2016, category 5,6 (recommend)"

After conducting an acceptance test to confirm no anomaly existing at the sister disk, creating replicas by use of rubber compounds at four locations (positions at 12:00, 3:00, 6:00 and 9:00) of U-shaped groove at outside of the aft side disk following the Service Bulletin regarding the above subject, the step of U-shaped grooves are measured and confirmed to be within the allowable limits. (See Table 2.) The technical report were issued for the same type engine users to check manufacturing error of the step exceeding the allowable limit for U-shaped groove of the 1st stage HPT disk and at the quality inspection as described in 2.6.2.3, it instructed the measuring the step by creating the replica as required by the decision of an inspector.

Table 2.

	Step of U-shaped Groove
Limit	0.0020 in max
Location of Replica	
12 o'clock	0.0015 in
3 o'clock	0.0014 in
6 o'clock	0.0014 in
9 o'clock	0.0015 in

(2) FPI based on the working procedure of the engine manufacturer

As the result of FPI verification investigation using a sister disk, the sister disk did not have any problem, and there were no crack indications.

At the time of implementing FPI on the sister disk at the engine overhaul shop of the Company, regarding facilities, systems, procedures, operators and inspectors did not have any disqualification in compliance with the 2.6.2.6 requirements.

2.14.1.3 The 1st Stage HPT Disk on Other Same Type Engine

According to the investigation carried out by the engine manufacturer, the step of U-shaped groove exceeding the allowable limits was not found from the HPT disk of the same type engine other than the engine of this accident with the implementation of the technical report in 2.14.1.2 (1).

2.14.2 Emergency Evacuation Slide

2.14.2.1 Emergency Evacuation System

The Aircraft has the evacuation exit doors at ten locations and each door equipped with an emergency slide /raft. This system deploys a slide automatically as soon as the door opened at the emergency situation and let passengers and crew to evacuate to outside of the aircraft. (See Figure 1. Door Layout for Emergency Evacuation.)

SDS (System Description Section) in the system relating to the manual provided by the aircraft manufacturer has the following description regarding the deploying time of the slide and the wind speed limit at the time of deployment;

The average time for door opening and slide/raft inflation is seven seconds. The slide/rafts operate correctly in wind as much as 25 kt.

2.14.2.2 Situation at Emergency Evacuation

According to the statements of the cabin attendants, they had deployed the doors at five locations of the right side of the Aircraft and attempted to evacuate, but the R5 door at the most rear side (hereinafter referred to as “R5 door”) was not fully deployed. For the door at the left side of the Aircraft, L1 door at the most front side had only the slide deployed, but it was not used. (See Photo 5.Emergency Evacuation Slide.) Furthermore, the situation of the emergency evacuation was recorded by the Monitoring camera at the Airport, it was confirmed that there were passengers with baggages to evacuate and no assistances at the bottom of the slide when the evacuation was started. Photo 6. shows the comparison of deploying R5 slide at the normal situation and at the accident.

Photo 7. shows the deploying situations of R3, R4 and R5 slides of the Aircraft at the time of the accident. Furthermore, the R3 slide is narrower in width and shorter in length compared to the R4 and R5.

Photo 5. Emergency Evacuation Slides

Photo 6. Comparison of R5 slide deploying status

Photo 7. Deploying situations of slides at R3, R4 and R5

2.14.2.3 Information of R5 Slide

Name; B777 Evacuation Slide/Raft

Part Number; 62774-424, Serial Number; 1192

Date of Manufacture; May, 2005

Date of Previous Inspection; March 16, 2016

(Overhaul at MNE-GMP Maintenance Center), boarding on HL7534 on April 16, 2016

2.14.2.4 The result of Investigation on R5 Slide

Approximately 5 cm long tear was confirmed at the right lower corner (at the right corner topside of the side of ground) of R5 slide outer material. As the results of investigating the details at the Aircraft Manufacuturer factory, R5 slide had no other anomaly other than that. (See Photo 8. R5 slide.)

Also, according to the latest inspection records (March, 2016) of R5 slide done by the Company, there was not air leak, malfunction to deploy and others. Furthermore, at the time to deploy the slide (12:43:22), No.2 Engine was idling and the cut off of No.2 engine was operated at 12:43:45 based on visual materials and FDR. (See Appended Figure 1. Records of FDR.)

According to the materials concerning the engine exhaust air flow by the Aircraft manufacturer, B777-300 Engine Exhaust verocity contours at idle thrust are 55 km/h and reach approximately 40 m from the rear of the Aircraft and narrows in width. (See Figure 7. Predicted Engine Exhaust Velocity Contours – Idle Thrust.)

Photo 8. R5 Slide

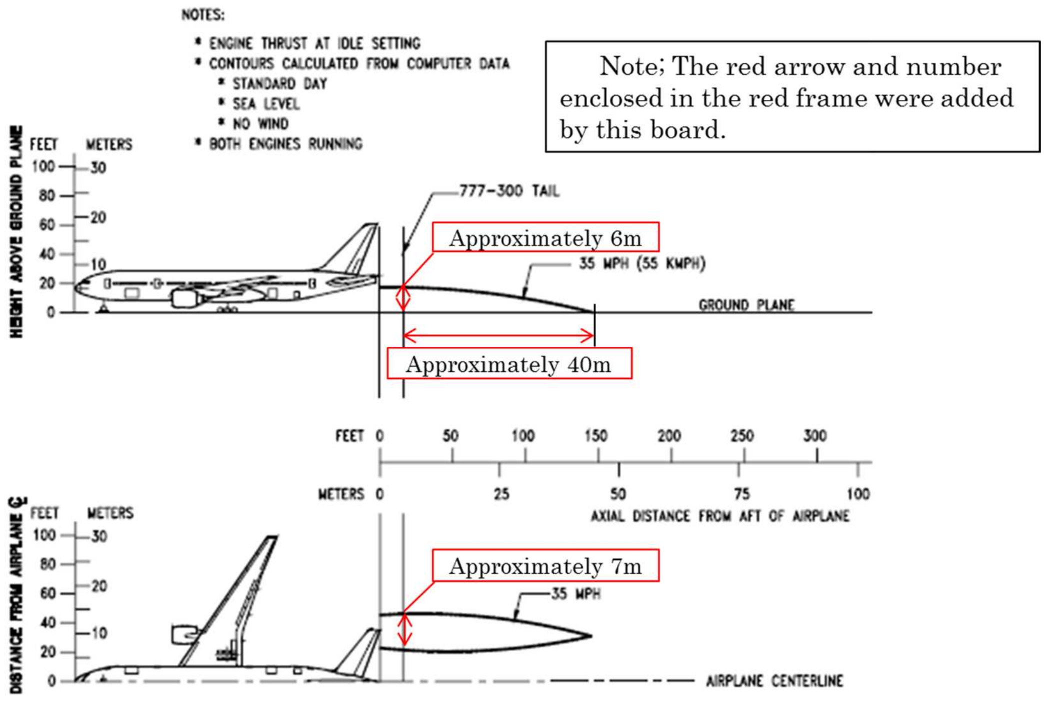


Figure 7. Predicted Engine Exhaust Velocity Contours – Idle Thrust

2.15 Information of Organization and Management

2.15.1 Operation Manual and rules of the Company

2.15.1.1 The Documents required to be onboard of Aircraft

According to the Company, the checklist (QRH) described in 2.1.3(2) was found in the rack at the rear side of the FO's seat, later. The Company regulates as follows. The Company specifies the document required to be on board of aircraft as follows;

(1) Confirmation Obligation by flight crew for documents to be onboard

B777 POM OPERATIONAL POLICY contains the following descriptions regarding the obligation of flight crew

CREW DUTIES	*Reference*	*CAP*	*F/O*	*PF*	*PM*
COCKPIT PREPARATION					
Check A/C documents	*FOM 6*	•	•		

(2) Documents required to be onboard of Aircraft

Regarding the documents required to be onboard of aircraft, FOM 1.3.1 has the following descriptions (excerpts);

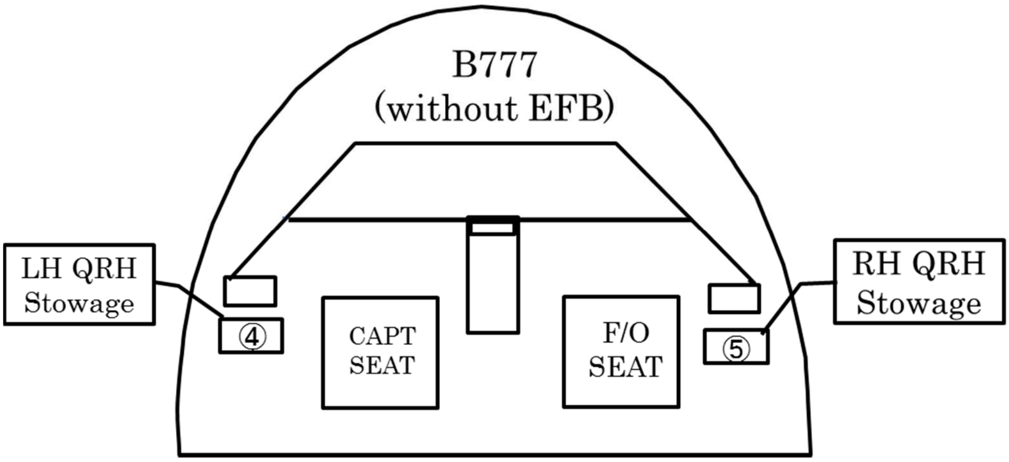
Operational Doc on Board

Legal Documents	*Documents /Manuals*	*Location*	*Loading Departments*

omission			
Operations Manual	*QRH*	*Cockpit*	Flight Operations Technical Support Department

(3) The location of onboard documents are specified as follows (excerpts);

No	*Location*	*Name of Publication*	*Note*
④	*Left Hand QRH Stowage*	*QRH, Captain Announcement Manual*	
⑤	*Right Hand QRH Stowage*	*QRH,POM*	



2.15.1.2 The Regulation regarding Engine Fire

Regarding the procedure when engine fire occurs, 777 Flight Crew Operations Manual of the Company regulates as follows;

FIRE ENG L,R

Condition: Fire is detected in the engine

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

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

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

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

5 If the FIRE ENG message stays shown:
Engine fire switch

(affected side).........................Rotate to the stop

and hold for 1 second

If after 30 seconds, the FIRE ENG message

stay shown:

Engine fire switch

(affected side)..........................Rotate to the other stop and hold for 1 second

－－－－－－－－－－－－－－－－－－－－－－－－－－－－－－－－－－－－－－－

6 - 11 Omission

2.15.1.3 Manuals provided for Emergency Evacuation and others

Concerning procedures and likes for an emergency evacuations of the Company were provided in FCOM（Flight Crew Operations Manual), FOM（Flight Operations Manual), 777POM, 777QRH, and COM （Cabin Operations Manual) of the Company as follows (excerpts);

(1) FCOM (Evacuation Checklist)

Condition: An evacuation is needed

1 Parking brake.............................Set C

2 OUTFLOW VALVE switches
(both)....................................MAN F/O

3 OUTFLOW VALVE MANUAL
Switches (both).....................Hold in OPEN
until the outflow
Valve indications show fully
open to depressurize the airplane F/O

4 FUEL CONTROL switches
(both)...................................CUTOFF C

5 Advise the cabin to evacuate. C

6 Advise the tower. F/O

7 Engine fire switches(both).................PULL F/O

8 APU fire switch................Override and pull F/O

9 If an engine or APU fire warning occurs:
Related fire
switch...................Rotate to the stop
and hold for 1 second F/O

(2) FOM（NON-NORMAL OPERATIONS 8.2.13, Outlined Excerpts）

■ *When an emergency evacuation is expected*

PIC	Cabin Crew
A:"Attention, crew at station"	Standby at their stations preparing for the next step.

■ *When an emergency evacuation is required*

PIC	First Officer
"Passenger evacuation."	
Conduct Passenger Evacuation Procedure in accordance with POM/QRH.	
PA: *"This is the Captain. Evacuate, evacuate."* *Evacuation Command S/W:ON(then silence the cockpit warning horn)*	*Notify Tower:* *"KE000, passenger evacuation, request emergency equipment."*
	Cabin Crew
	Initiate passenger evacuation
Note) If an emergency fire or other conditions make certain exits unusable, state the direction of egress, and evacuate on the runway, if possible. *The PIC should make a decision on the direction of exits depending on which engine has the fire, wind direction, attitude and position of the aircraft and the extent of aircraft damage.*	

(3) COM（ESCAPE THE AIRCRAFT 4.6 Outlined Excerpts）

4.6.1 EVALUATE

Cabin crew should evaluate the situation to decide evacuation when the aircraft stops moving. First of all, captain's PA is important to evaluate the situation. If there's not PA or other actions taken, Cabin Crew should call for Captain's PA by using Emergency signal.

