Runway Overrun During Rejected Takeoff
Gulfstream Aerospace Corporation G-IV, N121JM
Bedford, Massachusetts
May 31, 2014

Accident Report

NTSB/AAR-15/03
PB2015-105492

National Transportation Safety Board

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Notation 8721
Adopted September 9, 2015

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National
Transportation
Safety Board

490 L'Enfant Plaza, S.W.
Washington, D.C. 20594

National Transportation Safety Board. 2015. *Runway Overrun During Rejected Takeoff, Gulfstream Aerospace Corporation G-IV, N121JM, Bedford, Massachusetts, May 31, 2014*. Aircraft Accident Report NTSB/AAR-15/03. Washington, DC.

Abstract: This report discusses the May 31, 2014, accident in which a Gulfstream Aerospace Corporation G-IV, N121JM, registered to SK Travel, LLC, and operated by Arizin Ventures, LLC, crashed after it overran the end of runway 11 during a rejected takeoff at Laurence G. Hanscom Field, Bedford, Massachusetts. The two pilots, a flight attendant, and four passengers died. The airplane was destroyed by impact forces and a postcrash fire. Safety issues relate to the need for flight crew use of the challenge-verification-response format for checklist execution, analysis of flight operational quality assurance data to define the scope of procedural noncompliance in business aviation, replacement of nonfrangible fittings with frangible fittings for any objects along the extended runway centerline up to the perimeter fence, retrofit of the gust lock system on all existing G-IV airplanes to comply with the certification requirement that the gust lock limit the operation of the airplane so that the pilot receives an unmistakable warning if the lock is engaged at the start of takeoff, and guidance on the appropriate use and limitations of the review of engineering drawings in a design review performed as a means of showing compliance with certification regulations. Safety recommendations are addressed to the Federal Aviation Administration, the International Business Aviation Council, and the National Business Aviation Association.

For more detailed background information on this report, visit http://www.ntsb.gov/investigations/SitePages/dms.aspx and search for NTSB accident ID ERA14MA271. Recent publications are available in their entirety on the Internet at http://www.ntsb.gov. Other information about available publications also may be obtained from the website or by contacting:

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Abbreviations

AC	advisory circular
AEP	airport emergency plan
AFB	Air Force Base
AFM	airplane flight manual
ARFF	aircraft rescue and firefighting
ARP	aerospace recommended practice
ATCT	air traffic control tower
BED	Laurence G. Hanscom Field
C-FOQA	corporate flight operational quality assurance
CFR	*Code of Federal Regulations*
CRM	crew resource management
CVR	cockpit voice recorder
DoD	Department of Defense
EDT	eastern daylight time
EPR	engine pressure ratio
FAA	Federal Aviation Administration
FDM	flight data monitoring
FDR	flight data recorder
FOM	flight operations manual
FOQA	flight operational quality assurance
FPSOV	flight power shutoff valve
FSF	Flight Safety Foundation
Hanscom AFB-FD	Hanscom Air Force Base Fire Department

IBAC	International Business Aviation Council
IS-BAO	International Standard for Business Aircraft Operations
kt	knot
Massport	Massachusetts Port Authority
mi	mile
MLAT	multilateration
NBAA	National Business Aviation Association
NTSB	National Transportation Safety Board
PIC	pilot-in-command
PLA	power lever angle
QAR	quick access recorder
RSA	runway safety area
SIC	second-in-command
SMS	safety management system
SOP	standard operating procedure
TLA	throttle lever angle

Executive Summary

On May 31, 2014, about 2140 eastern daylight time, a Gulfstream Aerospace Corporation G-IV, N121JM, registered to SK Travel, LLC, and operated by Arizin Ventures, LLC, crashed after it overran the end of runway 11 during a rejected takeoff at Laurence G. Hanscom Field (BED), Bedford, Massachusetts. The airplane rolled through the paved overrun area and across a grassy area, collided with approach lights and a localizer antenna, passed through the airport's perimeter fence, and came to a stop in a ravine. The two pilots, a flight attendant, and four passengers died. The airplane was destroyed by impact forces and a postcrash fire. The corporate flight, which was destined for Atlantic City International Airport, Atlantic City, New Jersey, was conducted under the provisions of 14 *Code of Federal Regulations* (*CFR*) Part 91. An instrument flight rules flight plan was filed. Night visual meteorological conditions prevailed at the time of the accident.

During the engine start process, the flight crew neglected to disengage the airplane's gust lock system, which locks the elevator, ailerons, and rudder while the airplane is parked to protect them against wind gust loads. Further, before initiating takeoff, the pilots neglected to perform a flight control check that would have alerted them of the locked flight controls. A review of data from the airplane's quick access recorder revealed that the pilots had neglected to perform complete flight control checks before 98% of their previous 175 takeoffs in the airplane, indicating that this oversight was habitual and not an anomaly.

A mechanical interlock between the gust lock handle and the throttle levers restricts the movement of the throttle levers when the gust lock handle is in the ON position. According to Gulfstream, the interlock mechanism was intended to limit throttle lever movement to a throttle lever angle (TLA) of no greater than 6° during operation with the gust lock on. However, postaccident testing on nine in-service G-IV airplanes found that, with the gust lock handle in the ON position, the forward throttle lever movement that could be achieved on the G-IV was 3 to 4 times greater than the intended TLA of 6°.

During takeoff, the pilot-in-command (PIC) manually advanced the throttle levers, but the engine pressure ratio (EPR) did not reach the expected level due to the throttles contacting the gust lock/throttle lever interlock. The PIC did not immediately reject the takeoff; instead, he engaged the autothrottle, and the throttle levers moved slightly forward, which allowed the engines to attain an EPR value that approached (but never reached) the target setting.

As the takeoff roll continued, the second-in-command made the standard takeoff speed callouts as the airplane successively reached 80 knots, the takeoff safety speed, and the rotation speed. When the PIC attempted to rotate the airplane, he discovered that he could not move the control yoke and began calling out "(steer) lock is on." At this point, the PIC clearly understood that the controls were locked but still did not immediately initiate a rejected takeoff. If the flight crew had initiated a rejected takeoff at the time of the PIC's first "lock is on" comment or at any time up until about 11 seconds after this comment, the airplane could have been stopped on the paved surface. However, the flight crew delayed applying brakes for about 10 seconds and further delayed reducing power by 4 seconds; therefore, the rejected takeoff was not initiated until the accident was unavoidable.

The safety issues discussed in this report relate to the need for the following:

- **Use of the challenge-verification-response format for checklist execution.** The flight crewmembers' total lack of discussion of checklists during the accident flight and the routine omission of complete flight control checks before 98% of their last 175 flights indicate that the flight crew did not routinely use the normal checklists or the optimal challenge-verification-response format. This lack of adherence to industry best practices involving the execution of normal checklists and other deficiencies in crew resource management eliminated the opportunity for the flight crewmembers to recognize that the gust lock handle was in the ON position and delayed their detection of this error.
- **Analysis of flight operational quality assurance data to define the scope of procedural noncompliance in business aviation.** The National Transportation Safety Board (NTSB) found no data documenting the rate of flight crew compliance with required flight control checks in business aviation for the G-IV or any other airplane, yet checklists, callouts, and other standard operating procedures (SOP) are considered an important "soft" defense against threats and errors in business aviation. If the actual rate of procedural compliance is much lower than assumed, aircraft designers, regulators, and operators may need to help boost compliance or reconsider their assumptions about the reliability of flight crew adherence to routine checks and the level of safety protection afforded by such SOPs.
- **Replacement of nonfrangible fittings with frangible fittings for any objects along the extended runway centerline up to the perimeter fence.** After leaving the paved runway overrun and entering the grass, the airplane collided with structures that were not mounted on frangible supports. These structures were not required to be mounted on frangible supports; only structures inside the runway safety area (RSA) must have frangible supports. The NTSB recognizes that the Federal Aviation Administration (FAA) already encourages the incorporation of frangible fittings for structures in areas adjacent to RSAs and that it replaced the fittings at BED with frangible fittings after the accident. However, similar nonfrangible structures located outside of an RSA, but inside a perimeter fence and along an extended runway centerline, are likely present at other airports.
- **Retrofit of the gust lock system on all existing G-IV airplanes to comply with the certification requirement that the gust lock limit the operation of the airplane so that the pilot receives an unmistakable warning if the lock is engaged at the start of takeoff.** Performance calculations demonstrated that the interlock mechanism did not perform as intended. If the throttles had remained at the point where they initially contacted the interlock, the airplane would have reached rotation speed about 7 seconds later and about 1,200 ft farther down the runway than it did. In contrast, an interlock that limited TLA to 6° would have prevented the airplane from achieving any significant acceleration, thus constituting an unmistakable warning that would most likely have prevented the accident.

- **Guidance on the appropriate use and limitations of the review of engineering drawings in a design review performed as a means of showing compliance with certification regulations.** The G-IV gust lock/throttle interlock system was based on previously certificated Gulfstream airplane systems, and compliance with the applicable certification regulation (14 *CFR* 25.679, Control System Gust Locks) for the G-IV was demonstrated by a review of engineering drawings. There was no functional test of the design of the G-IV gust lock/throttle interlock system. A drawing review was an insufficient means of demonstrating compliance with 14 *CFR* 25.679 because of the complexities of the G-IV gust lock system. Design review as a means of compliance with a regulation and the specific documentation requirements are not defined in FAA guidance material such as FAA orders or advisory circulars.

The NTSB determines that the probable cause of this accident was the flight crewmembers' failure to perform the flight control check before takeoff, their attempt to take off with the gust lock system engaged, and their delayed execution of a rejected takeoff after they became aware that the controls were locked. Contributing to the accident were the flight crew's habitual noncompliance with checklists, Gulfstream Aerospace Corporation's failure to ensure that the G-IV gust lock/throttle lever interlock system would prevent an attempted takeoff with the gust lock engaged, and the Federal Aviation Administration's failure to detect this inadequacy during the G-IV's certification.

As a result of this investigation, the NTSB makes safety recommendations to the FAA, the International Business Aviation Council, and the National Business Aviation Association.

1. Factual Information

1.1 History of the Flight

On May 31, 2014, about 2140 eastern daylight time, a Gulfstream Aerospace Corporation G-IV, N121JM, registered to SK Travel, LLC, and operated by Arizin Ventures, LLC, crashed after it overran the end of runway 11 during a rejected takeoff at Laurence G. Hanscom Field (BED), Bedford, Massachusetts.[1] The airplane rolled through the paved overrun area and across a grassy area, collided with approach lights and a localizer antenna, passed through the airport's perimeter fence, and came to a stop in a ravine. The two pilots, a flight attendant, and four passengers died. The airplane was destroyed by impact forces and a postcrash fire. The corporate flight, which was destined for Atlantic City International Airport, Atlantic City, New Jersey, was conducted under the provisions of 14 *Code of Federal Regulations* (*CFR*) Part 91. An instrument flight rules flight plan was filed. Night visual meteorological conditions prevailed at the time of the accident.

The two pilots normally flew the airplane as a flight crew. Both were qualified to act as pilot-in-command (PIC) of the airplane and customarily changed seats between flights, with the pilot seated in the left seat acting as PIC and the pilot seated in the right seat acting as second-in-command (SIC). For the accident flight, the more senior of the two pilots, who was the chief pilot and director of maintenance for SK Travel, was the SIC, and the more junior pilot was the PIC.

About 1325, the airplane departed from its base at New Castle Airport, Wilmington, Delaware; flew to Atlantic City where the passengers boarded; and then flew to BED. The airplane landed at BED about 1544 and was parked on the ramp at one of the airport's fixed-base operators. The passengers left BED to attend a charitable event; the crew remained with the airplane and did not request maintenance or fuel services.

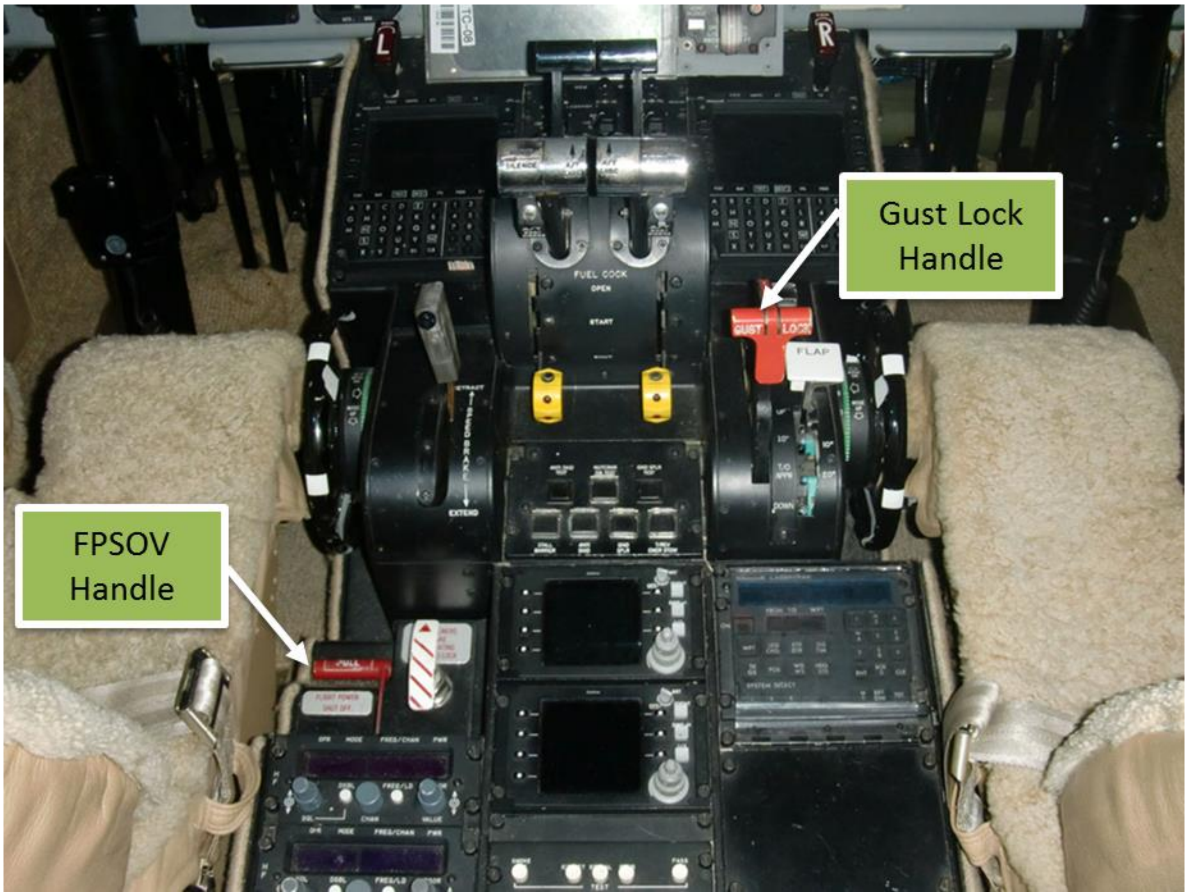
About 2128, the passengers returned to BED and boarded the airplane for the flight back to Atlantic City. The cockpit voice recorder (CVR) recorded sounds consistent with engine start beginning about 2130. The flap position recorded by the flight data recorder (FDR) changed from 0° to 20° at 2131:45. According to BED multilateration (MLAT) tracking data, about 2133, the airplane began to taxi to runway 11, and, at 2139:20, the airplane began turning onto the runway.[2] From the time the passengers boarded the airplane to the time the airplane reached the runway (a period of about 11 minutes), the CVR recorded minimal verbal communication between the flight crewmembers, and there was no discussion or mention of checklists or takeoff

[1] All times in this report are eastern daylight time (EDT) based on a 24-hour clock. SK Travel identified Arizin Ventures as the operator on the National Transportation Safety Board (NTSB) Pilot/Operator Aircraft Accident/Incident Report (Form 6120.1) submitted to the NTSB.

[2] MLAT is a surveillance system consisting of three or more ground stations placed in strategic locations that listen to transponder signal replies. MLAT is more accurate than conventional radar and provides positions once per second.

planning.[3] The G-IV Airplane Flight Manual (AFM) includes five checklists to be completed before takeoff: the Before Starting Engines checklist, the Starting Engines checklist, the After Starting Engines checklist, the Taxi/Before Takeoff checklist, and the Lineup checklist.

The airplane's mechanical gust lock system is used to lock the primary flight control surfaces (elevators, ailerons, and rudder) while the airplane is parked to protect them against wind gust loads. The system also restricts movement of the throttle levers. The G-IV AFM includes disengaging the gust lock as an item in the Starting Engines checklist. The gust lock system is disengaged by moving the gust lock handle (shown in figure 1) to the OFF (down) position.



Source: Gulfstream.

Figure 1. Exemplar G-IV control pedestal showing the gust lock handle in the ON (up) position and the flight power shutoff valve handle (FPSOV) in the OFF (down) position.

The G-IV AFM includes a flight control check as an item in the After Starting Engines checklist. During the flight control check, one of the pilots moves the elevators, ailerons, and rudder stop to stop to confirm that they move freely and correctly. According to FDR data, the

[3] Before engine start, the crewmembers briefly discussed whether a phone call had been completed and, while taxiing, discussed the taxi route to the runway.

flight crew did not complete a flight control check after engine start or at any time thereafter. The control surface positions for the elevator and rudder that the FDR recorded showed that the movement of these control surfaces was restricted during the taxi and takeoff attempt.

Between 2139:21 and 2139:31, as the airplane turned onto the runway, the CVR recorded a conversation between the flight crewmembers regarding the “rudder limit light” activating. These comments were consistent with the advisory message “RUDDER LIMIT” showing on the engine instrument and crew advisory system display. This message, which is displayed in blue letters, advises the flight crew when the airplane’s rudder actuator load limiter valve has been activated. The load limiter activates when the rudder contacts its stops and protects the airplane’s tail structure against overload by limiting actuator output load capacity. The load limiter also activates when the rudder is restricted from reaching its commanded position, as would be the case if the rudder was commanded to move with the gust lock engaged.

According to FDR data, at 2139:34, the brakes were released, and the throttle levers were advanced manually, resulting in the left and right engine pressure ratios (EPR) increasing to about 1.42 over a period of about 4 seconds, where they remained for about the next 5 seconds.[4] At 2139:43, the autothrottle was engaged, and the EPRs began to increase again. At 2139:46, maximum EPR values of about 1.6 were achieved, and the airplane reached a speed of about 60 knots (kts). The EPRs then reduced, dropping to about 1.53 and stabilizing. At 2139:46.6, as the EPRs were dropping, the PIC said, “couldn’t get (it manually any further).”[5]

The Lineup checklist in the G-IV AFM includes a note below the checklist items that calls for the pilot to confirm, at 60 kts during the takeoff roll, that the elevators are free and the control yoke has moved aft from the full forward to the neutral position.[6] Aft movement of the control yoke is expected due to the increasing aerodynamic forces on the elevators as the airplane accelerates during takeoff, which act to move the elevators from their at-rest position of about 13° trailing edge down to a 0° (neutral) position. The elevator position recorded by the FDR remained constant at about 13° trailing edge down as the airplane accelerated through 60 kts.

According to the CVR transcript, at 2139:51.3, the SIC said, “eighty,” indicating that the airplane had reached a speed of 80 kts. At 2139:57.5, the SIC said, “V-1,” indicating that the airplane had reached the takeoff decision speed, and 1.4 seconds later said, “rotate.”[7] One second later, at 2139:59.9, the PIC said, “(steer) lock is on.”[8] The PIC repeated this statement six times during the next 12.7 seconds.

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[4] EPR is a means of measuring the amount of thrust being produced by a jet engine; it is the ratio of the turbine discharge pressure divided by the compressor inlet pressure.

[5] The use of parentheses around a word in a CVR transcript indicates a questionable insertion.

