Crash During Experimental Test Flight
Gulfstream Aerospace Corporation GVI (G650), N652GD
Roswell, New Mexico
April 2, 2011

Accident Report

NTSB/AAR-12/02
PB2012-910402

National
Transportation
Safety Board

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Notation 8439
Adopted October 10, 2012

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490 L’Enfant Plaza, S.W.
Washington, DC 20594

National Transportation Safety Board. 2012. ***Crash During Experimental Test Flight, Gulfstream Aerospace Corporation GVI (G650), N652GD, Roswell, New Mexico, April 2, 2011*****. Aircraft Accident Report NTSB/AAR-12/02. Washington, DC.**

Abstract: This report discusses the April 2, 2011, accident involving an experimental Gulfstream Aerospace Corporation GVI (G650), N652GD, which crashed during takeoff from runway 21 at Roswell International Air Center, Roswell, New Mexico. The two pilots and the two flight test engineers were fatally injured, and the airplane was substantially damaged by impact forces and a postcrash fire.

Safety issues discussed in this report are the maximum lift coefficient for airplanes in ground effect; flight test standard operating policies and procedures; flight test-specific safety management system guidance; and coordination of high-risk test flights among flight test operators, airport operations, and aircraft rescue and firefighting personnel. Safety recommendations concerning these issues are addressed to the Federal Aviation Administration, the Flight Test Safety Committee, and Gulfstream Aerospace Corporation.

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Contents

Figures

Tables

Abbreviations and Acronyms

AC	advisory circular
ACO	aircraft certification office
AEO	all engines operating
AOA	angle of attack
APG1	first airplane performance group engineer
APG2	second airplane performance group engineer
APG3	third airplane performance group engineer
ARFF	aircraft rescue and firefighting
ATC	air traffic control
CFD	computational fluid dynamics
CFR	*Code of Federal Regulations*
CVR	cockpit voice recorder
FAA	Federal Aviation Administration
FDR	flight data recorder
FTE1	first flight test engineer
FTE2	second flight test engineer
FTE3	third flight test engineer
ICAO	International Civil Aviation Organization
MLG	main landing gear
NTSB	National Transportation Safety Board
OEI	one engine inoperative
PIC	pilot-in-command
PLI	pitch limit indicator

ROW	Roswell International Air Center
SIC	second-in-command
SMS	safety management system
SRB	safety review board
TIA	type inspection authorization
TSHA	test safety hazard analysis
$\mathbf{V_1}$	decision speed
$\mathbf{V_2}$	takeoff safety speed
$\mathbf{V_{LOF}}$	liftoff speed
$\mathbf{V_{MU}}$	minimum unstick speed
$\mathbf{V_R}$	rotation speed
$\mathbf{V_S}$	stall speed
$\mathbf{V_{SR}}$	reference stall speed

Executive Summary

On April 2, 2011, about 0934 mountain daylight time, an experimental Gulfstream Aerospace Corporation GVI (G650), N652GD, crashed during takeoff from runway 21 at Roswell International Air Center, Roswell, New Mexico. The two pilots and the two flight test engineers were fatally injured, and the airplane was substantially damaged by impact forces and a postcrash fire. The airplane was registered to and operated by Gulfstream as part of its G650 flight test program. The flight was conducted under the provisions of 14 *Code of Federal Regulations* Part 91. Visual meteorological conditions prevailed at the time of the accident.

The accident occurred during a planned one-engine-inoperative (OEI) takeoff when a stall on the right outboard wing produced a rolling moment that the flight crew was not able to control, which led to the right wingtip contacting the runway and the airplane departing the runway from the right side. After departing the runway, the airplane impacted a concrete structure and an airport weather station, resulting in extensive structural damage and a postcrash fire that completely consumed the fuselage and cabin interior.

The National Transportation Safety Board's (NTSB) investigation of this accident found that the airplane stalled while lifting off the ground. As a result, the NTSB examined the role of "ground effect" on the airplane's performance. Ground effect refers to changes in the airflow over the airplane resulting from the proximity of the airplane to the ground. Ground effect results in increased lift and reduced drag at a given angle of attack (AOA) as well as a reduction in the stall AOA. In preparing for the G650 field performance flight tests, Gulfstream considered ground effect when predicting the airplane's takeoff performance capability but overestimated the in-ground-effect stall AOA. Consequently, the airplane's AOA threshold for stick shaker (stall warning) activation and the corresponding pitch limit indicator (on the primary flight display) were set too high, and the flight crew received no tactile or visual warning before the actual stall occurred.

The accident flight was the third time that a right outboard wing stall occurred during G650 flight testing. Gulfstream did not determine (until after the accident) that the cause of two previous uncommanded roll events was a stall of the right outboard wing at a lower-than-expected AOA. (Similar to the accident circumstances, the two previous events occurred during liftoff; however, the right wingtip did not contact the runway during either of these events.) If Gulfstream had performed an in-depth aerodynamic analysis of these events shortly after they occurred, the company could have recognized before the accident that the actual in-ground-effect stall AOA was lower than predicted.

During field performance testing before the accident, the G650 consistently exceeded target takeoff safety speeds (V_2). V_2 is the speed that an airplane attains at or before a height above the ground of 35 feet with one engine inoperative. Gulfstream needed to resolve these V_2 exceedances because achieving the planned V_2 speeds was necessary to maintain the airplane's 6,000-foot takeoff performance guarantee (at standard sea level conditions). If the G650 did not meet this takeoff performance guarantee, then the airplane could only operate on longer runways. However, a key assumption that Gulfstream used to develop takeoff speeds was flawed and resulted in V_2 speeds that were too low and takeoff distances that were longer than anticipated.

Rather than determining the root cause for the V_2 exceedance problem, Gulfstream attempted to reduce the V_2 speeds and the takeoff distances by modifying the piloting technique used to rotate the airplane for takeoff. Further, Gulfstream did not validate the speeds using a simulation or physics-based dynamic analysis before or during field performance testing. If the company had done so, then it could have recognized that the target V_2 speeds could not be achieved even with the modified piloting technique. In addition, the difficulties in achieving the target V_2 speeds were exacerbated in late March 2011 when the company reduced the target pitch angle for some takeoff tests without an accompanying increase in the takeoff speeds.

Gulfstream maintained an aggressive schedule for the G650 flight test program so that the company could obtain Federal Aviation Administration (FAA) type certification by the third quarter of 2011. The schedule pressure, combined with inadequately developed organizational processes for technical oversight and safety management, led to a strong focus on keeping the program moving and a reluctance to challenge key assumptions and highlight anomalous airplane behavior during tests that could slow the pace of the program. These factors likely contributed to key errors, including the development of unachievable takeoff speeds, as well as the superficial review of the two previous uncommanded roll events, which allowed the company's overestimation of the in-ground-effect stall AOA to remain undetected.

After the accident, Gulfstream suspended field performance testing through December 2011 while the company examined the circumstances of the accident. In March 2012, Gulfstream reported that company field performance testing had been repeated and completed successfully. In June 2012, the company reported that FAA certification field performance testing had been successfully completed. Gulfstream obtained FAA type certification for the G650 on September 7, 2012.

The NTSB determines that the probable cause of this accident was an aerodynamic stall and subsequent uncommanded roll during an OEI takeoff flight test, which were the result of (1) Gulfstream's failure to properly develop and validate takeoff speeds for the flight tests and recognize and correct the V_2 error during previous G650 flight tests, (2) the G650 flight test team's persistent and increasingly aggressive attempts to achieve V_2 speeds that were erroneously low, and (3) Gulfstream's inadequate investigation of previous G650 uncommanded roll events, which indicated that the company's estimated stall AOA while the airplane was in ground effect was too high. Contributing to the accident was Gulfstream's failure to effectively manage the G650 flight test program by pursuing an aggressive program schedule without ensuring that the roles and responsibilities of team members had been appropriately defined and implemented, engineering processes had received sufficient technical planning and oversight, potential hazards had been fully identified, and appropriate risk controls had been implemented and were functioning as intended.

In its party submission for this accident investigation, Gulfstream stated that it accepted "full responsibility" for the accident and, in response, implemented corrective actions to preclude such an accident from recurring. One of these actions was to integrate safety management system principles and practices into the company's flight test operations. As a result of this investigation, the NTSB is issuing two recommendations to Gulfstream to commission an audit to evaluate the status of the company's safety management program before the start of its next major certification program and share lessons learned with aircraft manufacturers and flight test industry groups.

Additional actions to help improve the management and safety of flight test programs include providing aircraft manufacturers with flight test operating guidance and flight test safety guidelines based on best practices in aviation safety management. The NTSB is issuing two safety recommendations to the Flight Test Safety Committee (an independent flight test safety organization) and two recommendations to the FAA regarding the development of this guidance. The NTSB is also issuing one recommendation to the FAA to incorporate the flight test safety guidelines in an agency document.

In addition, the NTSB is issuing three other recommendations as a result of its investigation of this accident. One of these recommendations, addressed to the FAA, discusses the potential for domestic and foreign airplane manufacturers to overestimate an airplane’s stall AOA in ground effect. The other two recommendations, addressed to the FAA and the Flight Test Safety Committee, discusses advance coordination of high-risk flight tests among manufacturers, airport operators, and aircraft rescue and firefighting personnel.

1. The Accident

1.1 History of Flight

On April 2, 2011, about 0934 mountain daylight time,[1] an experimental Gulfstream Aerospace Corporation GVI (G650),[2] N652GD, crashed during takeoff from runway 21 at Roswell International Air Center (ROW), Roswell, New Mexico.[3] The two pilots and the two flight test engineers were fatally injured, and the airplane was substantially damaged. The airplane was registered to and operated by Gulfstream as part of its G650 flight test program. The flight was conducted under the provisions of 14 *Code of Federal Regulations* (CFR) Part 91. Visual meteorological conditions prevailed at the time of the accident.

Gulfstream was performing field performance flight testing to (1) gather data to support type certification of the G650 under 14 CFR Part 25, "Airworthiness Standards for Transport Category Airplanes,"[4] and (2) develop takeoff and landing speed schedules and distances for the G650 airplane flight manual. Takeoff performance tests began in October 2010; table 1 shows the takeoff performance test flight schedule through the date of the accident flight.[5] Figure 1 shows the G650 airplane (specifically, N652GD before the accident).

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[1] All times in this report are mountain daylight time.

[2] Gulfstream used the Roman numeral designation "GVI" for aircraft certification purposes and the designation "G650" for marketing purposes. These designations referred to the same airplane model and are used interchangeably in this report.

[3] ROW is owned and operated by the city of Roswell and is located about 3 miles south of the Roswell central business district. ROW has two active runways, 03/21 and 17/35. Runway 21 is 13,000 feet in length and 150 feet in width. Gulfstream chose ROW as a testing location because the airport's elevation (3,671 feet mean sea level) allowed takeoff performance data to be extrapolated to almost 10,000 feet mean sea level, which covered most airport elevations and eliminated additional testing requirements and performance penalties incurred when extrapolating data beyond certain limits.

[4] Title 14 CFR Part 25 addressed airplane performance and handling characteristics. Relevant sections of Part 25 included 25.101, "General"; 25.105, "Takeoff"; 25.107, "Takeoff Speeds"; and 25.143, "Controllability and Maneuverability."

[5] Gulfstream refers to a flight as the time from engine start to engine shutdown. Several takeoffs and landings, or test runs, can occur during a given flight. The takeoff performance flight tests were not numbered sequentially because other flight tests (including landing performance and systems flight tests) were being performed using the accident airplane. A total of 12 takeoffs were attempted on the day of the accident.

Table 1. Takeoff performance test flight schedule (through the date of the accident).

Date and location	Test flight number
Cecil Airport, Jacksonville, Florida	
October 19, 2010	65
October 20, 2010	67
Roswell International Air Center (Roswell I)	
November 10, 2010	81
November 11, 2010	83
November 14, 2010	86
November 15, 2010	87
November 16, 2010	88
November 17, 2010	89
November 18, 2010	91
Birmingham-Shuttlesworth International Airport, Birmingham, Alabama	
February 13, 2011	111
Roswell International Air Center (Roswell II)	
March 11, 2011	129
March 12, 2011	130
March 13, 2011	131
March 14, 2011	132
April 2, 2011	153

Note: Section 2.5.4 discusses the takeoff performance test flight schedule after the accident.

Figure 1. G650 airplane.

Source: Gulfstream.

The takeoff performance flight tests were being conducted with an angle-of-attack (AOA) limiter function disabled. The AOA limiter function was intended to be the primary stall protection system for the G650 (instead of a traditional stick pusher) once the airplane was certificated. The development of the AOA limiter software was not completed, so Gulfstream intended that the stick shaker would provide test pilots with a tactile warning of an impending stall. In addition, the pitch limit indicator (PLI)[6] on the primary flight display would provide the pilots with a visual indication of an impending stall. Figure 2 shows a representative PLI (as depicted in Gulfstream's draft G650 aircraft operating manual).

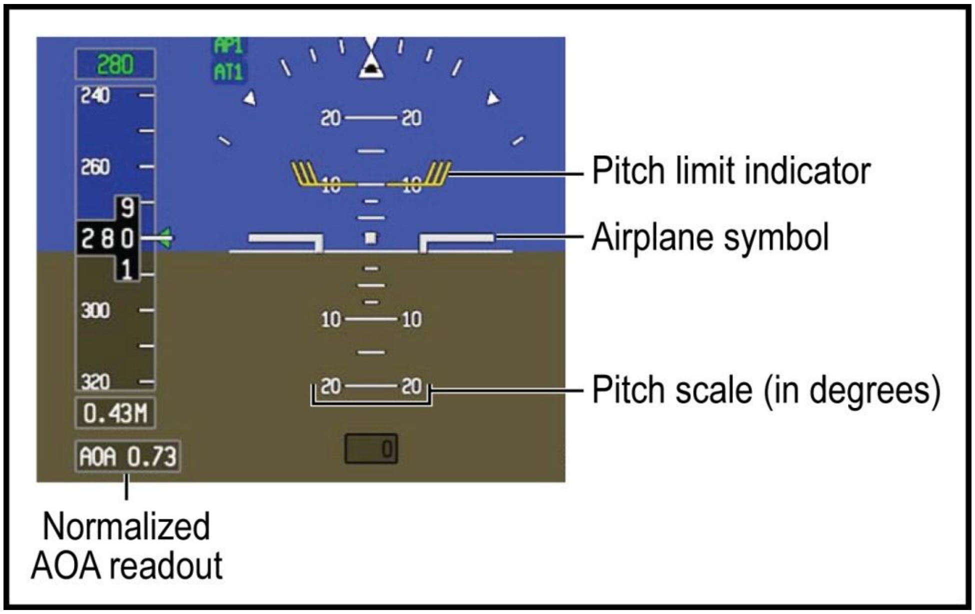

Figure 2. Pitch limit indicator.

Note: The PLI is displayed when the normalized AOA is greater than 0.7. Normalized AOA is a measure of the usable AOA range of an airplane, with a normalized AOA of 1.0 corresponding to the reference stall AOA in free air and a normalized AOA of 0.0 corresponding to the zero-lift AOA in free air. This figure is presented for information purposes only and is not intended to depict the flight conditions on the day of the accident.

Source: Gulfstream.

Of the nine test team members who were directly involved with testing at ROW on the day of the accident,[7] four were aboard the accident airplane, and five were located in the company's telemetry trailer, which was positioned near the end of a closed runway.[8] The four on-board test team members comprised the pilot-in-command (PIC), who sat in the left cockpit

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[6] The PLI indicates the pitch attitude at which the stick shaker activates. When the pitch attitude reference reaches the pitch attitude indicated by the PLI, the airplane is at stick shaker AOA, and the stick shaker activates. Pilots aim to keep pitch below the indicated limit.

[7] Additional maintenance and support personnel were also present when testing was conducted at ROW. On the day of the accident, a total of 25 Gulfstream personnel were present.

[8] The telemetry trailer was located about 7,400 feet from the runway 21 threshold and about 1,000 feet to the right of the runway 21 centerline.

seat and was the flying pilot; the second-in-command (SIC), who sat in the right cockpit seat and was the monitoring pilot; and two flight test engineers (FTE1 and FTE2), who sat at forward and aft workstations in the main cabin.[9] G650 flight test personnel indicated that one flight test engineer normally served as the on-board test conductor and that the other flight test engineer normally monitored the flight control system.[10]

The five test team members in the telemetry trailer were a third flight test engineer (FTE3), the airplane performance group head (APG1), two airplane performance engineers (APG2 and APG3), and a telemetry engineer. FTE3, who was in charge of flight test-related activities in the trailer (but was subordinate to FTE1), was relaying communications between telemetry trailer personnel and the on-board test team and providing wind information to the on-board test team. APG1 was verifying test conditions and comparing test results with performance objectives (in particular, the airplane's speed at 35 feet).[11] APG2 was placing markers in the flight test data stream to facilitate analysis at a later time. APG3 was observing operations in the telemetry trailer. The telemetry engineer was monitoring datalink connections between the trailer and the airplane.

According to test team members, FTE1 briefed the team members on the day before the accident. During this briefing, FTE1 indicated that the target pitch attitude for continued takeoff tests with the flaps set to 10º (flaps 10) would be reduced from 10º to 9º (± 1º). FTE1 also indicated that they should discontinue a test if pitch reached 11º during the initial takeoff and then decrease pitch and add engine power.[12] Gulfstream's principal engineer for airplane performance (who discussed the change in target pitch with FTE1 at an informal meeting in late March 2011) and APG1 stated that FTE1 made the change in target pitch to be consistent with the procedure for takeoff tests conducted with flaps set to 20º (flaps 20)[13] and ensure that the AOA would remain below the range at which two previous uncommanded roll events (as discussed in section 1.3.2) had occurred.

The takeoff speed schedules to be used by the flight crew consisted of tabulated values for the decision speed (V_1), rotation speed (V_R), and takeoff safety speed (V_2) as a function of flap setting and airplane gross weight; liftoff speed (V_{LOF}) values were included in the speed schedules for one-engine-inoperative (OEI) continued takeoffs.[14] The speed schedules were

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[9] The cabin was configured with five workstations, each of which included a crew seat, a desk, and a computer station. Three workstations were located on the right side of the airplane, and two workstations were located on the left side. (Three of the five workstations aboard the airplane were designed for Gulfstream flight test engineers; the other two workstations were designed for representatives from the engine and the avionics manufacturers.) According to Gulfstream personnel in the telemetry trailer, FTE1 was seated at the first workstation on the right side of the airplane, and FTE2 was seated at the second workstation on the left side of the airplane.

[10] The roles of FTE1 and FTE2 on the day of the accident are discussed in section 2.5.1.

[11] All altitudes in this report are expressed as height above ground level unless otherwise indicated.

[12] Test team members also indicated that, during the preflight briefing, FTE1 stated his belief that two previous G650 uncommanded roll events occurred when pitch exceeded 12º. During a second briefing later in the day, FTE1 reviewed in detail the test procedures for the flight. The PIC, the SIC, APG1, FTE2, and FTE3 attended both preflight briefings. APG2 attended the second briefing.

[13] Flaps 20 is the standard takeoff setting. Flaps 10 is used for high altitude and high temperature operations.

[14] V_1 is the maximum speed in the takeoff at which the pilot must take the first action to stop the airplane within the accelerate-stop distance. V_1 is also the minimum speed in the takeoff, after a failure of the critical engine, at which the pilot can continue the takeoff and achieve the required height above the ground within the takeoff distance. V_R is the speed at which a pilot initiates action to raise the nose gear off the ground during the acceleration to V_2. V_{LOF} is the airspeed at which an airplane first becomes airborne and no longer contacts the runway. V_2 is the speed that an airplane attains at or before a height above the ground of 35 feet with one engine inoperative.

based on the free-air (out-of-ground-effect) stall speeds of the airplane,[15] as determined by previous flight testing, and the Part 25 takeoff speed requirements. Figure 3 depicts the takeoff airspeeds in relation to the airplane's progress along a runway.

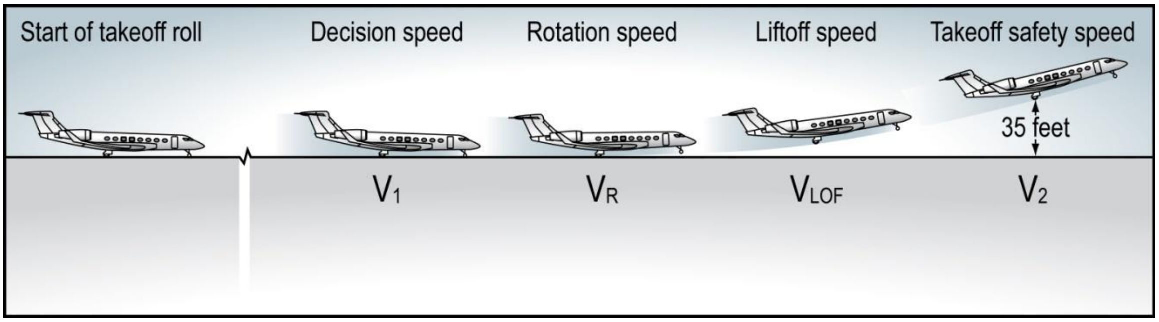

Figure 3. Takeoff airspeeds.

An on-board video/audio system recording[16] showed that the four flight test team members were aboard the airplane by about 0645. The first takeoff of the day began about 0717. A total of 12 takeoffs were attempted. Key events from the first 10 takeoffs are discussed in section 1.3.3. The 11th takeoff of the day began about 0926. During this takeoff (and the accident takeoff that followed), the test team was performing an OEI continued takeoff test with a flaps 10 configuration.

The procedure for performing an OEI continued takeoff, as specified in test card 7A,[17] was to align the airplane with the runway centerline, apply the brakes, set the engine power to the desired level, and then release the brakes. At a specified speed, the right thrust lever was moved to idle to simulate a failure of the right engine. At V_R, the control column was pulled with a specified force (60 to 65 pounds in this case) to initiate rotation, and the pull was then relaxed to "gradually capture [9º] pitch attitude." The test card indicated that the flight crew was to "maintain target pitch attitude until V_2 is achieved, then transition to speed." The main landing gear (MLG) was to be retracted after a positive rate of climb was established, and the pitch attitude was to be adjusted to maintain V_2 until either the gear retraction was complete or the airplane climbed through 400 feet, whichever occurred first. At that point, the test would be completed.

OEI continued takeoff flight tests were considered by Gulfstream to be high risk because of the potential hazards and possible outcomes associated with the tests. Gulfstream prepared a test safety hazard analysis (TSHA) for all tests determined to be medium or high risk.[18] The TSHA for OEI continued takeoff field performance tests indicated that, although the tests were

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[15] Ground effect refers to changes in the airflow over the airplane resulting from the proximity of an airplane to the ground. Ground effect is discussed further in section 2.3.

[16] The airplane's on-board video/audio system included an internal cockpit camera with a view of the flight deck and audio from the airplane's intercom system. The on-board recording began about 0630.

[17] Test cards describe the manner in which each test is to be conducted. A test card may need to be performed multiple times until it is successfully completed. For those cases, each test run is tracked separately; for example, test card 7A was attempted twice, and those test runs were designated 7A1 and 7A2.

[18] The TSHA defined the risk of a test by identifying potential hazards and estimating the probability and the severity of those hazards. The TSHA also specified risk controls (preventative actions/minimizing procedures and corrective techniques) that were to be used during the test.

high risk, the hazards associated with the tests ("aircraft departs runway/inadvertent ground contact") had a low probability of occurrence. The OEI continued takeoff TSHA did not identify low altitude stall and uncommanded roll as potential hazards.