Evaluate according to PIC's PA after landing or when rejected take-off （Excerpts）

PIC'S PA	*EVALUATION*	*CABIN CREW DUTY*
"Attention, crew at station."	*Emergency Evacuation Anticipated*	*Be prepared for emergency evacuation at right position.*
"This is the Captain" *"Evacuate, evacuate."*	Emergency Evacuation Required	*Command the emergency evacuation*

(4) COM 4.6.5 B(c)

(c) If an Evacuation is warranted

Command the evacuation as determined after communication with the captain and other crews.

(5) 4.6.6 EVACUATION INSTRUCT

Release Seatbelts !

Get Out! Leave Everything!

(*6) 4.6.8 ACTIVATE EXIT AND EVACUATION-Door Exit*

・*Quickly confirm armed status of exit.*

・*Open exit. Utilize all available exits by requesting passenger assistance when responsible for more than one exit.*

・*If exit is jammed or slide/raft is not usable, attempt to open it again and (if necessary),redirect passengers to an alternate exit using appropriate command.*

・*Command the first passengers. "Stay At Bottom! Help People Off!"*

2.15.2 Emergency Evacuation Training of Flight Crew

According to the records of the Company, the Company implements annual emergency evacuation training for flight crew and the PIC, the FO, Chief Purser and all cabin attendants had received this specified training.

2.15.3 How to inform the emergency evacuation of the Company to all passengers

Regarding how to act at the time of emergency evacuation, the Company explains to passengers by using demo-video and at the same time, having the safety leaflet at each seat to ensure all passengers to know that when to evacuate, takeoff high heels, do not take baggage, the passengers seated at the emergency exit seat should evacuate first and assist other passengers at the bottom of slide and others.

2.16 Additional Information

2.16.1 Fire Extinguishing System of the Aircraft

When a fire broke out from an engine, a warning bell activates and a master warning light and the red light of the fire handle turn on, "FIRE ENG L(R') (engine fire left (right))" in red characters is appeared on the display of EICAS. The Aircraft has equipped two bottles of fire retardants behind the panels of right side wall in the front baggage room, which operates independently as a fire extinguishing system to an engine fire. Pulling a fire handle activates operations to close a main cock of fuel and bleed air valve, to shut off the operating fluid of the hydraulic system, to stop power generation of a generator, and to prepare to fight fire by activating the fire retardant injection circuit. Turning the fire handle to the left or right discharges the fire extinguisher bottle. If the first fire extinguisher bottle did not extinguish the fire, turning the handle in the other direction will discharge the second fire extinguisher bottle. If the first injection could not extinguish the fire, turning the fire handle to other side enables to inject the second fire retardant. (See Photo #9. Fire Extinguishing System of B777 Engine.)

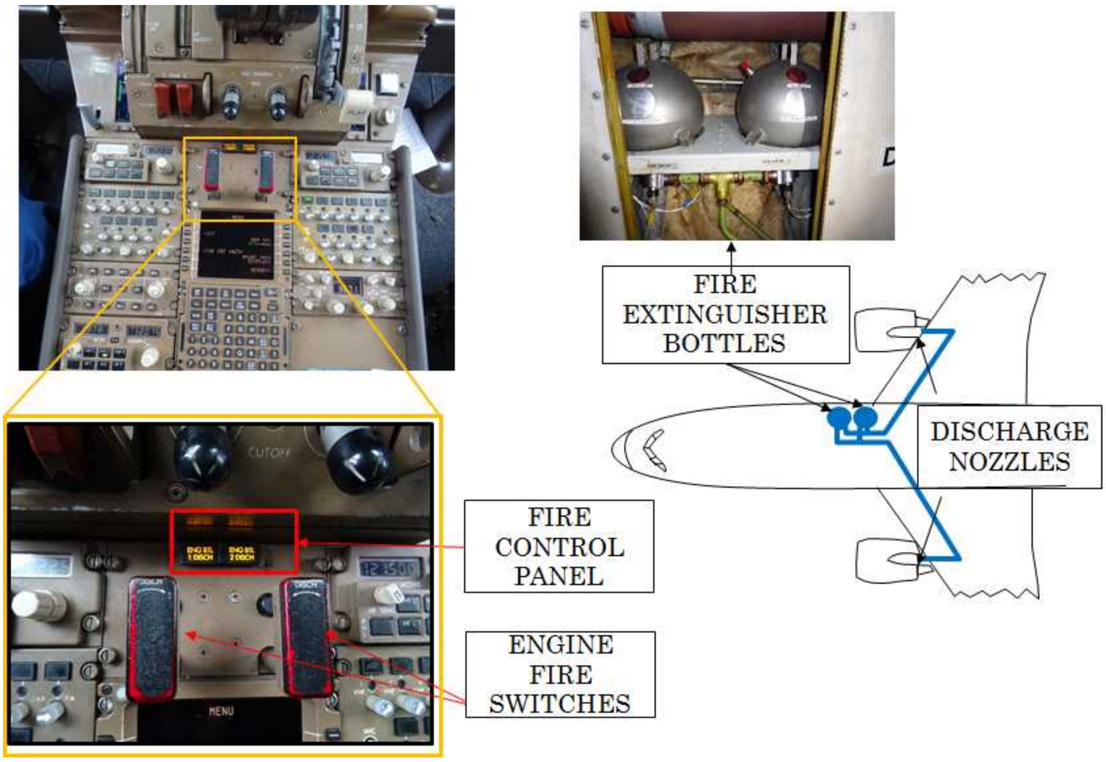


Photo 9. Fire Extinguishing System of B777 Engine

3. ANALYSIS

3.1 Qualification of Personnel

Both the PIC and the FO held valid airman competence certificates and valid aviation medical certificates.

3.2 Aircraft Airworthiness Certificate

The Aircraft had a valid airworthiness certificate and had been maintained and inspected as prescribed.

3.3 Relations to the Meteorological Conditions

As described in 2.7, when this accident occurred (at around 12:38), wind blew at about 20 kt from the almost right abeam Runway 34R. Because the fire and smoke accompanying the fire breakout from the No.1 engine was blown by this beam wind to the lee side which was the left side of the Aircraft, it is probable that the fire did not cause that much effect on the Aircraft and the cabin. Furthermore, using the right side slide of the Aircraft which was at the up wind side for the emergency evacuation, it is probable that there were not much effects by the fire and smoke. However, regarding why the R5 slide at its deploying was slipped to under the Aircraft, it is somewhat likely that as described later in 3.7.5, the strong abeam wind from the right combined with the thrust still being produced by the #2 engine at the ground idle setting could have the effects.

3.4 Fracture of the 1st stage HPT Disk

3.4.1 Factor to initiate a step at U-shaped groove

As described in 2.14.1.1, at the teardown investigation of the engine, the 0.010 inches (0.25 mm) high step which was exceeding the allowable limit was confirmed in U-shaped groove at aft side of the 1st stage HPT disk of the engine. As described in 2.6.2.3, it was specified to confirm that U-shaped groove was machined to be within the manufacturing allowable limit as verifying based on the product inspection by the machine operator and the quality inspection by the inspector at the time of manufacturing a disk by the engine manufacturer after the manufacturing. As described in 2.6.2.3,because U-shaped groove is machined from the outer side and inner side of the groove in order to level a step which is created on seam from the both sides, a machine operator shall adjust the clearance and obtain the standard value to set the final machining position as inserting 0.010

inches thick shim stock into a clearance between a blade tip of the machining tool and the bottom of U-shaped groove. This value will be fed into the vertical milling machine by using a keyboard and processed automatically, but the final machining position in real is programmed to send the tip of the machining tool to the lower position by 0.010 inches (0.25 mm) which is corresponding to the thickness of the shim stock. According to the verification done by the engine manufacturer, recreating the processing in a final processing position as setting no space between the tip for a tool and the bottom of U-shaped groove without using the 0.010 inches thick shim stock, the bottom of U-shaped groove was cut far and resulted in being the 0.010 inches high step.

In addition, as described in 2.6.2.3, when repairing after the manufacturing of the disk, U-shaped groove was not machined.

Based on these, regarding the step (hereinafter referred to as "the step in U-shaped groove") of exceeding the allowable value in U-shaped groove at the aft side of the 1st stage HPT disk was occurred, it is somewhat likely that the shim stock was not used properly at the process of manufacturing the disk for the machine operator to input a reference value to a vertical automatic lathe as a final machining position, or it is somewhat likely that a miss-input was made at the time to input a reference value to a vertical milling machine. In order to adjust the clearance, the work is carried out using shim stock as checking the condition by sight and fingertip touches and even an experienced machine operator has to use the shim stock procedurally, otherwise because there is a possibility to mistakenly estimate a reference value or to input erroneously a reference value, it is necessary for the engine manufacturer to revise the inspection methods and machining method of U-shaped groove from the view to prevent an occurrence of human errors.

3.4.2 Causes to initiate Cracks

As described in 2.14.1.1, at the engine teardown investigation, the step of exceeding allowable limit in U-shaped groove at the aft side of the 1st stage HPT disk was confirmed and investigating in detail around the step, cracks were revealed along the step in U-shaped groove near the parts of the disk fracture. Furthermore, as described in 2.6.2.3, because the repetitive stress is acting on the outer peripheral portion of the disk per a flight, therefore, if step and likes could be there, stress could be concentrated. Based on these, it is probable that the cracks were generated from these parts as repetitive stress acting on the step of exceeding the allowable limit in U-shaped groove at the aft side of the 1st stage HPT disk per a flight.

3.4.3 Causes to fracture

As described in 2.6.2.2, it is probable that the crack generated in U-shaped groove was propagating by the action of repetitive stress per a flight. As described in 2.6.2.7 and 2.6.2.8, the Company executed the FPI on the 1st stage HPT disk when disassembling the HPT module, but the crack was not found. As described in 2.14.1.1, as the result of analyzing the fractured surface, it is somewhat likely that the cracks in U-shaped groove of the 1st stage HPT disk may exist prior to the last inspection conducted at the engine repair shop on November 12, 2014. Based on these, it is probable that because the cracks were not be discovered at FPI conducted the previous inspection and due to the flight following the inspection, the cracks were propagating more to be fractured.

3.4.4 Causes to fail to find a step in U-shaped grooves

As described in 3.4.1, the step of exceeding the allowable limit for U-shaped groove at the aft side of the 1st stage HPT disk was occurred when the engine manufacturer was manufacturing the disk. However, as described in 2.6.2.4, it is highly probable that the step was not discovered at the product inspection which was done by the machine operator to confirm the HPT disk to be within a manufacturing standard value, and the quality inspection which done by the inspector to confirm the conformity to the design standard, and was shipped out.

As described in 2.14.1.1, 0.010 inches (0.25 mm) deep step was confirmed along the whole periphery of U-shaped groove of the aft side of the 1st stage HPT groove at the overhaul shop of the Company. It was somewhat likely that this confirmed step could be detected by naked eyes, because the confirmed step was five times of 0.002 inches (0.05 mm) which was the allowable value for the machined step at the time of manufacturing. As described in 2.6.2.3, it is highly probable that the machine operator and the inspector were conducting the tests following the test method specified in the work instruction and the manufacturing drawing like a visual observation, a palpation, and measurement by the measuring instrument, CMM (Coordinate Measuring machine) and others, depending on the parts to be inspected. However, the allowable value which determines a result of inspection is specified in the manufacturing drawing, but the parts of U-shaped groove is not specified as the critical location to be inspected like blades mounting slots and grooves spline machined for hub and shaft, therefore, 0.002 inches (0.05 mm) was applied for the allowable value for the whole of the 1st stage HPT disk as a standard value.

Furthermore, regarding the parts specified as the critical points to be inspected, notes regarding the detailed inspection and entries of the measurements were required for the work instruction, but for the other parts, only the results of inspection were recorded in the work instruction. Based on these, it is somewhat likely that the machine operator and the inspector did not pay sufficient attentions to U-shaped groove which is not specified as the critical inspection location and have failed to detect a step. As described in 2.14.1.3, according to the investigation results of the engine manufacturer after the accident, the other same type engine did not have the step exceeding the allowable limits. It is probable that because the engine manufacturer did not estimate a high potential to have a malfunction occurred at U-shaped groove, it was not specified as critical inspection parts. On the other hand, because the HPT disk is the part to receive repetitive stress, repeatedly, if there are slight scratches or step of exceeding manufacturing allowable limit, these could be a point to initiate the stress concentration or fatigue crack due to notch effect. It is necessary for the engine manufacturer to call attentions of machine operators and inspectors as a critical inspection location at the inspection process regarding the parts where step like the one in U-shaped groove could be caused by manufacturing.

