A Tragic First – Gulfstream G650 Flight Test Accident

Jake Howard, Gulfstream G650 Project Pilot

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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

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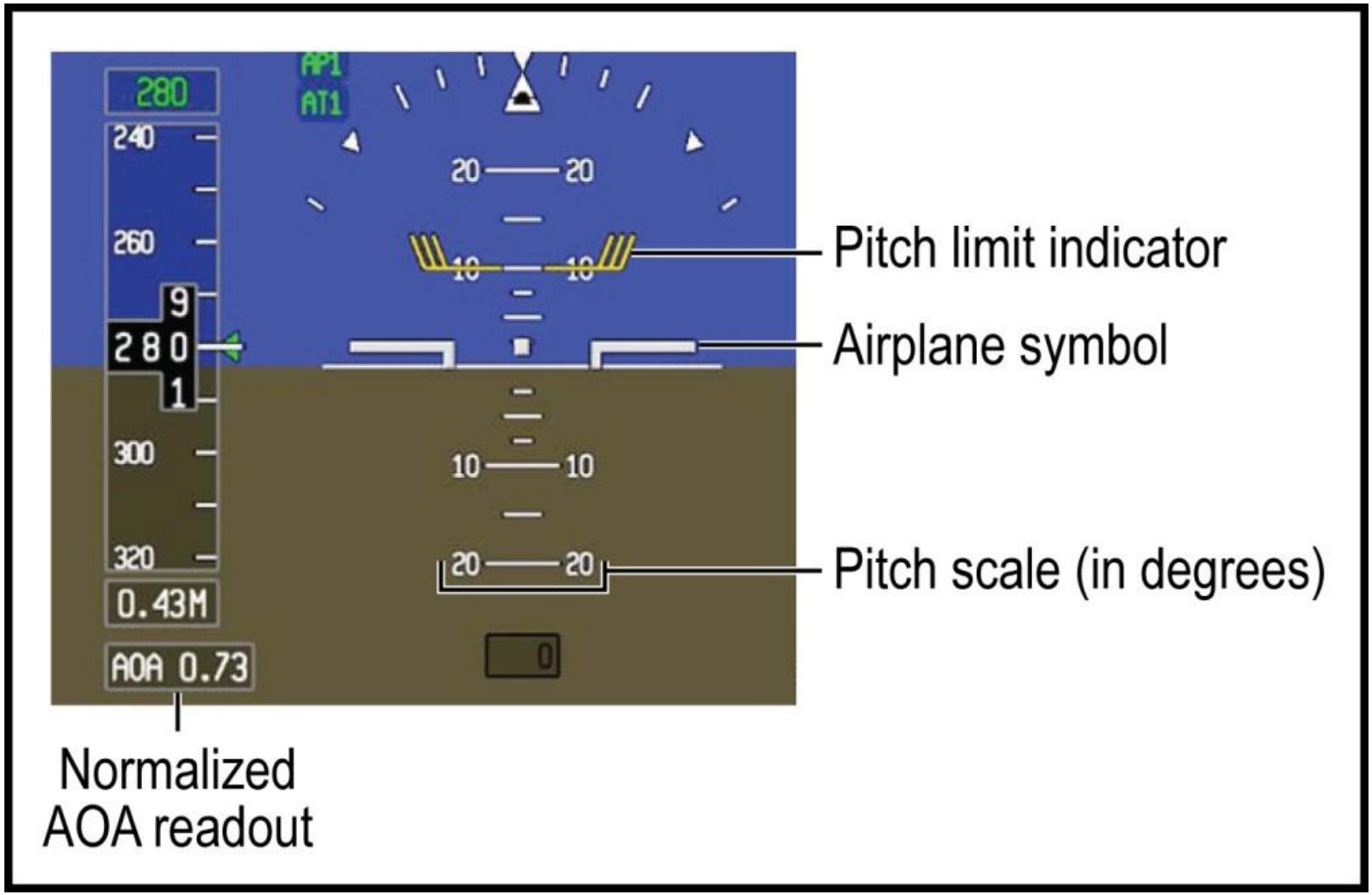
Accident Test Condition Synopsis

- 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 V_{EF}, retard R/H Throttle to idle thrust
  - Target 9° initial pitch attitude, then intercept V_2

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



PFD Video Recreation

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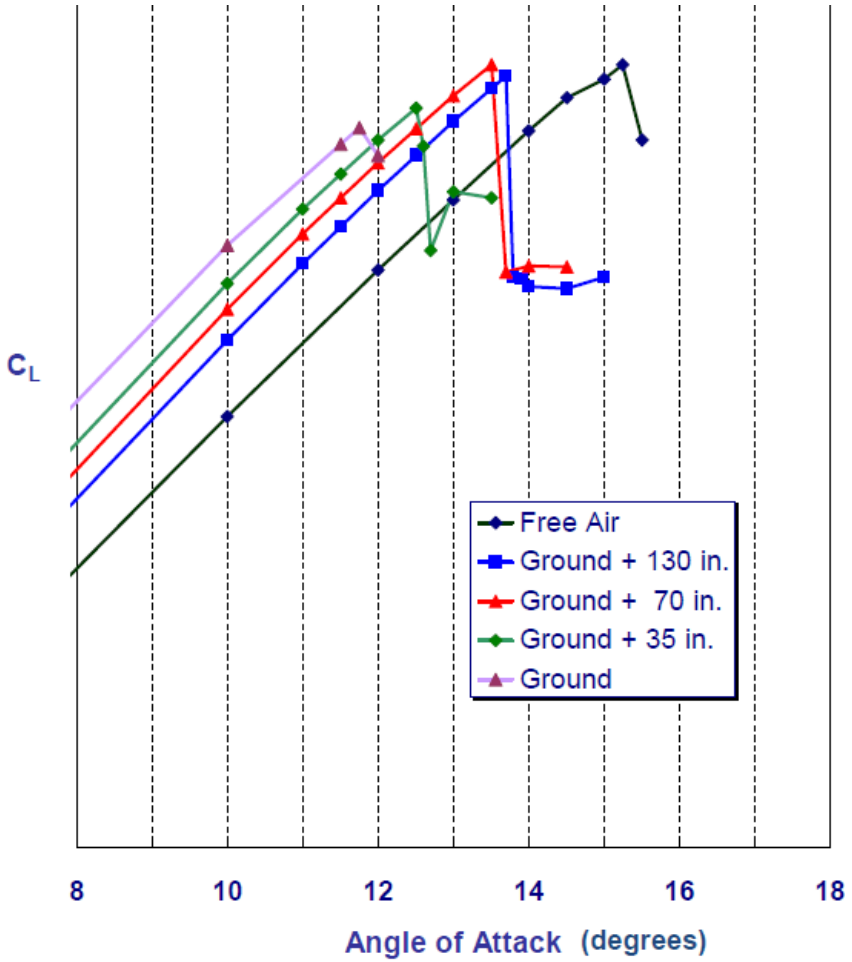
Contributing Factors

- 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 V_{MU} data and associated IGE C_L shift at V_{MU} pitch attitudes
  - Post-accident, extensive processing and data analyses revealed maximum decrement of ~4°

IGE Stall Development (post-accident)



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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

