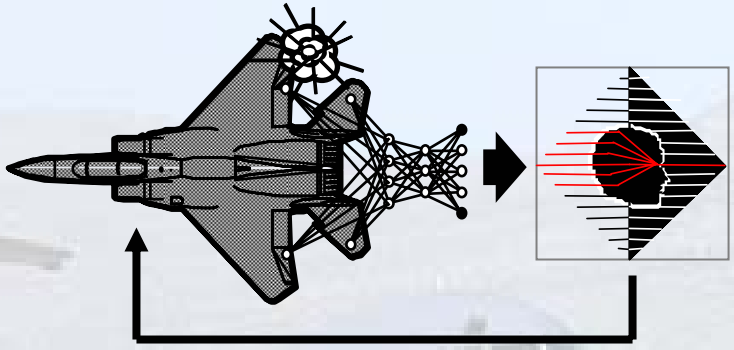
Neural Flight Control System

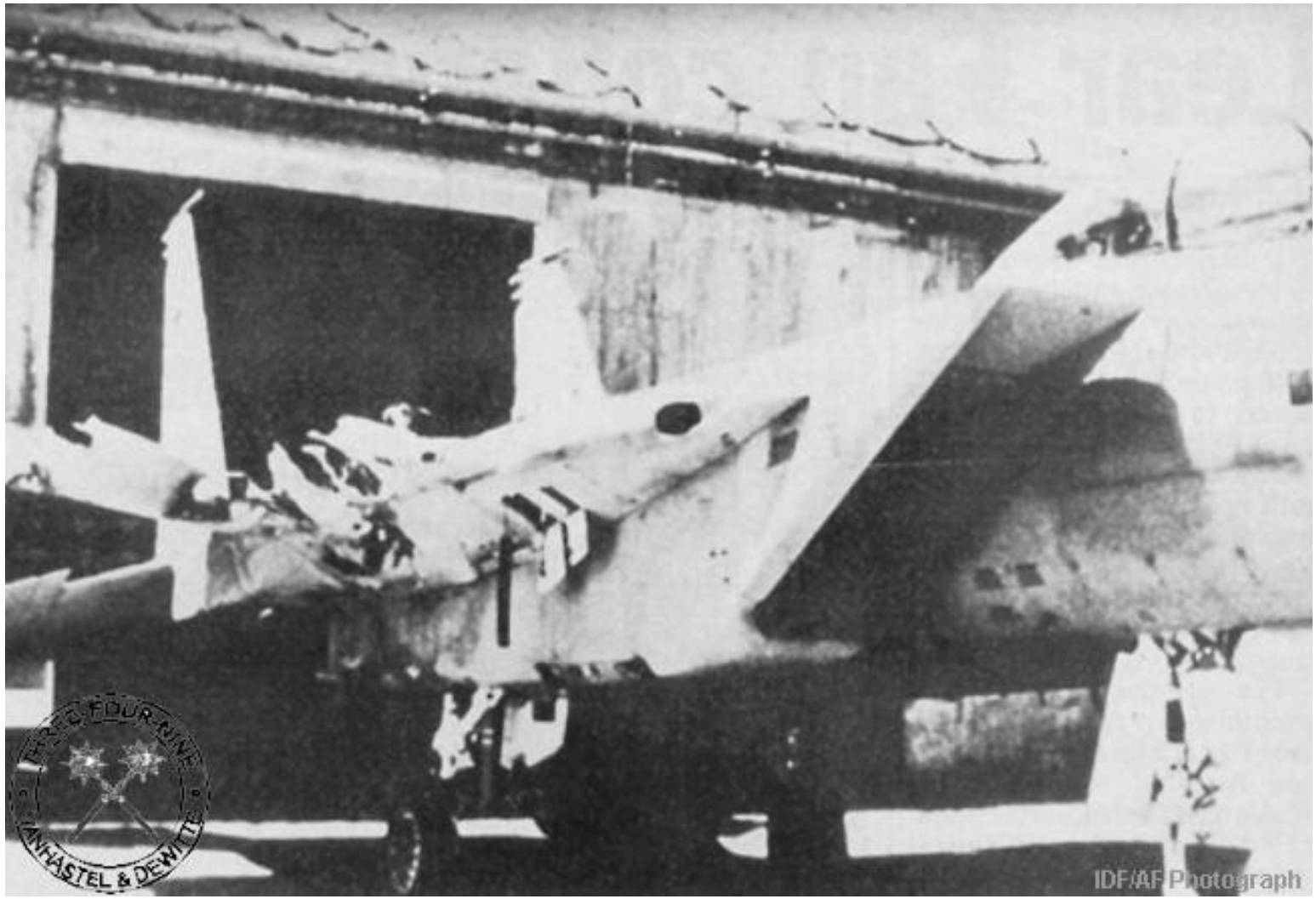
Damage Adaptive Flight Control



Karen Gundy-Burlet, Ph.D.