3.4.5 Causes to fail to discover cracks propagating from U-shaped grooves

As described in 3.4.3, it is somewhat likely that the cracks propagated from the step of exceeding the allowable limit of U-shaped groove was existing prior to the delivery to the engine repair shop of the Company on November 12, 2014, however, the latest FPI described in ⑧ of 2.6.2.7 did not reveal the propagated cracks.Furthermore, as described in 2.6.2.8 and 2.6.2.9, it could not be confirmed that there was a fact that could be a cause of this accident from the inspection system, inspection records, and others at the repair shop of the Company.

As described in 2.6.2.8, according to the Operator and the Inspector in charge of applying the FPI on the 1st stage HPT disk of the engine, the inspection was conducted as following the work procedure instructed by the engine manufacturer. First, after visually assessing the whole, then start to inspect the front side of disk as the locations of being highly importance. In addition, the Inspector and the Operator have never seen the crack at the U-shaped groove. As described in 2.14.1.3, according to the investigation results by the engine manufacturer, there was no preceding case U-shaped groove step of exceeding the allowable limit and this one was the first case. Based on these, regarding the reason that the cracks propagating from U-shaped groove could not be discovered, as described in 3.4.4, there was no case that the area of U-shaped groove had error till now, furthermore, because U-shaped groove is not point to be inspected with attention according to the inspection manual specified by the engine manufacturer, the Inspector and the Operator inspected with special emphasis on the critical inspection parts like mounting slots for turbine blades, on the other hand, it is somewhat likely that the cracks in U-shaped groove was failed to be detected. In addition, as shown in Photo 3 of 2.14.1.1, it is possible that the fact attributed because cracks was existing along the machining trace in U-shaped groove as dotting, it was difficult to find.

3.5 Damage of the No.1 Engine

3.5.1 Damage of the HPT Case

When watching the damaged condition of the No.1 engine, as described in Attachment 3 (2) to (4), there were no large scale damage on the No.1 engine inlet, fan blades, LPC and HPC, and traces of foreign matters were not confirmed. Furthermore, as described in Attachment 3 (6), the HPT case wall between 5:30 and 7 o'clock was bent radially outward and twisted which was approximately 36 cm (approximately 14 inches) long and approximately 11.4 cm (4.5 inches) wide along the periphery. In addition, the 1st stage HPT blades were fractured across the airfoil adjacent to the root platform and there were sectors of the 1st and 2nd stage HPT stator vanes at the bottom of the engine that were missing. After the accident, as described in 2.10, at the runway and the grassland in vicinity from the point of approximately 680 m from the inside of the runway threshold as the starting point to the north side of approximately 570 m, stator vanes including the metallic debris shown in Attachment 3 were found, as described in Attachment 3 (6) ⑥ and 2.14.1.1, according to the teardown investigation of the No.1 engine, metallic debris was a part of the fractured the 1st stage HPT disk rim and the fractured parts of the 1st stage HPT disk and the fractured face of the recovered rim were matched. Based on these, it is highly probable that the damaged parts of the HPT case of the No.1 engine was caused by the penetration due to centrifugal force the fractured rim part which were fractured and ejected out of the 1st stage HPT disk to almost 8 o'clock direction through the HPT case. At that time, it is highly probable that the 1st stage HPT blades and the 2nd stage HPT stator vanes were fractured and ejected due to centrifugal force through the opening of the HPT case to outside.

3.5.2 Damage to Fuel Oil Heat Exchanger

Regarding why the Fuel Oil Heat Exchanger had cracks generated, as described in Attachment 3 (10), but there were no damage impacted from outside, and as described in Attachment 3 (5), the inner diffuser case had cracks and missing pieces and as described in Attachment 3 (8), the tail cone mounting bolts were missing.

Therefore it is probable that those cracks were developed, when the 1st stage HPT disk rim had been fractured and released, and struck into the turbine case, a strong shock force was generated. In addition, it is also probable that engine run down loads, which were generated when the engine No.1 stopped suddenly following the disk rupture, was the contributing factor.

3.5.3 Damage to other parts

(1) Left-side Translating Cowl of the No.1 engine

As described in Attachment 3 (11), because missing pieces and burnt damage at the left side translating cowl of the No.1 Engine was confirmed and the 2nd stage HPT blades stuck in the inner wall of the dropped translating cowl, regarding the fracture of the left translating cowl, it is highly probable that as described in 3.5.1, it was generated that the 1st stage HPT disk rim parts was fractured and the fractured piece penetrated the HPT case to hit on the translating cowl.

(2) LPT and the Tail Cone

As described in Attachment 3 (7) and (8), it is somewhat likely that regarding why there were no apparent damage on LPT and tail cone, the fractured rim parts within the HPT, the HPT blades and others were ejected through the fractured opening to outside of the Aircraft.

(3) Outboard Flap

Regarding the cracks of the outboard flap, it is probable that the fragment flying due to the fracture occurred at the 1st stage HPT impacted on the flap and caused the cracks.

3.6 Engine Fire

3.6.1 Progress of the Fire Breakout from No.1 Engine

Regarding the progress of fire breakout from the No.1 engine, it is highly probable that as described in 3.5.1, the 1st stage HPT disk rim was fractured during the takeoff roll of the Aircraft and as described in 3.5.2, due to the impact forces and engine run down loads generated by the release of the fragment from the 1st stage

HPT disk through the engine case and the leaked fuel and engine oil through this cracks contacted the high temperature engine cases of the No.1 engine to be ignited.

3.6.2 Extinguishing Engine Fire

As described in 2.1.3, as confirming the fire breakout from the No.1 engine by the engine fire warning sound and warning message (hereinafter referred to as "the fire warning messages"), the PIC, following the procedure provided in FCOM of the Company described in 2.15.1.2, activated the first fire extinguisher bottle equipped to the Aircraft described in 2.16.1. Then the fire warning messages went out once, but five to ten seconds later, the fire warning messages reappeared. Therefore, attempting to extinguish the fire by using the second fire extinguisher bottle, the fire warning message went out again, and five to ten seconds later, again the fire warning message reappeared. Concerning these, as described in Attachment 3 (11) ③, it is probable that because an opening was created due to the breakage of the left translating cowl inner wall, the fire retardant agent were leaked from there and could not exhibit full effects of fire retardant.

3.7 Emergency Evacuation

3.7.1 Decision of the PIC

As described in 2.1.3 (1), it is highly probable that even though the attempts to extinguish the fire of the No.1 engine with uses of two fire extinguisher bottles were made, because the third fire warning message was displayed, the PIC decided to conduct the emergency evacuation. Furthermore, as described in 2.1.3 (6), at the same time as the message was disappeared by using the second fire extinguisher bottle, the first fire engine started to fight fire from aft of the Aircraft, but as described in 2.1.3 (1), when third fire warning message was displayed, since the PIC considered that there would take more time to commence the firefighting because he saw the fire engine of coming from the front, it is probable that he had decided that it is necessary for the emergency evacuation to be conducted in a hurry.

FOM(8.2.13) of the Company described in 2.15.1.3(2) contains descriptions like "the Pic should make a decision on the direction of exits depending on which engine has the fire, wind direction, attitude and position of the aircraft and the extent of aircraft damage" and "if an emergency fire or other conditions make certain exits unusable, state the direction of egress, and evacuate on the runway, if possible".

It is probable that the PIC decided to evacuate to the right side because the strong wind was blowing from the right abeam because of the No.1 engine fire.

3.7.2 Actions Taken by Flight Crew

(1) Instruction of Emergency Evacuation

As described in 2.1.3 (1), the PIC called for the emergency evacuation checklist in QRH to the FO to hurry to perform, but because the QRH was not at the specified position, the FO could not perform the checklist right away. While the FO was looking for QRH, it is highly probable that the PIC who thought that the emergency evacuation should be done in a hurry, implemented the procedure to stop the engine based on his memory. According to the FCOM (Emergency Evacuation Checklist) (B777QRH) of the Company described in 2.15.1.3 (1), after the both of fuel control switches were cut off and the engine was stopped, an announcement of emergency evacuation to the cabin should be made. As described in 2.1.3 (1), after cutting off the engine, the PIC stated to announce the emergency evacuation via PA.

However, according to the analysis of FDR, CVR, QAR records and Video, the time for the PIC to activate the emergency evacuation signal was at 12:42:51, the time to announce to conduct emergency evacuation from the right side emergency doors was 12:43:03, and the time for the fuel control switch of the No.2 engine to be cut off was 12:43:45. And the first door being opened was L1 door and the time was 12:43:17. Based on these, instruction of emergency evacuation prior to halting of the No.2 engine positioned in the evacuating direction was given, it is highly probable that the No.2 engine was stopped about 28 seconds later after the first door was opened. As described in 2.14.2.4, the wind velocity of the engine wake air flow is 55 km/h even at the time of idle thrust and when conducting the emergency evacuation prior to the engine stopped, there are potential threat that the passengers could be blown away by the engine wake air flow and others. It is necessary for the Company to revise the education and training in order to enforce the thorough compliance to emergency evacuation procedure.

(2) Regarding the misplacement of QRH

As described in 2.15.1.1, the Company provides manual (B777POM OPERSTIONSL POLICY) regarding the responsibilities of pre-flight check, the section in charge of boarding, the specified placement and the document to be on board.According to the manual, regarding QRH checklist in paper to be used at the time of emergency evacuation, the specified location is at the right of the FO and the left of the PIC, the Flight Technical Support section of the Company should put there and the PIC and the FO shall perform the checks on the loaded status respectively, prior to the departure.

As described in 2.1.3 (2), this QRH was the one that the FO took time to find because when the PIC called for this checklist of the FO, it was not at the specified location, as the result, the FO used the checklist in tablet. The QRH was found in a rack at rear of the FO seat, later date, as described in 2.15.1.1. Based on these, it is somewhat likely that the QRH was not placed at the specified location and the PIC and the FO did not check sufficiently or did not check the documents that should be loaded on an aircraft for sure prior to the departure. At the time of an emergency situation to compete for a moment, if the checklist could not be found, because there is possibilities that the action could be delayed and a recovery could not obtained, the Company should promote thorough inspection of the documents to be carried on an aircraft prior to a departure and it is necessary to publicize again the use of QRH on an emergency situation for sure.

3.7.3 Actions Taken by CAs

Chief Purser opened the L1 door and deployed the slide at the emergency evacuation, however, as described in 2.1.3 (3), because the Chief Purser was confident to conduct an emergency evacuation due to the prior notice given by the cabin attendant in charge of L3 door and decided by checking outside through L1 door in early stage to confirm that there were no obstacles to escape, it is somewhat likely that when receiving the emergency evacuation signal from the PIC, she opened the door in a flex. And instantly the Chief Purser was realizing that L1 slide could not be used and guided passengers to other doors. As described in 2.15.1.3 (5), 4.6.6 EVACUATION INSTRUCT in COM of the Company specifies to instruct “Get out! Leave everything” and as described in 2.1.3 (3), the chief Purser was making announcement to evacuate from the right side without baggage and cabin attendants shout at passengers not to take baggage and take heeled shoes off, but as described in 2.1.3 (6), many of passengers took the baggage and like to evacuate.

3.7.4 Publicification of Emergency Evacuation to Passengers

The Company is promoting the attention to how to cope with an emergency situation by demonstration video or an explanation by cabin attendants prior to a departure. However, when evacuating for a real emergency, as considering the case that passengers could be agitated and might not follow the instruction given by cabin attendants, it is desirable that air carriers and Civil Aviation Bureau should plan to promote the wide general public including passengers to have full knowledge regarding the safety information at emergency evacuation with the backup reasons like possible threat of heeled shoes and baggage to damage a slide to be unusable and others, and study how to promote more solid understanding and recognition.

Furthermore, in order to make prompt and safe emergency evacuation, remarks or safety information like leaving baggage as air carriers publicizing, how to use evacuation slide properly and leaving an aircraft side as soon as possible after the evacuation, should be checked in full and it is desirable even for passengers to act as understanding the criticality to follow instruction given by flight crew and cabin attendants when conducting and emergency evacuation in order to safe life of oneself and others.

3.7.5 Deployment of Slides

As described in 2.14.2.2, according to the video recording, the slides R3, R4 and R5 were blown toward the rear of the Aircraft right after the deployment, but it is probable that R3 slide fully deployed in about 6 seconds on the runway and R4 slide fully deployed in about 38 seconds on the runway. As described in 2.14.2.4, it is probable that the R5 slide was properly maintained and the gas filling status for deploying the slide was normal. Furthermore, it is probable that the tear at the top right corner of the ground end was caused because of the friction with the runway surface when it was fanned by the cross wind and the thrust from the #2 engine at its ground idle setting.

