Submission of CFM International
To the National Transportation Safety Board

Accident Involving
Southwest Airlines Flight 1380
17 April 2018

NTSB Public Docket: DCA18MA142

July 17, 2019

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Pursuant to 49 C.F.R. § 845.27, CFM International, Inc. (CFM) provides this submission to the National Transportation Safety Board (NTSB). CFM is a party to the NTSB's investigation into the accident involving Southwest Airlines (SWA) Flight 1380 on April 17, 2018. Other parties include the Federal Aviation Administration (FAA), SWA, The Boeing Company (Boeing) and Collins Aerospace (formerly United Technologies Aerospace Systems or UTAS).[1] As the Type Certificate Holder of the CFM56-7B engine, CFM's primary role in the investigation was to provide information regarding engine design and behavior (in particular, behavior after a fan blade separation) as well as provide historical information regarding the engine certification process and airframer integration. This submission documents CFM's (i) proposed findings drawn from factual information established during the course of the NTSB investigation, (ii) assessment of the probable cause of the accident, and (iii) proposed recommendations.

I. Executive Summary

The CFM56-7B series engine was jointly certified by the FAA and the Direction Générale de l'Aviation Civile (DGAC), which was later superseded by the European Union Aviation Safety Agency (EASA). Design of the CFM56-7B engine began in 1993. The engine was certified by the FAA and DGAC in 1996, and entered into commercial service in 1997. As of July 2019, there were over 15,000 CFM56-7B engines in commercial service with greater than 400 million hours of flight time and 200 million cycles of operation. There have only been two fan blade out (FBO) root separations in the service history of the CFM56-7B engine; one in August 2016, and the event at issue here, in April 2018. While FBO events are extraordinarily rare, they are by regulation accounted for during the certification process. Both FAA and the EU regulator require engine manufacturers to complete rigorous and extensive FBO testing before any engine is certified to enter service. The agencies approve the FBO testing plan in advance and ensure strict adherence to that plan during testing and certification.

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[1] The NTSB designated UTAS as a party to the investigation. During this investigation, UTAS became Collins Aerospace.

Design and certification of the CFM56-7B spanned approximately four years and involved many meetings and exchanges of data between CFM, Boeing, and the regulatory agencies. The coordination during the design and certification processes included development of joint models for the engine and airframe for FBO modeling as well as sharing the results of rig[2] and engine certification testing. This integration included but was not limited to formal transmittal of technical information regarding FBO per the relevant regulations. This includes detailed information about the engine's FBO performance and fan blade fragmentation data during numerous rig and certification tests. The CFM56-7B engine passed the regulatory certification requirements and demonstrated radial containment of blade fragments during FBO certification tests.

In Flight 1380, the engine performed as it was designed and certificated to perform. The engine radially contained all fan blade fragments, which followed a fragmentation pattern similar to what was documented during the certification process. After the FBO, portions of the fan cowl and inlet (which are part of the nacelle, which surrounds the engine, and are not part of the engine), were liberated. A portion of the fan cowl that was liberated damaged the airplane fuselage and a cabin window, creating a hazardous condition to the airplane and resulting in a fatal injury to one passenger.

Therefore, the probable root cause of the accident is the fan cowl liberation. The fan cowl loss is independent of the inlet departure as well as fan blade fragmentation which caused damage to the inlet.

As discussed below, CFM initiated fleet-wide actions to improve the reliability of the CFM56-7B fan blade. CFM concludes this document with recommendations arising from the investigation.

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[2] A rig test is an engineering test with partial hardware: full or partial set of blades, fan disk, fan shaft and fan case. It is conducted in a vacuum using an electric motor (not the engine itself) to drive the fan at the targeted fan speed of the FBO.

II. CFM International and the CFM56 Series of Engines

CFM is a partnership that began in 1974 between the General Electric Company (GE) in the United States and Safran Aircraft Engines (formerly Snecma) of France. Safran Aircraft Engines produces the Fan/Booster/Gearboxes and LPT (Low Pressure Turbine) modules of the CFM56 engine, while GE produces the Core engine module; that is, the HPC (High Pressure Compressor), Combustion chamber, and HPT (High Pressure Turbine) portions of the engine. CFM products include the CFM56-2, CFM56-3, CFM56-5 and CFM56-7B series engines which power Airbus, Boeing, and military airplanes.

In total, there are over 30,000 CFM56 engines flying today. CFM engines have accumulated over 1 billion engine flight hours. The CFM56-7B series engine entered service in 1997 and is the only engine type powering the Boeing 737NG airplane. Over 15,000 CFM56-7B engines are in commercial service and have accumulated more than 200 million engine flight cycles and 400 million engine flight hours, making it the single, largest engine fleet in commercial revenue service.

III. CFM56-7B Engine Certification Requirements, Fan Blade Out (FBO)

As the engine manufacturer, CFM obtained certification of *the engine* under Part 33 of then applicable FAA and DGAC requirements.[3]

Certification of the *engine* should not be confused with certification of the *airplane* for which the airframer (in this case, Boeing) is responsible under the FAR Part 25 regulations. Certification of the airplane includes certification of the airplane *powerplant*. Boeing obtained powerplant certification for the Boeing 737NG under Part 25 of the FAA regulations. Powerplant certification goes beyond the engine; it includes the nacelle, which surrounds the engine when it is installed on an airplane. The nacelle includes the following components[4]:

- Air Inlet

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[3] The DGAC (Direction Générale de l'Aviation Civile) has been superseded by EASA (European Union Aviation Safety Agency) in 2003. At the time of the CFM56-7B certification, the applicable engine regulations were: FAA: 14-CFR-Part 33.19(a) and Part 33.94; JAA: JAR-E 810(a) / ACJ E 810.

[4] NTSB Docket N°DCA18MA142, 8-A Powerplant Group Chairman's Factual Report, Nov. 13, 2018 page 12.

- Exhaust nozzles (Fan and Core Nozzles) and Centerbody
- Fan cowls
- Thrust Reverser assembly, which also serves as the cowling for the engine core

Because there are functional interfaces between the engine and the nacelle, the engine manufacturer and the airframer coordinate and exchange a significant amount of technical data throughout the design and certification processes.

Figure 1 depicts the forward portion of the engine and surrounding nacelle structures.

