G650 Flight Test Accident
Gulfstream Party Submission

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ACRONYMS AND ABBREVIATIONS

AEO	all engines operating
AFFF	aqueous film-forming foam
AFM	airplane flight manual
AGL	above ground level
AOA	angle of attack
AR	authorized representative
ARFF	aircraft rescue and firefighting
ASRS	Aviation Safety Reporting System
ATP	airline transport pilot
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
CG	center of gravity
C_L	coefficient of lift
COS	Continued Operational Safety
CTO	continued takeoff
CVR	cockpit voice recorder
DER	designated engineering representative
DGPS	differential global positioning system
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FCC	flight control computer
FCS	flight control system
FDR	flight data recorder
FN	net thrust, lbs
FPV	flight path vector
FTE	flight test engineer
FTSRB	Flight Test Safety Review Board
IGE	in ground effect
ISRT	Independent Safety Review and Audit Team
KCAS	knots calibrated airspeed
KE	kinetic energy
KEAS	knots equivalent airspeed

KIAS	knots indicated airspeed
KTS	knots
LWD	left wing down
MAC	wing Mean Aerodynamic Chord
MLG	main landing gear
MSL	mean sea level
MTOW	maximum takeoff weight
N1	engine fan speed
NAOA	normalized angle of attack
NLG	nose landing gear
NTSB	National Transportation Safety Board
NWS	nose wheel steering
OEI	one engine inoperative
PIC	Pilot-in-Command
PLA	power lever angle
PLI	pitch limit indicator
ROC	rate of climb
RTO	rejected takeoff
RWD	right wing down
SIC	Second-in-Command
SMS	safety management system
SOP	standard operating procedure
TC	type certificate
TED	trailing edge down
TEL	trailing edge left
TER	trailing edge right
TEU	trailing edge up
TM	telemetry
TSHA	Test Safety Hazard Analysis
TR	thrust reverser
V_1	takeoff decision speed
V_2	takeoff safety speed
V_{LO}	liftoff speed

V_{MCA}	minimum control speed, air
V_{MCG}	minimum control speed, ground
V_{MU}	minimum unstick speed
V_R	rotation speed
V_{S1G}	one-G stall speed
V_{SR}	reference stall speed
WOW	weight on wheels

1 INTRODUCTION

On April 2, 2011, about 0934 mountain daylight time, a Gulfstream GVI (G650) airplane, FAA Registration N652GD, crashed during takeoff at Roswell International Air Center Airport (ROW), Roswell, New Mexico. The aircraft was destroyed by post-crash fire. The two flight test pilots and the two flight test engineers on board were fatally injured. Gulfstream operated the aircraft as one of five G650 flight test aircraft under a FAA experimental certificate. The accident flight, designated by Gulfstream as Flight 153,[1] was a company developmental test flight, the purpose of which was to evaluate aircraft field performance during continued takeoff operations. At the time of the accident the aircraft was performing a one engine inoperative (OEI) continued takeoff (CTO) with its flaps deflected to 10 degrees, an alternate flap position used for high altitude/high temperature operations.

The aircraft experienced an unexpected aerodynamic stall of the right wing during the takeoff maneuver while in ground effect (IGE). After impact, collisions with obstacles on the ground caused a severe fire.

Gulfstream accepts full responsibility for the accident. Developmental flight test is inherently risky, but risks can and should be appropriately mitigated. The causal and contributing factors described below are human errors that are best understood within the context of each individual's duties at Gulfstream, and Gulfstream's obligations to provide appropriate levels of support. As such, all actions leading to the accident are Gulfstream's actions.

Gulfstream believes the following were the causal factors[2] leading to the accident:

- The stall angle of attack in ground effect and the maximum coefficient of lift (C_{LMAX}) in ground effect were overestimated.
- The takeoff speed schedule was not properly developed or verified, resulting in an unachievable test point for the accident run.
- Gulfstream's internal analysis, review and approval processes did not identify these two errors prior to field performance flight testing.
- Two prior IGE roll-off events in the G650 field performance program and other flight test anomalies arising from these improper speed schedules were not widely reviewed or properly understood.
- The Pitch Limit Indicator (PLI) and stick shaker settings did not provide adequate margin to stall in ground effect.
- The flight test team's focus on achieving speed targets diminished awareness of the aircraft's unexpected behavior (which, if recognized and addressed, could have called into question the underlying speed schedules).

[1] Gulfstream tracks test flight activity by "flight" number within each specific aircraft developmental flight test program, and tracks discrete takeoffs within a flight as "runs" and by run number.
[2] Gulfstream defines a "causal factor" as any action, behavior, omission, or deficiency that if corrected, eliminated, or avoided probably would have prevented the accident.

- The test procedure and pitch limits were insufficiently precise as to the timing of pitch adjustments. This allowed the flight test team to modify takeoff techniques in "real time" during testing, including during Flight 153, without thoroughly analyzing the risks of the new techniques or agreeing on mitigating responses to those risks.

Gulfstream also believes the following were contributing factors[3] to the accident:

- The Test Safety Hazard Analysis (TSHA) for OEI CTO testing did not expressly identify low altitude stall and roll-off as potential hazards with appropriate corrective actions, and did not specifically define abort criteria and response.
- The unexpected roll angle excursion may not have been initially detected and was not fully countered by the crew until just prior to initial wingtip strike. Reduction in angle-of-attack (to break the stall and restore lateral control power) was insufficient to safely fly the aircraft away, and the crew elected not to abort the takeoff (which may have been a viable option).
- The failure to reduce power after exiting the runway may have exacerbated the collisions that caused the fire.
- Turbulent air during takeoff caused the airspeed to be unsteady, which likely caused the pilot flying some difficulty achieving the target takeoff speeds.

Gulfstream concluded the following regarding the loss of the aircraft crew:

- The crew members survived initial impact.
- The aircraft fuel tanks were ruptured after the aircraft left the runway / taxiway and impacted structures on the ground, fueling a severe fire.
- The smoke, fire and extreme temperatures in the cabin overcame the crew almost immediately after they attempted to leave their seats and prior to reaching any viable emergency exit.

Following the accident, Gulfstream has conducted extensive (and perhaps unprecedented) additional analysis of in ground effect stall. As a result, in ground effect stall characteristics are well understood and have been incorporated into the aircraft's stall warning system. Revised speed schedules have been developed and tested using improved methods and have been confirmed through flight test as accurate.

Based on the results of the NTSB factual investigation as well as other safety reviews, Gulfstream has implemented many safety enhancements to its flight test program. Gulfstream has created an Aviation Safety Officer position, reporting directly to the President of the company. The Aviation Safety Officer will be responsible for ensuring that safety processes have been developed and are being followed for all Gulfstream flight test activities and flight operations activities. Gulfstream has also improved documentation, processes and procedures, increased support of flight test by design engineering, convened more detailed and frequent flight test safety review boards, and improved onboard emergency equipment for the test aircraft to better protect aircrews. Since the accident, Gulfstream has redoubled its efforts to strengthen its safety culture, not only in

[3] Gulfstream defines a "contributing factor" as any action, behavior, omission, or deficiency that set the stage for the accident, or increased the severity of the outcome.

flight test and flight operations, but throughout the company. Gulfstream's post-accident activities are described more fully in Sections 7 and 8.

The accident is specific to developmental flight test and has no meaningful implications for the in-service operations of the G650. The investigation revealed no mechanical or systems failures whatsoever. Engines, flight controls and other components performed as expected.

Telemetry (TM) data and other instrumentation on the flight test aircraft provided a large quantity of data that would have otherwise been unavailable via a Flight Data Recorder (FDR) alone. Over the course of the accident investigation, Gulfstream has provided a significant amount of otherwise unpublished data to the NTSB and has made technical experts available at all times to support the NTSB investigation. In addition, Gulfstream proactively provided to the NTSB a substantial amount of additional information and analysis in an effort to assist the NTSB in understanding all aspects of the precursory and accident events described in this Submission.

2 BACKGROUND

2.1 Gulfstream History

Established in the late 1950s, the company that evolved into Gulfstream Aerospace Corporation has been a world leader in business aviation for more than 50 years. During this time, Gulfstream has introduced numerous technologically advanced aircraft systems, many of which provide an enhanced level of safety. As the first aircraft manufacturer to be awarded an FAA type certificate for an aircraft with an Enhanced Vision System (EVS) as standard equipment, the developer of the first cockpit to incorporate Planeview®, and an industry leader in the development of Synthetic Vision – Primary Flight Display (SV-PFD) in commercial aircraft, Gulfstream has consistently demonstrated its commitment to safety, performance and reliability.

Gulfstream has won numerous industry distinctions, including two Collier Awards for aircraft design for the Gulfstream GV and G550 and its cockpit management systems. Gulfstream has also been awarded two Bendix Trophies for Aviation Safety, for the development of EVS and SV-PFD.

Until 2011, Gulfstream's accident history and safety record was the envy of the aviation industry. For the past 30 years, no Gulfstream jet aircraft design deficiency or company flight operation had been implicated as causative in any major incident or accident. Gulfstream is appropriately proud of this safety record, and this accident is considered a distinct and disappointing departure from our previous safety record. Accordingly, Gulfstream is investing substantial resources to ensure that it once again sets the standard for aviation safety..

2.2 Precursors to the Accident

2.2.1 Background

In a flight test program, company field performance testing is scheduled to take place following completion of certain prerequisite flight tests, which include air data calibrations, reference stall speed and stall characteristics development, V_{MCG} and V_{MCA} determination, climb performance evaluation, and nose wheel steering (NWS) and brake system tuning. Once the prerequisite tests are complete, the takeoff performance tests begin with V_{MU} testing to determine the minimum speed that can be achieved for liftoff and subsequent climb out of ground effect. Afterwards, a series of all engines operating (AEO) and OEI takeoffs are completed to validate the test procedure and target speeds. Once the procedure and target speeds are established, the AEO and OEI takeoffs are conducted at the necessary flap settings and range of thrust / weight conditions required. The takeoff procedure and takeoff reference speeds are designed to accommodate the abused takeoff demonstrations required by FAA regulations. The abused takeoff demonstrations require intentionally early, rapid and mis-trimmed takeoffs, and are, for safety purposes, scheduled last in the flight test program.

On the morning of the accident, the airplane was performing company takeoff performance testing, including CTO testing. Earlier that morning 11 takeoffs were successfully conducted prior to the accident takeoff. These included both AEO and OEI test points at two different flaps settings, Flaps 20^{o} (normal) and Flaps 10^{o} (alternate). At the time of the accident (run 7A2), the airplane was performing a takeoff with a simulated engine failure (right engine at idle), an OEI-CTO, at the alternate flap setting of 10^{o}. Abused takeoff testing had not yet begun.

2.2.2 The Flight Test Crew

2.2.2.1 The Pilot-in-Command (PIC)

The PIC, age 64, graduated from the United States Military Academy, received an MS from the Air Force Institute of Technology, and held an airline transport pilot (ATP) certificate for glider, single-engine and multiengine land airplanes with type ratings for Gulfstream GIV, Gulfstream GV, Gulfstream G-1159, Boeing B-707, and Boeing B-720 airplanes[4]. According to company records, the pilot flying had accumulated 11,237 hours total flight time, including 9,500 hours of PIC time. He had accumulated 263 hours in the Gulfstream GVI (about 160 hours of which were as PIC).

The PIC was a Distinguished Graduate of the United States Air Force Test Pilot School. His experience included performance, stability and control, and engine-out testing on the B-2 program as well as various Gulfstream Special Missions derivative programs. He was an FAA Designated Engineering Representative (DER) Test Pilot. He had been employed with Gulfstream since 1997, and was widely considered to be a knowledgeable and experienced test pilot who was a leader in the area of safety. In 2010, at the request of his supervisor, he had drafted a company manual titled *Aeronautics for Gulfstream Aviators* that was distributed to all Gulfstream pilots.

2.2.2.2 The Second-in-Command (SIC)

The SIC, age 51, graduated from the United States Coast Guard Academy and held an ATP certificate for single-engine and multiengine land airplanes with type ratings for Gulfstream GV, Gulfstream G-100, Boeing B-737, and Westwind Astra IA-1125 airplanes[5]. According to company records, the copilot had accumulated 3,940 hours total flight time,

[4] He also held a flight instructor certificate for glider, single-engine land, and multiengine land airplanes; and commercial privileges for single-engine and multiengine land airplanes.
[5] He also held commercial privileges for single-engine and multiengine land airplanes.

including 2,637 hours PIC time and 140 hours in the Gulfstream GVI (78 of which were as PIC).

The SIC was a graduate of the United States Naval Test Pilot School. His experience included high angle of attack (AOA) and Air Data Systems testing on the X-31 Vector program. He began employment with Gulfstream in 2007 as an Airborne Product Support captain. Although he was relatively new to large-cabin Gulfstream airplanes, within the company he was regarded as well-qualified, positive, and appropriately assertive.

2.2.2.3 The Lead FTE (FTE1)

FTE1, age 48, graduated with a Bachelor of Science in Aerospace Engineering from Iowa State University and had approximately 20 years of flight test experience. His experience included stall speeds and takeoff performance testing on the MD-11 program, stall speeds and climb performance testing on the C-130J program, and high AOA and maximum gross weight takeoff testing on the F-16 program. He was the Flight Sciences section chief for another aircraft manufacturer from 1999-2002, supervising aircraft performance tasks. He was an FAA Flight Analyst DER. He had been employed by Gulfstream since 2009, and was well-liked and widely considered to be safety-oriented, having worked to improve external safety markings on test airplanes and subsequently briefed local airport rescue and firefighting personnel about the test airplane. His safety-oriented nature could be partially attributed to his presence at another aircraft manufacturer's flight test department during a flight test accident[6].

2.2.2.4 The Second FTE (FTE2)

FTE2, age 47, graduated with a Bachelor of Engineering Science and Mechanics degree from the Georgia Institute of Technology and had formerly worked as a Gulfstream production test pilot. His experience included aircraft performance testing at the Douglas Aircraft Company, differential global position system (DGPS) testing at Gulfstream on the GV program, and air data, performance and flying qualities testing on the C-130J and C-5M programs. As a senior production test pilot for Gulfstream from 2006-2009, he had performed maintenance check flights, customer demonstration flights, training flights, and service flights on Gulfstream mid-cabin airplanes. Finally, he was involved in air data calibration and icing flying qualities testing on the G650. The airspeed calibration testing was considered within Gulfstream to be a difficult assignment, and the assignment reflected the fact that his colleagues considered him to be highly competent.

2.2.3 Gulfstream Flight Test

2.2.3.1 Gulfstream Flight Test - Legacy Programs

Gulfstream performed its own flight testing for the first time on Gulfstream IV Special Missions programs in the late 1980s, and established its own permanent flight test department for the GV development program in the mid-1990s. Along with the development of a permanent flight test function during the GV program, an increased emphasis on safety was also undertaken, illustrated by the development of the *Gulfstream Flight Test Standard Practices Manual* (FTSPM), which was created in 1995 and last updated in 1998. Initially based on feedback from other aircraft manufacturers, the

6 http://www.ntsb.gov/doclib/reports/2004/AAB0401.pdf

FTSPM established standard procedures for safe and effective conduct of flight tests, including risk assessment and risk alleviation, flight test personnel responsibilities, and design deficiency reporting. These procedures were the basis for a series of FAA and Gulfstream Memoranda of Understanding that established a jointly agreed upon risk assessment process for FAA certification programs. These procedures served the company well through the past 15 years as it successfully executed the flight test programs to develop and certify the new and novel Enhanced Vision System, two derivative aircraft models (G550 and G450), several Special Mission models (i.e., SEMA, CAEW and HIAPER) and numerous product improvements to the production models.