Intelligent Flight Control
Intelligent Controls and Diagnostics
Information Technology Strategic Research
Computing, Information and Communications Technology

Motivation

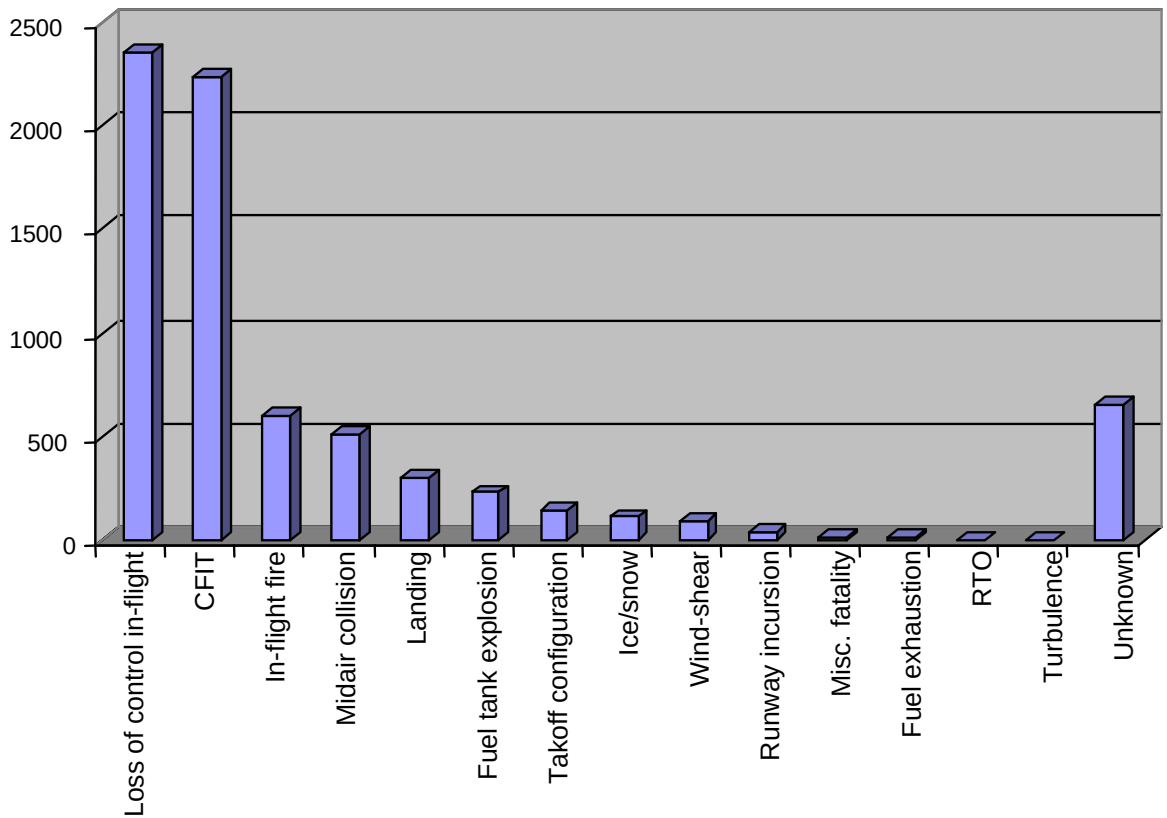


Source: http://www.f-16.net/library/stories/midair.html

Fatalities by Accident Category

Worldwide Commercial Jet Fleet, Boeing 2000 Statistical Summary

"… data for all FCS accidents over this 20 year period [1981-2000] was compared to total FCS accident rates for the latter 5 years to see if the insertion of new FCS technologies impacted accident rates. Cat-A-C accident rates were 1.33×10^{-6} and 1.26×10^{-6} per flight hr for the 20 year period and the latter 5 year period, thus no discernable difference was detected." - SRS Technologies March 2002 survey of data obtained from the Air Force Safety Center located at Kirkland AFB.



Flight Control Accidents & Incidents

(over 1500 lives lost)

Systems remaining operational after damage/failure usually include all engines and flaps, and often ailerons. Tail controls are usually lost.

Aircraft	Aileron	Flap	Rudder	Elevator	Stabilizer	Engines	Cause
UA DC-10	no	no	no	no	no	center out	fan disk/hyd
JAL B-747	no	yes	no	no	no	all OK	aft bulk/hyd
USAF C-5A	yes	yes	no	no	no	all OK	cargo ramp/hyd
USAF B-52H	yes	yes	no	no	no	all OK	hyd leak/tail
Turkish DC-10	yes	yes	no	no	no	all OK	door/cables/hyd
USN F/A-18	no	yes	no	yes	yes	all OK	stab LVDT/mec
USAF A-10	yes	yes	no	no	no	all OK	AAA/cables
USAF B-52G	yes	yes	no	no	no	all OK	hyd leak/tail
AA A300-600	yes	yes	no	yes	yes	yes	loss of vertical stabilizer
Alaska MD-83	yes	yes	yes	yes	no	yes	runaway stab
UA B-737, USair B-737	yes	yes	no	yes	yes	yes	rudder hardover