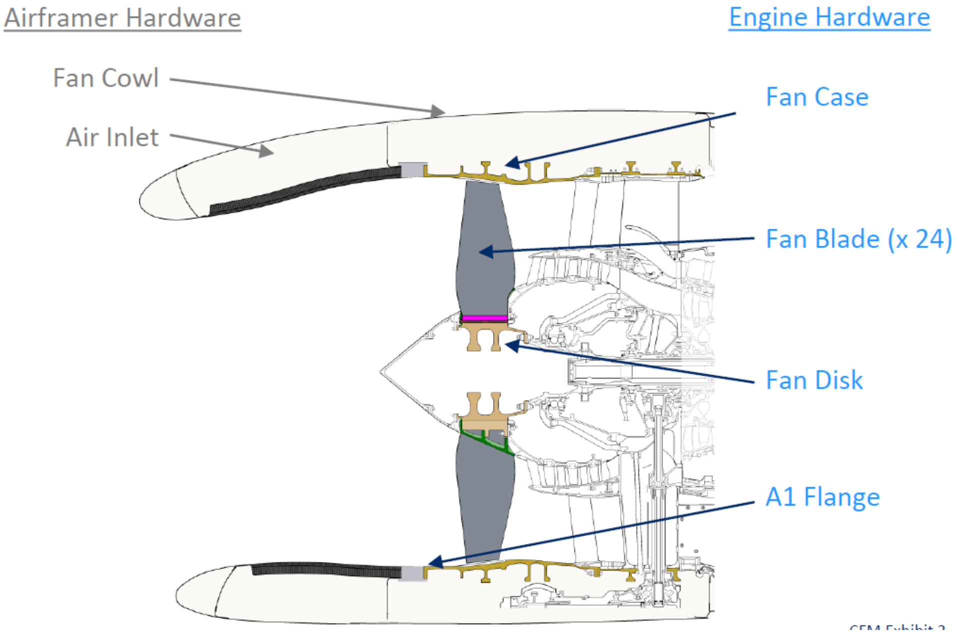

Figure 1: Engine and Nacelle Cross-Section Schematic[5]

The engine certification process is detailed and complex, involving several years of planning, designing, testing, validating findings, and exchanging data with the airframer.

One specific aspect of the engine certification requirement concerns the ability of the engine to withstand a fan blade separation or release, i.e., an FBO event. Though rare, FBO events can occur as a result of numerous potential causes, including bird strikes, foreign object damage, or

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[5] NTSB Docket N°DCA18MA142, 8-B CFM Supporting Documentation, Nov. 13, 2018, Exhibit 2.

fatigue failure of the fan blades. To ensure safe flight, both FAA and EASA set forth specific regulatory requirements applicable to an FBO event at both the engine[6] and nacelle/airplane level. For the engine, these regulations require: (1) a full scale demonstration of the engine capability during an FBO event and (2) the exchange of certain technical data related to the engine/airplane interface which includes the results of the engine FBO tests.

The FAA regulation requires that:

> *"…it must be demonstrated by engine tests that the engine is capable of containing damage without catching fire and without failure of its mounting attachments when operated for at least 15 seconds, unless the resulting engine damage induces a self-shutdown, …after… failure of the most critical compressor or fan blade while operating at maximum permissible r.p.m. The blade failure must occur at the outermost retention groove."*[7]

Because the nacelle is not part of the engine, the regulations do not require the airframer's production inlet to be installed during the certification testing, but rather permit the engine manufacturer to use a representative inlet. Fan cowls are not attached during the testing in order to permit a clear view (and high-speed video recording) of the engine. Upon completion of the certification test, the engine manufacturer is required to provide to the airframer and the Agencies "…*the maximum loads, and the energy and trajectory of the debris that exits the engine"*.[8]

The details of the certification testing demonstrating engine FBO capability are governed by a clear and defined *certification test plan,* which is approved by the regulators in advance of the test. Details within the test plan include the rotor speed of the engine at the time of fan blade release, the circumferential location of the fan blade release, and the instrumentation and recording devices that will be used to capture data during the FBO test. Joint meetings between engine manufacturer and the regulator(s) and airframer are held to define and refine all aspects of the test plan before it is executed. Once the regulator(s) approve the test plan, the engine manufacturer performs the FBO demonstration test with the regulators present to ensure

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[6] 14 C.F.R. § 33.94 & 33.19(a) and JAR-E 810(a)/ACJ E 810.

[7] 14 C.F.R. § 33.94; NTSB Docket N°DCA18MA142, 7-D FAA Supporting Documentation, Nov. 13, 2018, page 7.

[8] NTSB Docket N°DCA18MA142, 7-D FAA Supporting Documentation, Nov. 13, 2018, page 9.

compliance with the certification test plan. Given the short duration and highly transient nature of the FBO event, high-speed cameras and instrumentation are used to observe the engine behavior and fan blade fragments behavior. Data is then shared with the airframer through written reports and meetings that take place after FBO testing. Finally, FBO certification test data is documented in the Engine Installation Manual and Certification Reports.

IV. CFM56-7B Engine FBO Development, Testing and Certification History

The CFM56-7B development program started in 1993. In parallel, Boeing began the airplane (including the nacelle) design. At the outset, in order to assist the Boeing efforts, CFM shared its experiences with regard to FBO events *based on their existing product history.* The data CFM shared included the mass, quantity, direction, spiraling helix angle to the A1-flange (see Figure 1), sliding-panel area, velocity and energy of the fan blade fragments from prior FBO tests. CFM had observed that forward arc fan blade debris could occur as a result of FBO, and shared that information with Boeing.[9]

The multi-year development, testing, and certification of the CFM56-7B engine included numerous meetings between Boeing and CFM, as well as joint meetings with the regulators. In meetings and documents exchanged between Boeing and CFM, the companies identified and defined the data that would be communicated after the engine FBO rig and certification testing. While the FBO certification test is essentially a pass/fail demonstration test for the engine, the data obtained during the test is necessary to support the certification by the airframer of the nacelle at the airplane level. CFM provided the agreed-upon data to Boeing after the FBO rig and certification testing in multiple meetings and technical memorandums. In fact, CFM and Boeing exchanged more data than is required by regulation, both before and after the FBO testing.

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[9] These assumptions were further confirmed by CFM once the CFM56-7B design, rig and engine tests were complete.

A. Rig tests

During CFM56-7B engine development, CFM conducted a total of eight (8) FBO rig tests and two (2) FBO certification tests (engine level) as depicted in Figure 2.

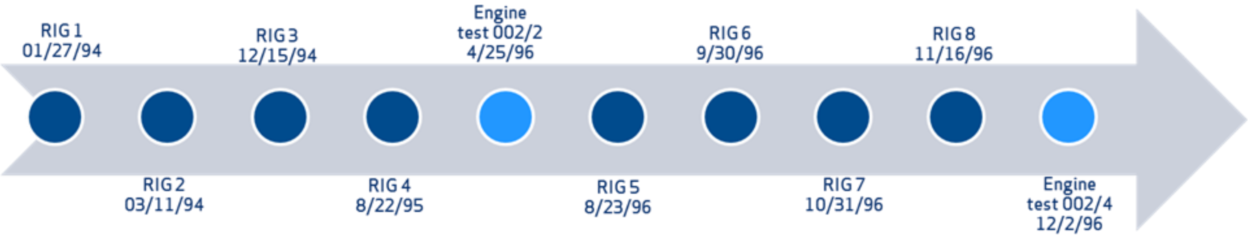

Figure 2 : FBO Rig and Certification Test Timeline

The first four (4) rig tests were conducted between January 1994 and August 1995 and were used to assess the fan blade fragmentation, fan case radial containment capability, fan blade axial retention, and fan blade interaction.

After the fan blade is released, the fan blade circumferentially impacts the engine fan case several times and is fragmented into several pieces: tip fragment, mid-span fragments and root panel (see Figure 3).