[6] The G-IV Pilot’s checklist, a copy of which was found in the accident airplane’s cockpit, contains abbreviated versions of the checklists in the AFM. The abbreviated checklists include checklist items only and do not include notes such as this one concerning confirmation of elevator movement at 60 kts.

[7] Takeoff decision speed, as defined in the G-IV AFM, is the “speed from which decision to continue takeoff results in takeoff distance that will not exceed available accelerate-go distance, or from which decision to bring airplane to full stop will not exceed accelerate-stop distance available.”

[8] There is no steer or steering lock system on the airplane.

According to FDR data, at 2140:05.7, the ground spoilers and flight spoilers moved up about 1° to 3°, both ailerons moved trailing edge up about 1°, and the yaw damper disengaged, which was consistent with the activation of the FPSOV. Activating the FPSOV by moving the FPSOV handle (shown in figure 1) up to the ON position removes hydraulic pressure from the actuators for the spoilers and the primary flight controls.[9] Because the spoilers are normally held down by their actuators, when hydraulic pressure is removed from the actuators, the surfaces will "float" due to aerodynamic loading on the spoiler surfaces. Similarly, when hydraulic pressure is removed from the aileron actuators, both ailerons will "float" due to aerodynamic loads. Also, in the absence of hydraulic pressure to the rudder actuator, the yaw damper will disengage because the rudder actuator will not respond to yaw damper inputs.

At 2140:10, about 11 seconds after the "rotate" call, at a groundspeed of about 162 kts and with about 1,373 ft of runway remaining, the FDR recorded the left and right brake pressures beginning to rise. The CVR did not record any verbal communication between the flight crewmembers regarding rejecting the takeoff. At 2140:14 (4 seconds after the brake pressure increase), the throttle levers were pulled back. According to FDR data, the ground spoilers did not automatically deploy following the throttle reduction, which is consistent with the activation of the FPSOV.[10] At 2140:14.3, the PIC said, "I can't stop it."

At 2140:15.3, the airplane exited the runway onto the paved overrun area at a groundspeed of about 151 kts, and, at 2140:15.5, the thrust reversers were deployed. At 2140:20 (about 5 seconds after exiting the runway), the airplane, traveling at a groundspeed of about 105 kts, exited the paved overrun area onto the grass. The CVR recorded the sound of an impact about 1 second later at a groundspeed of about 97 kts. FDR data ended at 2140:23.9 while the airplane was still in motion traveling at a groundspeed of about 90 kts.

The two air traffic controllers on duty in the BED air traffic control tower (ATCT) observed the airplane rolling down the runway at "high speed" but not lifting off. They saw the airplane exit the runway and pass through the paved overrun area, and they immediately began accident notification procedures. One of the controllers stated that the airplane was engulfed in flames "almost instantaneously" with it coming to a stop.

The airplane passed through the airport's perimeter fence and came to rest spanning a ravine formed by the Shawsheen River. The main wreckage was about 8,880 ft from the runway threshold, or 1,869 ft past the runway end and 849 ft past the end of the paved overrun area. Figure 2 is an aerial view of BED showing the location of the wreckage. The table that follows lists key events during the takeoff roll.

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[9] The FPSOV is intended for use in the event of a flight control actuator malfunction. The ailerons, elevator, and rudder revert to manual operation when the FPSOV is activated.

[10] Normally, the ground spoilers deploy automatically when the throttles are reduced to idle during a rejected takeoff, but the spoilers cannot deploy without hydraulic power.

Source: Massachusetts State Police.

Figure 2. Aerial photograph of the accident site.

Table. Selected events during the airplane's takeoff roll.

Event	Time (EDT)	Ground-speed (kts)	Distance from runway threshold (ft)	Distance to runway end (ft)	Distance to runway safety area end (ft)
Airplane turns onto runway 11	2139:20	4	96	6,915	7,935
Brakes released and power increased	2139:34	9	200	6,811	7,831
Autothrottle engaged	2139:43	44	569	6,442	7,462
"Couldn't get" comment on CVR	2139:46.6	65	898	6,113	7,133
80-kt call on CVR	2139:51.3	90	1,516	5,495	6,515
V_1 call on CVR	2139:57.5	119	2,612	4,399	5,419

Event	Time (EDT)	Ground-speed (kts)	Distance from runway threshold (ft)	Distance to runway end (ft)	Distance to runway safety area end (ft)
Rotate call on CVR	2139:58.9	125	2,899	4,112	5,132
First reference to “lock” on CVR	2139:59.9	129	3,113	3,898	4,918
FPSOV activated	2140:05.7	150	4,479	2,532	3,552
Brake pressures start to rise	2140:10.0	162	5,638	1,373	2,393
Peak groundspeed	2140:10.3	162	5,694	1,317	2,337
Last reference to “lock” on CVR	2140:12.6	157	6,315	696	1,716
Power reduced	2140:14.0	156	6,685	326	1,346
Reference to stopping ability on CVR	2140:14.3	155	6,763	248	1,268
Airplane exits runway onto paved overrun area	2140:15.3	151	7,011	0	1,020
Thrust reversers deployed	2140:15.5	149	7,072	-61	959
Airplane exits paved overrun area onto grass	2140:20.0	105	8,031	-1,020	0
Sound of impact on CVR	2140:21.0	97	8,206	-1,195	-175
End of FDR data	2140:23.9	90	8,662	-1,651	-631
Surveyed main wreckage location	n/a	0	8,880	-1,869	-849

1.2 Personnel Information

1.2.1 Pilot-in-Command

The PIC, age 45, who was seated in the left pilot seat, held an airline transport pilot certificate with a multiengine airplane rating and type ratings for the Gulfstream G-1159 (Gulfstream G-II/G-III), Gulfstream G-IV, Beechcraft BE-400/Mitsubishi MU-300, and Gates Learjet LR-JET airplanes. He had commercial privileges in single-engine airplanes and held a flight instructor certificate with single-engine airplane and instrument airplane ratings. The PIC's most recent Federal Aviation Administration (FAA) first-class medical certificate was dated April 15, 2014, with no restrictions or limitations.

The PIC's most recent training was a G-IV pilot recurrent course completed on September 17, 2013, at the FlightSafety International Wilmington Learning Center, New Castle, Delaware. The course included 16 hours of ground training and 12 hours of flight simulator training split equally between pilot-flying and pilot-not-flying (pilot-monitoring) duties. It fulfilled the requirements of a PIC proficiency check in accordance with 14 *CFR* 61.58. At the time of this training, the PIC reported that he had accumulated 8,275 hours of flight time as PIC and 1,400 hours in G-IV airplanes.

The PIC's flight time logbook was not located during the investigation. At the time of his April 2014 medical examination, he reported a total flight time of 11,250 hours, with 150 hours flown in the preceding 6 months.

The PIC had worked for the owners of SK Travel for about 12 years and had been flying the G-IV for them for about 7 years (since the owners acquired the airplane in June 2007). A contract pilot who had flown with the PIC two or three times several years before the accident characterized the PIC as a good pilot. He said that the PIC was very familiar with the airplane's checklists and that he conducted a complete flight control check before each of their flights; however, he said that the PIC did not use a formal item-by-item checklist. The contract pilot reported that he was aware that, when the gust lock was not disengaged before starting the engines, some pilots occasionally used the FPSOV handle to momentarily remove hydraulic pressure from the flight controls, which allowed the gust lock to be disengaged without shutting down the engines. The contract pilot did not attribute these comments to a specific pilot or flight crew.

According to the PIC's spouse, during the 3 days before the accident, the PIC did not have a trip and worked around the house. He followed his typical daily schedule, waking up about 0800 and going to bed about 2200. The PIC did not have any current medical issues or significant issues with sleep and appeared to be well rested each morning. On the day of the accident, the PIC woke up about 0800 and left for work about 1130.

The PIC's FAA medical records documented that he was a passenger in an airplane that crashed in 1992. As a result, he suffered multiple facial injuries, a fracture dislocation of his ankle, and a closed head injury; he was hospitalized for about 4 weeks. The PIC reported his hospitalization when he next applied for an FAA medical certificate in 1993 and continued to report it each time he applied for a medical certificate thereafter. In 1993, 1994, and 1995, the

PIC was issued first-class medical certificates by an aviation medical examiner without further review by FAA medical personnel. In 1996, FAA medical personnel requested and reviewed medical records concerning the PIC's injuries and hospitalization and then issued a first-class medical certificate with no restrictions. From 1996 to his most recent April 2014 medical examination, the PIC continued to routinely obtain first-class medical certificates.

1.2.2 Second-in-Command

The SIC, age 61, who was seated in the right pilot seat, held an airline transport pilot certificate with a multiengine airplane rating and type ratings for the Gulfstream G-1159 (Gulfstream G-II/G-III), Gulfstream G-IV, Gulfstream G-V, and Lockheed L-1329 (Jetstar/Jetstar II) airplanes. He had commercial privileges in single-engine airplanes and held a flight instructor certificate with single-engine airplane, multiengine airplane, and instrument airplane ratings. The SIC also held a mechanic certificate with airframe and powerplant ratings and a current inspection authorization. The SIC's most recent FAA first-class medical certificate was dated February 4, 2014, with a restriction that he must have available corrective lenses for near vision. The SIC's FAA medical records documented no significant medical conditions.

The SIC's most recent training was a G-IV pilot recurrent course completed on September 20, 2013, at the FlightSafety International Savannah Learning Center, Savannah, Georgia. The course included 16 hours of ground training and 12 hours of flight simulator training split equally between pilot-flying and pilot-not-flying duties. It fulfilled the requirements of a PIC proficiency check in accordance with 14 *CFR* 61.58. At the time of this training, the SIC reported that he had accumulated 18,200 hours of flight time as PIC and 2,800 hours in G-IV airplanes.

The SIC's flight time logbook included entries current through March 23, 2014. His flight time totaled 18,530.4 hours, with 14,441.8 hours in multiengine airplanes. He had accumulated 1,224.6 hours of actual instrument flight time and 2,597.2 hours as PIC at night.

The SIC had worked for the owners of SK Travel for about 27 years and had been flying the G-IV for them for about 7 years. Before the G-IV, the SIC had flown a G-III, a Jetstar II, and a Jetstar for the owners.

According to the SIC's spouse, during the 3 days before the accident, the SIC worked from home. He did not have a trip within that period, and his daily schedule was typical. He handled the day-to-day operations of the flight department and managed expense reports. He normally worked from home unless he needed to be at the hangar for some reason or he was on a trip. He usually woke up about 0600 and went to bed about 2130. He rarely had difficulty sleeping and did not have any current medical issues. On the day of the accident, he left for work about 0850.

1.2.3 Time Flown as a Flight Crew

According to the accident airplane's flight logs, the airplane was flown 308.8 hours in 2013 and 150.2 hours in 2014 (not including the flight time on the day of the accident), and the two pilots had operated the airplane as a flight crew for 84.5% of the hours in 2013 (261.1 hours) and 100% of the hours in 2014. They had flown the airplane 53 hours in the 90 days before the accident, with 8.9 hours flown in the last 30 days. Their most recent flights in the airplane before the accident were on May 20, 2014, when they flew four flight legs, totaling 2.7 hours.

1.2.4 Flight Attendant

The flight attendant, age 48, had worked for the owners of SK Travel for about 16 years and had worked on board the G-IV for about 7 years. She attended FlightSafety International's corporate cabin attendant recurrent training course at the Teterboro Learning Center, Moonachie, New Jersey, and satisfactorily completed the training on August 13, 2013. The course consisted of 11.5 hours of classroom training and 4 hours of airplane simulator training that included door and overwing exit operation and evacuation drills.

1.3 Aircraft Information

The accident airplane was a Gulfstream Aerospace Corporation G-IV, registration number N121JM, serial number 1399, manufactured on January 27, 2000.[11] It was powered by two Rolls-Royce Tay 611-8 engines. At the time of the accident, the airplane had accumulated about 4,945 total hours and 2,745 cycles.[12]

On April 22, 1987, the FAA granted type certificate approval for the G-IV under 14 *CFR* Part 25 (the airworthiness standards for transport-category airplanes). The G-IV was added as the most recent model in a series of derivative models (including the G-III and the G-IIB) that were approved and added to the type certificate originally issued for the G-II on October 19, 1967. The engine used on the G-IV had a higher thrust rating than the engines on the G-II, G-III, and G-IIB.

1.3.1 Gust Lock System

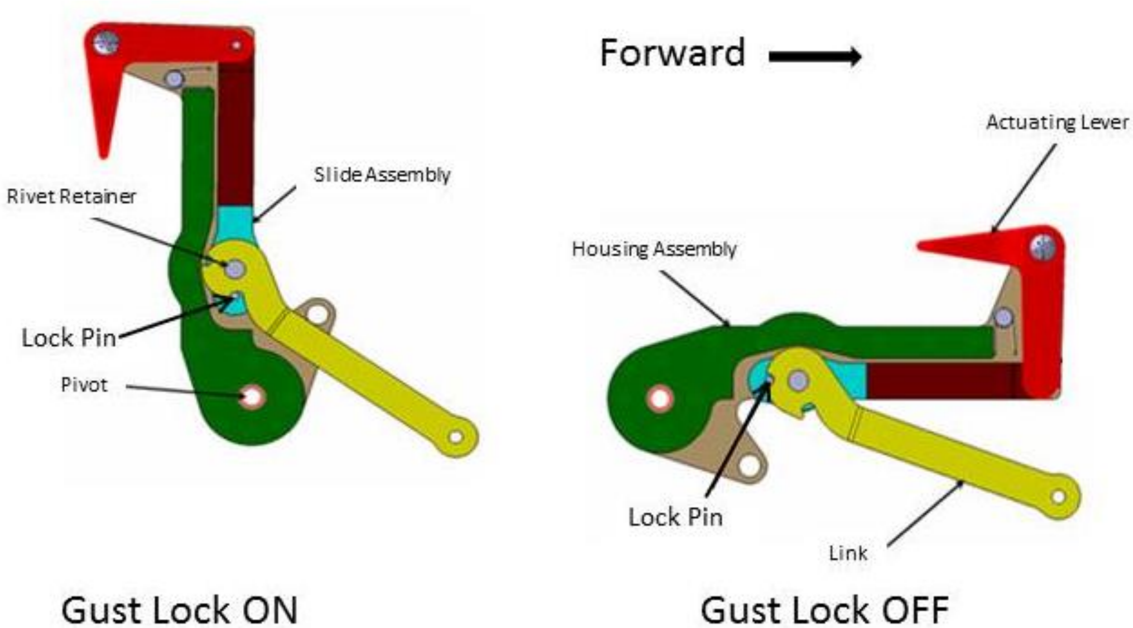
The gust lock system is a mechanical system that restricts the throttles and locks the ailerons, elevators, and rudder to protect them against wind gust loads while the airplane is parked. The ailerons and rudder are locked in the neutral position (0°), and the elevators are locked in the 13° trailing-edge-down position. The locks are mechanical hooks located near the control surfaces that are operated by a two-position, red-painted gust lock handle located on the right side of the control pedestal (see figure 1).

As shown in figure 3, the gust lock handle can be placed in either an up/aft position (gust lock on) or a down/forward position (gust lock off). Moving the handle forward and down to the OFF position releases the gust lock hooks and unlocks the flight control surfaces. Moving the handle aft and up to the ON position engages the gust lock hooks and locks the control surfaces. The gust lock handle latches internally in both the ON and OFF positions. A spring latch operated by the actuating lever must be unlocked before the handle can be moved out of

[11] The G-IV is no longer in production.

[12] An airplane cycle is one complete takeoff and landing sequence.

either latched position. The gust lock handle has 87º of rotation from the OFF position to the ON position. Figures 4a and 4b show an exemplar gust lock handle in the ON and OFF positions, respectively.



Source: Gulfstream.

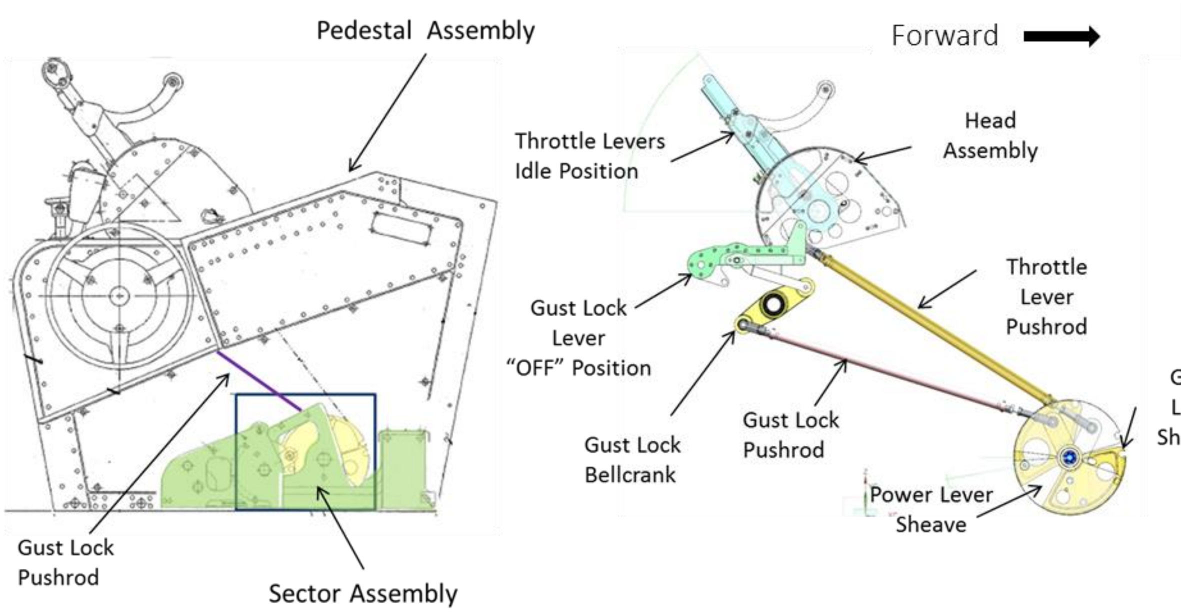
Figure 3. Diagram of a gust lock handle in the ON and OFF positions.

Figure 4a. Photograph of an exemplar gust lock handle in the ON position.

Figure 4b. Photograph of an exemplar gust lock handle in the OFF position.

Return springs in the gust lock system provide a constant force acting to unlock the gust lock hooks and pull the handle down to the OFF position. The handle is pulled up and aft to overcome the force of the springs and move the gust lock hooks into the locked position, and the spring latch is then engaged to hold the handle in the ON position. The spring latch mechanism consists of a spring-loaded slider containing a lock pin that engages a detent in the lock link in both the ON and OFF positions.

A mechanical interlock between the gust lock handle and the throttle levers restricts the movement of the throttle levers when the gust lock handle is in the ON position. The interlock is incorporated into the sector assembly below the pedestal, as shown in figure 5.



Source: Gulfstream (left diagram) and Rockwell Collins (right diagram).

Figure 5. Diagrams of a pedestal assembly showing the location of the sector assembly and the gust lock/throttle lever interlock mechanism.

The sector assembly consists of control cable sheaves mounted on a common axis, which transmit incoming motion of the throttle levers, gust lock, and other controls via pushrods to the appropriate control system cables. The interlock mechanism consists of stops on the gust lock sheave that interface with corresponding stops on the left and right throttle lever sheaves. These stops allow full throttle movement with the gust lock handle down and restricted rotation above idle at the throttle sheaves with the gust lock handle up. According to Gulfstream, the interlock mechanism was intended to limit throttle lever movement to a throttle lever angle (TLA) of no greater than 6° ± 1° during operation with the gust lock on. However, as described further in section 1.10, postaccident testing found that, with the gust lock handle in the ON position, the forward throttle lever movement that could be achieved on the G-IV was greater than the intended TLA of 6°.

