A Tragic First – Gulfstream G650 Flight Test Accident

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GULFSTREAM G650 FIRSTS

- First Aircraft Capable of traveling unrefueled 6000nm at 0.90M
- First Business Jet to fly 7000nm at 0.85M
- First Civil Aircraft Certified to Mmo of 0.925M
  - Sustainable for extended periods in Cruise Flight
- First Gulfstream Fly-By-Wire Aircraft
  - First Business Jet to Include EBHAs
- First Business Jet at 51000 ft to have Cabin Altitude of 4850 ft
- First Gulfstream Flight Test fatal accident
Reason We Are Here
Accident Test Condition Synopsis

• Date: April 2, 2011

• Location: Roswell, NM
  – Runway 21

• Company / Development Testing
  – 6002’s Flight #153
    • 12th test point of the flight

• Test Maneuver: Continued Takeoff, One engine inoperative
  – Heavy TOGW (88,000 lb), Forward CG, Flaps 10°
  – At VEF, retard R/H Throttle to idle thrust
  – Target 9° initial pitch attitude, then intercept V2
The Accident Test Point.....

• Things to note during the video:
  – Initial rotation to 9 deg, then pitch rate changed from 5 to 1 deg/sec
  – Pitch limit indicator tracking (AoA limit on a pitch presentation)
  – Roll develops just prior to becoming airborne
    • Ambiguous and subtle aircraft behavior and response to controls
      – Gradual increase in roll rate, no sharp break ~10 deg/sec maximum despite full opposite roll input
      – Yaw divergence to right despite full left rudder

• View through the windscreen / HUD
  – Lack of ‘over the nose’ visibility after rotation
  – Parked airplanes probably visible out right side
Video Recreation from Onboard Data

- Pitch limit indicator
- Airplane symbol
- Pitch scale (in degrees)
- Normalized AOA readout
Contributing Factors

- Aggressive takeoff speeds were targeted to maximize performance
  - Maximum performance needed to meet Product Specification for Takeoff Performance
- Testing was investigating technique variation to establish minimum $V_2$
  - Empirical approach with the Stick Shaker as the hard limit
- Incremental successes were obtained culminating in what were considered ‘good’ runs in the Flaps 20 configuration earlier on the accident flight
- Errors in Flaps 10 speeds resulted in too low of a rotation speed and unachievable $V_2$ target
Contributing Factors (cont.)

- Using incorrect critical AoA decrement for In-Ground-Effect (IGE) conditions
  - Traditional / theoretical AoA decrement was 2° for IGE
  - IGE 2° decrement was decreased ~1.6°
    - Based on analysis of VMU data and associated IGE $C_L$ shift at VMU pitch attitudes
  - Post-accident, extensive processing and data analyses revealed maximum decrement of ~4°
The Investigations

- NTSB minimal exposure to Flight Testing accidents
- Overwhelming amount of recorded data
- Pursuit to sequester and restrict access to data
  - Gulfstream “team” assigned to assist in investigation
- Email system searched for relative information
- Multiple interviews with associated Gulfstream personnel
  - NTSB interrogators from multiple disciplines
  - Corporate Lawyer present
  - All information officially recorded
  - Interviewees’ names along with all questions and responses will be released in public report
The Investigations (cont.)

• Investigators
  • May not be Test Pilots or Flight Test Engineers
  • Without flight test knowledge, extensive amount of time and patience required to explain flight testing
  • Lawyers interpret the spoken and written word differently than do engineers/test pilots

• “Maintain target pitch attitude until $V_2$ is achieved, then transition to speed.”
Accident Summary (What Could We Improve?)

- Aircraft was conducting OEI takeoff performance testing when the right wing stalled IGE, contacted the ground, departed the runway, and impacted concrete structure.

- Both wing fuel tanks were compromised and the aircraft was engulfed in fire.
What We Learned…

• Failure to properly develop and validate takeoff speeds which were erroneously low based on legacy assumptions

• Test Team’s focus on achieving $V_2$ speed required to meet performance guarantee

• Inadequate review of previous uncommanded roll events during G650 field performance testing

• Impact was survivable, but cockpit/cabin environment deteriorated quickly due to fire.

• Process/Procedure/Safety Program required improvements
What Have We Done Differently?