The G650 program's takeoff performance guarantee target was 6,000 feet ± 8 percent at standard sea level conditions.[19] Gulfstream indicated that achieving the target V_2 speeds was necessary to maintain the takeoff distance within the guaranteed target, or the operation of the airplane would be limited to longer runways. (For the G650, the runway length required for takeoff is minimized if the V_2 speed is minimized. Thus, there is a performance advantage to keeping the V_2 speed as close as possible to the minimum required.) The test team completed its first OEI continued takeoff test run (7A1), but the airspeed reached 145 knots at 35 feet and exceeded the target V_2 value (136 knots) by 9 knots. The OEI continued takeoff (with the same flap configuration) was being repeated during the accident test run to reduce V_2 to the target value for that run (135 knots).[20]

About 0931, a controller in the ROW air traffic control (ATC) tower reported that the wind was from 170º at 9 knots.[21] Gulfstream had a weather station on the airport that included a wind sensor. At 0932:07, the cockpit voice recorder (CVR)[22] recorded FTE3 telling the on-board test team that the wind was from 156º at 5 knots but that the wind speed had been as high as 8 knots. The PIC replied, "we are okay with where we're at." (According to company policy, wind speed for OEI continued takeoff testing was limited to 10 knots with a maximum crosswind component of 5 knots.)

Test run 7A2 began at 0933:00. According to the on-board video recording, at that time, the PIC advanced the thrust levers for takeoff. Recorded flight data (as described in section 1.2) showed that, between 0933:36 and 0933:37, when the airspeed was about 105 knots, the SIC moved the right thrust lever to the idle position. About that time, the CVR recorded the SIC stating "chop" to confirm this action.

At 0933:46, the CVR recorded the SIC stating, "standby, rotate." About 1 second later, when the airspeed was about 127 knots, the video recording showed the PIC pulling on the control column for rotation. At 0933:50, the pitch attitude and AOA reached about 10º,[23] and then the PLI appeared. About that time, cockpit displays showed that the airplane's wings were about level and that the slip indicator was displaced slightly to the left. At 0933:50.4, the airplane's pitch and AOA exceeded 11º. Immediately afterward, the CVR recorded the PIC stating, "[unintelligible] going on," and the video recording showed that the bank angle was

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[19] According to Gulfstream's website (http://www.gulfstream.com/products/g650, accessed July 16, 2012), the G650 was being designed to deliver "takeoff and landing performance with a balanced field length of just 6,000 feet." This guarantee was based on a takeoff gross weight of 99,600 pounds and a flaps 20 takeoff configuration; there was no performance guarantee for a flaps 10 takeoff configuration.

[20] The takeoff speed targets for test run 7A2 were slightly less than those for test run 7A1 because the airplane's weight was lighter during test run 7A2.

[21] In addition, the terminal aerodrome forecast for ROW that was valid at the time of the accident expected wind from 160º at 8 knots, visibility better than 6 miles, and clear skies.

[22] The CVR recording began at 0731:25 (during test run 2C2). A partial CVR transcript appears in appendix B to this report.

[23] The pitch angle is the angle between the airplane's longitudinal axis and the horizon. The AOA is the angle between the airplane's longitudinal axis and the airstream (velocity vector). With the wings level, pitch is equal to the sum of the flightpath angle and the AOA.

increasing to the right and that the PIC was making a slight left wheel input.[24] The video recording ended at this point.

Between 0933:52 and 0933:53, the CVR recorded the SIC and the PIC repeating, "whoa." Recorded flight data showed that the stick shaker activated at 0933:52.2 for 0.6 second (with the pitch at 12.7º and the AOA at 12.4º) and at 0933:53.5 for 6.4 seconds (with the pitch at 11.8º and the AOA at 12.2º). At 0933:53.6, the CVR recorded the electronic annunciation "bank angle"; recorded flight data showed that the bank angle at that time was about 16.2º. The PIC then stated, "power, power, power," and the SIC responded, "power's up"; flight data showed that the right thrust lever had been advanced all of the way forward about that time.[25] At 0933:58.5, the CVR recorded the electronic annunciation "bank angle," which was 30.5º at that time. The last communication recorded on the CVR (which was unintelligible) was at 0934:05, and the CVR recording ended at 0934:10.

The National Transportation Safety Board's (NTSB) aircraft performance study for this accident found that, when the airplane's AOA reached 11.2º during the accident takeoff, the AOA exceeded the stall AOA for the combination of flap setting, height above the ground, Mach number, and roll angle present at the time, resulting in a loss of roll control. This finding was based, in part, on the results of Gulfstream's simulation residual analysis,[26] which indicated that, at 0933:50.5, as pitch angle and AOA were increasing through 11.2º, large aerodynamic rolling and yawing moments to the right were acting on the airplane. These aerodynamic moments were indicators of flow separation on the right outboard wing and an asymmetric stall of the airplane. Before the accident, Gulfstream estimated that the in-ground-effect stall AOA would be 13.1º and set the AOA threshold for the activation of the stick shaker stall warning at 12.3º.[27]

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[24] The video recording showed that, until this point, the control wheel and the control column inputs for the accident flight appeared to be almost identical to those for the previous takeoff.

[25] Flight data showed that the right engine was at full power at 0934:00.

[26] After the accident, Gulfstream used an engineering simulator to compute the expected aerodynamic forces and moments acting on the airplane during the accident takeoff and compared these expected forces and moments with the actual aerodynamic forces and moments required to produce the airplane motion indicated in flight data. The differences between the required and expected aerodynamic forces and moments, called "simulation residuals," were measures of the forces and moments affecting the actual airplane that were not accounted for in the simulation.

[27] The AOA threshold for the activation of the stick shaker stall warning is manually set based on the free-air stall AOA, which Gulfstream predicted to be 14.7º. Ground effect is not considered when the stick shaker is set. The stall AOA decreases with an increasing Mach number. The free-air stall AOA values and the stick shaker thresholds (derived from the free-air stall AOA values) indicated in this report correspond to the Mach number at the target V_2 speed of the accident takeoff.

Recorded flight data and ground scars and markings on the runway and airport property indicated that, shortly after rotation, the airplane's right wing contacted the runway. The airplane subsequently yawed to the right, departed the right side of the runway, traveled along about 3,000 feet of airport property, and came to rest about 8,404 feet from the runway 21 threshold and 1,949 feet to the right of the runway centerline. Figure 4 shows the airplane's wreckage path and final position.

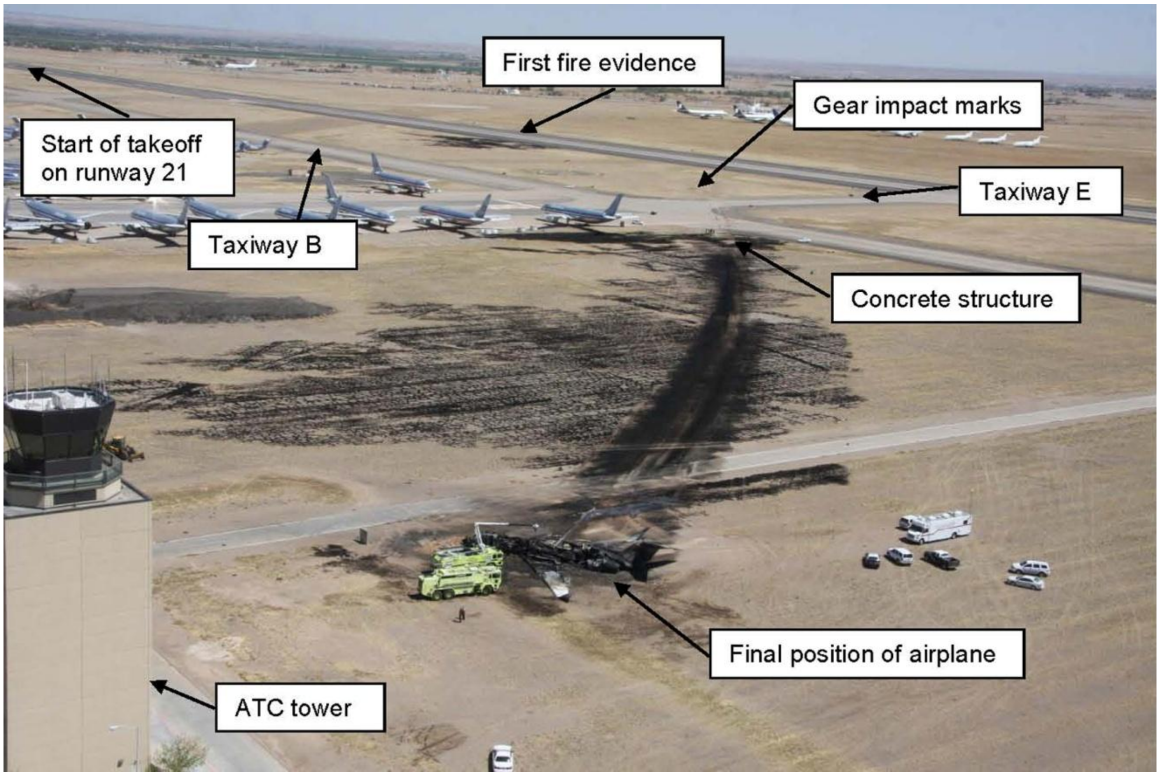

Figure 4. Aerial view of wreckage path.

Source: Roswell Police Department.

1.1.1 Wreckage, Impact, and Witness Information

The airplane's right wingtip first contacted runway 21 starting about 5,160 feet from the runway threshold. Intermittent scrape marks indicated that the right wingtip remained close to or in contact with the runway as the airplane departed the runway off the right side into a grassy area. There was evidence of a fire in the grass adjacent to the location where the airplane departed the runway. The right MLG tires contacted the ground (and then momentarily left the ground), followed by the left MLG tires, the right MLG tires for the second time,[28] and the nose gear. The MLG separated from its attachments, the nose gear collapsed, and the airplane began to skid on its belly across the intersection of two taxiways. Tire marks across the intersection

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[28] As discussed in section 1.1.2, flight data showed that the left MLG tire lifted off the runway first and that the right MLG tire lifted off the runway second.

were consistent with the right and left MLG being dragged by the airplane or the gear tumbling or sliding behind the airplane.

The airplane continued through the taxiway intersection and into a grassy area where the airplane impacted a runway boundary and taxiway location sign and a concrete structure (used for underground electrical access) located about 1,000 feet from the runway 21 centerline. Impact with the concrete structure caused extensive structural damage to the center wing box, including rupture of the fuel tank. Gulfstream personnel in the telemetry trailer observed black smoke and fire coming from the airplane after it hit this structure. The airplane also impacted an airport weather station, compromising the left wing fuel compartments. The airplane continued to slide until it came to rest about 300 feet from the ATC tower and on a heading of about 90º from the wreckage path.

Three controllers who were on duty in the ROW ATC tower at the time of the accident stated that, when the airplane came to a stop, there was a large amount of smoke toward the aft part of the airplane, and its tail could not be seen shortly afterward. The controllers stated that fire moved quickly from the back to the front of the airplane. The controllers indicated that the front left fuselage, including the main entry door, was visible when the airplane first stopped, but two of the controllers stated that they saw no movement of the door and no movement inside the airplane. All three controllers recalled seeing Gulfstream personnel from the telemetry trailer running toward the airplane when it came to a stop. APG2 reported that he reached the airplane within seconds after it came to rest but that, because of the intensity of the fire, it was impossible for him or any of the other telemetry trailer personnel to approach the airplane's main entry door or emergency exits.

Aircraft rescue and firefighting (ARFF) personnel at ROW were notified of the accident from the ATC tower via the crash phone.[29] The crash phone activated an alarm and called a standard telephone system that could be answered at multiple locations within the fire station. The ATC transcript showed that, at 0936:11, one of two ARFF vehicles maintained at ROW requested clearance to the accident site, which was provided 6 seconds later. (The second ARFF vehicle did not need a separate clearance to the accident site because it was following the other ARFF vehicle to the site.)

One of the test team members in the telemetry trailer (APG2) took photographs of the accident scene. The time stamp on the first photograph showed that it was taken at 0934:15. A photograph taken at 0937:22 showed no ARFF vehicles on scene, but a photograph taken at 0938:17 showed one ARFF vehicle on scene. The photographs also showed that the second ARFF vehicle was on scene 2 seconds later.

1.1.2 Aircraft Performance Study

The NTSB conducted an aircraft performance study to determine and analyze the motion of the accident airplane and the physical forces that produced that motion. The study defined the airplane's position and orientation throughout the accident test run and determined the airplane's

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[29] The Roswell Fire Department included a station at ROW. At the time of the accident, three fire department personnel—a lieutenant, a driver, and a firefighter—were on duty at the station.

response to control inputs, external disturbances, and other factors that could have affected its trajectory. The data used in the study included ground scars and markings on the runway and airport property, recorded flight data, weather information, and postaccident studies performed by Gulfstream. Table 2 summarizes the airplane's motion according to the results of the aircraft performance study.

Table 2. Aircraft performance study timeline of events.

Time	Event
0933:17 to 0933:35	The airplane was on the runway centerline and aligned with the runway heading, the power was set for takeoff, and the brakes were released. As the airplane accelerated down the runway after brake release, the PIC maintained a control wheel input of about 1º to 2º left, and the airplane's roll angle remained within 1º of level. The PIC maintained a rudder pedal deflection of about 0.5 inch to the right.
0933:36 to 0933:38	The right thrust lever was pulled back at the engine failure speed briefed for the takeoff (105 knots), and the thrust from the right engine decreased. The PIC moved the rudder pedal to about 1.4 inches left and modulated the input to maintain the runway heading.
0933:45 to 0933:47	As the airplane was accelerating through 123 knots, the SIC called "standby, rotate." As the airplane accelerated from 125 to 127 knots, the PIC pulled the control column 6º aft with about 50 pounds of force, and the elevators moved trailing edge up in response. A 0.5º-per-second right yaw rate developed.
0933:47 to 0933:50	The pitch rate reached a peak of 6º per second and then relaxed to about 1º per second as the pitch angle was increasing through about 9º. A right roll rate started to develop. The sideslip angle increased to about -3º as a result of the right yaw and a 2.5-knot left crosswind, and the roll angle increased to 1.4º. The PIC's control wheel input increased from about 1.8º left to about 11.9º left. The left MLG tires lifted off the runway (at 0933:48.8).
0933:50 to 0933:52	The right MLG tires lifted off the runway (at 0933.50.3). The stall on the right wing occurred at an AOA of 11.2º (at 0933:50.5). The PIC moved the control wheel from 11.9º left to 22.6º left. The roll rate to the right increased to about 4.9º per second. The yaw rate to the right started increasing continuously, passing 2° per second (at 0933:52). The PIC increased the left pedal deflection from about 1.6 to 2.8 inches.
0933:52.0 to 0933:52.7	The AOA reached 12.4º, and the stick shaker parameters changed from inactive to active. The PIC pushed the control column forward abruptly, moving it from 2.5º aft to 1.2º forward. The roll rate increased to a peak of 9.6º per second to the right. The PIC moved the control wheel abruptly from 26.5º left to 60º left (full deflection). The roll angle reached 15.5º right wing down and was increasing. The PIC moved the rudder pedal from 2.8 to 3.5 inches left (full deflection).
0933:52.5 to 0933:53.3	The pitch angle decreased from 12.9º to 11.5º, and the AOA decreased from about 12.7º to about 11.5º. The airplane's right wingtip contacted the runway at a roll angle of 13.4º. The roll rate then reversed rapidly from 9.6º per second to the right to 1.3º per second to the left. The PIC pulled back on the control column with about 38 pounds of force, moving the column to about 4º aft. The stick shaker parameters changed from active to inactive.
0933:53.5 to 0933:53.8	The right throttle resolver angle was advanced to match the left throttle resolver angle. Right engine power started to increase. The stick shaker parameters changed from inactive to active.
0933:54 to 0934:00	The PIC relaxed the control column to about 1.5º aft and then pulled back again with more than 60 pounds of force, moving the column to about 7.5º aft. The column remained aft, with the PIC pulling between 60 and 110 pounds of force. The yaw rate to the right increased to 9.5º per second. The roll angle increased to 32º right wing down. The roll rate then reversed, and the roll angle decreased to 17º right wing down. The pitch angle and the AOA fluctuated in response to the PIC's control inputs; the highest pitch angle and AOA achieved were 14.8º and 22.7º, respectively. When the MLG touched down (at 0934:00), the pitch angle and AOA were -0.2º and 9.5º, respectively. At that time, the stick shaker parameters changed from active to inactive.

1.2 Airplane Information

The Gulfstream G650 is a swept-wing airplane with a fly-by-wire flight control system. The G650's first flight occurred in November 2009. The accident airplane, serial number 6002, was manufactured by Gulfstream in 2010 and was one of five G650 airplanes operating under a special airworthiness certificate (experimental), dated March 2011, for conducting research and development and showing compliance with federal regulations. (This certificate superseded previous special airworthiness certificates dated April 2010 and February 2010.) The certificate detailed the operating limitations for the flight crew and the airplane.

The G650 was powered by two Rolls-Royce BR700-725A1-12 high-bypass-ratio turbofan engines. The airplane had one mechanical main entry door, four overwing emergency exits (two on the left side of the airplane and two on its right side), and a baggage door. G650 production airplanes were planned to seat up to 19 passengers.

At the time of the accident, the CVR and flight data recorder (FDR) systems installed on the airplane were neither certified nor validated by Gulfstream or the Federal Aviation Administration (FAA). (The airplane was not required to have a CVR or an FDR installed until the airplane was certified.) The FDR recorded only 10 seconds of the accident flight because of a wiring issue that resulted in power not being applied to the FDR until the weight-on-wheels indications transitioned from ground to air. (This wiring issue, which was reported in late 2010, had not been corrected at the time of the accident and was a deferred maintenance item.)

The airplane was also equipped with various devices that comprised the airplane's flight test information system, including a flight test data recorder. The flight recorder received inputs from a test interface system, a common airborne instrumentation system bus data acquisition unit, and a data bus system. Data from Gulfstream's weather station were also transmitted to the airplane and recorded by the flight recorder. Data from the flight recorder were then routed to the Gulfstream flight test data server and provided to the on-board flight test engineers at their computer workstations. Data from the common airborne instrumentation system bus data acquisition unit were routed to a telemetry system installed on the airplane, and selected data (standard parameters and those needed for the tests being conducted) were provided to the workstations in the telemetry trailer through the flight test data server in the trailer. According to Gulfstream, the flight test information system provided a large quantity of data that would not have been available with an FDR alone.

In addition, as previously stated, the airplane was equipped with an on-board video/audio system that included an internal cockpit camera and audio from the airplane's intercom system. The camera was mounted in the rear of the cockpit and above the pilots' heads with a forward-looking view toward the instrument panel. (The instrument panel was visible in the accident flight recording except for the right-side primary flight display and control column, which were partially obscured by the SIC.) The sounds and voices recorded on the airplane's intercom system were captured from the pilots' and flight test engineers' headset microphones and the airplane's radio system. The audio recording comprised on-board conversations among the test team members as well as ground communications, including those to and from the telemetry trailer.[30]

1.3 Flight Test History

The takeoff rotation technique used during the accident flight was based on a technique developed during flight testing in February 2011 to resolve a recurring V_2 overshoot (exceedance) problem. Section 1.3.1 provides information about this technique, which was also attempted during subsequent test flights and used (with modifications) during the accident flight. Section 1.3.2 describes the two previous uncommanded roll events and Gulfstream's understanding of the events before and after the accident. Section 1.3.3 describes the previous takeoffs on the day of the accident and the test team discussions that ensued.

1.3.1 Takeoff Technique Development Testing

On February 11, 2011, during a meeting to discuss issues from Roswell I field performance testing, the Gulfstream senior vice president of programs, engineering, and test and the Gulfstream vice president of the G650 program (also referred to as the G650 program manager) were informed that the recorded V_2 speeds were high. Specifically, the V_2 values at 35 feet were consistently higher than the target V_2 values planned for Roswell II testing. As a result, the field length needed for takeoff would be longer than the program's takeoff performance guarantee (6,000 feet ± 8 percent). Gulfstream personnel from the flight sciences, flight test, and flight operations departments believed that changes to the takeoff technique could improve these results.

Two days later, FTE1 led a 1-day takeoff technique development testing effort in Birmingham, Alabama (flight 111), during which time the test team assigned to that flight experimented with different takeoff rotation techniques and rotation speeds to try to eliminate the V_2 overshoots, which would reduce the field length needed for takeoff. A total of seven simulated[31] OEI continued takeoff test runs were performed using 20º of flaps and a target pitch attitude of 9º. The G650 project test pilot was the flying pilot, and the accident SIC was the monitoring pilot. Two flight test engineers (including FTE1) were also part of the on-board test team. (No airplane performance engineers were present for the test.)

Changes to the takeoff technique included (1) adding 2 knots to the V_R speed schedule for a given thrust-to-weight ratio while keeping V_{LOF} and V_2 the same and (2) increasing the pitch angle beyond the target pitch angle as soon as the airplane lifted off (instead of holding the target pitch angle until 35 feet). In addition, changes were made to the control column input used to initiate rotation. As the testing progressed, the abruptness and magnitude of this input

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[30] The NTSB created summaries and transcripts from the on-board video/audio recordings. The summaries described observations from the accident test run, previous test runs on the day of the accident, and other test runs that were flown at various times during field performance testing. These and other documents discussed in this report are available on the NTSB's website at http://dms.ntsb.gov/pubdms/search/hitlist.cfm?docketID=50904&CFID=28735&CFTOKEN=50339757.

[31] To increase safety during the test, the OEI condition was simulated by using symmetric, reduced thrust on both engines, which resulted in a total thrust equivalent to the OEI condition.

increased. According to the on-board video recording, FTE1 asked the G650 project test pilot whether he could convince FAA certification officials that the rotation technique being explored was a "normal technique."[32] The project test pilot responded that the technique would have to be modified "slightly."

The test team found that an abrupt column pull force of about 70 to 75 pounds was the most successful in reducing the magnitude of the V_2 overshoot. (The maximum column pull force permitted by FAA regulations was 75 pounds, as discussed in section 2.4.1.) The test team also found that, if the flying pilot rotated rapidly (at peak pitch rates between 6.1° and 8.5° per second) to the 9° target pitch attitude and then exceeded 9° shortly afterward, V_2 overshoots (and $V_2 + 10$ knot overshoots for all-engines-operating [AEO] takeoffs) could be reduced to within a few knots of the target speeds. The takeoff rotation technique that produced the best results during flight 111 resulted in a V_2 speed that was still about 3 knots high. According to Gulfstream's *GVI Field Performance Certification Flight Test Plan* (revision A, dated October 2010), the required tolerance for the target V_2 speed was ± 2 knots.

1.3.2 Uncommanded Roll Events

The two previous uncommanded roll events during field performance testing at ROW occurred on November 16, 2010 (during flight 88), and on March 14, 2011 (during flight 132). The circumstances surrounding these events are described below.

Flight 88

The flight 88 uncommanded roll event occurred during minimum unstick speed (V_{MU})[33] development testing at a flap setting of 20° and a pitch target of 9° to 10°. The flying pilot was the accident PIC, and the G650 project test pilot was the monitoring pilot. The PIC had participated in, but had not performed, previous V_{MU} tests in the G650. The uncommanded roll event (8° right wing down) occurred immediately after liftoff during the PIC's initial V_{MU} test run. The PIC expressed surprise at the rotation rates obtained,[34] which led to an overshoot of the target pitch attitude by 3°. The flight crew recovered the airplane (when the monitoring pilot pushed the control column forward to lower the nose and AOA), continued to climb out, and landed without further incident. The airplane did not contact the ground during the roll event. Testing was not stopped after the flight to investigate this matter. Instead, the test was repeated immediately afterward, and the PIC performed the maneuver successfully.