2.2.3.2 Flight Test Risk Management

Gulfstream has long recognized flight testing as an inherently hazardous activity, and has always placed an elevated emphasis on safety during tests involving an elevated level of risk, including field performance testing. Because these tests often explore new aircraft, aircraft configurations and aircraft systems at the edge of the flight envelope, a high level of crew readiness and hazard assessment is required.

In order to minimize risks associated with hazardous testing, it is important to conduct a thorough safety assessment beforehand to include fully analyzing the maneuvers to be tested, identifying the hazards and associated probabilities, and determining appropriate mitigation procedures. Extensive preparation and careful planning are required by a wide range of disciplines, including flight test engineers, instrumentation engineers, aircraft maintenance personnel, flight operations, and design engineering.

This flight test risk assessment process as outlined in the FTSPM was utilized for the G650 test program along with the guidance contained in FAA Order 4040.26, Aircraft Certification Service Flight Test Risk Management Program. As such, test risk assessments were included in the Flight Test Plans and for those tests classified as Medium or High Risk, TSHAs were generated and Flight Test Safety Review Boards (FTSRB) convened.

TSHAs are the product of the flight test engineer’s test safety assessment. They identify the hazards, cause, effects and probability that define the risk classification. They also provide the mitigation steps along with appropriate crew recovery techniques. The TSHAs are presented to and reviewed by the FTSRB.

The FTSRB is an inter-disciplinary group of management, engineering (both flight test and design engineering) and flight operations personnel. The board is responsible for reviewing tests and test safety information and concurring that the subject tests can be conducted as planned, with the prescribed mitigation strategies, and that the resulting overall level of risk is acceptable. Co-chaired by the Vice President of Flight Operations and Director of Flight Test, the board is also comprised of a senior management member, Chief Engineer, Chief Test Pilot, Project Pilot and senior FTE and Engineering personnel. Attendees at the FTSRB include Gulfstream technical experts as well as FAA personnel.

Gulfstream also utilized a Problem Reporting (PR) System to identify and address aircraft design related issues. This PR System was formally documented throughout the flight test program and included categorizations for aircraft design issues as they pertain to safety of flight, regulatory requirements, and customer satisfaction. Unfortunately, this PR System was not designed and was not used to report operational safety issues which were not recognized as aircraft design issues.

2.2.3.3 Gulfstream Flight Test - G650 Program

The G650 program began in 2005 and was officially announced in March 2008. The G650 represents Gulfstream's first "clean-sheet" design effort since the GII in 1968.

The G650 flight test program included 5 aircraft and approximately 190 employees, including 11 dedicated experimental test pilots and 30 flight test engineers. The test program utilized dedicated facilities for engineers, labs, workshops and aircraft hangars plus improved tools for data acquisition and real-time monitoring. This included a new telemetry station at the main facility and a mobile TM trailer that enabled support of concurrent missions locally and provided off-site capabilities including use during field performance tests at Roswell.

For field performance testing, three pilots with field performance testing experience were assigned (with two additional pilots being trained). There were also two senior FTEs who were FAA Flight Analyst DERs or Authorized Representatives (ARs) and four other FTEs assigned to field performance. In addition, two senior aircraft performance engineers from Flight Sciences and six additional performance engineers supported field performance testing on a rotating basis. The field performance test team also included approximately 20 support personnel (including instrumentation engineers, data specialists, and mechanics).

2.2.4 Previous Flight Tests Completed on G650

At the time of the accident, Gulfstream had completed all the prerequisite testing for takeoff performance, including reference stall speed development, determination of the minimum control speed on the ground (V_{MCG}) and in the air (V_{MCA}), and minimum unstick speed (V_{MU}) testing. A large portion of the V_{MU} testing was completed during the first series of company field performance tests performed in November 2010 at Roswell[7] and designated as "Roswell I." Roswell I flights encompassed flights 080 through 093, and also included the first G650 takeoff performance tests.

The series of test flights designated "Roswell II" encompassed flights 121 through 153 (the accident flight) and were flown in March and early April 2011. These tests include brake and anti-skid system tests, continuous takeoff performance, rejected takeoff performance, landing performance, unusable fuel and FAA Engine Margins, and lapse rate demonstrations. Takeoff tests were conducted on flights 129 through 132, and recommenced with flight 153.

3 ENGINEERING ASSUMPTIONS FOR FIELD PERFORMANCE TESTING

3.1 In Ground Effect (IGE) Stall Angle

Prior to the accident, a series of wind tunnel tests and flight tests were undertaken to determine stall angles of attack (α_{STALL}) for the G650. Wind tunnel tests were performed

[7] Gulfstream, like other aircraft manufacturers, uses the long, wide and ungrooved runway (Runway 3/21) at ROW for much of its field performance testing. Gulfstream designates each testing deployment by sequential Roman numerals, i.e. Roswell I, II. III, IV etc.

under free air conditions as well as in the presence of ground effects[8]. During the wind tunnel tests, Gulfstream recognized that the in ground effect tests did not provide sufficient fidelity in the data at or beyond stall. Flight testing was performed in free air only, as Gulfstream knows of no practical aircraft flight test techniques to confirm the accuracy of IGE stall angle decrements without unacceptable risks to flight crews, aircraft and airport property.

An IGE stall angle decrement on the order of 2° had been used on previous Gulfstream models. Historically, this assumption provided adequate margins of safety without further verification, since tail power limitations[9] forced the takeoff speeds to be relatively faster. It was believed that this decrement would approximate the actual decrement for the G650 as well. For the G650 test program, it was also assumed that the maximum coefficient of lift (C_{LMAX}) at in ground effect stall was equal to the C_{LMAX} at free air stall. This assumption is best characterized by the highlighted portion of Figure 1.

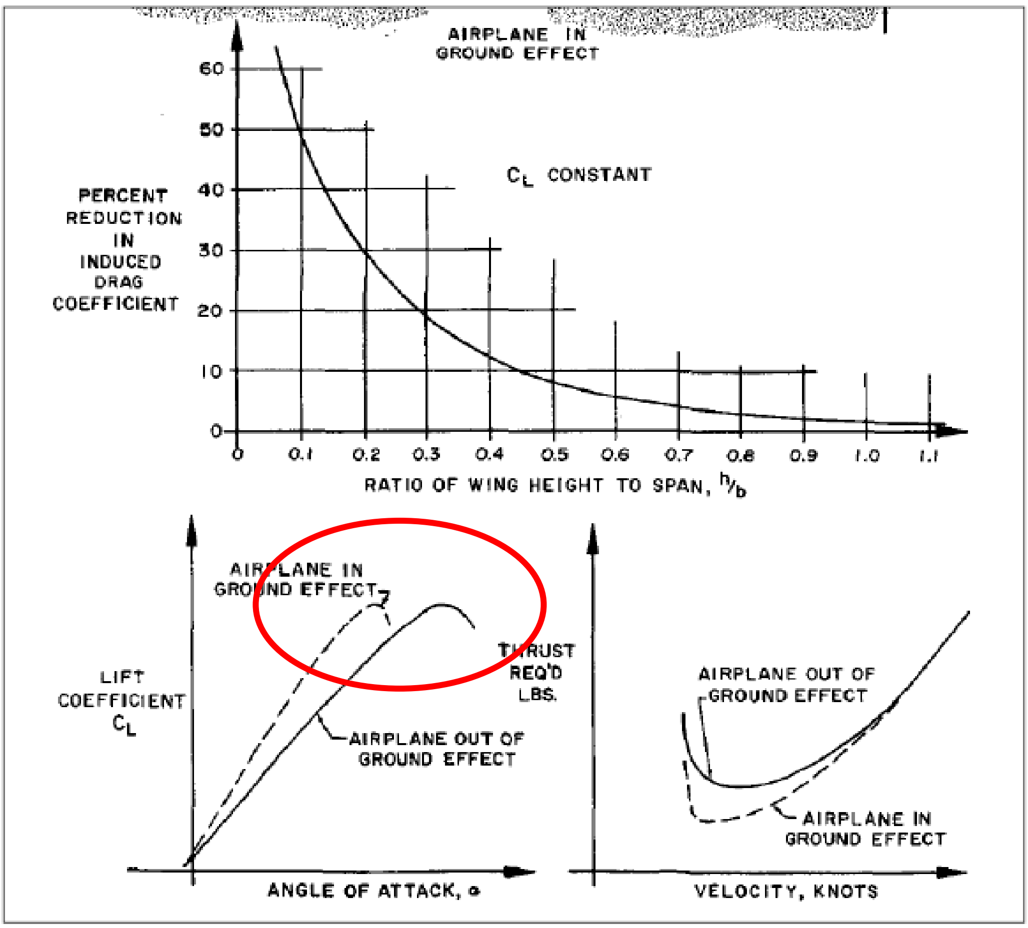

FIGURE 1 - GROUND EFFECTS ON AIRPLANE AERODYNAMICS EXCERPTED FROM REFERENCE 1

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[8] The influence of ground effects on an aircraft are predominant when the aircraft operates on or close to the ground. In this region, the aircraft stall angle of attack will be reduced relative to the stall angle of attack in free air conditions. These effects decrease rapidly as the aircraft climbs away from the ground and are usually absent once the aircraft is beyond a height of approximately one wing span off the ground.

[9] "Tail Power Limitation" in this context refers to the inability of the pilot to raise the nose of the aircraft to the climb out attitude until higher takeoff speeds are achieved because of control system design.

These assumptions were apparently used to create the following slide (rightmost graph in Figure 2) prepared for the Flight Test Safety Review Board (FTSRB) in October 2010 in preparation for field performance testing. Low speed wind tunnel test data for the regime immediately prior to the onset of stall and prior to C_{LMAX} was also used to further refine the estimate for the IGE stall decrement for G650. This data was used appropriately as a baseline to illustrate the planned build-up procedure for V_{MU} testing. The original wind tunnel data (leftmost graph in Figure 2) and the FTSRB illustration of ground effects are presented side-by-side in Figure 2.

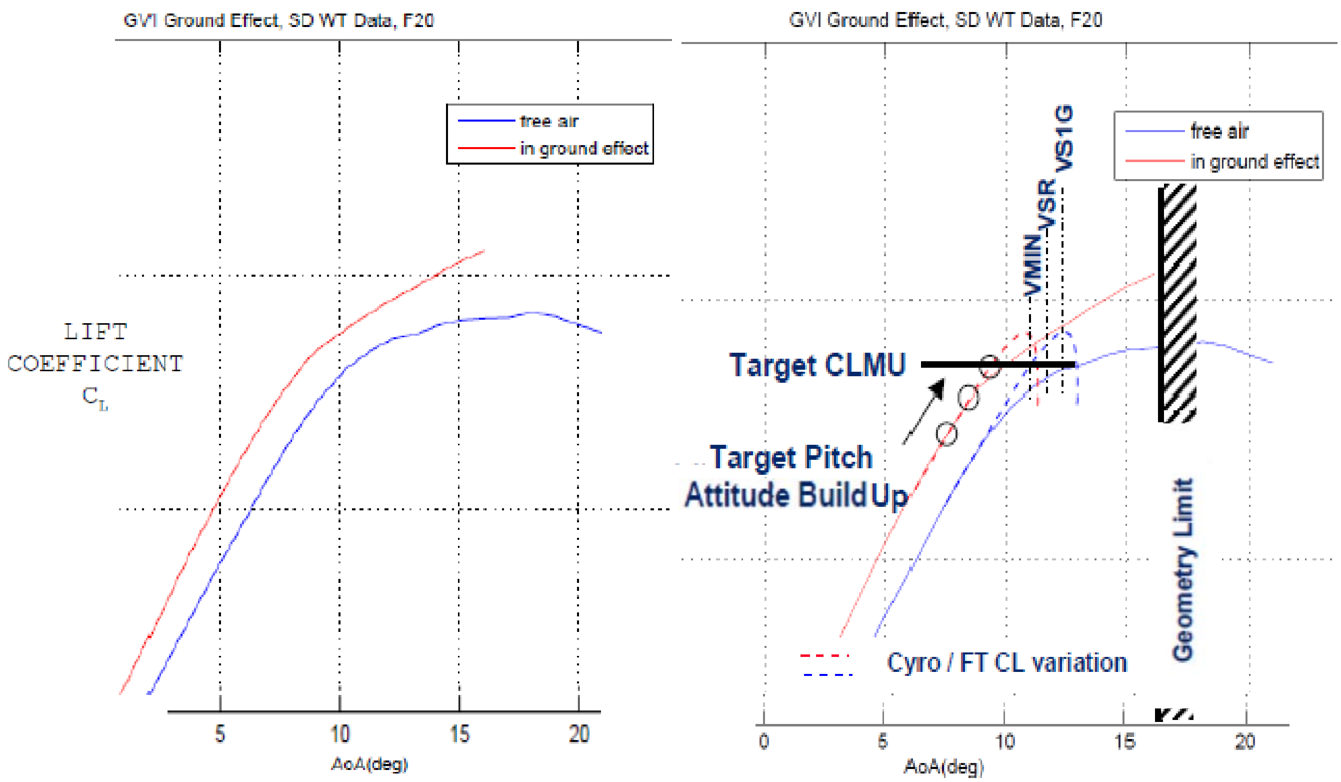

FIGURE 2 - BASIS FOR IGE STALL EFFECTS ASSUMPTIONS

Gulfstream determined following the accident that both the assumption for the IGE stall angle decrement and the assumption that the C_{LMAX} at IGE stall was equal to the C_{LMAX} at free air stall were in error as applied to the G650 (see Section 7.1). A wider review using more refined methods should have occurred and might have indicated that the IGE stall angle decrement was being underestimated. However, Gulfstream has concluded that as of October 2010 when the C_{LMAX} assumption was made, the analytical tools being used by Gulfstream would likely not have alerted Gulfstream to the error in the C_{LMAX} assumption.

Later, but still prior to the accident, when analyzed in combination with V_{MU} data gained during Roswell I testing and with free air flight test data, these assumptions also provided a basis by which the predicted IGE stall angle decrement was decreased from 2° to 1.5° for Roswell II testing. The decrease in the IGE stall angle decrement was believed to be reasonable, in part because it was based on flight test derived estimates that were perceived as reliable. This misplaced confidence in the accuracy of the IGE stall angle estimates further prompted the engineering staff to increase the stick shaker onset AOA for Roswell II (see Section 4.4 for more information regarding stick shaker settings). As will be explained further below, Gulfstream has concluded that this shaker setting adjustment would also have benefited from further analysis and a more formal review and approval processes. This additional error is one of the causal factors of the accident.

