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19 July 2019
66-ZB-H200-ASI-19098

Bill English
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BOEING

Subject: Boeing Submission for Southwest Airlines 737-700 N772SW Engine Failure and Depressurization, Philadelphia, PA - 17 April 2018

References: E-mail, 20 June 2019, NTSB to Boeing, SWA1380 Structures Report Review (NTSB Technical Review)

Dear Mr. English:

As requested in the reference e-mail regarding the technical review, please find the attached Boeing submission on the subject accident. Per your request we are sending this electronic version to your attention for distribution within the NTSB.

We would like to thank the NTSB for giving us the opportunity to make this submission. If you have any questions, please don't hesitate to contact us.

Best regards,

[redacted]

Robert J. McIntosh
Director, Product Safety

Enclosure: Boeing Submission to the NTSB for the subject accident

Submission to the

National Transportation Safety Board

for the

# Southwest Airlines 737-700 N772SW Engine Failure and Depressurization Philadelphia, PA 17 April 2018

**The Boeing Company**
**19 July 2019**

## INTRODUCTION

On April 17, 2018, at 1103 Eastern daylight time (EDT), Southwest Airlines flight 1380, a Boeing 737-700, registration number N772SW, powered by two CFM56-7B turbofan engines experienced a left engine failure and loss of portions of the engine inlet and fan cowl during climb through flight level (FL) 320. Fragments from the engine inlet and fan cowl struck the wing, empennage, and fuselage, resulting in one cabin window departing the airplane and cabin depressurization. The flight crew conducted an emergency descent and diverted into Philadelphia International Airport (KPHL), Philadelphia, PA. Of the 144 passengers and five crewmembers onboard, one passenger received fatal injuries and eight passengers received minor injuries. The airplane sustained substantial damage. This regularly scheduled domestic passenger flight was operating under 14 Code of Federal Regulations Part 121 from LaGuardia Airport (KLGA), Queens, New York, to Dallas Love Field (KDAL), Dallas, Texas.


### Submission Abstract

- The Boeing Company, as the airplane's manufacturer, is an invited party to the investigation and provides technical and operational assistance to the National Transportation Safety Board (NTSB) in their investigation.
- The conclusions presented in this submission are based on factual information received from the NTSB, Boeing expertise, the use of analytical tools, and a methodical investigation process.
- During climb, the left engine experienced an engine failure involving the loss of a single fan blade. This caused portions of the engine inlet and fan cowls and a passenger window to depart the airplane. One passenger received fatal injuries.
- The airplane and all airplane systems were functioning as expected prior to the engine failure. After the engine failure, the airplane systems and remaining structures functioned properly to maintain continued safe flight and landing.
- The engine control and fuel cutoff systems functioned as designed enabling shut down of the left engine when commanded by the flight crew.
- The flight crew and passenger oxygen systems performed as expected to protect the occupants during the depressurization and descent.
- The fan blade failure and the subsequent fan blade fragments and their trajectories resulted in the structural failures of the engine nacelle during the engine failure.


## BOEING ASSISTANCE WITH THIS INVESTIGATION

The National Transportation Safety Board (NTSB) is conducting the investigation into this Southwest Airlines 737-700 accident. Assisting the NTSB in their investigation are the Federal Aviation Administration (FAA); the NTSB's French equivalent, the Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA); CFM (General Electric Aviation and Safran); Boeing; Collins Aerospace; and other designated parties.

As the manufacturer of the 737-700 airplane, Boeing's specific role in this investigation has been to provide technical information regarding the airplane design, manufacture, and operation to assist the NTSB.

The NTSB requested that all parties submit proposed findings to be drawn from the factual information established during the course of the investigation. Boeing has responded to the NTSB request with this document, which:

- Provides an assessment of the factual information and other pertinent data;
- Identifies knowledge gained from the investigation; and
- Identifies conclusions supported by the knowledge gained from the investigation.

## BOEING ASSESSMENT

The Boeing assessment of the accident is based upon the facts as documented in the NTSB's factual reports, Boeing expertise, the use of analytical tools, and a methodical investigation process. These reports contain observations of the airplane and accident site, post-accident examination of airplane systems and components, flight data recorder (FDR) data, the cockpit voice recorder (CVR) transcript, airline maintenance records, materials and systems laboratory data, and crew interview data.

## WEATHER

The engine failure occurred near latitude 40.4411° N, longitude 76.2373° W, at FL320 northeast of Harrisburg, Pennsylvania. The nearest wind aloft reporting point at 1000 EDT noted wind at 30,000 feet from 290° at 64 knots with a temperature of -43° C, and a wind at 34,000 feet from 280° at 51 knots with a temperature of -42° C.[1] The flight diverted to KPHL, conducted a visual approach to runway 27L, and landed at 1121 EDT. The KPHL weather observation at 1054 EDT reported winds from 290° at 18 knots with gusts to 27 knots, 10 miles visibility or greater, broken ceiling at 4,800 ft AGL, broken skies at 8,000 ft AGL, and a temperature of 45° F (7° C).[2] Weather conditions were not considered to be factors in this accident.

## THE ACCIDENT AIRCRAFT

The Boeing Company delivered the airplane (registration N772SW, serial number 27880) on July 7, 2000. The airplane had 63,521 total hours with 37,021 total cycles at the time of the accident. The airplane was equipped with two CFM56-7B engines.

## FLIGHT AND CABIN CREW

The crew consisted of the Captain (CA) and First Officer (FO) and 3 flight attendants. The FO was the pilot flying (PF) and the captain was the pilot monitoring (PM) when the engine failure occurred. After the engine failure, control of the airplane was transferred and the captain became the PF.