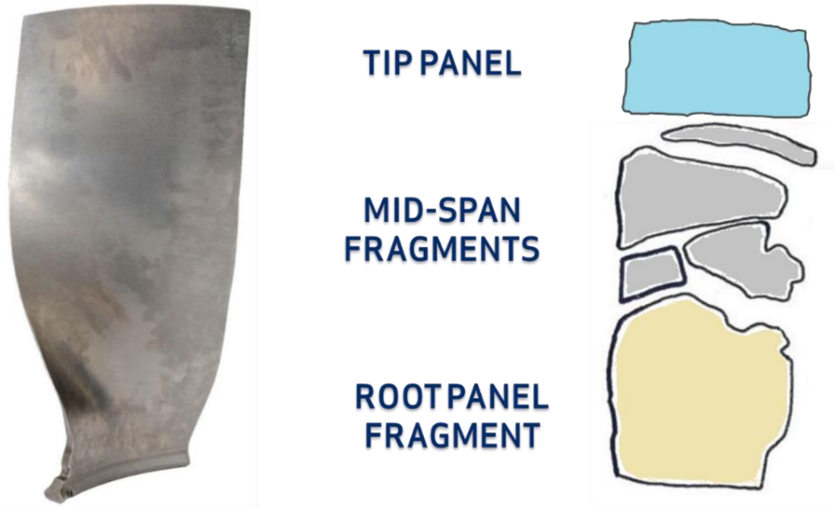

Figure 3 : Typical Fan Blade Fragmentation During FBO[10]

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[10] NTSB Docket N°DCA18MA142, 8-B CFM Supporting Documentation, Nov. 13, 2018, Exhibit 12.

The fan blade impact marks on the engine fan case represent the impact locations on the fan case and load transmission of the fan blade fragments. After each test, these marks were noted and evaluated to gain information about fan case and fan blade fragmentation behavior. Although not required by the regulations, in order to obtain additional technical information, an initial Boeing production inlet was installed by CFM on the fourth rig test in August 1995. Important data concerning the FBO capability of the production inlet design was obtained. During that test, a fan blade tip fragment penetrated through the inlet structure, suggesting that Boeing should modify the design of the inlet to avoid penetration in the event of an FBO. To assist, CFM shared the CFM56-7B fan blade fragmentation experience based on the first four (4) rig tests, FBO design loads (forcing functions), transient analysis and the estimated spiraling helix angle (15°) for the tip fragment (see Figure 4). Details of the mid span fragment mass, quantity and direction were also shared.[11]

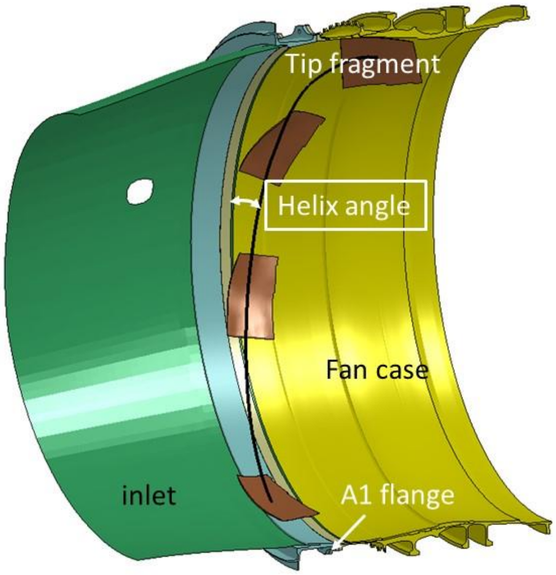

Figure 4 : Fragment helix angle definition

A series of meetings to review the test results were conducted between Boeing, UTAS and CFM. The inlet was also inspected by Boeing after the rig test during which it was installed**.** Based on the results of rig test #4, during which the inlet was installed, Boeing and UTAS reinforced their

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[11] This information was shared with Boeing during a presentation at a FBO Specialist Meeting in September 1995.

inlet using a containment doubler in the inner barrel of the inlet. They also stiffened the inlet attach ring as well and increased its axial length (See Figure 5).

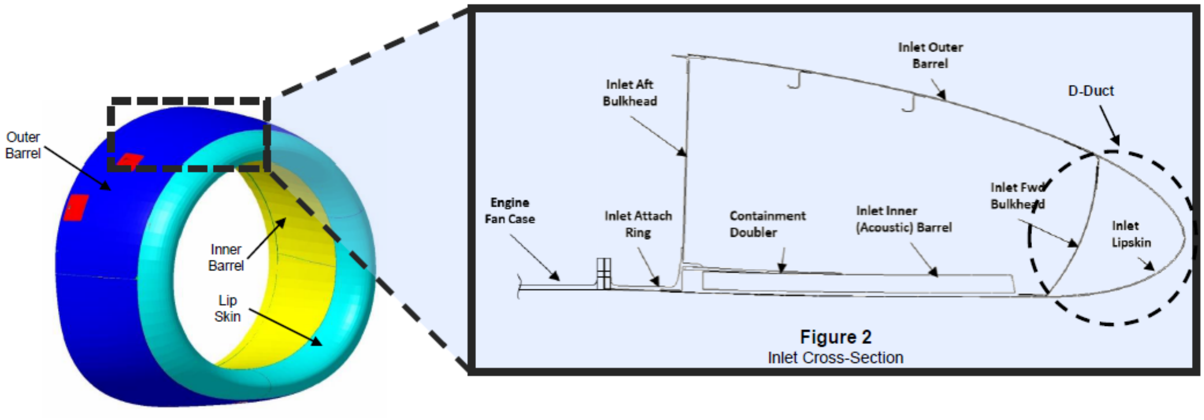

Figure 1
Inlet

Figure 2
Inlet Cross-Section

Figure 5 : Inlet structural overview[12]

During the first four rig tests, the fan blade fragmentation after the separation and impact on the fan case was consistent with that which occurred during subsequent rig and certification tests. The fan blade separated into three fragment categories: a tip fragment, multiple mid-span fragments, and a root panel fragment.

A consistent pattern was demonstrated in the FBO testing. That is, the tip fragment consistently moved forward; mid-span fragments moved forward and aft, and the root panel fragment always moved aft. Due to its mass and velocity, the tip fragment has the highest kinetic energy level of the fan blade fragments crossing the A1 flange. The average *mid span* fragment kinetic energy is approximately 60% lower than the average tip fragment kinetic energy.

CFM shared the fan blade fragmentation test results with Boeing. The containment doubler on the inlet designed by Boeing and UTAS was intended to contain the fan blade tip fragment since testing revealed it to be the highest energy, forward traveling fragment.

Although not required by the regulations, the Boeing production inlet containing the changes made after rig test #4 was installed by CFM on the first CFM56-7B engine FBO certification test

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[12] NTSB Docket N°DCA18MA142, 7-B Boeing Supporting Documentation, Nov. 13, 2018, page 4.

874-002/2, performed in April 1996. Prior to the certification test, both the FAA and DGAC approved CFM's engine certification testing plan and the DGAC was present to witness the test. No fan cowls were installed on the certification test, per standard industry practice, in order to permit observation and video recording of the fan case and fan case installed components during the test. The test instrumentation and high-speed camera placement were in accordance with the Agency approved test plan.