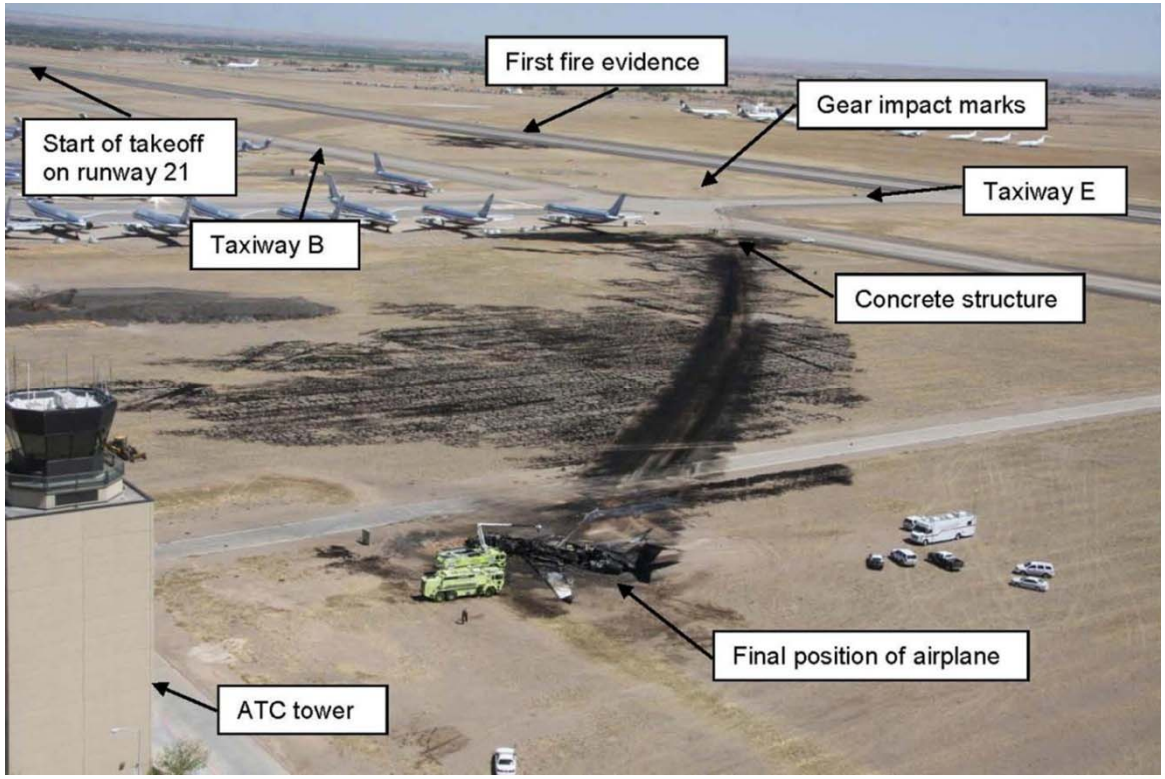
The Investigations (cont.)

- 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.**



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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

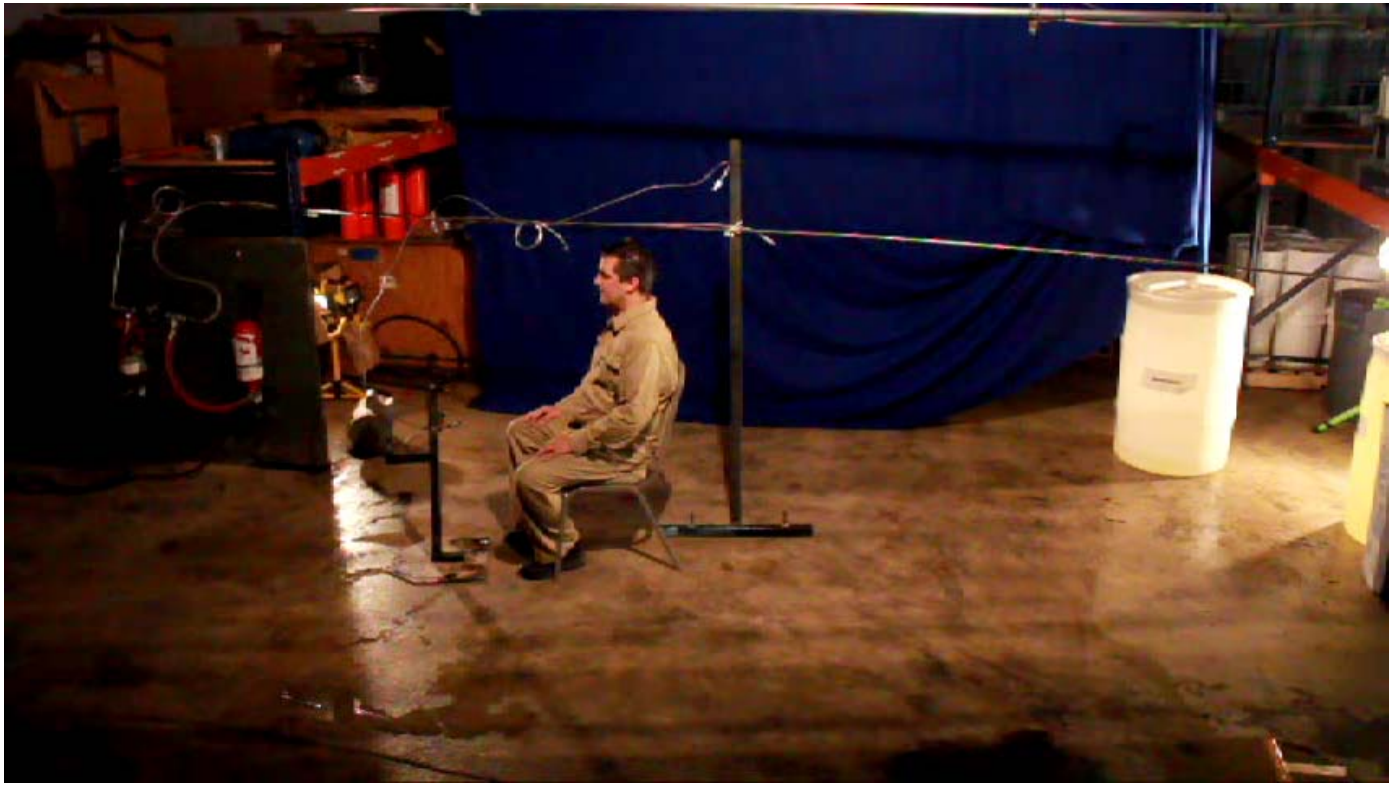
- System can be activated by multiple modes
  - Automatic (IR/UV Detectors in Cabin)
  - Manual Switches (Cockpit & FTE workstations)
  - Manual Back-up (each supply station)
- System shall be designed such that failure probability is less than 10E-6 and hazard classification is not more severe than 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