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[1] NTSB Meteorology Factual Report, dated 30 August 2018, page 30

[2] NTSB Meteorology Factual Report, dated 30 August 2018, page 12

## SEQUENCE OF EVENTS

Below is a chronological overview of the events that occurred based on the FDR data, cabin pressure controller and EEC non-volatile memory (NVM), CVR transcript, structural analysis, and crew interviews. The events below are referenced to an estimated elapsed time (+/- *minutes:seconds.milliseconds*) from when the engine failure occurred. References to explicit times represent local time during the event which was Eastern Daylight Time (EDT). All times should be considered approximate.

| Estimated Elapsed Time | Event Description |
|---|---|
| t = 00:00.000 | Left engine failure occurs at 1103 EDT (estimated based upon FDR data, including recorded acceleration, pitch, roll, and engine data). |
| t = +00:00.070 to +00:00.100 | Portions of the left engine fan cowl depart the airplane (estimated based upon structural progressive failure analysis). |
| t = +00:00.070 to +00:00.500 | Portions of the left engine inlet cowl depart the airplane (estimated based upon structural progressive failure analysis). |
| t = +00:00.070 to +00:03.170 | Passenger window departs the aircraft, likely as a result of an impact by portions of the left engine fan cowl (estimated based upon FDR data, depressurization analysis, and structural progressive failure analysis). |
| t = +00:04.400 to +00:05.400 | Cabin Altitude Warning is recorded on the FDR indicating that the cabin altitude reached approximately 10,000 feet. |
| t = +00:09.800 | Airplane begins to descend. |
| t = +00:34.410 to +00:35.410 | Left engine is shut down by flight crew when the left engine fuel control switch was moved from the RUN to CUTOFF position. |
| t = +08:50.800 | Cabin Altitude Warning is no longer active indicating that the cabin altitude is below approximately 10,000 feet. |
| t = +16:56.800 | Airplane touches down on runway 27L at KPHL. |

## POWERPLANT

The accident airplane was powered by two CFM56-7B24 turbofan engines. The left engine installed on the accident airplane (registration number N772SW) was engine serial number (ESN) 875134. This engine was installed on N772SW on November 29, 2012.

Examination of the left engine following the event revealed that fan blade no. 13 separated at the root and the dovetail remained attached to the fan disk. Fan blade no. 13 entered service when it was first installed in an engine in 2001 (not the accident event engine). At that time, it was installed with the 23 other fan blades that were on the accident aircraft's left engine, which stayed together as a set throughout their service history. The set of fan blades were installed on the accident engine in September 2012. The useful life of a fan blade is defined both by how many hours and how many takeoff/landing cycles it has flown since it was manufactured. At the time of the accident, the blades had accumulated 55,471 hours and 32,636 cycles.[3] When the fan blades were designed, they were expected to have a fatigue life of more than 100,000 cycles.

The fan blades were last overhauled before they were installed on the accident engine in September 2012. The blade overhaul process included, at the time, conducting a fluorescent penetrant inspection (FPI) to detect any cracks. No cracks were noted during the September 2012 inspection. The blades had been overhauled one previous time in April 2004.[4]

In between service visits, periodic visual inspection of the fan blade Cu-Ni-In coating and re-lubrication of fan blade dovetails were recommended by the engine manufacturer. This periodic maintenance was conducted within CFM recommended intervals over the life of the fan blades. Seven of these inspections and re-lubrications were accomplished since installation of the fan blades on the event engine in September 2012.[5]

As discussed more thoroughly below, the dovetail of fan blade no. 13 that remained attached to the fan disk was examined as part of the investigation. The fracture surface on that dovetail revealed features consistent with fatigue cracking. Two fan blade fragments were also recovered at the bottom of the fan case which, upon examination, were determined to be portions of the failed fan blade (no. 13).

## Laboratory Examination and Testing

All the recovered event fan blades and the hardware that attaches them to the fan disk (shims, platforms, and spacers) were examined at the NTSB Materials Laboratory in Washington DC; the GE Engineering Materials Systems Laboratory in Evendale, Ohio; and the Safran Failure Analysis Laboratory in Moissy-Cramayel, France.

The fracture surface of the dovetail remnant of fan blade no. 13 was inspected and examined using many techniques (visual, optical, scanning electron microscope, striation density, and metallographic). All other recovered fan blades were subjected to a combination of fluorescent penetrant inspection (FPI), ultrasonic inspection (UI), and eddy current inspection (ECI) techniques. No crack indications were observed on the other fan blades using these non-destructive methods.[6]

The NTSB, GE, and Safran laboratories performed extensive examination and analysis that determined the following:

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[3] Powerplant Group Chairman's Factual Report, dated 12 November 2018, pages 53-54

[4] Materials Laboratory Factual Report, dated 25 October 2018, page 3

[5] Powerplant Group Chairman's Factual Report, dated 12 November 2018, pages 53

[6] Powerplant Group Chairman's Factual Report, dated 12 November 2018, page 47

- Striations consistent with low-cycle fatigue crack growth were observed on the dovetail fracture surface of fan blade no. 13.

- Fan blade dovetail re-lube intervals appeared to reduce blade root stress.

- The Cu-Ni-In coating on the fan blade was intact and present on the contact faces at both sides of fan blade no. 13's dovetail.

- The total estimated number of cycles from development of a 0.0005 inch crack to fan blade no. 13 failure was approximately 20,000.[7]

- The crack in fan blade no. 13 that led to its failure most likely existed at the time the fan blade was overhauled in 2012, though the size of the crack may have been too small to be detected with the inspection method used at the time.

- Fan blade no. 13 failed earlier than anticipated due to stresses[8] that the fan blade was subjected to during its service life. While the stresses were reduced through modifications in how the fan blade was attached to the fan disk and how it was serviced, the high stresses early in the blade's service reduced its fatigue life, eventually leading to cracking and failure far earlier than anticipated.

## Regulatory Agency and Engine Manufacturer Actions

On August 27, 2016, a Boeing 737-700 operating as Southwest flight 3472 experienced a fan blade out (FBO) event while en route from New Orleans, Louisiana to Orlando, Florida. The aircraft diverted to Pensacola, Florida. The NTSB initiated an investigation[9] into that event. The investigation was still ongoing at the time the Philadelphia event occurred. During the investigation, CFM issued service bulletins (SB) calling for the inspection of fan blades on CFM56-7B engines with certain flight cycles and part numbers[10]. The FAA also issued a Notice of Proposed Rule Making (NPRM) in 2017 that would have made those inspections mandatory. At the time of the Philadelphia event there were no existing service bulletins or Airworthiness Directives (ADs) that would have required the inspection of the fan blade set installed on the left engine of the accident aircraft. That is because the engine and fan blade set did not meet the recommended threshold of flight cycles for inspection by the existing service bulletins.