• Aircraft Safety Modifications
  – Fire Suppression System
  – Additional Emergency Exits
  – New Onboard Emergency Equipment
  – “CUT HERE” Markings

• Flight Test Procedural Improvements

• Flight Test Incident Reporting

• Developed New Methods to Determine and Verify Vspeeds

• Crash Crew Booklet and ARFF Coordination (not exactly new)
G650 Fire Suppression – Requirements

• Developed System Based on Information from Cessna
  – Enhanced System Capabilities in close cooperation with GSL

• Provide on-board test crew with fire protection using GSL’s proprietary Firebane fire suppressant agent:
  – Fire Extinguishing
    • Including fires from reactive metals such as magnesium or lithium
  – Fire Prevention
    • Prevent re-ignition of flames for 2 minutes
    • Protect occupants wearing standard clothing for 10 seconds while exposed to constant 1800°F

• Agent to be discharged at following locations
  – Cockpit: Pilot, Co-Pilot, and Jumpseat Stations
  – Cabin: Two FTE Stations
  – Cabin: Egress Path
G650 Fire Suppression – Requirements

• System can be activated by multiple modes
  – Automatic (IR/UV Detectors in Cabin)
  – Manual Switches (Cockpit & FTE workstations)
  – Manual Back-up (each supply station)

• System shall be designed such that failure probability is less than 10E-6 and hazard classification is not more severe than Major
  – Failure to activate when commanded
  – Un-commanded / Inadvertent Activation
6001 Fire Suppression System Qualification

• Firebane is a non-toxic, biodegradable, liquid fire suppression and extinguishment agent. It is a non-irritant to skin and eyes, (baby shampoo) and does not pose an inhalation risk.

• Firebane is finishing analysis with EPA to be included on the SNAP (Significant New Alternative Program) list, which is a listing as Halon replacement.

• Spentex is certified and meets the standards of NFPA (National Firefighter Protection Association) for fire protection and electrical arc protection. Spentex performance exceeds that of Nomex.

• The fire suppression system hardware and software meets the military specifications for personnel in closed compartments.
System Development

- Partial system activation in G650 Structural Test Lab
- Extensive testing by GSL to size line length, nozzle positioning, and pressure tests to verify spray patterns and spray duration.
G650 Cabin Fire Suppression System

Basic System Components:
- Reservoir (3 gal) – Stage 1 Egress + Crew
- Reservoir (5 gal) – Stage 2 Egress
- Dispensing System - Stage 1 Egress + Crew: 15 Nozzles, Crew 10, Egress 5, discharge time 5 sec
- Dispensing System – Stage 2 Egress: 10 Nozzles, discharge time 40 sec
- Automatic and Manual Switching Modes to Activate or Shut Down Either System

Additional Safety Improvements:
- Flame resistant (Spentex) coverings
- Handheld FireBane Fire Extinguishers – at Emergency Exit Windows (3 PL)
- Smoke Hoods at each crew station
- Additional Window Emergency Exits- #2 RH/LH
G650 Fire Suppression – SPENTEX Blanket

Typical Spentex Liner Layup
Overall Thk = .196"

Nomex Thread Heat Resistant

Velco Fire Retardent 2" wide

Spentex Ripstop (thk = .023"

Spentex Felt (thk = .150"

Spentex Ripstop (thk = .023"

Spentex Liners With Velcro Sewn on

Floor Board Panel Assy

Acoustic Panels

Velcor + Speed Tape + Adhesive Bonded to Acoustic Panels

Gulfstream
G650 Fire Suppression – SPENTEX Blanket

Looking FWD

Looking AFT
Fire Suppression System

• GSL comparison of SPENTEX vs. NOMEX
3 sensors on each system for redundancy
STAGE 1: CREW STATIONS SPRAY PATTERNS
(10 NOZZLES, 2 EACH STATION)

STAGE 1: EGRESS PATH SPRAY PATTERNS
(5 NOZZLES)

CREW and STAGE 1 Egress Spray
5 Sec

OPT #1: 30 sec time delay
OPT #2: Manual Activation
OPT #3: System OFF switch

STAGE 2 Egress Spray
40 Sec
6001 Fire Suppression – System Operation

There are 3 options for STAGE 2 Activation:

- OPT #1: Crew Incapacitated; at STAGE 1 completion, a 30 second timer runs for AUTO start of STAGE 2.
- OPT #2: MANUAL Activation at any Crew location
- OPT #3: MANUAL selection of SYSTEM OFF at any Crew location
## 6001 Fire Suppression – System Operation

### STAGE 2: EGRESS NOZZLE SPRAY PATTERNS

<table>
<thead>
<tr>
<th></th>
<th>CREW and STAGE 1 Egress Spray</th>
<th>OPT #1: 30 sec time delay</th>
<th>OPT #2: Manual Activation</th>
<th>OPT #3: System OFF switch</th>
<th>STAGE 2 Egress Spray</th>
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<tr>
<td>Time</td>
<td>5 Sec</td>
<td>30 sec time delay</td>
<td>Manual Activation</td>
<td>System OFF switch</td>
<td>40 Sec</td>
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</table>

- **OPT #1:** 30 sec time delay
- **OPT #2:** Manual Activation
- **OPT #3:** System OFF switch
G650 Fire Suppression – Manual Activation
G650 Fire Suppression – Cockpit Controls

Pedestal Extension

Manual Activation Panel
What Have We Done Differently?