As described in 3.7.2, when deploying R5 slide, the No.2 engine was at idle thrust. As described in 2.14.2.4, according to the materials (Figure 7 Predicted Jet Engine Exhaust Velocity Contours – idle thrust) of the manufacturer of the Aircraft, the predicted jet engine exhaust velocity contours at idle thrust is 7 m wide at the rear end of the Aircraft, extends to the approximately 40 m ahead while being tapered at the level of approximate 6 m high and the wind velocity is about 30 kt. Calculating the resultant wind from the wind of the jet engine exhaust blow at setting of the heading at 335° as described in 2.10 with the wind direction 060°and velocity about 20 kt at the time of the accident described in 2.7, was resulting in the wind direction 007°and the velocity about 37.5 kt. The velocity is 1.5 times of the allowable limit which is 25 kt for the velocity to make a slide have normal deployment as described in 2.14.2.1. Because of this resultant wind's effect, it is somewhat likely that R5 slide which is at most rear end and the spacing to the ground is the longest, slipped under the rear end of the Aircraft by folded, deployed with its top caught by the runway therefore could not return to a normal standing position spontaneously as the effect of wind gone.

4. CONCLUSIONS

4.1 Summary of Analysis

(1) The PIC and the FO held both valid airman competence certificates and valid aviation medical certificates. Besides, the Aircraft had valid airworthiness certificate and had been maintained and inspected as prescribed. (3.1, 3.2)[16]

(2) Cause to generate step in U-shaped groove

It is somewhat likely that the step of exceeding allowable limit at the aft side of the 1st stage HPT disk could be generated due to the incorrect use of shim stock by the machine operator at the process to input the a reference value for final machining position to vertical automatic lathe when machining the disk or because errors could be input when inputting the a reference value into the vertical automatic lathe. For the engine manufacturer, from the views of preventing the human error, it is necessary to study the revision of the inspection method and the machining method of the U-shaped grove. (3.4.1)

(3) Cause of the crack generation

It is probable that a mis-match exceeding the allowable limit in the U-shaped groove at the aft side of the 1st stage HPT disk had received repetitive stresses at every cycle and the crack was generated originating from the step. (3.4.2)

(4) Cause of the 1st stage HPT disk fracture

It is probable that because the generation of cracks as originating from the step of exceeding the allowable limit in U-shaped grooves at the aft side of the 1st stage HPT disk were propagated by the repetitive force per a cycle, however, the FPI conducted during the process could not reveal the cracks and the cracks were propagated furthermore to be resulted in the fracture. (3.4.3)

(5) Cause to miss the step in U-shaped groove

It is somewhat likely that the machine operator and inspector did not pay full attention to U-shaped groove part which was not specified as a critical inspection point and had failed to detect the step. Since the heavy stress could repeatedly act on the HPT disk, slight scar or step of exceeding the allowable limit could be originating point of fatigue crack and stress concentrating point due to the notch effects. Therefore, it is necessary for the engine manufacturer to call the attentions

[16] The number listed in each sentence end of this clause, indicates a main clause number of "#3, Analysis" concerning the description of the each sentence.

of the machine operator or inspector to the parts where a step could be generated like U-shaped groove when machining, by specifying the parts as a critical inspection location. (3.4.4)

(6) Cause to miss the crack propagating from U-shaped groove

It is somewhat likely that the crack propagating from U-shaped groove could be existing prior to the delivery to the engine factory of the Company, but the crack could not be discovered at the latest FPI. Regarding this, an operator and an inspector inspected with an emphasis on the critical points like turbine blade mounting parts, on other hand, it is somewhat likely that the crack for U-shaped groove failed to be detected. Adding more, it is somewhat likely that the cracks which were dotted along the machining trace in U-shaped groove was difficult to find because of assimilating into the machining trace. (3.4.5)

(7) Damage of the HPT case

It is highly probable that the damage of HPT case at the No.1 engine was due to penetrating of the rim debris of the 1st stage HPT disk to the 8 o'clock direction through the HPT case because of a centrifugal force. (3.5.1)

(8) Damage of Fuel Oil Heat Exchanger

Regarding why the Fuel Oil Heat Exchanger got cracked, it is probable that when the fractured rim of the 1st stage HPT disk had been fractured and released, and struck into the turbine case, a strong shock force was generated, in addition, engine run down loads were generated when the No.1 engine stopped suddenly following the disk rupture. (3.5.2)

(9) Damage and others on other parts

Regarding the breakage of the left translating cowl, it is somewhat likely that it was created by the hitting of fractured rim debris of the 1st stage HPT disk.

Regarding why LPT and the tail cone did not have almost no damage, the fractured piece of the rim of the HPT was ejected through the opening caused by this ejection.

Regarding the cracks at the outboard flap, it is probable that it was caused by the hit by the ejected debris due to the fracture of the 1st stage HPT disk rim. (3.5.3)

(10) Process of the fire breakout from the engine

Regarding the progress of fire breakout from the No.1 engine, it is highly probable that due to the impact forces generated by the release of the fragment from the ruptured rim part of the 1st stage HPT disk through the engine case and the engine rundown loads generated when the engine stopped suddenly, the cracks were developed in the Fuel Oil Heat Exchanger and the fuel and engine oil leaking through these cracks contacted the hot area of engine cases of the No.1 engine to be ignited.(3.6.1)

(11) Extinguishing the engine fire

Regarding that the PIC attempted to extinguish the fire using two fire extinguisher bottles equipped on the Aircraft and once the fire warning message was gone, but it reappeared, again, it is probable that because the opening was created due to the damage to the inner wall of the left translating cowl, the fire extinguisher could not fully be effective. (3.6.2)

(12) Decision taken by the PIC

Even the PIC attempted to extinguish the fire using two fire extinguisher bottles equipped on the Aircraft, because the third fire warning message reappeared, it is highly probable that the PIC decided to conduct emergency evacuation and it is probable that because of the fire at the No.1 engine and strong abeam wind from the right, he decided to evacuate to the right side. (3.7.1)

(13) Response (action) taken by the flight crews PIC's

It is highly probable that the emergency evacuation was instructed prior to the No.2 engine stop in the direction of evacuation and it took about 28 seconds from the first door open and the No.2 engine stop. Regarding the instruction of emergency evacuation was given before the No.2 engine stop, it is somewhat likely that the PIC decided the emergency evacuation and then called for the emergency evacuation checklist of the FO and turned the emergency evacuation switch on at the same time, however, the FO could not find out the emergency evacuation checklist of QRH (paper), and he took some time to read out the emergency evacuation checklist in a tablet.

Regarding the reason that the FO could not find QRH, it is somewhat likely that the QRH was not placed at the specified location and the PIC and the FO checked insufficiently or did not check the documents that should be loaded on the aircraft for sure prior to the departure. The Company promotes thorough inspection of the documents to be carried on an aircraft prior to a departure and it is necessary to publicize again the use of QRH on an emergency evacuation. (3.7.2)

(14) Response (action) taken by cabin attendants

Regarding the fact that the chief purser opened the L1 door and let the slide deploy, as she judged there would be no problem to evacuate by looking outside through a window of L1 door in advance, it is somewhat likely that when she received the signal of emergency evacuation from the PIC, automatically she opened the L1 door. Instantly, as the chief purser recognized that it is not possible to evacuate through L1 door, she guided passengers to other door. The chief purser and cabin attendants announced that do not carry baggage to evacuate, but many of passengers had carried their baggage to evacuate. (3.7.3)

(15) Disseminating the knowledge regarding the emergency evacuation to the passenger;

Cabin attendants had instructed passengers to evacuate without baggage through the right side slide, but it is probable that many of passengers did not follow the instruction not to carry the baggage. It is desirable that air carriers and Civil Aviation Bureau should plan to promote the wide general public including passengers to have full knowledge regarding the safety information at an emergency evacuation with backup reasons like possible threat for heeled shoe and baggage to damage slide and cause the slide unusable and others, and study how to promote more solid understanding and recognition.(3.7.4)

(16) Deploying Slide

R5 slide slipped, bent in the rear under the fuselage and fully deployed with the tip caught on the runway due to the effect of the resultant wind in wind direction 007°and 37.5 kt of wind velocity and 20 kt of engine exhaust flow, it is somewhat likely that even after the engine exhaust flow of the No.2 engine were stopped, it was unable to return to a normal standing position.(3.7.5)

4.2 Probable Causes

It is highly probable that the causes of this accident were the fracture of the high pressure turbine (HPT) disk of the No.1 (left-side) engine during the takeoff ground roll, the penetration of the fragment through the engine case and the occurrence of subsequent fires.

Regarding the cause for the 1st stage HPT disk to be fractured, it is probable that a step was machined exceeding the allowable limit when machining U-shaped groove on the aft side of the 1st stage HPT disk to manufacture the engine and from this step the low-cycle fatigue crack was initiated and propagated during running of engine.

Regarding why the step could not be found, it is somewhat likely that defects failed to be detected at the time of the inspection by the manufacturer during the production process. And as for the cracks that were not found, it is somewhat likely that those cracks failed to be detected at non-destructive inspection on the disk by the Company at the time of maintenance of the engine in use.

Regarding the fire breakout from the No.1 engine, it is probable that due to the impact forces generated by the release of the fragment from the ruptured rim part of the 1st stage HPT disk through the engine case and the engine rundown loads generated when the engine stopped suddenly, the cracks were developed in the outer case of the Fuel Oil Heat Exchanger and the fuel and engine oil leaking through these cracks contacted the hot area of engine cases of the No.1 engine to be ignited.

5. SAFETY ACTIONS

5.1 Actions Taken by FAA

On March 9, 2017, FAA (Federal Aviation Administration of the United States of America) issued Airworthiness Directive (AD) concerning a turbofan engine manufactured by Pratt & Whitney. The contents, based on this accident, concerning PW4074, PW4074D, PW4077, PW4077D, PW4084D, PW4090 and PW4090-3 turbofan engine manufactured by Pratt & Whitney, requested an implementation of an inspection to evaluate the condition of an U-shaped grooves (web, rim, fillet) at back of the 1st stage HPT hub and not using the hub where defects were found at the inspection. The Airworthiness Directive means to improve the unsafe condition of these products and was effective on April 13, 2017.

5.2 Actions Taken by Engine Manufacturer

(1) Provisions of information and issuances of technical information for the engine users;

① On June 17, 2016, the engine manufacturer issued All Operator Wire Net Case 5 No.CAS-30064-Q7K9L2 to instruct users of the PW4000 series engines to apply FPI on all of the 1st stage HPT disk had been removed from the HPT module.

② On June 24, 2016, the engine manufacturer had issued PW4000-112A11 Operator Communication to instruct that all of the 1st stage HPT disk and the 1st stage rotor assemblies currently removed from HPT module of PW4000-112 engine to be disassembled and to inspect the aft web area for any indication to be a step at the area (web, rim and fillet) including U-shaped groove, sufficiently at the moment.

③ On September 23, 2016, the manufacturer issued P&W SB PW4G-112-72-342 (category 5 and 6) to instruct to apply the surface inspection and measure by creating replicas of the area including U-shaped groove at the aft side of the 1st HPT disk.

(2) Change of the 1st stage HPT disk manufacturing process;

The engine manufacturer changed the final finishing process of U-shaped groove at the 1st stage HPT disk to have the process by a machine only by canceling the process to have manual operation by a machine operator, in order to have no processing error.

(3) Change of the product inspecting process

The engine manufacturer added the inspecting process to records step of U-shaped groove at the inspection of the 1st stage HPT after manufacturing and add U-shaped groove inspection (creating replica of step at U-shaped groove and confirmation based on the use of Shadowgraph Machine) at the outside of the aft side of the disk based on the Service Bulletin described in 2.14.1.2 to the inspection of U-shaped groove.

5.3 Actions Taken by the Company

(1) The Company is carrying out the inspection on the 1st stage HPT disk based on the Service Bulletin issued by the engine manufacturer shown in 5.2.(1), for the same type engines used by the Company.

(2) The Company noticed all flight crew regarding the pre-flight check to check the on-boarding condition of the documents which should be on board on March 17, 2017.

(3) The Company reflected the training procedure for flight crew to carry out evacuation after the engine stops.

(4) Prohibition for passengers to carry baggage at the time of emergency evacuation

The Company added the illustration to call attention not to carry the baggage at the time of emergency evacuation into the demonstration video for aviation safety to show at all aircraft belonging to the Company.