3.2 Takeoff Reference Speed Development

During the GV program, the rotation speed (V_R), liftoff speed (V_{LO}), and takeoff safety speed (V_2) were expressed as a ratio of the reference stall speed (V_{SR}) and defined as a function of the aircraft's thrust-to-weight (T/W) ratio at V_{LO}. As a general rule for the GV, ratios of V_R/V_{SR}, V_{LO}/V_{SR}, and V_2/V_{SR} increased linearly as a function of T/W ratio. In addition, the spacing between these speeds also increased with increasing T/W ratios to reflect the higher accelerations expected at higher T/W ratios.

Gulfstream developed the target G650 takeoff speeds prior to Roswell I and II in part by referencing the legacy aircraft airspeed ratios from the GV program, in combination with the minimums for takeoff safety speed (V_{2MIN}) provided under 14 CFR Part 25.

Specifically, the V_2 was assigned an assumed value at the FAA minimums provided in 14 CFR 25.107(b) for the entire range of T/W ratios (14 CFR 25.107 states that the minimum V_2 speed cannot be less than $1.13*V_{SR}$). A V_2/V_{SR} ratio at the minimum threshold allowable by 14 CFR 25.107(b) was selected primarily to limit the balanced takeoff field length of the aircraft. The G650 rotation speeds and lift-off speeds were then formulated using the same speed increments from V_2 as the GV program. Further analysis to confirm that the FAA minimums would provide an achievable set of takeoff safety speeds was not undertaken. Unlike the GV program, the resultant trend for V_R/V_{SR}, V_{LO}/V_{SR}, and V_2/V_{SR} ratios decreased linearly as a function of T/W. Effectively, the V_R and V_{LO} speeds were decremented to guarantee a V_2 speed of $1.13*V_{SR}$ at all T/W values. At higher values of T/W this methodology established V_R speeds approaching the V_{SR} speeds.

Takeoff speeds were developed for specific pitch attitude targets for both flaps 10 and flaps 20 configurations. Prior to Roswell II, the initial pitch attitude target for flaps 10 was reduced to align with the flaps 20 initial pitch attitude target, regrettably without calculating new takeoff speeds (see Section 4.6).

Legacy (GIV and GV) Gulfstream aircraft were tail power limited, thus increasing the rotation speed as the aircraft approached maximum takeoff weight (MTOW). Design advances on the G650 provided greater tail power, allowing V_R to be more closely aligned with the targeted V_2 speed.

Gulfstream determined following the accident that the takeoff speeds for the G650 field performance flight test program were too slow for the test aircraft. Any attempt by the pilot to capture these incorrect target takeoff speeds, while on or near the ground, would increase the aircraft's AOA to near or beyond the IGE stall AOA. The error in the takeoff speeds was greater for Flaps 10 takeoffs than for Flaps 20 takeoffs (see Section 7.2 for discussion of speed development errors). Gulfstream further concluded that its internal analysis, review and approval processes were inadequate, as they did not lead to identification of the errors prior to flight test activities.

The characteristics of an aircraft attempting to takeoff below a suitable takeoff speed is described in the following excerpt from Reference 1:

> "During the takeoff phase of flight ground effect produces some important relationships. Of course, the airplane leaving ground effect encounters just the reverse of the airplane entering ground effect, i.e., the airplane leaving ground effect will (1) require an increase in angle of attack to maintain the same lift coefficient, (2) experience an increase in induced drag and thrust required, (3) experience a decrease in stability and a nose-up change in moment, and (4) usually a reduction in static source pressure and increase in indicated airspeed. These general effects should point out the possible danger in attempting takeoff prior to achieving the recommended takeoff speed. Due to the reduced drag in ground effect the airplane may seem capable of takeoff below the recommended speed. However, as the airplane rises out of ground effect with a deficiency of speed, the greater induced drag may produce marginal initial climb performance. In the extreme conditions such as high gross weight, high density altitude, and high temperature, a deficiency of airspeed at takeoff may permit the airplane to become airborne but incapable of flying out of ground effect. In this case, the airplane may become airborne initially with a deficiency of speed, but later settle back to the runway. It is imperative that no attempt be made to force the airplane to become airborne with a deficiency of speed; the recommended takeoff speed is necessary to provide adequate initial climb performance."

Under these conditions the general response of the aircraft could be described as sluggish or non-responsive, a characteristic highlighted by the Gulfstream flight crew on several occasions prior to the accident flight, but regrettably not communicated to the larger Gulfstream engineering community beyond the engineers in the TM trailer, such as to company aerodynamic specialists who might have recognized the underlying speed issue.

4 FIELD PERFORMANCE TESTING – BACKGROUND AND WARNING SIGNS

4.1 Flight Test Safety Review Board (FTSRB)

Prior to the start of field performance testing, an FTSRB was convened on October 7, 2010. In addition to customary personnel listed in Section 2.2.3.2, all of the crewmembers on the accident flight were present at this FTSRB.

FTE1 developed and presented the material for the field performance FTSRB. Discussions were held regarding all the field performance testing that was to be conducted, and risk levels were agreed upon (See Table 1).

TABLE 1 - FIELD PERFORMANCE TESTING RISK LEVELS

TSHA	No.	Risk Level
Field Performance – V_{MU}	83	High
Field Performance – One Engine Inoperative Takeoffs (OEI)	84	High
Field Performance – Accelerate Stops	85	Medium
Field Performance – Maximum KE RTO / Fuseplug Demo	86	High
Field Performance – Thrust Reverser Effectiveness Single TR	87	Medium
Field Performance – Landing Performance	88	Medium
Field Performance – Landing Performance Loss Of Half Brakes	89	Medium
Field Performance – Abused Takeoff	91	High
Thrust Reverser – Asymmetric Deployment	36	Medium
Flying Qualities – Minimum Control Speed Ground	81	High

All Field Performance TSHAs were reviewed, comments were incorporated, and the TSHAs were approved prior to the start of performance testing.

The TSHA covering the accident takeoff test point (No. 84 - OEI Takeoffs) identified the primary hazard driving the risk classification as "Aircraft Departs Runway / Inadvertent Ground Contact" due to "Engine Failure / Loss of Control."

Applicable preventative actions / minimizing procedures for OEI Takeoffs were identified as follows:

1. Testing to be conducted on a 13000' X 300' runway (ROW)
2. Brief local fire and rescue crews on test conditions
3. Service struts, brakes, and tires to recommended limits
4. Brief dual engine-out emergency procedures
5. Essential crew only
6. Winds limited to 10 knots total and components of 5 knots crosswind and 2 knots tailwind
7. Alternate control law maximum gains loaded prior to testing
8. The pilot flying shall have recent experience with the test maneuver or perform build-up maneuver(s) before conducting the test condition.[10]

Applicable corrective techniques are identified as follows:

1. For throttle chops: if the aircraft is airborne and one engine fails, advance PLA as required, decrease pitch attitude, establish a stable bank angle, accelerate and climb to any altitude. Minimize asymmetric thrust if possible
2. Make all turns into the operating engine and climb at no less than V_2 until 1500 AGL

In comparison, the TSHAs for both V_{MU} testing as well as Abused Takeoffs included over-rotation at low airspeed and low altitude stall as potential hazards. Wind levels were

[10] This item was added to the TSHA after the initial Flight Test SRB based on the review of the roll event experienced on Flight 088 (see Section 4.2.1).

limited to 5 knots total. The pilot was also directed to maintain airplane roll angle below 5°. The corrective technique for over-rotation / stall was defined as "decrease pitch attitude, maintain wings level, advance PLA on both engines, accelerate, and climb to desired altitude."

Included in FTE1's presentation was the predicted IGE stall angle decrement, as noted in Section 3.1. Several of FTE1's colleagues stated after the accident that the presentation appeared at the time to be very thorough and well-presented.

Following the accident, Gulfstream determined that the TSHA was insufficient as it identified neither over-rotation, excessive roll nor stall as potential risks, and did not adequately address the recovery options should an aerodynamic stall occur during the takeoff test.

4.2 V_{MU} Testing

V_{MU} testing determines the minimum safe liftoff speeds and is used as a limiting speed when establishing the takeoff speed schedule. The V_{MU} test technique is to rotate and hold a constant pitch attitude through liftoff and until out of ground effect. Unlike OEI CTO test procedures, the OEI V_{MU} is flown with symmetric thrust. Consistent with FAA guidance, in order to mitigate the risk level during V_{MU} testing, both engines are utilized and symmetric power is set at a level to provide the OEI-equivalent engine thrust at a variety of thrust/weight conditions. For these tests, the engines' throttles are pulled back to the predetermined setting at 60-80 knots, at which time the pilot provides a full aft column input. Upon nose rotation, the column force is reduced to capture and maintain the target pitch attitude. After liftoff, the pitch attitude is maintained through 100 ft above ground level (AGL), at which point the test point is considered complete and throttles are advanced as required. Significant company V_{MU} flight testing was conducted during Roswell I in November 2010.

4.2.1 Flight 088 - November 16th, 2010

While conducting a V_{MU} test point at Flaps 20°, the test was aborted approximately at the point of liftoff due to a roll-off that occurred. The pilot flying during Flight 088 was also the PIC on the accident flight, Flight 153.

Flight 088 Run 2A was the first V_{MU} test point of the mission and was also the first V_{MU} test point for the PIC on the G650. The flight was at a medium weight, which involves a forward center of gravity (CG) limit that is further aft than heavier weight conditions. Following the initial aft column input, the pilot flying experienced a faster rate of rotation than expected and the aircraft pitched quickly past the target 10° pitch attitude to 13°. The aircraft lifted off and rolled approximately 8° right wing down (RWD) before a forward column input was provided by the co-pilot and maximum power was applied. Following these inputs, pitch angle and AOA were reduced, and the airplane returned to wings level and continued climb out.

Afterwards, the test team concluded that the roll-off was the result of an overrotation by the pilot and that build-up tests should be required for any pilot that does not have recent experience with the planned maneuvers.

As a result of the event, the TSHA for V_{MU} testing was revised to ensure that the opportunity was given to the pilot(s) to perform proper build-up points (see Footnote 10). In addition, the PIC presented a summary of the event to a limited audience of flight test personnel (which consisted of several test pilots and flight test engineers) in which he described the event, and explained the added TSHA language. His presentation included audio, video, and flight test data.

The pilot's summary was not widely disseminated outside the initial group to which it was presented. Because this event was attributed to an incorrect technique due to a lack of proper build-up, the event was never analyzed in-depth with regards to stall and stall AOA.

After the accident, Gulfstream recognized that had a further technical review been conducted by Gulfstream engineering immediately following Flight 088, the data would have demonstrated that the stall, which resulted in the roll off, occurred at an AOA lower than the predicted AOA for IGE stall presented during the SRB. Such a review should then have led to further review of the predicted IGE stall assumption by those responsible for the initial determination.

4.2.2 V_{MU} Data Analysis

Several months after the completion of Roswell I testing, and just after resuming CTOs as part of Roswell II in late March 2011, the V_{MU} flight test data was reviewed and a preliminary flight test report prepared. The data analysis resulted in the following coefficient of lift (C_L) plot for Flaps 10 (where FN is thrust, in lbs):

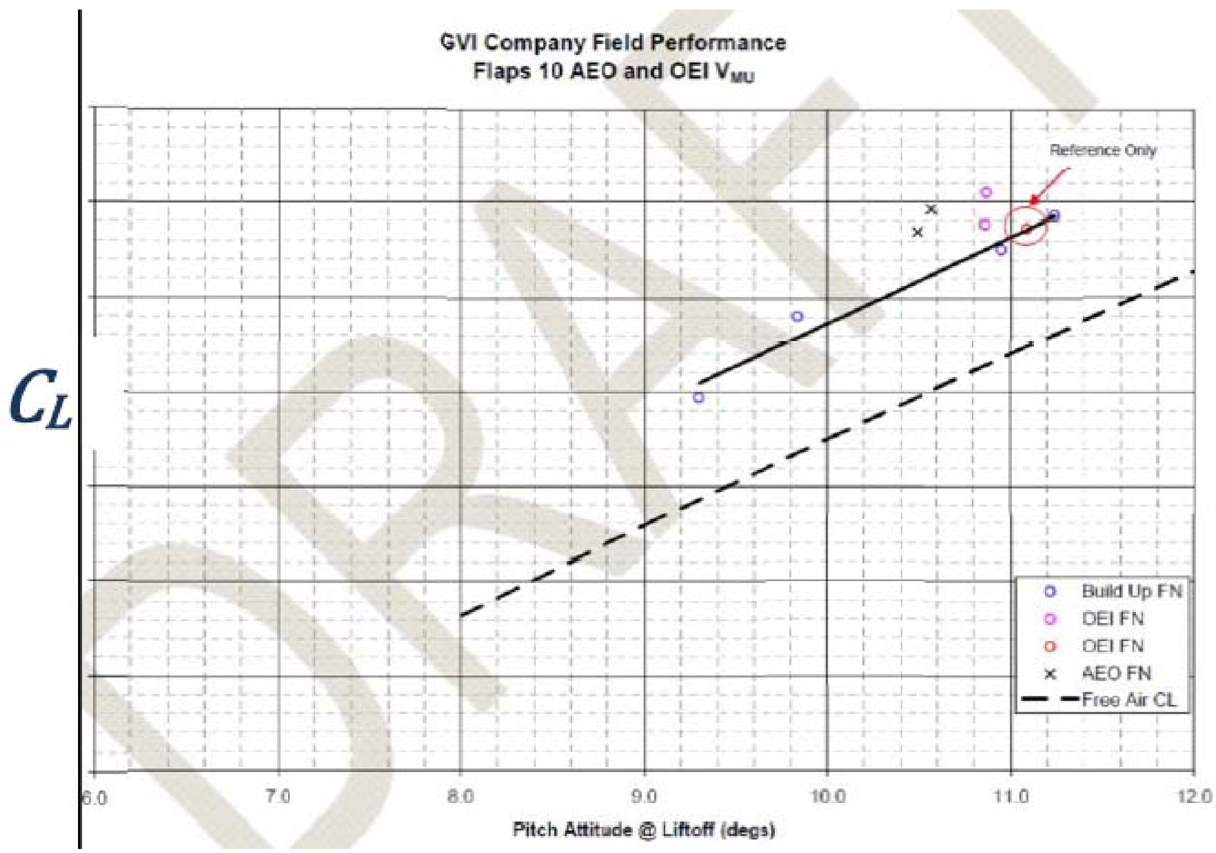

FIGURE 3 - FLAPS 10 PITCH VS. LIFT COEFFICIENT (FROM ROSWELL I V_{MU} DATA)

This analysis assumed that the C_{LMAX} would be equal for both IGE and free air (which is consistent with the US Navy's textbook "Aerodynamics for Naval Aviators," previously set out in Section 3.1 and Figure 1). However, had Flight 088's roll-off been used as a data point representing stall in comparison to flight test derived free air stall, this assumption regarding C_{LMAX} would have been proven incorrect (see Section 7.1).