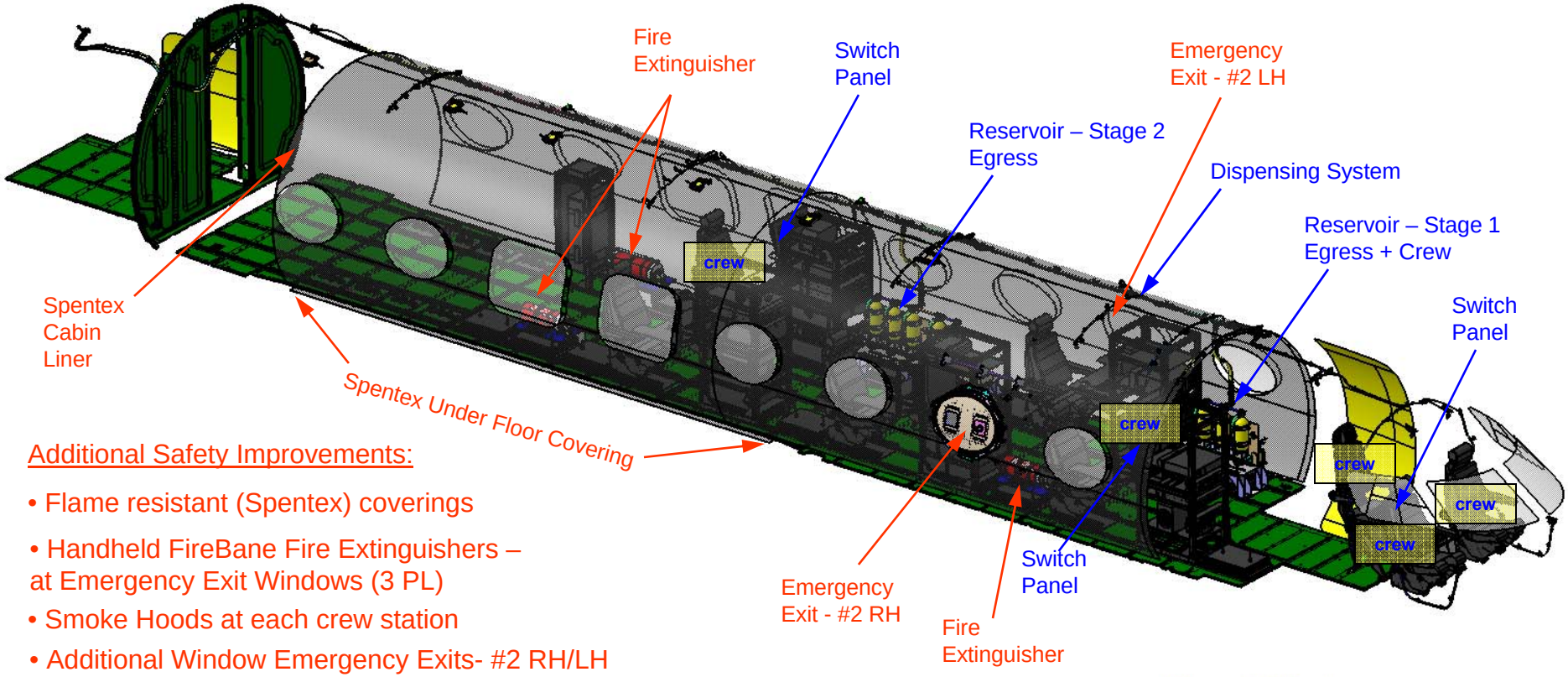
- **Partial system activation in G650 Structural Test Lab**
- **Extensive testing by GSL to size line length, nozzle positioning, and pressure tests to verify spray patterns and spray duration.**



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

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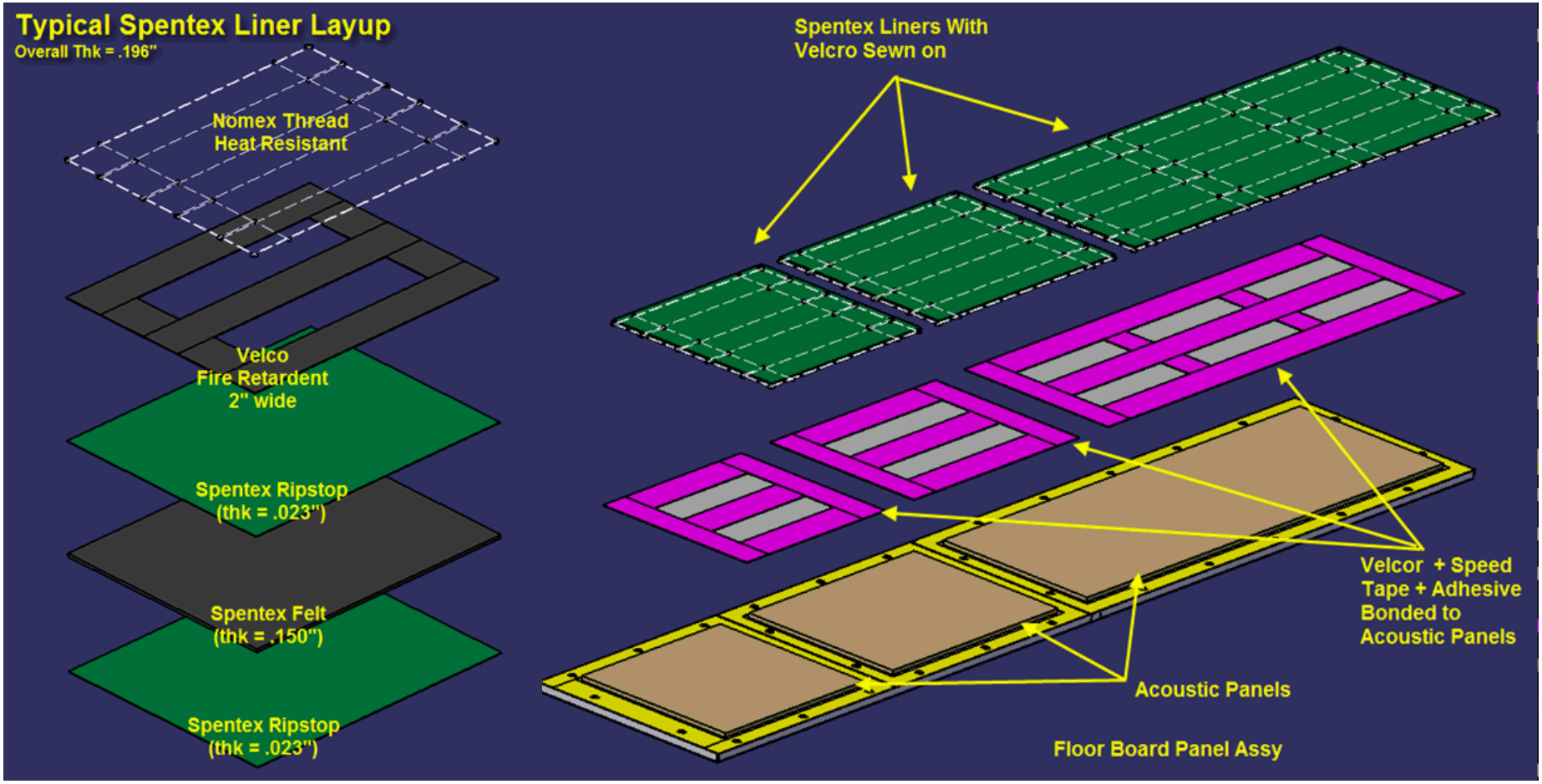
G650 Fire Suppression – SPENTEX Blanket



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G650 Fire Suppression – SPENTEX Blanket