After the Philadelphia event a series of service bulletins were issued by CFM that recommended inspections of fan blades in other CFM56-7B engines. The FAA also issued a series of ADs that made most of the inspections recommended by CFM's SBs mandatory. Here is a chart showing the various SBs and ADs:

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[7] Powerplant Group Chairman's Factual Report, dated 12 November 2018, Table 10

[8] Powerplant Group Chairman's Factual Report, dated 12 November 2018, page 110

[9] NTSB accident number DCA16FA217

[10] Powerplant Group Chairman's Factual Report, dated 12 November 2018, Table 9

| Action | SB | Date of SB release | AD | Date of AD Release |
|---|---|---|---|---|
| Required engines with greater than 30,000 flight cycles since new to be inspected within 20 days and the rest to be completed by August 31, 2018 | 72-1033 R0 | 4/20/2018 | 2018-01-51 | 4/20/2018 |
| Required inspections for certain blades with more than 20,000 flight cycles to be completed two months earlier, by June 30, 2018, and added a repetitive inspection every 3,000 flight cycles thereafter | 72-1033 R1 | 5/9/2018 | 2018-10-11 | 5/17/2018 |
| Shortened repetitive inspection period from every 3,000 flight cycles to every 1,600 flight cycles | 72-1033 R2 | 7/26/2018 | 2018-18-01 | 10/1/2018 |
| Instructions to update the inspection threshold for certain 737 business and military variants.<br>• Fans with more than 16,000 cycles since new should be inspected within 1,000 flight cycles or before reaching 20,000 flight cycles<br>• All other blades must be inspected before reaching 17,000 cycles since new<br>• If flight cycles since new is unknown, inspection must occur by November 30, 2018<br>• Imposing repeat inspection requirement every 1,600 flight cycles after the initial inspection | 72-1033 R3 | 11/6/2018 | N/A | N/A |

## AIRPLANE SYSTEMS AND STRUCTURES

The airplane and all airplane systems were functioning as expected prior to the engine event.

The left engine FBO event caused damage to the engine and nacelle structure. It also resulted in portions of the inlet and fan cowl separating from the nacelle. Some of those fragments struck the fuselage of the accident aircraft, resulting in one passenger window departing the aircraft and the depressurization of the cabin. One passenger received fatal injuries and eight others suffered minor injuries.

The adjacent airplane structures and systems in the engine strut and wing sustained the loads generated during the FBO event and maintained their integrity and function. After the FBO event the airplane systems and structures functioned properly to maintain continued safe flight and landing.

### Engine Control and Fuel System

Each engine fuel feed line on the 737-700 is equipped with a rear spar-mounted shutoff valve, also called the spar valve, to terminate fuel flow to an engine when it is shut down. After the flight crew moved the left engine start lever to CUTOFF, the left engine fuel shutoff spar valve on the accident aircraft closed as expected. This prevented further fuel flow to the damaged engine. No indications of an engine fire were recorded on the FDR or observed by the flight crew. There was no evidence of an under-cowl fire or fuel leak.[11]

### Engine Mounts and Fuel Tank Integrity

The engine mount structures of the 737-700 are designed to maintain their integrity and function during an FBO event. Examination after the event showed there was no evidence of damage to the forward and aft engine mounts and their associated links and attach hardware.[12] There were no penetrations observed common to the wing fuel tank structure and there was no evidence of any fuel leaks.

### Oxygen Systems

The 737-700 oxygen systems supply oxygen to the flight crew, cabin attendants, and passengers in the event of a depressurization. During this event, the flight crew was able to promptly don their oxygen masks and perform a descent to an altitude of 10,000 feet where they removed their masks and completed the remainder of the flight to KPHL. All of the passenger oxygen masks deployed from the passenger service units (PSU) above the passenger seats during the depressurization event. The flight attendants were able to don portable oxygen bottles, move through the cabin, and assist passengers to ensure each passenger was receiving oxygen from an overhead mask.[13]

### The Nacelle

The nacelle is the structure that surrounds the engine. At the front of the nacelle is the inlet. The inlet is an aerodynamic assembly that directs smooth, uninterrupted airflow into the engine, and around the external surface of the nacelle. Below are two diagrams showing the inlet on the front of the nacelle from different angles:

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[11] Powerplant Group Chairman's Factual Report, dated 12 November 2018, page 42

[12] Powerplant Group Chairman's Factual Report, dated 12 November 2018, page 31

[13] Survival Factors Group Chairman's Factual Report, dated 31 October 2018, page 7


**Fig. 1 and 2.** Pictures of CFM56-7B engine highlighting inlet.

The structure of the inlet includes an outer barrel, inner barrel, attach ring, aft bulkhead, forward bulkhead, and a lip skin at the front of the inlet. Below is a diagram showing some of those parts of the inlet, with each in a different color (the attach ring, aft and forward bulkheads are not shown):

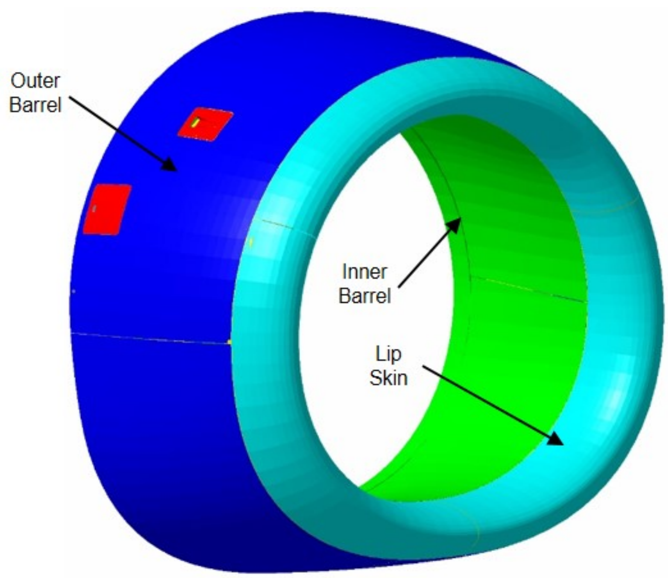


**Fig. 3.** Diagram of inlet.

The inner barrel of the inlet includes a containment doubler that, as described below, was added during the certification process to protect the inlet from damage caused by a forward traveling fan blade fragment. The containment doubler works by containing the fan blade fragment inside the inlet, reducing its energy as it travels through the inlet structure.  Below is a cross-section diagram of the inlet that shows the containment doubler and other parts of the inlet:

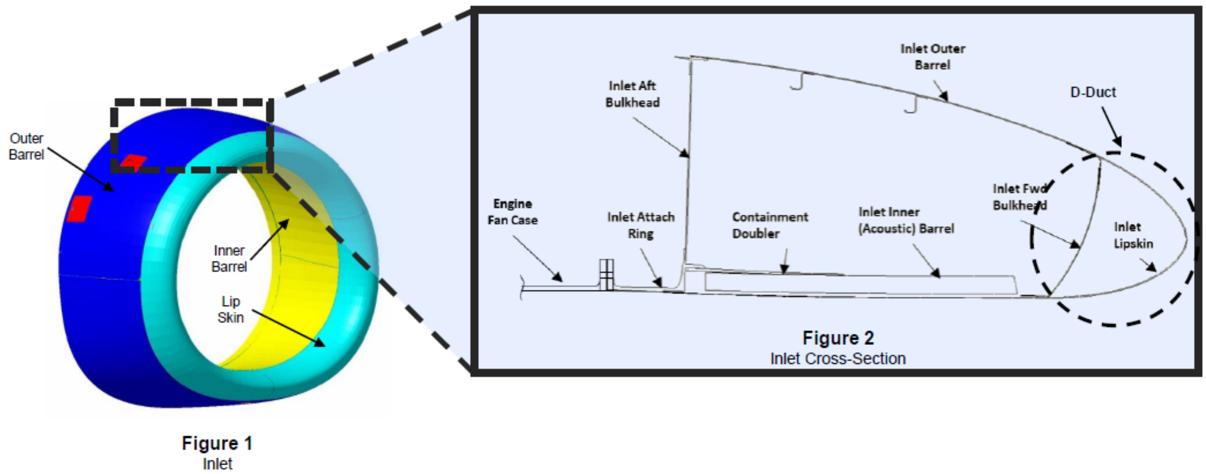


**Fig. 4.** Cross-section diagram of inlet.

Aft of the inlet on the nacelle is the fan cowl. The fan cowl is an aerodynamic fairing that encloses the engine fan case, extending from the aft end of the inlet to the forward end of the thrust reverser. The primary function of the fan cowl is to provide smooth aerodynamic flow along the external surface of the nacelle. Below is a diagram showing where the fan cowl is on the nacelle:


**Fig. 5.** Picture of CFM56-7B engine highlighting the fan cowl.

The fan cowl is constructed in two halves that are connected by three hinges at the top of the fan cowl. The two halves then close around the engine's fan case and are latched at the bottom by three latches. A radial support fitting attaches the bottom of the fan cowl to the engine fan case. Below is a diagram of the inside of the fan cowl:

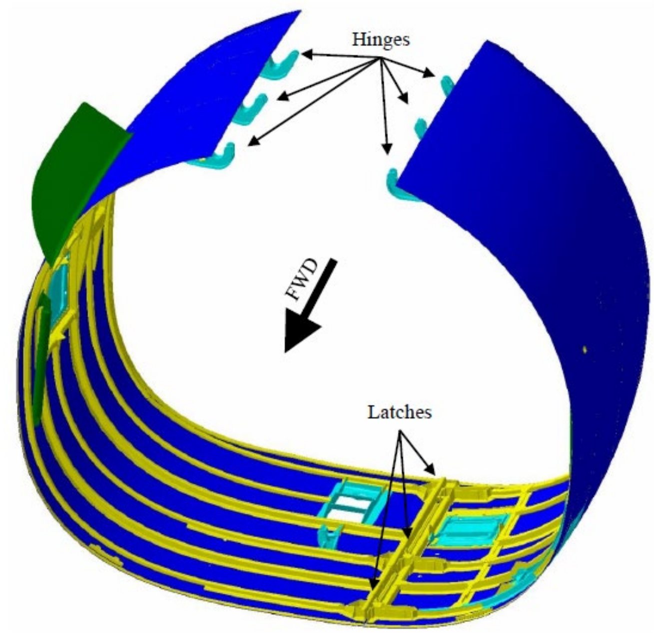


**Fig. 6.** Diagram of fan cowl.

## Damage to the Nacelle During the Accident

Following the separation of fan blade no. 13, portions of the left engine's inlet and fan cowl departed the airplane due to damage caused by the event. The inlet's inner barrel, aft of the containment doubler leading edge, remained attached to the engine fan case. Portions of the outboard fan cowl below the hinges also remained attached to the engine. A damaged portion of the inboard fan cowl remained attached to the engine with the lower half missing.

Following the accident, investigators attempted to recover as many of the pieces of the nacelle that had separated as possible. Approximately 90% of the inlet and 80% of the fan cowl structures were estimated to have been recovered.[14] As discussed more thoroughly below, those recovered structures were examined as part of the investigation.

## The Effect of Fan Blade Out Events on an Aircraft's Structure

The accident aircraft experienced an FBO event, which means that a fan blade in one of its engines broke off while in flight. Below is a picture showing the fan blades inside the fan case when they are all intact:

[14] Powerplant Group Chairman's Factual Report, dated 12 November 2018, pages 33 and 34