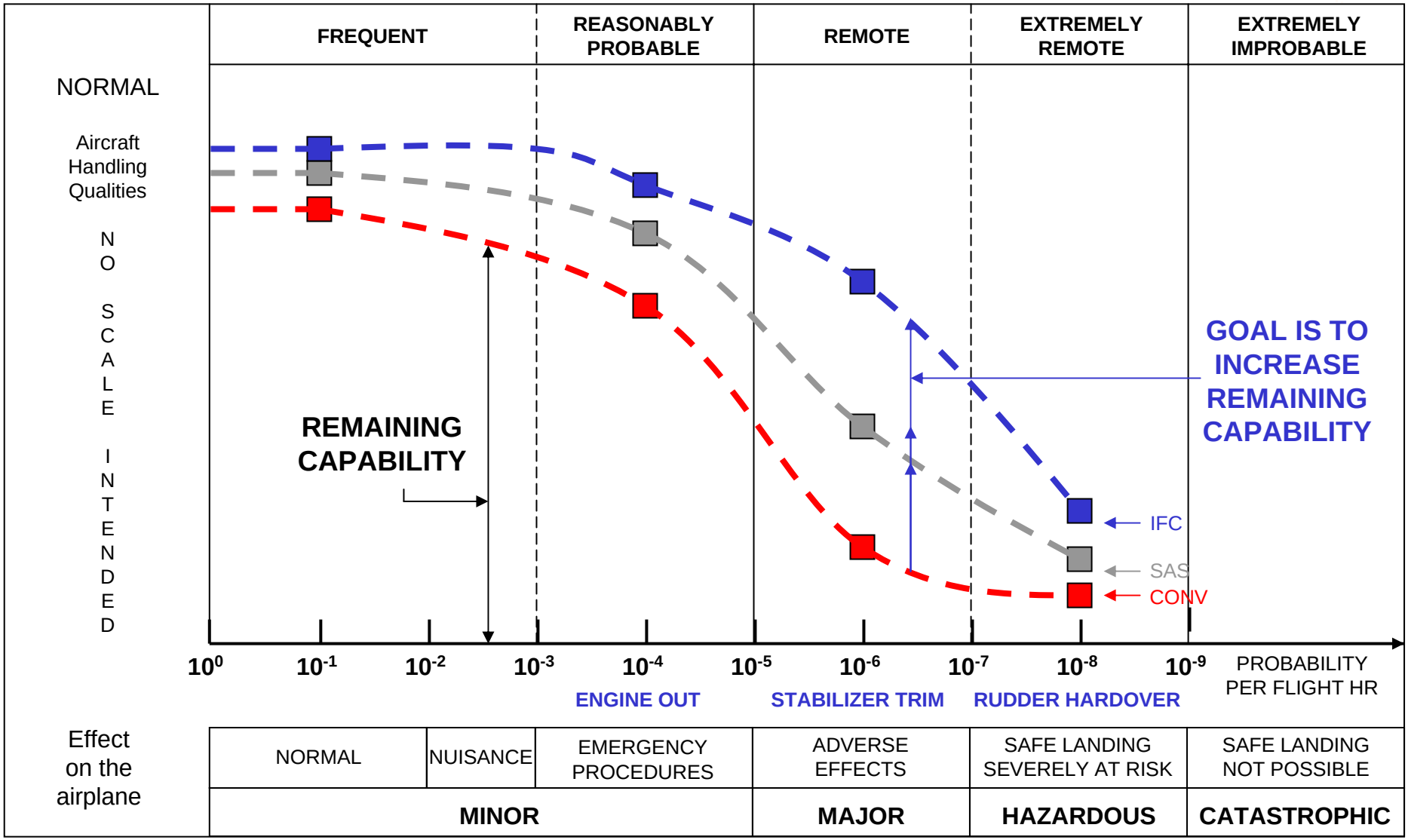
Objective

Develop a flight control architecture that can smoothly and automatically utilize alternate sources of control authority over a broad range of damage or failure conditions.

- **Goals:**
  - Good handling qualities in nominal flight.
  - Utilize alternate sources of control power for increased control authority and redundancy under failure conditions.
  - Show an improvement in handling qualities over the Second Generation (Gen-2) algorithm previously tested in 2001.

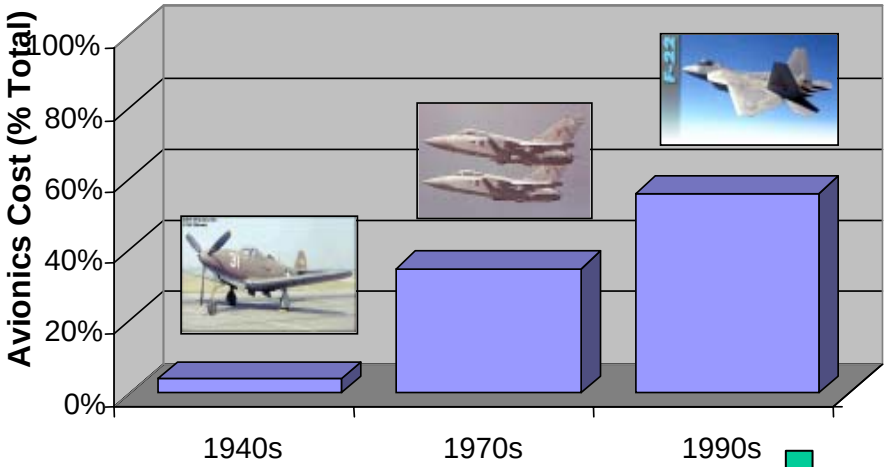
- **Technical Approach:**
  - Utilize Dynamic inverse with error controller and direct adaptive neural networks.
  - Control Reallocation algorithms
    - Daisy Chain (utilized in Gen-2)
    - Linear Programming optimal reallocation (LP)
    - Table-driven hierarchical scheme (I.e. super-daisy)
  - Adaptive Critic modifies reference model for Gen-3 re-allocation schemes.
  - Excludes propulsion control at this time.