The on-site flight test team, which included FTE1, determined (during an informal discussion after the flight) that the cause of the uncommanded roll was an excessively high rotation (over-rotation) by the flying pilot. It is not known whether any on-site test team member considered whether the airplane had stalled as a result of the over-rotation. (During a postaccident interview, the Gulfstream staff scientist for applied aerodynamics stated,

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[32] FAA test pilots must evaluate the flying qualities of an airplane (including the takeoff technique) as part of the certification process. This issue is discussed further in section 2.4.1.

[33] V_{MU} is the lowest demonstrated speed at which the weight of an airplane is completely supported by aerodynamic lift and thrust forces. V_{MU} data are used to determine the minimum speeds that must be achieved for liftoff and climb.

[34] The peak pitch rate during the flight was 6.4° per second.

"over-rotation of the aircraft…leads to a stall.") Further, the PIC and the other on-site test team members determined that a future uncommanded roll event could be avoided during testing by ensuring that the flying pilot was involved in build-up maneuvers[35] leading to the highest risk test condition.[36]

In addition, during a briefing in late November 2010, the PIC presented summary data from Roswell I V_{MU} testing to company flight operations and flight test engineering personnel. The data showed that the maximum AOA attained during the flight 88 uncommanded roll event was 11.5º. The participants at the briefing did not consider whether the airplane had stalled below the predicted in-ground-effect stall AOA estimate for Roswell I V_{MU} tests (12.2º). An analysis of flight 88 data performed by Gulfstream and the NTSB after the accident indicated that a stall occurred at an AOA of 11.6º.[37]

Flight 132

The flight 132 uncommanded roll event occurred during the second test run for an OEI continued takeoff (right engine reduced to idle) at a flap setting of 20º and a target pitch attitude of 9º. The flying pilot for flight 132 was the SIC of the accident flight, and the monitoring pilot was a company senior test pilot assigned to field performance testing. FTE1 was also part of the on-board test team.

The test card for the incident run stated, "rotate at Vr using 70 lb pull until rotation begins, reduce force to gradually capture 9º." During the test run, the accident SIC pulled with 65 pounds of force and held sufficient force on the column to allow the pitch angle to reach 12º about 0.5 second after liftoff; about 1 second later, the airplane rolled 8º to the right. The flight crew recovered the airplane (when the monitoring pilot pushed the control column forward to lower the nose and AOA) and continued the takeoff without the airplane contacting the ground.

Immediately after the event, the pilots discussed the uncommanded roll and the takeoff technique used. The accident SIC had been the monitoring pilot during flight 111 and, as such, observed the inputs of the flying pilot (the G650 project test pilot) as he developed the takeoff rotation technique. During flight 132, the accident SIC apparently tried to duplicate these inputs; according to the on-board video recording, the accident SIC told the senior test pilot that he had been looking at the G650 project test pilot's previous control input technique "at that rate" and "kinda got that into my head."

While still in the cockpit, the pilots attributed the event to a stall resulting from an early rotation at V_1 as well as an over-rotation that exceeded the target pitch attitude. After landing, the

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[35] According to the U.S. Naval Test Pilot School's *Flight Test Manual*, a build-up maneuver "is the process of proceeding from the known to the unknown in an incremental, methodical pattern…testing begins with the best documented, least hazardous data points and proceeds toward the desired end points." For more information, see *U.S. Naval Test Pilot School Flight Test Manual, Systems Testing,* USNTPS-FTM-NO.109 (Patuxent River, Maryland: Naval Air Warfare Center, 2000).

[36] At the time, the TSHA for V_{MU} tests stated the following: "V_{MU} testing will be approached in a build-up manner. Testing will begin at AEO high T/W [thrust-to-weight] conditions and proceed to the lower T/W conditions required. The number of required build-ups and repeat testing will be determined by the on-site test team." After flight 88, Gulfstream added the following information to the TSHA: "the pilot flying shall have recent experience with the test maneuver or perform a build-up maneuver(s) before conducting the test condition."

[37] The 11.6º value is slightly higher than the maximum 11.5º AOA noted in the PIC's November 2010 presentation because the 11.6º value includes corrections to the AOA to account for pitch rate.

senior test pilot commented that the takeoff maneuver had been performed too aggressively and emphasized slowing down the pitch rate to ensure that the target pitch attitude would not be exceeded. The pilots then practiced flight control inputs, and the senior test pilot briefed the next test run, which included "a moderate rate pull up to 9 degrees with both engines operating" to allow the accident SIC to gain confidence to perform the OEI continued takeoff maneuver. The accident SIC then performed the briefed takeoff maneuver without incident.

During additional test runs, the test team continued to modify the takeoff rotation technique. According to the on-board video recording, after one of these test runs, FTE1 told the senior test pilot that he wanted to look at the performance data from the test runs and discuss the data with other Gulfstream personnel. FTE1 added, "the thing is, this [the takeoff technique] has got to be something…the FAA can do, it can't be this hard a technique."

According to the senior test pilot, he and FTE1 met informally after flight 132, and FTE1 expressed concern that the airplane had stalled. FTE1 noted that "we were at" an AOA of 11.5º during the event but that an in-ground-effect stall was not predicted to occur until at least an AOA of 13º.[38] Because the AOA during the event had remained 1.5º below the predicted in-ground-effect stall AOA, the senior test pilot and FTE1 did not attribute the event to a stall but instead to a "lateral-directional disturbance" (that is, a roll event due to sideslip) that was aggravated by the unavailability of the yaw damper, which had been deactivated because of a temporary in-flight restriction resulting from a previous event.[39] The senior test pilot suggested that, to prevent an uncommanded roll from recurring, takeoff testing should be discontinued until the yaw damper was back in service; FTE1 agreed with this suggestion. An analysis of flight 132 data performed by Gulfstream and the NTSB after the accident indicated that a stall occurred at an AOA of 11º and that the sideslip angle was -3º during the onset of the stall.

1.3.3 Previous Test Runs on Day of Accident

The test team completed three test cards (2C, 3A, and 6C) with a total of 10 test runs before performing the two test runs associated with test card 7A (as previously described in section 1.1). During the test runs, the on-board test team explored takeoff rotation techniques to resolve the V_2 overshoot problem using an iterative trial-and-error approach.[40]

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[38] The stick shaker did not activate during the flight 132 uncommanded roll event because the shaker activation setting was 90 percent of normalized AOA and the maximum normalized AOA during the event was about 86 percent. The PLI was likely displayed because the normalized AOA was greater than 0.70.

[39] On March 3, 2011, during a certification flight test examining thrust lapse rates, the airplane (which was being flown by an FAA test pilot) drifted to the right during the initial takeoff roll, but the drift could not be controlled with the rudder. The flight crew aborted the takeoff and determined that the problem could recur. After the event, Gulfstream flight control engineers found that a change in the airplane's fly-by-wire flight control software had affected the yaw damper system. Gulfstream then issued a temporary in-flight restriction that required monitoring of residual yaw rates or deactivation of the yaw damper system. After the flight 132 uncommanded roll event, OEI field performance testing was discontinued until the yaw damper issue was corrected and the temporary in-flight restriction was canceled. (The airplane was used in the meantime for field performance tests that were not related to takeoff performance.) The restriction was lifted on March 18, 2011, and OEI continued takeoff testing resumed during the accident flight.

[40] The information in this section reflects the test team members' comments as captured by the on-board video/audio system. The CVR transcript (in appendix B) begins just before the final two test runs were conducted and does not include comments from test runs 2C, 3A, and 6C.

Test card 2C was a flaps 20 AEO continued takeoff, which was performed four times starting about 0717. The on-board video/audio recording showed that, before the takeoff on test run 2C1, the SIC asked, "if we do an 11 degrees we're gonna abort, correct?" to which the PIC responded "yes." This exchange was consistent with FTE1's instruction to the test team (during preflight briefings on the day before the accident) that the test should be discontinued if pitch reached 11° during initial takeoff and that the pitch should then be decreased and engine power added. This exchange was also the only time during the flight tests that an on-board test team member referenced the 11° limit. After test run 2C3 was completed, the PIC expressed concern about capturing V_2 + 10 knots at 35 feet, stating, "the only thing I can say is you're not gonna be at 9 degrees very long if you want to catch V_2"; FTE1 agreed.

Test card 3A was a flaps 20 OEI continued takeoff (similar to the flight 132 test run during which an uncommanded roll occurred), and three test runs were conducted starting about 0808. After test run 3A1, the PIC noted that he would have to aim for 15° or 16° of pitch to capture V_2. (The NTSB recognizes that, at some point after liftoff, pitch must increase above 11° to maintain the target V_2 as the airplane begins to climb.) The PIC indicated that he was doing "a nice smooth ramp" and "I'm not doing that jerk stuff…it just doesn't work" regarding his initial input on the control column.[41] He added, "that's not the way they're going to fly the airplane, and I don't think the FAA's gonna like it either…it's such a great flying airplane, you shouldn't have to abuse it to get [it] flying."[42] FTE2 reported that the force on the column was about 60 pounds, to which the PIC stated, "that works, that's comfortable," and the SIC stated, "a ramp to 60 [pounds] worked pretty good." After test run 3A2, FTE1 stated to the PIC, "when you pause at the pitch I guess you're staying there a little while," and they discussed that, to capture V_2, pitch would need to be increased above the 9° target earlier in the takeoff until the increase in pitch became, according to the PIC, "almost like a continuous maneuver."

During test run 3A3, the PIC pulled on the column more gradually and with less force than during test runs 3A1 and 3A2 but increased pitch above 9° immediately after the MLG was raised (which occurred about 1.8 seconds after both the left and the right weight-on-wheels indications had changed from "on ground" to "in air").[43] After test run 3A3, FTE1 stated, "I think that's it," and the PIC stated, "we're done, I think we caught it there…we must be onto something now." The PIC also indicated that he was happy with the "nice smooth ramp input" and the column force of 50 to 55 pounds.

Test card 6C was a flaps 10 AEO continued takeoff, which was performed three times starting about 0842. Before test run 6C1 began, the PIC stated that he would rotate the airplane until the pitch reached 9°, wait for a positive rate of climb, and then capture V_2. The PIC also stated that more than 20° of pitch would be required to maintain V_2 (+ 10 knots) with both engines.[44] After test run 6C1, the PIC stated, "you just can't do it [the pitch required to maintain

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[41] A ramp input is a gradual but steady increase from the resting to the target value (compared with a step input, which is a near-instantaneous increase from the resting to the target value). The "jerk" on the control column mentioned by the PIC referred to the takeoff technique developed during flight 111, which involved a step input.

[42] In addition to quantitative test data, pilot qualitative comments are important during the field performance testing phase. Test pilots generally have extensive experience piloting different types of aircraft, so they can understand what constitutes acceptable handling qualities when performing typical mission-related maneuvers.

[43] During test run 3A1, the MLG was raised about 3.8 seconds after the in-air weight-on-wheels indications, and pitch increased above 9° about 2 seconds later. During test run 3A2, the MLG was raised 2.5 seconds after the in-air weight-on-wheels indications, and pitch increased above 9° about 3.5 seconds later.

[44] Gulfstream limited this pitch angle to 20° based on passenger comfort.

V_2 + 10 knots] within 20º.” FTE1 reported that the column pull force was 53 pounds and that the pitch was 10.5º.[45] In a communication from the telemetry trailer to the on-board test team, FTE3 stated that she thought that the target pitch was 9º. FTE1 confirmed her statement.

Also after test run 6C1, the airplane was taxied off the runway and then to the telemetry trailer. While the airplane was parked, the SIC had a discussion with FTE1 about the desired rotation technique, describing it as a pull to 9º, a hesitation, and then another pull. The PIC, who had previously left the cockpit on a break, returned and stated that APG1 was “saying we don’t want to hang out at 9º very long. Engine-out we gotta just keep it coming.” The SIC responded that he and FTE1 had just been discussing the matter and indicated that the 9º target pitch was “just like a thought, a goal to go toward, but as soon as you get to it you gotta start pulling again to keep the speed down.” The PIC agreed with the SIC’s comment. Afterward, the airplane was taxied back to the runway for the next test run.

During test run 6C2, the PIC stated, “[looking for] V_2, well you can’t really capture it here anyway, but [this run] looked good to me.” FTE1 indicated that the column pull force was 56 pounds and that the pilots had “nailed” the pitch. (The 9º pitch target was captured and held for about 3.5 seconds before increasing above 9º about 1.4 seconds after the MLG was raised.) After the test run, FTE1 stated, “we were pretty fast at 35 [feet] on that one.” (The V_2 + 10 knot target was exceeded by 12 knots.) The PIC stated, “there’s very little time at 9 [degrees]…you wanna try one more and I’ll just pause at 9 [degrees] and just keep going?” FTE1 agreed with the PIC’s plan. The PIC then stated, “I’ll capture it and boom we’re back into it...it’s almost a continual rotation. You can target 9 [degrees], but you don’t want to hang out there very long,” In addition, the PIC pointed out, “now we’re into kind of a technique thing here in how we’re gonna do this,” to which FTE1 replied, “that’s what I was hoping, [to] just spend today just to get something we like.”

During test run 6C3, the PIC stated, at rotation, “I’m going up, got 9 [degrees], I’m going up, didn’t stay there very long that time.” FTE1 stated, “okay that’s good.” The PIC asked, “did you like that one?” and FTE1 responded, “that was better on the pitch” and “you’re [seven] knots fast…so that was a lot better.” FTE3 (in the telemetry trailer) then communicated to the test team, “speeds were better this time, pitch is a little high.” (Pitch reached 11º about 0.5 second after liftoff.) The PIC explained to FTE3 that “we didn’t pause very long at 9 [degrees]. We’re trying to capture that V_2 at 35 [feet], so…it’s just not there very long, so I think that’s what you were seeing.”

The team then moved to test card 7A. For test run 7A1, the PIC maintained the target pitch until 2.6 seconds after liftoff, and V_2 was exceeded by 9 knots. After test run 7A1, FTE1 commented about the delay in liftoff that occurred after initially achieving the 9º target pitch. The PIC replied, “well we’re pausing, because we’re tryin’ to do this capture, and I think we’re getting too focused on that…‘cause if you have a real engine failure, the guys aren’t gonna be lookin’ at nine degrees, they’re gonna be lookin’ at tryin’ to get to V_2.” The accident occurred during the test run that followed (7A2). Despite the test team’s efforts to develop a takeoff rotation technique that would enable the airplane to achieve the target speeds at 35 feet, all of the completed takeoffs exceeded their target speed by 4 to 12 knots, as shown in table 3.

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[45] Afterward, pitch leveled out between 9º and 10º for about 3.7 seconds and increased above 10º about 2.4 seconds after the MLG was raised.

Table 3. Flight 153 test runs.

Test run	Flap setting	Engine status	V_2 (OEI), V_2 + 10 knots (AEO)		
			Target speed (in knots)	Actual speed at 35 feet (in knots)	Difference in knots
2C1	20	AEO	148	152	4
2C2	20	AEO	148	156	6
2C3	20	AEO	147	154	7
2C4	20	AEO	147	153	6
3A1	20	OEI	136	142	6
3A2	20	OEI	135	140	5
3A3	20	OEI	135	139	4
6C1	10	AEO	148	158	10
6C2	10	AEO	147	159	12
6C3	10	AEO	146	153	7
7A1	10	OEI	136	145	9
7A2	10	OEI	135	N/A	N/A

2. Investigation and Analysis

2.1 General

Gulfstream records indicated that the PIC had accumulated 11,237 hours total flight time, with 263 hours total G650 flying time, and the SIC had accumulated 3,940 hours total flight time, with 140 hours total G650 flying time. The records also indicated that the PIC and the SIC had received their most recent PIC proficiency checks (for GV-series airplanes)[46] in February 2011 and November 2010, respectively. Both pilots had extensive military and flight test pilot experience.[47] The investigation found that the flight crew was properly certificated and qualified in accordance with applicable federal regulations.

FTE1 led the G650 field performance flight testing effort and had extensive experience conducting aerodynamic performance flight tests. FTE2 was responsible for G650 airspeed calibration testing, and the day of the accident was the first time that he had participated in G650 field performance testing. (FTE2 was filling in for another flight test engineer who was unable to make the trip to ROW because of a scheduling conflict.)

The accident occurred at a time of day normally associated with relatively high levels of alertness, and the on-board test team had been on duty for about four hours. Although the early morning start time in Roswell (about 0630 with a hotel meeting time about 0530) raised the possibility of sleep restriction resulting from an inability to fall asleep early enough to obtain adequate rest, this possibility seems unlikely because three test team members (the SIC, FTE1, and FTE2) had maintained an early schedule at home and traveled two time zones west on the day before the accident, which would have made it easier for them to fall asleep early in the evening and wake early in the morning. The PIC had traveled two time zones west nine days before the accident, which provided him with a long enough adjustment period to adapt to the local time zone. However, according to colleagues who were at ROW during this time, the PIC maintained a consistently early sleep and wake schedule (and interacted primarily with colleagues who did the same), which would have minimized the impact of consecutive early morning waking times.

A review of portable electronic device records and interviews with the on-board test team's colleagues and next of kin revealed no evidence of restricted sleep opportunities in the days before the accident. However, evidence detailing the on-board test team's actual sleep quantity and quality the night before the accident was not available.[48] Such information was also unavailable for the PIC and FTE2 for previous nights. Thus, insufficient information was available to determine whether fatigue was a physiological factor for the on-board test team members on the morning of the accident. However, the flight crew had been performing challenging flying tasks to a high level of precision for about three hours before the accident

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[46] Gulfstream's most recent previous flight test program involved the GV airplane, which was certified in April 1997.

[47] Appendix A provides additional information about the PIC's and the SIC's qualifications and experience.

[48] Such evidence could be obtained from a self-report or from a bed partner (that is, someone who shares the same sleeping arrangements) report. All Roswell II test team members were checked into separate hotel rooms the night before the accident.

occurred, and a review of audio, video, and flight test data recordings documenting the crewmembers' performance revealed no indications that their performance was impaired.

Postaccident toxicological testing performed on the PIC's blood revealed the presence of brompheniramine, an over-the-counter antihistamine medication (with potentially impairing side effects) used in the treatment of hay fever and other allergies. The pre-mortem concentration of the drug in the PIC's blood is uncertain because antihistamines can be subject to post-mortem redistribution in the body.[49] In addition, the performance-impairing effects of the brompheniramine can be offset by stimulant drugs such as caffeine and theobromine,[50] which were also present in the PIC's blood.[51] The pilot's wife and colleagues stated that they were unaware of his use of this medication, so they were unable to describe the PIC's dosage or frequency of use. A consultation report provided to the NTSB by the Office of the Armed Forces Medical Examiner concluded that the performance-impairing effects of the medication on the PIC could not be definitively determined in this case.[52]

The investigation found that the airplane was operated in accordance with the special airworthiness certificate issued by the FAA. The recovered airplane components showed no evidence of any preimpact structural, engine, or system failures.

Although a slight (2.5-knot) left crosswind just before liftoff made roll control slightly more challenging for the PIC,[53] the crosswind did not cause the airplane to stall. Thus, weather was not a factor in this accident.

This analysis discusses the accident sequence, Gulfstream's development of the in-ground-effect stall AOA estimate and the takeoff speed schedules for the G650 airplane, and the company's management of the G650 program. Safety issues related to this accident are discussed in section 3.

2.2 Accident Sequence

According to APG1, during preflight briefings on the day before the accident, FTE1 explained that the target pitch for all takeoffs would be 9º. In addition, the PIC stated that a target column pull force of 60 to 65 pounds "would be more repeatable" than the 70- to 75-pound

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[49] A. Sen, A. Akin, K.J. Craft, D.V. Canfield, and A.K Chaturvedi, "First-generation H1 antihistamines found in pilot fatalities of civil aviation accidents, 1990-2005," *Aviation, Space, and Environmental Medicine*, vol. 78, pp. 514-522, 2007.

[50] Caffeine and theobromine are stimulant compounds found in coffee, tea, and chocolate.

[51] K. Miller and P.J. Standen, "Differences in performance impairment due to brompheniramine maleate as a function of the sustained-release system," *British Journal of Clinical Pharmacology*, vol. 14, pp. 49-55, 1982.

[52] At the suggestion of the NTSB, Gulfstream issued a memorandum to its pilots on March 22, 2012, about the potential adverse side effects associated with some antihistamine medications. The memorandum urged the pilots to review the caution labels on antihistamine medication packaging and contact their aviation medical examiner with any questions.

[53] Data from the Gulfstream weather station showed that the wind just before liftoff was from 155º at 5.5 knots. The runway magnetic heading was 217º, which resulted in a crosswind of about 2.5 knots. The crosswind was within the 5-knot limit specified by the TSHA for the OEI continued takeoff test.

column pull force that was used in a previously developed takeoff rotation technique and "would not be dependent upon jerking the airplane controls around."[54]

During the test runs on the day of the accident, the takeoff rotation technique was further relaxed to a "nice smooth ramp" of 50 to 55 pounds of column pull force. However, the on-board test team members recognized that V_2 could not be successfully achieved at the reduced rotation rate (resulting from the reduced column forces) if the PIC held the pitch attitude at the 9º target pitch for any length of time. As a result, to achieve the target V_2 speeds, the test team focused on using progressively shorter pauses at the 9º target pitch before increasing pitch further. For example, during test run 3A3, pitch increased above 9º about 3.5 seconds earlier than during the two previous test runs (3A1 and 3A2). Similarly, during test run 6C2, pitch increased above 9º about 1.2 seconds earlier than during the previous test run (6C1).

It is important to note that, during each of those test runs, pitch did not increase above 9º until the airplane had lifted off and the gear handle had been raised.[55] However, during test run 6C3, pitch increased above 9º before the airplane had lifted off. The in-air weight-on-wheels indication and gear retraction command occurred nearly simultaneously when pitch was about 10º. After pitch reached 11º (about 0.5 second after liftoff), a pause in pitch between 11º and 11.5º occurred for about 1 second before pitch began increasing again. (This brief pause likely prevented the airplane from stalling.)

During preflight briefings on the day before the accident, FTE1 indicated that, if pitch reached 11º during the initial part of a takeoff, the test should be discontinued. However, after liftoff, as the flight crew transitioned from maintaining the 9º target pitch to tracking the V_2 speed, pitch would be expected to exceed 11º, but FTE1 did not specify how long during the takeoff the 9º pitch target or the 11º pitch limit would apply. Test cards included the 9º pitch target, but they did not specify how long the pitch target applied or include the briefed 11º pitch limit.

Several Gulfstream pilots and engineers involved with the G650 program had different understandings of how long the pitch target and pitch limit applied. For example, the Gulfstream G650 project test pilot and the company senior test pilot stated that the initial target pitch could be exceeded as required to achieve V_2 regardless of whether the airplane had lifted off. However, Gulfstream's principal engineer for airplane performance and APG1 indicated that the initial target pitch was a limit while the airplane was on the ground but that pitch could be increased beyond the target after liftoff to achieve the target V_2. It is possible that the on-board test team members also had different interpretations of the 9º pitch target (and the 11º pitch limit), which would have rendered these procedural risk controls ineffective for avoiding high AOAs while in ground effect.

Until test run 6C3, the PIC's execution of the takeoff maneuvers was generally consistent with the Gulfstream engineers' understanding of when pitch could be increased above the initial

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[54] According to APG1, FTE1 also stated that a 60- to 65-pound target column pull force would "reduce the amount of 'bobble' [a reversal of the pitch rate] on pitch." She explained that the bobble had occurred during previous test runs because "the pitch was peaking out, decreasing quite a bit, and then recovering throughout the climb."

[55] Raising the gear handle to the "up" position commands the MLG to retract, which, for the G650, is completed about 7.4 seconds after the handle is raised.