4.3 Roswell I CTO Testing and Birmingham (KBHM) Technique Development

The technique for OEI CTO flight testing was developed by Gulfstream, and is similar to the technique used during flight testing on previous Gulfstream models. To simulate a right engine failure, the copilot is to pull the right hand throttle back to idle at a speed approximately 20 knots below V_1. At V_R, the pilot is to provide a rapid aft column input until a nose-up pitch rate is achieved, then gradually capture a target pitch attitude. As the airplane lifts off and accelerates, the pilot is to increase pitch attitude to capture the target V_2 speed.

For Roswell I flights, the takeoff technique was to capture and hold a target pitch angle (10° for Flaps 10, 9° for Flaps 20) through 35 feet (although 35 feet was not on the cards, this is how FTE1 briefed the maneuvers for the flights during Roswell I):

1. Configure aircraft for takeoff.
2. Align aircraft on runway and apply brakes.
3. Set L & R PWR as specified.
4. Release brakes.
5. At target V_{EF}, fail RH engine using a throttle to IDLE.
   a. Use rudder and NWS control as required for directional control.
6. Rotate at V_R using ___ lb pull until rotation begins, reduce force to gradually capture 10° pitch attitude.
7. Maintain target pitch attitude until V_2 is achieved, then transition to speed.
8. Retract gear after positive Rate-Of-Climb (ROC) is established.
9. Adjust pitch attitude to maintain V_2 to the lesser of gear retraction complete or 400 ft AGL.

Following Roswell I, an evaluation by engineering personnel of the initial takeoff performance tests revealed that the airplane was significantly exceeding its takeoff field length performance target of 6,000 ft (+/- 8%). While the takeoff field length performance target is based on sea-level, ISA conditions at Flaps 20, Flaps 10 performance is also important for takeoffs from high altitude airports in high temperature conditions.

It was believed by the Roswell test team that the takeoff field length could be shortened (specifically, the air segment) via changes to the takeoff technique, in which the higher pitch angles needed to capture the target V_2 speed could be attained once the aircraft was off the ground. As a result, a single flight (forward CG, heavy weight conditions), Flight 111, was conducted at KBHM on February 13, 2011 to evaluate the revised technique for Flaps 20 takeoffs. The copilot for Flight 111 was also the SIC on the accident flight.

Using what has been described as an "aggressive pull" of the control column to maximize pitch rotation rate at V_R, followed by further pitch increases following liftoff to reduce the acceleration of the aircraft prior to capturing the target V_2, the new technique produced results that were promising. This revised technique (together with a 2 knots increase to the rotation speed) was intended to be carried forward to Roswell II. The developmental tests performed during Flight 111 with this technique were not performed at Flaps 10, nor at other aircraft weight and CG conditions.

4.4 Increase of Shaker Onset AOA (α_{shaker})

Roswell I testing included several instances in which the stick shaker activated during takeoff. This activation is not compliant with 14 CFR Part 25 regulations, which do not permit shaker activation during takeoff maneuvers counted to demonstrate conformance with the regulations.

The V_{MU} data (detailed in Section 4.2.2) indicated that the IGE stall angle decrement was approximately 1.5°, .5° less than the previously assumed 2° decrement. As a result, and as a way to avoid instances of shaker activation during Roswell II testing, a decision was made, and concurred with by several others in flight test, flight sciences and flight operations, to increase the value of α_{shaker} from 85% normalized angle of attack (NAOA) to 90% NAOA. It was predicted that this increase would still provide approximately 1° of margin between shaker activation and stall.

Stick shaker and the corresponding PLI[11] displayed in the cockpit are the stall warning devices available for flight test crew use. The PLI is the primary tool used by Gulfstream's flight test pilots to confirm that they are operating at safe pitch attitudes.

Following the accident, Gulfstream determined that the assumption that the C_{LMAX} would be equal for both IGE and free air was in error. This assumption underpinned the analysis of the IGE stall angle. The company's original setting of shaker onset angle (at 85% NAOA based on free air stall, a legacy Gulfstream aircraft value) had itself already placed the aircraft's stall warning system at or beyond IGE stall at the accident conditions. This subsequent increase in shaker onset angle moved the aircraft's stall warning system even further past IGE stall. As a result, the PLI was not an accurate representation of a safe margin to IGE stall and provided misleading information to the pilots.

4.5 Flight 132 - March 14th, 2011

A second roll-off event occurred during OEI CTO testing at ROW. The pilot flying during Flight 132 was also the SIC on the accident flight, Flight 153. The fuel load for this flight was in the light weight band as opposed to Flight 111, in which the SIC (as copilot) observed the takeoff technique development with fuel load in the heavy weight band. This resulted in the takeoff CG being approximately 6% further aft, which would result in higher pitch rates using the same column technique.

The technique used for Flight 132 Run 3B2 was the same as that of the accident flight, with a target pitch attitude of 9°, albeit at Flaps 20° and at a lighter weight than the accident flight. Due to a Flight Control Computer (FCC) yaw damper issue, the yaw damper was selected off for this flight.

[11] The PLI is displayed when the normalized AOA is greater than 70% and is used as a visual cue to alert the pilot to an impending stick shaker. As the flight path vector (FPV) approaches the PLI, the pilot is approaching stick shaker activation. The distance between the PLI and FPV is zero when the stick shaker is activated.

In Flight 132 Run 3B2, the pilot pulled aft on the column approximately 2 knots prior to the V_R callout, and overrotated the aircraft past the target pitch attitude to approximately 12°. The aircraft lifted off and rolled approximately 9° RWD before a rapid forward column input was provided by the copilot and maximum power was applied, allowing the airplane to return to wings level and continue flight.

Although the roll-off event was initially discussed by the event copilot (who was the senior pilot for the flight) and FTE1 as a possible stall, further review of the data on-site at Roswell revealed that the roll-off had occurred prior to the predicted IGE stall angle. During the ensuing discussion, both FTE1 and the senior pilot expressed confidence in Gulfstream's engineering predictions, especially given the senior pilot's experience with free air stall development for the aircraft in earlier flight testing. This led them to characterize and report the event as a lateral directional control disturbance caused by early rotation, overaggressive aft column input and the unavailability of the yaw damper.

Following the conclusion of Flight 132, because the stall event was mischaracterized as a lateral directional control disturbance related to the inactive yaw damper, those outside of the Roswell field performance group who were made aware of the roll-off event were not alerted to a need for further review. FTE1 requested that the Flight Sciences Control Law group analyze whether the AOA Limiter stall protection planned for the production aircraft would have prevented the Flight 132 roll off. The response was that the AOA limiter would not have activated.

No further takeoff field performance testing was conducted between Flight 132 and the accident flight.

4.6 Reduction of Flaps 10 Target Pitch Angle

After Flight 132, the initial V_{MU} data analysis was briefly discussed with one of the senior aircraft performance engineers supporting field performance testing. As part of this review, a proposal was discussed to change the target pitch angle for Flaps 10 performance takeoffs be reduced to 9° to provide consistency with the Flaps 20 technique, as well as to lower the pitch angle target for abused takeoff testing that was yet to be completed (for abused takeoffs, a pitch angle 2° higher than the normal target pitch angle must be targeted).

Since there was no performance guarantee at Flaps 10, the proposal was accepted, and the target pitch angle for Flaps 10 takeoffs was changed to 9°. Unfortunately, no simultaneous adjustments to the takeoff speeds were made as a result of the pitch target change. After the accident and following review of the V_{MU} report, Gulfstream determined that the speeds should have been increased by approximately 4 knots based on the reduction in the target pitch attitude. While this failure to increase speeds contributed further to the unrealistic speed targets that the accident crew was attempting to achieve, as further explained in Section 7.2 below, this speed error was only a part of more fundamental errors in takeoff speed development.

5 FLIGHT 153

5.1 Pre-Flight Meetings

Two pre-flight briefings took place prior to the accident flight – the first was conducted at approximately 1400 on April 1st, upon arrival of the crew at ROW. Attendees at the briefing included the crew as well as engineering representatives who were present at ROW to support the testing. This briefing focused primarily on the takeoff maneuver technique and the key parameters for CTO testing, including an initial column force of approximately 60 lbs and a target pitch angle of 9°.

Further discussion of the pitch angle target included the pilot and one of the flight test engineers reflecting on previous pitch overshoots during performance testing, with the pilot and flight test engineer reportedly saying "we've already been there, we don't want to go there again." The discussion continued and it was agreed that the maneuver would be terminated and recovered by immediately reducing angle of attack (a "push") if a pitch angle of 11° to 12° was reached. The pilot was particularly concerned about pitch overshoot, reportedly saying that he "didn't like it."

The second pre-flight briefing was conducted at approximately 1800 on April 1st, at a nearby hotel. According to engineering personnel present at the briefing (primarily the same personnel present at the 1400 briefing), each flight test card was reviewed, detailing the test technique, aircraft configuration, limitations / restrictions, test procedures for each card, and a review of the TSHAs. The not-to-exceed pitch angle of 11° or 12° at liftoff was discussed again, as well as the agreement to end and recover the maneuver with a "push" if the pitch limit was exceeded. The pilot reportedly again said, "I don't want to go there."

The briefing did not include a formal delegation of pitch angle monitoring duties to a particular member of the flight crew or the TM crew.

5.2 Runs 2, 3, and 6

(Note: Reference 2 includes detailed information on each takeoff, including crew discussion and other observations of the *On Board Video Recording Group*.)

A total of 11 takeoffs were accomplished on the day of the accident prior to the accident run. Prior to the accident run, both AEO and OEI CTOs were conducted at Flaps 20 (Runs 2 and 3, respectively), as well as AEO CTOs at Flaps 10 (Run 6). Run 7A1 was the first OEI CTO of the day conducted with Flaps 10, and Run 7A2 was the accident run.

The accident flight test pilots and FTE1 are recorded as having an on-board conversation as they began the flight testing reminding each other, and confirming, that they were going to use an 11° abort threshold as discussed the night before, and exceeding this value would lead to aborting the test maneuver. There was no discussion concerning what technique would be used to accomplish the abort, nor was there any assignment of safety monitoring of pitch angles to any crew member. As testing proceeded during that morning, this abort threshold was never discussed again. Instead, the test crew mutually agreed to proceed with a pilot technique requiring a continuous increase in pitch following V_R while attempting to achieve the V_2 speeds.

During the Flaps 20 OEI takeoffs, run 3A1, the pilot targeted and maintained 9° of pitch and following takeoff determined that 15°-16° of pitch was required to maintain V2.

During the next run, 3A2, the pilot commented that 12.5°-13° of pitch was required to maintain V_2, but that it overshoots and then comes back. In later discussions with FTE1 the PIC said he was trying to find the pitch to shoot for to hold V_2, and it looked like it should take 13°-14°. The crew discussed the fact that in targeting 9°, they were still exceeding V_2 and a continuous maneuver was required in order to capture V_2. They all agreed on a technique of pitching to get airborne and then continuing the pull to capture V_2. There was discussion that the target takeoff speeds were as slow as they wanted to go, unless they were going to be performing V_{MU} takeoffs.

Before the next run, an FTE in the TM trailer (TM-3 per Reference 2) told the crew that on Run 3A2 they were about 2 knots low on V_R and 3.5 knots high on the V_2. The PIC then said "we're not going to hang out long at 9, we're just going to hit nine and then we're gonna go for the 13 to 14 for V_2." FTE1 said "yep." The PIC said "it's almost a continuous maneuver." He added that 3 knots above V_2 was not bad, because 2 knots was the test criterion. The speed at 35 feet was critical according to their discussions. He then said "nine degrees, based on that is a pretty good target…because that's how they're determining their distance."

After the last Flaps 20 OEI takeoff, run 3A3, FTE1 said "I think that's it." PIC said "we're done; I think we caught it there." FTE1 said "yeah." The PIC said "we must be onto something now." FTE1 said the airplane was "still pretty heavy" and he thought they would continue on testing the Flaps 10 maneuvers and "tomorrow we'll go for score on it." The PIC said he was happy with the nice smooth ramp input and 50-55 pounds force. He added that they were drifting a little bit (probably a comment on lateral drift during the takeoff roll), but he was not feeding any roll [control] in because he didn't want to "contaminate it" (he was probably referring to keeping the roll control centered so the drag of the aileron and spoilers would not reduce takeoff performance). A post-accident review of the takeoff data for this run shows that for this run the airplane lifted off during the initial rotation at approximately 5 degrees of pitch, which is within the expected behavior for those particular test conditions.

After stopping to discuss the next test points, which were to be Flaps 10 AEO points, the crew commented that the target takeoff speeds didn't change much from Flaps 20 to Flaps 10, except that the V_2 actually increased.

The final Flaps 10 AEO CTO (Run 6C3) was the culmination of this iterative approach, and the aircraft reached approximately 8.7° before lifting off. Run 6C3 was different than any of the previous runs as it did not include a pause at the target 9° pitch angle. Conversations amongst the crew following Run 6C3 were positive, including comments like "okay, that's good" and "that was a lot better." There was only one minor comment regarding pitch angle, with TM-3 noting that "pitch is a little high." The PIC responded to TM-3 with "we didn't pause very long at 9. We're trying to capture that V2 at 35, so we're just, it's just not there very long, so… I think that's what you were seeing." FTE1 said "that helps".

5.3 Run 7A1

Card 7 was for Flaps 10 OEI takeoff tests. For Run 7A1, the target V_1 speed was 126 KCAS, the target V_R speed was 128 KCAS, the target V_{LO} speed was 133 KCAS, and the target V_2 speed was 136 KCAS. For comparison purposes when the Flaps 20 OEI tests were accomplished 3 runs earlier and at a slightly higher weight, the V_R speed was 131 KCAS, and the target V_2 speed was 135 KCAS. Thus, at a lighter weight and with less flaps the rotate speed was 3 knots slower, and the V_2 speed was only 1 knot higher.

During the takeoff the airplane reached the target 9° pitch angle at 0926:22.7, but did not liftoff until about 3 seconds later (wheel speeds indicate that the left MLG wheels lifted off first, followed 0.6 seconds later by the right MLG wheels), with an additional delay of 4-5 seconds before the aircraft began to climb above 5 feet AGL. Liftoff occurred at a speed of 135 KCAS. After liftoff, the pilot continued to hold the 9° pitch target, and the airplane continued to accelerate. As the airplane approached 35 ft AGL, pitch was increased and stabilized at 15°. Based on prior comments by the PIC on the pitch attitude required to hold V_2, the PIC would be expected to have known this attitude and would have maneuvered to it while achieving V_2. The rotation to liftoff characteristics for the test point being conducted should have been indicative that the rotate speeds were too slow and the aircraft was at the target pitch angle on the ground awaiting acceleration to liftoff speed (as in V_{MU} testing[12]). Directly comparing this run to the last Flaps 20 OEI takeoff, run 3A3, where the airplane lifted off at approximately 5 degrees of pitch could have alerted the test team to the issues with the Flaps 10 takeoff speeds. Reference 2 indicates that the SIC attempted to raise the gear twice (unsuccessfully due to the aircraft still being on the ground) before successfully raising the gear on his third attempt. This change in pacing of the transition from ground to air mode was significantly longer for this run.