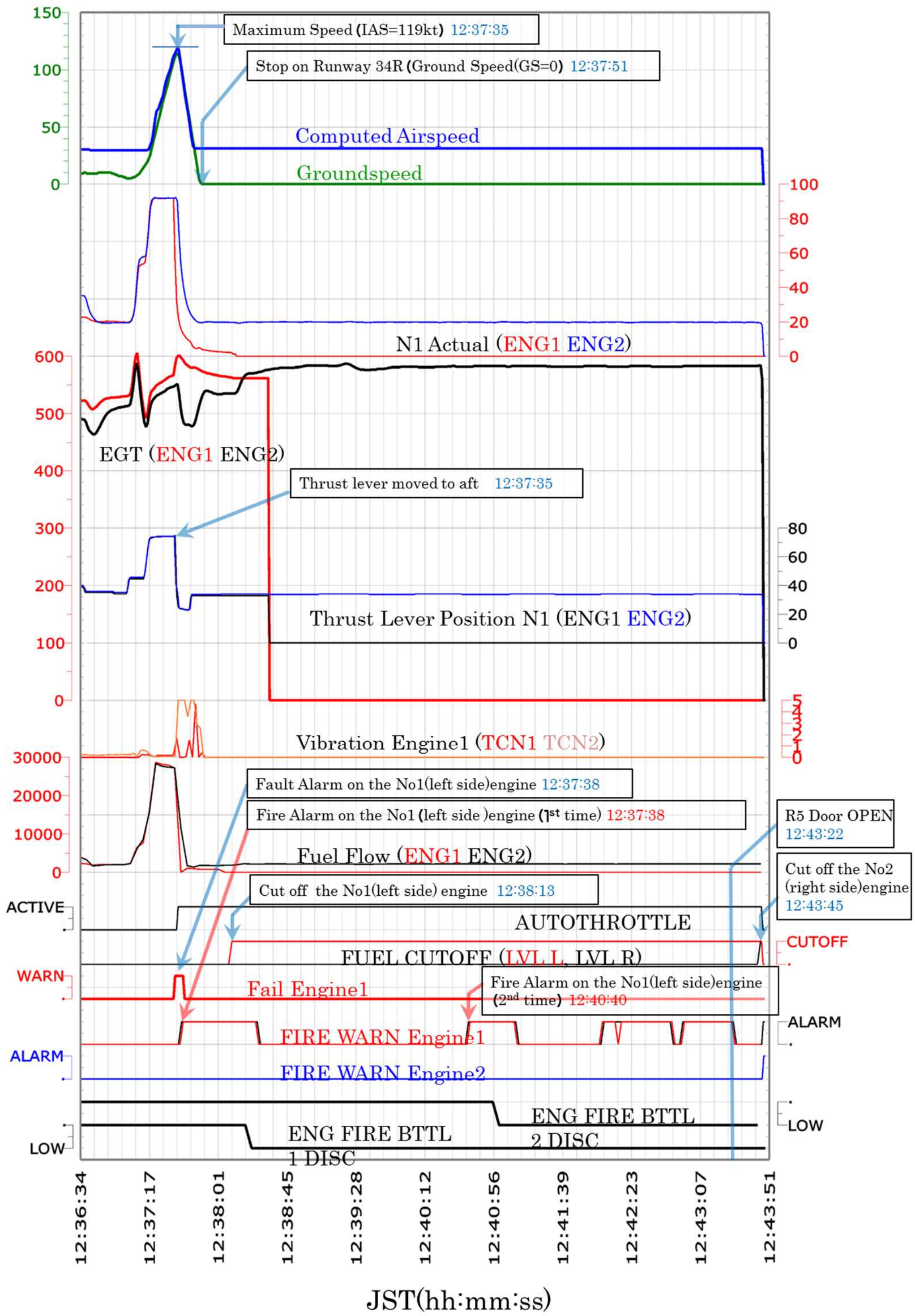
(5) The Company revised the Evacuation Part of the Cabin Operation Manual to add the item for the cabin attendants to have a control of passengers, which was applied since October 17, 2016. The main contents are as follows;

① Describe the instruction to leave the baggage to evacuate and the request to assist the following passenger to the passenger sitting at emergency seat, in Korean and English as before, in Japanese and Chinese to be added.

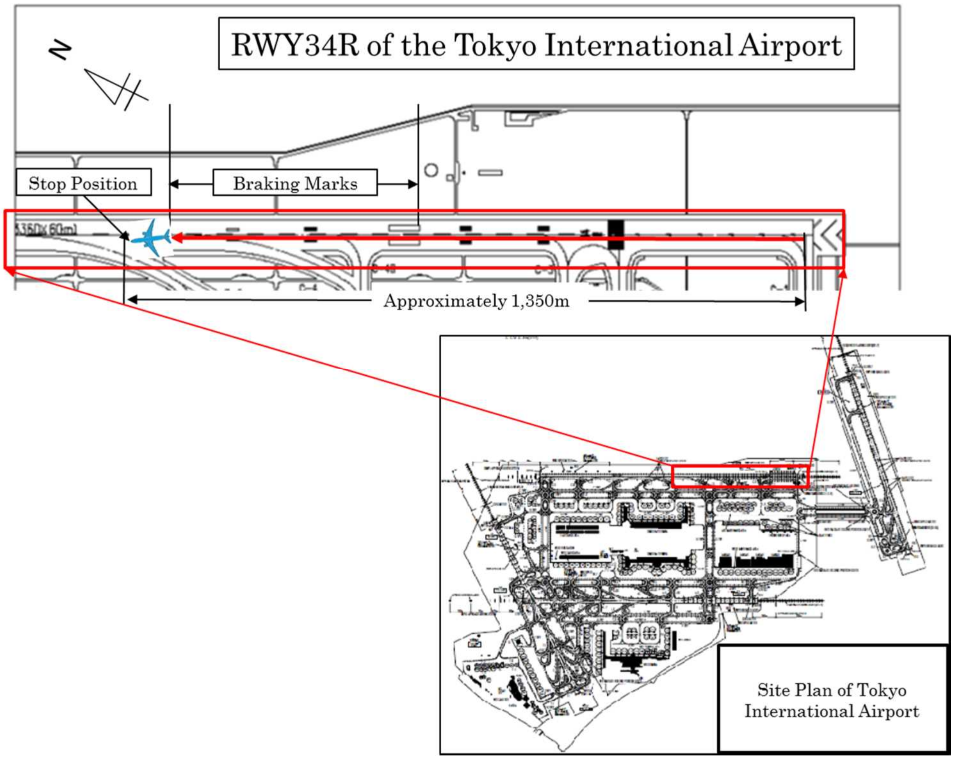
② At the time of unexpected emergency landing, it is critical to grasp the situation, therefore inform the information of the situation in Korean and English to passengers. Considering the nationalities of passengers, if possible, the cabin attendant could use other languages to instruct additional information.

③ When the flow of evacuation halts or the speed decreases, check the cabin for any passenger remained. When the assigned area is empty, the cabin crew can pre evacuation than some other passengers and control the passengers outside the aircraft.

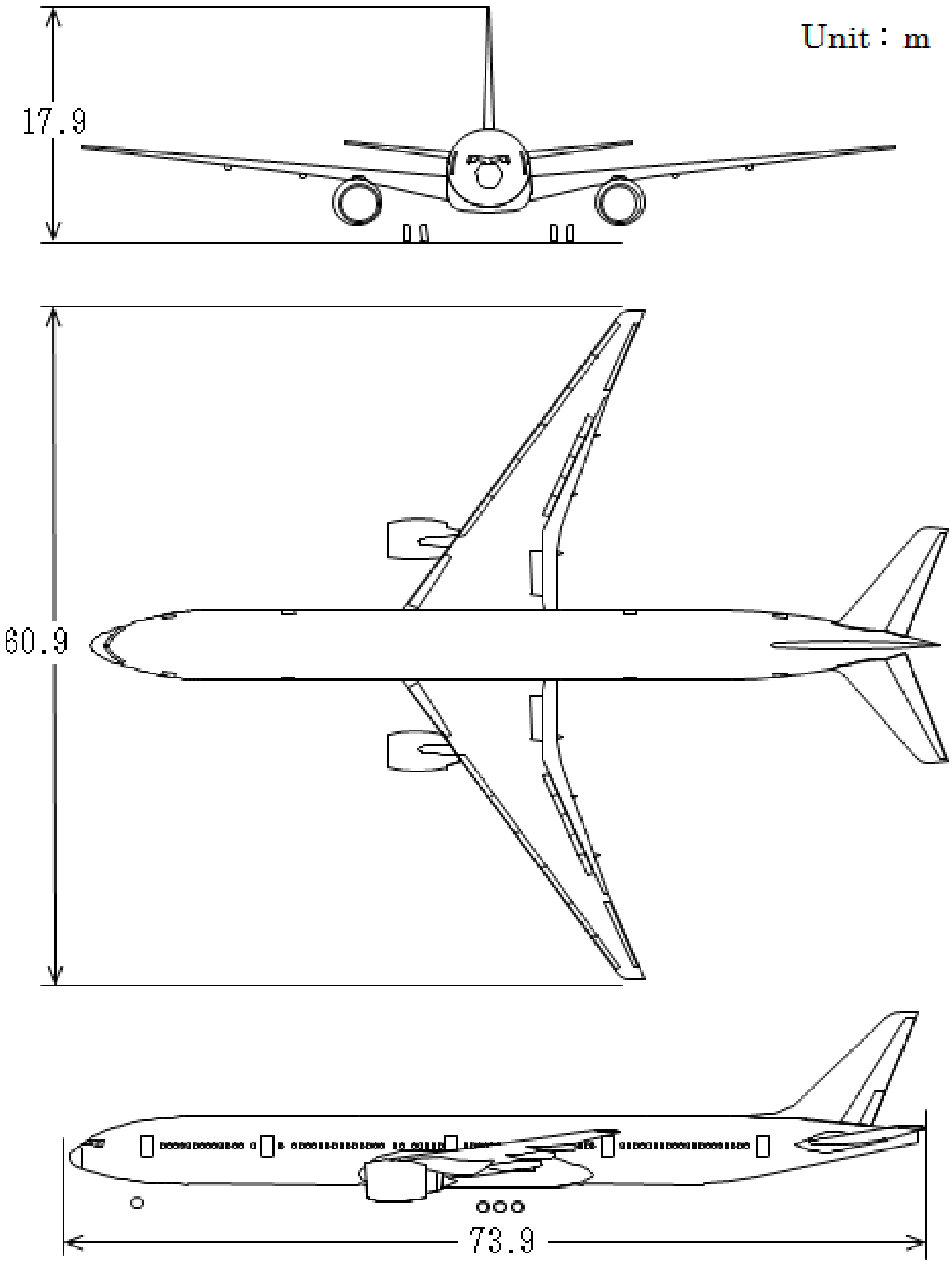
Appended Figure 1.: FDR Record



Appended Figure 2.: Estimated Route of Take-off Roll



Appended Figure 3.: Three-view drawing of Boeing 777-300



Attachment 1.: Records of CVR, FDR, and Video

JST	Voice	Content
		(omitted)
12:36:53	TWR	Korean Air 2708, wind 070 at 21, runway34R, cleared for take-off.
	F/O	Cleared for take-off runway34R, Korean Air 2708.
	CAPT	Cleared for take-off. You have control, I have ATC. Take-off time set.
37:17	F/O	TO/GA
37:18	CAPT	Thrust reference -take-off thrust set. I have thrust.
	F/O	You have thrust.
37:30	CAPT	80kt hold.
37:35		" Bang" (Engine Explosive Sound)
37:36		"ENG FAIL" (Voice Alert)
37:37	TWR	Korean Air 2708, your No1 engine fired. Stop immediately, Stop immediately.
37:38		1st Fire Bell Sound
37:39	F/O	Speed Brakes - UP, No.2 reverse
37:45	F/O	Korean Air 2708, reject take-off on runway34R.
	TWR	Understood. We saw fire from your No1 engine.
37:51	VIDEO/ FDR	GS=0
	CAPT	Engine fire.
	F/O	Fire engine left.
		Parking break - set
37:57	CAPT	Crew at the station, crew at the station.
38:00 ~38:08	CAPT	Fire engine left. Memory Items. (Order)
	CAPT (F/O)	Fire engine left. Memory Items. A/T ARM S/W L/H - off (Confirm L), L/H Thrust lever - idle (Confirm L), Fuel control S/W L/H - cut off (Confirm)
	CAPT	Cut off
38:10	FDR	FUEL CUT OFF, FF.VALVE CLOSE, N1=0, N2=0
38:11	CBN	Ladies and gentlemen, we are unable to take-off. Further

~38:54		information will be informed shortly. (in Korean, English) We are waiting for the take-off clearance. Please wait at your seat. (Japanese)
38:18	F/O	Engine fire switch - pull, still fire, rotate
38:20	FDR	ENGINE FIRE BOTTLE No.1 - OPEN
38:25 ~38:29	TWR	Korean Air 2708 fire trucks are going to you.
	F/O	I'm sorry. Say again.
	TWR	Fire vehicle going to around you.
	F/O	Thank you.
38:31	CAPT	Fire is gone.
	F/O	Yes, fire is out.
	CAPT	Fire is gone?
	F/O	Yes sir, fire is gone.
	CAPT	Contact again and inform them fire is gone.
38:51	F/O	Korean Air 2708, Fire is gone.
	L3 CA	IPN Call to CAPT
	TWR	Thank you, stand by, hold position.
	F/O	Holding present position, Korean Air 2708.
39:00	CAPT	Hello … Hello.
	L3 CA	CAPT. There is smoke from engine on L3 side.
	CAPT	Extinguished fire. Fire truck has just reached and in preparation. Please wait.
	L3 CA	Yes, sir.
39:12	CAPT	It seems fire is gone.
39:57	PURS	It seems fire was occurred at the back. Now, fire truck arrived and will extinguish fire.
	CAPT	Hello … Hello.
	PURS	Yes, captain.
	CAPT	We have left engine fire. We extinguished, and fire was gone. And fire truck arrived and extinguished fire. No evacuation needed. Please wait. If it possible, please inform them what I told you.
	PURS	Fire was extinguished, now?
	CAPT	Yes, fire has gone.