9º target after liftoff. However, the execution of test run 6C3 was more consistent with the Gulfstream pilots' understanding that pitch could be increased above 9º before liftoff, resulting in the "continuous maneuver" that the on-board test team was discussing. (After the accident, Gulfstream specified, on the TSHA for OEI continued takeoff tests, that the 9º pitch attitude target would not be exceeded until liftoff was confirmed.)

During test run 7A1 (the first flaps 10 OEI continued takeoff test of the day), the pitch angle reached the initial 9º target about 3 seconds before the airplane lifted off. The in-air weight-on-wheels indication occurred as the airplane reached 135 knots, which was 2 knots above the 133-knot target V_{LOF} and 1 knot below the 136-knot target V_2.[56] Pitch was held at 9º until 1.5 seconds after gear retraction and was then increased to 14º as the airplane reached 35 feet (about 8.5 seconds after liftoff). At that time, the airspeed was 145 knots, which was 9 knots above the target V_2.

After the test run, the test team noted that the airspeed at 35 feet exceeded the target V_2 speed and discussed how the takeoff technique might be modified during the next test run to reduce the V_2 overshoot. The PIC indicated that the maneuver could be repeated with a shorter pause at the target pitch value. The test team did not discuss that the airplane had reached the 9º target pitch about 3 seconds before liftoff or that the airplane had lifted off at an airspeed that was 1 knot below the target V_2 speed. Also, as with previous test runs, no team member questioned the safety of the takeoff technique or considered whether the test procedures or takeoff speed schedules needed to be reevaluated. The NTSB concludes that the test team's focus on achieving the V_2 speeds for the flight tests and the lack of guidance specifying precisely when the pitch angle target and pitch limit applied during the test maneuver contributed to the team's decision to exceed the initial pitch target and the pitch angle at which a takeoff test was to be discontinued.

During the accident takeoff (test run 7A2), there was no pause at the 9º pitch target, and the pitch rate slowed only as the airplane pitched through 9º about 1 second before liftoff.[57] The airplane then stalled during liftoff at a pitch angle and an AOA of about 11.2º.[58] The NTSB concludes that the airplane stalled at an AOA that was below the in-ground-effect stall AOA predicted by Gulfstream (13.1º) and the AOA threshold for the activation of the stick shaker stall warning (12.3º). The test team members' exceedance of the stall AOA likely resulted, in part,

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[56] Gulfstream's chief flight test engineer stated that the 1-knot difference between the actual V_{LOF} and the target V_2 during test run 7A1 (which immediately preceded the accident test run) was a "fairly obvious" indication that the target V_2 speed was too low. However, some of the earlier test runs on the day of the accident (for example, test runs 3A2 and 3A3) involved target V_{LOF} and V_2 speeds that were only 1 knot apart, yet no one recognized this "fairly obvious" indication at the time. The chief flight engineer continued, "I don't think there were enough individuals looking at the data trying to understand what the airplane was doing…I think everyone was focused on trying to achieve the target…V_2 speeds [instead of] looking at what the airplane was…telling them."

[57] For test run 7A2, "liftoff" refers to the right MLG liftoff, which occurred at 0933:50.3 (1.5 seconds after the left MLG lifted off and 0.2 second before the stall).

[58] During test run 7A2, the PIC essentially duplicated the pitch control inputs and pitch profile from test run 6C3. However, during test run 7A2, the PIC did not reduce the pitch rate as soon as he did during test run 6C3; as a result, the pitch during liftoff for test run 7A2 was about 1º higher than that for test run 6C3. Also, the roll angle and roll rate during test run 6C3 remained closer to zero than they did during test run 7A2. These factors helped to keep the AOA across the span of the wing lower during test run 6C3 than during test run 7A2. (The maximum recorded AOA for test run 6C3 was 10.3º.) Also, during test run 6C3, the airplane was about 2 feet higher off the ground when pitch reached 11º than the airplane was at the same pitch during test run 7A2, which would have resulted in a somewhat higher stall AOA for the earlier test run.

from their confidence in, and reliance on, the PLI and stick shaker system, which they did not realize had been set too high to account for the actual in-ground-effect stall AOA.

Also during the accident takeoff, an uncommanded roll to the right began about 2 seconds before liftoff. The PIC made a left control wheel input of about 12º, which reduced the roll rate from 1.5º to about 0.9º per second. Liftoff occurred at a bank angle of 2.6º, and the roll rate increased immediately afterward to about 5º per second. The PIC stated "[unintelligible] going on" and doubled the amount of control wheel and rudder correction he was using (to counteract the increasing roll and yaw), but these actions did not stop the roll.

About 1.8 seconds after liftoff, with pitch tracking just under the PLI and the bank angle exceeding 10º, the SIC began to exclaim "whoa" multiple times. About 2 seconds after liftoff, pitch increased above the PLI, the stick shaker activated, and the PIC responded by pushing the control column forward and adding full left control wheel and full left rudder to counteract the roll. (The stick shaker activated at the programmed AOA, but a stall on the right outboard wing had already occurred.) About 2.3 seconds after liftoff, the right wingtip struck and began to drag along the ground at a bank angle of 13.4º. Pitch then decreased below the PLI, and stick shaker activation stopped. The PIC made a brief aft control column input and then held the column slightly aft while continuing to apply full left wheel and full left rudder. Even though pitch had decreased below the PLI, the airplane remained stalled, and the right wingtip continued to drag along the ground as the airplane veered off the runway.

About 3.3 seconds after liftoff, one or both pilots advanced the right thrust lever, the PIC called out repeatedly for power, and the SIC confirmed, "power's up." However, the airplane rolled farther to the right, pivoting on its right wingtip. The stick shaker activated again and continued to activate for the next 6.4 seconds (which was essentially the remainder of the flight). About 4.3 seconds after liftoff, at a bank angle of 18º and with pitch increasing to 13.8º, the PIC pulled back abruptly on the control column. The pitch and AOA responded accordingly, eventually increasing to peak values of 14.8º and 22.7º, respectively. The PIC maintained this substantial aft column input for several seconds while continuing to maintain full left control wheel and rudder. The bank angle increased to a maximum of 32º before the airplane began to roll out of the bank, the pitch angle decreased, and the fuselage impacted the ground. The NTSB concludes that a stall on the right outboard wing produced a right rolling moment that the flight crew was not able to control, which led to the right wingtip contacting the runway and the airplane departing the runway from the right side.

After the airplane departed the runway, the airplane's impact with a concrete structure resulted in extensive structural damage[59] and a postcrash fire, which completely consumed the fuselage and cabin interior. The SIC and both flight test engineers were found out of their seats and at locations indicating that they had been able to move within the cabin after the accident. (The PIC was found in his seat and was likely prevented from getting out of the seat because his leg was pinned under the instrument panel.) The SIC and FTE1 were found near the main entry door, and FTE2 was found near the center of the cabin. Thus, the cabin maintained livable space for a short time. Autopsy reports indicated that the cause of death for all four on-board test team

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[59] The fuselage was fractured between the forward and aft emergency overwing exits. Also, both overwing exits on the left side of the airplane did not remain in place during the accident sequence and were found away from the airplane wreckage.

members was inhalation of smoke and soot and extensive thermal burns. The NTSB concludes that the impact forces from the accident were survivable, but the cabin environment deteriorated quickly and became unsurvivable because of the large amount of fuel, fuel vapor, smoke, and fire entering the cabin through the breaches in the fuselage.

Because of the postcrash fire, the only viable exit after the accident was the main entry door. The latching mechanism and latching and locking handle for the door were found in the wreckage after the accident in the locked and latched position. However, because of extensive fire damage to the door, the NTSB could not determine whether the door was able to be operated or whether an attempt to open the door was made after the accident.

The NTSB was not able to determine whether the emergency response for this accident was as timely as it could have been because of the lack of information about the initial notification time.[60] On the basis of available evidence, the NTSB believes that the emergency response time was understandable given that ARFF vehicles had to approach the scene cautiously to avoid bystanders who were quickly assembling near the accident site.

2.2.1 Flight Crew Response to Stall and Roll

The PIC made proper control inputs in response to the roll that occurred during liftoff, but these inputs did not stop the roll. When the stick shaker initially activated, the PIC took appropriate action and pushed forward on the control column to reduce pitch below the PLI while keeping pitch high enough to facilitate a rapid climb. However, the PIC did not know that the airplane remained in a stall that overpowered the lateral controls and prevented him from leveling the wings.

When the stick shaker activated for a second time, the PIC should have again pushed forward on the control column to break the stall. However, the PIC’s first airplane-nose-down column input (in response to the stick shaker’s initial activation) had not allowed him to regain roll control of the airplane, which must have confused the PIC because the cessation of the shaker’s activation and the position of the PLI both indicated that the airplane was below the pitch angle and AOA that would result in a stall.[61] (During a postaccident interview, the Gulfstream senior test pilot stated that he and other G650 test pilots relied on the PLI to prevent takeoff stalls during flight testing.)

The inability to break the stall and regain roll control of the airplane and the extremely short time available to recover the airplane resulted in a high level of stress for the PIC, as indicated by his expressions of alarm (“whoa whoa”) and repetitive commands (“power power power” twice) after the first and second activations of the stick shaker, respectively. When individuals are subjected to high stress and extreme time pressure, cognitive processing becomes impaired, and individuals tend to revert to automatic, well-learned behaviors.

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[60] The NTSB plans to address this issue in a forthcoming safety recommendation letter.

[61] The PLI indicated proximity to stall based on the free-air reference stall AOA without any adjustment for the estimated reduction in the stall AOA due to ground effect.

The PIC had a well-learned response for potential stall events—pushing the nose down and increasing thrust. However, when these actions did not work and the airplane continued to veer off the runway, the PIC reverted to another well-learned behavior—pulling back on the control column to climb away from the ground. Even if the PIC had pushed forward rather than pulled back on the control column after the second activation of the stick shaker, it is highly unlikely that this or any other control input could have prevented the airplane's impact with the ground given the airplane's attitude, trajectory, and proximity to the ground. The NTSB concludes that, given the airplane's low altitude, the time-critical nature of the situation, and the ambiguous stall cues presented in the cockpit, the flight crew's response to the stall event was understandable.

After the accident, Gulfstream revised its TSHA for OEI continued takeoffs and included, as additional hazards, over-rotation at low airspeed and low altitude stall. The risk level for the test remained high, the probability of occurrence for the hazards associated with the test was changed from low to "occasional," and the hazards were classified as "catastrophic." The TSHA also included the following corrective techniques to discontinue the maneuver if the pitch attitude exceeded the PLI: (1) decrease AOA, advance the thrust levers, regain control, and climb to a safe altitude or (2) decrease AOA, retard both engines, and land.

2.2.2 Overview of Factors Leading to Accident

Several Gulfstream actions, as explained in detail in sections 2.3 through 2.5, led to the circumstances surrounding the accident. Specifically, during the G650 program, Gulfstream

- overestimated the actual in-ground-effect stall AOA for the G650 during the accident flight, resulting in the AOA threshold for stick shaker activation being set too high and the flight crew not receiving any warning before the actual stall occurred;
- used a flawed assumption in determining the takeoff speeds for the G650, resulting in V_2 speeds that could not be achieved because they were too low;
- exacerbated the error in V_2 speeds before the accident flight by decreasing the target pitch angle for some continued takeoff flights without an accompanying increase in the takeoff speeds;
- failed to fully investigate two previous uncommanded roll events that occurred during G650 field performance flight testing;
- focused on refining pilot technique to resolve the V_2 overshoot problem (so that the G650 takeoff performance guarantee could be achieved) instead of investigating the root cause for the V_2 overshoots; and

- failed to establish adequate flight test operating procedures, adjust the G650 flight test schedule to account for program delays, and develop an effective flight test safety management program.

2.3 Stall Angle of Attack Estimates

As stated in section 1.1, ground effect refers to changes in the airflow over the airplane resulting from the proximity of the airplane to the ground. Ground effect results in increased lift and reduced drag at a given AOA as well as a reduction in the stall AOA; thus, the stall AOA is lower for airplanes in ground effect compared with the stall AOA for airplanes in free air (out of ground effect). Ground effect decreases as the distance from the ground increases and is generally negligible above a height equivalent to the wing span of the airplane (which is about 100 feet for the G650). Figure 5 depicts the changes in the airplane's lift and stall AOA due to ground effect.

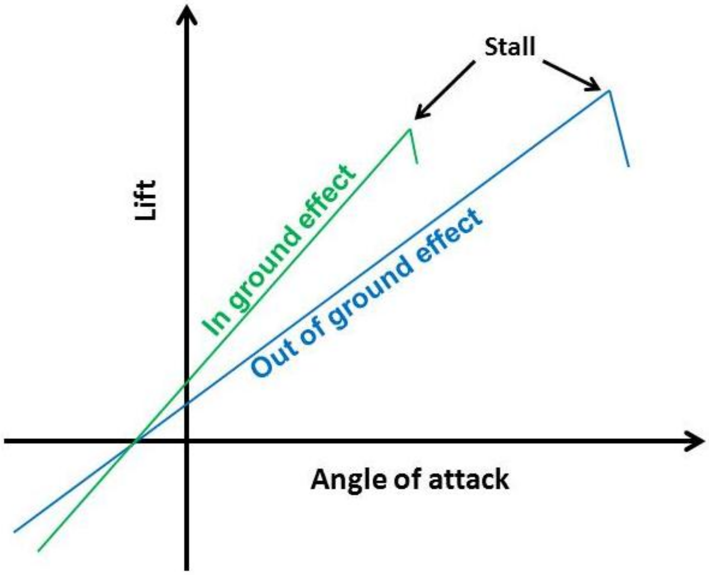

Figure 5. Airplane lift versus angle of attack in and out of ground effect.

During an October 7, 2010, meeting of the Gulfstream flight test safety review board (SRB),[62] an estimate of the reduction, or decrement, from the free-air stall AOA to the in-ground-effect stall AOA was presented as 2º. This 2º decrement (which was previously provided to Gulfstream's flight test engineering department by the company's flight sciences department) was based on G650 low-speed wind tunnel testing. A 2º decrement was also used during the GIV and other Gulfstream programs.[63] After the accident, a G650 aerodynamicist indicated that the decrement was a generally accepted and agreed-on value that could not be further refined during flight tests because of the expectation that the airplane would always be operated below the stall AOA near the ground.

During a March 24, 2011, meeting to discuss Roswell II takeoff performance testing,[64] FTE1 indicated that he had revised the decrement from the free-air to in-ground-effect stall AOA to about 1.6º. During a postaccident interview, the director of flight test engineering stated that FTE1 had computed the revised decrement based on his analysis of coefficient of lift data derived from the Roswell I V_{MU} test results. Thus, it is likely that FTE1 wanted to use a decrement for upcoming flight tests that was based on actual flight test data rather than continue to use the estimated decrement from wind tunnel testing and previous company programs. However, FTE1's revision to the decrement appeared to be based on an incorrect interpretation of the V_{MU} test results. Specifically, FTE1's revision assumed that the G650 in ground effect possessed a similar maximum lift coefficient as in free air.

In addition to the revised decrement for the in-ground-effect stall AOA, the stick shaker activation threshold had been changed (starting with flight 125 on March 7, 2011) from 85 to 90 percent of normalized AOA,[65] which reduced the margin for stall protection. The Gulfstream chief flight test engineer stated that he and FTE1 made this change to allow predicted takeoff speeds to be achieved without stick shaker activations that would invalidate tests. (During some takeoff performance testing, flight test teams were encountering stick shaker activations at the 85 percent normalized AOA stick shaker setting, which were interfering with the teams' ability to acceptably demonstrate required maneuvers.) The increased stick shaker setting was expected to provide stall warning about 1º below the estimated in-ground-effect stall AOA. Those present at the March 24, 2011, meeting agreed to keep the stick shaker activation setting at 90 percent of normalized AOA for Roswell II takeoff performance testing.

For the accident flight, the free-air stall AOA was 14.7º, and the 1.6º decrement for the in-ground-effect stall AOA resulted in a predicted in-ground-effect stall AOA of 13.1º. Thus, the stick shaker AOA set to 90 percent of normalized AOA (equivalent to an actual AOA of 12.3º)

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[62] According to Gulfstream, the flight test SRB was an interdisciplinary group of management, flight test engineering, design engineering, and flight operations personnel. The flight test SRB was convened in October 2010 to discuss the G650 field performance test plan. About 30 Gulfstream personnel attended the SRB, including the vice president of flight operations and the director of flight test, who chaired the flight test SRB; the four test team members who were aboard the accident flight; and the two other test pilots who performed G650 field performance flight testing. During the SRB, FTE1 presented slides detailing the test objectives, approach, conditions, and procedures; ground support; airplane configuration; and hazard analyses.

[63] The GIV airplane was certified in April 1987.

[64] This meeting was not a reconvening of the flight test SRB. According to Gulfstream, airplane performance engineers, control law personnel (who developed algorithms for the AOA limiter and the stick shaker), and flight test engineers were present at the meeting.

[65] As stated in section 1.1, normalized AOA is a measure of the usable AOA range of the airplane.

provided a 0.8º margin to the in-ground-effect stall AOA assumed at the time.[66] However, the stick shaker (and the PLI) did not provide any warning before the actual stall on the accident flight, which occurred at an AOA of about 11.2º. The NTSB's aircraft performance study for this accident found that the flight test data that Gulfstream had collected during previous G650 field performance takeoffs, particularly the data from the flight 88 and flight 132 uncommanded roll events, were sufficient to quantify the changes in aerodynamic lift and the actual reduction in the stall AOA because of ground effect. Thus, Gulfstream should have been able to accurately predict the G650 in-ground-effect stall AOA before the accident flight.

Gulfstream did not have an adequate process to ensure that, if an unexpected outcome (such as an uncommanded roll) occurred during G650 high-risk flight tests, a senior-level engineering review of those events would be performed before the flight tests continued. As a result, Gulfstream did not thoroughly analyze either the flight 88 or flight 132 uncommanded roll events to determine their causes until after the accident. The U.S. Naval Test Pilot School's *Flight Test Manual* advised the following: "in the event a data point yields an unexpected result or a series of data points creates an unexpected trend, evaluation stops until the results are analyzed and explained." Also, a U.S. Air Force Flight Test Center document defined an "unusual event" or "unexpected test result" as "any occurrence that warrants a safety-related pause in the test program" and indicated that, if an unusual event were to occur, "applicable test points will be placed on hold.…[until] a plan of action is determined."[67]

Gulfstream had performed such analyses after similar events occurred on certification test flights during the GIV and GV programs.[68] During a postaccident interview, Gulfstream's chief test pilot stated that the FAA's participation during the GIV and GV certification test flights might have accounted for the difference in the level of attention given to the uncommanded roll events during those flights compared with that given to the G650 events.[69] Also, the wingtip contacted the runway during the GIV flight test, and the wing drop during the GV flight test resulted in a hard landing, but neither runway contact nor a hard landing occurred during the flight 88 and flight 132 events. Because the G650 uncommanded roll events were not fully

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[66] The increase in stick shaker AOA from 85 to 90 percent normalized AOA was equivalent to an AOA increase from 11.6º to 12.3º at the flaps 10 setting and Mach number at the time of the accident and a decrease in stall margin from 1.5º to 0.8º. APG1 stated that, before the accident, she did not know that a 5 percent change in normalized AOA reduced the stall margin by nearly 50 percent. After the accident, Gulfstream specified, on the TSHA for OEI continued takeoff tests, that the stick shaker and PLI settings would maintain an in-ground-effect stall AOA margin of at least 1º.

[67] *Test Safety Review Process*, U.S. Air Force Flight Test Instruction 91-105 (Edwards Air Force Base, California: Air Force Flight Test Center, 2012).

[68] During the GIV program, an uncommanded roll event occurred during V_{MU} takeoff performance certification testing. The airplane stalled before the stick pusher activated, rolled sharply, and struck its right wingtip on the runway. Gulfstream analyzed the event and determined that the stall occurred while the airplane was in ground effect and at an AOA that was 2º lower than the free-air stall AOA. Gulfstream also analyzed the airflow separation pattern over the airplane's wing and developed aerodynamic devices to slow the spread of airflow separation during a stall. During the GV program, an uncommanded roll event (a right roll in excess of 20º immediately after liftoff) occurred during V_{MU} certification testing. Gulfstream analyzed this event in two test reports and found that the roll rates and attitudes that occurred during the maneuver were primarily caused by a left crosswind that directly affected the airplane while it was at a "very low" airspeed. For one of the reports, Gulfstream performed a theoretical analysis using a computer model to understand the effects of control input and crosswind component on rolling characteristics.

[69] Flight testing is conducted in two phases. A manufacturer conducts developmental flight testing to ensure that an aircraft can meet the requirements of applicable *Federal Aviation Regulations*. The FAA conducts certification flight testing to confirm that the aircraft has been developed according to the applicable regulations. Additional information about developmental and certification flight testing is discussed in section 2.5.

analyzed before the accident, the flight 88 event was attributed to an over-rotation by the flying pilot, and the flight 132 event was attributed to a lateral-directional disturbance influenced by the unavailability of the yaw damper.[70]

Flight test data indicated that, at the takeoff Mach numbers, the free-air, flaps 20 stall AOA for flights 88 and 132 was 14.2º. Thus, the predicted in-ground-effect stall AOA for those flights was 12.2º (based on the 2º decrement between the free-air stall AOA and the in-ground-effect stall AOA that was assumed at the time of those flights). However, the NTSB's analysis of the data from flights 88 and 132 (using Gulfstream's postaccident simulation residual analysis for these flights) estimated that, on the basis of these flights, the maximum decrement in the stall AOA due to ground effect was about 3.5º. This finding was close to the flaps 20 in-ground-effect stall AOA decrement of about 3º that was determined by Gulfstream's postaccident computational fluid dynamics (CFD) analysis.[71] On the basis of the CFD results, Gulfstream determined after the accident that the flight 88 and flight 132 events resulted from a stall of the right outboard wing at a lower-than-expected AOA.

Gulfstream's postaccident CFD analysis also indicated that the decrement for the in-ground-effect stall AOA at flaps 10 (the accident flap setting) was as much as 3.25º, which was about twice the 1.6º estimate that Gulfstream was using at the time of the accident.[72] The NTSB concludes that, if Gulfstream had performed an in-depth aerodynamic analysis of the cause of two previous G650 uncommanded roll events, similar to the analyses performed for roll events during previous company airplane programs, the company could have recognized that the actual in-ground-effect stall AOA for the accident flight test was significantly lower than the company predicted.

It is important to note that knowledge of the actual decrement between the free-air and in-ground-effect stall AOA is not required to safely conduct field performance flight tests as long as the airspeeds used during the tests are developed correctly. Gulfstream's development of the takeoff speeds used during G650 field performance tests is described in the section that follows.

2.4 Takeoff Speed Schedules

When the GV airplane was certified in April 1997, 14 CFR 25.103, "Stall Speed," stated that the reference speed used as the basis for minimum operating speeds (including V_2) was the stall speed (V_S). The regulation defined V_S as the minimum speed obtained in a stalling maneuver, and Part 25 indicated that the minimum V_2 must be at least 1.2 times V_S.

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[70] As indicated in section 1.3.2, the pilots of flight 132, while still in the cockpit, initially attributed the event to a stall, but the cause of the event was later changed after review of the data showed that the AOA during the event had remained 1.5º below the predicted in-ground-effect stall AOA.

[71] CFD is the science of solving the fluid equations of motion numerically with digital computers. The results can be extracted numerically or serve as a basis for visualizations. Gulfstream conducted a postaccident CFD analysis of the effect of the proximity of the ground on the aerodynamics of the G650 (in both the flaps 10 and flaps 20 configurations) to determine the influence of the ground on the stall AOA.