• **Aircraft Safety Modifications**
  – Fire Suppression System
  – *Additional Emergency Exits*
    – New Onboard Emergency Equipment
    – “CUT HERE” Markings

• Flight Test Procedural Improvements
• Flight Test Incident Reporting
• Developed New Methods to Determine and Verify Vspeeds
• Crash Crew Booklet and ARFF Coordination
G650 Additional Emergency Egress

Slide 30
G650 Additional Emergency Egress

- Cabin Window #2 L & R
- Baggage Compartment
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What is Your Egress Path?

- Assume Emergency Exits blocked, MED is INOP… what now?
  - Use crash ax to create egress path
  - How many have actually **USED** one? And made enough of a hole to escape?

- Fuselage vs Window evaluation: Cabin Window was tested

- Tools Evaluated:
  - 36V Circular saw
  - 4 lb pointed hammer
  - Crash Ax
  - 10 lb sledge hammer
  - 4.9lb Halligan tool
G650 Custom Egress Tool

- Results: difficulty in breaking window with available tools.
- Customized Egress Hammer developed.
  - 6 lb, extendable handle, One side pointed, one side tapered
- Current recommended process is to use saw to cut external window and use egress hammer to remove acrylic.
- Further evaluations are planned using scrap fuselage/windows. All FTE/ Pilots will have opportunity to use equipment.
G650 New Emergency Equipment

CUSTOM HAMMERS (2)

BATTERY POWERED CIRCULAR SAW

BOX CUTTERS (2)
What Have We Done Differently?

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G650 External Markings

- These markings had never been included on GAC Test Aircraft.
What Have We Done Differently?

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  - Additional Emergency Exits
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- **Flight Test Procedural Improvements**
  - Flight Test Incident Reporting
  - Developed New Methods to Determine and Verify Vspeeds
  - Crash Crew Booklet and ARFF Coordination
Flight Test Policy Changes

- Reviews found Corporate Policy work hours exceeded.
  - Policy states 60 hr/week and no more than 13 consecutive days without Senior Leadership Approval.

- Lead to improved focus on Crew Rest, including Maintenance and TM support, especially when offsite with limited team.

- Revised Flight Crew Duty day for MED and HIGH risk testing.

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<tr>
<th>Maximum number of sequential duty days</th>
<th>Quantity</th>
<th>Quantity with Approved Waiver</th>
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<td>7 days</td>
<td>7 days</td>
<td>8 days</td>
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<th>Maximum number of work hours in a 7-day duty period</th>
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<td>60 hr</td>
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<th>Maximum Flight Duty Period</th>
<th>Any High Risk Tests</th>
<th>Any Medium Risk Tests</th>
<th>All Other Flights</th>
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<td>11 hr</td>
<td>14 hr</td>
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<th>Maximum Flight Hours / Day</th>
<th>Any High Risk Tests</th>
<th>Any Medium Risk Tests</th>
<th>All Other Flights</th>
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<tbody>
<tr>
<td>6 hr</td>
<td>N/A</td>
<td>8 hr</td>
<td>12 hr</td>
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Safety Program

- **WAS**
  - Corporate Safety Program with an ‘Aviation Safety Officer’ within Flight Operations
    - Safety Officer investigated incidents inside Gulfstream and was requested to assist with accidents involving Gulfstream airplanes

- **IS**
  - Implemented Safety Management System in 2012
  - Aviation Safety Officer position at “Leadership Team” level
  - Appointed Aviation Safety Managers, Advisors, Investigators, and Representatives within Flight Operations, Flight Test Engineering, and Engineering groups
  - ‘Flight Operations – Test’ audited and received IS-BAO Level 1 certification in 2012 (First Flight Test Organization to receive IS-BAO certification)
    - ‘Flight Operations – Demonstration’ has been IS-BAO certified for 5 years, currently Level 3
Audits