Looking FWD

Looking AFT

Fire Suppression System

- **GSL comparison of SPENTEX vs. NOMEX**

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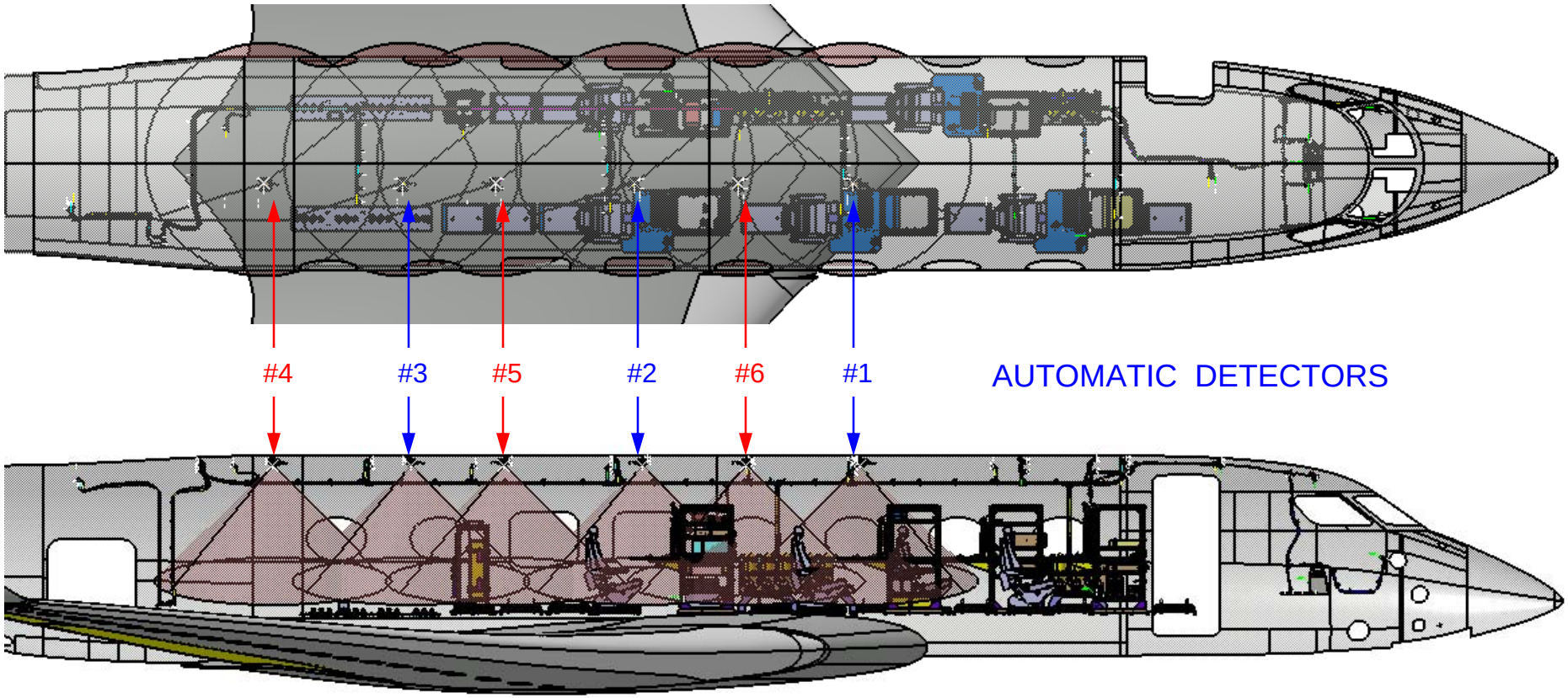
6001 Fire Suppression – Optical Sensors



3 sensors on each system for redundancy

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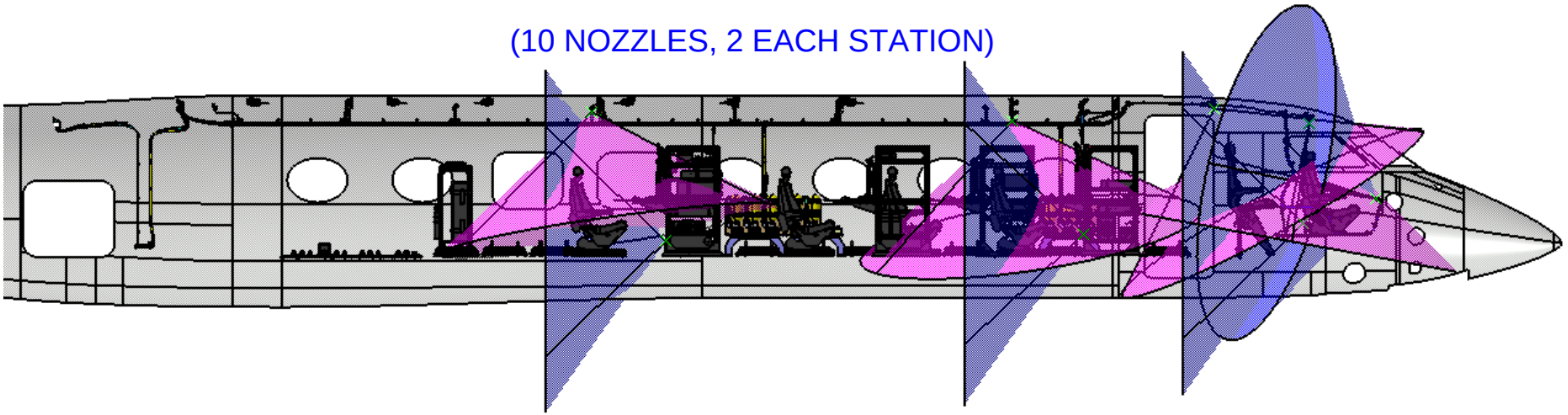
6001 Fire Suppression – System Operation