[72] The results of this CFD analysis, along with the airplane-nose-right sideslip angle, the reduced height of the right wingtip due to the right roll angle, and the increased AOA on the right wing due to the right roll rate, were consistent with a stall occurring on the right wing at 0933:50.5, as indicated by Gulfstream's simulation residual analysis for the accident flight. The CFD analysis also indicated that, at non-zero sideslip, the downwind wing would stall first, which was consistent with the circumstances of the accident.

The FAA issued a final rule (Amendment 25-108, published at 67 *Federal Register* 70812, November 26, 2002) to change the reference V_S because of concerns that the speed margins between V_S and each minimum operating speed might be less than intended. Specifically, according to the FAA's final rule, V_S could be less than the lowest speed at which the airplane's weight was still entirely supported by aerodynamic lift. The final rule defined a new reference stall speed (V_{SR}) as a calibrated airspeed chosen by the applicant (that is, the airplane manufacturer) that could not be less than the 1-g stall speed, which was the "minimum speed for which the lift provided by the wing is capable of supporting the weight of the airplane."[73] The final rule became effective in December 2002.

The final rule indicated that the multiplying factors that were used to determine the minimum operating speeds using a reference speed based on V_S were not appropriate for defining those speeds using V_{SR}. As a result, the multiplying factors to obtain minimum operating speeds were reduced. The minimum V_2 was changed to be at least 1.13 times V_{SR}. Gulfstream established the certification basis for the G650 in March 2007 (after Amendment 25-108 became effective) and decided to make the airplane's V_2 speed identical to the minimum V_2 speed allowed by regulation (1.13 times V_{SR}). However, as discussed in this section, this decision became the primary reason that the V_2 speeds were too low.

The method used to develop the takeoff speed schedules for the G650 differed from the method described in Gulfstream's *Model GVI Data Analysis Methods* document (dated June 25, 2009), which made it more difficult for the company to recognize that the airplane could not achieve V_2 speeds as low as 1.13 V_{SR}. The document presented data analysis methods and flight test procedures that were to be used to develop the takeoff speed schedules for the G650 field performance tests. Section 9.1 of the document described test procedures and stated that, for determining takeoff distances and takeoff speed schedules, a preliminary flight manual would be prepared and updated before testing to reflect the results of V_{MU} tests (among other tests), which would refine original analytical estimates of takeoff speed schedules and provide "a more accurate data base for establishing target test speeds."

Section 8 of the data analysis methods document described V_{MU} testing and its role in the development of the takeoff speed schedules. The document explained, "demonstrated V_{MU} speeds are normally used as the basis from which the normal speed schedules are developed (V_1, V_R, [and] V_2)…rotation and liftoff speed increments are added to the V_{MU} baseline speeds to work *forward* to the operational speeds." However, Gulfstream determined, during GIV certification testing, that rotation and liftoff speed increments added to the V_{MU} baseline speeds resulted in V_2 values that were slightly less than the required 1.2 V_S, which led to a redefinition of the speed schedules based on the V_2 requirement at 35 feet. Specifically, as explained in the document, "appropriate increments were then subtracted from the V_2 requirement to work *backwards* to V_{LO} and V_R."[74] This same approach was used for the G650 program but with V_2 established as 1.13 V_{SR}.

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[73] In its notice of proposed rulemaking supporting this change (61 *Federal Register* 1260, January 18, 1996), the FAA stated, "redefining the airplane reference stall speed as the 1-g stall speed would result in a higher level of safety in those cases where current methods could result in artificially low operating speeds." The FAA also stated that its review of NTSB accident reports from 1983 to 1992 found no accidents caused by inconsistent or inappropriate reference stall speeds.

[74] In the *Model GVI Data Analysis Methods* document, V_{LO} represented the liftoff speed.

Gulfstream assumed that, similar to the GIV program, working forward from V_{MU} to V_2 would result in V_2 values for the G650 program that were lower than the minimum V_2 values allowed by regulation. However, during field performance tests, the G650's speed was consistently faster than 1.13 V_{SR} at 35 feet, even with aggressive rotation techniques. Working forward from the G650 V_{MU} speeds to obtain V_{LOF} and V_2 (as was done initially on the GIV program before working backward from the minimum allowable V_2 values to V_{LOF} and V_R) would yield V_2 speeds that were higher than the minimum 1.13 V_{SR} required by regulation. Thus, if Gulfstream had used V_{MU} data to confirm its assumption that V_2 values for the G650 program would be lower than the minimum V_2 values allowed by regulation, the company might have realized that its assumption was not valid because of the change in the minimum V_2 speeds (which, in turn, could have led to more realistic and higher target V_2 speeds). The NTSB concludes that Gulfstream's decision to use a takeoff speed development method from a previous airplane program was inappropriate and resulted in target V_2 values that were too low to be achieved.

The speed increments from V_2 to V_{LOF} and from V_2 to V_R that Gulfstream used to determine the target V_{LOF} and V_R for the G650 were not based on G650 tests (as specified in the data analysis methods document) but were instead based on similar increments that applied to the G550 airplane.[75] As a result, because the actual speed increment between V_{LOF} and V_2 for the G650 was greater than the increments based on the G550 airplane, liftoff at the target V_{LOF} resulted in V_2 overshoots. In addition, because the increments based on the G550 airplane were applied to V_2 speeds that were too low, the G650 was being operated during field performance tests at lower airspeeds and higher AOAs and with smaller margins to stall than on previous Gulfstream airplane programs.

The takeoff speed schedules for the Roswell II field performance tests were developed by Gulfstream's airplane performance group (which was within the company's flight sciences department).[76] However, the airplane performance group did not review FTE1's draft report of the Roswell I V_{MU} test data until 1 month after the accident.[77] Even though the report had not been finalized before the accident, the test data could still have been used to develop the takeoff speed schedules. Because the airplane performance group had not retrieved and analyzed these data, the group missed an opportunity to determine that the V_{MU} data did not support V_2 speeds as low as 1.13 V_{SR}.

Also, the airplane performance group did not perform an analysis that considered the dynamics of the rotation maneuver to verify that the airplane could achieve takeoff speed schedules that were based on the minimum allowable V_2 and speed increments from the G550

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[75] The G550 airplane was certificated in August 2003.

[76] APG1 was the official head of the G650 airplane performance group. The principal engineer for airplane performance had been the acting group head during the G650's preliminary design phase but had passed responsibility for the group to APG1 as the program matured. According to the principal engineer, he had "overall general responsibility" for the G650 program along with responsibilities for new and existing company airplane programs.

[77] FTE1's draft report of the V_{MU} test results was completed about 1 week before the accident occurred and was awaiting supervisory review. Although Roswell I V_{MU} testing was completed more than 3 months before Roswell II testing began, FTE1 was not able to complete this report sooner likely because of his numerous other responsibilities for the G650 program, which are discussed in section 2.5.1.

airplane.[78] If Gulfstream had performed such an analysis or tested the takeoff speed schedules in its integrated test facility,[79] the company could likely have determined, before the start of field performance testing, that the target V_2 speeds were too low to be achieved.

In addition, the V_2 overshoot problem appeared to be unique to the G650: during postaccident interviews, Gulfstream pilots, engineers, and managers stated that they did not know of similar problems achieving V_2 on any other company or other manufacturer's airplanes. However, the NTSB found no evidence indicating that Gulfstream had formally considered erroneously low target V_2 speeds as the possible root cause for the V_2 overshoot problem.[80] The NTSB concludes that, by not performing a rigorous analysis of the root cause for the ongoing difficulties in achieving the G650 V_2 speeds, Gulfstream missed an opportunity to recognize and correct the low target V_2 speeds.

The difficulties in achieving the V_2 speeds were exacerbated by the reduction in the target pitch angle from 10º to 9º for flaps 10 takeoffs without an accompanying increase in the takeoff speed schedules.[81] The airplane performance principal engineer stated that neither he nor FTE1 (or anyone else associated with the G650 program) had recognized (until after the accident) that the reduction in the target pitch would necessitate an upward adjustment in the takeoff speeds. If the need for this change had not been overlooked, the airplane performance group could have retrieved the V_{MU} data needed to compute the lift coefficient in ground effect and make the appropriate speed adjustments (even though this effort would have duplicated some work done by FTE1 in drafting the V_{MU} report).

According to the principal engineer for airplane performance, with the reduction in target pitch attitude from 10º to 9º for flaps 10 takeoffs, the resulting V_{LOF} values essentially matched

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[78] Such an analysis could be accomplished using either simple or sophisticated methods. A simple analysis could be based on geometrical diagrams of the takeoff segments, and a sophisticated analysis could be based on three- or six-degree-of-freedom simulations that use mathematical models of the airplane and atmosphere to solve the equations of motion and compute the airplane's flightpath as a function of time.

[79] Gulfstream's integrated test facility was a fixed simulator used for research, development, and evaluation of the G650's electrical and computer systems. The facility was also equipped with cockpit and video displays to simulate the airplane's environment and motion. The G650 project test pilot stated that the integrated test facility was not used to validate the takeoff speeds because its fidelity was poor. However, the NTSB believes that the fidelity of the integrated test facility before the accident would likely have been sufficient for investigating the difficulties associated with the V_2 overshoots.

[80] The NTSB notes that, after a test run during flight 111, FTE1 was trying to figure out what to do about pitch attitude because the target pitch had been reached 1 second before liftoff. FTE1 stated, "I think if you pull harder we're just gonna make it worse." The G650 project test pilot (the flying pilot) agreed and then stated, "unless you make your V_2 faster." However, the pilot's suggestion was never formally considered. In addition, audio recorder evidence indicated that, during subsequent flights, the Gulfstream senior test pilot and the G650 project test pilot noted that, for some airplane weights, the V_R for flaps 10 was lower than the V_R for flaps 20, and they questioned FTE1 about this issue. FTE1 responded that the speeds were similar to those that had been used during Roswell I field performance tests and that the V_2 for flaps 10 was higher than the V_2 for flaps 20. The pilots seemed satisfied by FTE1's explanation.

[81] On March 27, 2011 (6 days before the accident), FTE1 met informally with the airplane performance principal engineer and requested that the target pitch for flaps 10 takeoffs be reduced from 10º to 9º (primarily because of FTE1's concerns about an AEO 2º over-rotation test). The principal engineer agreed to this request. Also during the informal meeting, the principal engineer learned that FTE1 had just finished drafting a report on the V_{MU} data from the Roswell I flight tests. FTE1 briefly reviewed the report with the principal engineer but did not give him a copy (because the report was awaiting supervisory review). The principal engineer stated that he was not concerned that the Roswell II tests were scheduled to occur before the report was finalized because he thought that FTE1 had the necessary data to safely proceed with the testing. The flight test engineering group head believed that the V_{MU} report did not need to be finalized as long as the flight test engineers could look at the V_{MU} data and create any necessary plots.

the original target V_2 values, so the PIC had "an almost impossible task" to pull back on the control column immediately after liftoff to achieve V_2. A postaccident analysis of the V_{MU} data by the principal engineer showed that the liftoff speed at flaps 10 and a pitch angle of 9° would be 4 knots faster than the liftoff speed at a pitch angle of 10°. However, even if the liftoff speed had been increased by 4 knots, the resulting V_2 speeds would still likely have been too low given that the flaps 10 V_2 overshoots on the day of the accident ranged from 7 to 12 knots.

2.4.1 Rotation Technique

Gulfstream's desire to achieve the G650's takeoff performance guarantee focused the company's attention away from the need to investigate the soundness of the target takeoff speeds. Instead, as discussed in sections 1.3.1 and 1.3.3, the company focused on refining pilot technique to solve the V_2 overshoot problem.

The certification regulations for airplane handling qualities in 14 CFR Part 25 included both quantitative and qualitative criteria. Regarding quantitative criteria, section 25.143, "Controllability and Maneuverability," paragraph (d), stated that the maximum control force for two-handed, short-term longitudinal control inputs was 75 pounds. Regarding qualitative criteria, paragraph (b) of section 25.143, stated, "it must be possible to make a smooth transition from one flight condition to any other flight condition without exceptional piloting skill, alertness, or strength." Also, section 25.101, "General," paragraph (h), stated that the procedures used to determine the takeoff flightpath (among others) must be able to be "consistently executed in service by crews of average skill." Further, section 25.105, "Takeoff," paragraph (b), stated that takeoffs made to determine takeoff performance data could not require exceptional piloting skill or alertness.

A takeoff technique needs to be well defined for the technique to be "consistently executed in service by crews of average skill." However, the G650 takeoff technique appeared to still be evolving given that the test pilots of flights 111, 132, and 153 had different methods for accomplishing the technique. For example, the monitoring pilot of flight 132 (a senior test pilot) thought that the technique developed by the G650 project test pilot during flight 111 was too aggressive when it was performed by the accident SIC (during the test run resulting in an uncommanded roll). Nevertheless, the adjustments made to the technique during flight 132 still caused FTE1 to be concerned about whether FAA certification pilots would be able to accomplish it.[82] The PIC of the accident flight thought that the technique used by the senior test pilot (during previous flights) was "pretty jerky" because of the abrupt column inputs, and the accident PIC indicated that the "jerk stuff…just doesn't work." The accident PIC also expressed concern about how the FAA would react to the technique.

During flight 153, the takeoff rotation technique was progressively modified from an abrupt column pull of 60 to 65 pounds to "a nice smooth ramp" with lower (50- to 55-pound) column pull forces. However, the modified technique, which also necessitated increasing pitch to higher angles progressively earlier after rotation to keep the speeds down, resulted in larger V_2 overshoots than those that had been obtained during flight 111. The less aggressive technique

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[82] Gulfstream records and witnesses indicated that, on March 30, 2011 (3 days before the accident), the SIC and FTE1 practiced takeoffs in the integrated test facility.

also resulted in longer takeoff distances, which would have precluded Gulfstream from attaining the G650 program's takeoff performance guarantee.

FAA certification flight test pilots ultimately determine whether an airplane's handling qualities meet the qualitative criteria of Part 25. However, on the basis of comments from Gulfstream flight test pilots and the concerns expressed by FTE1, the takeoff technique that was initially developed during flight 111 and attempted during flight 132 would not likely have been certifiable. Pilots would not have been able to consistently execute this technique during service without "exceptional piloting skill," as required by sections 25.143 and 25.105, and by flight crews "of average skill," as required by section 25.101. Also, the takeoff technique developed during flight 111 that came the closest to achieving the target V_2 speeds involved an overshoot of about 3 knots (which was above the required ± 2-knot tolerance for the target V_2 speed), and the technique had not been successfully demonstrated on any takeoff performance flight test after flight 111. The NTSB concludes that, before the accident flight, Gulfstream had sufficient information from previous flight tests to determine that the target V_2 speeds could not be achieved with a certifiable takeoff rotation technique and that the V_2 speeds needed to be increased.

2.4.2 Postaccident Changes

After the accident, Gulfstream revised its takeoff airspeed development and testing methods. According to Gulfstream, airspeeds are now generated using a desktop computer simulation[83] that represents the dynamics of the maneuver, the aerodynamics of the airplane in and out of ground effect, and the "control effectiveness" of the airplane. Gulfstream indicated that the desktop computer simulation was developed to more precisely model the takeoff maneuver and predict V_2 speeds that ensure, among other things, (1) an achievable and repeatable initial pitch attitude at rotation and (2) a suitable margin between the operating AOA and the stall AOA during in-ground-effect operations and the climb to the obstacle clearance height. The revised takeoff airspeed development and testing methods were used to determine updated G650 takeoff speeds for the accident flight test conditions, as shown in table 4. As indicated in the table, the updated V_2 speed was 15 knots (11 percent) faster than the V_2 speed provided to the accident test team.

Table 4. Updated takeoff speeds for accident flight test conditions.

Takeoff speed	Speed for flight 153 (knots)	Revised speed (knots)	Difference (knots)
V_R	127	137	10
V_{LOF}	132	140	8
V_2	135	150	15

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[83] A desktop simulation uses computer code to drive flight control inputs and thus can be run without a pilot in the loop.

Gulfstream reported that it took other actions after the accident to improve airspeed development and testing, including the following:

- Pilot-in-the-loop simulations in the integrated test facility were used to develop and verify an acceptable and repeatable takeoff rotation technique that did not require exceptional piloting skill before the technique was used during flight tests.
- The results of Gulfstream's postaccident CFD analysis were used to update flight test methods and instrumentation on the G650 airplane and in the telemetry trailer and generate safety-of-flight AOA margins to be used during flight testing.
- Two separate real-time desktop computer simulations at flight test sites were used to provide improved real-time monitoring and analysis of the general handling characteristics of the G650 airplane during all takeoff testing phases. Gulfstream indicated that, if test aircraft demonstrated abnormal handling qualities, reduced acceleration during the ground roll, and/or excessive air phase or climb-out times than those predicted by the on-site desktop computer simulations, testing would be stopped so that the data could be thoroughly reviewed. Gulfstream further stated that, if the cause of any problem could not be immediately identified and corrected, testing would be discontinued until the problem could be satisfactorily explained.

In addition, Gulfstream indicated that it implemented actions (besides increased takeoff speeds) to ensure the safe operation of the G650 in achieving the 6,000-foot takeoff performance guarantee. First, Gulfstream modified the takeoff technique to reduce the necessary column pull forces so that a pilot could reliably attain the initial pitch attitude within 3 to 4 seconds. Second, Gulfstream changed the stall warning system (for both flight test and production airplanes) so that the in-ground-effect stall AOA would be continuously computed in the flight control computer using the height above the ground and Mach number. Gulfstream believed that this change would provide pilots with increased situational awareness and would help ensure a timely reaction if an over-rotation were to occur. Last, the maximum takeoff thrust was increased by 5 percent to minimize the performance penalties associated with higher takeoff speeds.

2.5 G650 Program Management

Field performance testing was one component of the G650 flight test program. As previously stated, field performance testing was being conducted to gather data to support type certification and facilitate the development of takeoff and landing speed schedules and distances for the G650 airplane flight manual.[84]

Similar to other commercial flight test programs, G650 field performance testing was to progress in two distinct phases: developmental flight testing and certification flight testing. The

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[84] The *GVI Field Performance Certification Flight Test Plan* listed the following field performance maneuver categories: V_{MU} speeds, takeoff performance, abused takeoff assessment, rejected takeoff/accelerate-stop demonstrations, thrust reverser effectiveness, landing performance, and aero coefficient determination free rolls.

purpose of developmental flight testing is to explore an airplane's flying capabilities and collect and analyze data that could be used to define the airplane's performance envelope. During this period, Gulfstream was to collect and analyze these flight test data. At the conclusion of developmental flight testing, Gulfstream would provide reports summarizing this information to the FAA for review. Afterward, the FAA would approve a type inspection authorization (TIA), and field performance would move to the certification flight testing phase. During the certification flight test phase, Gulfstream would repeat specific tests selected by the FAA, under the direct supervision of FAA personnel, to verify compliance with type certification requirements.

According to FAA Order 8110.4C, *Type Certification*, section, 2-6, i(1), the FAA does not consider developmental flight testing to be part of the type certification process or the FAA's flight test program. As a result, the FAA had little to no direct role in developmental flight testing. Further, although the FAA required Gulfstream to develop and share G650 project certification plans, communicate internal schedules, and keep the FAA generally informed about G650 developmental flight testing program-related issues, the development and reinforcement of internal company policies and procedures for the safe and efficient conduct of developmental flight testing was Gulfstream's responsibility.

Many manufacturers consider developmental flight testing policies and procedures to be proprietary information; as a result, manufacturers typically employ highly individualized strategies for organizing and conducting their developmental flight testing programs. The NTSB identified several weaknesses in Gulfstream's management of the G650 developmental flight testing program that contributed to the unachievable takeoff speeds and the incorrect estimate of the in-ground-effect stall AOA. Specifically, managerial shortcomings in technical planning and oversight, program scheduling, and safety risk management resulted in an environment that was conducive to errors, and these managerial shortcomings allowed the errors to propagate across G650 flight test program activities and remain undetected until after the accident. The deficiencies in Gulfstream's management of the G650 developmental flight testing program are discussed in sections 2.5.1 through 2.5.3.

2.5.1 Technical Planning and Oversight

Gulfstream's *Flight Test Standard Practice Manual* (which was issued in 1995 during the GV flight test program and updated in October 1998) was the formal policy document governing personnel and group roles and responsibilities during the G650 flight test program. The manual reflected the decision of its author, a former Gulfstream director of flight test (during the mid-1990s), to separate flight test coordination and conduct duties from data analysis and report writing duties so that these duties would be assigned to different engineers.[85] When the former director of flight test left Gulfstream, responsibility for the continued development and implementation of the manual passed to the new director of flight test, who still held that position at the time of the accident. However, at that time, the manual had not been updated in

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[85] The former director of flight test believed that this separation of duties would help maintain the fast pace of the GV program, ensure that each function would be properly performed, and make Gulfstream's flight test processes more standardized and efficient and more closely aligned with those of larger manufacturers.

more than 12 years,[86] and some company practices were no longer consistent with those described in the manual.[87] In particular, the separation of flight test coordination and conduct duties and data analysis and report writing duties was not maintained; as a result, individual flight test engineers who conducted specific areas of testing from start to finish were responsible for all of these duties.

In accordance with this practice, FTE1 had assumed most of the test coordination and conduct responsibilities for G650 field performance flight testing.[88] In addition, FTE1 had assumed responsibility for flight test data analysis and report writing. About 1 week before the accident, FTE1 finished drafting a report on the V_{MU} test results and provided a copy of the report to his supervisor, the flight test engineering group head. If flight test coordination and conduct duties had been separated from data analysis and report writing duties, as outlined by the *Flight Test Standard Practice Manual*, then the V_{MU} data analysis and report writing tasks could have been performed by another engineer in parallel with the planning and preparation for Roswell II testing.[89] Further, if this separation of duties had occurred, the airplane performance group could have had finalized data to refine the takeoff speeds used during field performance testing. These data, in turn, could have helped airplane performance engineers identify that the target V_2 speeds for Roswell II testing were too low and make the necessary corrections to the speeds.

Gulfstream had not established adequate control gates in its field performance flight testing plan to prevent Roswell II continued takeoff testing from proceeding before the takeoff speed schedules had been checked against the V_{MU} test results. Control gates are key decision points in a systems engineering development effort that are normally overseen by technical managers.[90] Control gates ensure that prerequisite tasks are completed before work progresses to a new project phase. Because the V_{MU} test results were needed to refine the takeoff speed schedules, a technical manager, such as the flight test engineering group head, chief flight test

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[86] The senior vice president of programs, engineering, and test and the vice president of the G650 program were aware that the *Flight Test Standard Practice Manual* was out of date, but neither they nor any other Gulfstream manager took action to update it. The senior vice president of programs, engineering, and test believed that, even though the manual was outdated, the company's management of the G650 flight test program was consistent with industry norms.

[87] In addition, new employees had not been trained on the *Flight Test Standard Practice Manual*; Gulfstream flight test pilots, flight test engineers, and flight sciences personnel were unfamiliar with the manual's contents; and company managers were not ensuring compliance with the manual.

[88] FTE1's test coordination and conduct responsibilities included developing the field performance test plan; delivering presentations at the flight test SRB meeting; overseeing test preparation, including the development of test cards; leading pre- and post-flight briefings; and serving as the on-board test conductor. During the weeks before the accident, FTE1 was focused on preparing for Roswell II testing and was leading the effort to develop a takeoff technique that would meet the G650's takeoff performance guarantee. In addition, FTE1 was preparing to lead another area of testing involving flight with ice shapes affixed to the airplane's airfoils, and he was serving as a member of the SRB that was analyzing the cause of the March 3, 2011, yaw damper malfunction.