Expected Benefits: Safety



Expected Benefits: Design Cycle

Reduce Costs



Estimated Cost Savings = $50M
($0.5M per software version)

Improve Efficiency (example: F-15E)

Candidate Control Law	Software Coding and Development	Software Test Facility (Bench Test)	Hardware Test Facility (Iron Bird)	Aircraft Ground Test	Aircraft Flight Test
100 Software Versions	604,000 mh	239,000 mh	166,000 mh	81,000 mh	642,000 mh

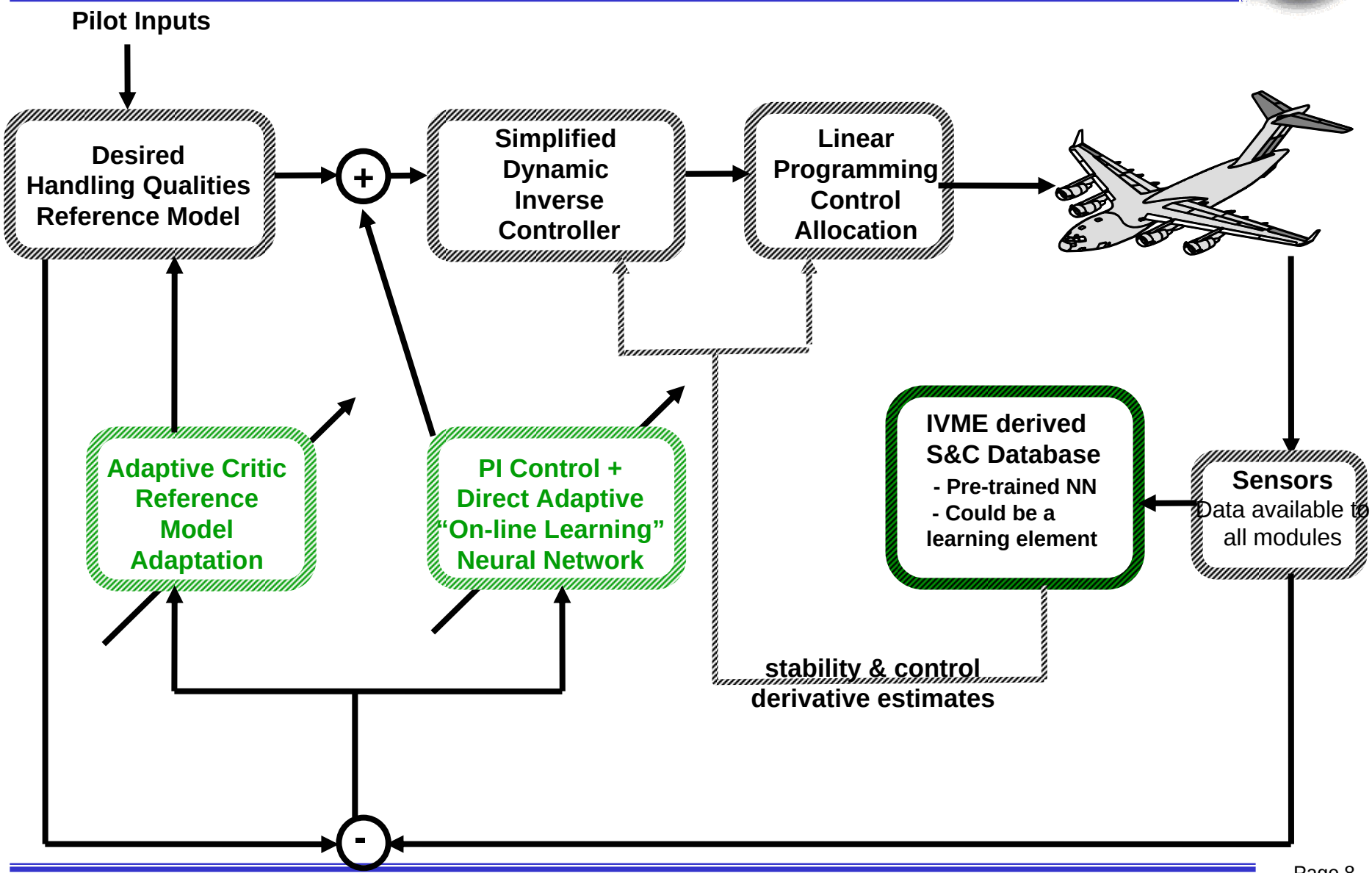
Total
1,732,000 mh
596 Flights

Estimated Time Savings = 157 to 1
(38 mh per software version)

IFCS Controller Architectures

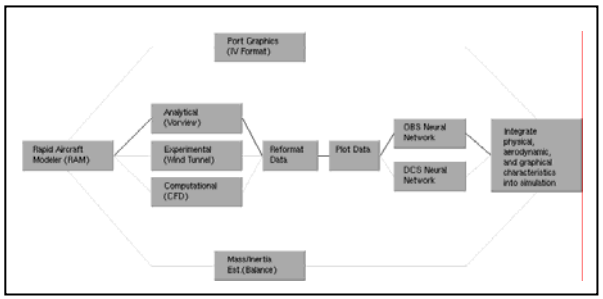
Goal:

Demonstrate aircraft survivability following damage

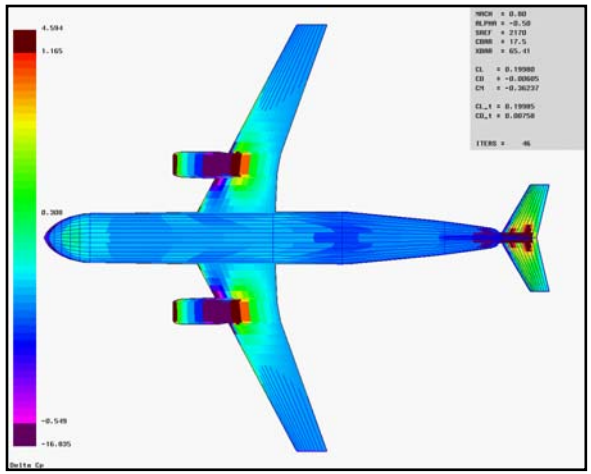


Pre-Trained Neural Networks

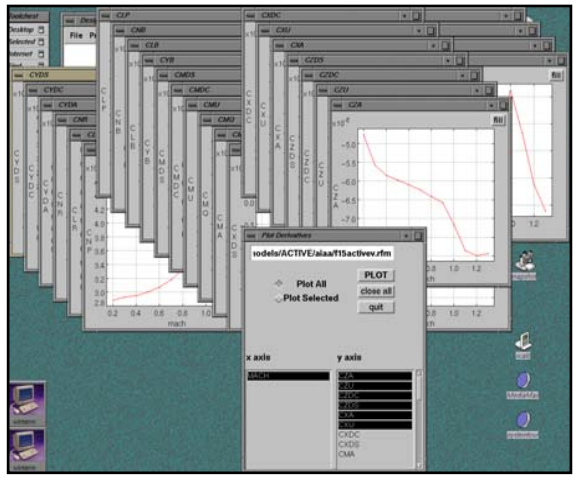
Step 1
Integrated Vehicle Modeling Env.
Rapid Aircraft Modeler (RAM)

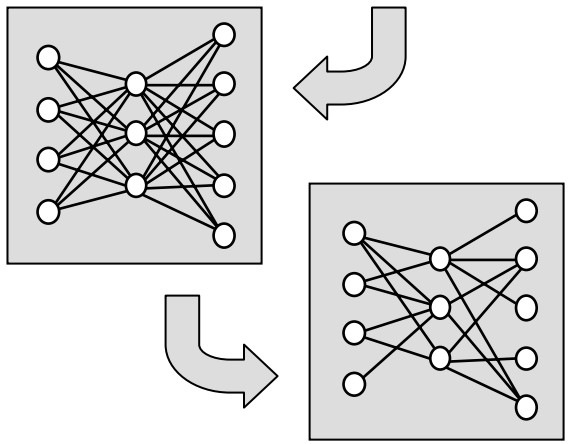


Step 2
Vortex Lattice Code (VORVIEW)
Mass/Inertia Estimates (Balance)



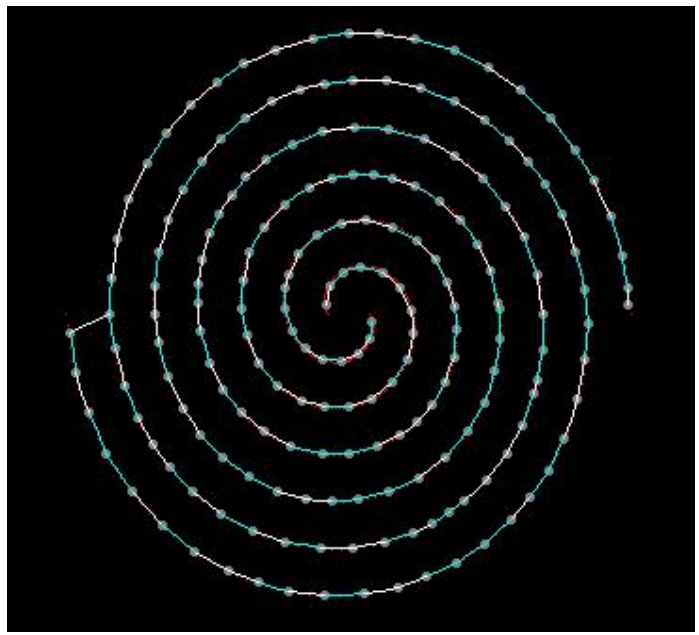
Step 3
Levenberg Marquardt neural net
Optimal Pruning Algorithm





- Topology Representing Network
  - Kohonen Learning: A Self-Organizing Map in which a "Best-Matching" node and a neighboring node are adjusted to match an input vector more closely.
  - Hebbian Learning: Reinforces the strengths of connections between nodes.

Two-Spirals Example



Test Overview

Tests will consist of takeoff and approach and landing and tactical descent scenarios under different flight conditions. The performance of three different controllers will be evaluated under nominal and simulated failure conditions.