It is possible for the gust lock handle to stop in a position that is between the ON and OFF positions with the gust lock hooks remaining engaged. This intermediate handle position can occur if the gust lock handle is unlatched and moved forward from the ON position toward the OFF position, but the gust lock hooks remain engaged due to contact forces at the gust lock hook/pin interface. Contact forces at the gust lock hook/pin interface can be caused by forces acting on a flight control system while the gust locks are engaged. Examples of possible forces include hydraulic loading from a flight control actuator, manual loading from pilot input, or aerodynamic loading on a flight control surface. Hydraulic loading can occur if the gust lock handle is not released before engine start, as the AFM procedures require. The interlock mechanism will allow greater throttle lever movement the farther forward the gust lock handle is from the ON position. One degree of forward gust lock handle movement will allow about one additional degree of TLA.

1.3.2 Gust Lock System Certification

The certification standard applicable to the G-IV gust lock system is 14 *CFR* 25.679, Control System Gust Locks. This requirement states, in part, the following:

> (a) There must be a device to prevent damage to the control surfaces (including tabs), and to the control system, from gusts striking the airplane while it is on the ground or water. If the device, when engaged, prevents normal operation of the control surfaces by the pilot, it must—
>
> (1) Automatically disengage when the pilot operates the primary flight controls in a normal manner; or
>
> (2) Limit the operation of the airplane so that the pilot receives unmistakable warning at the start of takeoff.

At the NTSB's request, the FAA provided its formal interpretation of 14 *CFR* 25.679(a)(2) in an August 29, 2014, letter and stated the following:

> This is a performance based requirement and an applicant can use any means at their disposal, so long as it shows compliance with the rule. To comply with this paragraph applicants use various means to limit the operation. Examples include gust locks that when they are engaged, also prevent throttle lever/actuator advance. Some airplanes incorporate gust locks that hold the nose wheel offset such that if throttles are advanced the airplane will tend to circle on the ground. Both of these means of compliance limit the operation of the airplane. The FAA emphasizes the rule language that states, "must—(2) Limit the operation of the airplane" to prevent pilots from ignoring or mistaking visual and aural take off warnings.

The FAA also provided its definition of "unmistakable warning" as it relates to the installation of a gust lock system, stating that it "consider[s] the examples given above as unmistakable warnings in that they limit the operation of the airplane. With respect to 25.679, the FAA considers an 'unmistakable warning' to be a warning that physically limits the operation of the airplane to prevent an unsafe takeoff."

The NTSB asked Gulfstream how the G-IV gust lock system complied with 14 *CFR* 25.679. Gulfstream responded on September 26, 2014, and cited the following features of the gust lock system when engaged:

- it restricts the operation of the pilot controls (yoke, column, rudder pedals);
- it limits the operation of the throttle levers; and
- as an additional warning feature, the gust lock handle is painted red and located prominently adjacent to the flap handle such that there is physical contact with the pilot's hand during the selecting of flap position.[13]

Gulfstream stated that "these features limit the operation of the airplane and would provide an unmistakable warning to the crew."

Although the gust lock system, including the gust lock/throttle interlock, on the G-IV airplane was similar to the system installed on the G-II, G-III, and G-IIB, Gulfstream made some geometric design changes to the gust lock/throttle interlock architecture for the G-IV. These changes included increasing the gust lock handle's range of motion and modifying the floor sector assembly to accommodate the new kinematics of the system. Gulfstream's pedestal assembly and floor sector assembly drawings detailed the component-level requirements resulting from the gust lock/throttle interlock design changes.

During certification of the G-IV, the FAA approved Gulfstream's means for showing compliance with 14 *CFR* 25.679(a)(2), which was to perform an engineering review of three drawings associated with the gust lock system. One drawing comprised the design and specification requirements for the interface between the gust lock system and the flight control systems, and two drawings comprised the design and specification requirements for the interface between the gust lock system and the throttle levers (gust lock/throttle interlock). According to Gulfstream, compliance with 14 *CFR* 25.679(a)(2) "was found by review of the drawings," and "further historical documentation has not been located to confirm any additional validation and verification of the 6° requirement beyond the compliance finding." Gulfstream reported to the NTSB that postaccident analysis and testing "verified that the current detailed pedestal design does not meet the 6° throttle interlock specification requirement."

1.3.3 Autothrottle

The G-IV autothrottle can be engaged during takeoff after a minimum 1.17 EPR has been achieved; the autothrottle software inhibits autothrottle engagement before reaching 1.17 EPR. When the autothrottle is engaged, the throttles automatically advance to the target EPR that the pilot has selected. At 60 kts, the autothrottle automatically enters HOLD mode, and electrical power is removed from the autothrottle servos while the clutches remain engaged and maintain the EPR achieved at that time. In HOLD mode, the autothrottle will not move the throttles, so if a pilot manually retards the throttle levers, they will remain in their new reduced position. The

[13] The operation of the flap handle from the PIC's seat was not hindered by the gust lock handle when in the ON position.

autothrottle servos will remain depowered until the HOLD mode cancels automatically once the airplane has climbed to 400 ft above ground level.

1.4 Meteorological Information

The reported weather at BED at 2156 on the day of the accident included calm winds, visibility 10 miles (mi), clear skies, temperature 8°C (46°F), dew point 6°C (43°F), and altimeter 30.28 inches of mercury.

1.5 Airport Information

BED is located 1.5 mi southwest of Bedford, Massachusetts, at an elevation of 132 ft mean sea level. Runway 11/29 is 7,011 ft long and 150 ft wide with a grooved asphalt surface and a 0.1% gradient. At the end of runway 11 is a paved overrun area measuring 1,020 ft long and 200 ft wide, which is part of the runway safety area (RSA) for runway 11.[14] A flat grassy area about 758 ft long extends from the end of the RSA to the chain-link fence marking the airport perimeter. An approach lighting system (for approaches to runway 29) and a localizer antenna are located within the grassy area along the extended runway centerline. The Shawsheen River is located immediately outside the perimeter fence at the bottom of a ravine that is about 15 ft deep and 69 ft wide.

The airport, which is owned and operated by the Massachusetts Port Authority (Massport), is certificated under 14 *CFR* Part 139 with Index B aircraft rescue and firefighting (ARFF) capabilities.[15] Located adjacent to Hanscom Air Force Base (AFB), BED is a joint-use (civil/military) airport, and, at the time of the accident, the Hanscom AFB Fire Department (Hanscom AFB-FD) performed ARFF services under a contract between Massport and the Department of Defense (DoD). The contract stated that the ARFF services that Hanscom AFB-FD provides "shall at all times meet the standards prescribed by [14 *CFR*] Part 139 and FAA certification alerts and advisories, as applicable to BED as an Index B airport."

BED's most recent annual airport certification inspection before the accident occurred on March 25 to 27, 2014. At the time of this inspection, BED personnel provided the FAA airport certification inspector with a copy of a March 20, 2014, memorandum from the Hanscom AFB-FD chief to the BED airport manager, which stated that Hanscom AFB-FD met the "requirements for all ARFF in accordance with DoD I[nstruction] 6055.06, *Fire & Emergency Services Program*." The memorandum provided documentation "to substantiate ARFF training and vehicle response capability" that included an ARFF operations checklist, an ARFF vehicle report, and an ARFF personnel training summary. Additionally, the memorandum indicated that from January 1 to March 21, 2014, Hanscom AFB-FD responded to two

[14] An RSA is a clear area around a runway that is free of objects and structures. According to FAA Advisory Circular (AC) 150/5300-13, "Airport Design," the RSA standards applicable to BED are a width of 500 ft, a length before landing of 600 ft, and a length beyond the runway of 1,000 ft.

[15] BED is an Index B airport based on five or more average daily departures of aircraft at least 90 ft long but less than 126 ft long, as defined in 14 *CFR* 139.315.

ARFF emergencies with an average response time of "less than 3 minutes and 100% compliance with DoD requirements."

1.6 Flight Recorders

The airplane was equipped with an L-3 Communications/Fairchild FA2100 solid-state CVR that recorded 2 hours of digital cockpit audio. The digital audio was successfully downloaded, and a transcript was prepared covering the period from 2110:19.7 to 2140:24.5 (see appendix A).

The airplane was equipped with a Loral/Fairchild F1000 solid-state FDR that records a minimum of 25 hours of airplane flight information in a digital format. The FDR was downloaded normally. The accident flight was the last flight on the recording, and its duration was about 9 minutes from the time that the FDR powered on (during engine start) to the time that the FDR stopped recording.

The airplane was also equipped with a quick access recorder (QAR) that records a copy of the data provided to the FDR and stores it on a removable compact flash card. The data on the card were downloaded normally. The QAR recording contained 303 hours of data and 176 takeoff events, including the accident takeoff.

The NTSB reviewed the QAR data to determine if a complete or partial control check was performed before each takeoff. The NTSB defined a complete control check as stop-to-stop motion of the elevators, ailerons, and rudder and a partial control check as stop-to-stop motion of one or two of the three primary flight controls. Of the 176 recorded takeoff events, the NTSB identified 2 complete and 16 partial control checks. The airplane's flight logs indicated that the accident pilots comprised the flight crew on each of these flights, which took place between August 31, 2013, and May 31, 2014. The most recent partial control check (stop-to-stop movement of the elevators and ailerons but not the rudder) was performed 12 flights before the accident flight. The NTSB also reviewed each takeoff event to note the airspeed at the time that the elevators began to move during the takeoff roll. In each case, except for the accident takeoff, the elevators began to move at an airspeed of about 60 to 80 kts.

Additionally, the NTSB examined QAR data for the previous 20 takeoffs to determine how the flight crew advanced the throttles. On each of these takeoffs, the flight crew manually advanced the throttles continuously with no intermediate stops to a power lever angle (PLA) of about 30°, achieving an EPR of about 1.7 (the EPR for a maximum thrust takeoff), and then engaged the autothrottle.[16]

1.7 Wreckage and Impact Information

Tire skid marks consistent with braking began about 1,400 ft from the end of runway 11 and continued until just before the end of the paved overrun area (for a total of about 2,400 ft). After the pavement ended, the ground sloped down slightly to a small service road. Beginning

[16] See section 1.10.5 for information about the relationship between TLA and PLA.

past the road and about 55 ft from the end of the paved overrun area, three distinct sets of ruts consistent with the nose, left main, and right main tires were dug into the grass. The main gear ruts continued for about 40 ft and then abruptly became shallower. The nose gear rut continued for about 85 ft, and the lower portion of the nose gear assembly was found at the end of the rut.

Shallow ground scarring led from the ruts to the main wreckage, which was located in a ravine about 850 ft from the end of the paved overrun area. The left main gear door, a 6-ft-long inboard section of the left flap, and the left main gear assembly were found along the debris path. Three approach light structures located along the debris path were knocked down and broken.

The localizer antenna located about 670 ft from the end of the paved overrun area was knocked down and broken. Multiple localizer antenna support poles were severed about 17 to 18 inches above their bases. The grass between the localizer antenna and the ravine was blackened and charred. Just before the ravine, the airport's chain-link perimeter fence was knocked down. The airplane was found spanning the width of the ravine with the tail on the airport side; the engines, wings, and fuselage in the ravine; and the cockpit on the far side of the ravine (see figure 6). Most of the airplane was destroyed by fire, with the greatest fire damage occurring near the wing root area of the fuselage. All major portions of the airplane were accounted for at the accident site.

Source: Massachusetts State Police.

Figure 6. Aerial photograph of the accident site showing the main wreckage.

The forward fuselage structure, including the cockpit and main entry door, remained mostly intact from the fractured nose cone aft about 14 ft. Aft of this point, the fuselage structure was destroyed by fire. The main entry door was partially opened by rescuers using the external door handle.

The interior of the cockpit and the main door entryway were heavily sooted, melted, or destroyed by fire. Inspection of the cockpit revealed that the gust lock handle was in the OFF position (gust lock off), and the FPSOV handle was in the ON position (hydraulic power removed from flight controls). The left control display unit, located on the left forward side of the pedestal, was out of its slot and lying on top of the pedestal; later examination found that the unit's mounting screws were not in the secured position.

1.8 Medical and Pathological Information

The Commonwealth of Massachusetts Chief Medical Examiner's Office performed autopsies on both pilots, the flight attendant, and two of the four passengers. The autopsies described soot deposition in airway passages, severe thermal injuries, and few traumatic injuries.

The FAA's Civil Aerospace Medical Institute performed toxicology testing on samples from the PIC and the SIC. The report for the SIC indicated that no ethanol or drugs were detected in the samples tested. The report for the PIC indicated that no drugs were detected; two types of alcohol, n-butanol and ethanol, were detected in blood; and no ethanol was detected in brain or muscle tissue.[17]

The PIC's toxicology test indicated that his blood carboxyhemoglobin saturation was 27%, and the SIC's test indicated that his was 61%.[18] Additionally, the Massachusetts State Police Forensic Services Group tested blood samples from the flight attendant and each passenger for the presence of carboxyhemoglobin; the flight attendant and three of the four passengers tested positive, and one passenger tested negative.

The Commonwealth of Massachusetts Chief Medical Examiner's Office determined that the cause of death for both pilots, the flight attendant, and three of the four passengers was "smoke inhalation and thermal injuries." The cause of death for one passenger, who was not autopsied and tested negative for carboxyhemoglobin, was not determined.

1.9 Survival Aspects

The airplane was configured with two pilot seats, one cockpit observer seat, eight single passenger seats, and two triple passenger divans. It had six exits: the main entry door located on the left side of the airplane just aft of the cockpit; four overwing emergency exit windows (two

[17] Ethanol is the alcohol found in beer, wine, and spirits but may also be produced in body tissues by microbial action after death. N-butanol is primarily produced by microbial action after death.

[18] Carboxyhemoglobin is the compound that is formed when inhaled carbon monoxide combines with hemoglobin in the blood. Carboxyhemoglobin levels reflect carbon monoxide exposure, which increases in fires.

on each side of the airplane); and the baggage compartment door located on the left side of the airplane aft of the wing.[19]

The PIC was found in the cockpit kneeling on the left seat with his head against the left cockpit wall. The left oxygen mask compartment in the cockpit was found open with the oxygen mask lying on the floor in front of the left seat near the PIC. The SIC was found sitting in the right cockpit seat facing inboard with one foot on the forward entry floor and the other on the center console. One passenger was found kneeling in the aisle facing the main entry door, and another was found lying in the aisle between the cabin and the main entry door. A third passenger and the flight attendant were found near the front of the cabin on the left side of the airplane between two seats. The fourth passenger was found lying in the center aisle between the seats just forward of the wing. Figure 7 depicts this information.

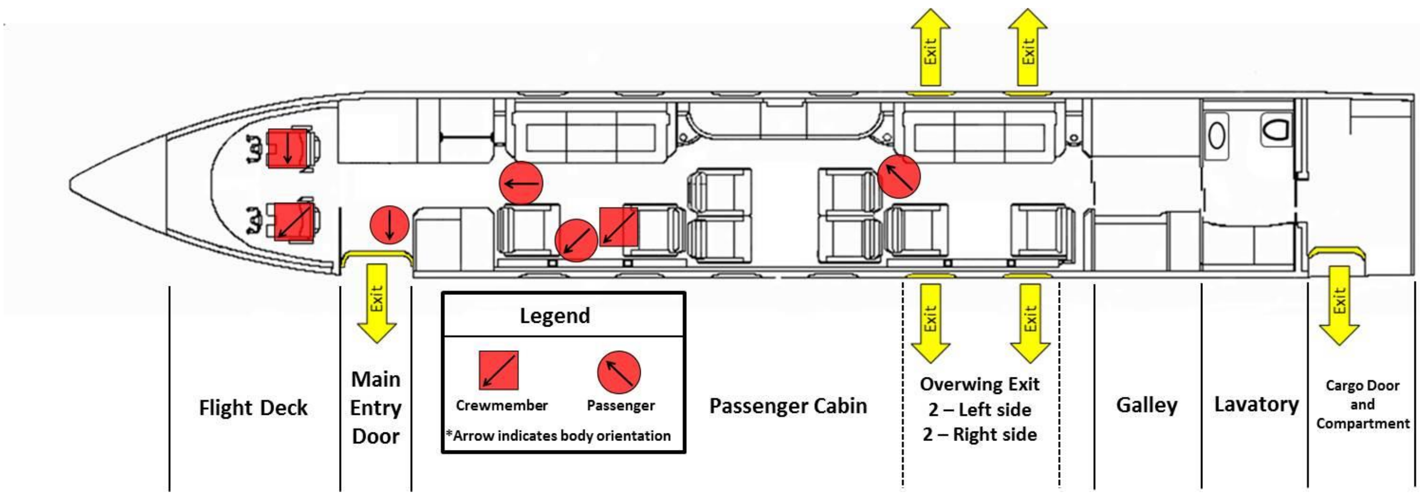


Figure 7. Diagram of the seating configuration showing occupant location and orientation.

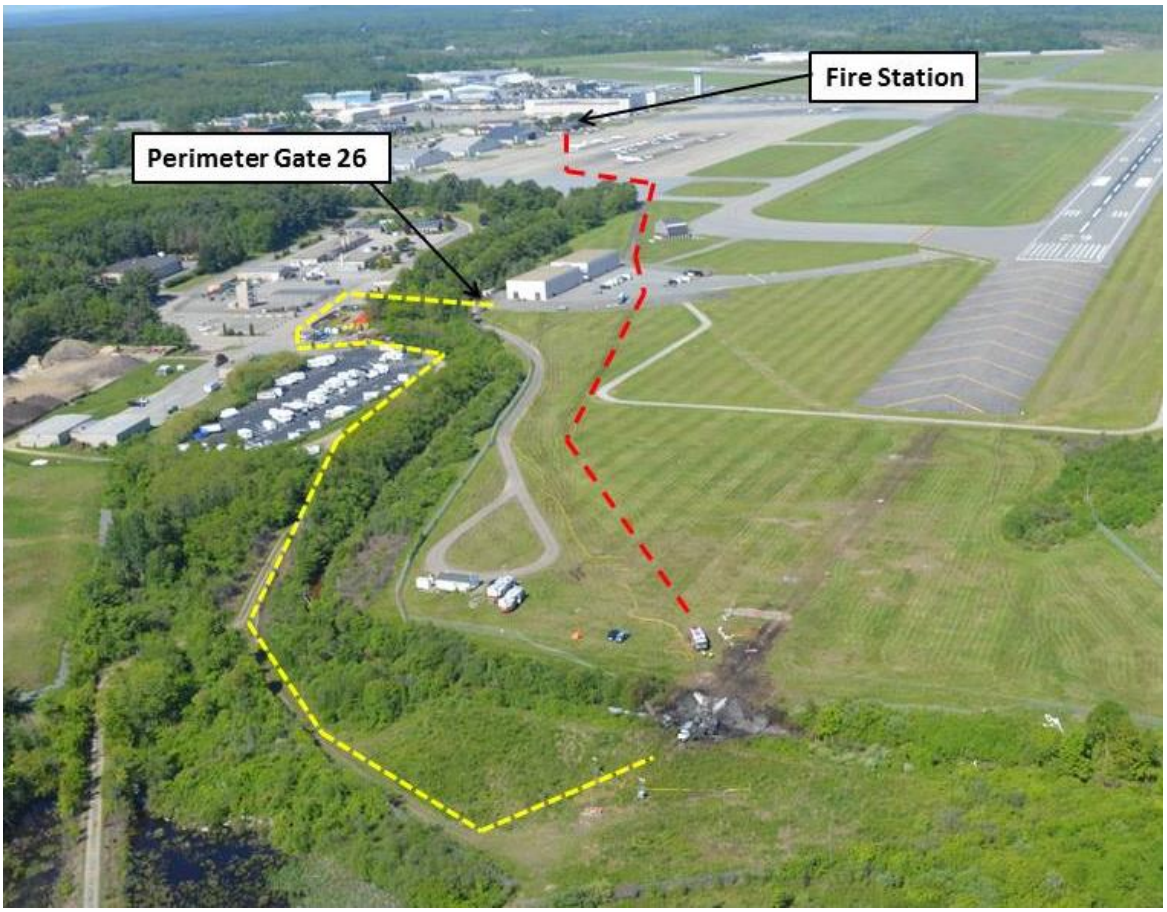
Title 14 *CFR* 91.519, Passenger Briefing, paragraph (b), requires the PIC to ensure that all passengers have received a safety briefing; such briefings provide passengers with pertinent information in the event of an emergency. It is unknown whether a passenger safety briefing was conducted before the accident flight. The CVR did not record any evidence of a passenger safety briefing during the accident flight, but this briefing could have occurred before engine start or out of the CVR's recording range. It is also possible that the briefing occurred before the inbound flight and that the PIC determined that the briefing did not need to be repeated.[20]

[19] The baggage compartment door was accessible through the lavatory at the aft end of the cabin and could be used as a supplementary emergency exit at the crew's direction.