B. Certification tests

The engine behavior exhibited during the certification test on engine 874-002/2 can be summarized in two phases. The *first phase* (130 ms) encompassed the release of a single fan blade via the detonation of explosives in the root of the blade and the following nine (9) revolutions of the fan rotor. This phase included the blade fragmentation, containment, primary impact loading and resulting displacement wave on the engine and inlet. Ten (10) revolutions after the single blade release, five (5) additional blades were released due to a fan blade axial retention hardware failure (this was the *second phase* of the test), due to loads induced by the remaining blades tip rub forces on the fan case.

The first phase of the certification test 874-002/2 demonstrated that the engine fan case successfully radially contained the blade fragments (there was no radial penetration). During this phase of the certification test, the engine did not catch fire, did not fail from its mounts and, at the end of the test, the engine was able to be successfully shut down.[13]

After the first FBO test, CFM and Boeing collaborated on the instrumentation data analysis to determine predicted loads throughout the engine and nacelle structure from a FBO event. CFM shared relevant data with Boeing, including high speed camera footage of the test itself.

In a technical coordination memorandum to Boeing, CFM provided the mass and velocity of the tip fragment (the highest energy, forward-traveling fragment) that was observed during this certification test.[14] The inlet was inspected by Boeing. Damage to the inlet included 360-degree

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[13] *See* 14 C.F.R. §§ 33.19 and 33.94. Both of these regulations pertaining to containment are the same currently as they were when the CFM56-7B was certified.

[14] Coordination Memorandum n°8604, CFM to Boeing, February 7, 1997.

failure of the aft bulkhead inner joint. High-speed camera videos and post-test hardware observations revealed that during the *first phase* of the certification test no fan blade fragments penetrated the inlet containment doubler from the initial, single blade release. But, after the first phase of the initial certification test, the additional fan blades released generated considerable damage to the fan case and the inlet. The inlet damage consisted of through penetrations and missing inner and outer barrel material.

As a result of the loss of additional blades in the 874-002/2 certification test, CFM modified the fan module design to improve fan blade axial retention capability during a FBO event. Four additional rig tests were conducted to validate the modified fan blade axial retention capability (see Figure 2).

CFM conducted a second certification test in December 1996[15]. The second certification test successfully demonstrated the axial retention capability. In this test, CFM confirmed the fan blade fragment trajectories and loads were consistent with the first certification test on engine 874-002/2. The results of the test (including fragment trajectories, and loads) were shared with both regulatory Agencies and Boeing.

The results of the certification testing were documented and approved by the regulatory Agencies. The engine Installation Manual for the CFM56-7B engine was also approved by the regulators, issued by CFM, and provided to the airframer. The Installation Manual contains various data related to the powerplant installation such as dimensions, weight, approved fuels, oils, and forward and aft mount loads. FBO fragmentation information, including the energy levels and trajectory of tip and mid-span fragments exiting the inlet or exhaust, is also contained within the Installation Manual; that information was based on the two certification engine tests conducted by CFM.

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[15] For the second certification test, consistent with regulations, a representative inlet was installed on the engine. Boeing did not request a production inlet for the second certification test as the data needed for the inlet was gathered during the first certification test.

V. Flight 1380

A. Overview

On April 17, 2018, at 1103 eastern daylight time, Southwest Airlines Flight 1380, a Boeing 737-7H4, N772SW, a regularly scheduled domestic passenger flight operating under 14 Code of Federal Regulations Part 121 from La Guardia Airport (LGA), Queens, New York, to Dallas Love Field (DAL), Dallas, Texas, experienced an FBO. The engine performed as designed during the FBO and all fragments were radially contained within the fan case, as required by regulation. Portions of the fan cowl and inlet were separated[16] during the event. A portion of the fan cowl struck the fuselage and a cabin window of the airplane resulting in cabin depressurization. The flight crew conducted an emergency descent and diverted into Philadelphia International Airport (PHL), Philadelphia, Pennsylvania. Of the 144 passengers and five crewmembers onboard, one passenger received fatal injuries and eight passengers received minor injuries. Hereafter in this submission, this accident will be referred to as the Flight 1380 event.

Flight Data Recorder (FDR) information indicates that after the blade separated, the engine initially stalled but began to recover after about 2 seconds. It then entered a state of pulsing surges for approximately 20 seconds. The crew retarded the throttles to flight idle at approximately 24 seconds after the blade separation. Until throttle pull back, the left engine continued to operate and attempted to meet commanded thrust levels based on the throttle position and the engine control logic. Based on post-flight FDR data analysis, the flight crew cut fuel flow to the engine 36 seconds after the FBO in order to shut down the engine. Progressive failure analysis results show the inlet and fan cowl separated within 0.5 seconds of the blade release and that the subsequent engine powered run down was not a contributor to the inlet or fan cowl separation.

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[16] NTSB Docket N°DCA18MA142, 8-A Powerplant Group Chairman’s Factual Report, Nov.13, 2018, pages 26-27.

B. Detailed Technical Assessment

1. *Fan Blade Fragmentation and Trajectories*

After the FBO, all of the fan blades were present in their fan disk mounting locations[17] with the exception of the separated blade (Blade #13). Visual examination of the separated fan blade dovetail revealed features consistent with fatigue initiation on the convex side near the Leading Edge (LE)[18].

As discussed, during an FBO event, after the fan blade is released, it circumferentially impacts the fan case several times and it is fragmented as follows: the tip fragment, several mid-span fragments, and the root panel. The fan blade impact marks on the engine fan case represent the impact locations on the fan case and load transmission from the fan blade fragments. After fragmentation, blade fragments slide in the fan case with a helical trajectory, either axially forward or aft. Two blade fragments -- the root panel fragment and one mid span fragment -- were found in the engine between the fan blade axial plane and the fan outlet guide vanes (OGV's). One fan blade platform was also liberated. Based on evidence of platform seal traces on the trailing blade to the released blade and CFM experience, the platform very likely broke into pieces, went backward and pieces were ingested into the fan flow path of the engine.

No blade fragments radially penetrated the engine fan case; all fragments were radially contained within the fan case, in accordance with regulatory requirements.

One tip fragment and several mid span fragments moved forward of the A1 flange.[19] Additional evaluation of the markings on the fan case and inlet supports that the blade tip fragment edge crossed the plane of the A1 flange at an approximate helix angle of 15 degrees. This was determined based on clear imprints of the fan blade tip radius between the 6:00 and 7:00 o'clock positions (ALF: Aft Looking Forward). In terms of the tip fragment center-of-gravity (CG), the tip

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[17] NTSB Docket N°DCA18MA142, 8-A Powerplant Group Chairman's Factual Report, Nov.13, 2018, page 38.

[18] NTSB Docket N°DCA18MA142, 15 - Materials Laboratory Factual Report 18-049, Nov.5, 2018, Fig6 page 23

[19] NTSB Docket N°DCA18MA142, 8-A Powerplant Group Chairman's Factual Report, Nov.13, 2018, pages 37-40 and 81-82.

fragment CG likely crossed the A1 flange with a maximum angle of 20 degrees[20]. This angle is supported by three distinct tip fragment trailing edge imprints[21] on the fan case corresponding to three locations of the tip fragment in time during the event. These imprints support a rotational motion of the tip fragment as it progressed forward in its helical path.