Upon completion of the run, the data indicated that the aircraft speed at 35 ft AGL was approximately 145 KCAS, a 9 knot overshoot of the target V_2 speed. After completion of the test point, there was no discussion or comment by the flight crew, onboard test engineers, or the test team in the TM trailer regarding the aircraft dwelling at 9° until sufficient airspeed was attained to liftoff.

The airplane landed, executed a 180° left turn, and the crew then waited about a minute before initiating Run 7A2. Due to the fuel weight burned on the previous run new target takeoff speeds, 1 knot slower, were provided.

The crew discussed the results of run 7A1 amongst themselves and the TM trailer. The 9 knots overshoot of the target V_2 was attributed by the PIC to the attempt to capture and maintain the 9° pitch target. The PIC didn't believe that this focus would be a reasonable expectation of a customer flight crew, and suggested that for the next run, the accident run, he employ a continuous maneuver with a focus of targeting 9° pitch, but then keep going (pulling up to capture V_2). Other field performance test pilots provided testimony to the NTSB that they were using the PLI and stick shaker as their AOA limit during this portion of the flight maneuvers. All field performance test pilots shared a belief that the test card allowed a transition from the stated target pitch attitude to V_2 when 'achieving' V_2, even though the language of the card stated "maintain target pitch attitude until V_2 is achieved, then transition to speed." The maneuver the PIC was suggesting was the same

[12] As noted in Section 4.2, V_{MU} test points have additional safety features (as opposed to OEI runs), as they are conducted with both engines operating at reduced thrust settings (each engine providing half of the maximum single engine thrust) in order to minimize bank and yaw excursions. In addition, the engine spool up time from a setting above idle is significantly reduced compared to a setting at idle. In Run 7A1 the crew inadvertently performed an OEI V_{MU} test point with a real asymmetric thrust configuration rather than a safer symmetric configuration as allowed by FAA Guidance.

maneuver he had successfully used just two runs earlier on Run 6C3 (a successful AEO test) as well as on the Flaps 20 OEI run 3A3. His decision in this regard was ratified by the SIC and FTE1, with no recorded comment from engineers monitoring the activity in the TM trailer.

5.4 Run 7A2

For Run 7A2, the target V_1 speed was 125 KCAS, the target V_R speed was 127 KCAS, the target V_{LO} speed was 132 KCAS, and the target V_2 speed (speed at 35 ft AGL) was 135 KCAS.

The initial phase of accident Run 7A2 was performed by the PIC exactly as he and the other crew members had discussed, and based upon their technique refinement during previous takeoffs that morning. The right engine was retarded to idle at the planned speed of 107 KCAS, the aircraft was commanded to rotate (and the nose was raised) at 127 KCAS, and the PIC applied a gradual continuous rotation maneuver thereafter and remained below PLI and shaker. The SIC was apparently focused on his task of raising the landing gear as soon as the WOW transitioned to air mode and allowed landing gear retraction.

Recorded wheel speeds indicate that the left MLG lifted off first, (at 0933:48.2), indicating that the aircraft had already begun to roll to the right. The PIC commanded pitch angle to increase past 9°, reaching 11° by the time the right MLG lifted off a couple of seconds after the left MLG (at 0933:50.2). This "liftoff[13]" occurred at a speed varying between 129 and 132 KCAS (against a target V_2 of 135 KCAS). Roll angle at "liftoff" was approximately 2° RWD, (with a roll rate of 2° per second RWD), and sideslip had reached a maximum of 4° nose right. The PIC commented at approximately 3 degrees of bank and 11.5° of pitch, "* (going on)", which Gulfstream believes was "what's going on?"

In addition to the unexpected right roll of the aircraft, immediately after "liftoff", the pilot applied more left rudder, to approximately 19° trailing edge left (TEL), to successfully counter the yaw that routinely occurs in OEI takeoffs. In the next 2 seconds, the airplane sideslip angle transitioned from 4° nose right to 2° nose left, but the aircraft remained rolled to the right.

The right wing was in aerodynamic stall at the point where pitch attitude reached 11.2 degrees, or 1.0° below where the PLI and shaker were set for stall warning.

Within two seconds of "liftoff" the SIC was heard exclaiming "oh, whoa whoa whoa whoa."

By the same time as the SIC exclamation, (By 0933:52.2), the PIC had applied full left rudder to 26° TEL. The pilot wheel was at a position of 26° left wing down (LWD) out of a maximum 60° of travel. Roll angle had increased to 11° RWD, roll rate had increased to 8° per second RWD, and AOA had increased to approximately 12.2°. At 0933:52.2, the Flight Control Computer (FCC) commanded the stick shaker to activate.

Within about 0.4 second after shaker activation, the PIC had applied full left wheel and applied a momentary elevator input of 1° trailing edge down (TED), equivalent to a

[13] For purposes of this section, "liftoff" is described as the point when all wheels are off the ground. As the right wing dragged along the ground during most of this sequence, liftoff in this case did not result in the aircraft becoming airborne in the normal sense of that word.

relaxation of the column rotation force from a 22 lb pull force to 10 lb push force. The ailerons and spoilers responded to full travel within 0.5 second as designed.

At 0933:52.5, the right wing tip struck the runway for the first time, and within 2.3 seconds of main wheel landing gear “liftoff,” and at 0933:52.7, the FCC commanded the shaker to deactivate as the AOA dropped below 12.2°.

At this point the airspeed had reduced to between 129 and 131 KCAS; roll angle was 17° RWD, with the right wingtip on the runway, with the roll rate continuing to increase to 10° per second RWD. AOA was about 12.0°.

The PIC commanded about 9° of TEU elevator (approximately 40 lbs pull force), increasing the pitch of the aircraft until the shaker activated again at 0933:53.4, at which time elevator input decreased to about 4° TEU (20 lbs pull force). The right engine throttle was also advanced to full throttle at 0933:53.4. The automated aural warning system of the aircraft announced “bank angle, bank angle,” with the PIC requesting “power power power” a second following the throttle command. Less than a second after the PIC’s call for power, the SIC responded “power power power’s up.” The PIC continued to pull aft on the column for the remainder of flight, as elevator command increased to the maximum travel of 23° TEU, indicating the PIC’s intention to attempt to fly out of the crisis. The shaker was active for the remainder of flight until just before the airplane’s RH MLG touched down at 0933:59.8.

At 0933:54.3, the right wingtip struck the ground again and remained on the ground for the remainder of the accident.

After a second shaker activation at 0933:53.4, AOA, roll angle, and sideslip angle increased to maximums of 17°, 32° RWD, and 17° nose right, respectively. Airspeed decreased to 117 KCAS and the airplane rolled back to the left before impacting the ground. Details regarding the airplane’s path and impact with structures on the ground are included in Section 6.

While the PIC was highly experienced with aircraft stall recovery techniques on a variety of aircraft prior to the G650, the PIC had not been involved in developmental stall testing of the G650. It is indeterminate as to whether the accident aircrew ever realized that an aerodynamic stall had occurred or whether they may have suspected other causes for the roll-off, such as winds or a possible flight control issue.

With a right bank angle of about 2° at “liftoff” and with his forward view of the ground and obstacles outside of the pilot’s windshield blocked by the glare shield, the pilot had limited awareness of his flight trajectory in relation to the runway and obstacles near the runway, such as the TM trailer and parked aircraft. In addition, as he was pulling during the rotation, the ‘cockpit’ was in an upward climb even though the right wingtip was dragging on the ground. It is possible that upon recognizing the crisis that had developed with this takeoff, he judged the aircraft’s trajectory towards the parked aircraft and Gulfstream TM trailer beside the runway an unacceptable risk for a complete abort of the flight, opting instead to try to power out of the situation as was detailed in the TSHA recovery procedures and briefed for the flight. Other factors that may have influenced the PIC’s decision to attempt to fly out of the maneuver may have included: pilot training, previous experience flying away successfully from roll-offs, TSHA guidance, and the likely damage to the aircraft resulting from aborting the maneuver versus the possibility of a successful flyaway with minimal aircraft damage.

Gulfstream estimates, in hindsight, that the best chance of survival following the roll of the aircraft on "liftoff" (essentially a loss of control) was to have fully retarded the throttles and pushed the nose hard over upon first recognition of the crisis. Aborting to a stop after liftoff had not been briefed by the test crews at any time during OEI testing and may not be consistent with their prior flight training and experiences.

5.5 Success-Oriented Focus

Like many organizations comprised of success-oriented individuals, Gulfstream's G650 test team was committed to completing an ambitious test schedule and delivering robust performance capability to its customers. This success-oriented focus is a natural human tendency and may have contributed to the mutual confidence the team had in each other, and a reluctance to challenge assumptions and highlight anomalous aircraft behavior during tests. This group dynamic may explain the modifications in "real time" to test technique development in hopes of achieving elusive takeoff speed targets. Moreover, the failure to cease further testing and investigate previous roll-off events and other leading indicators of flawed takeoff speed schedule data demonstrated a lack of risk identification and investigative process emphasis. The events listed below are noteworthy as they relate to the narrow focus on parameter achievement, arguably at the exclusion other key safety-of-flight criteria.

- Review of Reference 2 indicated that the test team was increasingly focused on achieving V_2 targets as they proceeded through the takeoff performance testing points during Field Performance Testing, generally, and including the day of the accident.
- Before Flight 153, the difficulty in achieving the desired V2 speed was in conflict with 14 CFR 25.105(b) which stipulates that "no exceptional piloting skill or alertness" will be required in determining takeoff data. It should have been apparent that given the challenging technique being explored to achieve the targeted speeds, something was amiss about the derived speed schedules.
- Discussions regarding continued refinement of the takeoff technique occurred throughout the testing program, beginning with Birmingham, continuing through Roswell II during flights such as Flight 132, and including further conversations among the Flight 153 flight test crew.
- Despite several pilot and crew comments (beginning during Birmingham and continuing through Flight 153) concerning both the difficulty of achieving the target takeoff speeds and the validity of the takeoff speed schedule, no further actions were taken.
- TM Engineers' requests during Flight 153 that the test crew relax the initial pull force more slowly.
- The SIC focused during Flight 153 on raising the landing gear immediately following establishment of positive rate of climb, as he had been coached during Flight 111.

- During Flight 153, there was a lack of discussion amongst the test crew following Run 6C3, which indicated pitch prior to “liftoff” approaching the previously agreed upon abort criterion of 11°.
- During Flight 153, there was a lack of discussion following Runs 3A3 and 7A1, which illustrated abnormal behavior in that the airplane did not liftoff until approximately three seconds after reaching the target pitch angle, and did not climb above 5 ft AGL for another 4-5 seconds. The abnormal behavior was further illustrated by the SIC’s repeated unsuccessful attempts to raise the landing gear on Run 7A1.

This channelized attention on V_2 speed was so intense that awareness of the aircraft’s unexpected behavior (that should have called into question the underlying speed schedules) was diminished.

5.6 Wind and Airspeed Data

The TSHA for OEI CTO testing limits winds to 10 knots total and components of 5 knots crosswind and 2 knots tailwind. Wind data transmitted from the Gulfstream weather station to the airplane display and TM trailer indicated total winds of approximately 5 knots at 155° starting prior to brake release and continuing during the takeoff roll up to approximately liftoff.

Actual wind data at brake release was within established limits for the test (4.2 knots crosswind with a 2.9 knots headwind component). Average wind heading was within 5° of the heading transmitted to the airplane.

Weather station data does indicate a gust between rotation and liftoff to approximately 8 knots, but it should be noted that the weather station was approximately 0.25 NM from the airplane at the time of rotation (see Figure 4).

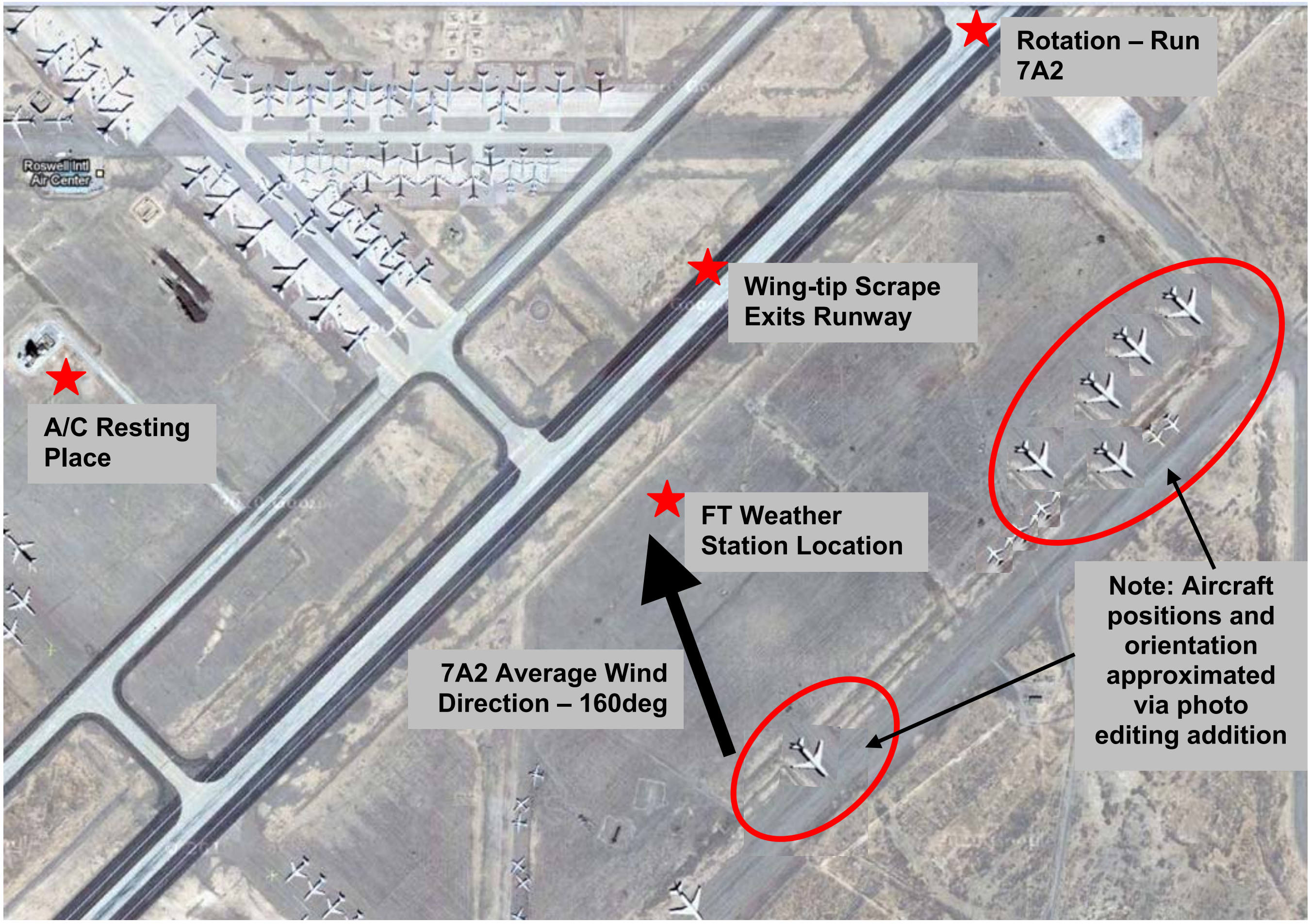

FIGURE 4 - WEATHER STATION LOCATION IN RELATION TO AIRPLANE DURING ACCIDENT RUN

Review of airspeed data for Runs 7A1 and 7A2 revealed that the airspeed value and trend for these runs was much more turbulent than for earlier runs on the day of the accident. This phenomenon was observed by the SIC after Run 7A1, and for this reason the crew agreed that Run 7A2 would be their last takeoff of the day. In general, the "noise" in the airspeed data increased as winds became more variable as the day progressed. Gulfstream also identified in its analysis after the accident the presence of several large aircraft to the left-hand side of the runway along the accident path, each of which would produce a wake that would eventually reach the region near the point of rotation for the aircraft. The position and orientation of these aircraft are approximated in Figure 4 (denoted by red ovals). Any wind effects transmitted by these parked aircraft may not have been recorded by the weather station.