• Initial and Follow-up by Team of “Disinterested” Experts (“Independent Safety Review Team”)
  – Outsider’s perspective can be beneficial
  – Provided recommendations for shortcomings in Flight Ops and Flight Test
  – Challenges
    • Background and experiences of auditor(s) can be different and unlike operation being audited
      – Governmental agencies have no expectation of profit
      – R&D testers have not been exposed to certification and progression to production/completion operations
      – Scaling of operations differ between OEMs
    • Findings / recommendations can be difficult to reconcile / implement
“Improvement” Challenges

• Test Flight Crew Assignments
  – Most experienced and minimum personnel for higher risks
    • Training
    • Attrition
    • Acquisition of new hires
    • Age effects – perceived or actual

• Test Safety Hazard Analysis (TSHA) and Flight Test Cards
  – Progressively departing from ‘reasonable man’
    • Evolving into reproduction of test plan / test card
    • Increased segregation and classification level of risks
    • Written for the un-informed reader
    • Increased text
    • Increased review time prior to each flight
What Have We Done Differently?

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- Flight Test Procedural Improvements

- *Flight Test Incident Reporting*

  - Developed New Methods to Determine and Verify Vspeeds
  - Crash Crew Booklet and ARFF Coordination
Flight Test Incident Reporting

- Two previous events, a $V_{MU}$ test and CTO, resulted in rolloffs.
- Both events were reviewed and determined a root cause.
  - $V_{MU}$ event was determined to be over-rotation and overshoot of pitch target. First piloted $V_{MU}$ on G650 by PIC.
    - Prior to next flight, TSHA revised to require build-up maneuvers for pilot proficiency
  - CTO was an early and over-rotation resulting in exceeding pitch target
    - IFR in place at time prohibiting Yaw Damper use. Preceding maneuvers showed increasing objectionable lat-dir oscillations
    - Unexpected behavior attributed to a lateral-directional disturbance in combination with improper test procedure
    - Takeoff testing was discontinued until Yaw Damper was available
Flight Test Incident Reporting

- Corrective Action was taken for each event
  - The ‘Root Cause’ was addressed for both events
  - The value of the aerodynamic data was not recognized until after the accident

- FTIR was instituted to document incidents or unexpected test results that could lead to an unsafe condition
  - Initiates investigative process
  - May restrict further testing until investigation completed
  - Integrated into SMS

- And the challenge with this is the definition of “unexpected test results” being part of the reason why we test.....
What Have We Done Differently?

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- Flight Test Procedural Improvements
- Flight Test Incident Reporting
- **Developed New Methods to Determine and Verify Vspeeds**
- Crash Crew Booklet and ARFF Coordination
New Methods for Vspeeds

• G650 takeoff speed schedule was developed using a 6-DOF, nonlinear Matlab®-based simulation
  – Capable of simulating: AEO, OEI, RTO, Vmu, partial-power scenarios
  – Uses CFD-generated ground effect data (over 1-million CPU hrs to generate) along with wind tunnel control powers and vortex lattice rate damping
  – Validated using previous G650 T/O data
  – Final speed schedule required 125k-150k simulation runs, taking 14hrs running in parallel on 24 processors
  – Speed schedule developed numerically for the entire weight, altitude, temperature range of the G650 envelope
  – Employed an iterative root-finding method based on Part 25 regulations and α-margin to ground effect stall for AEO and OEI abused takeoff condition
  – 8-month development time

• Speed schedule results checked using PIL evaluation in ITF
• Simulation run prior to each takeoff in TM during test campaign
• Comparison of Flight Test vs. Prediction made real time
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Crash Crew Booklet and ARFF Coordination

• For G650, Kent created a reference book to hand out. ARFF Coordination has **always** been conducted when testing offsite.

• NTSB identified Response time as an issue. Post-Accident, ARFF was “In-Position” on stand-by during Field Performance testing.
Summary

- Gulfstream, with support from GSL, has developed a Fire Suppression system for use on GAC Flight Test aircraft.
- Additional Safety enhancements have been developed for GAC Flight Test aircraft.
- A New Aviation Safety Office has been created.
- Processes and Procedures have been reviewed, revised, documented and will continue to be improved.
Final Thoughts

• “Complacency or a false sense of security should not be allowed to develop as a result of long periods without an accident or serious incident. An organization with a good safety record is not necessarily a safe organization.”

• “Real knowledge is to know the extent of one’s ignorance.”
  – Confucius

• “Processes” will not necessarily prevent accidents…. the completion of a risk assessment does not necessarily make anything safer.
  – Roger Beazley, 2007 FTSW Keynote Speech

• “In the middle of difficulty lies opportunity.”
  – Albert Einstein