There are no continuous fragment markings caused from the tip fragment observable in the inlet diameter forward of the A1 flange. There is an area of missing material on the inlet A1 flange lip, which could explain the lack of inlet markings[22]. It is likely that the tip fragment impacted the lip, sheared the corner, and lost contact with the inlet[23]. Based on CFM analysis, this would alter the trajectory of the tip fragment and result in a more axially forward trajectory.[24] The tip fragment re-engaged the inlet and penetrated the inner barrel at the forward edge of the containment doubler where the inlet subsequently separated.

2. Inlet Damage

Based on the physical evidence obtained, the data strongly supports that the tip fragment penetrated in the inner barrel back skin in the 10:30-11:30 o'clock (ALF) area (30 degree circumferential distance, see Figure 6).[25]

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[20] As discussed in the section addressing the Structures Report (NTSB Docket N°DCA18MA142, 7 - Structures Report 2 Tech Review Version, June 26, 2019), CFM does not agree with the Structures Report statement that the tip fragment could have crossed the A1 flange of the fan case at a 30 degree angle. The evidence does not support that statement.

[21] NSTB Docket N°DCA18MA142, 7 - Report from Party - CFM, June 26, 2019, Figures 4.10 to 4.12, pages 26-27

[22] NSTB Docket N°DCA18MA142, 7 - Report from Party - CFM, June 26, 2019, Figure 4.17, page 30

[23] NSTB Docket N°DCA18MA142, 7 - Report from Party - CFM, June 26, 2019, Figures 4.18 & 4.19, page 31

[24] NSTB Docket N°DCA18MA142, 7 - Report from Party - CFM, June 26, 2019, page 32

[25] NSTB Docket N°DCA18MA142, 7 - Report from Party - CFM, June 26, 2019, pages 39-40

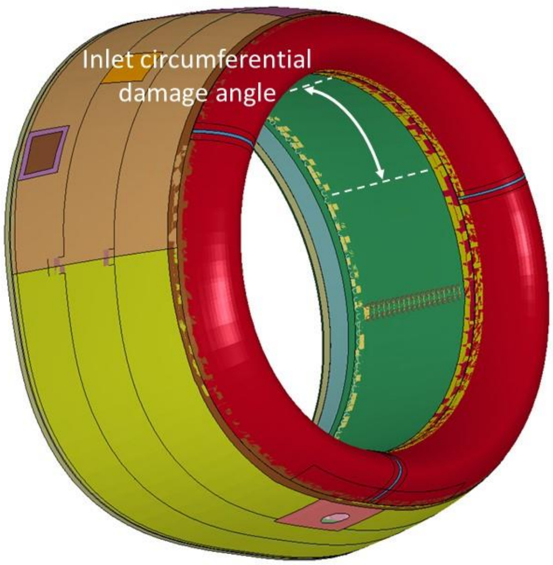

Figure 6 : inlet circumferential damage angle definition

A mid-span fragment subsequently passed through this penetration area, which is demonstrated by the markings on the hardware.

Additional inner barrel backskin damage cited in the Structures Report as located in the 11:30-12:45 o'clock (ALF) zone[26] is not supported by the physical evidence. There is no radial outward deformation, no radial crushed honeycomb, or trajectory markings in this zone.[27] The condition of the inlet in areas away from the 10:30-11:30 o'clock (ALF) zone is likely due to the tearing from the applied inlet loads. Microscopic traces of Titanium existing on the separation plane cannot be conclusively attributed to fan blade high energy fragments as there are other sources of Titanium including the inlet forward bulkhead, which after the inlet separated, likely impacted the separation surface**.**

CFM inlet damage analysis supports the inner barrel back skin damage from primary blade fragment penetration is limited to 30 degrees (10:30 to 11:30). Data does not support that fan blade fragment created damage beyond 30 degrees to the inner barrel back skin.

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[26] NTSB Docket N°DCA18MA142, 7 - Structures Report 2 Tech Review Version, June 26, 2019, Fig.8 page 15

[27] NSTB Docket N°DCA18MA142, 7 - Report from Party - CFM, June 26, 2019, pages 41-43.

3. Analytical Predictions and Correlations

CFM and Boeing collaborated on analytical simulation of the FBO event. The simulation validated the blade breakup behavior and blade impact loads into the fan case, and displacement wave characteristics, which occur in the first fan revolution after the blade separation. This was consistent with certification and pre-certification testing.

Using the impact loads and predicted damage, Boeing utilized a progressive failure analysis approach to estimate the nacelle behavior later in the event as documented in the Structures Report[28].

a) For the fan cowl, the displacement wave transmitted loads and energy into the fan cowl via its radial restraint feature (see Figure 7):

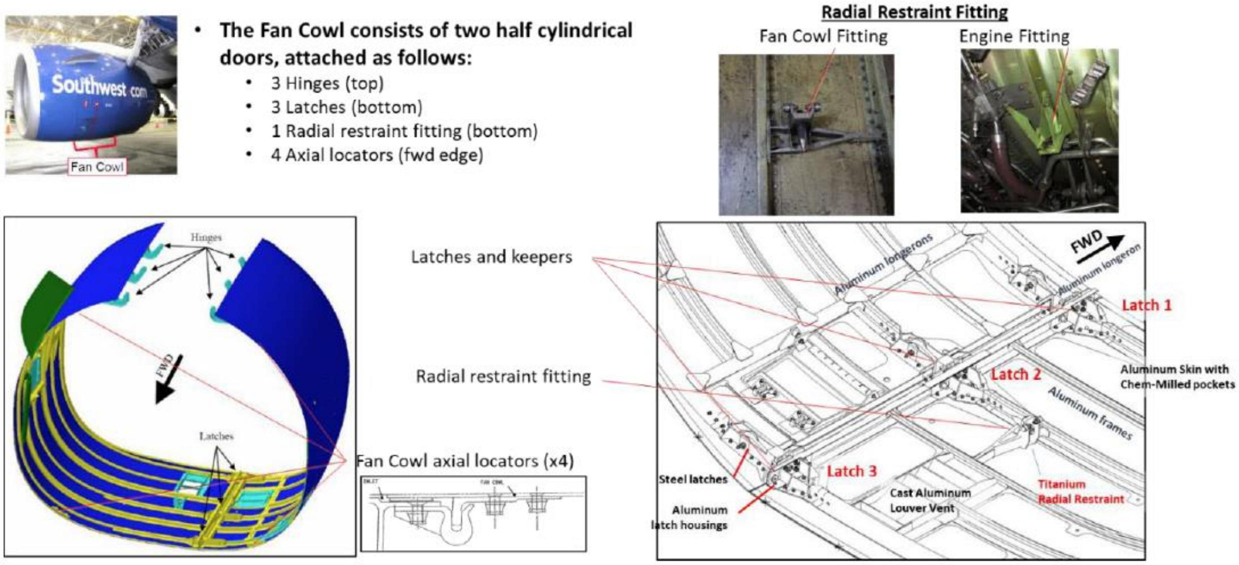

Figure 7: fan cowl structural overview[29]

This behavior was different than the original assumption used by Boeing/UTAS at the time of the airplane certification. It was assumed then that the radial restraint fitting would fail prior to transmitting high loads to the fan cowl. [30] In the Flight 1380 event, the loads were

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[28] NTSB Docket N°DCA18MA142, 7 - Structures Report 2 Tech Review Version, June 26, 2019, page 22
[29] NTSB Docket N°DCA18MA142, 7 - Structures Report 2 Tech Review Version, June 26, 2019, page 8.
[30] NTSB Docket N°DCA18MA142, 7 - Structures Report 2 Tech Review Version, June 26, 2019, page 32

sufficient to initiate cracking at corners of the vent cutout which then propagated into the fan cowl skin, which resulted in portions of the fan cowl being liberated.