[89] Gulfstream's airplane performance group took the initiative to analyze the data from flight 111 (the takeoff technique development testing that occurred in February 2011) and some continued takeoff testing that occurred in early March 2011. However, the group did not take the initiative to analyze V_{MU} flight test data. The principal engineer for airplane performance and APG1 stated that, although the responsibility for some data analyses was somewhat unstructured, the responsibility for the V_{MU} data analysis was clearly the responsibility of the flight test department.

[90] Key decision points and control gates are discussed in publicly available references on systems engineering and engineering program management, including the *National Aeronautics and Space Administration Space Flight Program and Project Management Handbook*, NASA Procedural Requirements document 7120.5, February 2010.

engineer, manager of flight test engineering, or director of flight test engineering, should have verified that V_{MU} data analysis had been completed before continued takeoff testing began.

In addition, Gulfstream's processes for validating the soundness of engineering methods used during G650 field performance flight testing were deficient. For example, company managers responsible for technical oversight did not ensure that effective processes for validating the computed target takeoff speeds had been implemented. Such processes could have included an independent review of the calculations by experts who were separate from the airplane performance group, which generated the calculations. Also, a review of the flight 111 test results by a group of independent experts within the company might have provided the perspective necessary to recognize that attempts to achieve the computed target V_2 speeds would be unproductive (given that the takeoff rotation technique developed during the flight was only able to reduce the V_2 speed to within 3 knots of the target speed). Further, as previously stated, a validation of the speeds using a physics-based dynamic analysis program or a flight (or desktop) simulation could have revealed that the target speeds were too low.[91]

Because of the inappropriate distribution of workload among G650 engineers, absence of control gates to ensure that the results of the V_{MU} testing were fully understood before the next testing phase began, and inadequate processes for validating the target takeoff speeds, the NTSB concludes that deficiencies in Gulfstream's technical planning and oversight contributed to the incorrect speeds used on the day of the accident.

Another shortcoming in Gulfstream's technical planning and oversight was the inadequate development and implementation of on-site team member roles and responsibilities. FTE1 was normally the test conductor (and, as such, coordinated with the pilots and other test team members on various matters, reviewed test card instructions, and provided speeds and trim settings), the PIC and SIC executed the takeoffs, and APG1 monitored the airspeed at 35 feet. A second flight test engineer aboard the airplane (FTE2 on the accident flight) normally monitored the airplane's fly-by-wire flight control system for known failure modes, which was a practice that had been followed throughout the field performance testing effort and was required by the company because of a temporary in-flight restriction. However, FTE2 was not familiar with the flight control system monitoring task because he had not previously participated in G650 field performance testing.

In a March 29, 2011, e-mail to his supervisor (among others), FTE1 indicated that he would also be responsible for the flight control system monitoring task and would delegate other on-board duties to FTE2. (A senior flight test pilot stated that a flight test engineer could simultaneously perform both duties but that the performance of each duty could be diminished.) Audio recorder evidence indicated that, during the flight tests on the day of the accident, FTE1

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[91] The airplane performance principal engineer stated that a dynamic program to validate the takeoff speeds was not used for the G650 because of the "upfront work" and "effort involved" to develop the program. Nevertheless, as previously noted, the NTSB believes that Gulfstream's simulation capabilities at the time of the accident (such as its integrated test facility) would likely have been sufficient for validating the takeoff speeds.

monitored the flight control system and served as the test conductor; FTE2's responsibilities were unclear because he spoke very little and appeared to be mostly passive during the tests.[92]

Resolution of the longstanding V_2 overshoot problem was critical to the success of the G650 program. As a result, the V_2 parameter was highly significant and became the focus of the test team's attention along with the takeoff techniques that were being modified during attempts to achieve the target speed. However, besides FTE1, no flight test or airplane performance engineer had been explicitly assigned the responsibility for monitoring other safety-related parameters, including maximum pitch and AOA while in ground effect.[93] Although the pitch limit was briefed on the day before the accident and was discussed by the pilots before testing began, the pitch limit was not explicitly referenced afterward by any test team member.

APG1 indicated that she was not monitoring the maximum in-ground-effect pitch because she thought that FTE1 was monitoring pitch. She stated that the airplane performance engineers in the telemetry trailer were not required to monitor specific safety parameters and that the engineers' role was to observe the testing and verify test conditions. As a result, no one in the telemetry trailer was comparing the maximum pitch while in ground effect with the briefed limit and notifying the on-board test team when the limit was reached so that the test could be discontinued.

Gulfstream's failure to assign an engineer in the telemetry trailer with the responsibility for monitoring safety-related parameters and for stopping testing if specific criteria were exceeded demonstrated a poor use of available resources, which resulted, in part, from the inadequate definition of team member roles in the company's flight test policies and procedures. If one of these engineers had been assigned the responsibility for monitoring real-time data during each test run and had thoroughly examined the data before the next test run began, the test team might have recognized that the target V_2 speeds were incompatible with the performance of the airplane and understood that further attempts to resolve the V_2 overshoot problem through variations of the rotation technique would be unproductive.[94] The NTSB concludes that, because Gulfstream did not clearly define the roles and responsibilities for on-site test team members, critical safety-related parameters were not being adequately monitored and test results were not being sufficiently examined during flight testing on the day of the accident.

2.5.2 Program Schedule

Gulfstream had a 5-year window, ending on September 28, 2011, in which to complete the activities necessary to obtain G650 type certification, in accordance with 14 CFR 21.17,

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[92] FTE2 had only a few significant verbal interactions with the test team. On three occasions, he reported the column force used during rotation. On three other occasions, he looked up speeds or provided other information at FTE1's request. On one occasion, FTE1 asked FTE2 how he was doing because he seemed quiet, and FTE2 responded that he was "just logging and checking."

[93] Although FTE3 had not explicitly been assigned the responsibility to monitor pitch, she alerted the on-board test team (immediately after test runs 6C1 and 6C3) that pitch was high during those test runs. However, her observations were dismissed by FTE1 and the PIC.

[94] The parameters that should have been evaluated to make these determinations included the airplane's acceleration, rotation rate, pitch angle, AOA, liftoff speed, and climb rate.

"Designation of Applicable Regulations."[95] The company had established an aggressive schedule to ensure the completion of G650 flight testing within this time frame,[96] but the established schedule could not be maintained because of delays with the development of airplane systems. In a July 29, 2010, letter to the vice president of the G650 program, the FAA's Atlanta Aircraft Certification Office (ACO)[97] manager asked Gulfstream to examine the impact of these delays on company testing and FAA certification efforts and "adjust the GVI schedule as necessary to allow adequate time for these activities to take place without compromises to safety or quality." In January 2011, Gulfstream provided the Atlanta ACO with a revised schedule, which the ACO's G650 project manager indicated was ambitious but not overly aggressive. However, delays continued to occur, and, by March 2011, the ACO's G650 project manager had become concerned about the schedule.[98]

During a March 25, 2011, weekly teleconference with the Atlanta ACO, Gulfstream asked if it could deviate from the planned testing approach and accomplish the TIA for stall speeds in two parts to avoid delays resulting from a setback with the development of the airplane's flight control system. In a March 31, 2011, letter to Gulfstream, the Atlanta ACO denied this request, citing a reluctance to approve too many flight test "work-arounds." The letter also stated the following:

> For some time now the FAA has expressed our concerns about the overly aggressive schedule, and for some time now you have acknowledged 'unofficially' that things are slipping; however, the company TIA schedule continues to reflect a pace that has proven to be unrealistic.

The Atlanta ACO's letter cautioned that "given the number of schedule slippages to date, and the number of company and certification tests that have yet to be performed…it would be prudent for Gulfstream to be ready in case there is a need to file for an extension of the original [type certificate] application." Gulfstream had not developed a formal response to the letter before the accident, which occurred 2 days later.

During a weekly teleconference on April 1, 2011, with the Atlanta ACO, Gulfstream presented its most recent flight test schedule, which indicated that the company expected to

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[95] If type certification had been completed within this 5-year window, Gulfstream would have been required to implement the certification and safety requirements of the Part 25 amendments that were effective at the beginning of the window. Because certification was not completed within this window, Gulfstream was responsible for incorporating the new certification and safety requirements imposed by amendments that became effective between the beginning of the previous 5-year window and the beginning of the new 5-year window.

[96] Gulfstream had publicly committed to obtaining G650 type certification by the third quarter of 2011 and delivering the first production-line airplanes to customers by the end of 2011. The G650 lead flight test engineer stated that he had expressed concern to senior managers that the schedule did not allow for contingencies and that everything would have to proceed as planned for the program to meet its certification deadline. According to the lead flight test engineer, senior managers indicated that they were willing to accept the risk.

[97] According to FAA personnel, the FAA has no formal oversight authority for a company's developmental flight tests but does have such oversight authority for certification flight tests. The Atlanta ACO, which is within the FAA's Aircraft Certification Service, was responsible for overseeing G650 certification flight tests. The Atlanta ACO held weekly teleconferences with Gulfstream to receive updates on the progress of the company's flight test program and the scheduling of certification flight tests, including field performance. At the time of the accident, the FAA had overseen certification flight tests in several areas but not field performance.

[98] The Atlanta ACO's G650 project manager was concerned that quality and safety issues could result if Gulfstream worked at the pace that would be required to meet the existing schedule.

present the field performance TIA for FAA review on April 23, 2011.[99] During a postaccident interview, the flight test engineering group head stated his belief that the April 23 deadline would not have been achievable because of the amount of field performance testing work that needed to be completed. The flight test engineering group head indicated that, although flight test personnel had been working hard to complete their work as quickly as possible, they thought the flight test schedule was unrealistic. APG1 stated that there "just seemed to be pressure to continue tests, to continue flying."

Before the accident, no senior Gulfstream official had proposed extending the certification date beyond the end of the 5-year certification window. The director of flight test believed that the schedule in place at the time of the accident was reasonable, and the vice president of the G650 program believed that the schedule was "aggressive but achievable." The director of the G650 flight sciences department anticipated that the schedule would slip, but he indicated that management had avoided extending the schedule because, if it were extended, "people would take it a little bit easier and [the project pace] would slow down a little bit." He added, "we like to keep a sense of urgency at Gulfstream to keep things moving."

Intense schedule pressure can lead to decision biases, shortcuts, and errors that negatively affect safety. Robust organizational processes can counterbalance these tendencies, reduce the likelihood of errors, and identify and correct those errors that occur. In this case, schedule pressure was not counterbalanced by robust organizational processes for technical oversight and safety management. This situation likely contributed to Gulfstream's key engineering and oversight errors and allowed other errors to propagate undetected. The company's key engineering and oversight errors that likely resulted, in part, from schedule pressure and adversely affected the safety of G650 field performance flight testing included the following:

- Gulfstream's willingness to proceed with takeoff performance testing before analysis of V_{MU} test data was completed,
- Gulfstream's development of takeoff speed schedules for Roswell II testing without adequate consideration of the V_{MU} data from Roswell I testing,
- Gulfstream's decision to experiment with pilot technique during high-risk testing rather than conduct a thorough analysis of the V_2 overshoot problem,
- FTE1's and the airplane performance principal engineer's decision to change the target pitch for flaps 10 OEI continued takeoff tests without determining the impact of the change on the takeoff speeds, and
- FTE1's last-minute addition of a pitch limit without ensuring that this limit was adequately defined on applicable test cards.

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[99] When the flight test SRB was held in October 2010, field performance flight testing was scheduled for completion in November 2010, and FAA certification flight testing was scheduled to be completed by February 2011. However, because of delays in the development of airplane systems, only one-half of the field performance tests were completed in November 2010.

In addition, the G650 team's inadequate investigation of, and willingness to accept oversimplified explanations for, the uncommanded roll events that occurred during flights 88 and 132 likely resulted, in part, from schedule pressure.

In its party submission, Gulfstream stated that schedule pressure was not a contributing factor to this accident. However, Gulfstream also stated that the company had been committed to completing an "ambitious" test schedule for the G650, which might have contributed to "a reluctance to challenge assumptions and highlight anomalous aircraft behavior during tests." However, the reluctance to challenge assumptions and highlight anomalous airplane behavior because of schedule pressure can lead to reductions in safety if well-developed organizational processes are lacking. Thus, the NTSB concludes that Gulfstream's focus on meeting the G650's planned certification date caused schedule-related pressure that was not adequately counterbalanced by robust organizational processes to prevent, identify, and correct the company's key engineering and oversight errors.

2.5.3 Safety Management Processes

A July 2008 memorandum of understanding between Gulfstream and the Atlanta ACO, as required by FAA Order 4040.26A, *Aircraft Certification Service Flight Safety Program* (dated March 23, 2001), established a "jointly agreed upon flight test risk assessment program" for evaluating and minimizing risk during FAA certification testing. According to the memorandum, Gulfstream would provide a risk assessment section in all certification flight test plans submitted to the FAA, identify tests considered high or medium risk,[100] and provide TSHA forms defining procedures for minimizing the risk associated with these tests. The FAA would then review these strategies and ensure that they were acceptable before the start of certification flight testing. The FAA attended flight test SRB meetings for the G650, but the FAA's concurrence with the proposed risk assessments and hazard mitigation strategies discussed during these meetings was not required for company developmental flight testing. However, the FAA would not issue a TIA for a particular area of testing until the agency had concurred with all proposed risk assessments.

Procedures for conducting flight test risk assessments were described in Gulfstream's *Flight Test Standard Practice Manual*, the Atlanta ACO's *Standard Operating Procedures, Flight Test Risk Management and Risk Assessment Process,* and FAA Order 4040.26A, all of which were referenced in the July 2008 memorandum of understanding. The FAA's review of Gulfstream's flight test risk assessment process determined that the company had established an adequate level of safety for FAA certification flight test programs, which implied that Gulfstream's process generally complied with the guidance referenced in the memorandum.

Although the memorandum of understanding applied only to FAA certification flight testing, Gulfstream personnel stated that the risk assessment process referenced in the memorandum was also used for company developmental flight testing. For example, the G650 project test pilot stated that Gulfstream made risk classification decisions by referencing FAA

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[100] Appendix 3 of FAA Order 4040.26A provided definitions for FAA risk hazard levels. High risk was defined as a "test or activities which present a significant risk to personnel, equipment, or property, even after all precautionary measures have been taken. This necessitates close oversight at all levels." Medium risk was defined as a "test or activities which present a greater risk to personnel, equipment, or property than normal operations and require more than routine oversight."

Order 4040.26A and reviewing classifications assigned to different tests during previous Gulfstream flight test programs. Also, the results of Gulfstream's risk assessment process for field performance testing were evaluated during the October 2010 flight test SRB meeting. In addition, flight test personnel and pilots who participated in field performance flight testing reported that flight test team members carefully reviewed the hazards and risk mitigation strategies described in the TSHAs before all high- and medium-risk tests. However, Gulfstream did not identify excessive rotation, low altitude stall, or uncommanded roll as potential hazards for OEI continued takeoff tests, even though similar events had occurred during the GIV and GV programs.

Even though Gulfstream's *Flight Test Standard Practice Manual* stated that the risk assessment process involved "an ongoing cycle of examination, description and review by a safety review board," Gulfstream lacked a well-defined, ongoing process for ensuring that risk mitigation strategies developed through the company's risk assessment process remained adequate to ensure an acceptable level of safety as G650 developmental flight testing progressed. Most notably, the two previous uncommanded roll events that occurred during flights 88 and 132 were not adequately reported or investigated. No one conducted a thorough analysis of the physics of these two events to determine that the airplane had stalled below the predicted stall AOA. Instead, the test team members involved in these events developed oversimplified, incomplete, or inaccurate explanations of cause.[101] These explanations were accepted by key personnel associated with the G650 program (including FTE1, APG1, and the principal engineer for airplane performance) without adequate supporting analysis, which likely occurred in part because of schedule-related demands.

In August 2010, the FAA issued Advisory Circular (AC) 120-92A, "Safety Management System [SMS] for Aviation Service Providers," to provide a framework for SMS development by aviation service providers. The AC described the four components of safety management: safety policy, safety risk management, safety assurance, and safety promotion.[102] At the time of the accident, the company had not developed an SMS program for its flight test operations,[103] and senior managers, including the senior vice president of programs, engineering, and test and

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[101] As previously stated, flight 88 was determined by the test team (while still on site) to have resulted from an over-rotation to 13º airplane-nose-up pitch. Flight 132 data were reviewed by FTE1 and the senior test pilot, and the event was attributed to a lateral-directional disturbance (resulting from the unavailability of the yaw damper system) because the airplane's AOA did not exceed the predicted stall AOA.

[102] According to the AC, an organization must (1) define policies, procedures, and organizational structures to accomplish its goals (safety policy); (2) have a formal system of hazard identification to control risk to acceptable levels (safety risk management); (3) ensure that the risk controls being practiced continue to achieve their intended objectives (safety assurance); and (4) promote safety as a core value with practices that support a sound safety culture (safety promotion).

[103] According to Gulfstream's vice president of flight operations, Gulfstream began developing an SMS for its flight operations department about 5 years before the accident. (The SMS initially covered demonstration flights and was subsequently expanded to cover sales and product support flights.) The Gulfstream *Flight Operations Manual* in effect at the time of the accident (dated March 31, 2010) stated that "an effective safety management system is the foundation for a successful and well-maintained flight department" and "the company and flight department are committed to taking an aggressive role in maintaining the highest level of safety as well as defining and correcting risks that could affect safety."

the vice president of the G650 program, had not appointed key safety personnel, such as a company-wide safety manager or a flight test safety officer.[104]

AC 120-92A stated that, after safety risk management has been performed and risk controls are operational, an organization must ensure, through safety assurance activities (that is, system safety and quality management processes), that these risk controls are adequate and continue to be effective. However, safety assurance activities were not a well-established and integrated part of Gulfstream's flight test safety management. Safety assurance can be accomplished by collecting the data necessary to document an organization's safety performance. Although Gulfstream had a reporting system to detect and correct design-related safety issues, Gulfstream had no formal reporting system for safety-related operational events that occurred during flight tests, such as the uncommanded roll events that occurred during flights 88 and 132.[105] Gulfstream did not have adequate policies and procedures in place so that these and other anomalous events would be formally reported and would require cross-functional root cause analysis and a possible reconvening of the flight test SRB.

Flight test personnel stated that problems occurring during flight tests were handled through direct communication with appropriate parties, and the chief flight test engineer stated that serious safety issues would likely be reported up the chain of command fairly quickly. However, the director of flight test stated that he had not been informed about the uncommanded roll event that occurred during flight 132 until a few days before the accident, and the vice president of the G650 program, the company senior vice president of programs, engineering, and test, and the G650 director of flight sciences stated that they had not been informed about either the flight 88 or flight 132 events. In addition, the Gulfstream vice president of flight operations (who co-chaired the flight test SRB) stated that he was not aware of the change to the decrement for the in-ground-effect stall AOA or the change in the stick shaker activation setting until after the accident.

Flight test personnel also stated that a meeting of the flight test SRB could be reconvened if a problem were to occur during flight testing. However, a flight test SRB meeting was not reconvened after the flight 88 uncommanded roll event because, according to Gulfstream personnel, it was fairly well understood that the event had resulted from an over-rotation of the airplane, and the PIC (the flying pilot for flight 88) had formally briefed colleagues about the change in test protocol that resulted from the event.

Similarly, no flight test SRB meeting was reconvened after the flight 132 uncommanded roll event. During postaccident interviews, Gulfstream personnel provided conflicting explanations regarding why a flight test SRB was not held to review the flight 132 event. Although FTE1 and the Gulfstream senior flight test pilot believed that the flight 132 event

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[104] Interviews with current and former company personnel indicated that Gulfstream had a chief safety officer position from 2000 to 2002. A former employee who filled this position stated that, when he left the company in 2002, the flight test program had "a pretty rigorous safety culture" with thorough procedures for risk management. The senior vice president of programs, engineering, and test stated that the position was abolished because the chief safety officer did not have enough work to do.

[105] By fully analyzing the GIV and GV uncommanded roll events (as stated in section 2.3), Gulfstream was able to effectively mitigate this risk during those programs. Because the flight 88 and flight 132 uncommanded roll events were not fully analyzed before the accident, the uncommanded roll risk was not mitigated during the G650 program.

resulted from a lateral-directional disturbance that could have been avoided with an active yaw damper system, the principal engineer for airplane performance, the manager of flight test, and the director of flight test believed that the flight 132 event was an over-rotation similar to the flight 88 event, which was presumed to be well understood. Postaccident interviews showed that, months after the accident, key Gulfstream personnel continued to misunderstand some details of flights 88 and 132, including the AOAs at which the events began.

If the uncommanded roll event on flight 132 had been properly investigated and found to have been caused by a stall of the right outboard wing, Gulfstream could have determined that the March 2011 change to the stick shaker activation threshold from 85 to 90 percent of normalized AOA did not provide enough margin to stall. (Because the flight 132 uncommanded roll event began at a normalized AOA of about 86 percent, the stick shaker did not activate.) The NTSB concludes that Gulfstream’s flight test safety program at the time of the accident was deficient because risk controls were insufficient and safety assurance activities were lacking.

2.5.4 Postaccident Actions

After the accident, Gulfstream suspended field performance testing while the company examined the circumstances of the accident. (Other developmental flight tests continued after the G650 returned to flight in late May 2011.) Field performance testing resumed in December 2011 after the company implemented corrective actions. In March 2012, Gulfstream reported that company field performance testing at ROW had been repeated and completed successfully. In June 2012, the company reported that FAA certification field performance testing had been successfully completed at ROW. Gulfstream obtained FAA type certification for the G650 on September 7, 2012.

Gulfstream issued an updated *Flight Test Standard Practice Manual* in November 2011. According to Gulfstream, the manual revisions reflected the company’s most recent processes and procedures. Also, the manual described the company’s current organizational structure and the corresponding roles and responsibilities and included a section on accident and incident reporting and procedures to expedite subsequent data reviews.

In September 2011, Gulfstream created an aviation safety officer position, which had been filled on an interim basis until a permanent selection was made in April 2012. The aviation safety officer reports directly to the president of the company. According to Gulfstream, the aviation safety officer is responsible for ensuring that safety processes have been developed and are being followed for all Gulfstream flight test and flight operations activities. Gulfstream also stated that the aviation safety officer would facilitate SMS implementation within the company’s flight operations, flight test, and engineering departments.

3. Safety Issues

3.1 Maximum Lift Coefficient in Ground Effect

As stated in section 2.3, in March 2011 FTE1 revised the decrement from the free-air stall AOA to the in-ground-effect stall AOA from 2º to 1.6º. This revision appeared to be based on his analysis of V_{MU} test results that assumed incorrectly that the maximum lift coefficient of the G650 in ground effect was the same as the airplane's maximum lift coefficient in free air. However, Gulfstream's postaccident CFD analysis indicated that the maximum lift coefficient of the G650 in ground effect was actually lower than the maximum lift coefficient in free air and found that the decrement from the free-air stall AOA to the in-ground-effect stall AOA was about 3°. Consequently, FTE1's incorrect assumption (that the maximum lift coefficient would be the same both in and out of ground effect) exacerbated the error in the predicted decrement between the free-air and in-ground-effect stall AOA. Because the maximum lift coefficient and stall AOA in ground effect were overestimated, the airplane's AOA threshold for stick shaker activation and the PLI were set too high, and the flight crew received no tactile or visual warning before the actual stall occurred.

The NTSB found that contradictory information existed in technical literature about the maximum lift coefficient for airplanes in ground effect. Some sources indicated that the maximum lift coefficient in ground effect was similar to that in free air (as apparently assumed by FTE1),[106] whereas other sources indicated that the maximum lift coefficient would be reduced in ground effect. The NTSB determined, through conversations with Gulfstream, other manufacturers, and the FAA, that the potential for the maximum lift coefficient in ground effect to be reduced might not be recognized industry-wide. Given the results of Gulfstream's CFD analysis and the findings of this accident investigation, it is clear that the maximum lift coefficient for at least some airplanes could be reduced in ground effect and that assumptions to the contrary could result in an overestimation of the stall AOA in ground effect and could increase the risk of a stall in ground effect with little or no stall warning.