- Controller Comparisons
  - Gen-2 system (Daisy Chain)
  - Gen-3 option a: Adaptive Critic & Linear Programming theory optimal control reallocation
  - Gen-3 option b: Adaptive Critic & Table-driven hierarchical scheme (I.e. super-daisy)
- Scenarios
  - Approach and Landing with a failed tail (frozen stabilizer, elevators, rudder)
  - Approach and Landing with all ailerons and spoilers frozen)
  - 2 Engine-Out takeoff
  - Tactical descent to landing with multiple cascading failures
  - All with winds 190/10, light turbulence

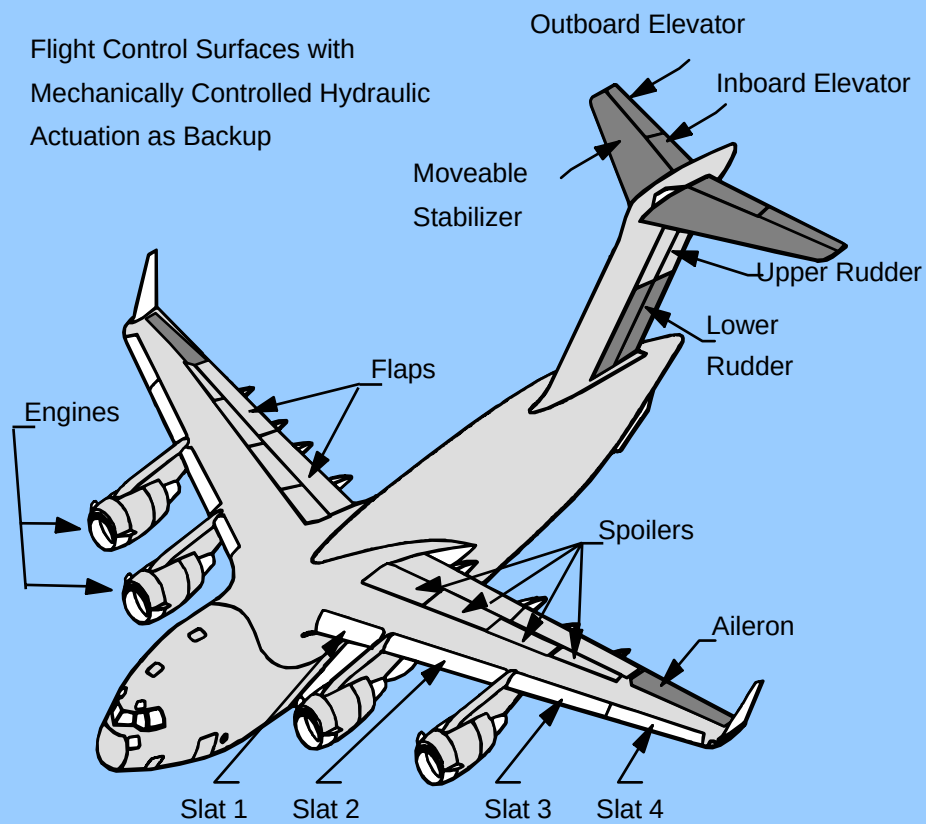
Test Article - Boeing C17

- Block 13 aerodynamics model integrated in to Advanced Concepts Flight Simulator.
- SCAS is from 1989 model, and will not be used in this experiment except to become familiar with the simulation.