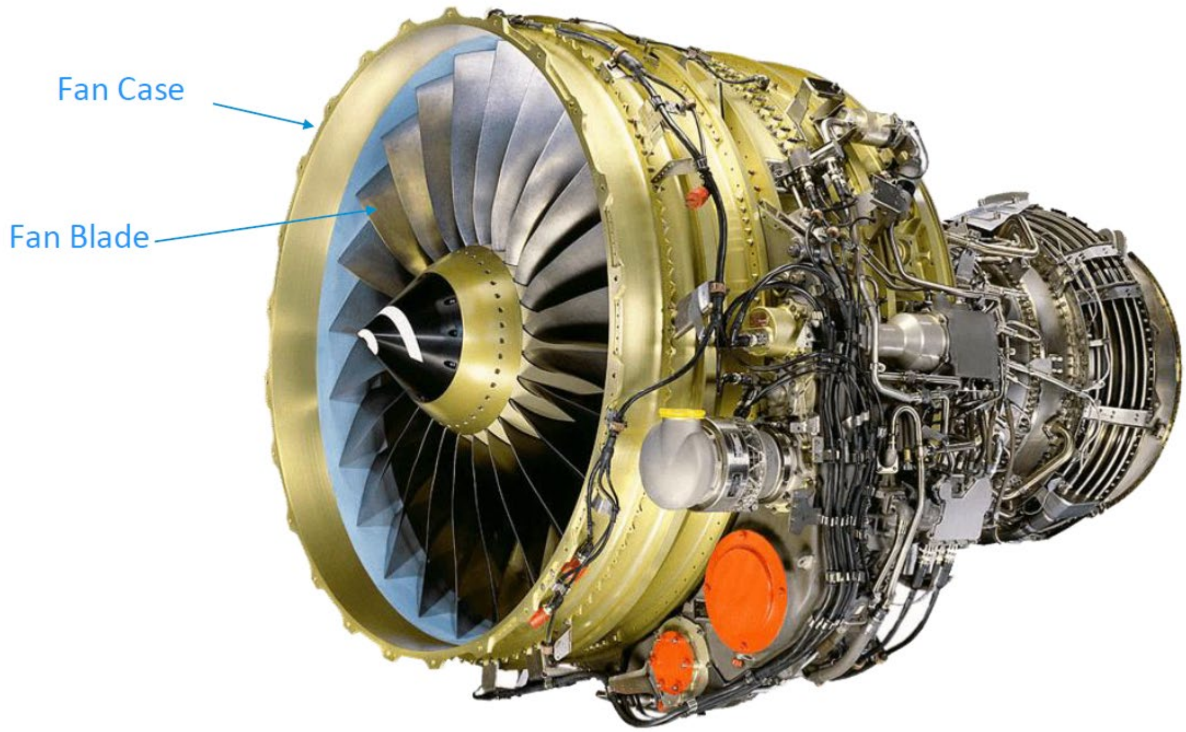


**Fig. 7.** Picture of a CFM56-7B.

In considering the effects of the FBO event on an aircraft's engine and the surrounding structure, it is helpful to break the event down into four phases based on our current understanding which has evolved since 737-700 certification:

- **Impact phase (0.0 to 0.02 seconds)**: When the aircraft engine is running, the fan blades are rotating at high speeds. When part of a fan blade breaks off, the forces from the rotation cause it to travel away from the center of the fan disk, striking the fan case that surrounds the engine. That impact imparts forces into the fan case that cause it to deform outwards. That outward deformation can be viewed as a displacement wave that then travels both around the circumference of the fan case and forward and aft of the impact point until it depletes its energy. That deformation can cause damage to the surrounding structure. The impact also typically causes the portion of the fan blade that strikes the fan case to break into fragments of different sizes that can travel forward into the inlet or aft into the rest of the engine. When traveling forward into the inlet, the fragments are often rotating around the circumference of the fan case and inlet in a helical pattern, scraping across the fan case and then inlet. As they travel forward in the helical pattern, those fan blade fragments can cause damage to the inlet. Below is a diagram illustrating the helix angle at which fan blade fragments can travel:

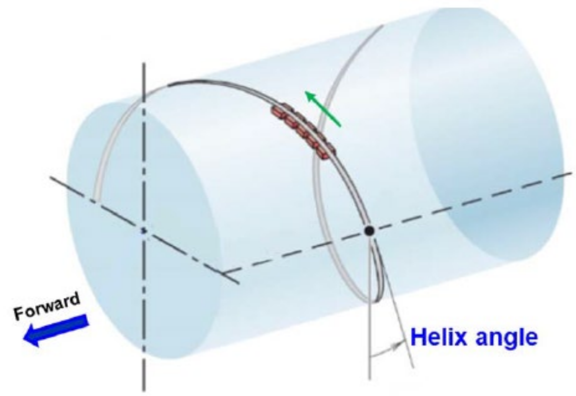


**Fig. 8.** Diagram showing helical pattern of forward-moving fan blade fragments.

- **FBO surge phase (0.02 to 0.2 seconds)**: With one fan blade missing, the fan rotor becomes unbalanced, which causes the remaining fan blades to rub against the fan case (normally there is clearance between the fan blades and the fan case). That contact in turn rapidly slows the fan rotor and related components, changing the pressure within the engine, which is normally carefully balanced. At the same time, the absence of one fan blade disrupts the normal air flow through the engine, causing additional pressure changes. The result of all this is a surge of high-pressure air flow through the engine, exiting the front and back of the engine. That surge can cause additional damage to the inlet.

- **FBO rundown phase (0.02 to 2.0 seconds)**: Following an FBO event, the fan rotor decelerates as the engine shuts down. This deceleration or “run down” typically takes approximately 2 seconds. During this time the surrounding structure experiences significant vibratory loading from the fan rotor deceleration, fan blade rubbing forces, and the imbalanced engine.

- **Windmilling phase (2.0 seconds to landing)**: Even after the engine decelerates, the fan continues to rotate due to airflow through the engine, albeit at a slower speed than when the engine is powering rotation. The continued imbalance caused by the damage to the fan blades imparts vibratory imbalance loads on the connecting structure.

## FBO Certification History

As part of the FAA’s certification, engine and aircraft manufacturers are required to meet certain requirements in the event that an FBO condition occurs.[15]

To address the FAA FBO regulations for the 737-700, Boeing developed analytical models and used state-of-the-art tools available at the time to predict the loads that the engine and surrounding structure would likely experience in an FBO event. Boeing conducted two structural analyses. The first modeled the rundown loads on the engine and the structures attached to the engine in the first few seconds after an FBO event, before the engine is shut off. The second modeled the entire airplane to help assess the effect of windmilling vibratory loads

[15] FBO certification requirements are discussed in more detail within the Powerplant Group Chairman’s Factual Report, dated 12 November 2018, sections 6.1 and 6.2.

imparted by the rotating, unbalanced fan from engine shutoff to landing. Boeing then provided these loads to CFM, who designed and manufactured the accident engine, and Collins, who designed and manufactured the inlet and fan cowl. CFM and Collins designed their components to withstand these predicted loads while remaining attached to the aircraft.