The NTSB concludes that the inherent risks associated with field performance flight testing, and V_{MU} testing in particular, could be reduced if airplane manufacturers considered the potential for a lower maximum lift coefficient in ground effect when estimating the stall AOA in ground effect. Therefore, the NTSB recommends that the FAA inform domestic and foreign manufacturers of airplanes that are certified under 14 CFR Parts 23 and 25 about the circumstances of this accident and advise them to consider, when estimating an airplane's stall AOA in ground effect, the possibility that the airplane's maximum lift coefficient in ground effect could be lower than its maximum lift coefficient in free air. (Part 23, "Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes," has takeoff speed requirements that are similar to those in Part 25.)

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[106] For example, a peer-reviewed 2007 technical paper by an aerospace engineer (who was employed by a different airplane manufacturer than Gulfstream) stated, "the aircraft in ground effect possesses a similar [maximum lift coefficient] as in-flight, but the absolute AOA for stall has reduced."

3.2 Flight Test Operations Manual Guidance

Gulfstream's *Flight Test Standard Practice Manual* was not required to be enforced or updated as circumstances warranted. The company's key engineering and oversight errors that led to the accident might have been prevented if the company had (1) better designed the organizational processes used during G650 developmental flight testing, such as those used for workload distribution and sequencing of work, (2) codified those processes in a flight test standard operations manual, and (3) trained its personnel on the manual to ensure compliance with the manual's policies and procedures.

The FAA did not have any formal oversight of the policies and procedures used during Gulfstream's developmental flight testing and, as a result, could not require the use of an approved flight test operations manual during the testing. Guidance to help manufacturers develop, implement, and maintain an effective flight test operations manual would help ensure that well-developed work processes, policies, and procedures are in place for flight test operations.

In November 1994, the Society of Flight Test Engineers, the Society of Experimental Test Pilots, and the American Institute of Aeronautics and Astronautics formed a joint organization, known as the Flight Test Safety Committee, to "promote flight safety, reduce the risk of mishap, promote risk reduction management and continually improve the profession's communication and coordination."[107] To achieve this goal, the committee provided recommended flight test safety best practices on its website and maintained a computerized database containing flight test-related data collected from the industry. The committee also holds annual meetings to "provide an open forum where test safety issues can be presented, discussed and probed with other members and disciplines of the flight test community." Thus, the Flight Test Safety Committee is in an ideal position to promote and lead an effort to develop flight test standard operating policies and procedures that could be disseminated to manufacturers.

The findings of this investigation showed that Gulfstream's flight test standard operating policies and procedures were not effective in distributing workload appropriately, establishing control gates for key decision points, implementing processes for validating engineering methods, and clearly defining the roles and responsibilities for on-site test team members. As a result, the NTSB concludes that effective flight test standard operating policies and procedures that are fully implemented by manufacturers would help reduce the inherent risks associated with flight testing. Therefore, the NTSB recommends that the Flight Test Safety Committee, in collaboration with the FAA, develop and issue flight test operating guidance for manufacturers that addresses the deficiencies documented in this report regarding flight test operating policies and procedures and their implementation, and encourage manufacturers to conduct flight test operations in accordance with the guidance. The NTSB also recommends that the FAA work with the Flight Test Safety Committee to develop and issue these guidelines.

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[107] Representatives from other organizations, including the FAA and the National Aeronautics and Space Administration, are also members of the Flight Test Safety Committee. For more information about the committee, see http://www.flighttestsafety.org/, accessed July 3, 2012.

3.3 Safety Management System Guidance

As stated in section 2.5.3, adequate safety assurance processes were not incorporated into Gulfstream's flight test safety program, even with the company's development of an FAA-accepted flight test risk assessment program for certification flight testing. Safety assurance processes are important because they help ensure that an organization's existing risk controls are functioning as intended. Such processes can alert an organization that it needs to reinforce or revise its existing risk controls because of changes to an airplane system or the operating environment or the emergence of previously unrecognized hazards. Safety assurance activities might not have been integrated into Gulfstream's flight test safety program because FAA Order 4040.26A, which Gulfstream used to develop its risk assessment process, provided guidance in terms that were specific to the FAA's organizational structure, thus diminishing the usefulness of the order as a source of guidance for manufacturers to follow when developing their flight test safety programs.

In January 2012, the FAA issued Order 4040.26B, *Aircraft Certification Service Flight Test Risk Management Program*, which superseded Order 4040.26A. The FAA stated that the new version of the order had been changed to make it more consistent with the requirements of an SMS. The revised order clarified the FAA's policies and procedures about reporting safety-significant events.[108] The revised order included a sample reporting form and stated, "the primary focus of [safety-significant event] reporting is to document and disseminate information, to capture lessons learned, and to minimize the chance of another occurrence." As with the previous version, Order 4040.26B was not an ideal source of guidance for manufacturers to use in developing their flight test safety programs because the order was also structured and worded to reflect the organizational structure and function of the FAA's Aircraft Certification Service.

The Gulfstream vice president of flight operations stated that the company's SMS (which emphasized safety assurance processes, including safety reporting programs) had not been extended to the flight test department because of a lack of relevant guidance that specifically addressed flight test operations. The NTSB considered whether existing official guidance could be used by manufacturers to develop and maintain a robust flight test SMS that included adequate safety assurance processes.

The International Civil Aviation Organization's (ICAO) *Safety Management Manual* provided extensive information on safety management concepts and standards and described best practices in aviation safety management.[109] The SMS guidance in AC 120-92A was aligned with ICAO's SMS framework. Although the manual and the AC were not specific to flight test operations, these resources contained valuable information about aviation safety management that could be used by manufacturers to develop a flight test SMS. For example, AC 120-92A stated that the SMS framework was applicable to "a wide variety of types and sizes of operators" and was "designed to be scalable and allow operators to integrate safety management practices into their unique business models." Nevertheless, there would be a safety benefit to having flight

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[108] FAA Order 4040.26A defined a safety-significant event as "any ground or flight event that does not qualify as an Incident or Accident...that affects or could affect the safety of an FAA aircraft (including rental aircraft) or crewmember."

[109] International Civil Aviation Organization, *Safety Management Manual*, Document 9859-AN/474 (Montreal, Canada: ICAO, 2009).

test-specific SMS guidance, especially because many flight tests are considered high risk and existing guidance does not address the challenges associated with experimental operations.

All U.S. commercial aircraft manufacturers reference FAA Order 4040.26B because FAA certification flight testing must be conducted under the risk management program outlined in the order or under a manufacturer's risk management program that is consistent with the order.[110] As a result, the order would be a logical place for the FAA to promulgate enhanced SMS guidance for flight test operations that is tailored to the needs of manufacturers. The NTSB concludes that flight test SMS guidance specifically tailored to the needs of manufacturers would help promote the development of effective flight test safety programs. Therefore, the NTSB recommends that the Flight Test Safety Committee, in collaboration with the FAA, develop and issue flight test safety program guidelines based on best practices in aviation safety management, and encourage manufacturers to incorporate these guidelines into their flight test safety programs. The NTSB also recommends that the FAA work with the Flight Test Safety Committee to develop and issue these guidelines. The NTSB further recommends that, after the Flight Test Safety Committee has issued flight test safety program guidelines, the FAA include these guidelines in the next revision of FAA Order 4040.26, *Aircraft Certification Service Flight Test Risk Management Program*.

Gulfstream reported that, since the time of the accident, it has taken several actions to cultivate a positive organizational safety culture. The company has performed safety-related reviews and assessments, updated flight test operating procedures, and created positions for an aviation safety officer and three subordinate safety managers (in the flight test, flight operations, and engineering departments). According to Gulfstream, the aviation safety officer (who was hired in April 2012) has been tasked with identifying flight test industry best practices; facilitating SMS implementation across the company's flight test, flight operations, and engineering departments; and ensuring that safety processes are fully developed and implemented. Because this work is currently in progress, it is difficult for the NTSB to assess the adequacy of the company's flight test SMS. The successful integration of safety management principles and practices into Gulfstream's flight test operations will require continued high-level management commitment and considerable cultural change.

During the summer of 2011, Gulfstream underwent an external audit "to assess the level of safety across the flight test operation." In response to the audit, Gulfstream developed several short- and long-term action items for each major finding. For example, the audit found that a stronger company safety culture needed to be fostered, and the company responded by appointing key safety personnel and beginning to pursue the integration of SMS principles and practices into its flight test operations. (The findings of Gulfstream's external audit were consistent with the NTSB's determination that Gulfstream's safety management was deficient at the time of the accident.) Thus, external safety audits are a useful mechanism for assessing the status of an organization's safety management efforts and identifying weaknesses.

The NTSB concludes that external safety audits would help Gulfstream monitor the implementation of safety management principles and practices into its flight test operations and sustain long-term cultural change. To ensure that the SMS implementation process can be

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[110] Gulfstream's risk assessment program was consistent with FAA Order 4040.26A, and the company's procedures for assessing and mitigating risks were similar to those described in the order.

sustained between major certification programs (in case knowledge of the lessons learned from this accident fades over time),[111] the NTSB recommends that Gulfstream commission an audit by qualified independent safety experts, before the start of the next major certification flight test program, to evaluate the company's flight test SMS, with special attention given to the areas of weakness identified in this report, and address all areas of concern identified by the audit.

Finally, lessons learned from Gulfstream's efforts to implement a flight test SMS could help other manufacturers develop similar programs and could help the Flight Test Safety Committee develop flight test safety program guidelines, as requested by Safety Recommendation A-12-60. The NTSB concludes that flight test safety would be enhanced if manufacturers and flight test industry groups had knowledge of the lessons learned from Gulfstream's implementation of its flight test SMS. Therefore, the NTSB recommends that Gulfstream provide information about the lessons learned from the implementation of its flight test SMS to interested manufacturers, flight test industry groups, and other appropriate parties.

3.4 Coordination of High-Risk Flight Tests

At the time of the accident, Gulfstream had planned to conduct field performance flight tests, some of which were classified as high risk, at ROW for 3 months. During postaccident interviews, the ROW airport superintendent stated that he was aware that Gulfstream was planning flight tests at ROW and that Gulfstream would usually notify airport operations[112] of the company's planned arrival date and the expected duration of the tests.[113] ROW ARFF personnel stated that, before Gulfstream began its flight tests, one of the accident pilots briefed firefighters on the G650 airplane and provided a booklet titled *Gulfstream GVI Crash Crew Information* (dated November 1, 2010), which provided pertinent information regarding the G650 airplane for emergency responders.[114]

Gulfstream did not advise ROW airport operations or ARFF that some of the flight tests were classified as high risk or indicate when these high-risk flight tests would occur. The FAA does not require airport operators to be notified of high-risk flight tests or have ARFF readiness procedures during high-risk flight test operations. Nevertheless, a lieutenant at the ROW ARFF

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[111] Major certification programs involve a new type certificate or major derivative and utilize multiple test airplanes. Gulfstream had previously downsized its flight test department between the GIV and GV programs and between the GV and G650 programs. According to the company's former director of flight test, this practice made it "very difficult" to maintain continuity of experience. Also, as previously stated, the company appointed a chief safety officer in 2000, but that position was abolished 2 years later.

[112] Title 14 CFR Part 139, "Certification of Airports," provides the governing rules for airports with scheduled air carrier service (that is, aircraft with more than nine passenger seats). (Operations at ROW included daily air carrier service.) Airport operations personnel are responsible for the day-to-day operations at an airport and ensure compliance with the Part 139 certificate (as detailed in the airport certification manual). Airport operations personnel are also responsible for overseeing the airport emergency plan; ARFF carries out the plan's emergency response and manages its own equipment, facilities, and personnel.

[113] Other aircraft manufacturers and military organizations conducted flight test operations at ROW, but airport personnel stated that they were not aware of these flight test operations until after they began. The ROW airport certification manual did not require flight test operators to notify airport operations about flight tests. (Notification was only required if the operator planned to position telemetry or wind equipment on the airport or if flight test personnel planned to drive onto the airport.)

[114] According to the Roswell Fire Department division chief, firefighters who were not based at the ARFF station but were ARFF trained also received aircraft familiarization training on the G650 before Gulfstream began its flight tests at ROW.

station indicated that he had told Gulfstream that the fire department would be available to stand by on request (either at the standard location for emergency landings or at another predetermined location), but Gulfstream did not make such a request.

Because high-risk flight tests present a significant risk to personnel, equipment, or property, a higher probability exists (compared with other flights) that an emergency situation requiring ARFF might develop. If flight test operators notified airport operations and ARFF about upcoming high-risk flight tests, airport operations could ensure that adequate ARFF resources would be available and that actions to increase readiness, such as staging vehicles and personnel, could be taken before the high-risk tests were conducted.

The NTSB notes that three of the four occupants of the accident airplane were found out of their seats and at locations indicating that they had been able to move within the cabin after the airplane came to a stop. The cause of death for all four airplane occupants was smoke inhalation and thermal injuries. Although a reduced response time might not have changed the outcome of this accident, under different circumstances, a reduced response time could affect the outcome of an emergency situation.

The NTSB concludes that advance coordination between flight test operators and airport operations and ARFF personnel for high-risk flight tests could reduce the response time to an accident site in the event of an emergency. Therefore, the NTSB recommends that the FAA inform 14 CFR Part 139 airports that currently have (or may have in the future) flight test activity of the importance of advance coordination of high-risk flight tests with flight test operators to ensure that adequate ARFF resources are available to provide increased readiness during known high-risk flight tests.

After the accident, Gulfstream added, to its TSHAs for high-risk flight tests, the requirement that local ARFF support be “in-position” outside the fire station to allow for an expeditious response in the event of an accident. It is important that all flight test operators provide airport operators and ARFF with advance notice of high-risk flight tests for all current and future developmental aircraft programs so that coordination can occur before the flight tests. As a result, the NTSB also recommends that the Flight Test Safety Committee encourage its members to provide notice of and coordinate high-risk flight tests with airport operations and ARFF personnel.

4. Conclusions

4.1 Findings

1. The test team's focus on achieving the takeoff safety speeds for the flight tests and the lack of guidance specifying precisely when the pitch angle target and pitch limit applied during the test maneuver contributed to the team's decision to exceed the initial pitch target and the pitch angle at which a takeoff test was to be discontinued.

2. A stall on the right outboard wing produced a right rolling moment that the flight crew was not able to control, which led to the right wingtip contacting the runway and the airplane departing the runway from the right side.

3. Given the airplane's low altitude, the time-critical nature of the situation, and the ambiguous stall cues presented in the cockpit, the flight crew's response to the stall event was understandable.

4. The impact forces from the accident were survivable, but the cabin environment deteriorated quickly and became unsurvivable because of the large amount of fuel, fuel vapor, smoke, and fire entering the cabin through the breaches in the fuselage.

5. The airplane stalled at an angle of attack (AOA) that was below the in-ground-effect stall AOA predicted by Gulfstream and the AOA threshold for the activation of the stick shaker stall warning.

6. If Gulfstream had performed an in-depth aerodynamic analysis of the cause of two previous G650 uncommanded roll events, similar to the analyses performed for roll events during previous company airplane programs, the company could have recognized that the actual in-ground-effect stall angle of attack for the accident flight test was significantly lower than the company predicted.

7. Gulfstream's decision to use a takeoff speed development method from a previous airplane program was inappropriate and resulted in target takeoff safety speed values that were too low to be achieved.

8. By not performing a rigorous analysis of the root cause for the ongoing difficulties in achieving the G650 takeoff safety speeds (V_2), Gulfstream missed an opportunity to recognize and correct the low target V_2 speeds.

9. Before the accident flight, Gulfstream had sufficient information from previous flight tests to determine that the target takeoff safety speeds (V_2) could not be achieved with a certifiable takeoff rotation technique and that the V_2 speeds needed to be increased.

10. Deficiencies in Gulfstream’s technical planning and oversight contributed to the incorrect speeds used on the day of the accident.

11. Because Gulfstream did not clearly define the roles and responsibilities for on-site test team members, critical safety-related parameters were not being adequately monitored and test results were not being sufficiently examined during flight testing on the day of the accident.

12. Gulfstream’s focus on meeting the G650’s planned certification date caused schedule-related pressure that was not adequately counterbalanced by robust organizational processes to prevent, identify, and correct the company’s key engineering and oversight errors.

13. Gulfstream’s flight test safety program at the time of the accident was deficient because risk controls were insufficient and safety assurance activities were lacking.

14. The inherent risks associated with field performance flight testing, and minimum unstick speed testing in particular, could be reduced if airplane manufacturers considered the potential for a lower maximum lift coefficient in ground effect when estimating the stall angle of attack in ground effect.

15. Effective flight test standard operating policies and procedures that are fully implemented by manufacturers would help reduce the inherent risks associated with flight testing.

16. Flight test safety management system guidance specifically tailored to the needs of manufacturers would help promote the development of effective flight test safety programs.

17. External safety audits would help Gulfstream monitor the implementation of safety management principles and practices into its flight test operations and sustain long-term cultural change.

18. Flight test safety would be enhanced if manufacturers and flight test industry groups had knowledge of the lessons learned from Gulfstream’s implementation of its flight test safety management system.

19. Advance coordination between flight test operators and airport operations and aircraft rescue and firefighting personnel for high-risk flight tests could reduce the response time to an accident site in the event of an emergency.

4.2 Probable Cause

The National Transportation Safety Board determines that the probable cause of this accident was an aerodynamic stall and subsequent uncommanded roll during a one-engine-inoperative takeoff flight test, which were the result of (1) Gulfstream's failure to properly develop and validate takeoff speeds for the flight tests and recognize and correct the takeoff safety speed (V_2) error during previous G650 flight tests, (2) the G650 flight test team's persistent and increasingly aggressive attempts to achieve V_2 speeds that were erroneously low, and (3) Gulfstream's inadequate investigation of previous G650 uncommanded roll events, which indicated that the company's estimated stall angle of attack while the airplane was in ground effect was too high. Contributing to the accident was Gulfstream's failure to effectively manage the G650 flight test program by pursuing an aggressive program schedule without ensuring that the roles and responsibilities of team members had been appropriately defined and implemented, engineering processes had received sufficient technical planning and oversight, potential hazards had been fully identified, and appropriate risk controls had been implemented and were functioning as intended.

5. Recommendations

As a result of this investigation, the National Transportation Safety Board makes the following recommendations:

To the Federal Aviation Administration:

Inform domestic and foreign manufacturers of airplanes that are certified under 14 *Code of Federal Regulations* Parts 23 and 25 about the circumstances of this accident and advise them to consider, when estimating an airplane's stall angle of attack in ground effect, the possibility that the airplane's maximum lift coefficient in ground effect could be lower than its maximum lift coefficient in free air. (A-12-54)

Work with the Flight Test Safety Committee to develop and issue detailed flight test operating guidance for manufacturers that addresses the deficiencies documented in this report regarding flight test operating policies and procedures and their implementation. (A-12-55)

Work with the Flight Test Safety Committee to develop and issue flight test safety program guidelines based on best practices in aviation safety management. (A-12-56)

After the Flight Test Safety Committee has issued flight test safety program guidelines, include these guidelines in the next revision of Federal Aviation Administration Order 4040.26, *Aircraft Certification Service Flight Test Risk Management Program*. (A-12-57)

Inform 14 *Code of Federal Regulations* Part 139 airports that currently have (or may have in the future) flight test activity of the importance of advance coordination of high-risk flight tests with flight test operators to ensure that adequate aircraft rescue and firefighting resources are available to provide increased readiness during known high-risk flight tests. (A-12-58)

To the Flight Test Safety Committee:

In collaboration with the Federal Aviation Administration, develop and issue flight test operating guidance for manufacturers that addresses the deficiencies documented in this report regarding flight test operating policies and procedures and their implementation, and encourage manufacturers to conduct flight test operations in accordance with the guidance. (A-12-59)

In collaboration with the Federal Aviation Administration, develop and issue flight test safety program guidelines based on best practices in aviation safety management, and encourage manufacturers to incorporate these guidelines into their flight test safety programs. (A-12-60)

Encourage members to provide notice of and coordinate high-risk flight tests with airport operations and aircraft rescue and firefighting personnel. (A-12-61)

To Gulfstream Aerospace Corporation:

Commission an audit by qualified independent safety experts, before the start of the next major certification flight test program, to evaluate the company's flight test safety management system, with special attention given to the areas of weakness identified in this report, and address all areas of concern identified by the audit. (A-12-62)

Provide information about the lessons learned from the implementation of its flight test safety management system to interested manufacturers, flight test industry groups, and other appropriate parties. (A-12-63)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

DEBORAH A.P. HERSMAN
Chairman

ROBERT L. SUMWALT
Member

MARK R. ROSEKIND
Member

EARL F. WEENER
Member

Vice Chairman **CHRISTOPHER A. HART** did not participate.

Adopted: October 10, 2012

6. Appendixes

Appendix A: On-board Test Team Information

The Pilot-in-Command

The pilot-in-command (PIC), age 64, received a Federal Aviation Administration (FAA) commercial pilot certificate with airplane single- and multiengine land and Boeing 707 (visual flight rules only) ratings in April 1981. The PIC's application for this certificate indicated his flight time as a military pilot, which included 1,560 hours as PIC and 600 hours as second-in-command (SIC). In January 1991, the PIC was issued an airline transport pilot certificate with a Learjet rating. Between October 1997 and October 1998, the PIC added Gulfstream GV, Boeing 707 and 720 (visual flight rules only), and G-1159 (GII/GIII) ratings to his airline transport pilot certificate. The PIC's most recent FAA first-class airman medical certificate was issued on January 18, 2011.

In August 1997, the PIC began working for Gulfstream as an experimental test pilot. He was the project pilot for several flight test programs and conducted several field performance tests. The PIC also conducted field performance certification testing on the GV-SP, which included minimum unstick speed tests and one-engine-inoperative continued takeoff tests. Before his employment with Gulfstream, the PIC attended the U.S. Air Force Test Pilot School (1977 to 1981), graduating with distinction; held various flight test-related positions in the U.S. Air Force (1981 to 1989); was a DC-9 first officer for a Part 121 air carrier (February to October 1990); and worked for Northrop Grumman as a senior engineering test pilot and a chief test pilot (October 1990 to August 1997).

Gulfstream records indicated that, at the time of the accident, the PIC had accumulated 11,237 hours total flight time, with 263 hours total G650 flying time and 160 hours total G650 PIC time. The records also showed that the PIC had flown 117, 63, 39, and 21 hours in the 90, 60, 30, and 7 days preceding the accident. FAA records indicated no accidents, incidents, or enforcement actions for the PIC.

The Second-in-Command

The SIC, age 51, received an FAA commercial pilot certificate with airplane single- and multiengine land ratings in July 1990 based on his military flight time. In November 2006, the SIC was issued an airline transport pilot certificate with a Boeing 737 rating. Between August 2007 and December 2009, the SIC added an IAI-1125/G100 rating and a GV rating to his airline transport pilot certificate. His most recent FAA first-class airman medical certificate was dated October 12, 2010.

In July 2007, the SIC began working for Gulfstream as a captain in the airborne product support department. In April 2010, the SIC was reassigned to the experimental flight test department. Before his employment with Gulfstream, the SIC was a test pilot for the U.S. Navy (January 2000 to August 2002); a program manager for the U.S. Joint Advanced Tactical Missile Systems and AIM-9X programs (September 2002 to March 2004); and an officer-in-charge at

Cecil Field for the Defense Contract Management Agency, where he conducted functional check flights on F-18/A-F airplanes (March 2004 to June 2007).