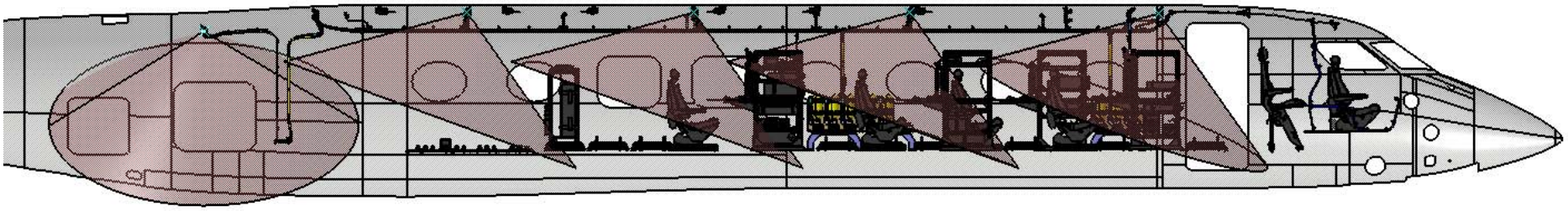
STAGE 1: CREW STATIONS SPRAY PATTERNS

(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

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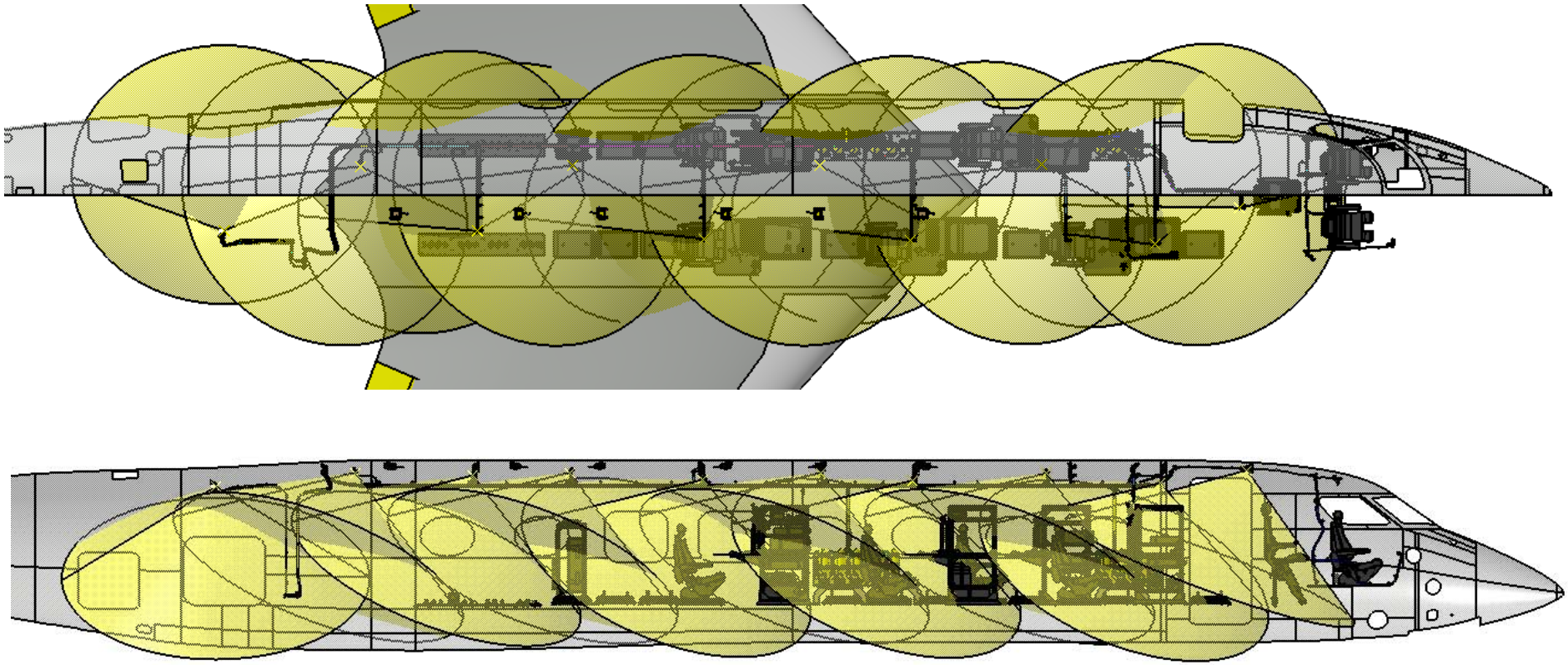
6001 Fire Suppression – System Operation

- **There are 3 options for STAGE 2 Activation:**

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

  - **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

(10 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**

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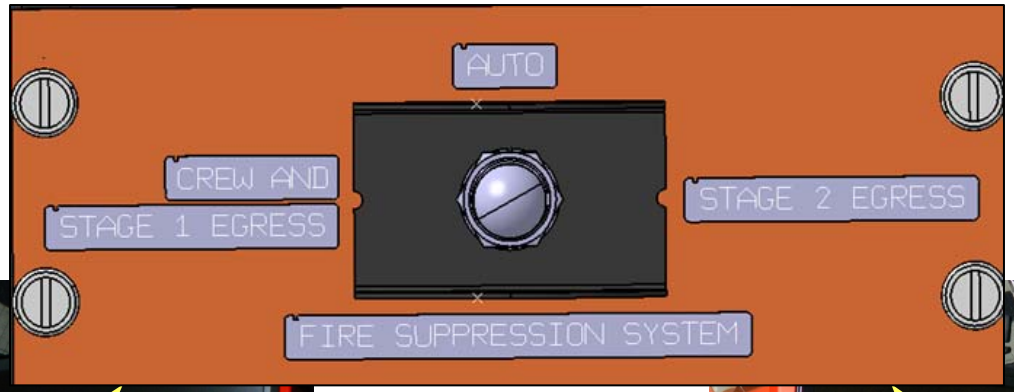
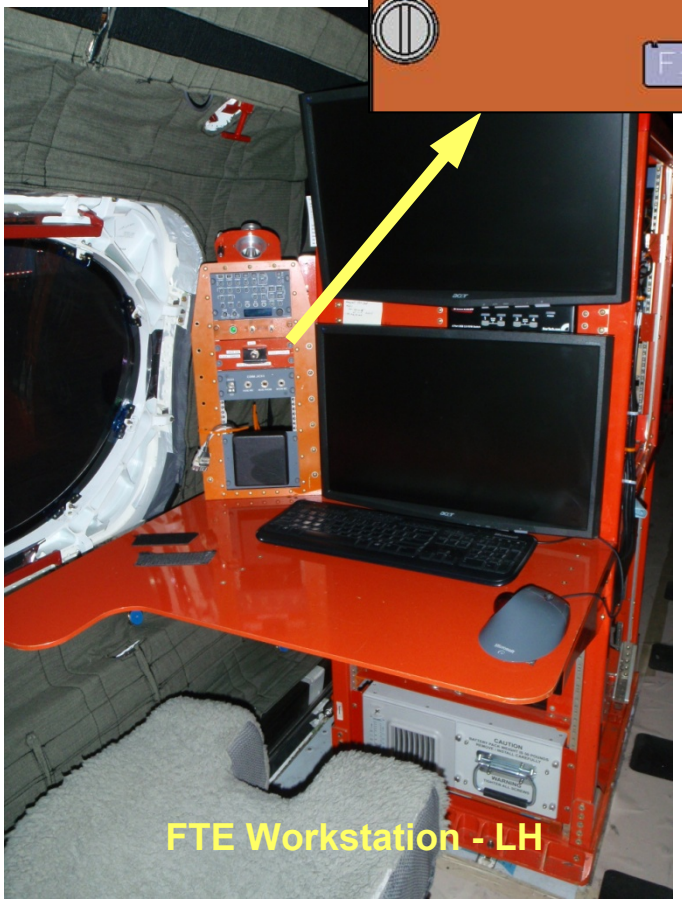
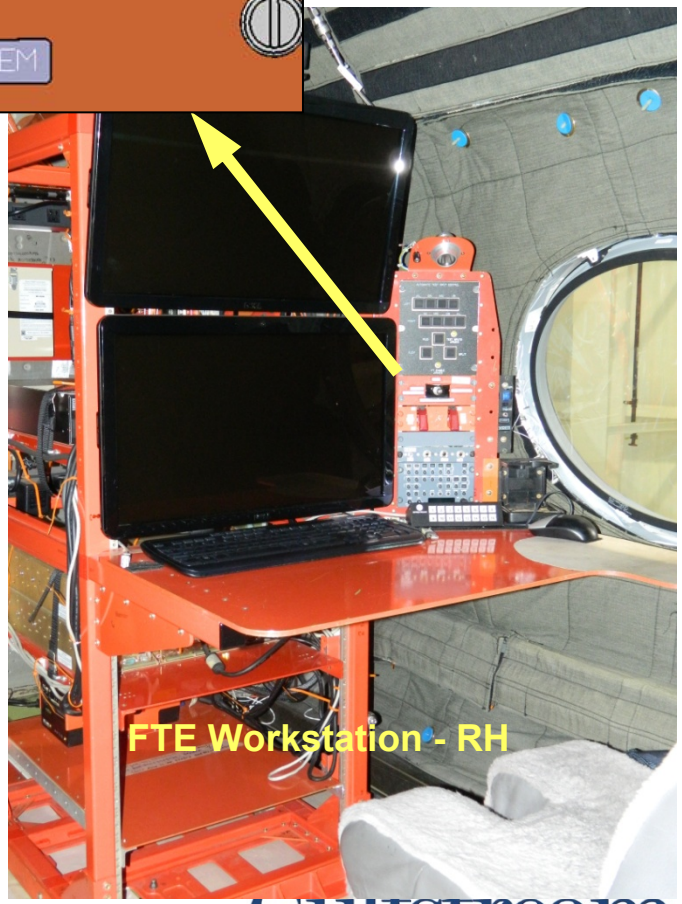
G650 Fire Suppression – Manual Activation