The engine also underwent extensive testing for 14 CFR Part 33 certification. As part of the regulatory requirements for FBO, engine manufacturers are required to (1) design and manufacture the fan case to prevent blade fragments from punching through it and (2) measure the behavior of the fragments that travel forward or aft beyond the fan case so that the aircraft manufacturer can account for them. The type of testing needed to meet these requirements is specified in the regulations and the resulting data provided by CFM helped Boeing and CFM understand the way the fan blades behave after release, confirm the accuracy of the models' predictions, and validate the engine and surrounding structure would perform as expected. There were two types of tests performed during the certification of the 737-700 and CFM56-7B: rig tests and certification tests.

In a rig test, a prototype partial engine is mounted in a vacuum chamber and one blade is rigged to release using explosives. These preliminary tests were designed to collect information about how the engine performs during an FBO event, including the way blades break up and how the fan case contains them.

In a certification test, the engine is mounted on a test-stand in open air. One blade is rigged to release using explosives so that at least 80 percent of the blade breaks off at the highest permissible rotation speed. This is a system-level test designed to demonstrate compliance with regulations requiring that the fan case contain all blade fragments. These certification tests are required under FAR Part 33 related to engine certification, which is separate from aircraft certification under FAR Part 25. As a result, aircraft manufacturers like Boeing are not required to test adjacent structure, such as the nacelle, as part of these Part 33 tests (though a test inlet does need to be used, as the inlet imparts stiffness to the fan case). Nonetheless, during the certification of the 737-700, Boeing decided to include a production-representative inlet on one of these certification tests to collect additional data and validate the design of the inlet. Boeing also chose to include a representative inlet on one of the rig tests as well, again to gather additional data and validate the design.

During rig and certification tests, high-speed cameras record the fan case from all angles. The fan cowl cannot be installed during the test, as it would hide the fan case from the cameras. Including the fan cowl in the test also is not necessary, as the purpose of the test is to certify the fan case's ability to contain the broken fan blade, and the fan cowl does not help the fan case with containment. While the fan cowl is not tested, it is designed and certified using the models described above that predict the loads that it will be subjected to during an FBO event. The loads used in those models are validated by data gathered during the tests.

Over a two-year period, the CFM56-7B engine underwent eight rig tests and two certification tests.

The first three rig tests were held in 1994. These tests helped CFM understand how the blades behaved after release and confirm that the fan case contained all the fragments. In each of these tests, blades installed adjacent to the released blade experienced failures in the components that hold each fan blade in place (collectively called the axial retention system). Following each test, the axial retention system was subsequently modified to prevent the loss of adjacent trailing blades. In these first three rig tests, all blade fragments were contained by the fan case.

These first three rig tests provided consistent information about the way in which the fan blade fragments and how those fragments travel. The next step was to do a rig test with production hardware and all fan case accessories. While not required by regulation, Boeing knew from its experience on other models that valuable information could be gained by conducting rig tests using a production-representative inlet. Unlike fan cowls, inlets interact with the fan case and affect the way the fan case behaves during FBO events. As a result, Boeing used a production-representative inlet on the fourth rig test in 1995 ("rig test 4"). At that point, the inlet did not yet have a containment doubler.

During rig test 4, the inlet sustained significant damage. The inlet inner barrel sustained damage from a blade fragment that spiraled forward beyond the fan case and pierced through the inlet. Additionally, the inlet attach ring, and a small portion of the inner barrel under the attach ring, sustained some structural failures.

Following rig test 4, CFM defined the size and trajectory of the blade fragment that damaged the inlet (10-15 degree helix angle, mass of approximately 2 pounds, velocity of 853 feet/second).[16] CFM, Boeing, and Collins worked together to analyze the results of the test and worked together to make two significant changes to the inlet design to prevent the damage observed in rig test 4 from occurring in the future. To address the failed containment, Boeing required[17] Collins to design the containment doubler to contain blade fragments. The length of the doubler depends on certain variables, including the angle at which the fragment enters the inlet and the size of the fragment. The wider the angle or the larger the size of the fragment, the longer the doubler must be to contain it. In designing the containment doubler, Collins used the trajectory and fragment size that CFM had defined based on data from rig test 4, with an increased conservatism added by Boeing.[18] Collins redesigned the inlet attach ring to increase the stiffness of the inlet and to accommodate the addition of the containment doubler.

A certification test of the redesigned engine occurred in April 1996. Although not required, Boeing decided to again include a production-representative inlet in the test to validate the changes that had been made to the inlet. During the initial part of the test, which was intended to involve the release of only one blade, the damage caused by fragments from the first blade to be released matched the Boeing analytical model predictions and were contained by the doubler. After a short time, five additional blades released due to a failure of the blade's axial retention system. These five trailing blades penetrated 160 degrees around the engine through both the inlet and fan case. Accordingly, the axial retention system of the blades needed to be modified. Notably, despite the significant damage caused by the release of six blades, the inlet remained attached during this test.

Following this test Boeing and Collins again met to discuss the results of the test. After reviewing high-speed footage from the test, they determined that the containment doubler had successfully contained the fragments from the first blade that was released and prevented significant damage from being done to the inlet, thus validating the design of the containment

[16] Powerplant Group Chairman's Factual Report, dated 12 November 2018, page 69 and page 76

[17] Powerplant Group Chairman's Factual Report, dated 12 November 2018, page 70

[18] Powerplant Group Chairman's Factual Report, dated 12 November 2018, page 70

doubler. CFM made changes to the engine design to ensure that in a future FBO event, the release of one blade would not result in other blades being released.

To resolve the axial retention issues, CFM conducted five additional tests - four rig tests and one certification test. None of these tests incorporated production-representative inlets, as the prior tests had validated the inlet design. In all five tests, blade breakup and containment characteristics were consistent with prior tests. After the final certification test CFM confirmed that the weight and speed of the fragments were consistent with the values that CFM defined based on data from rig test 4.

During the testing discussed above, CFM collected information on the size and trajectories of blade fragments and gathered extensive data on the other forces that occurred during FBO testing. Boeing and CFM worked together to analyze that data and determine how it would affect the aircraft's structure.