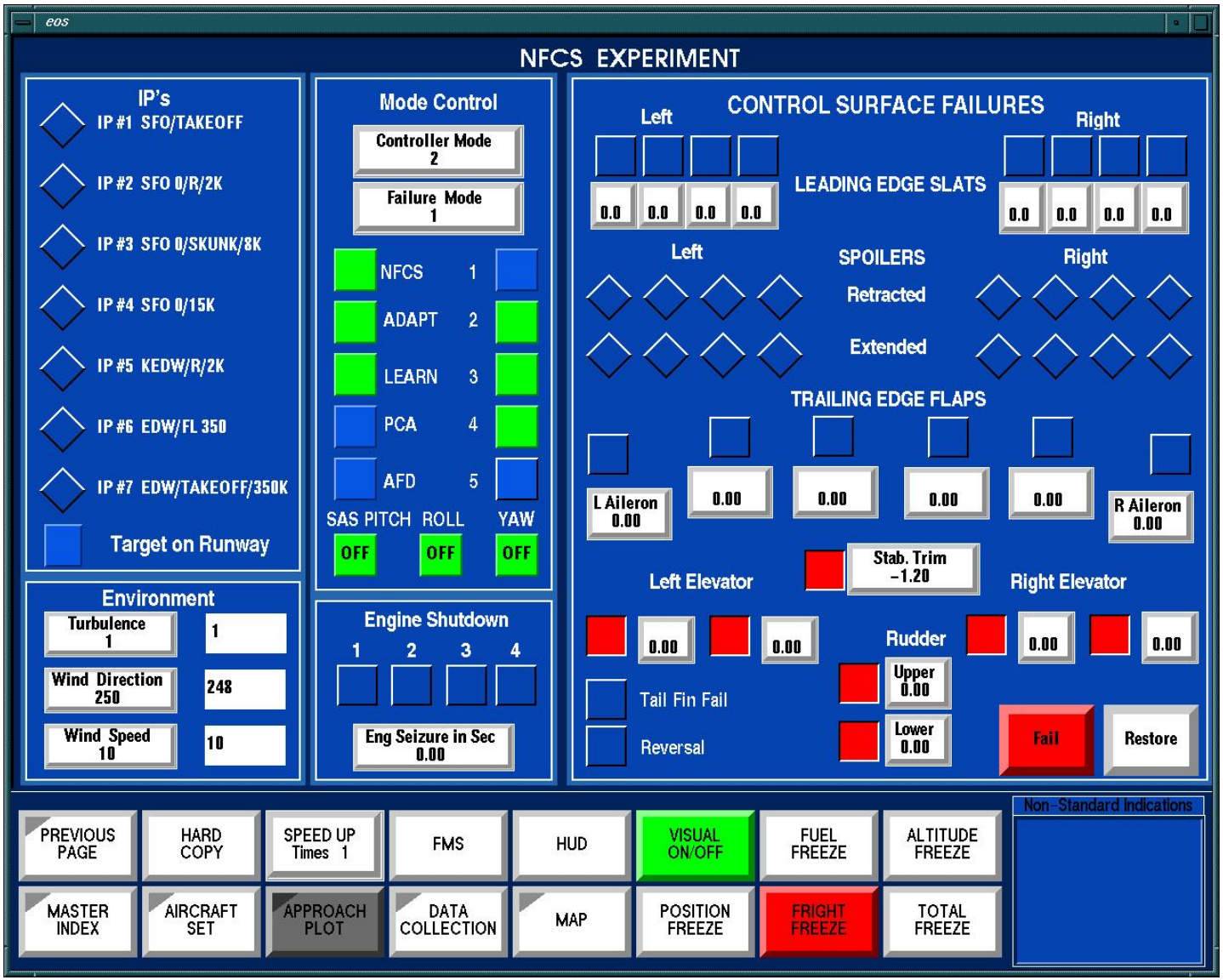
22 CONTROL SURFACES

• 2 flap sections on each wing	4
• 4 leading edge slats on each wing	1
• 4 spoilers on each wing	8
• 1 outboard aileron on each wing	2
• 2 rudders (upper & lower) on vertical tail	2
• 2 elevators (inbd. & outbd.) on each horizontal tail	4
• 1 movable stabilizer	1

4 Pratt & Whitney F-117-PW-100 ENGINES



Experiment Control Page

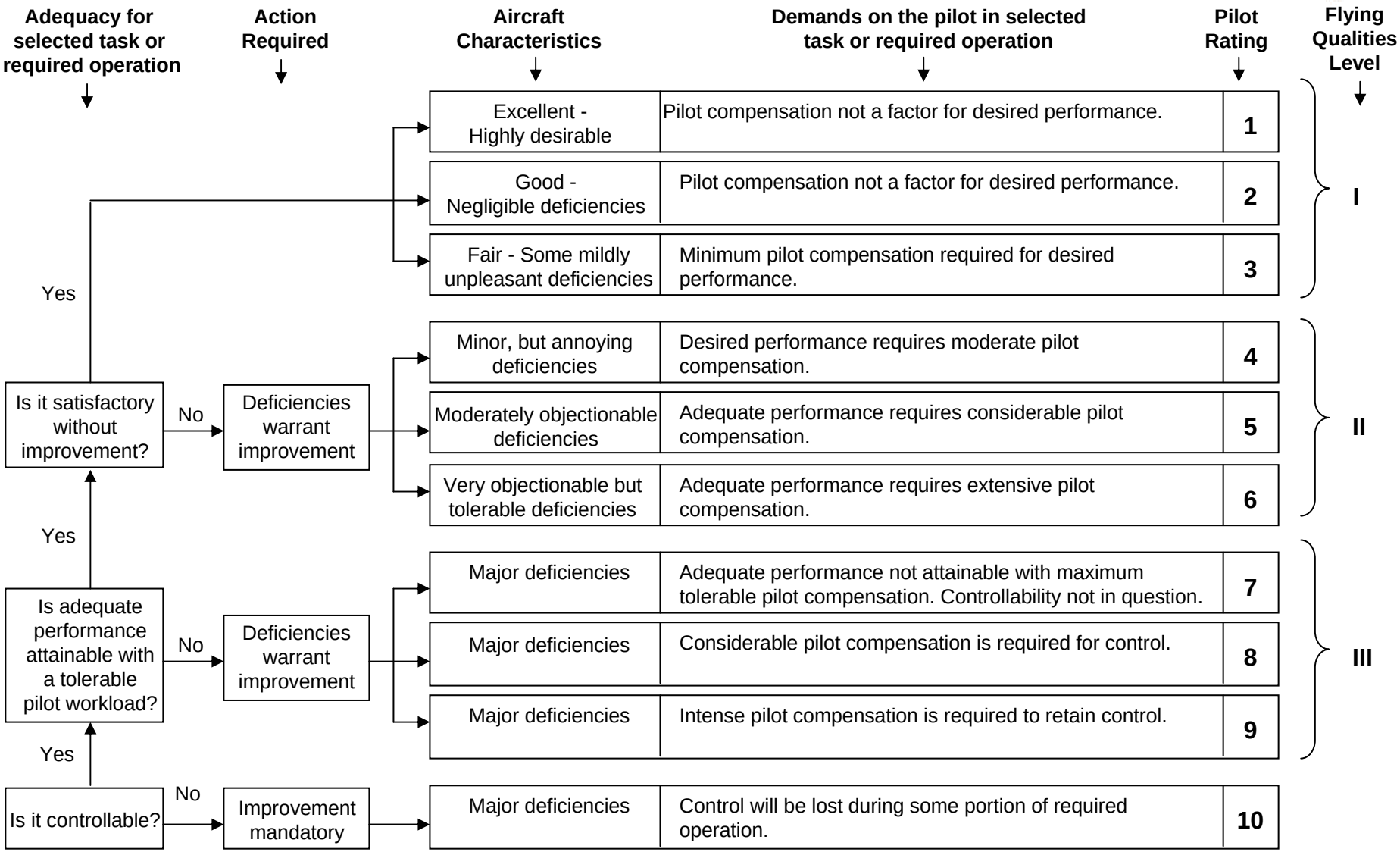


Evaluation Criteria

- **Evaluate Handling Quality Maneuvers based on:**
  - Cooper-Harper ratings
  - Pilot comments
  - Landing performance
  - Stick activity (workload estimate)