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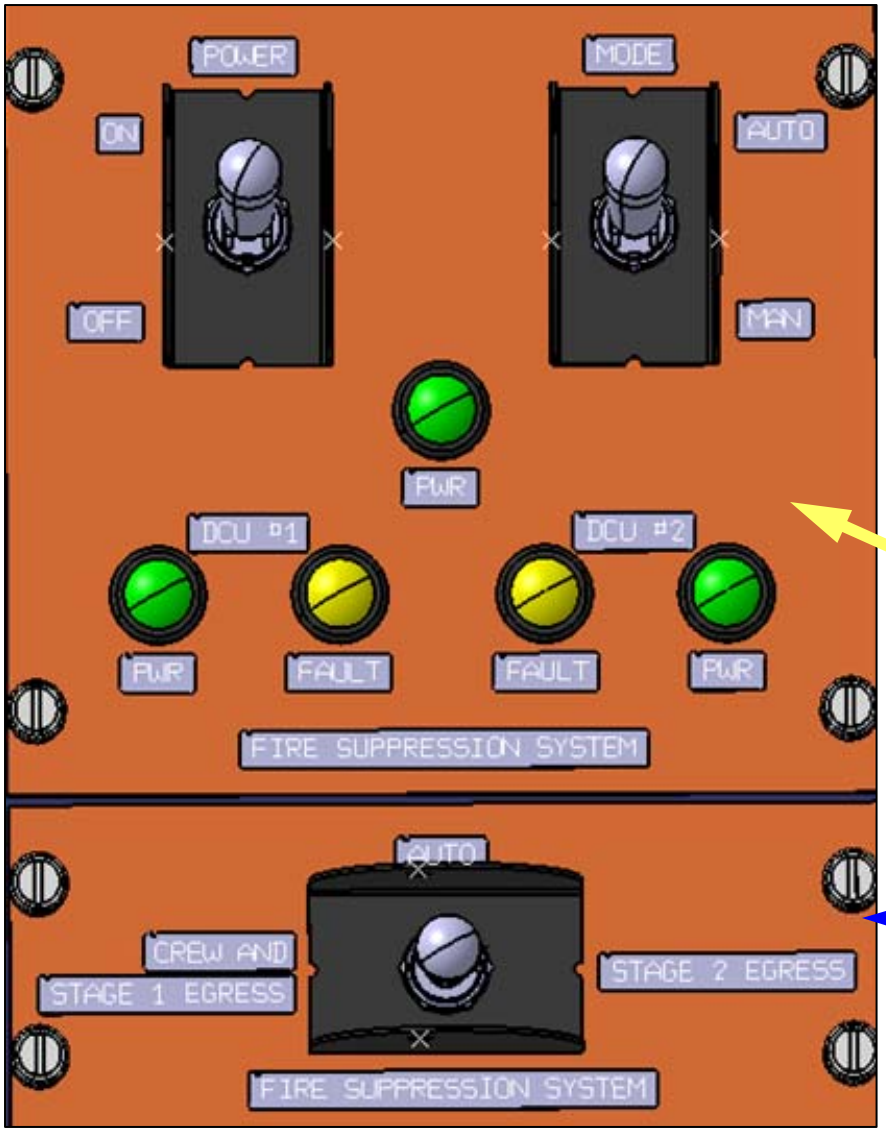
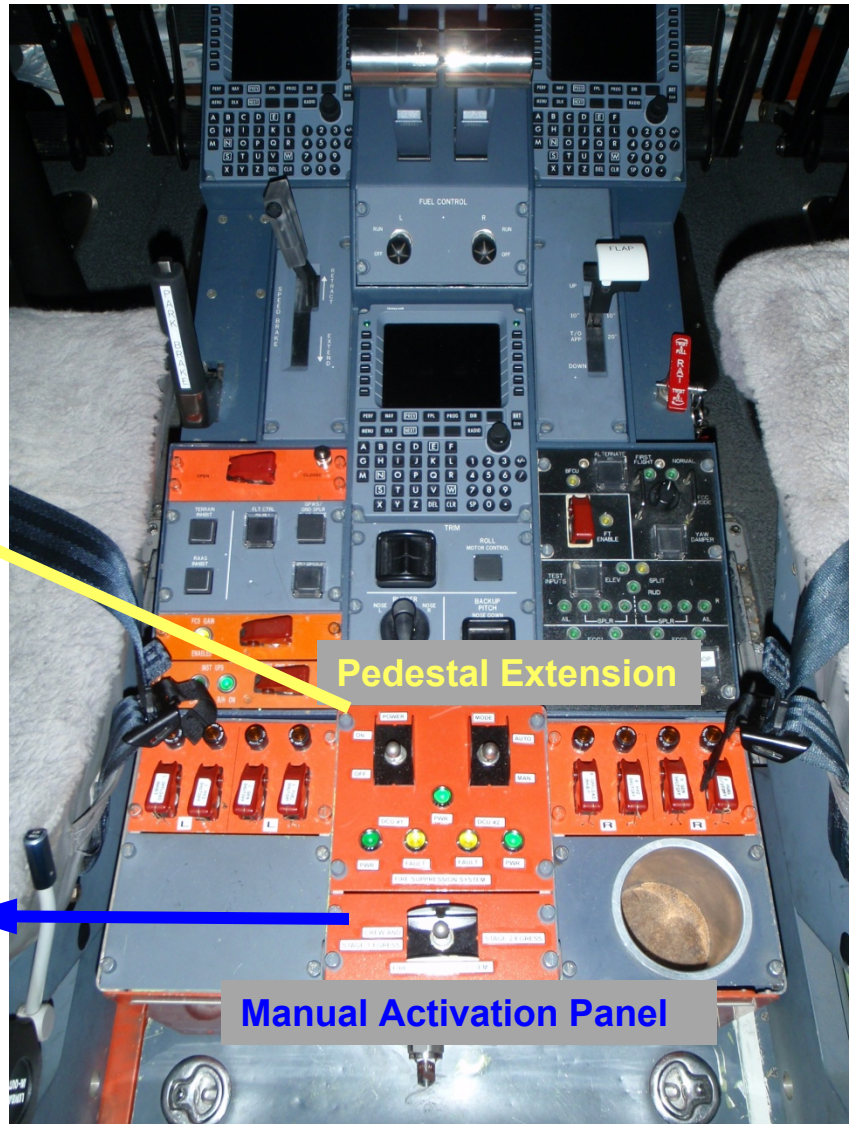
G650 Fire Suppression – Cockpit Controls