[20] Title 14 *CFR* 91.519(b) allows a PIC to forego a safety briefing if the PIC determines that the passengers are familiar with the contents of the briefing.

1.9.1 Emergency Response

According to the Hanscom AFB-FD chief, seven Hanscom AFB-FD vehicles responded to the accident.[21] Each vehicle traveled about 4,750 ft from the Hanscom AFB-FD station to the airport side of the ravine. Some of these vehicles subsequently traveled to the nonairport side of the ravine. Figure 8 shows the routes to the accident site. Additional firefighting support was provided by mutual aid from the surrounding towns of Bedford, Lexington, and Lincoln, Massachusetts.



Source: Massachusetts State Police.

Figure 8. Aerial photograph of BED showing routes to the accident site.

Note: The route from the fire station to the airport side of the accident site is shown by the red dashed line, and the route from perimeter gate 26 to the nonairport side of the accident site is shown by the yellow dashed line.

[21] The seven Hanscom AFB-FD vehicles that responded were Crash 9, Crash 10, Engine 4, Engine 6, Rescue 3, Tanker 7, and a foam trailer. Four of these vehicles (Crash 9, Crash 10, Engine 4, and Engine 6) were firefighting vehicles that carried varying amounts of water, dry chemical, and foam. The other three vehicles were support vehicles: Rescue 3 was a light-duty vehicle, and Tanker 7 and the foam trailer carried water and foam, respectively, to refill the tanks of the firefighting vehicles.

According to radio communications that the Hanscom AFB-FD dispatch recorded, Hanscom AFB-FD personnel learned of the accident via an Alert 3 notification (which indicates an accident on or near the airport) from the BED ATCT at 2140:23. At 2141:49, Rescue 3, a light-duty vehicle, left the fire station and, about 3 seconds later, reported smoke in the air and visible fire near the end of runway 11. Upon arriving at the accident scene, Rescue 3 personnel encountered "heavy smoke and fire" coming from the crashed airplane and conducted a primary search of the area up to the edge of the ravine for victims.

At 2142:56, Crash 10, a firefighting vehicle with a capacity of 1,000 gallons of water, 130 gallons of foam, and 500 lbs of dry chemical, left the fire station en route to the crash site. In addition, three other firefighting vehicles (Crash 9, Engine 4, and Engine 6) proceeded from the fire station to the crash site. Crash 10 and Crash 9 drove on scene together about 50 ft apart. Crash 9 personnel stated that they applied agent to spot fires on the grass area about 100 ft in front of the main fire and then applied foam to the main fire until it was knocked down enough so that fire crews could get closer to the scene.[22]

By 2145:07, about 5 minutes after the Alert 3 notification, both Crash 10 and Crash 9 (Hanscom AFB-FD's largest firefighting vehicle with a capacity of 3,300 gallons of water, 500 gallons of foam, and 500 lbs of dry chemical) were fighting the fire. Firefighters on scene characterized the airplane as engulfed in flames on both sides of the ravine.

About 2207, Crash 9 ran out of foam and shut down, and, about 2210 (30 minutes after the Alert 3 notification), Crash 10 reported running out of water "again." Shortly thereafter, Engine 4 was sent to the fire hydrant about 1,200 ft away to lay a hose to pump water back to the accident site. Both Engine 4 and Engine 6 had bypassed this hydrant on the way to the crash site. By 2224, Crash 9 had been resupplied with water and foam, and firefighting operations resumed.

Hand lines were deployed to fight the ground fire in the grass area that the airplane had passed through, to fight the fire in the brush around the airplane, and to apply additional foam to the airplane. Rescue 3 personnel indicated that they searched close to the airplane on the runway side of the ravine; however, they were unable to cross the ravine due to fire on the airplane and in the river. About 2213, the Hanscom AFB-FD incident commander requested personnel at the scene to move away from the edge of the ravine because of explosions in the water.

The Hanscom AFB, Lexington, and Lincoln fire departments made numerous attempts to put personnel and equipment on the nonairport or east side of the ravine. About 2229, Engine 6 personnel indicated that they would be "going on the outside thru Hartwell [gate] to see if they can get on the backside of this aircraft," but Engine 6 personnel did not reach the other side of the ravine. (The Hartwell gate is the main gate to Hanscom AFB; it is not an airport perimeter gate and does not provide access to the east side of the ravine. Airport perimeter gate 26, which is shown in figure 8, does provide access to the east side of the ravine.) About 2244, Engine 4's fire officer informed the incident commander that there was no way to gain entry to the cockpit from the airport side of the ravine because it was "too steep [and there was] debris in the way."

[22] National Fire Protection Association document 402, "Guide for Aircraft Rescues and Fire-Fighting Operations," states that, "if upon arrival at an aircraft accident the operator of the first-arriving ARFF vehicle encounters a small fire, the best tactic would be to extinguish it rapidly."

About 2319, the incident commander advised all Hanscom AFB-FD personnel that a Lexington ladder truck would attempt to use its ladder as a bridge over the ravine to access the cockpit. About 2323, Engine 4's fire officer notified the incident commander that Lexington firefighters were on the other side of the ravine making their way down; about 6 minutes later, the fire officer reported that Lincoln firefighters were attempting to gain access to the cockpit. About 2332, Lexington firefighters requested help with entry into the cockpit from Engine 4's fire officer. About 2341, Engine 4 arrived on the other side of the ravine, joining Lexington firefighters; about 6 minutes later, Engine 4 personnel were at the nose of the airplane.

About 2351 (2 hours 10 minutes after the Alert 3 notification), the main entry door was opened by Engine 4 personnel. According to Engine 4's fire officer, the door was opened using a tool to depress the button on the door to release the handle. After the handle was lifted, the door opened freely. Engine 4's hand lineman stated that "[he] used the pick end of the tool to pop out the door handle. There was little to no resistance to lift up on the handle freeing the door locks."

1.10 Tests and Research

1.10.1 Airplane Performance Study

The NTSB conducted an airplane performance study to (1) calculate the position of the airplane relative to the threshold and end of runway 11 throughout the attempted takeoff (with the results shown in the table in section 1.1), (2) estimate the time and distance required for the airplane to achieve takeoff speed if the EPR had remained about 1.42, and (3) estimate the braking friction developed by the airplane during the flight crew's attempt to reject the takeoff.[23] The airplane performance study also evaluated the results of simulations performed in a G-IV level D training simulator to determine the effects of rejecting the takeoff sooner in the takeoff roll.[24]

Acceleration calculations indicated that, compared with an EPR of about 1.53 (the stabilized EPR value after the EPR peak), at an EPR of 1.42 (the stabilized EPR value before the EPR peak), the airplane would have taken an additional 7.4 seconds and needed an additional 1,170 ft of available runway to reach a speed of 127 kts. The estimate of the braking friction that the airplane developed during the flight crew's attempt to reject the takeoff indicated that the brakes were providing the retarding force that would normally be expected on a dry, paved runway.

Investigators from the NTSB, Gulfstream, and the FAA performed multiple rejected takeoffs in the G-IV simulator to evaluate the effect of various pilot actions on the accelerate-stop distance of the airplane under the loading and environmental conditions of the

[23] As stated in section 1.1, FDR data showed that, when the throttle levers were advanced manually, the left and right EPRs increased to about 1.42 during a period of about 4 seconds, where they remained for about the next 5 seconds (when the autothrottle was engaged and the EPRs began to increase again before reducing and stabilizing).

[24] The FAA certifies flight simulators at levels A through D, with level D being the highest or most realistic. Level D simulator requirements include a motion platform with all six degrees of freedom, a visual system with an outside-world view of at least 150°, and realistic sounds in the cockpit.

accident. In particular, the investigators performed exercises to evaluate whether the airplane could be brought to rest on the runway or paved overrun area if the rejected takeoff procedure outlined in the G-IV Operating Manual was applied shortly after the point at which the CVR recorded the first “lock is on” comment. The rejected takeoff procedure specified that the flying pilot (the PIC in this case) should take the following steps: (1) retard throttle levers to idle and apply maximum braking, (2) deploy spoilers, and (3) use reverse thrust if desired. In addition, exercises were performed to determine what effect spoiler deflection would have on the speed at which the airplane departed the runway and paved overrun area. (As previously mentioned, FDR data indicated that the spoilers did not deploy during the deceleration segment of the ground roll, consistent with activation of the FPSOV.)

The exercises indicated that the airplane could have been stopped on the paved surface if the flight crew had rejected the takeoff at the time that the CVR recorded the first “lock is on” comment. The exercises also indicated that full deployment of the spoilers when the throttle levers were pulled back (14 seconds after the first “lock is on” comment) would not have significantly diminished the speed at which the airplane departed the runway but could have reduced the speed at which the airplane departed the paved overrun area by about 9 kts, corresponding to a 16% decrease in the airplane’s kinetic energy at that point.

Calculations using the deceleration that the FDR recorded after the throttles were pulled back indicated that, if the rejected takeoff procedures outlined in the AFM (simultaneous braking and power reduction) had been applied as late as about 11 seconds after the first “lock is on” comment, the airplane could have been stopped on the paved surface, even without functioning spoilers.

1.10.2 Interlock Analysis and Testing

At the NTSB’s request, Rockwell Collins (the manufacturer of the pedestal assembly) performed a mechanical tolerance analysis of the G-IV gust lock/throttle lever interlock mechanism and determined that the worst-case maximum TLA achievable with the gust lock handle in the ON position was 23°. Additionally, Rockwell Collins found that, if incorrect rigging procedures were used, the maximum TLA achievable could be as much as 26°.[25]

The NTSB performed testing on the accident airplane’s pedestal assembly to determine the TLA achievable when the gust lock handle was in the ON position. Initially, the throttles could be advanced to a TLA of 27° before resistance was felt from contact with the interlock. The NTSB later discovered that the lock pin in the handle’s slider assembly was broken and that only stubs remained on both sides of the slider assembly. These stubs provided enough contact force to prevent gust lock handle travel to the OFF position when using light-to-medium hand force. As greater hand force was used, the handle moved farther forward, eventually reaching the OFF position.[26] The gust lock handle was replaced with another gust lock handle that had an

[25] The G-IV maintenance manual contains two cockpit pedestal assembly rigging procedures because there are two different pedestal assemblies (with different part numbers) that can be installed on the G-IV airplane. Incorrect rigging could occur if the wrong procedure is followed.

[26] See section 1.10.6 for further discussion of the broken lock pin.

intact lock pin, and testing showed that the throttle levers could then move to a TLA of 22° before the interlock was contacted.

1.10.3 Foreign Object (Sunglasses) Testing

During the examination of the airplane's gust lock/throttle lever interlock mechanism, a pair of sunglasses was found inside the pedestal, near the aft side of the sector assembly sheaves in the direct vicinity of the left throttle lever sheave and the gust lock sheave. The glasses were charred, and the left lens was found separated from the frame and broken.

The NTSB used the accident sunglasses as well as a representative new pair of sunglasses during tests to try to restrict the gust lock sheave in various ways. During tests with the sunglasses placed where they were initially found, the greatest restriction observed allowed the gust lock handle to move down about 15° from the ON position. Any forward movement of the left throttle lever rotated the throttle sheave such that the glasses were moved to a lower position, which allowed the gust lock sheave to have more range of travel before contacting the glasses. With the left throttle lever moved to a TLA of 25°, the most restrictive test case observed allowed the gust lock handle to have 62° of downward movement from the ON position.

Testing with the sunglasses placed in positions other than the position where they were initially found revealed a number of possible ways to restrict the movement of the gust lock sheave. The greatest restriction observed was with the sunglasses placed on top of the gust lock sheave and wedged between the sheave and the surrounding structure, which allowed the gust lock handle to move down about 8° from the ON position. However, this degree of restriction was achieved by careful placement of the sunglasses in a position that they would not likely have reached inadvertently.

1.10.4 Intermediate Gust Lock Handle Position Testing

The NTSB's testing on an exemplar G-IV demonstrated that all gust lock hooks disengaged when the gust lock handle was about 14° forward of the ON position. Testing on another G-IV showed that, with the rudder gust lock hook preloaded using rudder trim input, the gust lock handle could be retained in an intermediate position with all gust lock hooks remaining engaged. With the gust lock handle in this position, the throttle levers could move to a TLA of 41° before the interlock would restrict movement. Further, testing on a third G-IV showed that 2.5 units of rudder trim input with hydraulics on could create enough contact force to keep the hooks engaged and the gust lock handle in an intermediate position with only return springs acting to pull down the gust lock handle. Two of these airplanes were specifically tested to determine the associated PLA values when the gust lock lever was in the intermediate position and the throttles were moved forward until they contacted the interlock.[27] The PLA reached 28° on one airplane and 35° on the other airplane.

[27] During its testing to determine the interlock function on exemplar G-IV airplanes, the NTSB considered the PLA in addition to TLA because PLA was recorded on the FDR (unlike TLA), as discussed in the next section.

A Gulfstream analysis estimated that, at an airspeed of 150 kts with the elevator surface positioned 13° trailing edge down, aerodynamic loading could result in an elevator gust lock hook (if engaged) loading of 785 lbs. Gulfstream further estimated that a crew input force of about 189 lbs on a gust lock handle in the ON position would be required to disengage the elevator gust lock hook at that airspeed.

1.10.5 Throttle Lever Angle, Power Lever Angle, and Engine Pressure Ratio Relationship

TLA is not recorded on the FDR, but PLA is recorded. PLA is measured at the engine by a position transducer that detects the input lever position at the engine fuel control. The input levers are mechanically connected to the throttle levers; as the throttle levers are moved forward or aft, the input levers move, and engine thrust (which is recorded on the FDR as EPR) increases or decreases accordingly. The PLA and EPR relationship varies slightly from engine to engine. EPR depends on ambient air temperature; for a given PLA, the colder the temperature, the greater the EPR will be. According to Gulfstream, a G-IV can typically achieve 1.59 EPR (the minimum EPR for a reduced thrust takeoff) with a PLA of 20° if the ambient air temperature is about -5°C/23°F or with a PLA of 25° if the ambient air temperature is about 15°C/59°F. Interpolating these data for the ambient air temperature of 8°C/46°F, as recorded at the time of the accident, a PLA of about 23° would have been required to achieve 1.59 EPR.

According to the FDR, the maximum PLA achieved during the takeoff was 24.3° for the left engine and 25.7° for the right engine, which occurred at 2139:45. About 1 second later, the recorded EPRs reached their maximums of 1.617 for the left engine and 1.614 for the right engine. The PLAs and EPRs then decreased to and stabilized at about 20° and 1.53, respectively.

Although the PLA and TLA values are similar near idle, they diverge as power is increased, and the PLA and TLA relationship varies somewhat from airplane to airplane. The TLA range of travel is from 0° to 58°, and the PLA range of travel is from 0° to 39°. Postaccident evaluation of nine in-service G-IVs found that, with the gust lock handle in the ON position, the TLA that could be achieved varied from 18.2° to 24.2°. Measurements on four of these airplanes found that, with the throttle levers contacting the interlock between about 18° and 23°, the PLA was on average about 4° lower than the corresponding TLA. The maximum difference among the test airplanes was 6.1° (with the PLA lower than the TLA), and the minimum difference was 2.8° (with the PLA lower than the TLA).

1.10.6 Lock Pin Examination

As previously mentioned, the lock pin in the gust lock handle's slider assembly was broken. The NTSB's laboratory examination revealed that the pin had fractured into at least three pieces with the middle section missing and only small stubs remaining on both sides of the slider assembly. As shown in figure 9a, the left stub piece was recessed into the pin hole in the left side of the slider assembly bracket, and the right stub piece protruded from the pin hole in the right side of the slider assembly bracket into the path of the lock link's travel. Figure 9b shows an exemplar gust lock handle pin.

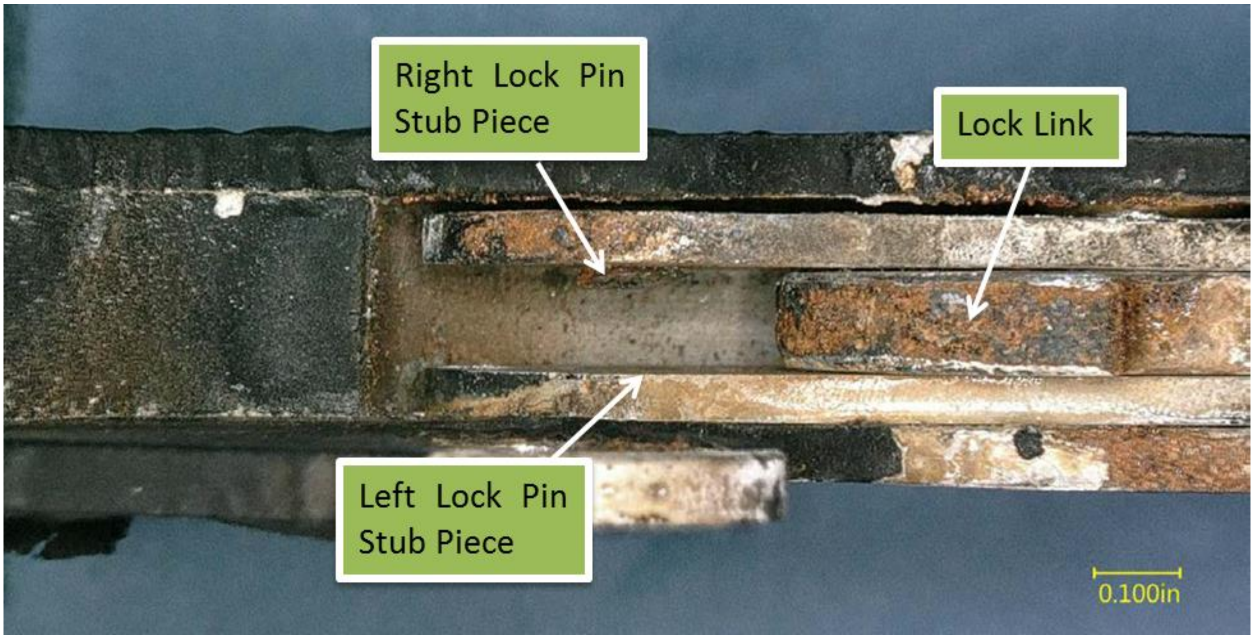


Figure 9a. Photograph of the left and right lock pin stub pieces.