Gulfstream records indicated that, at the time of the accident, the SIC had accumulated 3,940 hours total flight time, with 140 hours total G650 flying time and 78 hours total G650 PIC time. The records also showed that the SIC had flown 89, 72, 44, and 2 hours in the 90, 60, 30, and 7 days preceding the accident. FAA records indicated no accidents, incidents, or enforcement actions for the SIC.

The First Flight Test Engineer

The first flight test engineer (FTE1), age 48, was the lead flight test engineer. In June 2009, FTE1 began work at Gulfstream as a senior technical specialist within the flight test engineering department. He conducted aerodynamic performance tests and led the G650 takeoff performance test program. On October 1, 2010, FTE1 became a Gulfstream flight analyst designated engineering representative.[115] Before his employment with Gulfstream, FTE1 worked for McDonnell Douglas as a flight test and performance engineer on the C-17 program (1987 to 1995), Lockheed Martin Aeronautical Systems Company as a senior specialist in flight test engineering for the C-130J program (1995 to 1999), Bombardier Aerospace Flight Test Center as the flight sciences section chief (1999 to 2002), and Lockheed Martin as a senior specialist in flight test operations for the F-16 program (2002 to 2009).

The Second Flight Test Engineer

The second flight test engineer (FTE2), age 47, was responsible for G650 airspeed calibration testing. (As stated in section 2.1, the day of the accident was the first time that FTE2 had participated in G650 field performance testing; he was filling in for another flight test engineer who was unable to make the trip because of a scheduling conflict.) In November 2006, FTE2 began working for Gulfstream as a senior production test pilot for airworthiness on G150 and G200 airplanes. In April 2009, FTE2 became a flight test engineer for the G650 test program. Before his employment with Gulfstream, FTE2 worked for Lockheed Martin (2004 to 2006), Atlantic Southeast Airlines as a first officer and then captain on the CRJ-200 and a first officer on the EMB-120 (2000 to 2004), Lockheed Martin as a contract flight test engineer for the C-130J and C-5M test programs (1997 to 2000), Gulfstream as a contract flight test engineer for the GV certification program (1996 to 1997), FAA as a contract project engineer (1994 to 1996), and Douglas Aircraft Company where he performed tests involving aircraft performance and flying qualities for the T-45A and MD-11 airplanes (1988 to 1993). In addition, FTE2 served in the U.S. Army Reserve as a CH-47D and UH-1H helicopter pilot (1983 to 1997).

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[115] Designated engineering representatives are appointed by FAA aircraft certification offices to represent the agency in examining, inspecting, and testing aircraft for the purpose of issuing aircraft certificates.

Appendix B: Cockpit Voice Recorder Transcript

The following is a partial transcript of the Universal cockpit voice recorder, serial number 202, installed on an experimental Gulfstream Aerospace Corporation GVI (G650), N652GD, which crashed during takeoff in Roswell, New Mexico, on April 2, 2011. The recording started at 0731:25 and ended at 0934:10. The transcript begins at 0923:43, before test runs 7A1 and 7A2 were conducted. (The accident occurred during test run 7A2.)

LEGEND

CAM	Cockpit area microphone voice or sound source
HOT	Flight crew audio panel voice or sound source
RDO	Radio transmissions from N652GD
TM	Radio transmission from the telemetry trailer
TWR	Radio transmission from the Roswell airport tower controller
-1	Voice identified as the Pilot
-2	Voice identified as the Co-pilot
-3	Voice identified as the Flight test engineer
-?	Voice unidentified
*****	Unintelligible word
#	Expletive
@	Non-pertinent word
( )	Questionable insertion
[ ]	Editorial insertion

Note 1: Times are expressed in Mountain Daylight Time (MDT).

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.

CVR Quality Rating Scale

The levels of recording quality are characterized by the following traits of the cockpit voice recorder information:

Excellent Quality	Virtually all of the crew conversations could be accurately and easily understood. The transcript that was developed may indicate only one or two words that were not intelligible. Any loss in the transcript is usually attributed to simultaneous cockpit/radio transmissions that obscure each other.
Good Quality	Most of the crew conversations could be accurately and easily understood. The transcript that was developed may indicate several words or phrases that were not intelligible. Any loss in the transcript can be attributed to minor technical deficiencies or momentary dropouts in the recording system or to a large number of simultaneous cockpit/radio transmissions that obscure each other.
Fair Quality	The majority of the crew conversations were intelligible. The transcript that was developed may indicate passages where conversations were unintelligible or fragmented. This type of recording is usually caused by cockpit noise that obscures portions of the voice signals or by a minor electrical or mechanical failure of the CVR system that distorts or obscures the audio information.
Poor Quality	Extraordinary means had to be used to make some of the crew conversations intelligible. The transcript that was developed may indicate fragmented phrases and conversations and may indicate extensive passages where conversations were missing or unintelligible. This type of recording is usually caused by a combination of a high cockpit noise level with a low voice signal (poor signal-to-noise ratio) or by a mechanical or electrical failure of the CVR system that severely distorts or obscures the audio information.
Unusable	Crew conversations may be discerned, but neither ordinary nor extraordinary means made it possible to develop a meaningful transcript of the conversations. This type of recording is usually caused by an almost total mechanical or electrical failure of the CVR system.

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
07:31:25.2	[start of recording]		
Start of Transcript			
		09:23:43.5 **TWR**	Gulftest three one ah one eighty approved wind one seven zero at seven runway two one right seventy correction ah right ninety left two seventy approved cleared for takeoff.
		09:23:55.5 **RDO-2**	cleared for takeoff on two one with the teardrop Gulftest three one.
09:23:59.8 **HOT-3**	okay this time we're gonna be doin' a the (card) seven ah Alpha which is the max takeoff power to ah idle on the right engine.		
09:24:03.1 **HOT-2**	card seven.		
09:24:03.4 **HOT-?**	one hundred.		
09:24:04.0 **HOT-1**	engine out, engine out?		
09:24:06.0 **HOT-2**	right?		
09:24:11.5 **HOT-3**	at ah V-1 minus twenty so.		
09:24:12.5 **HOT-1**	(do) we use ah-		
09:24:14.6 **HOT-1**	let's just use a hundred knots for that that's just V-1 minus twenty we just round it off five and so a hundred knots will be (V-E-F).		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
09:24:15.9 **HOT-2**	okay.		
09:24:18.3 **HOT-?**	* * * hundred * * one twenty eight, one thirty six rotate will be one trims are the same.		
09:24:19.9 **HOT**	on runway two one [electronic voice].		
09:24:24.6 **HOT-3**	trims (is) eight point oh.		
09:24:27.4 **HOT-1**	trims are the same.		
09:24:28.7 **HOT-2**	this is slower accel- just call it right at the number?		
09:24:30.6 **HOT-3**	yeah.		
09:24:32.0 **HOT-3**	yeah that's all- * good.		
09:24:33.8 **HOT-1**	let's do that.		
09:24:35.1 **HOT-2**	so rotate's one twenty eight's the call.		
09:24:37.9 **HOT-3**	you're lookin' for one thirty six *.		
09:24:38.3 **HOT-1**	card seven.		
09:24:38.9 **HOT-2**	airspeed one thirty six we're settin' in there.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
09:24:42.7 **HOT-1**	thirty six is V-2.		
09:24:43.8 **HOT-2**	six.		
09:24:45.6 **HOT-2**	speeds spoilers armed.		
09:24:47.7 **HOT-1**	and ah let’s see your engine cut * is ah * is about one hundred nice round number.		
09:24:52.6 **HOT-2**	flaps are ten. 's good.		
09:24:54.7 **HOT-2**	still want the trim at eight correct?		
09:24:56.6 **HOT-3**	that's correct.		
09:24:56.9 **HOT-1**	yeah.		
09:24:57.8 **HOT-2**	set, this is M-T-O.		
09:24:59.7 **HOT-1**	fuel remaining we got thirty two seven.		
09:25:02.1 **HOT-1**	(we're) eighty eight point two now.		
09:25:04.8 **HOT-2**	so we're doing the M-T-O correct, seven Alpha?		

TIME and **SOURCE**	**INTRA-COCKPIT COMMUNICATION CONTENT**	TIME and **SOURCE**	**AIR-GROUND COMMUNICATION CONTENT**
09:25:07.0 **HOT-3**	that's correct seven Alpha we I don't have a pull-back for the other ones.		
09:25:10.5 **HOT-2**	okay.		
09:25:11.1 **HOT-3**	roger *.		
09:25:11.7 **HOT-1**	M-T-O to throttle chop right, okay.		
09:25:13.4 **HOT-2**	yup.		
09:25:14.0 **HOT-1**	okay.		
09:25:15.2 **HOT-3**	get this one good I'll give you a banana.		
09:25:15.2 **HOT-1**	* *.		
09:25:17.1 **HOT**	[sound of laughter].		
09:25:17.3 **HOT-1**	I already have one.		
09:25:20.1 **HOT-1**	a banana all right.		
09:25:21.7 **HOT-1**	okay you're gonna you're gonna get that at one one hundred * * this here and then give me a little bit of a lead on the rotate.		

TIME and SOURCE	**INTRA-COCKPIT COMMUNICATION CONTENT**	**TIME and SOURCE**	**AIR-GROUND COMMUNICATION CONTENT**
09:25:24.8 **HOT-2**	a hundred one twenty eight, and I have one thirty six.		
09:25:29.8 **HOT-2**	when you're targeting nine on the pitch just a pause during liftoff.		
09:25:31.0 **HOT-1**	yeah actually no lead on the V-R just tell me V-R * cause it's more (anemic). all right you ready? okay configuration's good there we go.		
09:25:44.9 **HOT-1**	okay we're cleared?		
09:25:45.8 **HOT-2**	power's set we are cleared.		
09:25:47.3 **HOT-1**	you guys ready?		
09:25:48.5 **HOT-3**	ah ready in the back.		
09:25:49.0 **HOT-1**	okay brake release twenty five fifty here we go.		
09:25:49.6 **HOT-3**	ready.		
09:25:55.3 **HOT-2**	power's set.		
09:25:58.2 **HOT-2**	airspeeds alive.		
09:25:58.7 **HOT-1**	okay my yoke.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
09:26:05.1 **HOT-2**	eighty knots.		
09:26:05.9 **HOT-1**	okay.		
09:26:10.5 **HOT-2**	right throttle's back.		
09:26:19.5 **HOT-2**	stand by rotate, ah.		
09:26:25.1 **HOT-1**	(straight)?		
09:26:31.4 **HOT-2**	if the brake fails (stop) we're gonna have to recycle the circuit breakers.		
09:26:34.8 **HOT-2**	still climbing target one thirty six.		
09:26:37.3 **HOT-3**	'kay check the trim for me at ah V-2?		
09:26:43.5 **HOT-1**	* still on the ground is that why it didn't want to come up or what?		
09:26:45.5 **HOT-2**	yeah yeah it took that long.		
09:26:46.7 **HOT-1**	oh it did okay there's ah trim is ah trim is good.		
09:26:51.2 **HOT-3**	okay.		

TIME and SOURCE	**INTRA-COCKPIT COMMUNICATION CONTENT**	**TIME and SOURCE**	**AIR-GROUND COMMUNICATION CONTENT**
09:26:51.7 **HOT-1**	ah think that's fine I mean I I'm within a few knots of it I mean it's less that ah probably less than ten pounds of pull there it is, it's about fifteen degrees.		
09:26:59.4 **HOT-2**	all right.		
09:27:59.8 **HOT-1**	I think we're good * gear's comin' up.		
09:27:00.1 **HOT**	[sound similar to altitude pre-selector warning tone].		
09:27:02.2 **HOT-?**	okay.		
09:27:02.4 **HOT-3**	test point's done?		
09:27:03.2 **HOT-2**	we gotta cycle the circuit breakers.		
09:27:05.2 **HOT-1**	on the brake by wire yeah that's on the overhead.		
09:27:08.4 **HOT-2**	'kay.		
09:27:14.4 **HOT-2**	pull, one two three in. brake by wire failure is gone.		
09:27:24.3 **HOT-1**	it's rescinded.		
09:27:24.9 **HOT-2**	* good.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
09:27:26.8 **HOT-1**	I'll get below one sixty we'll get the flaps they seem to like that better for some reason.		
09:27:37.3 **HOT-1**	okay flaps twenty.		
09:27:38.4 **HOT-2**	okay twenty comin'.		
09:27:50.9 **HOT-1**	gear down landing checklist.		
09:27:53.2 **HOT-2**	gear's comin'.		
09:28:02.7 **HOT-2**	three down 'n locked flaps are twenty ground spoilers armed.		
09:28:05.0 **HOT**	[sound of single chime].		
09:28:06.6 **HOT-2**	nose-wheel steering is on.		
09:28:07.6 **HOT-1**	it's on still on.		
09:28:09.3 **HOT-2**	brakes are good.		
09:28:11.2 **HOT-2**	no CAS * messages are inhibit.		
09:28:11.6 **HOT**	[sound similar to altitude pre-selector warning tone].		
09:28:14.2 **HOT-2**	just flaps to go.		

TIME and SOURCE	**INTRA-COCKPIT COMMUNICATION CONTENT**	**TIME and SOURCE**	**AIR-GROUND COMMUNICATION CONTENT**
09:28:15.3 **HOT-1**	roger that.		
09:28:23.1 **HOT-1**	okay landing flaps.		
09:28:24.3 **HOT-2**	okay comin'.		
09:28:29.4 **HOT-2**	*.		
09:28:34.0 **HOT-1**	they're not moving?		
09:28:35.6 **HOT-2**	well the lever's lifting up but it's not comin' down.		
09:28:39.1 **HOT-2**	looks like it's.		
09:28:41.8 **HOT-2**	* * nice handle isn't it.		
09:28:42.2 **HOT-1**	yeah * got ah got a bad flap lever. *.		
		09:28:44.2 **TWR**	Gulftest three one wind one niner zero at seven runway three cleared to land.
09:28:45.8 **HOT-?**	*.		
		09:28:49.6 **RDO-2**	cleared to land runway three Gulftest three one.
09:28:52.5 **HOT-2**	all right flaps in transit.		

TIME and SOURCE	**INTRA-COCKPIT COMMUNICATION CONTENT**	**TIME and SOURCE**	**AIR-GROUND COMMUNICATION CONTENT**
09:28:53.9 **HOT-1**	they movin' now?		
09:28:54.6 **HOT-2**	yup.		
09:28:55.2 **HOT-1**	what do you think it was?		
09:28:56.6 **HOT-2**	I don't know. just didn't feel- just *. yeah.		
09:28:57.2 **HOT-1**	little ah W-D forty of something. well we di- that's an issue that's an issue on some of the airplanes. not sure we're real fond of that flap lever.		
09:29:05.9 **HOT-2**	(ground) flaps spoilers we're cleared to land.		
09:29:09.3 **HOT-1**	cleared to land.		
09:29:16.5 **HOT-2**	still a little heavy.		
09:29:18.6 **HOT-1**	yup. roger that.		
09:29:20.7 **HOT-1**	little quartering tailwind.		
09:29:21.2 **HOT**	minimums [electronic voice].		
09:29:23.2 **HOT**	approaching zero three [electronic voice].		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
09:29:28.2 **HOT-1**	what are you guys showin' for winds.		
09:29:29.8 **HOT**	three hundred [electronic voice].		
09:29:31.0 **HOT-3**	four knots at ah one fifty four.		
09:29:32.9 **HOT-1**	okay. that's not bad.		
09:29:36.6 **HOT**	two hundred [electronic voice].		
09:29:42.7 **HOT**	one hundred [electronic voice].		
09:29:45.8 **HOT**	fifty [electronic voice].		
09:29:46.9 **HOT**	forty [electronic voice].		
09:29:48.1 **HOT**	thirty [electronic voice].		
09:29:49.2 **HOT**	twenty [electronic voice].		
09:29:50.6 **HOT**	ten [electronic voice].		
09:29:56.4 **HOT-2**	good spoilers.		
09:29:58.9 **HOT-2**	there's one thirty.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
09:29:59.4 **HOT-1**	one thirty. okay.		
09:30:01.8 **HOT-2**	good, good T-R's.		
09:30:16.3 **HOT-2**	seventy knots.		
09:30:18.6 **HOT**	six thousand remaining [electronic voice].		
09:30:26.5 **HOT-2**	so what y'all wanna do next.		
09:30:27.7 **HOT**	five thousand remaining [electronic voice].		
09:30:28.6 **HOT-3**	well. what did they think of that run in the trailer?		
09:30:32.9 **HOT-3**	we were a little fast at V-2 but ah.		
09:30:35.2 **HOT-1**	well we can do another one and just less of a pause we just almost a continual maneuver then.		
09:30:37.3 **HOT-?**	less of a pause.		
09:30:37.4 **HOT**	four thousand remaining [electronic voice].		
09:30:41.0 **HOT-1**	yep I can do that. target nine and just keep going I'm mean its ah.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
		09:30:41.9 **TM**	standby.
09:30:46.1 **HOT-2**	yeah.		
09:30:46.6 **HOT-1**	I don't know how else we're gonna do it.		
09:30:46.9 **HOT-3**	seemed like we're kinda hangin' there for a little bit.		
09:30:48.5 **HOT**	three thousand remaining [electronic voice].		
09:30:49.1 **HOT-1**	well we we're pausing 'cause we're trying to do this capture and I think we're getting ah too focused on that. yeah I.		
09:30:53.5 **HOT-3**	wrapped on that.		
09:30:55.9 **HOT-1**	I think it's a target and then ah because if you have a real engine failure the guys aren't gonna be lookin' at nine degrees they're gonna be looking at trying to get V-2 they're not payin' any attention to that. so, what I think.		
09:31:01.6 **HOT**	two thousand remaining [electronic voice].		
		09:31:04.3 **RDO-2**	and tower Gulftest three one like to do a one eighty at the end and takeoff on two one teardrop return.
09:31:07.9 **HOT-1**	it's an abnormal.		

TIME and SOURCE	**INTRA-COCKPIT COMMUNICATION CONTENT**	**TIME and SOURCE**	**AIR-GROUND COMMUNICATION CONTENT**
		09:31:09.0 **TM**	* (target) * (V-2) *.
09:31:09.1 **HOT-2**	yeah.		
		09:31:11.0 **TWR**	* three one one eighty approved runway two one right ninety left two seventy approved cleared for takeoff wind one seven zero at niner.
		09:31:19.6 **RDO-2**	* approved cleared for takeoff runway two one Gulftest thirty one.
09:31:23.3 **HOT-2**	all right flaps comin' back up.		
09:31:26.3 **HOT-2**	run your trim up to eight.		
09:31:30.7 **HOT-3**	eighty seven so.		
09:31:35.0 **HOT-1**	eight still good?		
09:31:35.2 **HOT-2**	go with the same V-speeds?		
09:31:36.2 **HOT-3**	one twenty five one twenty seven one thirty five so a knot off.		
09:31:40.3 **HOT-2**	okay.		
09:31:41.0 **HOT**	one hundred remaining [electronic voice].		

TIME and SOURCE	**INTRA-COCKPIT COMMUNICATION CONTENT**	**TIME and SOURCE**	**AIR-GROUND COMMUNICATION CONTENT**
09:31:44.7 **HOT-2**	twenty seven.		
09:31:49.0 **HOT-2**	one thirty five.		
09:31:50.4 **HOT-1**	one thirty five.		
09:31:51.1 **HOT-1**	why don't you set that for me. yup.		
09:31:52.0 **HOT-2**	one thirty five there.		
09:31:55.5 **HOT-2**	* three flaps are ten (ground) spoilers are armed nose-wheel steering hydraulics.		
09:31:59.0 **HOT-3**	trim is eight.		
		09:32:00.5 **TM**	winds are starting to pick up.
09:32:02.7 **HOT-1**	yeah wha- what ya got now @ for winds?		
09:32:06.1 **HOT**	on runway two one [electronic voice].		
		09:32:07.2 **TM**	one five six at five right now but I've seen it up to eight.
09:32:11.6 **HOT-1**	oh really? okay I think we're still okay with where we're at.		

TIME and **SOURCE**	**INTRA-COCKPIT COMMUNICATION** **CONTENT**	TIME and **SOURCE**	**AIR-GROUND COMMUNICATION** **CONTENT**
09:32:16.5 **HOT-2**	yeah the airspeed on that one you could you could tell it really paused it paused like it was kinda rollin' like it had a couple seconds couple seconds then it just jumped. it just like went.		
09:32:22.2 **HOT-3**	yeah yeah boom.		
09:32:26.7 **HOT-3**	yeah I think this is probably the last takeoff then.		
09:32:28.8 **HOT-1**	right okay.		
09:32:30.1 **HOT-3**	and then we'll eh so you could start rounding the fuel truck up.		
09:32:35.2 **HOT-2**	this is seven-A-two?		
09:32:37.1 **HOT-3**	yeah.		
09:32:37.5 **HOT-2**	seven Alpha two.		
09:32:38.7 **HOT-1**	did you guys hear that back there we'll go ahead and think about the fuel truck. here I'll give 'em a call on mobile.		
		09:32:45.1 **RDO-1**	and Gulftest three one ah mobile looks like ah we're gonna do another run and we'll be ah looking for the fuel truck.
09:32:54.7 **HOT-1**	don't know if they can see us down there or not, all right guys ready. same deal we got ten we got eight.		

TIME and SOURCE	**INTRA-COCKPIT COMMUNICATION CONTENT**	**TIME and SOURCE**	**AIR-GROUND COMMUNICATION CONTENT**
09:32:57.8 **HOT-?**	yup.		
09:32:58.4 **HOT-?**	yeah.		
09:33:00.9 **HOT-2**	okay cleared for takeoff.		
09:33:02.3 **HOT-1**	here we go.		
09:33:07.8 **HOT-1**	a ah it's gonna be card seven and your gonna have that one at hundred knots.		
09:33:11.4 **HOT-2**	seven * two chop at a hundred. one twenty seven rotate one thirty five speed.		
09:33:13.7 **HOT-1**	you guys ready?		
09:33:15.4 **HOT-1**	okay and we're cleared right?		
09:33:16.3 **HOT-2**	yes sir.		
09:33:16.9 **HOT-1**	okay thirty three seventeen is brake release.		
09:33:22.2 **HOT-2**	power set.		
09:33:25.5 **HOT-1**	airspeed's alive I got the yoke.		

TIME and SOURCE	**INTRA-COCKPIT COMMUNICATION CONTENT**	**TIME and SOURCE**	**AIR-GROUND COMMUNICATION CONTENT**
09:33:27.0 **HOT-2**	'kay.		
09:33:32.3 **HOT-2**	eighty knots.		
09:33:37.8 **HOT-2**	chop.		
09:33:41.4 **HOT**	[sound of bump].		
09:33:45.7 **HOT-2**	standby, rotate.		
09:33:50.8 **HOT-1**	* (going on).		
09:33:52.1 **HOT-2**	oh whoa whoa whoa whoa.		
09:33:52.8 **HOT-1**	whoa whoa.		
09:33:52.8 **CAM**	[sound of increased background noise].		
09:33:53.6 **HOT**	bank angle, bank angle [electronic voice].		
09:33:54.3 **HOT-1**	power power power.		
09:33:55.2 **HOT-2**	power power power's up.		
09:33:56.6 **HOT-1**	power power power.		

TIME and SOURCE	**INTRA-COCKPIT COMMUNICATION CONTENT**	**TIME and SOURCE**	**AIR-GROUND COMMUNICATION CONTENT**
09:33:57.4 **HOT-2**	no no no no. *.		
09:33:58.5 **HOT**	bank angle, bank angle [electronic voice].		
09:34:00.0 **HOT-1**	ah sorry guys.		
09:34:02.4 **HOT**	[sound similar to triple chime alarm].		
09:34:04.7 **HOT-?**	* * *.		

End of Transcript

09:34:10.3 [end of recording]