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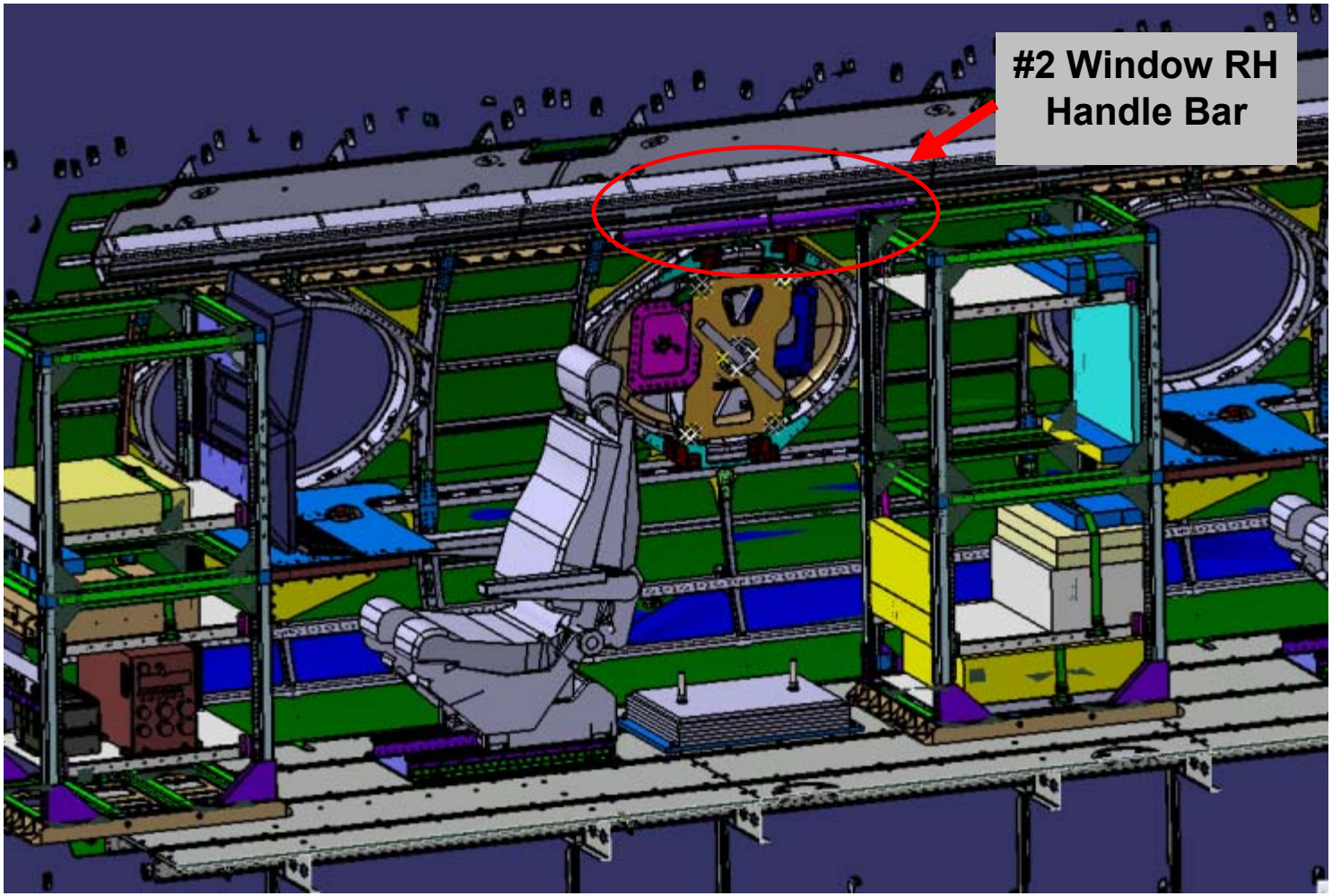
G650 Additional Emergency Egress



FWD

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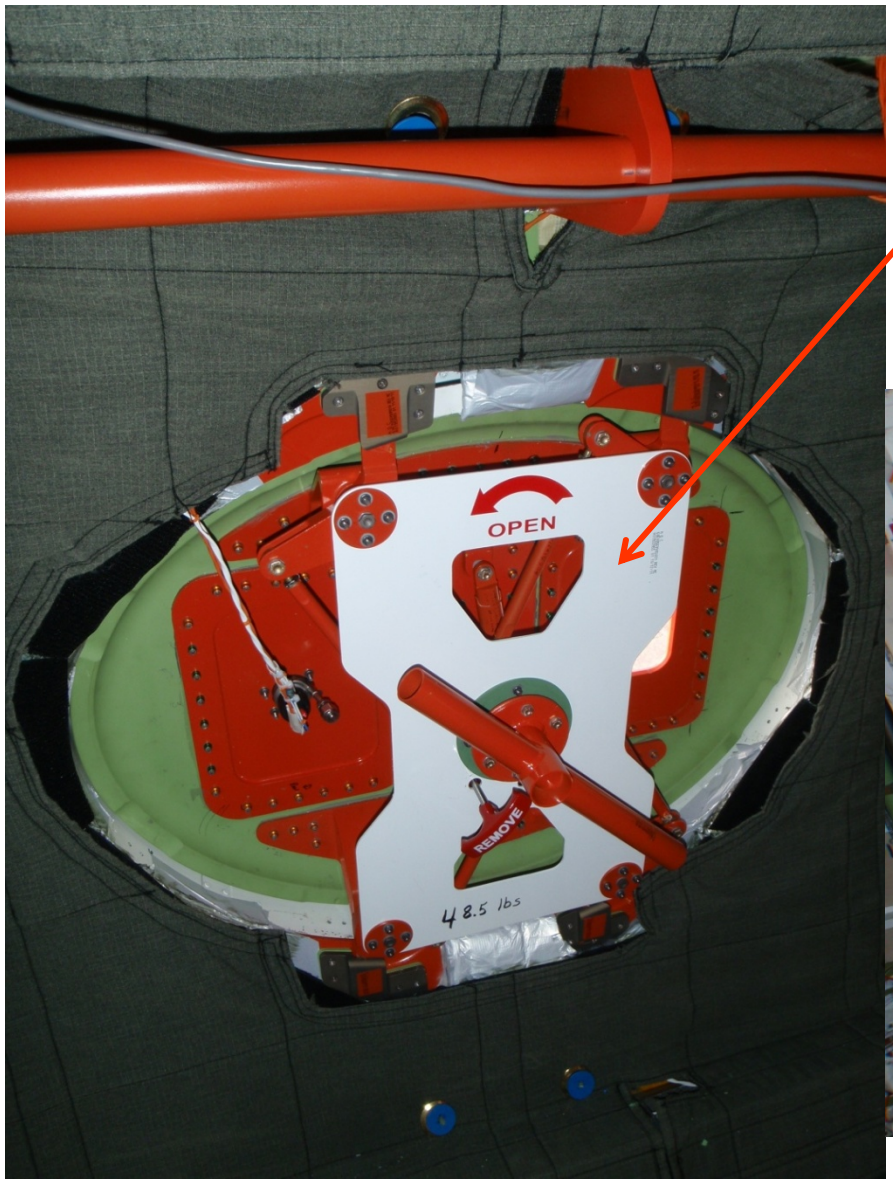
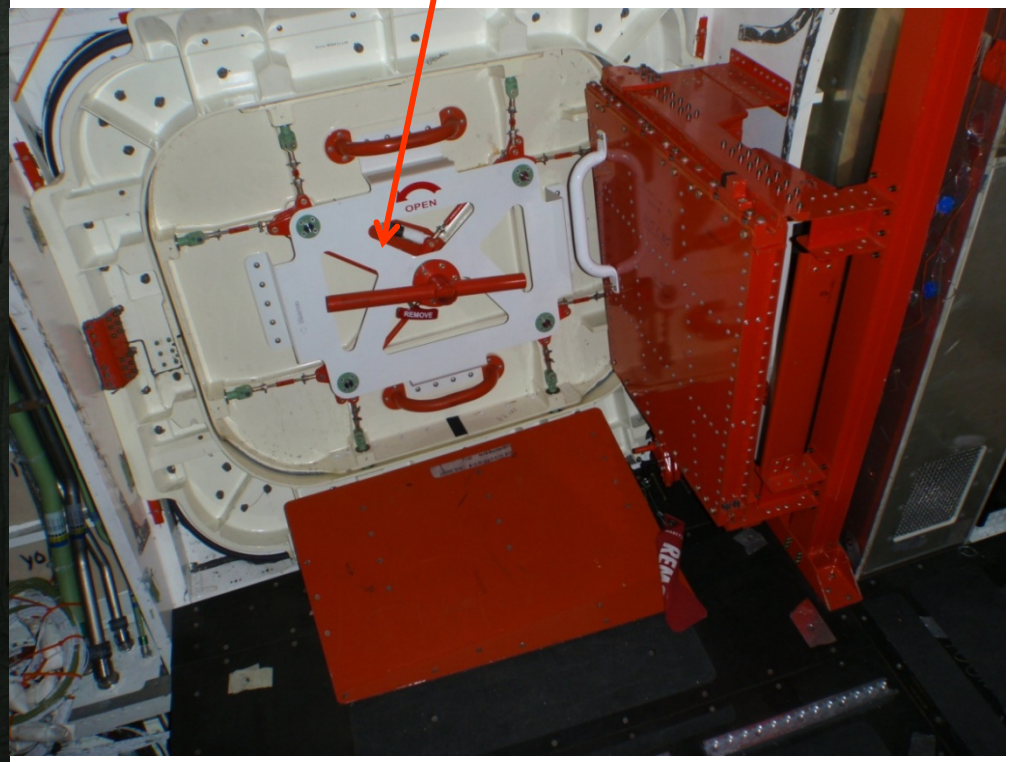
G650 Additional Emergency Egress