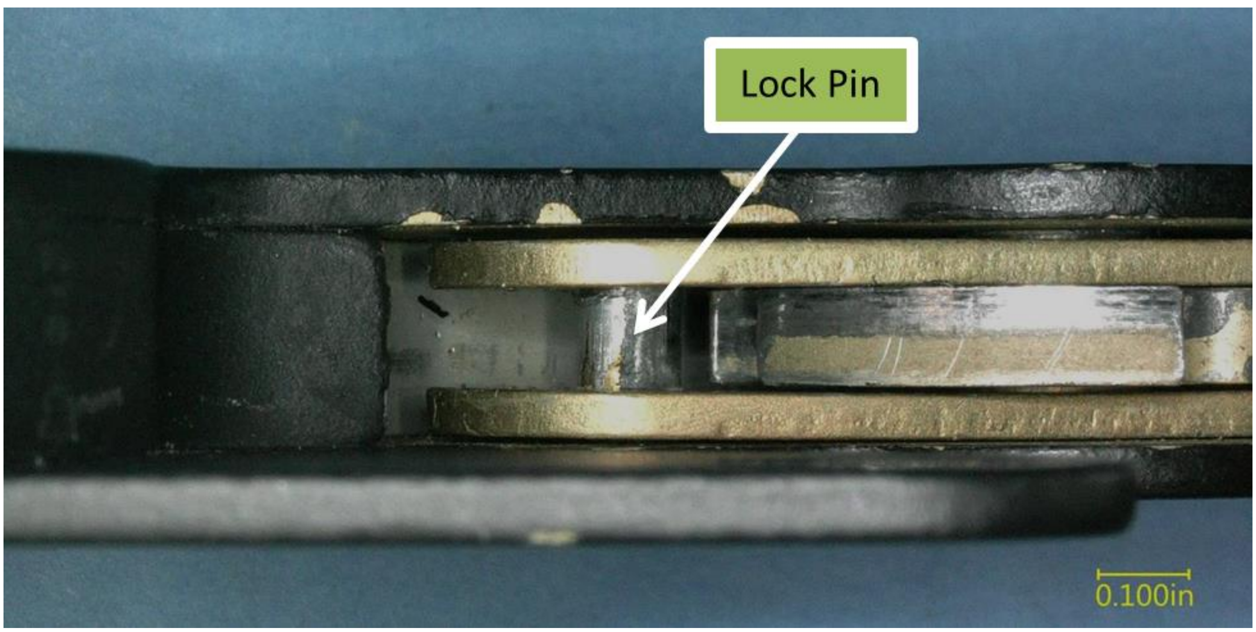


Figure 9b. Photograph of an exemplar gust lock pin.

The right stub piece was significantly deformed with smearing damage consistent with the gust lock handle going from the ON position to the OFF position (see figure 10).[28]

[28] Smearing damage occurs when there is relative motion between two surfaces that are in physical contact. The contact can result in mechanical removal of material, deformation, and wear scars on one or both of the contacting surfaces.

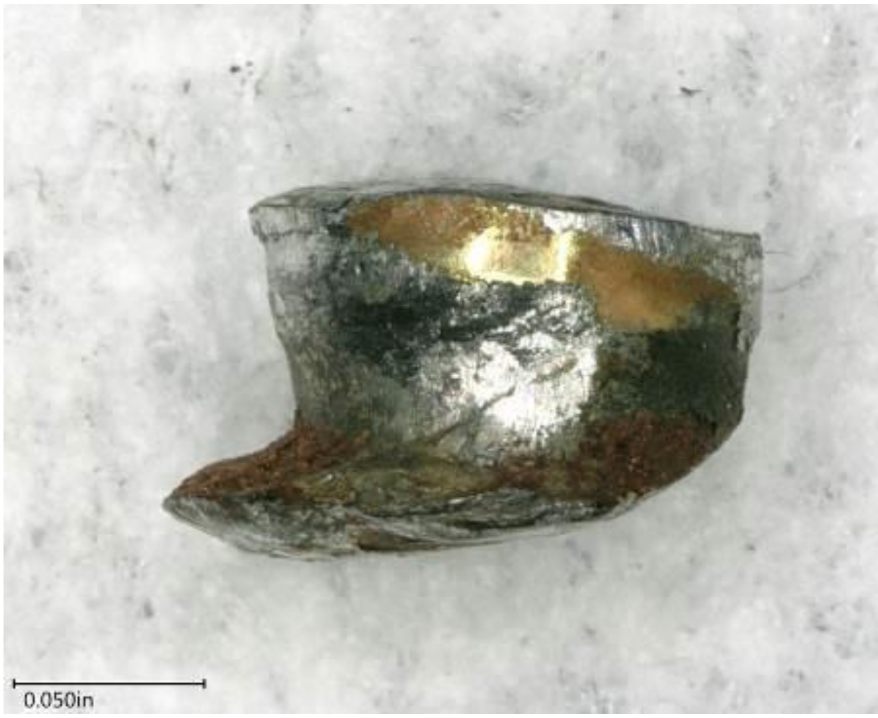


Figure 10. Photograph of the right lock pin stub piece.

The flat fracture surface of the left stub piece was examined using a scanning electron microscope in the as-received condition before cleaning. Heavy corrosion deposits obscured the fracture surface features. The piece was then cleaned and reexamined, and flattened and smeared areas were observed on the fracture surface. No distinguishing features indicative of fatigue cracking were noted.

According to the engineering drawing of the gust lock handle assembly, the lock pin is to be made from drill rod material, which is precision-ground tool steel rod.[29] The drawings did not specify any material properties (such as hardness or shear strength) or a specific type of tool steel drill rod for the lock pin. Energy dispersive x-ray spectroscopy analysis revealed that the pin was composed of steel and met the general compositional parameters for drill rod.

1.11 Organizational and Management Information

The accident airplane was registered to SK Travel, LLC, and operated by Arizin Ventures, LLC. A lease agreement was in effect between SK Travel and Arizin Ventures that specifically prohibited operation of the airplane for compensation or hire under 14 *CFR* Part 135. Individuals familiar with the operation of the airplane confirmed that the airplane was used solely for personal and business purposes in accordance with 14 *CFR* Part 91.

[29] Tool steel is a term used for a broad class of more than 40 different types of high-hardness, abrasion-resistant steels that are well suited to be made into tools.

At the time of the accident, SK Travel operated a single airplane (the accident G-IV) and employed three people (the two pilots and the flight attendant). In addition to his duties as a pilot, the SIC also served as the chief pilot and director of maintenance for SK Travel, coordinating pilot training and maintenance activity for the airplane. The PIC and the flight attendant had no additional duties. As previously mentioned, the accident pilots normally flew the airplane as a flight crew. Contract pilots were used only occasionally when one of the two pilots was on vacation or was otherwise not available. The airplane's flight logs indicated that the most recent use of a contract pilot was on May 12, 2013, more than 1 year before the accident.

Other than the lease agreement, no documentation related to the operation of the airplane under the name of Arizin Ventures was located. The NTSB recovered and reviewed a flight operations manual (FOM) associated with SK Travel. The manual covered organization and administration, safety management, operating procedures, emergency procedures, qualifications and training, and aircraft maintenance. Safety management included a risk assessment process for individual flights that considered pilot qualifications and experience, the operating environment, and equipment limitations. Additional documentation and review were required for elevated risk scores. The NTSB's review of the risk assessment process and the known factors related to the accident flight indicated that the corresponding risk assessment score for the accident flight was low and did not require any further review or documentation.

Audits of the SK Travel safety management system (SMS) were conducted by a third-party auditor in accordance with the International Business Aviation Council's (IBAC) International Standard for Business Aircraft Operations (IS-BAO), which is an industry code of best operational practices. Although conforming to the code standards is voluntary, recognition for the implementation of and conformance to the standards is available through an auditing process that results in an IBAC certificate of registration, which is valid for 2 years. The IS-BAO program is available to member organizations of the IBAC, and SK Travel was a member of the National Business Aviation Association (NBAA), which is a member organization of the IBAC.

An initial audit, completed on July 29, 2010, found that SK Travel complied with the IS-BAO standards at the stage 1 level (basic SMS). A second audit, completed on May 10, 2012, found that SK Travel complied with the IS-BAO standards at the stage 2 level (demonstration of effective SMS). The report for the 2012 audit noted that flight operations were not observed because no flights were scheduled during the audit period. At the time of the accident, the SIC was reportedly preparing for a third audit of SK Travel.

1.12 Additional Information

1.12.1 Gulfstream Postaccident Safety Actions

In response to this accident investigation, Gulfstream released two separate Maintenance and Operations Letters (issued June 13, 2014, and August 18, 2014) addressed to all Gulfstream operators. Both letters emphasized the importance of adhering to AFM procedures to confirm flight control integrity and freedom of movement. The letters reminded operators of the following AFM procedures:

- Ensure the gust lock is OFF prior to starting engines (not applicable for G650)
- Check flight controls for freedom and correct movement prior to taxi/takeoff
- Confirm the elevators are free during the takeoff roll.

Additionally, the second letter informed operators of the following:

> While a throttle interlock is incorporated in the design of the gust lock system, if proper unlock procedures are not followed, movement of the throttle to a position capable of providing sufficient engine power for autothrottle engagement and takeoff power may be possible for GIV models. Throttle movement is not an absolute indicator of the gust lock status for any Gulfstream model. **The freedom of flight control movement is the ultimate indicator the gust lock is fully released for all Gulfstream models.** [emphasis in the original]

According to Gulfstream and FAA representatives, as of the date of this report, Gulfstream was actively working on a modification to the G-IV gust lock/throttle lever interlock designed to limit the amount of throttle movement with the gust lock system engaged to the intended certification limits. In addition to limiting throttle movement, the modification was expected to replace the lock pin in the gust lock handle with a pin made from a material with a defined strength and include recurring compliance checks to ensure that the interlock system would continue to function as intended. FAA representatives stated that the FAA would begin the process of mandating the modification immediately after Gulfstream completes it and that this process typically takes 6 to 12 months.

1.12.2 Massport Postaccident Safety Actions

In June 30 and July 7, 2015, e-mails to the NTSB, Massport provided information on the agency’s postaccident actions, which included the following:

- **Establishment of a Massport ARFF unit at BED.** Effective November 2015, a new Massport ARFF unit will assume primary responsibility for ARFF operations at BED. At that point, Hanscom AFB-FD will provide secondary ARFF support and will continue to provide primary support for structural fires.

- **Grid Maps/Gate Maps.** The BED grid map, which is part of the airport certification manual required by 14 *CFR* Part 139, identifies locations and features on and around the airport. BED uses a separate map to show all of the airport gates. Massport will add the airport gate map to the airport emergency plan (AEP) during the next scheduled revision of the AEP in November 2015.
- **ARFF Training for Mutual Aid Responders.**
  - Massport has compiled quick response guides and delivered them to the Bedford, Concord, Lexington, and Lincoln fire departments;
  - two large BED maps have been delivered to each local fire department for training;
  - aircraft training and hangar familiarization programs have been provided, and will continue to be provided, to local fire departments and Hanscom AFB-FD;
  - monthly airfield response and communication drills have been implemented to maintain consistency with airfield familiarization and communications with the ATCT;
  - crash charts of different aircraft for training and response have been delivered to local fire departments;
  - BED has been added to Massachusetts Fire District 13, expanding fire resources;
  - a fuel farm familiarization PowerPoint presentation has been developed and shared with local fire departments, and site visits from local fire departments to the fuel farm were scheduled for September 2015;
  - Massport Fire Rescue is developing a training curriculum for mutual aid partners, “Adapting and Using Structural Rescue and Firefighting Equipment for Aircraft Rescue and Firefighting,” to be implemented on November 1, 2015, and to include rescue techniques, use of hydraulic rescue tools, and water supply;
  - an airport/community hazard analysis and incident command workshop has been developed and is under review by local fire chiefs—the workshop will involve local fire, police, and other town officials and will aid in joint preparedness and the identification of response management challenges for an aircraft accident on or off the airport; and
  - a unified command organization structure, including airport operations, fire, police, and emergency medical service commanders, has been established for all incidents to improve joint operations and incident action planning.
- **Radio Interoperability.** Massport has taken the following steps regarding interoperability:
  - identified a common fire ground frequency for interoperability for the Hanscom AFB-FD and local fire departments;
  - identified a second frequency for command if needed;

- led an interoperability tabletop exercise/workshop in May 2015 in which almost 40 stakeholders participated; and
- developed an incident command system communications plan, which has been approved by local fire chiefs and is currently under review by the emergency medical service providers.

2. Analysis

The flight crew was properly certificated and qualified in accordance with federal regulations and company requirements, and both pilots had substantial experience flying the G-IV. Information about their recent activities does not suggest that the flight crewmembers were fatigued. The investigation found no evidence that the SIC had any significant medical condition or used any drug that might have been impairing.

The PIC sustained a closed head injury in 1992. Although closed head injuries may lead to persistent cognitive deficits or altered personality traits, there is no evidence that the PIC experienced these symptoms. Toxicology testing identified ethanol in the PIC's blood but not in his brain or muscle. Since ethanol is readily distributed throughout the body after ingestion, it is most likely that the identified ethanol was not from ingestion but was formed by microbial action after death. The NTSB concludes that the flight crew was qualified to operate the airplane, and the use of alcohol or drugs, fatigue, and medical conditions were not factors in the flight crew's performance.

Other than the broken lock pin in the gust lock handle, which will be discussed in section 2.1, the investigation found no evidence of any preimpact structural, engine, or system failures. The NTSB considered the possibility that the sunglasses found inside the pedestal jammed the gust lock sheave, limiting the movement of the gust lock handle, but postaccident testing demonstrated that this scenario was unlikely. Further, the NTSB could not determine when the sunglasses entered the pedestal. They could have entered the pedestal during the impact sequence or during wreckage recovery and transport by falling into the hole created when the unsecured left control display unit was dislodged from its slot.

2.1 Accident Sequence

The flight crew made a series of errors that culminated in the airplane overrunning the runway. Before starting to taxi, the crewmembers made two of these errors. First, they neglected to release and stow the gust lock handle as would normally be accomplished during the engine start process. Second, they neglected to perform a flight control check after the engines were started. Further, a review of QAR data revealed that the flight crewmembers had neglected to perform complete flight control checks before 98% of their previous 175 takeoffs in the airplane, indicating that this oversight was habitual and not an anomaly.

The FDR recorded restricted motion of both the elevator and rudder throughout the taxi and attempted takeoff. This restricted motion indicates that the gust lock system was engaged because it is the only system on the airplane capable of restricting two independent flight control surfaces, and the restricted motion is consistent with the flight crew failing to disengage the gust lock system as called for in the Starting Engines checklist.

Disengaging the gust lock system requires a pilot to unlatch the gust lock handle and move it forward and down from the ON position to the OFF position. Normally, once the gust lock handle is unlatched, the return springs in the gust lock system pull the handle to the full down position. However, if there is a load acting on one of the primary flight controls, the gust lock handle can hang in an intermediate position with the gust lock hooks remaining engaged.

The NTSB considered the possibility that the flight crew released the gust lock handle before engine start and that it stopped in an intermediate position but determined that possibility was unlikely. For this to occur, one of the pilots would have had to unlatch the gust lock handle and let go of it without ensuring that it moved to the full down position. However, pilots typically leave a hand on the gust lock handle until it reaches the full down position to resist the downward pull of the return springs and prevent the handle from striking the pedestal. Therefore, it is unlikely that the flight crew attempted to reposition the gust lock handle to the full down position before starting the engines.

Further, the flight crew had an opportunity to detect that the gust lock system was engaged by conducting a flight control check as called for in the After Starting Engines checklist, but the FDR data indicated that a flight control check was not done. Therefore, the NTSB concludes that the flight crew failed to disengage the gust lock system as called for in the Starting Engines checklist and failed to conduct a flight control check as called for in the After Starting Engines checklist, during which the crewmembers would have detected that the gust lock system was engaged. Further, the NTSB concludes that, given that the flight crew neglected to perform complete flight control checks before 98% of the crewmembers' previous 175 takeoffs in the airplane, the flight crew's omission of a flight control check before the accident takeoff indicates intentional, habitual noncompliance with standard operating procedures (SOP).

In addition, the flight crew did not notice that the gust lock handle was in the ON position during taxi, line up, or the initial portion of the takeoff roll. Pilots are faced with many demands for visual attention during the taxi and takeoff phases of flight; therefore, they would likely not inspect the gust lock handle unless they were specifically checking its status, a step the accident flight crew did not perform during engine start. Further, although the gust lock handle was painted red, a color that is visually conspicuous in daytime lighting conditions, the accident occurred at night in lower lighting conditions, when the color red is less conspicuous and would, therefore, be less easily noticed by either pilot.

As the airplane turned onto the runway, activation of the yaw damper or an inadvertent rudder pedal input moved the rudder control surface until it was restricted by the gust lock mechanism, and pressure increased in the rudder actuator until the rudder limiter activated.[30] The flight crewmembers noticed the "RUDDER LIMIT" message as the airplane turned onto the runway and, after a brief discussion, discounted its importance. The AFM states that this message is advisory and that no crew action is required. Thus, the flight crew's decision to disregard the message and continue the takeoff was consistent with published procedures. Although the rudder limit message appeared because of the interaction of the engaged gust lock with the yaw damper system, this message is not normally used to alert flight crews to the status

[30] When taxiing the G-IV, steering is accomplished using the airplane's nose wheel steering tiller, and no rudder pedal inputs are intentionally made. When the G-IV enters a turn, the yaw damper system senses the combination of yaw rate and lateral acceleration and commands rudder to oppose the turn.

of the gust lock system. Thus, the appearance of this message did not alert the flight crew to the gust lock's engaged status.

Next, as the takeoff roll began, the PIC encountered a restriction to forward movement of the throttle levers but did not immediately reject the takeoff. On the basis of prior takeoff data, the flight crew typically manually advanced the throttle levers until the PLA was about 30°, achieving an EPR of about 1.7, before engaging the autothrottle. On the accident takeoff, the throttle levers were manually advanced to an initial PLA of only about 17.5°, and the EPR achieved was about 1.42, where it remained for about 5 seconds. This EPR plateau at a lower-than-normal level likely resulted from the throttles contacting the gust lock/throttle lever interlock. When the gust lock handle is in the ON position, the throttles can move freely until the interlock is contacted and further forward travel is stopped. Testing on in-service G-IV airplanes and the accident airplane's pedestal assembly suggests that for the interlock to be contacted at a PLA of 17.5°, the gust lock handle had to have been in the ON position (further supporting that it was not in an intermediate position) and that the gust lock handle's lock pin was likely intact at the time.

The PIC was likely aware of the throttle lever restriction because the interlock restricted the throttle levers to about 50% of the range of movement that the flight crew typically used. The PIC would not normally have encountered a restriction, and the restriction prevented him from smoothly setting takeoff power at an EPR of 1.7 before engaging the autothrottle, as the flight crew had consistently done on previous takeoffs. Despite encountering this abnormal throttle lever restriction, the PIC did not immediately call out the problem or call for a rejected takeoff before engaging the autothrottle. The absence of a prompt verbal statement about the restriction is an example of ineffective communication, which is inconsistent with best practices for crew resource management (CRM).[31]

The EPR began to increase above the 1.42 plateau as the autothrottle commanded an increase in power. The target EPR was likely set to 1.7, which was the flight crew's normal target EPR. The PLA increased about 7° to 8°, reaching the maximum recorded PLAs of 25.7° and 24.3° for the right and left engines, respectively, with corresponding EPRs of about 1.6 achieved for both engines. Testing showed that, with the throttle levers positioned at the interlock, engaging the autothrottle achieved some additional PLA but disconnected before achieving a 7° to 8° increase. The most likely explanation for an increase of this magnitude is that the gust lock handle's lock pin failed at this time.[32] If the lock pin had remained intact, it is

[31] AC 120-51E, "Crew Resource Management Training," dated January 22, 2004, describes best practices for CRM. The AC states that effective CRM behaviors involve the provision of "necessary information at the appropriate time," including "alerting others to developing problems" and providing information "with appropriate persistence until there is some clear resolution."