	PURS	If so, we will return to gate?
	CAPT	Yes.
	PURS	Yes, sir.
	CAPT	For now, situation what I said to you...
	PURS	Do I need to tell all?
	CAPT	Just… Ahh… Evacuation checklist
40:40	FDR	ENGINE FIRE ALARM (2nd time)
		2nd Fire Bell Sound
40:41	F/O	Fire engine comes again…
40:44	PURS	Do I need to tell technical problem?
	CAPT	Hold on please.
40:52	CAPT	Contact Tower again.
	F/O	Korean Air 2708, We got a Fire engine L/H message again.
	TWR	Roger.
	CAPT	Fire.
40:59	FDR	ENGINE FIRE BOTTLE No.2 - OPEN
41:01	TWR	Korean Air 2708, right now fire engine reaching your No.1 engine.
	F/O	Roger thank you, Korean Air 2708.
	F/O	Fire truck arrived.
41:11	CAPT	Bottle discharged again…
	F/O	Fire is gone again.
	CAPT	OK.
	CAPT	Left side ----
41:38	F/O	2 fire trucks are coming forward.
42:06	PA	Ladies and gentlemen,
42:07		3rd Fire Bell
42:08 ~42:38	CBN	We just rejected take-off for technical problem. Further information will be informed shortly. (in Korean, English and Japanese)
42:09	F/O	Fire engine left message.
	CAPT	Need to Evacuation
42:13	F/O	Tower Korean Air 2708, we got a fire engine L/H message again
	TWR	Roger.

42:22	CAPT	Tower Korean 2708, we still got the message. We need evacuation to the right hand side.
	TWR	Understand.
42:30	CAPT	Evacuation.
	F/O	Roger, Korean 2708.
42:37	CAPT	Evacuation Checklist. (Order)
42:51	CAPT	Evacuation signal sound
42:52	F/O	Evacuation Checklist. (reply)
43:03	CAPT	EVAC, EVAC, EVAC to the right hand side.
43:14	CAPT	Evacuation Checklist. (Order)
43:17	F/O	Stand by.
43:17	VIDEO	L1, R1 DOOR OPEN
43:22	VIDEO	R5 DOOR OPEN
43:22	CAPT	You can find in this…
43:26	F/O	Evacuation Checklist. (reply)
43:27	F/O	Parking Brake - set Outflow Valve S/Ws (both) - manual
43:27	VIDEO	R4 SLIDE deployment bounce to the fuselage
43:29	VIDEO	R2 DOOR OPEN
43:36	F/O	Outflow Valve Manual S/Ws (both) - hold and open position
43:41	CAPT	Fully open completed
43:43	F/O	Fuel Control S/Ws (both) - cut off
43:45	CAPT	Both Cut off
43:45	QAR	FUEL CUT OFF RH（5m35s from the LH engine cut off)
	F/O	Advise the CBN to evacuate
	F/O	Advise the Tower
43:48	FDR	FDR recording terminated. (03:43:52)
43:50	CAPT	TWR, Korean Air 2708, mayday, evacuate, evacuate on the 34R.
	TWR	Understood.
43:50	VIDEO	Passengers commence to evacuate via R3 door
44:04	VIDEO	R4 slide fully deployed.
44:06	VIDEO	Passengers commence to evacuate via R4 door

Time (JST) has been proved by a time signal recorded in ATC communication.

Legend; TWR　Tokyo　Tower　124.35 MHz

CPT; Cockpit　CPT; Captain

F/O; First Officer　PURS; Purser

CA; Cabin Attendant　CBN; Cabin

IPN; Intercom　PA; Passenger Address System

Time Correction for FDR, CVR and QAR were set by making the ATC communication recorded in CVR and VHF radio transmission signal recorded in QAR and FDR with a time signal recorded in ATC communication.

Attachment 2.: FPI (SPOP-84) PROCESSING of KAL

PRE-INSP → Check work order and part damage condition

PENETRANT APPLY → Dipping(4~49℃) PMC4354-2(Level4) (Ultra-high sensitivity) applied and check part condition with UV Light

DRAIN REST → Drain/Dwell (20~60min)

PRE-RINSE → Water Spray (40psi Max) (10~38℃)

EMULSIFIER APPLY → Dipping PS643(PMC4355) (concentration 20±3%)

FINAL RINSE → Water Spray (40psi Max) Rinse and check part condition with UV Light

DRY → Part Drying (71℃ Max) Take out part just after dry out water on part surface

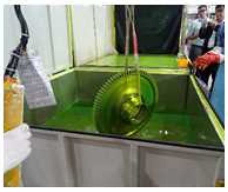
DEVELOPER APPLY → Dry Developer Spray PMC4356 Developing Time 10min

INSPECTION → UV Light Intensity (1,000㎼/㎠ at 15") Darkroom Luminous Intensity under 20 lux

RECORD & SYS INPUT → Work Order Complete (ERP Close)

CLNG & SHOP-OUT → Part Flow Next Process

①Penetrant Apply



Penetrant Tank

②Emulsifier Apply

Emulsifier Tank

③Remove the excess penetrant from the surface

④Developer Apply

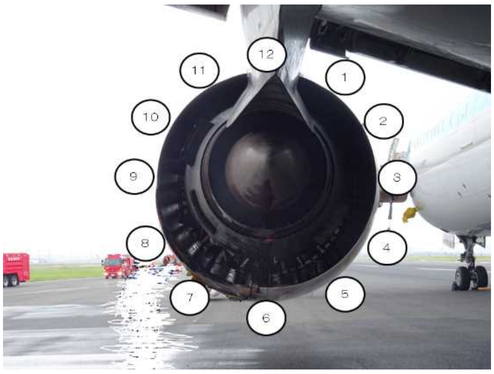
Dry Type Developer Apply

⑤Inspection

Black light inspection in the Dark Room

Attachment 3.: The No.1 Engine

The No.1 engine of the Aircraft was as follows. Furthermore, the following sentence uses the clockwise numbering shown on the periphery of the rotating axis of the engine as its center as looking from aft of the Aircraft to forward. The left and right of the engine are indicated as seeing from aft of the Aircraft to forward. (See Photo #1.)



(1) General

The left side of the No.1 engine and the external components were burnt and sooted. (See Photo #2. The left side of the No.1 engine.) The right side of the engine did not have any sooting or thermal damage. The insulation blanket over the fuel and hydraulic lines and the covering on the lines was undamaged. (See Photo #3. the right side of the No.1 engine.) The main gearbox deoiler vent tube was severed in line with the hole in the HPT case.

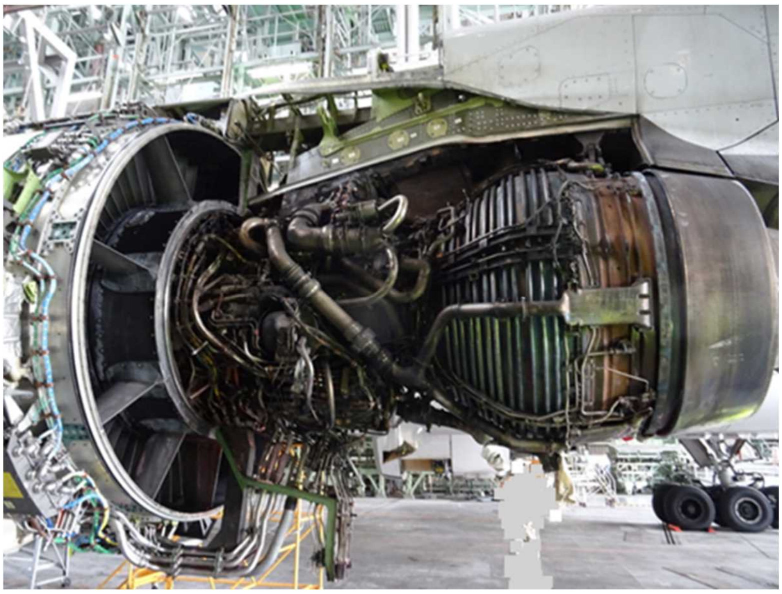
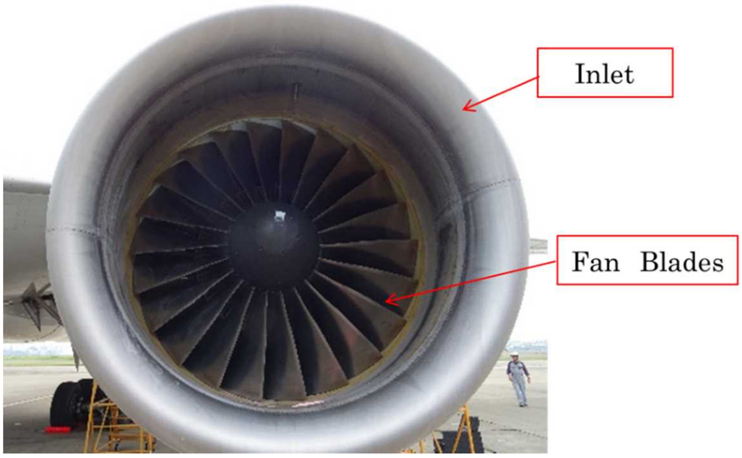


Photo #2. The left side of the No.1 engine

Photo #3. The right side of the No.1 engine

(2) Inlet and fan blade

The inlet and fan blade did not have any apparent damage. There were no trace of sucking objects like birds from outside. When the fan was rotated, the LPT rotated concurrently. (See Photo #4. Inlet and Fan Blade.)



Photo#4. Inlet and Fan Blades

(3) LPC

The LPC inlet did not have any apparent damage. The stator vane leading edges did not have any corresponding damage.

(4) HPC

The 15th stage compressor blades at the most rear HPC were all in place. The tip of the blades were bent slightly opposite the direction of rotation. The previous stage stator vane were all in place and had no damage.

(5) Diffuser Case

The outer diffuser case did not have any indications of a rupture or thermal distress. The diffuser case rear flange between about 5:30 and 6:30 was bent radially outward. The inner diffuser case had five cracks between the aft flange and the center part of the case that varied in length from 1.5 (3.81) to 10.5(26.67 cm) inches. At about 12 o'clock, there was an approximately 2 inch (5.08 cm) by 1 inch (2.54 cm) piece missing from the case. (See Photo #5 Inner Diffuser Case)

Photo #5. Inner diffuser case

(6) The HPT

① The HPT case wall between 5:30 and 7 o'clock was bent radially outward and twisted which was approximately 36 cm (approximately 14 in) long and approximately 11.4 cm (4.5 in) wide along the periphery. (See Photo #6-1. The damage of the HPT case and Photo #6-2. The damage of the HPT case.)