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**

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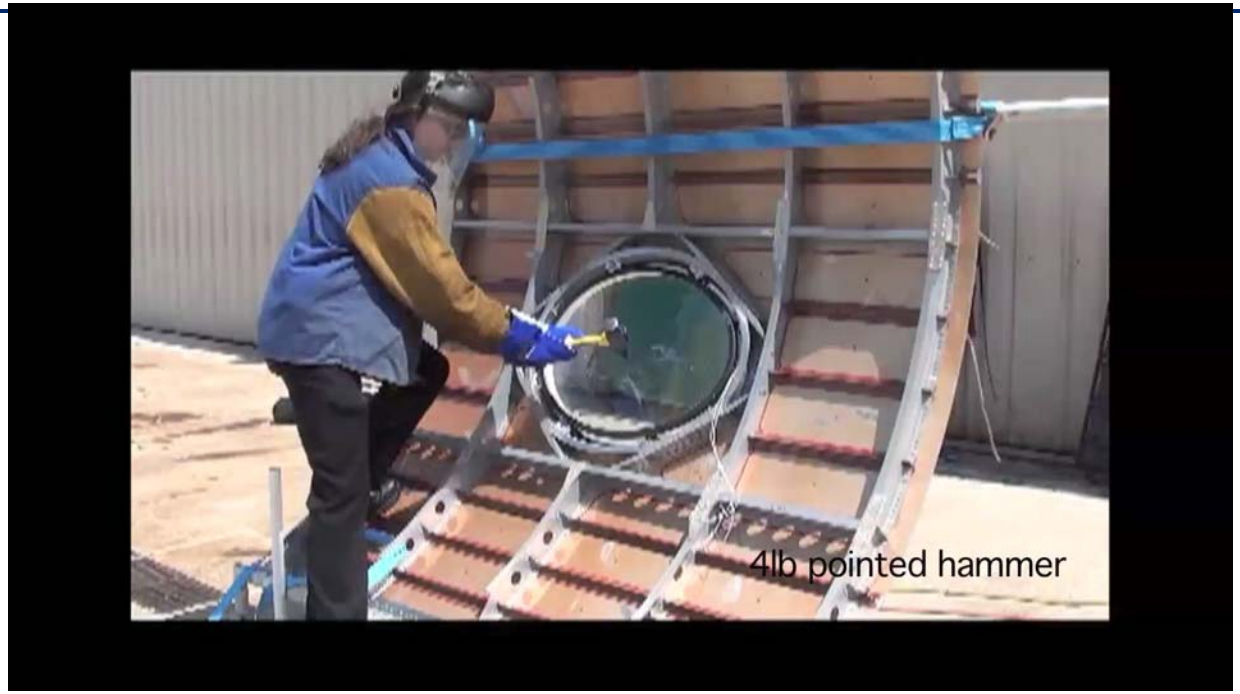
G650 Custom Egress Tool



- **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.**

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G650 New Emergency Equipment

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G650 External Markings

- **These markings had never been included on GAC Test Aircraft .**

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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.**

		Quantity [2]	Quantity with Approved Waiver [3]
Maximum number of sequential duty days [4]		7 days	8 days
Maximum number of work hours in a 7-day duty period [5]		60 hr	70 hr
Maximum Flight Duty Period [6,7]	Any High Risk Tests [8]	10 hr	N/A
	Any Medium Risk Tests [8]	10 hr	11 hr
	All Other Flights	12 hr	14 hr
Maximum Flight Hours / Day	Any High Risk Tests [8]	6 hr	N/A
	Any Medium Risk Tests [8]	7 hr	8 hr
	All Other Flights	10 hr	12 hr [9]
	All Other Flights with augmented crew [10]	14 hr	16 hr

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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

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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…..**

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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

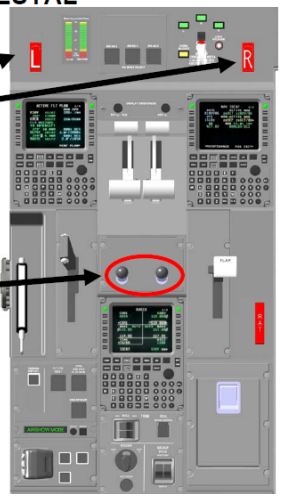
- **For G650, Kent created a reference book to hand out. ARFF Coordination has always been conducted when testing offsite.**
- **NTSB identified Response time as an issue. Post-Accident, ARFF was "In-Position" on stand-by during Field Performance testing.**

GULFSTREAM GVI
CRASH CREW INFORMATION

GULFSTREAM GVI
CRASH CREW INFORMATION
COCKPIT CENTER PEDESTAL

TWO FIRE EMERGENCY CONTROL HANDLES. **PULL OUT FIRE EMERGENCY HANDLES TO SHUT OFF ALL FLUIDS TO ENGINES.**

TWO ENGINE FUEL CONTROL SWITCHES. **PULL OUT TO UNLOCK AND MOVE DOWN TO SHUTOFF.**



GULFSTREAM GVI
CRASH CREW INFORMATION
OVERWING EXITS

- OVERWING EMERGENCY EXITS.

- EXTERIOR EMERGENCY DOOR LOCK ACCESS AND RELEASE.

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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. "**
  - ***ICAO, 'Accident Prevention Manual, 1984.***
- **"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***

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