[32] Postaccident calculations determined that a 68-lb load applied to the throttle levers, a 119-lb load applied to the gust lock handle, or a 211-lb load applied to the sector assembly control cable sheaves (autothrottle is capable of inputting a 120-lb load to the sector assembly) would have resulted in a failure of the lock pin. Thus, the pin could have broken due to a manual load applied to the throttle levers, a manual load applied to the gust lock handle, a load applied by the autothrottle combined with a manual load, or some combination of these loads. If the pin had a preexisting condition or wear, it is possible that the failure could have occurred with less load than described above.

likely that the autothrottle would either have disconnected or have added a smaller increase in PLA than observed before going into HOLD mode.[33]

It is unclear why the PIC engaged the autothrottle, as it would seem extremely imprudent to continue a takeoff after encountering a substantial restriction to throttle lever movement while setting takeoff power. The PIC did not likely understand the reason for the throttle lever restriction and attempted to force the levers forward with the help of the autothrottle. As a result of the autothrottle engagement, and possibly due, in part, to manual forces applied to the throttle levers, the lock pin in the gust lock handle was likely broken or compromised, allowing the throttle levers to move forward and the engines to attain an EPR value that approached the target setting. This increase in EPR may have contributed to the flight crewmembers' confusion about the nature of the problem and given them some confidence that they could continue the takeoff and get airborne.

The maximum obtained PLA position occurred about the same time as the airplane reached 60 kts and the autothrottle went into HOLD mode. Normally, when the autothrottle enters HOLD mode, it maintains the PLA positions captured at that time. However, in this case, after the autothrottle entered HOLD mode, the PLAs reduced and stabilized near 21°, and the EPRs also reduced and stabilized near 1.53. The NTSB considered three possible reasons for the reduction in PLA and EPR: one of the pilots manually reduced power, one of the pilots pulled back on the gust lock handle, or a spring back of the throttles occurred as the autothrottle entered HOLD mode. As discussed in appendix B, insufficient evidence exists to determine the reason for the reduction in PLA and EPR.

As the EPRs were decreasing from their maximum values, the CVR recorded the first comment made by either pilot during the takeoff roll, which was the PIC's comment, "couldn't get (it manually any further)." This comment strongly suggests that the PIC was aware of the throttle lever restriction. However, the SIC did not verbally respond, and the CVR did not record any discussion between the flight crewmembers. The SIC's failure to acknowledge the PIC's statement about the restriction and the PIC's continuation of the takeoff without any verbal acknowledgement from the SIC (or any clear resolution of the problem) are additional examples of ineffective communication that is inconsistent with best practices for CRM.

As the airplane accelerated through an airspeed range of 60 to 80 kts during takeoff, the PIC did not check the elevator for freedom of movement or notice that the control yoke was not moving from the full forward position to the neutral position as a result of the restriction imposed by the gust lock. Although this check is not included in the Lineup checklist that was found in the cockpit, a note below the Lineup checklist in the AFM states that such a check should be performed. In addition, standard maneuvers and callouts in training materials that the flight crewmembers used during their recurrent training at FlightSafety International state, "by 80 knots, air loads will cause the yoke to move from full forward to the neutral position indicating that the elevator is free" and that "if this does not occur by 80 knots, the takeoff should be aborted." A review of QAR data from the airplane's previous 175 takeoffs revealed that the elevators always began to move toward neutral at an airspeed of 60 to 80 kts.

[33] During testing on a small sample of in-service G-IV airplanes, the autothrottle added about 1° to 4° of PLA before disconnecting.

The flight crewmembers had likely failed to notice the absence of movement of the control column between 60 and 80 kts because they treated this issue as a passive check during a phase of flight that is normally visually demanding for both pilots. The flight crewmembers had likely not previously experienced a problem with a locked elevator during takeoff, so they were probably not watching closely for elevator movement. Another potential reason for this oversight is that, about this time, the PIC's attention appears to have been focused on the anomalies he had encountered with throttle lever movement, as evidenced by his comment "couldn't get (it manually any further)." In addition, SOPs specify that the PIC should first place a hand on the control yoke at a speed of about 80 kts, which would eliminate the opportunity for a tactile indication of control column movement between 60 and 80 kts. By 80 kts, the control column would normally have stabilized in a neutral position, so the pilot would not typically feel it move. The only cue that something was wrong by that point was the displaced position of the yoke, which was only a few inches forward of normal, a condition that the PIC apparently did not notice.

The takeoff roll continued, and about 5 seconds after the PIC's "couldn't get (it manually any further)" comment, the SIC began making the standard takeoff speed callouts. The callouts took place over about 8 seconds, and 1 second after the final "rotate" callout, the PIC made his first "(steer) lock is on" comment. During the 13 seconds that elapsed between the PIC's "couldn't get (it manually any further)" comment and his first "(steer) lock is on" comment, the airplane's speed increased from about 65 kts to about 129 kts.

The flight crew did not immediately initiate a rejected takeoff when the PIC attempted to rotate the airplane, discovered that he could not move the control yoke, and began calling out "(steer) lock is on." At this point, the PIC clearly understood that the elevator was immobilized because the gust lock was engaged. The airplane performance study determined that, if the flight crew had initiated a rejected takeoff in accordance with the G-IV AFM at the time of the PIC's first "lock is on" comment or at any time up until about 11 seconds after this comment, the airplane could have been stopped on the paved surface. However, the flight crew delayed initiating a rejected takeoff for about 10 seconds, and a further delay of 4 seconds existed between brake application and power reduction; therefore, the rejected takeoff was not initiated until the accident was unavoidable.

Human factors research indicates that response time is longer for unexpected events than for expected events. When a flight crew is confronted with a sudden, abnormal event, responses are more likely to be delayed or inappropriate, and a reaction time of 8 to 10 seconds may not be unusual (Casner, Geven, and Williams 2013, 477-485). However, in this case, the delay in initiating a rejected takeoff was apparently exacerbated by the flight crew's attempt to use an ineffective strategy to resolve the problem and continue the takeoff. FDR data indicated that about 6 seconds after the PIC first called out "(steer) lock is on," one of the pilots attempted to resolve the situation by operating the FPSOV handle. The use of the FPSOV is called for in the AFM emergency procedure for an immovable flight control. However, a G-IV pilot indicated that he was aware that at least some G-IV pilots used the FPSOV to relieve hydraulic pressure and allow the gust lock handle to be moved to the OFF position if it stopped in an intermediate position due to a hydraulic load on one of the gust lock hooks. Testing verified that this technique, although not approved by Gulfstream, is effective when the airplane is parked on the ground or taxiing at low speeds but would not likely be effective at takeoff speeds due to aerodynamic loading on the elevator.

By the time that the FPSOV was activated, the airplane's speed had increased to about 150 kts. According to a postaccident analysis provided by Gulfstream, the hand force required to push the gust lock handle forward and disengage the elevator gust lock hook at 150 kts due to aerodynamic loading would have been about 189 lbs. A pilot would not likely have the physical strength to disengage the gust lock at such speeds.[34] The postaccident OFF position of the gust lock handle is consistent with one of the pilots unlatching the handle and attempting to push it down to the OFF position but being unable to do so because of aerodynamic loading of the elevator. With the handle in an intermediate position, as the airplane's speed decreased, the aerodynamic load would have decreased, eventually allowing the return springs to pull the handle down to the OFF position.

A pilot would not likely be aware of the difficulty involved in releasing the gust lock system at high speeds without having a very detailed, engineering-level understanding of the flight control system. Thus, the delay in initiating a rejected takeoff likely resulted, in part, from surprise but also from a knowledge-based mistake stemming from an incomplete mental model of the gust lock system. The NTSB concludes that, about the time that the airplane reached a speed of 150 kts, one of the pilots activated the FPSOV, likely in an attempt to unlock the flight controls, but this action was ineffective because high aerodynamic loads on the elevator were likely impeding gust lock hook release.

Complicating matters, although the PIC repeatedly stated his concern about the status of the gust lock, the SIC never replied. In addition, although one or both pilots likely attempted to disengage the gust lock using the FPSOV, neither pilot explicitly verbalized his intent to do so, and neither pilot verbally commanded a rejected takeoff after this strategy proved unsuccessful. This lack of two-way communication was inconsistent with best practices for CRM, and the absence of standard callouts diminished the flight crew's ability to develop a shared understanding of the situation, decide on an appropriate course of action, and execute that course of action. Thus, the NTSB concludes that the flight crew delayed initiating a rejected takeoff until the accident was unavoidable; this delay likely resulted from surprise, the unsuccessful attempt to resolve the problem through the use of the FPSOV, and ineffective communication.

2.2 Use of Checklists

According to the G-IV AFM, five normal checklists should be accomplished by the flight crew before takeoff: the Before Starting Engines checklist, the Starting Engines checklist, the After Starting Engines checklist, the Taxi/Before Takeoff checklist, and the Lineup checklist. Although one of the pilots could have completed one or more of these checklists silently, the pilots did not discuss or call for any of these checklists, execute any of the checklist items using standard verbal callouts, or verbally acknowledge the completion of any of these checklists. As

[34] Anthropometric data indicate that a 95th-percentile male in a seated position can exert a maximal static force of between 154 and 172 lbs when asked to push with one hand on a vertical grip located above the thigh with the elbow hanging straight down at the shoulder 90˚ to the floor, and with the forearm parallel to the floor, increasing to between 172 and 180 lbs as the upper arm swings forward about 30˚ (Herzberg 1963).

previously discussed, two of these checklists include an item that involved either confirming that the gust lock was off or performing another action that would have alerted the flight crew that the gust lock was not off; evidence indicates that the flight crew omitted performance of both items.

Errors of omission are some of the most common everyday forms of error, even among highly skilled experts, and have occurred in about 20% of flight crew-involved major accidents (Dismukes 2006). To counteract this vulnerability in flight crew performance, the NTSB and other organizations have long advocated the use of checklists as a memory aid during normal operations (NTSB 1969 and FAA 2008).[35] In addition, AC 120-51E indicates that checklists are key to the comprehensive framework of SOPs considered foundational for effective CRM.

For optimum benefit, normal checklist items should be verbally called out by flight crewmembers using a challenge-verification-response format (Degani and Wiener 1990). The monitoring pilot (the SIC in this case) would read a checklist item, the flight crew would verify that the check or action has been properly performed, and the flying pilot (the PIC in this case) would call out a response. When executed in this fashion, checklists can help a flight crew recall the steps for configuring the airplane, specify a logical sequence and distribution of workload, enhance mutual supervision (crosschecking), and support shared awareness of the airplane's configuration. Due to these benefits, the challenge-verification-response method has become the industry standard, with many air carriers requiring flight crews to execute normal checklists in this manner. However, a pilot who had previously flown the G-IV airplane with the PIC stated that the PIC had memorized the G-IV checklists and that he did not normally ask for the checklists to be formally completed. This interview statement, the total lack of discussion of the checklists during the accident flight, and the routine omission of flight control checks during their last 175 flights indicate that the flight crewmembers did not routinely use the normal checklists or the optimal challenge-verification-response format. These behaviors likely resulted from a complacency that evolved over time because the two pilots flew the same airplane almost exclusively with each other over multiple years.

Executing checklists by memory or without standardized verbal callouts removes many of their benefits and leaves a flight crew more susceptible to error. Thus, the flight crewmembers' nonadherence to best practices for checklist execution made it more likely that they would commit an error of omission and that such an error would go undetected. The NTSB concludes that the flight crewmembers' lack of adherence to industry best practices involving the execution of normal checklists eliminated the opportunity for them to recognize that the gust lock handle was in the ON position and delayed their detection of this error.

The SK Travel FOM indicated that the company required its pilots to complete all checklists during flight operations. In addition, a letter signed by the owners of SK Travel that was contained in the SK Travel FOM informed pilots that they could be subject to punitive measures, up to and including termination, if they did not adhere to SOPs, which would

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[35] Safety Recommendations A-88-68 and A-88-72 also addressed checklist use as a memory aid during normal operations. The recommendations can be accessed at the NTSB's website at www.ntsb.gov.

presumably include the company's required use of normal checklists.[36] However, this guidance did not specify how the checklists were to be completed or what callouts were to be made, which considerably weakened the guidance. Moreover, FDR data indicated that the pilots were routinely noncompliant with the SOP that involved performing the control check specified in the After Starting Engines checklist, and no mechanism was in place for the company to detect this routine noncompliance. The chief pilot, who was responsible for ensuring compliance with the company SOPs, was one of the two flight crewmembers. The company did not have a flight data monitoring (FDM) program, and the pilots were not regularly surveilled for compliance with SOPs by outside qualified personnel.

The company had successfully passed safety audits, the most recent of which was in 2012, overseen by a contractor to the IBAC as part of the IBAC's IS-BAO program. Regarding checklist usage, the 2012 audit determined that the company had checklists consistent with the G-IV AFM and that proper checklist usage was verified during annual PIC proficiency checks in a simulator. The 2012 audit did not include any observation of the flight crew during a flight; however, it is possible that an in-flight observation of the flight crew during an IS-BAO audit would not have revealed the extent of the flight crew's typical noncompliance with SOPs. Nonetheless, audit standards could have included a provision indicating that company policies and procedures should specify preferred methods for checklist execution, but the standards did not include such a provision. Although the existence of such policies and procedures would not have guaranteed flight crew compliance, they would have provided a clear message to the flight crew about best practices regarding checklist execution. Because there was no such requirement in place for SK Travel to pass an IS-BAO audit, the audit did not encourage SK Travel pilots to use an optimal challenge-verification-response format for performing checklists, and the audit was therefore not as effective as it could have been for encouraging safe operating practices.

The NTSB concludes that independent safety audits performed by an industry safety organization did not adequately encourage best practices for the execution of normal checklists. Therefore, the NTSB recommends that the IBAC amend IS-BAO auditing standards to include verifying that operators are complying with best practices for checklist execution, including the use of the challenge-verification-response format whenever possible.

2.3 Procedural Noncompliance

A troubling aspect of this accident is the flight crew's pattern of noncompliance with an important step in the manufacturer's After Starting Engines checklist—the flight control check—which appears to have been intentional. Because the flight crewmembers could not be interviewed, and because they had not recently flown with other pilots who could provide detailed insights into their motivations in this area, there is little hard evidence upon which to base an analysis of the reasons for the flight crew's intentional noncompliance. However, the

[36] The preamble to the SK Travel FOM states, in part, "you, as the operational and technical staff, will always have my full support as long as you operate professionally in accordance with this Flight Operations Manual. I also wish to make it understood that all staff have a duty to openly and honestly report events and hazards. You can be assured that such reports will be thoroughly investigated in a non-punitive manner. However, willful disregard of the regulations and established SOPs will not be tolerated and may result in termination."

crewmembers' behavior can be placed in context, and some possible reasons for it can be identified by referring to the broader scientific literature on procedural noncompliance.

Research observations and airline industry data indicate that procedural noncompliance is not uncommon in professional aviation. The authors of a 1990 National Aeronautics and Space Administration study reported that two out of six airline crews they observed on one particular wide-body airplane type neglected to perform all flight phase checklists during a flight (Degani and Wiener 1990). Line operations safety audit data from more than 20,000 airline flights conducted between 1996 and 2013 revealed that 49% of such flights involved at least one instance of intentional noncompliance (Werfelman 2013). In addition, relatively recent data from airline FDM programs indicated that flight crews continue 97% of unstable approaches to landing, which is against most airline policies (Burin 2011). Thus, procedural noncompliance occurs during normal operations, even among the flight crews of major airlines.

Industry data also indicate that procedural noncompliance substantially increases the likelihood of subsequent flight crew errors (Werfelman 2013). Thus, it is not surprising that procedural noncompliance is also a factor in major accidents. An NTSB study of flight crew-involved major accidents that occurred between 1978 and 1990 found that 24% of the errors made in these accidents were procedural errors, making it the most common category of errors (NTSB 1994). The procedural errors identified in the study included numerous examples of procedural noncompliance. Of the 10 takeoff accidents examined, for example, 6 involved uninitiated or inadequately performed checklists that were causal to the accident. This noncompliance resulted in attempted takeoffs with mistrimmed control surfaces (two accidents), flaps not extended (two accidents), incorrect use of engine anti-ice systems (one accident), and locked controls (one accident). Although this study is more than 20 years old, examples of flight crew procedural noncompliance have also been documented in recent accidents (NTSB 2014 *Descent* and NTSB 2014 *Crash*). In addition, the NTSB included "strengthen procedural compliance" on its 2015 Most Wanted List of Transportation Safety Improvements.

Various theories have been advanced to explain why flight crews might intentionally deviate from required procedures, including personality characteristics, culture (professional, company, and crew), goal conflicts, and resource constraints (Karwal, Verkaik, and Jansen 2000 and Woods and others 2010). However, the remarkable consistency of this flight crew's omission of such checks (as indicated by QAR data) suggests shared crew attitudes about the necessity of the flight control check. Although it is unknown whether the crewmembers consciously omitted the performance of a flight control check during the accident flight, it is likely that they decided to skip the check at some point in the past and that doing so had become their accepted practice.

When flight crewmembers perform a routine check repeatedly over a long period of time and never encounter an example of its effectiveness as a safety protection, they may experience a decreased perception of the check's importance (Degani and Wiener 1990). As a result, they may begin to skip the check and reallocate their efforts toward other goals that they regard as more important. Such changes can lead to the development of new group norms about what is expected and an increasing mismatch between written guidance and actual operating practice. This increasing mismatch has been described as "procedural drift" (Dekker 2006). Procedural drift likely played a role in the accident flight crew's procedural noncompliance.

Major airlines devote considerable energy and resources to promoting flight crew standardization and adherence to SOPs to counter this phenomenon. One characteristic of a large commercial airline may facilitate such efforts to prevent procedural drift. A large pilot workforce means that individual pilots are frequently paired with new colleagues rather than being paired together with each other for long periods of time. Pilots must perform their tasks in a standardized fashion to work effectively with colleagues they have met for the first time. Under those conditions, it can be more difficult for habitual noncompliance to become established in a crew's behavior pattern, especially the establishment of a new set of norms that condones the routine omission of normal safety checks. Smaller business operators with much smaller pilot workforces, such as the dedicated two-pilot crew involved in this accident, might face a much greater risk of procedural drift because their operating practices could more easily drift in parallel. Thus, the accident flight crewmembers may not have been an outlier regarding their noncompliance with the required flight control check.

The NTSB found no data documenting the rate of flight crew compliance with required flight control checks in business aviation on the G-IV or any other airplane, yet checklists, callouts, and other SOPs are considered an important "soft" defense against threats and errors in business aviation. If the actual rate of procedural compliance is much lower than assumed, aircraft designers, regulators, and operators may need to take steps to boost compliance or reconsider their assumptions about the reliability of flight crew adherence to routine checks and the level of safety protection afforded by such SOPs. Fortunately, data monitoring technology now exists to evaluate this question empirically.

The NBAA is an industry organization founded in 1947 that has a mission to "foster an environment that allows business aviation to thrive in the United States and around the world" (www.nbaa.org/about, accessed July 7, 2015). The NBAA maintains a safety committee that provides industry leadership on safety by "identifying significant industry risks and serving as a center of expertise on a wide range of safety matters" (www.nbaa.org/about/leadership/committees/safety, accessed July 7, 2015). The committee's recent efforts have included organizing a range of safety meetings and the "development of a data-driven safety agenda for business aviation, via membership in the FSF [Flight Safety Foundation] Corporate Flight Operational Quality Assurance [C-FOQA] Steering Committee and participation in the C-FOQA pilot project."

The C-FOQA program, which was developed in 2005 by Austin Digital in cooperation with the FSF and has since been trademarked as "C-FOQA Centerline," is an FDM program modeled after airline FDM programs known as flight operational quality assurance (FOQA) programs. According to Austin Digital, C-FOQA Centerline "fully encompasses all aspects of airline-level FOQA and FDM," including the "identification, analysis and management of operational safety risks" (www.ausdig.com/services/c-foqa-centerline, accessed July 7, 2015). Participation in C-FOQA Centerline by business aviation departments operating under 14 *CFR* Part 91 is not required, but some operators choose to voluntarily participate in this program. The C-FOQA Centerline program is advised by a user's group, some of whom serve on a steering committee that meets regularly to help manage the program. Methods for contributing deidentified C-FOQA Centerline data to the FAA's Aviation Safety Information Analysis and Sharing system are currently being explored.