Increased wind activity as well as the presence of several large aircraft upwind of the runway may have contributed to unsteady airspeed. Consequently, capture of a target takeoff speed would have been more difficult for the pilot. Gulfstream concludes that the unsteady airspeed, when coupled with the incorrect takeoff speed schedule, may have been a contributing factor to the accident.

6 CRASH DYNAMICS AND SURVIVABILITY

Following the dynamic events set forth in Section 5.4, the airplane rolled left from its severe right roll attitude, striking the ground in a grassy area to the right of the runway at approximately 09:34:00. The airplane was moving in the direction of Gulfstream's TM trailer. The wreckage review set out in the NTSB factual reports documents that the RH main landing gear contacted the ground first, followed by the LH main landing gear, the RH gear again (which came off the ground briefly after initial contact), and finally the nose gear. Per design, both main landing gear collapsed and separated from the airplane (to prevent rupture of the wing fuel tanks), and the nose gear remained underneath the airplane. As the airplane slid through the grass adjacent to the runway and across an airplane taxiway, it impacted a concrete electrical shaft, which ruptured the right wing fuel tank. While significant sparking was reported prior to this point, upon impact with the concrete electrical shaft, the fuel from the aircraft ignited and the airplane became engulfed in flames. The airplane also impacted an earthen berm, causing a large, visible crack from the base to crown of the fuselage, intersecting the forward emergency exit openings. The airplane continued to slide and impacted a weather station, rupturing the left wing fuel tank. In addition, a steel support C-beam for the weather station entered the left engine. The fire, which began at the wings, worked its way forward as the fire intensified and the aircraft slowed its forward progress. The aircraft came to a stop within about 15 seconds of striking the ground, and the fire quickly engulfed the front of the airplane as reported by the witnesses and photos of the airplane during the fire. The second photograph of the airplane on fire[14] documents that within 2 minutes of the aircraft coming to rest the intense fire was fully consuming the aircraft forward of the tail due to the prevailing winds.

According to Gulfstream witnesses who observed the aircraft pass in front of them, and ATC tower personnel who watched the aircraft skidding straight towards them, coming to rest just several hundred feet in front of the tower, the airplane fire was intense, having started underneath the fuselage at the compromised wing at least 1000' prior to the aircraft coming to rest.

Post-accident wreckage review confirmed that two of the four over wing emergency exit doors had departed the aircraft during the accident sequence, likely before the aircraft came to rest, and likely as the result of crash dynamics as opposed to any egress action by the crew.

The evidence confirms that while the crew members survived the initial impact, the smoke, fire, and extreme temperatures in the cabin overcame the crew almost immediately after they attempted to leave their seats and prior to reaching the last potentially viable

[14] Among the photographs taken by a Gulfstream witness, eleven of which are set out in Attachment 14 to the NTSB's Survival Factors Factual Report, is an additional photo, provided to the NTSB, taken one minute fifty four seconds after Photograph 1 (which the photographer says was taken at or before the moment the aircraft comes to rest) and before Photograph 2 of Attachment 14. This photograph documents the tail of the aircraft, already completely blackened from soot, coming into view, with the tower in the background, as the smoke cloud had already been blown forward over the fuselage and well beyond by the prevailing winds.

emergency exit, the main entry door[15]. Other egress paths were blocked by the fire and smoke.

7 POST-ACCIDENT STUDIES AND RETURN TO FIELD PERFORMANCE TESTING

During the several months following the accident, Gulfstream identified, as acknowledged earlier, critical deficiencies in the Company's understanding of the IGE stall characteristics for the G650 and its development of takeoff reference speed schedules. Correction of these deficiencies, together with other process reviews and improvements underlay the Company's return to Field Performance Testing in late 2011 and through the first half of 2012. This section addresses the specific discoveries and changes in Field Performance Testing since the accident.

7.1 IGE Stall Characteristics

Following the accident, Gulfstream determined that additional study of IGE stall characteristics was necessary. With recent advances in Computational Fluid Dynamics (CFD)[16], a practical CFD analysis of IGE issues became increasingly possible, although to Gulfstream's knowledge not yet widely utilized by any other aerodynamic concern. Gulfstream acquired new generation CFD software[17] in April 2011 for free air, high lift analyses, but expanded its original intended application to analyze the influence of ground effect on aircraft stall characteristics following the accident.

A CFD study was performed post-accident in an attempt to further quantify the ground effects on IGE stall angle (α_{STALL}). In excess of 1.3 million CPU hours of CFD computations were conducted on various aircraft operating parameters, including angle of attack, ground height, flap angle, angles of sideslip, bank angle, angles of aileron and spoiler deflections using the NSU3D solver. CFD results were then compared against wind tunnel data, flight test data, and data from the three stall events (Flights 088, 132, and 153).

7.1.1 IGE Stall AOA

Results of the CFD analysis with regards to IGE α_{STALL} are summarized in Figure 5. The analysis indicates that the Flaps 10 α_{STALL} is approximately 11.7° at ground height. Compared to free air α_{STALL} values, the analyses indicate a ground effect decrement of approximately 3° (versus a predicted ground effect decrement of 1.5° at the time of the accident). It was also noted that the ground effect decrement narrows quickly as the aircraft becomes airborne, with the aircraft α_{STALL} reaching pre-accident predicted values at approximately 16 ft (ground + 130"). A similar decrement was noted for Flaps 20.

[15] See replacement Figure 7 contained in the Errata to Survival Factors Group Chairman's Factual Report (Reference 7a). The replacement figure provides a more accurate approximate location of the victims' remains than the original Figure 7 of Reference 7. Gulfstream has also furnished to the Survival Factor's Group Chairman a figure that includes the actual floor plan of the accident aircraft to scale.
[16] A branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze fluid flows using high performance multi-processor computers.
[17] The software was NSU3D, a Reynolds-Averaged Navier Stokes code marketed by Scientific Simulations, LLC.

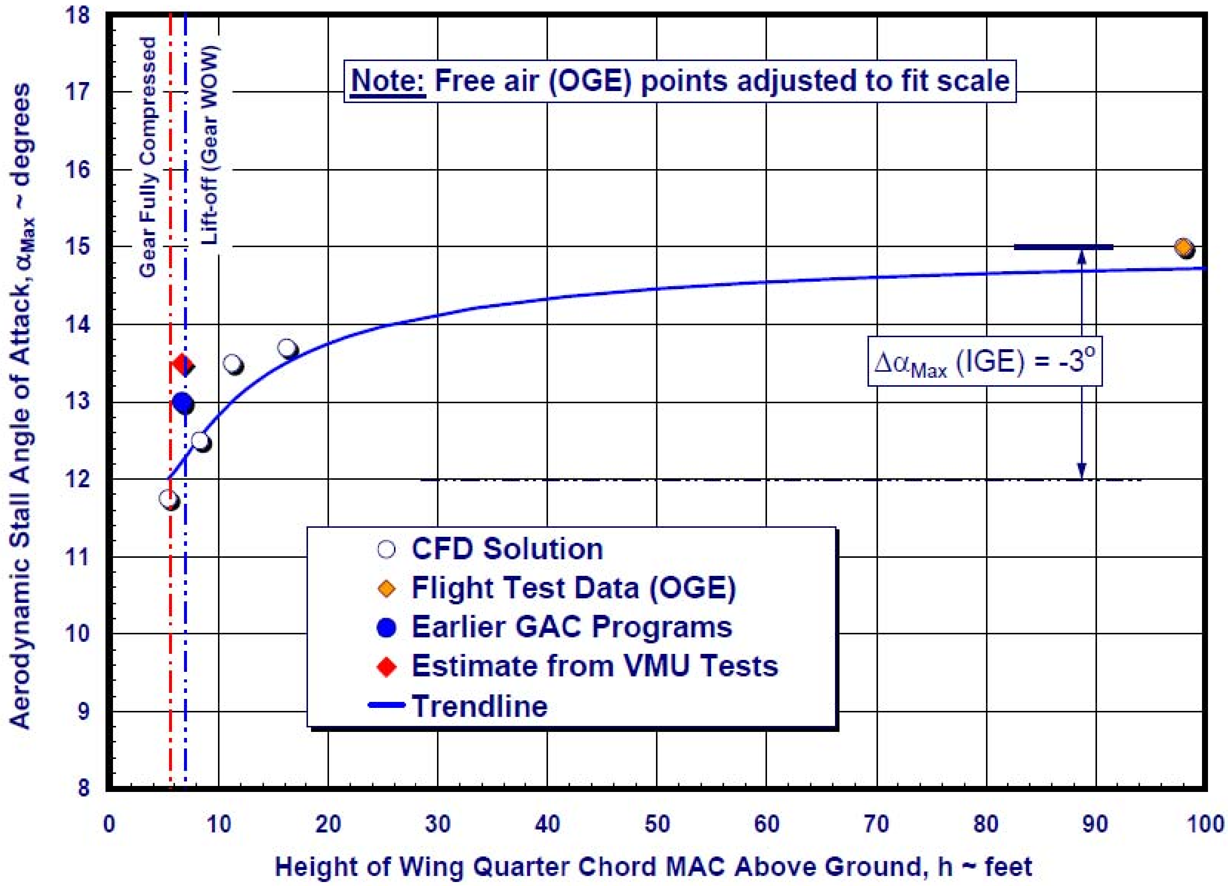

FIGURE 5 - GROUND EFFECT ON STALL AOA (FLAPS 10°)

Further CFD analysis was conducted to quantify the effects of sideslip on α_{STALL}. This analysis showed no decrement of α_{STALL} for sideslip angles below 5 degrees. Flight test data from steady heading sideslip testing indicated that no decrement to α_{STALL} was present below 10° of sideslip. During the accident run the maximum sideslip angle was 4° prior to wing tip strike.

Gulfstream concluded from this investigation that the G650 IGE stall angle was overestimated at the time of the accident by approximately 1.5°, and believes that this error was one of the causal factors of the accident.

7.1.2 IGE C_{LMAX} Characteristics

In addition to the overestimation of IGE stall angle, the CFD study also revealed that C_{LMAX} in ground effect was lower than the C_{LMAX} in free air (See Figure 6).

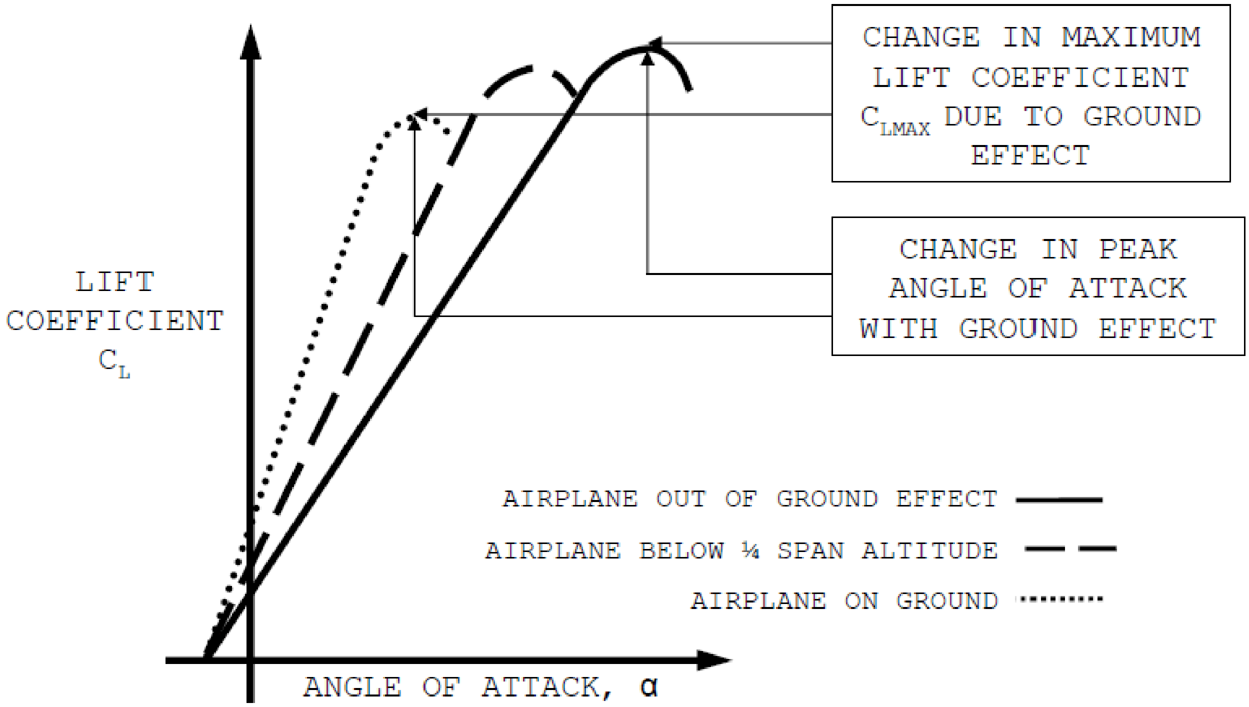

FIGURE 6 - GROUND EFFECTS ON C_{LMAX}

Figure 6 contradicts the widely-accepted industry literature illustrated by Figure 1. Reference 5, a paper focusing on the effect of leading edge contamination, also implies that the C_{LMAX} at ground effect stall is equal to the free air stall C_{LMAX}.

The assumption by Gulfstream prior to the accident that C_{LMAX} was not reduced in ground effect resulted in further overestimation of the IGE α_{STALL} following the Roswell I V_{MU} data analysis. This assumption supported further movement of the stick shaker setting from 85% NAOA to 90% NAOA. As discussed earlier, the new CFD analysis demonstrated that instead of providing margin to stall, the shaker onset AOA was actually higher than the IGE α_{STALL}. The post-accident CFD analysis therefore supports Gulfstream's conclusion not only that the shaker did not provide adequate margin, but also the pilot's likely reliance on the equivalently set PLI led him to fly into IGE stall conditions. Gulfstream believes that this intentional but mistaken modification of stick shaker / PLI settings was a causal factor of the accident.

In the interest of flight test operational safety, Gulfstream will publish the results of its post-accident analysis of ground effects.