Based on markings on the fuselage, the aft latch portion of the liberated fan cowl struck the fuselage, causing the window to liberate.[31] The Boeing analysis predicts the fan cowl disengaged within 0.070 seconds after the blade separation.[32]

b) In terms of the inlet, the impact loads and energy were key contributors to the inlet loss. The Boeing analysis indicates that the displacement wave induced a partial inner lip skin-to-forward bulkhead joint failure and also caused 360-degree failure of the nacelle's aft bulkhead at the inner flange. This was due to fastener shear and failure of some of the aft bulkhead circumferential splices. With the aft bulkhead unable to transmit load to the outer barrel, the inner barrel became critical for the retention of the inlet.

CFM, as part of the Structures Group, agreed with a circumferential 70-degree penetration damage level as a starting value to permit Boeing to launch the Progressive Failure Analysis. CFM further analysis of the physical evidence gathered during the course of this investigation does not support the initial 70-degree assumption adopted by the Structures Group Team. The evidence supports, at most, 30 degrees of circumferential damage.

With the penetration damage and damage to the aft bulkhead, the progressive failure analysis indicated the inlet would depart the airplane in ~ 0.5 seconds after the blade separation. Progressive damage analysis for penetration damage less than 70 degrees was not conducted, but Boeing fracture mechanics studies indicated the critical crack size was ~35 degrees circumferential length (or less) *without* the fan cowl being present. These results indicate that the estimated 30-degree circumferential damage from blade fragments described earlier is the same order of magnitude as the damage tolerance of the inlet at the separation plane. Larger circumferential penetration damage of the inlet (e.g., the assumed 70-degree penetration damage level) is not supported by the evidence.

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[31] NTSB Docket N°DCA18MA142, 7-A Structures Factual Report, Nov. 14, 2018, pages 22-24.

[32] NTSB Docket N°DCA18MA142, 7 - Structures Report 2 Tech Review Version, June 26, 2019, page 20.

C. Comparison to Certification Test Results

The fan case impact pattern (based on marks, physical evidence on the fan case, and recovered blade fragments) of the Flight 1380 event is very similar to the pattern observed after certification test 874 002/2. The angular position of the impact varied because of the location of the released blade (see Figure 8– ESN 875134 refers to Flight 1380). The impact pattern was located at 6:30 o'clock position for Flight 1380 due the fan blade release angle estimated at 3:30-4:00 o'clock (ALF). For certification test 874-002/2, the fan blade release angle was 12:30 o'clock and the resulting impact pattern was between 3:00 and 3:30 o'clock (ALF).

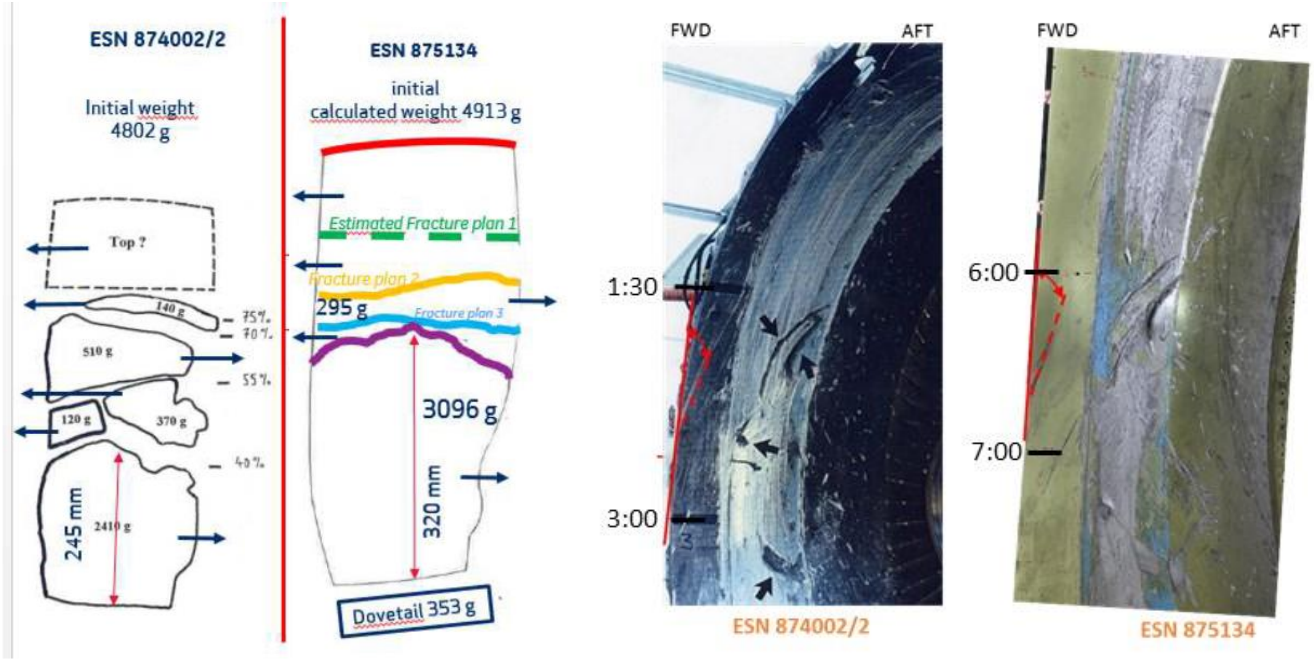

Figure 8 : CFM56-7B fan blade fragmentation and tip fragment imprints at A1 flange – Certification experience versus Flight 1380 event[33]

The fragmentation (quantity and mass) and direction of the fragments in the Flight 1380 event were very similar to the fragmentation and direction of the fragments during the FBO certification test. In the 874-002/2 certification test (performed with Boeing's type design production inlet), three mid-span fragments and the tip fragment exited forward of the A1 flange with the root panel fragment and one mid-span fragment exiting aft (see Figure 8).

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[33] NSTB Docket N°DCA18MA142, 7 - Report from Party - CFM, June 26, 2019, Fig 2.1 page 9 + Fig4.1 page 20

In both Flight 1380 event and the 874-002/2 certification test, all fragments were radially contained by the fan case (see Figure 8, which graphically compares the fragmentation between the certification test and Flight 1380).