Through the C-FOQA Centerline program, a repository of data has been developed that could shed light on the rate of procedural compliance in business aviation. As demonstrated by the NTSB's review of data from the accident airplane's QAR, it is relatively simple to evaluate flight data to detect the completion of a flight control check before takeoff. Data collected through the C-FOQA Centerline program could be analyzed through automated queries to determine the frequency that required flight control checks are accomplished and calculate the rate of omission. Such an analysis would allow the business aviation industry to estimate the magnitude of procedural noncompliance regarding a well-defined before-takeoff safety check. The NTSB concludes that an analysis of flight operational quality assurance data specifically evaluating the rate of noncompliance with flight control checks before takeoff could help define the scope of procedural noncompliance in business aviation and guide the development of strategies to address it.

The NTSB believes that the NBAA is in a unique position to lead such a data analysis effort due to its safety leadership in the business aviation community and its longstanding involvement with the C-FOQA Centerline program. Therefore, the NTSB recommends that the NBAA work with existing business aviation FOQA groups, such as the C-FOQA Centerline Steering Committee, to analyze existing data for noncompliance with manufacturer-required routine flight control checks before takeoff and provide the results of this analysis to NBAA members as part of the NBAA's data-driven safety agenda for business aviation.

2.4 Survival Aspects

According to one of the controllers who witnessed the takeoff attempt, the postcrash fire erupted "almost instantaneously" with the airplane coming to a stop in the ravine. Wreckage examination and firefighter statements indicated that the fire originated near the wing root area of the fuselage and spread rapidly, rendering the airplane's overwing emergency exit windows unusable and blocking access to the baggage compartment door located aft of the wing. Therefore, the only viable exit was likely the main entry door. Although postaccident examination of the main entry door's locking mechanism found the door to operate normally, the occupants did not open it.

All seven occupants were found unrestrained and in positions consistent with movement within the airplane after the crash. The PIC was found kneeling in his seat facing his open oxygen mask compartment, suggesting that he may have returned from the forward entry area to the cockpit and attempted to don his oxygen mask. The SIC was found in a position suggesting that he may have been attempting to leave the cockpit. One passenger was found near the main entry door, one passenger was found in the aisle leading from the cabin to the main entry door, and the other two passengers and the flight attendant were found in the cabin in positions suggesting that they were attempting to move forward toward the main entry door.

The occupants' as-found positions and the few traumatic injuries described by the autopsies indicate that the accident was initially survivable. However, the occupants did not exit the airplane, and autopsy and toxicological reports indicated that the cause of death for six of the seven occupants was smoke inhalation and thermal injuries. The NTSB concludes that the impact forces from the accident were survivable, but the cabin and cockpit environment quickly deteriorated due to the postcrash fire, which erupted immediately, spread rapidly, and prevented the occupants from escaping.

2.4.1 Aircraft Rescue and Firefighting Response

Within 5 minutes of the Alert 3 notification, Hanscom AFB-FD firefighting vehicles (Crash 9 and Crash 10) had reached the airport side of the ravine and were fighting the fire. According to the firefighters, the airplane was engulfed in flames and was inside the ravine, which acted as a shield and kept the fire and heat centrally located and difficult to fight. Firefighting activities continued for about 25 minutes and focused on the primary ARFF purpose of controlling and extinguishing the fire. Then, for about 14 minutes, no water was applied to the fire due to the need to resupply the vehicles with water. This delay could have been avoided if a resupply hose had been dropped at a fire hydrant about 1,200 ft away when the vehicles drove past it on their way to the crash site. The NTSB concludes that, although it did not affect the survivability of this accident, had a resupply hose been placed at the fire hydrant in the vicinity of the accident site before the ARFF vehicles exhausted their water supply, the 14-minute delay in resuming firefighting activities could have been avoided. The NTSB notes the importance of following proper firefighting procedures to ensure the best possible outcome regarding occupant survivability after aircraft accidents and incidents.[37]

Confusion ensued about how to put personnel and equipment on the nonairport (east) side of the ravine to reach the nose of the airplane. About 48 minutes after the initial notification, a Hanscom AFB-FD firefighting vehicle reported that it would attempt to reach the nose of the airplane using the Hartwell gate; however, this gate does not provide access to the east side of the ravine. Perimeter gate 26 located between the fire station and the accident site (shown on figure 8) provides access to the east side of the ravine; however, the location of this gate was not shown on the airport grid map in the BED AEP. According to Massport, the location of the perimeter gate was shown on an airport gate map, but this map was not included in the AEP.

According to FAA AC 150/5200-31, "Airport Emergency Plan," the airport grid map should identify locations and terrain features on and around the airport that are significant to emergency operations. The AC states that all ARFF vehicles, airport operator vehicles, and mutual aid vehicles should carry a copy of the airport grid map for reference. Although a grid map may not account for every possible location for an off-airport event, the map should be designed to effectively support identification and access to accident sites adjacent to the airport property, as in the case of this accident. The NTSB concludes that, had the BED AEP included a gate map, or had the perimeter gates been depicted on the grid map, the ARFF personnel's confusion about how to reach the nonairport side of the ravine would likely have been reduced. In a July 7, 2015, e-mail detailing postaccident changes, Massport stated that it planned to add

[37] Title 14 *CFR* 139.317, Aircraft Rescue and Firefighting: Equipment and Agents, provides the minimum requirements for water and agent on every ARFF vehicle for an initial fire attack. National Fire Protection Association document 1003, *Standards for Airport Fire Fighter Professional Qualifications*, states that fundamental aircraft firefighting techniques include the management of extinguishing agents and that the requisite knowledge for replenishing extinguishing agents includes resupply procedures, operation procedures for ARFF vehicle replenishment, and procedures for pumps and transfer devices.

the airport gate map to the BED AEP during the next scheduled AEP revision in November 2015.

As mutual aid firefighters from the Lincoln Fire Department attempted to gain entry to the airplane about 1 hour 47 minutes after the Alert 3 notification, they were confused about the main entry door's operation. The door was opened only after Hanscom AFB-FD ARFF personnel arrived on the east bank of the ravine to help the Lincoln firefighters. In this case, the lack of knowledge about an airplane door's operation on the part of a mutual aid company did not affect occupant survivability. However, if an aircraft accident were to occur near BED in the future, a mutual aid company could be the first to arrive on site, and any confusion about how to open an aircraft door could adversely affect the outcome for the passengers and crew on board. According to FAA AC 150/5210-17C, "Programs for Training of Aircraft Rescue and Firefighting Personnel," when mutual aid agreements exist with municipal fire services surrounding an airport, all parties should receive familiarization training. In its June 30, 2015, e-mail detailing postaccident changes, Massport reported that it has provided, and would continue to provide, aircraft familiarization training to the mutual aid companies supporting BED.

The NTSB notes that the outcome of the accident regarding occupant survivability would likely have been the same if the missteps during the emergency response (involving water resupply procedures, firefighter knowledge of the locations on and around the airport that are significant to emergency operations, and G-IV main entry door operation procedures) had not occurred. The air traffic controllers who witnessed the accident airplane depart the runway stated that the airplane became engulfed in flames "almost instantaneously." Although evidence showed that the occupants had enough time to start a self-evacuation, the deteriorating conditions due to the postcrash fire precluded the occupants from evacuating the airplane. The NTSB also notes that the actions of the ARFF personnel who applied agent to grass fires near the accident site (as discussed in section 1.9.1) did not delay the initial fire attack on the airplane or change the outcome of this accident regarding occupant survivability.

2.4.2 Use of Frangible Structures

After leaving the paved runway overrun and entering the grass, the airplane struck the approach lighting system for runway 29, the runway 11 localizer antenna, and the airport perimeter fence. These structures were not, and were not required to be, mounted on frangible supports; only structures inside the RSA must have frangible supports.[38] However, the NTSB notes that these structures at BED were located on airport property, along the extended centerline of the runway, and on relatively flat terrain.

The damage that the airplane sustained from impacting the nonfrangible supports was not thoroughly assessed because the postcrash fire consumed much of the airplane structure that likely struck these objects. However, all of the support structures that came in contact with the

[38] Title 14 *CFR* 139.309(b)(4) requires all fittings inside the RSA to be frangible but does not apply to fittings outside the RSA.

airplane were either broken or bent, and the airplane was likely substantially damaged as a result of contacting these structures.

After the accident, the FAA used frangible fittings when replacing the approach lighting and localizer structures damaged in the accident. According to the FAA, its decision to use frangible fittings was made to enhance safety. The FAA's decision is consistent with its statement in AC 150/5220-23, "Frangible Connections," that "to further the overall goal of safety on the airport, it is highly encouraged that these frangibility provisions be incorporated in the areas adjacent to safety areas whenever possible."

After a March 5, 2003, accident in Burbank, California, involving Southwest Airlines flight 1455, the NTSB issued Safety Recommendation A-03-11, which asked the FAA to require all 14 *CFR* Part 139 certificated airports to upgrade all RSAs that could, with feasible improvements, be made to meet the minimum standards established by AC 150/5300-13, "Airport Design." Among its activities in response to this recommendation, the FAA initiated a program to relocate or make frangible FAA-owned navigational aids that are located in RSAs. On March 23, 2015, the FAA reported to the NTSB that these improvements were on track for completion by the end of fiscal year 2018. As of May 4, 2015, Safety Recommendation A-03-11 was classified "Open—Acceptable Response" pending completion of these improvements.

The NTSB recognizes that the FAA already encourages the incorporation of frangible fittings in areas adjacent to RSAs and that it replaced the fittings at BED with frangible fittings after the accident. However, similar nonfrangible structures located outside of an RSA, but inside a perimeter fence and along an extended runway centerline, are likely present at other airports. Although structures within RSAs are checked for frangibility during an airport's annual Part 139 certification inspection and the FAA has a program to relocate structures or make them frangible, structures outside RSAs are not checked and made frangible. The NTSB is concerned that the FAA currently has no procedure for identifying nonfrangible structures outside of RSAs or prioritizing replacement of their nonfrangible fittings with frangible fittings wherever feasible.

The NTSB concludes that the replacement of nonfrangible fittings with frangible fittings on structures located outside of, but adjacent to, an RSA, such as the approach lights and localizer antenna struck by the accident airplane, would minimize the potential for damage to an airplane that is unable to stop within the RSA during a runway overrun. Therefore, the NTSB recommends that the FAA identify nonfrangible structures outside of an RSA during annual 14 *CFR* Part 139 inspections and place increased emphasis on replacing nonfrangible fittings of any objects along the extended runway centerline up to the perimeter fence with frangible fittings, wherever feasible, during the next routine maintenance cycle.

2.5 Gust Lock Design and Certification

The certification basis for gust lock systems, 14 *CFR* 25.679, required Gulfstream to ensure that the system in the G-IV limited the operation of the airplane in such a manner that the pilot received unmistakable warning at the start of takeoff. As stated in its August 29, 2014, letter to the NTSB, the FAA considers an unmistakable warning to be "a warning that physically limits the operation of the airplane to prevent an unsafe takeoff."

The NTSB asked Gulfstream how the G-IV gust lock system complied with 14 *CFR* 25.679. Gulfstream responded on September 26, 2014, and stated that the following three features of the gust lock system would provide an unmistakable warning to the flight crew:

(1) it restricts the operation of the pilot controls (yoke, column, rudder pedals) during the AFM-required flight control checks;

(2) it limits the operation of the throttle levers; and

(3) as an additional warning feature, the gust lock handle is painted red and located prominently adjacent to the flap handle.

However, in this accident, none of these protections were effective in preventing an unsafe takeoff. The first protection was ineffective because of the flight crew's habitual noncompliance with SOPs. The second protection was ineffective because the G-IV gust lock/throttle interlock did not limit the movement of the throttle levers to 6° as the design specified. The third protection was ineffective because the flight crew failed to notice the position of the gust lock handle despite its color and proximity to the flap handle, likely due to a combination of the night lighting condition at the time of the accident, which made the color red less conspicuous, and geometry. The gust lock handle is located next to the flap handle, which makes the flap handle less accessible when the gust lock handle is in the ON position but does not prevent the selection of a takeoff flap setting (which occurred shortly after engine start in this case).

Further, the restriction of the throttles is the only one of the three gust lock protections that Gulfstream cites that meets the FAA's definition of an unmistakable warning as "a warning that physically limits the operation of the airplane to prevent an unsafe takeoff." The other two protections require the pilots to perform other operations to identify that the gust lock is engaged. In addition, as stated earlier and demonstrated in this accident, error-free human performance is not consistently attainable. However, if the throttle restriction had performed as intended and provided an unmistakable warning as required by 14 *CFR* 25.679, the other two protections would have been less critical.

Postaccident testing on the accident airplane and in-service G-IV airplanes demonstrated that the forward throttle lever movement that could be achieved with the gust lock ON was 3 to 4 times greater than the intended TLA of 6°. Additionally, performance calculations showed that the throttle restriction did not perform as intended; if the throttles had remained at the point where they initially contacted the interlock (at a PLA of 17.5° and a corresponding EPR of about 1.42), the airplane would have reached rotation speed about 7 seconds later and about 1,200 ft farther down the runway than it did. In contrast, an interlock that limited TLA to 6° would have prevented the airplane from achieving any significant acceleration, thus constituting an unmistakable warning that would most likely have prevented the accident. The same cannot be said for the other two protections, which depend on consistent flight crew adherence to SOPs.

The NTSB concludes that, because the gust lock system in G-IV airplanes does not limit the operation of the throttle levers with the gust lock engaged to provide an unmistakable warning at the start of takeoff, as was originally intended when the airplane was certificated, the gust lock system in the G-IV does not comply with 14 *CFR* 25.679. Therefore, the NTSB recommends that, after Gulfstream develops a modification of the G-IV gust lock/throttle lever interlock, the FAA require that the gust lock system on all existing G-IV airplanes be retrofitted to comply with the certification requirement that the gust lock physically limit the operation of the airplane so that the pilot receives an unmistakable warning at the start of takeoff.[39]

The G-IV gust lock/throttle interlock system was based on previously certificated airplane systems (the G-II, G-IIB, and G-III), and compliance with 14 *CFR* 25.679 for the G-IV was demonstrated by a review of engineering drawings. Gulfstream did not perform, and was not required by the FAA to perform, any engineering certification tests, inspection, or analysis of the gust lock system as it would be installed on the G-IV airplane to verify that the system had met its functional requirements of showing compliance with section 25.679. The NTSB believes that a drawing review was an insufficient means of demonstrating compliance with section 25.679 because of the complexities of the G-IV gust lock system as installed on the airplane. Specifically, the G-IV gust lock system was complex because (1) Gulfstream made design changes to the G-IV gust lock/throttle interlock system architecture, (2) the engines on the G-IV had a higher thrust rating than the engines on the previously certificated Gulfstream airplanes on which the gust lock's design was based, and (3) the gust lock system was an integrated system that interfaced with the flight control system and the engine control system.

The NTSB concludes that the FAA missed opportunities to detect the inadequate design of the gust lock system during the G-IV's certification because the FAA relied solely on a review of engineering drawings to determine if the system met certification requirements. The NTSB further concludes that Gulfstream's use of a G-IV drawing review alone to show compliance with 14 *CFR* 25.679 led to a gust lock/throttle interlock system that did not comply with the regulation. Had verification testing or analysis been performed, Gulfstream would have identified that the gust lock/throttle interlock system allowed throttle lever movement well beyond 6° when the gust lock handle was in the ON position.

Review of the FAA's and Gulfstream's certification processes found that, since the original G-IV certification efforts during the 1980s, the FAA and industry have worked together to provide improved guidance for establishing acceptable means for showing compliance with applicable regulations for aircraft systems. Due to the increase of highly integrated complex systems on aircraft, the FAA and industry focused their attention on the need for a top-down iterative approach to the systems' development. As a result of this effort, in 1996, SAE International published Aerospace Recommended Practices (ARP) 4754, *Certification Considerations for Highly-Integrated or Complex Aircraft Systems*.[40] A retitled revision of ARP 4754, *Guidelines for Development of Civil Aircraft and Systems*, ARP 4754A, was published in December 2010.

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[39] According to Gulfstream and FAA representatives, as of the date of this report, Gulfstream was actively working on a modification to the G-IV gust lock/throttle lever interlock, and the FAA planned to begin the process to mandate the modification immediately after Gulfstream completes it. The NTSB strongly supports these efforts.

[40] SAE International, initially established as the Society of Automotive Engineers, is a professional association and standards organization for engineering professions in various industries, including aerospace.

Since the original G-IV certification, Gulfstream has adopted a systems engineering approach to design development, which includes a structured plan to validate that design requirements are complete and correct and verify that the design, as implemented, meets those requirements at all levels by incorporating ARP 4754A into the design process. Gulfstream now uses requirements management tools, such as relational databases that provide full requirements traceability and verification from aircraft level to piece part level. It is likely that the use of a systems engineering approach, such as that provided in the ARP 4754A guidance, would identify the need for substantiation beyond a review of engineering drawings to verify that a gust lock system meets its design requirements at all levels of the design. The NTSB concludes that, if the G-IV's gust lock system had been developed using Gulfstream's current design process, Gulfstream would likely have developed, validated, and verified a gust lock system that would limit the throttle lever movement to 6°.

The NTSB believes that Gulfstream's current design process would not result in a review of engineering drawings (without a verification test or analysis) serving as the entire means of showing compliance with 14 *CFR* 25.679. However, the NTSB is concerned that there is a lack of guidance available on the use of a design review as a means of compliance with aircraft certification regulations; as a result, manufacturers may rely on, and the FAA may accept, a design review in cases in which its use is inappropriate.[41] According to the FAA, a design review is a common means of showing compliance with a number of aircraft certification regulations, and it may be appropriate in some cases. However, a design review as a means of compliance with a regulation and its specific documentation requirements are not defined in FAA guidance material such as FAA orders or ACs. Additionally, a design review is often intertwined with another means of showing compliance (similarity), and specific requirements for each are not delineated in FAA documentation. The NTSB concludes that, without clear guidance, the use of drawing reviews as the sole method of compliance determination may not be sufficiently robust to verify that FAA aircraft type certification requirements have been met. Therefore, the NTSB recommends that the FAA develop and issue guidance on the appropriate use and limitations of the review of engineering drawings in a design review performed as a means of showing compliance with certification regulations.

[41] FAA Order 8110.4C, *Type Certification*, lists acceptable means of compliance with certification regulations as "ground test, flight test, analysis, similarity, or other acceptable means of compliance." As used in this section, a design review means an inspection of engineering documents and falls under the category of other acceptable means of compliance.

3. Conclusions

3.1 Findings

1. The flight crew was qualified to operate the airplane, and the use of alcohol or drugs, fatigue, and medical conditions were not factors in the flight crew's performance.

2. The flight crew failed to disengage the gust lock system as called for in the Starting Engines checklist and failed to conduct a flight control check as called for in the After Starting Engines checklist, during which the crewmembers would have detected that the gust lock system was engaged.

3. Given that the flight crew neglected to perform complete flight control checks before 98% of the crewmembers' previous 175 takeoffs in the airplane, the flight crew's omission of a flight control check before the accident takeoff indicates intentional, habitual noncompliance with standard operating procedures.

4. About the time that the airplane reached a speed of 150 knots, one of the pilots activated the flight power shutoff valve, likely in an attempt to unlock the flight controls, but this action was ineffective because high aerodynamic loads on the elevator were likely impeding gust lock hook release.

5. The flight crew delayed initiating a rejected takeoff until the accident was unavoidable; this delay likely resulted from surprise, the unsuccessful attempt to resolve the problem through the use of the flight power shutoff valve, and ineffective communication.

6. The flight crewmembers' lack of adherence to industry best practices involving the execution of normal checklists eliminated the opportunity for them to recognize that the gust lock handle was in the ON position and delayed their detection of this error.