7.2 Takeoff Reference Speed Methodology and Development

Following the accident, a review of flight test cards and interviews with flight test personnel present in the TM trailer indicated that the target takeoff speeds for the accident takeoff were properly transcribed from the performance tables published prior to the accident flight. In addition, a set of test cards belonging to one of the pilots was recovered from the wreckage and indicated that the pilots were indeed targeting the speeds that had been provided.

Post-accident analyses revealed that the V_R, V_{LO} and V_2 takeoff speeds for this testing were too slow, and the spacing between these speeds was too small. The unexpected takeoff behavior noted on Run 7A1 (reference Section 5.3) was primarily due to the improper speed targets prescribed for the test point. In Run 7A1 the actual liftoff speed was approximately equal to the target V_2 speed, meaning that the test point as written was practically impossible to achieve.

The post-accident review of the aircraft takeoff maneuvers during flight testing and methodology employed to develop airspeeds revealed several shortcomings:

- G650 takeoff speeds were developed based on the performance characteristics of legacy aircraft. The speeds were adjusted to the FAA-regulated minimum requirements for safety speed in order to minimize balanced field length. The analytical tool used to develop the takeoff field performance parameters was deficient in that it relied on empirical data from legacy aircraft. In addition, the tool lacked the capability to assess margins to α_{STALL} and accurately model aircraft dynamics.
- During Roswell I and II testing, when the test crews experienced difficulties achieving the target V_2 speeds, they began to refine the takeoff technique in an attempt to capture the target speeds. A further examination of the target speeds themselves was not performed.
- Takeoff speeds were not adjusted to account for the reduced target pitch angle for Flaps 10 takeoffs during Roswell II, which resulted in speeds for the accident maneuver being an additional 3-4 knots too slow.

Gulfstream concluded that the improper speed targets led to an unachievable test point on the accident run. This was not recognized by the test team during previous runs (Runs 3A3 and 7A1 in particular) or from reviews of flight test data. Gulfstream believes that the improper speed targets and accompanying lack of recognition are causal factors of the accident.

7.3 Speed Schedule Development / Validation

Following the accident, a new methodology was introduced to develop takeoff reference speeds, which takes into account Gulfstream's post-accident understanding of the G650 IGE stall based upon its CFD study, and avoids the errors created by using the legacy aircraft data and FAA operating minimums. This new methodology employs a four part approach, which is described in the following paragraphs. Some parts of this methodology would have been available in October 2010 prior to the initiation of field performance testing and should have been used. However, methods that rely upon later-generated G650 field performance and CFD data would not have been available at that time.

7.3.1 Part One - Desktop Speed Synthesis and Field Performance Evaluation

The post-accident method proposed at Gulfstream for airspeed development does not employ legacy airspeed data, but instead generates airspeeds using a three degree-of-freedom desktop simulation that represents the dynamics of the maneuver, the aerodynamics of the aircraft in and out of ground effect, and the control effectiveness for the specific aircraft. This desktop simulation was developed to more precisely model the take-off maneuver and predict representative takeoff safety speeds. This method employs a numerical algorithm, which solves the equations of motion to properly model the physics of the takeoff, including the dynamics of the maneuver between lift-off and the FAA obstacle clearance height of 35 ft AGL. The resulting algorithm is benchmarked against the existing Integrated Test Facility (ITF) and flight test data to ensure it precisely models the dynamics of the aircraft. The ITF is a stationary, fixed-base simulator which interfaces with aircraft hardware and a six degree of freedom numerical simulation of the aircraft dynamics. Once benchmarking is completed, the program is used to develop a set of takeoff speeds which ensure, among other considerations: 1) an achievable and repeatable initial pitch attitude at rotation and 2) a suitable margin between the operating angle of attack and the stall angle of attack during ground effect operations and climb out to 35 ft AGL. These final airspeeds are designed to guarantee a specific stall margin during all engines takeoffs, single engine takeoffs, and abused takeoffs. Within the algorithm, the final airspeeds are also checked to always ensure that the regulatory margins relative to V_{MU}, V_{MCG}, and V_{SR} are satisfied.

7.3.2 Part Two - Integrated Pilot-in-the-Loop Simulation for Speed and Technique Validation

The post-accident approach to take-off speed development also uses the G650 ITF to validate the take-off speeds developed at the desktop level in a pilot-in-the-loop environment[18]. While the ITF's principal function is to verify aircraft hardware, at Gulfstream the ITF is also used for pilot training and technique development for hazardous testing within the safety of a laboratory environment. The G650 ITF is thoroughly benchmarked against flight test maneuvers performed during the company flight test program to ensure that it correctly models the aircraft dynamics.

After the accident, the ITF was employed in a dual role to help in the development of the G650 take-off speeds. The first role was the development and verification of a suitable and repeatable pilot technique (one that does not require exceptional pilot skill, as required by FAA regulations), which would allow the aircraft to safely rotate to the initial pitch attitude and to lift-off and climb-out through 35 ft AGL. A technique was developed, tested and verified using multiple Gulfstream pilots and several FAA pilots performing controlled all-engine and single engine take-offs before migrating the technique onto the flight test aircraft.

In a secondary (but equally important) role, the ITF was used to verify that the aircraft would operate as predicted by the desktop simulation across a range of airfield elevations and for all aircraft takeoff weights. This secondary task provided an additional verification of the established takeoff speeds from the desktop simulation prior to the start of field performance testing.

[18] For this purpose, the term "pilot-in-the-loop" is an industry expression to imply human interaction with a numerical model of the aircraft in a simulator environment.

7.3.3 Part Three - In Ground Effect Stall Warning

Initially, the information extracted from the post-accident CFD study was used to more precisely define takeoff speeds and later was employed to generate safety of flight AOA margins to be used in flight testing. The takeoff speeds, pitch targets, and AOA margins were monitored during post-accident field performance testing in real time both onboard the aircraft as well as by a ground support crew of engineering personnel in the telemetry trailer. In order to improve safety and pilot awareness, an enhancement to the stall warning system was developed in the Flight Control Computer (FCC) software utilizing the G650 radio altimeters which indicate height above the ground. Knowing the height above the ground and air data Mach number, the IGE α_{STALL} can be computed. Combining this with a suitable margin to stall, the FCC can drive the pitch limit indicator (PLI) on the attitude indicators on both the primary flight display (PFD) and the heads up display (HUD) providing the pilots with an unprecedented level of ground effect situational awareness. Lastly, in the event the aircraft AOA encroaches upon this margin to stall, the FCC will then activate the stall warning stick shaker.

7.3.4 Part Four – Improved Flight Test Monitoring and Support

Following the accident, during field performance testing, additional engineering specialists supporting flight testing are located on-site at telemetry stations for improved real-time monitoring and analysis of the general handling characteristics of the aircraft during all phases of the takeoff testing. These engineers utilize two independent and dissimilar real-time desktop simulations to predict the aircraft characteristics for each maneuver being flown and provide the expected minimum margins to aerodynamic stall. Prior to the start of each takeoff run, estimates of the minimum margins are developed by each simulation, compared for validity, and communicated to the crew on the test aircraft before the aircraft is released for takeoff. As an additional level of safety, a build-down to the published takeoff speeds during the initial phase of each takeoff test has been implemented. If during any takeoff the aircraft shows abnormal characteristics different from predicted[19] by the on-site desktop estimates, testing would be halted. The data would then be thoroughly reviewed prior to proceeding with the next test. If the cause of any abnormal characteristics cannot be immediately identified and corrected, testing is halted until the phenomenon is satisfactorily explained.

7.4 Field Performance Takeoff Technique Review and Adjustment

As noted in Sections 4 and 5, development of the takeoff technique employed during the pre-accident field performance testing was an iterative process throughout the regime of performance flight tests, including Flight 153. Gulfstream observed, however, that the flight card takeoff technique had not been changed since the initial takeoff performance testing at Roswell I. In addition, interviews with Gulfstream personnel indicated that the technique was not clear as to the timing of pitch adjustments – some personnel indicated that the initial target pitch angle should be held through 35 ft AGL; others indicated that pitch could be increased once airborne and a positive rate of climb was established.

[19] In this case, abnormal characteristics could include but are not limited to the following: slow aircraft responsiveness, lack of acceleration during the ground phase, excessive air phase or climb-out times, and unexpected encroachment on stall angle margins.

Due to the confusion noted with regards to the technique, Gulfstream concluded that the test card's lack of precision as to the timing of pitch adjustments could be a contributing factor to the accident.

7.4.1 Revised Test Procedure / Technique

Using the methodology described in Section 7.3.2, a revised technique for CTO testing was utilized for the remainder of the company CTO tests. The steps are listed as follows from the flight card for the post-accident Roswell field performance test:

1. Configure aircraft for takeoff.
2. Align aircraft on runway and apply brakes.
3. Set L & R PWR.
4. Release brakes.
5. At V_R-20 chop power to L ENG to IDLE. Use rudder and NWS as required for directional control.
6. At V_R, perform a progressive control column pull to approximately one-half aft displacement from the neutral position so that the airplane pitch response occurs within approximately one (1) second. A moderate pitch rate should be maintained until achieving the initial pitch attitude target of 9 degrees.
7. Maintain target pitch attitude until aircraft is confirmed in "air" and it is necessary to increase the pitch attitude to capture V_2. Do not retract landing gear.
8. Adjust pitch attitude to maintain target climb speed to 100 ft AGL. Do not exceed 20 deg pitch attitude. Maneuver complete at 100 ft.

The revised technique restricts pitch attitude from exceeding the initial pitch target while on the ground and assures a safe liftoff with at least 1° of margin to IGE α_{STALL}. After the company field performance tests were completed and the takeoff speed schedules validated (to include assurance liftoff would be reached prior to reaching the initial pitch target), the text in Step 7 was changed to read:

7. Maintain target pitch attitude until it is necessary to increase the pitch attitude to capture V_2. Do not retract landing gear.

7.5 Review of TSHAs for Performance Testing

As noted in Section 4.1, the TSHA for the accident takeoff test point (No. 84 - OEI Takeoffs) identified the primary hazard driving the risk classification as "Aircraft Departs Runway / Inadvertent Ground Contact" due to "Engine Failure / Loss of Control." Unlike the TSHAs for abused takeoffs and V_{MU} takeoffs, the OEI TSHA did not identify over-rotation at low airspeed and low altitude stall as potential loss of control causes, nor did it identify a roll angle limit. Unlike V_{MU} or abused takeoff tests, the underlying assumption for the OEI TSHA was that the normal takeoff procedure and takeoff speed schedule would provide adequate margin such that inadvertent stall was not a consideration. It is now recognized that this assumption is not valid until the takeoff speed schedule is fully validated by testing. In the process of returning to Field Performance tests, this TSHA was reviewed and revised to include several modifications:

- Included additional hazards for over-rotation at low airspeed and low altitude stall (OEI takeoffs) with associated corrective techniques. The corrective technique identifies an option, at pilot discretion, to either a) decrease angle of attack, advance throttles and regain control and climb to safe altitude, or b) decrease angle of attack and retard both engines and land.
- Added the requirement that the local Crash Fire Rescue (CFR) support to be "in-position" outside the fire station to allow for the most expeditious response time in the event of an accident (high risk tests only).
- Specified that the 9° initial takeoff pitch attitude target limitation would not be exceeded until liftoff was confirmed.
- Specified that the stick shaker and pitch limit indicator (PLI) settings would maintain an IGE stall AOA margin of at least one degree.
- Stated the roll angle limitation along with information on wing tip strike.
- Required use of TM support and interim data review between each test maneuver, including the requirement of concurrence between TM support and flight crew to continue to the next test condition.
- Established wind gust spread limitation of 5 knots.
- Added that the displayed airspeed would be monitored to determine if fluctuations are too large to support continued testing.

The revised TSHA was successfully employed during Gulfstream's post-accident company field performance testing. As noted in the previous section, after the company field performance tests were completed and the takeoff speed schedules were validated, the procedural step to confirm liftoff was removed from the test procedure and therefore removed from the TSHA.

8 ADDITIONAL POST-ACCIDENT IMPROVEMENTS

8.1 Safety Reviews Undertaken

Since the accident Gulfstream has conducted a thorough internal Engineering Safety Review Board process and conducted internal reviews of relevant engineering organizations and processes. In addition, at Gulfstream's request, outside counsel selected and retained a group of experts to conduct a privileged and confidential review of the safety practices and culture in all of Gulfstream's flight test and flight operations activities and to provide advice on industry best practices. In order to avoid any conflict with the NTSB investigation, the scope of this external review purposefully did not include a review of the accident.

The findings from all of these activities, as well as information from Gulfstream's ongoing support of the NTSB investigation, formed the basis of a comprehensive safety action plan that Gulfstream has been implementing since the time of the accident. Some elements of the safety action plan are relevant to the causes of the accident; others are not. All are included in this submission in order to give a complete picture of Gulfstream's focus on safety actions following the accident. Features of this plan that are not already described in Section 7 are documented in this section.

8.2 Process Documentation

While certain sections of the Gulfstream's Flight Test Standard Practices Manual adequately covered pre-accident processes (e.g., the risk assessment and risk alleviation requirements of the TSHA), the 1998 manual was outdated in several areas. The most recent versions expand the manual to provide new material and are otherwise modified to:

- More accurately reflect the multi-phased workflow of the flight test process starting from the early stages of planning through detailed planning, execution and final reporting and project closure.
- Reflect the current organizational structure along with the corresponding roles and responsibilities.
- Include a new section on Accident and Incident Reporting to enhance communication of incidents (such as Flight 088 and Flight 132) and expedite subsequent data reviews. This process provides guidance on the definition of an incident, specifies details to provide in the report, and identifies the standard distribution of the report to senior technical and management personnel along with the newly created Aviation Safety Officer position (described in Section 8.5).
- Update the Safety Review Board process to include details on when reconvening an SRB should be required.
- Include a requirement for periodic audit of the processes to allow for formal incorporation of lessons learned and industry best practices.

A dedicated Flight Operations Test Pilot Manual was also created, which replaced and expanded upon flight test operations information that existed in the pre-accident Flight Operations manual. The document is electronic and in PlaneBook™ format, which provides many features for document management. The objective of the new manual is to capture Gulfstream processes, corporate policies, Federal Aviation Regulations (FARs) and standard operating procedures (SOPs), as well as any documents and manuals that exist outside the department about which test pilots need working knowledge to understand roles and responsibilities of the various parties involved in flight test activities. All of the test pilots have this information provided via iPads, through which Gulfstream is able to provide automatic updates to the information.

Long-term actions were also identified, including the establishment of an electronic document library for flight test engineers that is accessible via iPad, creation of a *Gulfstream Flight Test Guide* to document details on flight testing techniques and lessons learned to complement existing FAA guidance, and increased participation in industry Flight Test committees and symposiums.

The final information configuration will integrate Flight Operations, Flight Test Engineering, and Engineering in a single document management system that provides for standardization of document format, ease of access, and sharing of information of common interest. This is designed to ensure that governing processes are understood by all responsible parties, which can then be coupled with data to allow for appropriate communications to ensure safety of operations.