In terms of fragment trajectory, there was a slight difference in helix angle at the exit of the fan case between the certification test and the Flight 1380 event. During certification test, the tip fragment edge crossed A1 flange with an angle of 15°. Continuous marks observed on fan case and inlet suggest that the tip fragment center of gravity (CG) had same trajectory as tip fragment edge.[34]

In the Flight 1380 event, the blade tip fragment edge crossed the plane of the A1 flange at an approximate helix angle of 15 degrees but the tip fragment center-of-gravity trajectory was at a slightly higher helix angle (~20 degrees). This somewhat higher CG helix angle, and/or the impact on the A1 flange inlet lip, may have caused the tip fragment to travel forward of the containment doubler which did not occur in the certification test.

In the Flight 1380 event, the fan blade tip fragment penetrated the inlet inner barrel back skin and the generated damage propagated under subsequent displacement wave and flight loads.[35]

VI. CFM Initiated Actions

The Flight 1380 FBO event occurred while CFM was in the midst of a fleet-wide inspection program of all fan blade dovetails on the CFM56-7B engines. CFM had initiated a comprehensive evaluation of the CFM56-7B fan blade dovetail area after an FBO incident that occurred on August 27, 2016, on SWA Flight 3472, involving a fan blade separation and inlet loss but no fan cowl separation. The flight crew performed an in-flight shutdown of the engine and the airplane diverted to Pensacola International Airport (PNS) where it landed safely with no injuries. The Flight 3472

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[34] NSTB Docket N°DCA18MA142, 7 - Report from Party - CFM, June 26, 2019, page 15.

[35] Since certification, Boeing/UTAS changed the material of the back skin. Al 2024 T62 was used at the time of the certification; Al 2024 T81 was introduced post certification and was the material of the Flight 1380 inner barrel back skin.

incident represented the first FBO in the history of the CFM56-7B engine, after it had been in service for approximately 20 years and had accumulated over 300 million flight hours.[36] As with Flight 1380, in the Flight 3472 event, the CFM engine met FAA technical regulatory requirements, including the radial containment within the fan case of the blade fragments.

Though the engine performed as designed and tested during the Flight 3472 FBO event, CFM promptly set out to determine why the FBO occurred and implement inspection programs to prevent future FBO events. CFM proceeded in three key phases: *investigation and failure analysis*, *development of enhanced inspections* in the area of interest of the fan blade dovetails and *implementation* of fleet-wide enhanced inspection program.

A. Root Cause Investigation

Immediately following the Flight 3472 event, CFM launched an intensive analysis to understand the details and root cause of the FBO. The fan blade cracking was determined to result from a Low Cycle Fatigue (LCF) phenomenon with initiation on the convex side leading edge at the top of the pressure face of the dovetail.[37]

Metallurgic striation density measurements showed that even after a crack began at the fan blade root, it remained stable for approximately 15,000 subsequent cycles[38], which represents approximately 8 more years of operation. This crack behavior provides an opportunity to detect a crack prior to failure through enhanced inspections.

B. Enhanced Inspection Development

Historically, CFM56-7B fan blades were inspected through a fluorescent penetrant inspection (FPI) technique when undergoing blade repair. The Flight 3472 event root cause investigation determined that the crack detectability with FPI could be negatively affected by the surface

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[36] Prior to the Flight 3472 event, CFM had experienced two partial fan blade losses associated with bird strikes. A partial fan blade loss is very different from a FBO; the fragmentation and loads are not comparable.

[37] NTSB Docket N° DCA16FA217, Airworthiness Group Chairman's Factual Report, Nov.13, 2018, page 70

[38] NTSB Docket N° DCA16FA217, Airworthiness Group Chairman's Factual Report, Nov.13, 2018, page 14

conditions of the blade. CFM evaluated complementary inspection techniques and subsequently developed two additional inspection techniques for the blade dovetail. The first inspection technique utilizes eddy current array probes to inspect the blade dovetail. This inspection is performed during blade repair when the fan blade coating is removed and refurbished. It was added to the Engine Shop Manual (TASK 72-01-200-01 Fan Rotor Blade – Inspection) in November 2016. The second inspection technique uses a contact ultrasonic probe which can be performed while the fan blades remain coated, but are removed from the engine. This allowed the inspection to be performed during regular “overnight” inspections on the airplane. Both the eddy current and ultrasonic inspections examine the full axial length of the fan blade dovetails on both the concave and convex sides.

The inspections were released to the fleet after developing the required specific tooling, validating the detection sensitivity and demonstrating the technique through sampling inspections on blades which had operated in revenue service. It was implemented in early 2017, beginning with a sampling program at Southwest Airlines (SWA) and through Service Bulletins (see §VI.C for details) to the CFM56-7B fleet beginning in March 2017.

C. Fleet-wide Inspection Implementation

With the availability of the enhanced inspection methods, CFM defined a fleet-wide inspection program. Before the program was launched, tooling assets had to be manufactured and training provided to the large, diverse operator base of the CFM56-7B engine given there were over 15,000 engines in use – approximately 350,000 blades – with 250 operators around the world.

The initial data obtained using the enhanced inspection techniques allowed CFM to refine the blade inspection priorities; this is reflected in the evolution of the Service Bulletins (SB) issued by CFM.

- SB 72-1019 Category 2 was issued on March 24, 2017 and called for an ultrasonic inspection of high time Fan Blade Dovetails. The targeted population was blades installed on engines that had accumulated more than 15,000 cycles since the last engine shop visit. The “time since engine shop visit” was viewed as a proxy for cycles since fan blade overhaul.

- SB 72-1024 Category 2, issued on July 28, 2017, continued the use of ultrasonic inspection of high time Fan Blade Dovetails. But, it targeted specific fan blades based on fan blade part number (P/N) 340-001-022-0 (first fan blade to enter revenue service) and its derivatives. The goal was to identify and inspect the oldest blades in the fleet. CFM used the blade part number because operators were not required to track cyclic usage by fan blade serial number.

An additional action proposed by CFM and agreed to by Boeing following the Flight 3472 event was the revision of the Aircraft Maintenance Manual (AMM) criteria[39] in June 2017 for the fan blade dovetail coating spalling. The objective was to clarify and refine the serviceable limits of coating spalling of the fan blade dovetail pressure faces as it was identified as an aggravating factor on stress levels in the cracking location during the root cause investigation.

On August 25, 2017, the FAA issued NPRM 2017-17828 (a proposed Airworthiness Directive (AD)), with the comment period closing on October 10, 2017, mandating the ultrasonic inspection contained in the Service Bulletins. In parallel, EASA issued PAD No. 17-132 followed by 17-132R1. The EASA AD 2018-0071 was issued on March 26, 2018, with an effective date of April 2, 2018 and required an ultrasonic inspection of the fan blade P/N 340-001-022-0 and derivatives within 9 months after the effective date of the AD.

The FAA was in the process of finalizing an AD which mandated the inspections recommended in SB 72-1019 and SB 72-1024 at the time the Flight 1380 event occurred. An additional SB (72-1033) was also in final review with both EASA and FAA that recommended *repetitive* ultrasonic inspections on all CFM56-7B fan blades.