7. Independent safety audits performed by an industry safety organization did not adequately encourage best practices for the execution of normal checklists.

8. An analysis of flight operational quality assurance data specifically evaluating the rate of noncompliance with flight control checks before takeoff could help define the scope of procedural noncompliance in business aviation and guide the development of strategies to address it.

9. The impact forces from the accident were survivable, but the cabin and cockpit environment quickly deteriorated due to the postcrash fire, which erupted immediately, spread rapidly, and prevented the occupants from escaping.

10. Although it did not affect the survivability of this accident, had a resupply hose been placed at the fire hydrant in the vicinity of the accident site before the aircraft rescue and firefighting vehicles exhausted their water supply, the 14-minute delay in resuming firefighting activities could have been avoided.

11. Had the Laurence G. Hanscom Field airport emergency plan included a gate map, or had the perimeter gates been depicted on the grid map, the aircraft rescue and firefighting personnel's confusion about how to reach the nonairport side of the ravine would likely have been reduced.

12. The replacement of nonfrangible fittings with frangible fittings on structures located outside of, but adjacent to, a runway safety area (RSA), such as the approach lights and localizer antenna struck by the accident airplane, would minimize the potential for damage to an airplane that is unable to stop within the RSA during a runway overrun.

13. Because the gust lock system in Gulfstream Aerospace Corporation G-IV airplanes does not limit the operation of the throttle levers with the gust lock engaged to provide an unmistakable warning at the start of takeoff, as was originally intended when the airplane was certificated, the gust lock system in the G-IV does not comply with 14 *Code of Federal Regulations* 25.679.

14. The Federal Aviation Administration (FAA) missed opportunities to detect the inadequate design of the gust lock system during the Gulfstream Aerospace Corporation G-IV's certification because the FAA relied solely on a review of engineering drawings to determine if the system met certification requirements.

15. Gulfstream Aerospace Corporation's use of a G-IV drawing review alone to show compliance with 14 *Code of Federal Regulations* 25.679 led to a gust lock/throttle interlock system that did not comply with the regulation.

16. If the Gulfstream Aerospace Corporation G-IV's gust lock system had been developed using Gulfstream's current design process, Gulfstream would likely have developed, validated, and verified a gust lock system that would limit the throttle lever movement to 6°.

17. Without clear guidance, the use of drawing reviews as the sole method of compliance determination may not be sufficiently robust to verify that Federal Aviation Administration aircraft type certification requirements have been met.

3.2 Probable Cause

The NTSB determines that the probable cause of this accident was the flight crewmembers' failure to perform the flight control check before takeoff, their attempt to take off with the gust lock system engaged, and their delayed execution of a rejected takeoff after they became aware that the controls were locked. Contributing to the accident were the flight crew's habitual noncompliance with checklists, Gulfstream Aerospace Corporation's failure to ensure that the G-IV gust lock/throttle lever interlock system would prevent an attempted takeoff with the gust lock engaged, and the Federal Aviation Administration's failure to detect this inadequacy during the G-IV's certification.

4. Recommendations

To the Federal Aviation Administration:

Identify nonfrangible structures outside of a runway safety area during annual 14 *Code of Federal Regulations* Part 139 inspections and place increased emphasis on replacing nonfrangible fittings of any objects along the extended runway centerline up to the perimeter fence with frangible fittings, wherever feasible, during the next routine maintenance cycle. (A-15-30)

After Gulfstream Aerospace Corporation develops a modification of the G-IV gust lock/throttle lever interlock, require that the gust lock system on all existing G-IV airplanes be retrofitted to comply with the certification requirement that the gust lock physically limit the operation of the airplane so that the pilot receives an unmistakable warning at the start of takeoff. (A-15-31)

Develop and issue guidance on the appropriate use and limitations of the review of engineering drawings in a design review performed as a means of showing compliance with certification regulations. (A-15-32)

To the International Business Aviation Council:

Amend International Standard for Business Aircraft Operations auditing standards to include verifying that operators are complying with best practices for checklist execution, including the use of the challenge-verification-response format whenever possible. (A-15-33)

To the National Business Aviation Association:

Work with existing business aviation flight operational quality assurance groups, such as the Corporate Flight Operational Quality Assurance Centerline Steering Committee, to analyze existing data for noncompliance with manufacturer-required routine flight control checks before takeoff and provide the results of this analysis to your members as part of your data-driven safety agenda for business aviation. (A-15-34)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

T. BELLA DINH-ZARR
Vice Chairman

ROBERT L. SUMWALT
Member

EARL F. WEENER
Member

Adopted: September 9, 2015

Board Member Statement

Member Robert L. Sumwalt filed the following concurring statement on September 14, 2015.

To all outward appearances, SK Travel had the hallmarks of a well-run flight department. They were operating a top-of-the-line business jet. They had long-time employment stability – something not often found with small aviation departments. They did their training at FlightSafety International instead of just trying to do it "on the cheap." The chief pilot was described as being very meticulous about the airplane's maintenance. They had undergone two voluntary industry audits and were preparing for their third audit, in itself a remarkable feat.

The auditor for their second voluntary audit had the following glowing comments:

- "The Safety Management System (SMS) of this operator is well-developed;"
- "Best practices are consistently employed in all facets of the program;"
- "Continuous SMS improvement is actively pursued;"
- "The flight operations manual is remarkably well-written and comprehensive;"
- "Safety culture within the department is shared among all team members;"
- "Open reporting of hazards is consistently encouraged by management;"
- "Solid safety program, maturing nicely."

Despite these positive comments, our investigation revealed an operation in which checklists and flight control checks were not accomplished by the flight crew, as specified in their training and the aircraft operations manual. In order to successfully complete training, neither of these omissions would have been acceptable. However, considering that each crewmember successfully completed recurrent training eight months before the crash, they obviously knew and demonstrated they were aware of these requirements.

Given that they knew how they were supposed to operate, why did these crewmembers perform to the contrary? Why did they intentionally act one way when being checked, and perform another way – a way contrary to basic good airmanship – in actual operations?

Complacency is one explanation that comes to mind. Perhaps an overconfidence developed out of routine, wherein the crew believed their method of operations didn't require these procedural items. Whatever the reason, the result proved catastrophic.

Although the crewmembers may have become complacent, I have to believe the owners of this airplane expected the pilots to always operate in conformity with -- or exceed -- their training, aircraft manufacturer requirements, and industry best practices. Yet, as evidence showed in this investigation, once seated in their cockpit, these crewmembers operated in a manner that was far, far from acceptable.

There is a saying: "You can fool the auditors, but never fool yourself." These crewmembers made the critical mistake of attempting to fool both – a mistake that was costly, unfortunate, and tragic.

I hope the lessons from this crash can be used to emphasize the critical need to combat complacency, eradicate intentional noncompliance, and perform like true professionals. Passengers who place their lives in the hands of flightcrews deserve and expect no less.

5. Appendixes

Appendix A: Cockpit Voice Recorder Transcript

The following is a transcript of an L-3/Fairchild FA2100-1020 cockpit voice recorder, serial number unknown, installed on a Gulfstream G-IV, N121JM, which crashed during takeoff from Laurence G. Hanscom Field, Bedford, Massachusetts, on May 31, 2014. This transcript incorporates the addendum issued on July 13, 2015.

LEGEND

CAM	Cockpit area microphone voice or sound source
HOT	Flight crew audio panel voice or sound source
RDO	Radio transmission from N121JM
GND	Radio transmission from the Hanscom ground controller
TWR	Radio transmission from the Hanscom airport tower controller
-1	Voice identified as the second in command
-2	Voice identified as the pilot in command
-3	Voice identified as cabin crewmember
-?	Voice unidentified
*****	Unintelligible word
#	Expletive
@	Non-pertinent word
( )	Questionable insertion
[ ]	Editorial insertion

Note 1: Times are expressed in eastern daylight time (EDT).

Note 2: Generally, only radio transmissions to and from the accident aircraft were transcribed.

Note 3: Words shown with excess vowels, letters, or drawn out syllables are a phonetic representation of the words as spoken.

Note 4: A non-pertinent word, where noted, refers to a word not directly related to the operation, control or condition of the aircraft.

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
19:36:10.0	**Start of Recording**		
21:10:19.7	**Start of Transcript**		
21:10:19.7 **CAM**	[unintelligible vocalizations].		
21:15:04.6 **CAM**	[unintelligible vocalizations].		
21:16:31.3 **CAM**	[unintelligible vocalizations].		
21:17:35.3 **CAM-3**	[unintelligible vocalizations consistent with speech outside of the cockpit].		
21:28:04.2 **CAM-?**	* *.		
21:28:07.9 **CAM-1**	probably.		
21:28:17.1 **CAM-?**	* *.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
21:28:42.6 **CAM-3**	can you check with @ to see if he called uhm @, when you got (down) there?		
21:28:46.7 **CAM-2**	I think he just did.		
21:28:48.9 **CAM-?**	* * *.		
21:28:53.1 **CAM-3**	alright, you jumpin up?		
21:28:58.6 **CAM-?**	* *.		
21:29:28.1 **CAM-3**	* *.		
21:29:34.1 **CAM-3**	*.		
21:29:49.2 **CAM**	[reduction of background noise followed by mechanical sounds]		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
21:30:02.7 **CAM-2**	* * @ asked me to ask you whether you called @ already.		
21:30:07.8 **CAM-1**	@ yeah.		
21:30:08.4 **CAM-2**	okay. that's what I told I thought so. Just wanted make sure.		
21:30:24.3 **CAM**	[sounds consistent with engine start]		
21:31:14.5 **CAM**	[sounds consistent with engine start]		
		21:31:15.9 **ATIS**	Hanscom tower information Juliet zero zero five one Zulu. winds three zero zero at three. visibility one zero. sky clear. temperature niner. dewpoint four. altimeter three zero two seven. arriving departing runway one one. visual approach in use. taxiway Mike from runway five * Hill hangar's closed. readback all hold short instructions advise on initial contact you have information Juliet.

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
21:31:37.3 **CAM**	[sound similar to thump]		
21:31:41.3 **CAM**	[sound similar to click]		
21:31:42.5 **CAM**	[sound similar to click]		
21:31:44.1 **CAM**	[sound similar to click]		
21:31:45.4 **CAM**	[sound similar to click]		
21:31:48.6 **CAM**	[sounds similar to multiple clicks]		
		21:31:52.1 **RDO-1**	and Hanscom ground Gulfstream one two one Juliet Mike at Jet Aviation with ah Juliet ready to taxi.
21:31:57.1 **CAM**	[sounds similar to click and thump]		
21:31:58.1 **CAM**	[sound similar to thump]		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
		21:32:02.6 **GND**	Gulfstream one two one Juliet Mike Hanscom ground runway one one taxi via Sierra Tango Echo cross runway five midfield.
		21:32:16.0 **RDO-1**	okay I'm sorry ah what was that again for Juliet Mike?
		21:32:18.7 **GND**	Gulfstream one Juliet Mike from Jet runway one one taxi via Sierra Tango Echo cross runway five midfield.
21:32:22.1 **CAM**	[sounds of engine noise changing]		
		21:32:24.6 **RDO-1**	Sierra Tango Echo cross runway five one two one Juliet Mike thanks.
21:32:52.9 **CAM-2**	yeah the diagram there's a connector here Mike guess they're not using that.		
21:33:01.9 **CAM-1**	ah used to be able go out that way.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
21:33:04.1 **CAM-2**	yeah now -		
21:33:04.3 **CAM-1**	but they got the ah taxiway all dug up.		
21:33:34.9 **CAM-2**	go to one one * * Tango to cross five right?		
21:33:41.0 **CAM-1**	ah Sierra Tango- eh Sierra Echo Tango cross runway five yes.		
21:34:29.5 **CAM-2**	taxiway-		
21:34:30.8 **CAM-1**	Sierra Tango Echo		
21:34:32.3 **CAM-2**	(thank you)		
21:35:53.6 **CAM-2**	cleared to cross, right?		
21:35:54.6 **CAM-1**	yup cleared to cross.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
		21:36:16.4 **GND**	Gulfstream one Juliet Mike on the other side of five you contact the tower have a good flight.
		21:36:20.6 **RDO-1**	Juliet Mike have a good evening now.
		21:36:55.1 **RDO-1**	and Hanscom tower Gulfstream one two one Juliet Mike will be ready when reaching.
		21:37:00.1 **TWR**	* one two one Juliet Mike Hanscom tower turn right heading two five zero runway one one cleared for takeoff.
21:37:03.1 **CAM-?**	*.		
		21:37:07.9 **RDO-1**	okay after departure it'll be a left turn heading two five zero and we're cleared for takeoff one two one Juliet Mike.
		21:37:12.9 **TWR**	that's a right turn.

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
		21:37:14.3 **RDO-1**	a right turn two five zero one two one Juliet Mike.
		21:37:16.9 **TWR**	thank you.
21:37:20.2 **CAM-3**	I tried him but I didn't get him *.		
21:37:21.7 **CAM-1**	oh I got @ he's ah he's was gonna run out and get something to eat and I told him we'd be there about twenty after ten.		
21:37:22.7 **CAM-3**	(okay).		
21:37:27.8 **CAM-3**	(okay).		
21:38:26.8 **HOT**	[sound similar to seat belt chime].		
21:38:33.9 **CAM-2**	we're cleared for takeoff?		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
21:38:34.8 **CAM-1**	cleared for takeoff right turn heading two five zero.		
21:38:37.2 **CAM-2**	'kay.		
21:39:05.9 **CAM**	[sound similar to power increase]		
21:39:21.1 **CAM-2**	it says rudder limit light is on.		
21:39:23.9 **CAM-1**	what's that?		
21:39:24.7 **CAM-2**	the rudder limit light is on.		
21:39:26.4 **CAM-1**	are you using your rudders?		
21:39:27.8 **CAM-?**	no * *.		
21:39:31.1 **CAM-?**	huh.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
21:39:33.7 **CAM**	[sound similar to power increasing further]		
21:39:45.5 **CAM**	[sound similar to ground roll]		
21:39:45.7 **CAM-?**	hmmm.		
21:39:46.6 **CAM-2**	couldn't get (it manually any further).		
21:39:51.3 **CAM-1**	eighty.		
21:39:57.5 **CAM-1**	V-1.		
21:39:58.9 **CAM-1**	rotate.		
21:39:59.9 **CAM-2**	(steer) lock is on.		
21:40:02.7 **CAM-2**	(steer) lock is on.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
21:40:03.7 **CAM-2**	(steer) lock is on.		
21:40:04.4 **CAM-2**	(steer) lock is on.		
21:40:05.2 **CAM**	[sounds similar to thump and squeak]		
21:40:06.6 **CAM-2**	(steer) lock is on.		
21:40:07.5 **CAM-2**	(steer) lock is on.		
21:40:12.6 **CAM-2**	(steer) lock is on.		
21:40:14.3 **CAM-2**	I can't stop it.		
21:40:16.2 **HOT**	[sound of triple chime].		
21:40:19.6 **CAM-2**	oh no no.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
21:40:21.0 **CAM**	[sound of impact].		
21:40:24.5	**End of Recording**		
21:40:24.5	**End of Transcript**		

Appendix B: Analysis of Power Lever Angle and Engine Pressure Ratio Behavior

This analysis discusses the PLA and EPR behavior that the FDR recorded during the initial part of the takeoff. About 4 seconds after brake release, the EPR plateaued at a lower-than-normal level of about 1.42, likely due to the throttles contacting the gust lock/throttle lever interlock. The PLA attained at this time was about 17.5°. Testing on the accident airplane's pedestal assembly demonstrated that, with the gust lock handle in the ON position and an intact lock pin installed, the throttles contacted the interlock at a TLA of 22°. With the actual broken lock pin installed, the throttles contacted the interlock at a TLA of 27°. Testing performed on four in-service G-IV airplanes showed that a TLA of 22° converts to an expected PLA range of 15.4° to 19.3°, and a TLA of 27° converts to an expected PLA of 18.8° to 23.6°.[1] Further, during testing performed on two in-service G-IV airplanes, PLAs of 28° on one airplane and 35° on the other airplane were observed with the gust lock handle in an intermediate position and the throttles moved forward until they contacted the interlock. These data suggest that, for the interlock to be contacted at a PLA of 17.5° during the accident takeoff, the gust lock handle was in the ON position, and the lock pin was likely intact at the time.

After remaining about 1.42 for about 5 seconds, the EPR began to increase again when the autothrottle was engaged. The PLA increased about 7° to 8°, reaching maximum recorded PLAs of 25.7° and 24.3° for the right and left engines, respectively, with corresponding EPRs of about 1.6 achieved for both engines. As discussed in section 2.1, the most likely explanation for an increase of this magnitude is that the gust lock handle's lock pin failed at this time, allowing the throttle levers to move forward and resulting in the observed maximum PLAs and EPRs.

The maximum obtained PLA position occurred about the same time as the airplane reached 60 kts and the autothrottle went into HOLD mode. Normally, when the autothrottle enters HOLD mode, it maintains the PLA positions captured at that time. However, in this case, after the autothrottle entered HOLD mode, the PLAs reduced and stabilized near 21°, and the EPRs also reduced and stabilized near 1.53. The NTSB considered three possible reasons for the reduction in PLA and EPR that occurred between about 2139:46 and 2139:48: one of the pilots manually reduced power, one of the pilots pulled back on the gust lock handle, or a spring back of the throttles occurred as the autothrottle entered HOLD mode.

First, it is possible that one of the pilots manually reduced power (by moving the throttle levers back). Although it seems unlikely that the flight crew would intentionally reduce power at this point during the takeoff roll, no FDR or CVR evidence excludes this possibility.

Second, it is possible that one of the pilots pulled back on the gust lock handle. To release the gust lock handle from the ON position, the handle has to be pulled back slightly before it can be unlatched and moved forward to the unlocked position. If the throttles are contacting the interlock when the handle is moved back, the interlock will drive the throttles back toward idle in

[1] This analysis assumes that the actual TLA/PLA conversion value for the accident airplane was within the range identified on the four baseline test airplanes. The NTSB notes that four airplanes constitute a small sample size and that the accident airplane was possibly outside of these bounds.

relation to the degree the handle is pulled back. If the autothrottle is in HOLD mode, it will not move the throttles forward once they have been moved back, so the throttle levers will remain in their new reduced position (until moved by one of the pilots). During testing on an exemplar G-IV, with the throttles contacting the interlock and the autothrottle in HOLD mode, the gust lock handle was pulled back, unlatched, and released from the ON position. The throttle levers moved back, the EPRs on both engines reduced by 0.06, and the PLAs reduced by 4°. Each throttle lever remained in its new reduced position. The accident EPR reduction of about 0.07 and PLA reduction of about 4° are similar to the values observed during the test, suggesting that the EPR reduction could have resulted from an attempt to release the gust lock handle from the ON position.

Third, it is possible that the PLA reduction was a function of the autothrottle engagement, autothrottle HOLD mode, and a broken lock pin in the gust lock handle. During the time the EPR was increasing, the autothrottle would have been pushing the throttles into the interlock. Normally, the interlock would act as a hard stop because an intact lock pin would prevent forward movement of the gust lock handle. However, testing on the accident airplane demonstrated that the broken lock pin allowed for the interlock to act as a restriction that provided resistance, but the restriction could be pushed through with increased force. At the same time that this restriction was encountered, the airspeed reached 60 kts, the PLA and EPR achieved their peak values, and the autothrottle went into HOLD mode. When in HOLD mode, the autothrottle is depowered while the clutches remain engaged. Although it is expected that the autothrottle HOLD mode would have held the PLA steady at the value obtained when the airplane reached a speed of 60 kts, the NTSB notes that this exact combination of factors was not replicated during postaccident testing.

There was insufficient evidence to determine whether any of these three possibilities resulted in the observed reduction in PLA and EPR.

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