8.3 Flight Test Data Analysis

Review and analysis of flight test data is now completed more quickly, using enhanced and existing tools and disciplined processes. To avoid a repeat of the missed opportunity for broad review following Fights 88 and 132, the test crew will now provide a formal incident report as described in the preceding section. This provides not only communication of the incident, but also recommended limitations until the incident is further understood.

Gulfstream has also expanded protocols for test support requiring senior cognizant engineers from appropriate multiple disciplines to be present at all flight briefs for each test classified as medium- or high-risk. This enables a more effective peer review of potential anomalies observed during flight and determines if immediate post-flight data analysis is needed or if testing should be halted until a better understanding of the results is obtained. If required or requested, flight test data can be processed and downloaded onto the network within hours of test flight completion. Post-flight data analysis criticality is based on anomalies or unexpected results observed by the test crew in real-time.

Gulfstream reviewed FTE workload and organizational alignment and made changes to better accomplish data analysis, reduction, and expansion tasks. For example, when field performance testing was resumed, the FTE on-board the aircraft had the responsibility of test execution. A senior FTE served as the test conductor in the TM trailer, and additional FTEs were assigned to processing, analyzing, and reporting data. Gulfstream continues to review the roles and responsibilities of the Flight Test Engineering and design engineering organizations, including how best to distribute the workload for test execution, data reduction, and report writing to support future flight test programs.

8.4 Engineering

Gulfstream improved processes to ensure that data and flight reports are promptly available for review by the appropriate engineering disciplines. As noted in the preceding section, Gulfstream also identified senior engineering specialists to support all high risk testing. In particular, the team assigned to support field performance flight testing was selected to facilitate rapid, yet thorough, data reduction and expansion activities. Within Flight Test Engineering, issuance of regular Flight Reports (short summaries of each aircraft's daily flight test activities) was assigned an increased priority.

As a result of dedicated engineering reviews, Gulfstream has drafted a plan to enhance the engineering simulation capability to improve confidence in the pre-flight data estimates, improve pilot-in-the-loop assessments with a higher fidelity flight simulation, and improve the computing power necessary to support a more integrated engineering modeling and simulation environment for future aircraft development with the focus on reducing flight test risk and improving safety.

In addition to the extensive use of CFD to better understand stall characteristics in ground effects, Gulfstream will continue to expand the use of higher-order CFD and implement methods to develop reliable data at the extremes of the flight envelope and in the non-linear regime such as stall and post-stall characteristics, Mach number effects, Reynolds Number effects, buffet boundaries, stability and control boundaries, etc.

The simulation environment will be improved through higher-fidelity models to better represent not only the dynamics of takeoff and landing performance, but also stall and post-stall characteristics, maximum sideslip conditions, aircraft response with system failures, and any planned high-risk maneuver with the intent to perform and evaluate these high-risk flight test conditions in a simulated environment prior to demonstrating and verifying the expected characteristics on the flight test aircraft. With that expectation, Gulfstream is also investigating technology advances in simulation hardware that better represent a realistic environment and provide relevant pilot cues such as out-the-window visuals and/or motion.

The enhanced simulation tools and methods will be used with a more integrated approach between the engineering, flight test, and flight operations groups. Multi-disciplinary technical reviews are to be conducted for validation of the database, the simulation modeling, and the expected aircraft flight characteristics in preparation for flight test. The affected parties will have more visibility as to the state and maturity of the simulation at any point of the development with configuration and version control mechanisms. Pilot evaluations in the simulation environment will be conducted with the appropriate technical disciplines present for timely and efficient results.

Gulfstream is committed to dedicating the resources necessary to implement these improvements in an effort to advance its predictive capability and reduce risk in future flight test programs.

For future flight test programs, Gulfstream will strictly ensure that test requirements documents be created by design engineering in advance of the creation of associated flight test plans by Flight Test Engineering. The document review and approval process will involve a broader multidiscipline senior peer review and authorization. The company is also exploring the benefits of further integrating the flight test engineering and design engineering functions to enhance both safety and efficiency.

A review of flight test data access and control procedures will be undertaken to improve engineering's access to flight test data, while balancing the benefits of immediate access to raw data by the engineering community (as is being done currently with select areas of engineering) with the requirement for sufficient validation and control of the data.

8.5 Safety Culture

Gulfstream is committed to continual safety improvement and enhancement of safety culture. To that end, following the accident, Gulfstream conducted significant safety-related reviews and assessments. The results have provided a basis for determining improvements but also a baseline for future trend analysis. Gulfstream leadership has re-affirmed its commitment to cultivating a positive and vibrant organizational safety culture and supporting initiatives that further safety promotion company-wide.

In September 2011, Gulfstream created an Aviation Safety Officer ("ASO") position, reporting directly to the President of the company. The ASO is responsible for core safety management system compliance as well as identification, development and implementation of flight test industry "best practices." This will encompass all Gulfstream flight operations including experimental flight test, production flight test, demonstration flights, and product support and other corporate flight activity. Additionally, the ASO will facilitate SMS implementation within the Gulfstream flight operations, flight test, and engineering communities, ensuring gapless synergy among all aircraft and systems developmental competencies. The position had been filled on an interim basis until April 2012 when Gulfstream announced the appointment of an experienced US Navy Flight Test professional as ASO.

8.5.1 Safety Management System (SMS) Initiatives

Several years ago, Gulfstream recognized the efforts of the International Civil Aeronautics Association (ICAO) and national regulatory authorities to encourage initiation and development of effective Safety Management Systems (SMS) to improve aviation safety. To support safety as Gulfstream's highest priority, and to ensure Gulfstream's compliance with these future regulatory standards, Gulfstream developed a company-wide SMS development and implementation plan that would apply across all organizations and operations including design, manufacturing, flight operations and product support.

The Gulfstream corporate SMS program began in 2007 within its Part 145 service and repair station organizations. Today all ten of Gulfstream's Service Centers operate under an SMS. Also in 2007, Gulfstream's Flight Operations implemented an SMS for demonstration and corporate transportation activities. At that time, there was no template for incorporating SMS into Flight Test Operations. Gulfstream's manufacturing organizations began implementation of an SMS in 2011. Since the accident, SMS implementation has been initiated within the remainder of Flight Operations and within Flight Test Maintenance, with stand-up completion scheduled for 2012. As a part of this activity, software has already been implemented and utilized to collect data on hazards and incidents in ground and flight operations. The current corporate focus is acceleration of the SMS implementation within flight test engineering and design engineering organizations.

In February 2011, Gulfstream committed to participate in the FAA SMS Pilot Program for Design and Manufacturing organizations. Gulfstream is one of 14 aviation product companies selected to participate in a project that requires the participants to conduct a gap analysis of their company processes and procedures against a set of SMS principles and attributes, develop an implementation plan to address the gaps and start integrating key SMS elements into their business practices. The results of this pilot program will be used by the FAA to determine their approach to SMS rulemaking and development of the SMS requirements that may be associated with an actual SMS rule. In the interest of further enhancing its commitment to continued airworthiness and product integrity, the scope of Gulfstream's SMS Pilot program was a Continued Operational Safety (COS) initiative which would surpass the current regulatory requirements for event reporting and issue investigation and mitigation. To date, Gulfstream has completed the detailed gap analysis, developed an implementation plan and is currently working to develop enhanced COS processes for all Gulfstream type design products and models of aircraft. Commitments to this FAA pilot program and Gulfstream's progress are best reflected earlier this year by Gulfstream's becoming the first Type Design Holder to successfully exit Level 1 of the FAA pilot program – this accomplishment required completion of detailed gap analysis, development of an implementation plan, and concurrence by the FAA SMS team.

8.6 Schedule and Workload

After review of the facts and circumstances, Gulfstream believes that schedule pressure was not a contributing factor to this accident. During the course of the G650 development program, the program schedule had been extended several times. By the date of the accident, the then-current flight test schedule had clearly become overly optimistic and was perceived by some as unduly ambitious. There was ample testimony from those involved with the flight test program that they were ignoring the schedule at any point that it threatened to compromise safety. Specifically, there is no evidence that the field performance flight test crew allowed any schedule pressure to affect their safety of operations. All employees who were questioned on the subject acknowledged that there were schedule pressures in all flight test programs they had ever been involved with, and only two employees suggested that the schedule pressure for the G650 program was greater than they had experienced in other programs. But even these two employees, who were knowledgeable about the accident at the time of their interviews, and familiar with the field performance testing at the time it was going on, agreed that schedule pressure played no part in the accident. Even the employees most critical of the ambitious schedule testified that the flight test community ignored the published schedule, and flew only when it was appropriate and safe to do so. Two engineers who were responsible for providing speed schedules thought that "in hindsight" schedule pressure might have played a role in the accident. However, Gulfstream's analysis of speed development described above does not suggest that schedule pressure played a role in the errors that were made in speed schedule development.

Notwithstanding Gulfstream's conclusion that schedule pressure did not cause the accident, Gulfstream has already dedicated greater resources, including personnel, equipment, and flight months for future flight test programs in order to mitigate concerns with schedule and workload. While crew duty day limits were not revised, flight hour limits were created based on risk levels, and the consecutive workday limit was revised as noted in Table 2. Furthermore, maintenance activities were prioritized for Sundays to help facilitate the consecutive workday limit. Crew rotations for company high risk tests were eliminated. A three shift (8 hours per shift) maintenance schedule was imposed to provide 24-hour coverage and to reduce overtime.

TABLE 2 - PRE- AND POST-ACCIDENT FLIGHT CREW, FTE, AND CRITICAL TM PERSONNEL DUTY LIMITATIONS

	Pre-Accident	Post-Accident[20]
Flight Hour Limit – Low Risk Testing	12 hours	10 hours
Flight Hour Limit – Medium Risk Testing	10 hours	7 hours
Flight Hour Limit – High Risk Testing	10 hours	6 hours
Consecutive workday limit	13 days	7 days / 60 hours

[20] Defined waivers may be authorized by the Director and Vice President of Flight Operations.

8.7 Survivability Improvements

The flight test aircraft now utilized for field performance testing has been outfitted with the following items, intended to improve the survivability of an accident:

- Onboard fire suppression system
- Additional personnel equipment (improved flight suits and hoods)
- Additional egress options (removable window plugs on the LH and RH #2 windows)
- Additional safety equipment (portable fire extinguishers, saws, smoke hoods, crash ax)

As noted in Section 7.5, airport ARFF readiness has been elevated for all high risk testing.

9 THE TAKEOFF PERFORMANCE OF G650 TODAY

Following a thorough review and extensive cooperation with the NTSB in determining the precursor events and direct causes of this tragic accident, the G650 returned to flight testing on May 28, 2011, and Field Performance Testing was resumed in December 2011.

All field performance test points have been re-flown using the new techniques and processes developed during the company's post accident improvement process as outlined in Section 8. Additionally, following extensive post accident analysis, Gulfstream determined that the targeted Balanced Field Length could be preserved with a 5% increase in the thrust generated by the G650 engines. The additional thrust was provided by Rolls-Royce prior to recommencing field performance testing. FAA certification (TIA) field performance testing is currently in process. Revised speed schedules have been developed using improved methods and have been confirmed through flight test as accurate. IGE stall characteristics are well understood and have been incorporated into the aircraft's stall warning system. While the FAA has yet to comment on its certification activity, Gulfstream, based upon satisfactory completion of its own testing prior to commencement of FAA testing, is confident that the demonstrated results accurately reflect the field performance of the G650.

10 CONCLUSION

The aircraft experienced an unexpected aerodynamic stall of the right wing during the takeoff maneuver while in ground effect. After impact, collisions with obstacles on the ground caused a severe fire.

Gulfstream believes the following were the causal factors leading to the accident:

- The stall angle of attack in ground effect and the C_{LMAX} in ground effect were overestimated.
- The takeoff speed schedule was not properly developed or verified, resulting in an unachievable test point for the accident run.
- Gulfstream's internal analysis, review and approval processes did not identify these two errors prior to field performance flight testing.

- o Two prior IGE roll-off events in the G650 field performance program and other flight test anomalies arising from these improper speed schedules were not widely reviewed or properly understood.
- o The PLI and stick shaker settings did not provide adequate margin to stall in ground effect.
- o The flight test team's focus on achieving speed targets diminished awareness of the aircraft's unexpected behavior (which, if recognized and addressed, could have called into question the underlying speed schedules).
- o The test procedure and pitch limits were insufficiently precise as to the timing of pitch adjustments. This allowed the flight test team to modify takeoff techniques in "real time" during testing, including during Flight 153, without thoroughly analyzing the risks of the new techniques or agreeing on mitigating responses to those risks.

Gulfstream also believes the following were contributing factors to the accident:

- o The TSHA for OEI CTO testing did not expressly identify low altitude stall and roll-off as potential hazards with appropriate corrective actions, and did not specifically define abort criteria and response.
- o The unexpected roll angle excursion may not have been initially detected and was not fully countered by the crew until just prior to initial wingtip strike. Reduction in angle-of-attack (to break the stall and restore lateral control power) was insufficient to safely fly the aircraft away, and the crew elected not to abort the takeoff (which may have been a viable option).
- o The failure to reduce power after exiting the runway may have exacerbated the collisions that caused the fire.
- o Turbulent air during takeoff caused the airspeed to be unsteady, which likely caused the pilot flying some difficulty achieving the target takeoff speeds.

Gulfstream concluded the following regarding the loss of the aircraft crew:

- o The crew members survived initial impact.
- o The aircraft fuel tanks were ruptured after the aircraft left the runway / taxiway and impacted structures on the ground, fueling a severe fire.
- o The smoke, fire and extreme temperatures in the cabin overcame the crew almost immediately after they attempted to leave their seats and prior to reaching any viable emergency exit.

Gulfstream accepts full responsibility for the accident and for the development and implementation of corrective actions.

Following the accident, Gulfstream has conducted detailed additional analysis of IGE stall. As a result, IGE stall characteristics are well understood and have been incorporated into the aircraft's stall warning system. Revised speed schedules have been developed and tested using improved methods and have been confirmed through flight testing as accurate.

Based on the results of the NTSB factual investigation as well as other safety reviews, Gulfstream has implemented many safety enhancements. Gulfstream has created an Aviation Safety Officer position, reporting directly to the President of the company. Gulfstream has also improved documentation, processes and procedures, increased support of flight test by design engineering, convened more detailed and frequent flight test safety review boards, and improved onboard emergency equipment for test aircraft to better protect aircrews.

This accident was specific to developmental flight test and has no meaningful implications for the in-service operations of the G650. The investigation revealed no mechanical or systems failures whatsoever. Engines, flight controls and other components performed as expected.

Although developmental flight test is inherently risky, this accident could have been avoided. A significant number of pre-conditions went uncorrected, including inadequate aerodynamic performance development, data analysis, and peer review processes. Failure to communicate unexpected test results and channelized attention in continued pursuit of unobtainable takeoff speed values are indicative of shortcomings in the development process that may have been partially masked by the success-oriented team environment.

While the tragedy cannot be undone, Gulfstream has fully evaluated the causes of the accident, as well as other aspects of its flight test, flight operations and engineering organizations and made necessary and appropriate improvements and enhancements. Gulfstream takes seriously its responsibility to continually evaluate and improve its safety practices, procedures and culture, company-wide.

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