Examination of the blade fracture surface from Flight 1380 revealed features consistent with fatigue initiation and with the blade fracture surface in the Flight 3472 event. As a result of this finding, the existing inspection field plan was highly accelerated. This expedited process was enabled because CFM had already developed the enhanced inspection techniques, tooling, and training and had launched fleet-wide inspections following the Flight 3472 event.

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[39] AMM TASK 72-21-02-200-801-F00 is a specific task specifying the fan blade coating inspection and serviceability limits.

On April 20, 2018, CFM issued Service Bulletin 72-1033 applicable to CFM56-7B series engines recommending ultrasonic inspections of all fan blades on engines that had accumulated 20,000 engine cycles since new (CSN) and repetitively thereafter at intervals not to exceed 3,000 engine cycles.

Since the blades were an untracked component, a prioritization regimen was developed. The first targeted population was to inspect fan blades within 20 days (before May 10, 2018) on all engines which were above 30,000 CSN.

CFM issued a Revision 1 of the SB 72-1033 on May 10, 2018 to define two (2) additional targeted populations with short inspection compliance times. This SB Revision provided for:

- Inspection of all fan blades known to be above 20,000 CSN or more by June 30, 2018. If fan blade cycles were unknown, the SB called for inspection of all engines above 20,000 CSN or engines having experienced more than one shop visit.
- Inspection or clearance by available documentation (proving blade CSN was less than 20K CSN) for the remainder of the engines and blades by August 2018.

Additional details of these SB's are described in Section 9.5.1. of the Powerplant Group Chairman's Factual Report.[40]

Two additional revisions of the SB 72-1033 were later issued:

- SB 72-1033 Revision 2 (issued July 27, 2018) which reduced the inspection interval from 3,000 to 1,600 cycles to accommodate crack propagation variation and to provide at least two opportunities to detect a crack prior to blade separation. On average, it is predicted there are 5-6 inspection opportunities to detect a crack.
- SB 72-1033 Revision 3 (issued November 6, 2018) which reduced the initial threshold for ultrasonic inspection from 20,000 to 17,000 fan blade CSN to provide additional robustness to the blade inspection program.

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[40] NTSB Docket N°DCA18MA142, 8-A Powerplant Group Chairman's Factual Report, Nov. 13, 2018, pages 100-103.

All revisions of SB 72-1033 have been mandated through AD's by both the FAA and EASA to prevent future events and contribute to the safety of the fleet.[41]

In addition to the fleet inspection program, CFM took additional actions to improve the reliability and durability of the fan blade dovetail. In October 2018, in collaboration with Boeing, CFM revised the Maintenance Planning Document (MPD) task for the fan blade relube to reduce the relubrication interval from 3,000 to 1,600 cycles. This shorter relubrication interval promotes reduced friction levels in the fan blade dovetail/disk contact zone.

CFM has also updated the fan blade dovetail requirements for the shot peening repair (Repair 004) and coating refurbishment repair (Repair 002). CFM has designated Repair 004, "*Shot peening of the Fan Rotor Blade*", as a "source substantiated" repair to ensure the operation imparts the design intended beneficial residual stresses and limits potential process variation. The updated Repair 004 was validated July 2018.

In Repair 002, "*Reconditioning of the CuNiIn Thermal Spray coating and The Dry Film lubricant varnish on the fan Rotor Blade Root*", CFM has instituted more stringent requirements via the following changes:

- Periodic specimens required every 24 hours
- Coating overspray and abrasive blasting restricted from fan blade radius
- Additional fan blade dovetail thickness coating measurements

The updated Repair 002 was approved July 2018.

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[41] *See* FAA Emergency AD (EAD) 2018-09-51, FAA AD 2018-09-10, FAA AD 2018-10-11, FAA AD 2018-18-01, and EASA Emergency AD (EAD) 2018-0093E, EASA AD 2018-0109, EASA AD 2018-0211. Additional ADs requiring CFM56-7B fan blade repetitive inspections as per SB 72-1033 Revision 3, have been published by FAA and EASA after publication of [NTSB Docket N°DCA18MA142, 8-A Powerplant Group Chairman's Factual Report] (FAA AD #2018-26-01 issued on Dec. 26, 2018 and EASA AD #2019-0018 issued on Jan. 30, 2019.)

VII. Probable Cause

The probable cause of the accident was the liberation of a portion of the fan cowl, which created a hazardous condition by impacting the airplane fuselage and cabin window.

The following sequence of events is supported by the factual evidence, including the engine and nacelle hardware condition, laboratory and metallurgical evaluations of the hardware, analysis of the digital data recorded during the event, and state-of-the art analysis of the engine and nacelle behavior after the blade loss.

The probable sequence of events during Flight 1380 is as follows:

- A low-cycle fatigue crack initiated in the fan blade root after ~15,000 cycles of operation and propagated for ~18,000 cycles of additional operation (total of 33,000 cycles of operation or 17 years of operation);
- Blade separated at root at crack location;
- Initial impact was on fan case at 3:30, with the heaviest impact force occurring near the 6:00 position of the fan case;
- Deflections and loads from the blade impact are transmitted from the fan case through the fan cowl radial restraint fitting located near the 6:00 position;
- These transmitted loads initiate cracks within the fan cowl structure. Those cracks are propagated from mechanical and aerodynamic loading and result in the fan cowl liberation in less than 0.1 second after blade release;
- A portion of the fan cowl that was liberated damaged the airplane fuselage and a cabin window, creating a hazardous condition to the airplane and resulting in a fatal injury to one passenger.

The loading and the displacement wave predicted behavior were shown to be consistent with certification test experience. However, in the original loading assumptions used by Boeing/Collins at the time of the engine and airplane certification, it was assumed that the radial restraint fitting would have failed, prior to transmitting high loads to the fan cowl. The remaining structure was assessed and the cowls were predicted to sustain the FBO loading without departure.

During the event, a significant inlet portion of the nacelle was also liberated and created damage to the airplane based on the evidence gathered during the investigation.

VIII. CFM Recommendations

In addition to the fleet-wide actions already discussed (see. §VI), CFM makes the following recommendations:

Recommendation relative to engine and nacelle FBO development and integration:

- *Launch industry committee working group to study recent FBO trends and learnings*

  Several FBO events have occurred across the aviation industry over the past several years. The working group would include but not be limited to the regulators, airframers, and engine manufacturers. The objective of this working group would be to compile legacy and recent FBO events, determine what, if any, common factors exist among them and identify and communicate relevant lessons learned throughout the industry.

Recommendation relative to fan blade field management:

- *Consider use of enhanced Non-Destructive Testing (NDT) inspections on metallic fan blades that use coated dovetails during coating refurbishment and repair*

  The dovetail coating used to avoid parent metal fretting of the blade dovetail and the processes required for the coating can potentially modify the detection capability of the FPI process in the uncoated state. This can result from the background fluorescence from the grit blasted surface which potentially masks the existence of an LCF crack as well as the potential for residual coating preventing the inspection fluid from flowing into the crack. This detectability variation was observed in the laboratory evaluation of fan blades in the uncoated condition (parent metal) exhibiting LCF cracks in the area of interest. The potential enhanced inspection could be considered when the coating is removed during the refurbishment process.