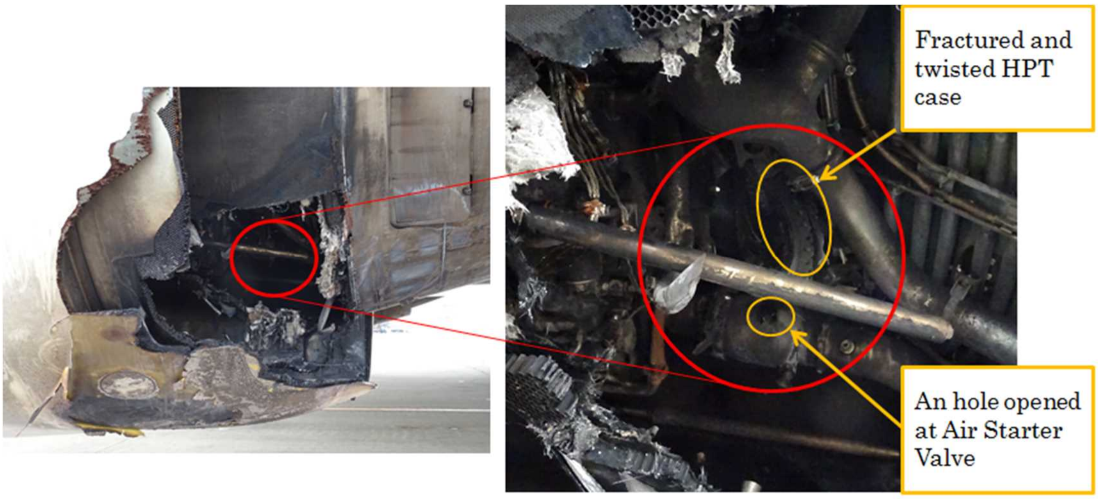


Photo #6-1. The damage1 of the HPT case

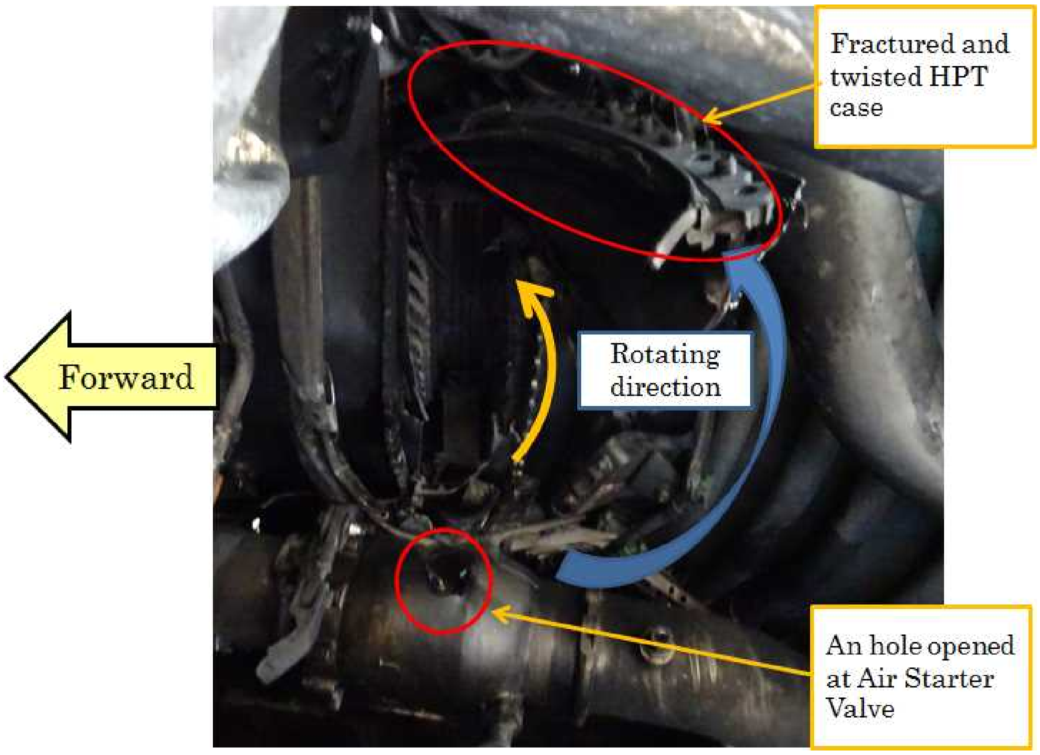


Photo #6-2. The damage2 of the HPT case

It was confirmed that the 1st stage HPT blades and the 2nd stage HPT stator vanes were missing from the roots. (See Photo #7. Fractured condition of the 1st stage HPT blades and the 2nd stage HPT stator vanes.)

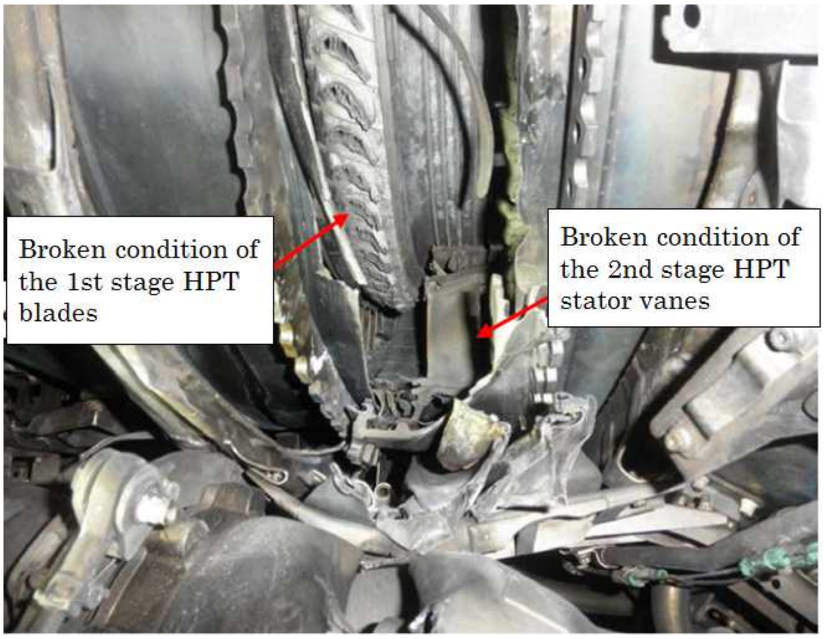


Photo #7. Fractured condition of the 1st stage HPT blades and the 2nd stage HPT stator vanes

② There was a raised edge on the edge of the tab that corresponded to a notch in the edge of the hole in the starter air duct valve. (See Photo #8. A Hole opened in Air Starter Valve.)

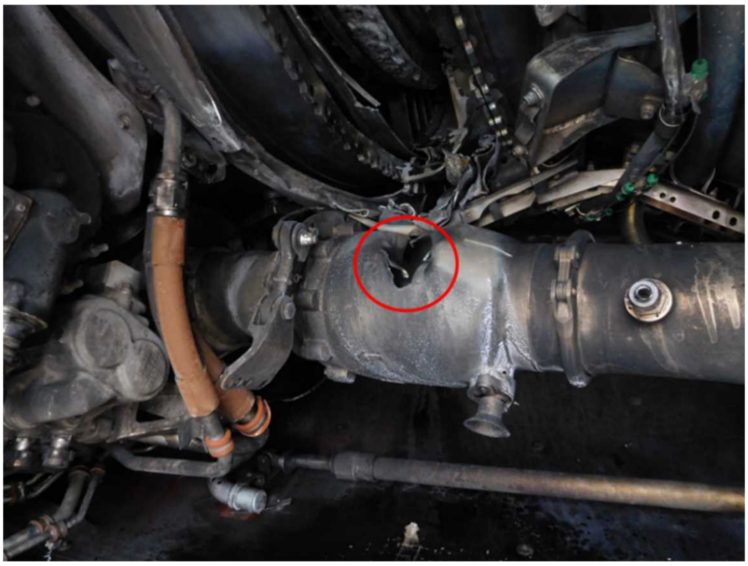


Photo #8. A Hole opened in Air Starter Valve

③ The HPT case's forward flange was missing bolts between 3:30 and 8:30 and the aft flange was missing bolts between 5:30 and 7:30.

④ Investigating the runway and an adjacent area after the accident, stator vanes and others of the 1st stage HPT and the 2nd stage HPT were recovered. (See Photo #9. Recovered Stator Vanes and others.)

Photo #9. Recovered Stator Vanes and others

⑤ A piece of the 1st stage turbine disk rim was recovered from amidst the debris that was recovered from Runway 34R. The piece was about 7.8 inches (20 cm) long and weighed 1.875 kg (4.134 lb) with seven blade slots. (See Photo #10. Piece of the 1st stage HPT disk rim.)

Photo #10. Piece of the 1st stage HPT disk rim

There was a ratchet mark[17] on the fracture surface at the 1st stage HPT disk rim. (See Photo #11. Ratchet Marks.)

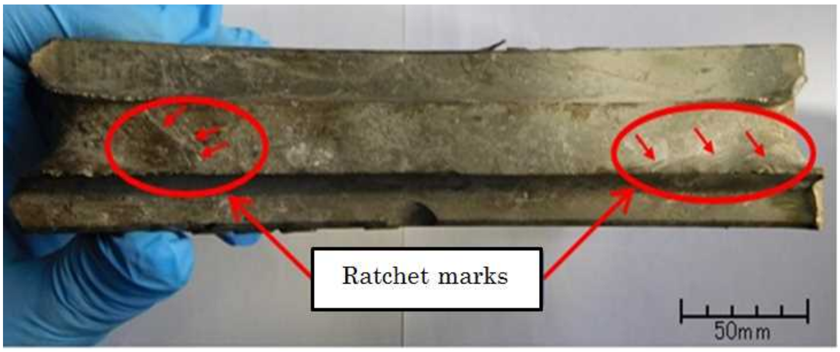


Photo #11. Ratchet Marks

⑥ As conducting a teardown inspection on the No.1 engine, approximately 20 cm (7 in) long piece from the rim of the 1st stage HPT disk was missing. The missing piece surface and the fractured face of the fragment of the rim part shown in Photo #7 were matched.

(7) LPT

The LPT blade of the last stage LPT (the ninth stage) were all in place and did not have any apparent impact damage. There were several ninth stage LPT blades that had spatter on.

(8) Tail Cone (Exhaust Pipe)

Tail cone was still attaching to an exhaust pipe case. Nine tail cone mounting bolts at the positions (the lower side) from 4:00 to 8:00 were missing. (See Photo #12 .Tail Cone)

[17] "Ratchet marks" are the step-like junctions between adjacent fatigue cracks that propagate and link up.


Photo #12. Tail Cone

(9) Lubricating Oil System

The lubricating oil was confirmed to be in the oil tank. The magnetic chip detectors (MCD) for the accessory gearbox were pulled for examination, but the MCDs did not have any debris or fuzz on the magnetic tips. The main oil filter and the oil had no debris nor an acid odor.

(10) Fuel Oil Heat Exchanger

The main body case of Fuel Oil Heat Exchanger located at 8 o'clock of the HPT case had cracks and soot by thermal damage, but there were no damage impacted from outside. Three cracks were confirmed at the rear of the main body, and the longest crack was approximately 34 cm (13.4 in) long. (See Photo #13-1 Fuel Oil Heat Exchanger and Photo #13-2 Cracks of Fuel Oil Heat Exchanger.)

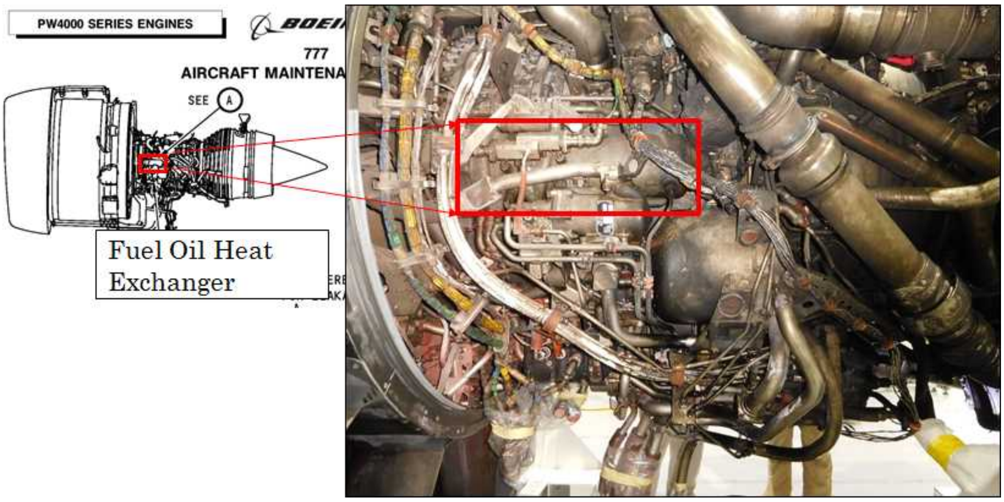


Photo #13-1. Fuel Oil Heat Exchanger

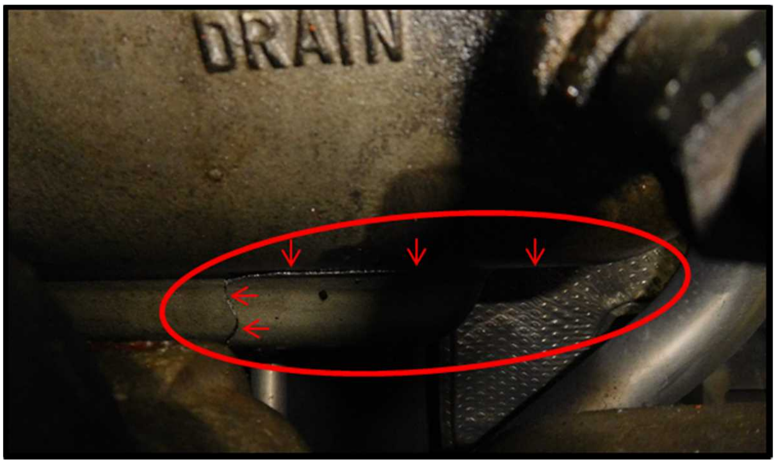


Photo #13-2. Cracks on the Fuel Oil Heat Exchanger

(11) Engine Cowl

① Inlet cowl

Impacting marks or damage was not confirmed on the right and left inlet cowl.