The data developed from those efforts were then used to validate the Boeing models. Each rig or certification test used only one clock position release angle at which the blade was released, modeling allowed Boeing to take the data from the test and apply it to the nacelle based on different fan blade clock position release angles. It also allowed Boeing to account for other variables that might affect the forces involved in an FBO event, such as different levels of fuel that might be present when the event occurs (affects wing dynamic response) and also whether the FBO event occurred on a left or right engine. All told Boeing modeled 144 different FBO event scenarios, involving twenty four different release angles, three different fuel levels, and releases in both left and right engines.

The result of all this modeling was to define the worst-case forces that critical parts and interfaces of the nacelle might be subjected to during an FBO event. That information was then supplied to Collins, who substantiated that the portions of the nacelle it designed (the inlet and fan cowl) could withstand those forces. With respect to the inlet, that substantiation included assumed damage caused by blade fragments, which was defined based on data from the tests. Consistent with the rig and certification test results, the substantiated foreseeable damage was limited to areas within the containment doubler.

## Fan Blade Fragment Trajectories During the Accident Event

The investigation examined the remaining attached inlet structure from the left engine of the accident aircraft along with the portions of the inlet that were recovered. Based on evidence obtained during that investigation, the NTSB and parties worked together to assess the fragment-induced inlet damage.

The released fragments of a fan blade are typically discussed as falling into three categories: (1) tip panel, (2) mid-span fragments, and (3) a root fragment. Below is a diagram providing an example of these fragments next to a photograph of an intact blade:

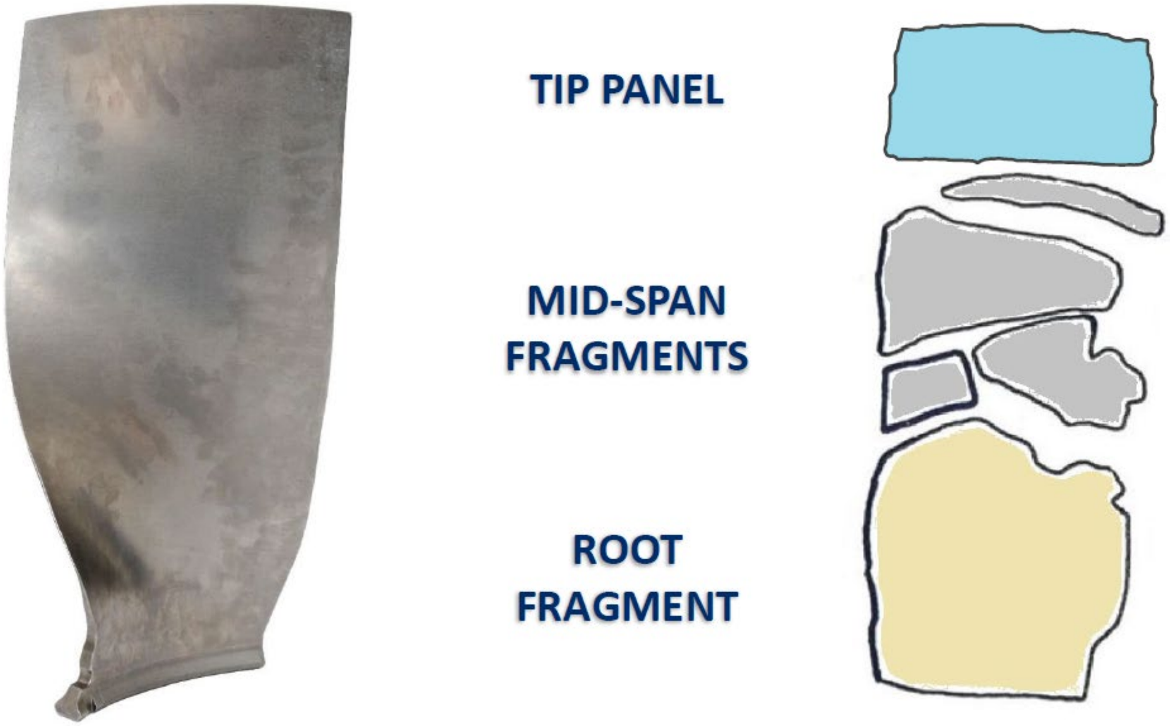


**Fig. 9.** Comparison of intact fan blade and the three blade fragment categories.

The tip panel is typically the most energetic fragment that enters the inlet.

Boeing and Collins calculated the helix angle at which the blade fragments entered the inlet during this event by examining scrapes inside the inlet (called witness marks) and the damage observed in the inlet. Based on witness marks, Boeing and Collins have concluded that the fan blade tip first hit the fan case at about the 6:00 o'clock position[19]. It then broke into a number of fragments, with the tip panel and some mid-span fragments traveling forward into the inlet. Based on witness marks, the tip panel entered the inlet near the 6:45 o'clock position with a helical trajectory angle of about 30 degrees. Traces of the fan blade material (titanium alloy Ti-6Al-4V) were found on a section of compressed core in the inlet. Tracing the path the fragments followed back to the fan case demonstrated that the tip panel was traveling at a 30-degree helix angle when it entered the inlet, consistent with the witness marks observed in the aft part of the inlet[20]. Evidence also demonstrates that the mid-span fragments of fan blade no. 13 entered the inner barrel at helix angles between 20 and 30 degrees.[21]

Boeing does not believe that the witness marks or the observed damage can be explained by a tip fragment traveling at a helix angle of less than 30 degrees.

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[19] All directional references to clockwise and counterclockwise are made aft looking forward (ALF) as is the convention unless otherwise stated. All numbering is in the circumferential direction starting immediately clockwise from the 12:00 o'clock position and progressing sequentially clockwise ALF unless otherwise stated. The direction of rotation of the engine is clockwise ALF.

[20] Report from Party – Collins dated 18 April 2019, page 16

[21] Report from Party – Collins dated 18 April 2019, page 23

The 30-degree angle observed in this event was significantly higher than the 15-degree angle that CFM had defined and validated based on data from development and certification tests.

## Analysis of the Damage to the Nacelle During the Accident Event

The NTSB asked Boeing to model the accident event to better understand the cause of the damage sustained by the inlet and fan cowl. Boeing used data collected during the investigation, including data from observations and laboratory examinations of recovered components. Using that data, Boeing employed current state-of-the-art structural analysis methods, which were not available at the time of certification, to conduct a progressive failure analysis. Boeing then validated that analysis by comparing the results to the actual hardware recovered following the accident. The below paragraphs summarize the results of that analysis for both the inlet and fan cowl and Boeing's interpretation of them.

<u>Inlet</u>: The inlet was damaged during the accident event by forward traveling fan blade fragments that entered the inlet along a helical path with fragment quantity, total mass, and trajectory exceeding the values defined at the time of certification. The resultant inlet damage was significantly greater than the damage level observed and predicted during certification.

The results of the accident event analysis were consistent with the inlet experiencing initial structural damage during the displacement wave and fan blade fragmentation phases, which then propagated during the engine rundown phase, resulting in large portions of the inlet departing the aircraft. The inner barrel, which was initially damaged by fan blade fragment impacts forward of the containment doubler, sustained additional damage from the imbalance loading during rundown. The minimum level of inlet damage attributed to fan blade fragments (150° of damage to the inner barrel perforate skin as well as 70° of damage through the inner barrel back skin forward of the containment doubler) was confirmed via metallurgical evaluation which considered the lack of fatigue striations along fracture surfaces, titanium fan blade material transfer, and scanning electron microscopy evaluation. During the rundown, the remaining inner barrel that was not damaged by fan blade fragments experienced a 360° circumferential failure, allowing separation from the rest of the inner barrel.

As described above, the containment doubler was designed to prevent the type of damage to the inlet that was observed during the accident. The doubler was designed to protect against the worst-case blade fragment trajectory and size, as defined based on data gathered during the development process, with an additional layer of conservatism. That definition was validated by subsequent data from multiple development and certification tests, which showed similar sizes and trajectories of fragments. It was also validated by CFM's experience with other engine models, which demonstrated similar blade fragment characteristics. The doubler was tested during a certification test (002/2). Boeing and Collins carefully studied the results of that test and concluded that the doubler had performed as expected. In this event, however, the size and trajectory of the blade fragment exceeded what was defined during the certification.[22] This caused fan blade fragments to travel past the containment doubler, causing significant damage to the inlet.

<u>Fan Cowl</u>: The damage to the fan cowl was also unexpected. During the certification process, Boeing had modeled how an FBO event would affect the fan cowl based on twenty four

[22] Structures Group Chairman's Factual Report, dated 21 June 2019, page 16

different release angles (clock position). Those models, while done with the state-of-the-art technology for the time, were limited in their ability to predict how all potential load paths would transmit loads throughout the structure. In the accident, the fan blade fragment impacted the engine fan case near the 6 o'clock position, near the radial restraint fitting. That impact resulted in local deformation in the fan case that transmitted loads through the radial restraint fitting and into the fan cowl differently from what was anticipated at the time of certification. This load caused cracks to form in the fan cowl skin and frames that propagated, resulting in portions of the lower part of each fan cowl half separating and departing the airplane.

## KNOWLEDGE GAINED DURING THE INVESTIGATION (Findings)

The following knowledge gained is pertinent to drawing conclusions:

- Weather conditions were not a factor in this accident.
- During climb the left engine experienced an engine failure involving the loss of a single fan blade. Portions of the engine inlet and fan cowls and a passenger window departed the airplane, which tragically resulted in fatal injuries to one passenger.
- The airplane and all airplane systems were functioning as expected prior to the engine event. After the engine event, the airplane systems and remaining structures functioned properly to maintain continued safe flight and landing.
- The fan blade failure and the subsequent fan blade fragments and their trajectories resulted in the structural failures of the engine nacelle during the engine failure.
- Fan blade fragments entered the inlet along a helical path with fragment quantity, total mass, and angles in excess of those defined at the time of certification. Inlet damage from these forward travelling blade fragments was significantly greater than the damage level defined at the time of inlet certification.
- Structural damage caused by forward traveling fragments resulted in portions of the inlet departing within 0.5 second.
- The fan blade impacted the fan case adjacent to the radial restraint fitting location at 6:00. Due to the energy introduced into the fan cowls at this location, cracks initiated and propagated in the inboard fan cowl during subsequent FBO rundown and external aerodynamic pressure loading.
- As a result, portions of the fan cowl departed the airplane within 0.1 second after blade release.

## CONCLUSIONS

Boeing believes that the evidence supports the following conclusions for the accident:

> This accident occurred due to failure of the left engine and the subsequent engine nacelle damage resulting from forward traveling fan blade fragments and fan blade-out loads generated during the event. The engine failure was due to a fracture in a single fan blade that showed signs of low cycle fatigue crack growth. The fan blade failed earlier than expected due to stresses that the fan blade was subjected to during its service life. Portions of the inlet cowl departed the airplane due to fan blade fragment damage to the inlet inner barrel forward of the containment doubler significantly greater than the damage level defined and evaluated at the time of inlet certification. Portions of the fan cowls departed the airplane due to the impact of the fan blade on the engine fan case at the 6 o'clock position and subsequent load transfer to the fan cowl structure.

## BOEING ACTIONS

As a result of this investigation, Boeing has taken the following actions:

- Boeing released Fleet Team Digest article 737NG-FTD-71-18001 in July 2018 informing 737NG operators of the ongoing NTSB investigation into this event and the issuance of CFM SB 72-1033 and associated airworthiness directives from the FAA (AD 2018-09-51) and EASA (AD 2018-0093) related to fan blade inspections for fatigue damage.
- Boeing released a temporary revision for the repetitive fan blade dovetail lubrication interval in the Boeing 737-600/-700/-800/-900/-900ER MPD on October 12, 2018 in accordance with dovetail inspection interval recommendations from the engine manufacturer. The revised repetitive lubrication interval is every 1,600 cycles or 4,000 flight hours whichever comes first. The MPD was updated to include this revised fan blade dovetail lubrication interval in the June 15, 2019 revision.
- Boeing continues to work with the FAA, engine manufacturers, and the industry as part of the FAR 21.3 continued airworthiness corrective action process.