② Fan cowl

No damage was confirmed on the right and left fan cowl.

③ Translating cowl[18]

The right and left translating cowls were in place and the latches were locked. The aft edge of the left translating cowl had a large section, that was approximately 107 cm (42 in) wide axially at it widest by about 279 cm (110 in) long

[18] "Translating Cowl" is the cowling of having a role of nozzle injecting air from the fan and a role to inject the air from fan forward as providing a clearance between the fan cowl and sliding back position of this cowl.

circumferentially missing from the aft edge between 6:30 to 9 o'clock that exposed the core cowl. (See Photo # 14.Damage of Translating Cowl)

It was confirmed that the paint on the exterior of the aft side of the left translating cowl below the missing section was blistered or burned away. The left translating cowl (thrust reverser) inner wall had an approximately 94 cm (37 in) long circumferentially by 79 cm (31 in) wide axially, an there was another hole that was burned away. The interior of the left fan duct and translating cowl (thrust reverser) inner wall were sooted. There were two pieces of the 2nd stage HPT vane embedded in the inner surface of the translating cowl of the missing section.

④ The right side translating cowl

The right side translating cowl was not damaged, sooted or thermally stressed. The inner wall of translating cowl and associated fan duct did not have soot.

⑤ Aft cowl

The aft cowl pressure relief doors at 2, 4, 8 and 10 o'clock were all open.

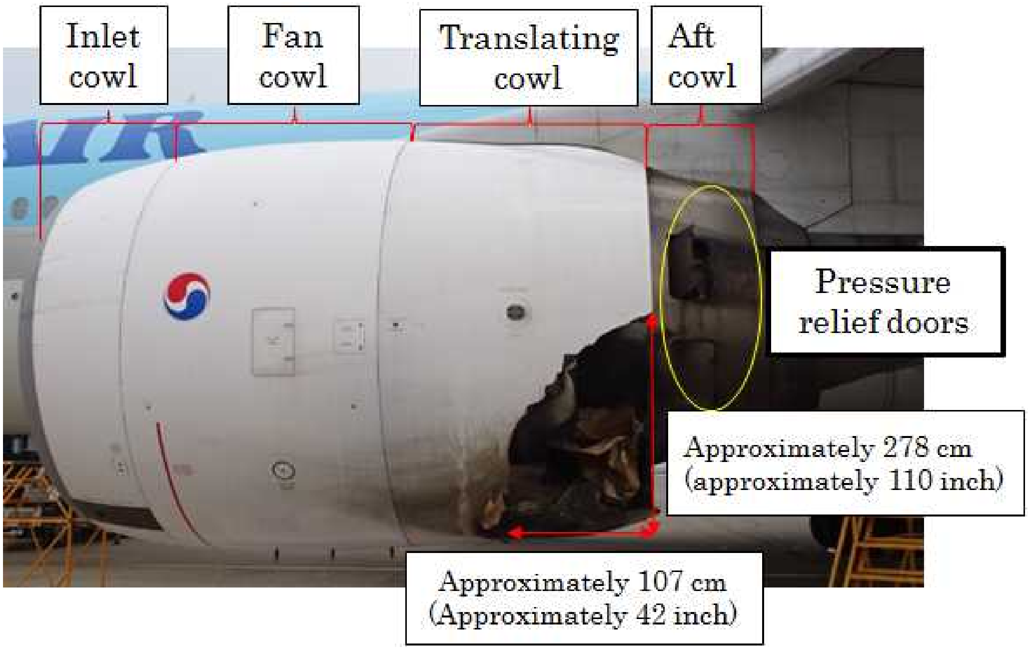


Photo # 14. Damage of Translating Cowl

Attachment 4.: Photos of Fractured Surface

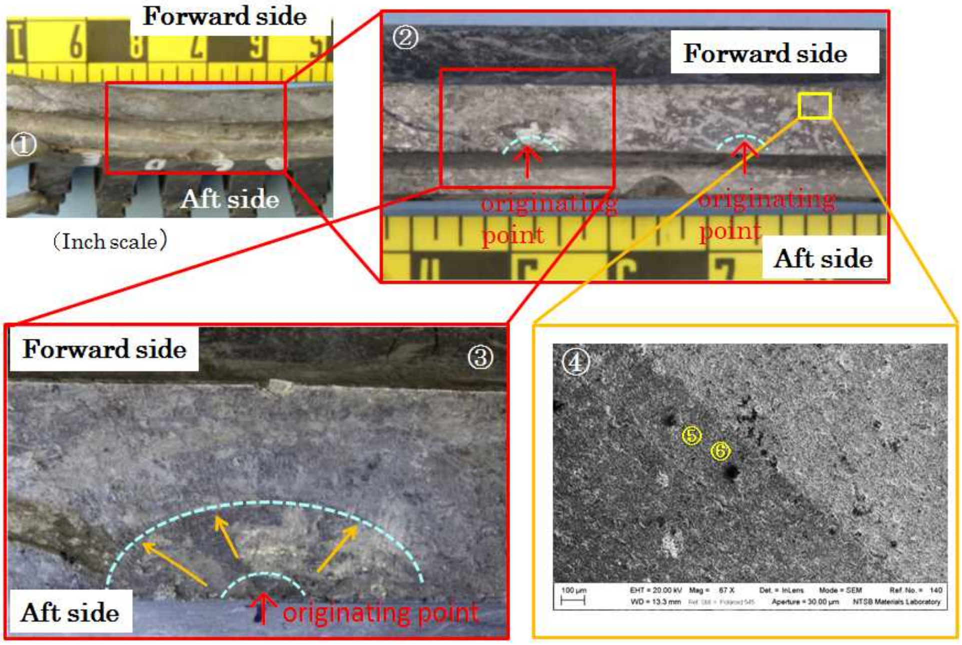
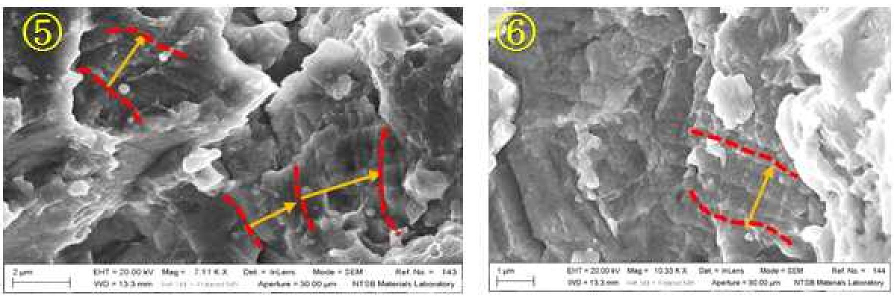


Photo ① and ②: Beach mark (Seashell pattern) from the originating point was confirmed at the fatigue crack propagation area at the fractured surface of fractured and ejected debris of the 1st stage HPT disk rim part.

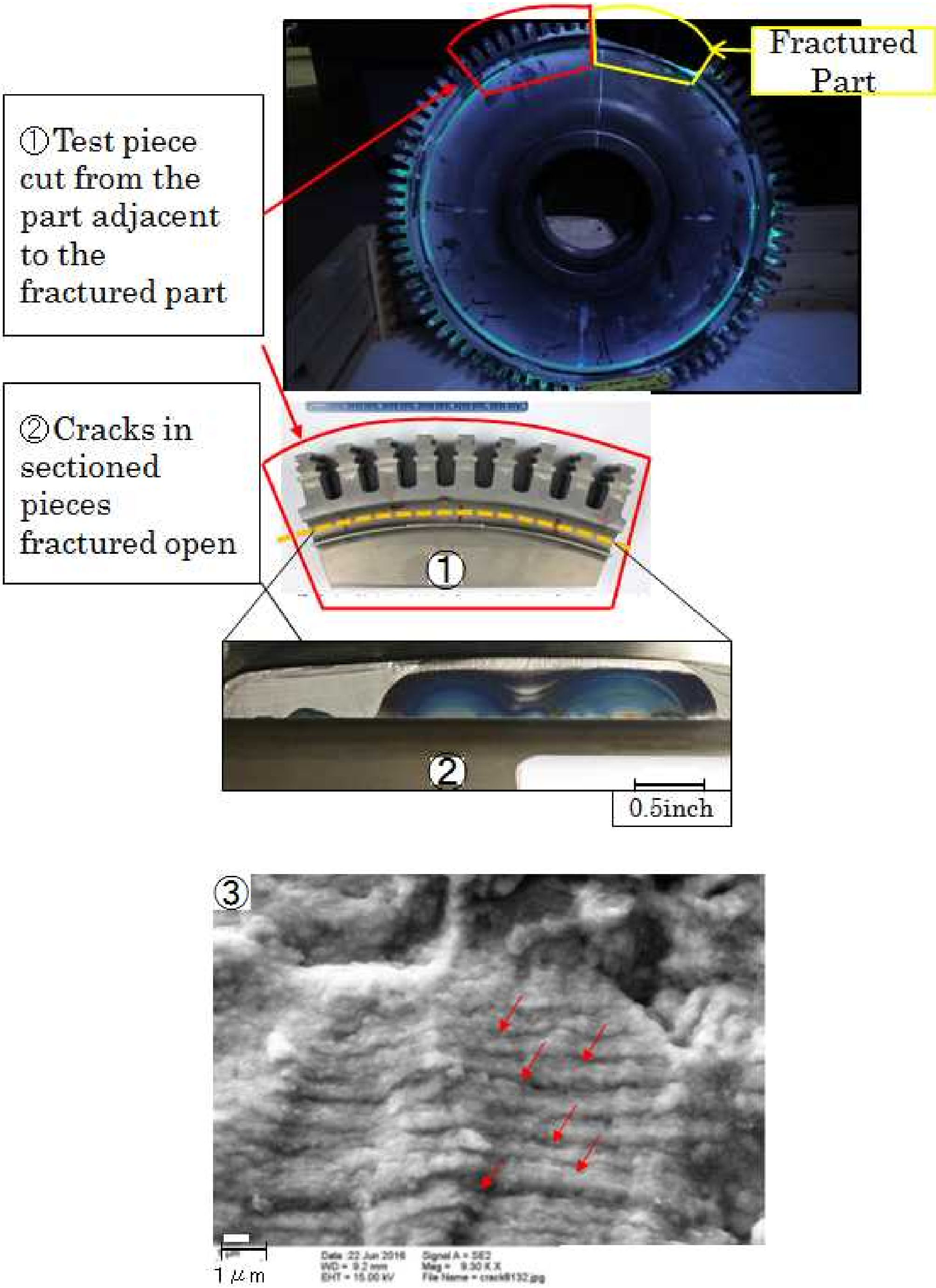
Photo ③ : Crack propagates from originating point at the aft side of the disk to the forward side. The fractured surface exhibited significant mechanical damage. The fatigue progression exhibited a bluish heat tint.

Photos ⑤ and ⑥ was the pictures enlarged and photographed parts enclosed by yellow lines shown in Photo ④ via Scanning Electron Microscope (SEM) and striation which is a characteristics of fatigue fracture surface was confirmed.



Legend	Blue dotted curve : Beach mark Red dotted curve : Striation Yellow arrow : Direction of crack propagation

Attachment 5.: Striations of a Test piece at the crack



③Magnify a crack via an electron microscope.
(Stable striations(Red Arrows) were confirmed.