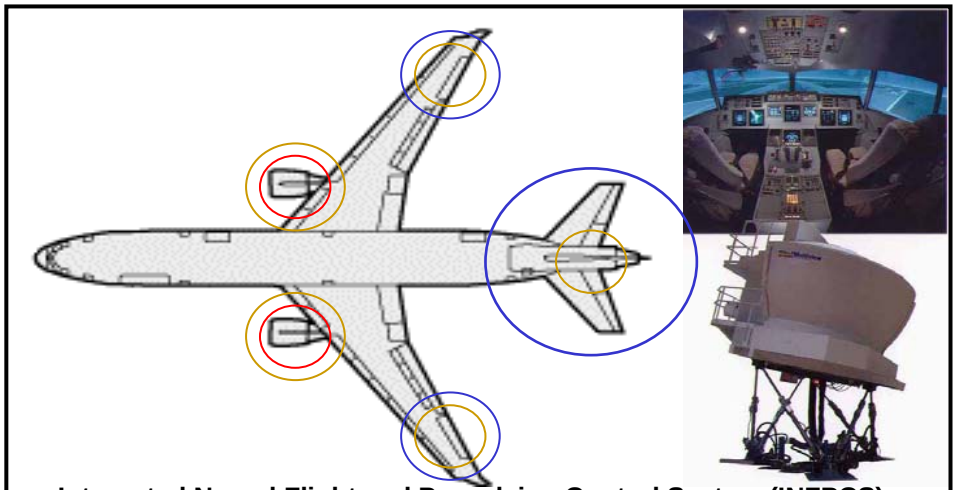
  Pilot's Prioritized Tasks
  - Achieve and maintain aircraft stability.
  - Achieve a "safe" runway takeoff or landing
  - Ensure that speed remains within "operational limits"
  - Strategize aircraft configuration (flap settings, front vs. back-side approach, consider ground effect, winds and turbulence, remaining in the confines of the runway)
  - In tactical descent, do not exceed 20 degrees nose-down (to protect the motion system).

Cooper-Harper Pilot Rating Scale



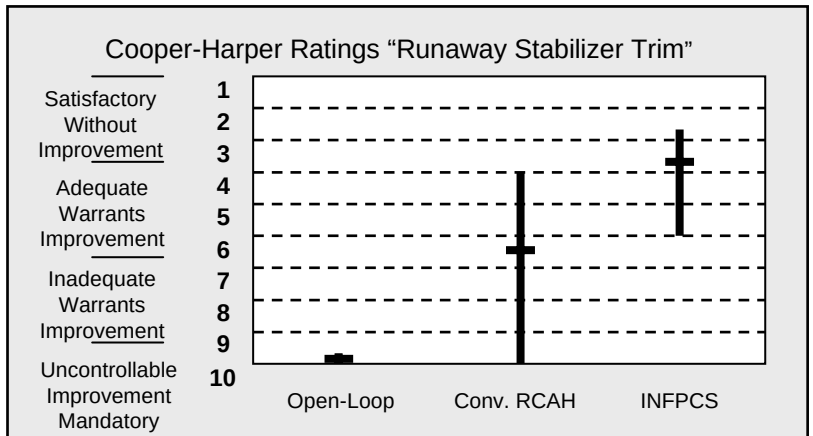
INFPCS Results

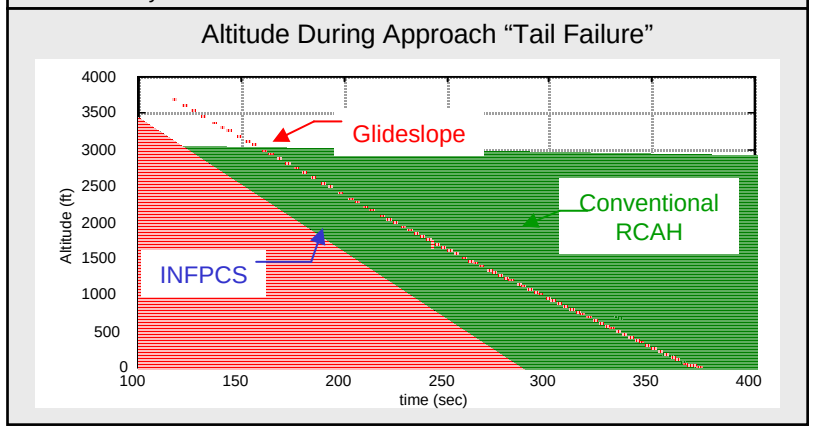
Accomplishment: Accomplishments include reduced or eliminated need for a-priori knowledge of the nominal plant dynamics, explicit parameter identification, and the type/extent of failure or damage, incorporation of a Rate-Command-Attitude-Hold (RCAH) capability, fine-tuned handling qualities, redundant control power in the event of the loss of actuator control, additional control authority in the event of actuator control saturation, and demonstrated ability to provide improved handling qualities for severe failures in a reduced flight envelope that would otherwise result in a catastrophic event.



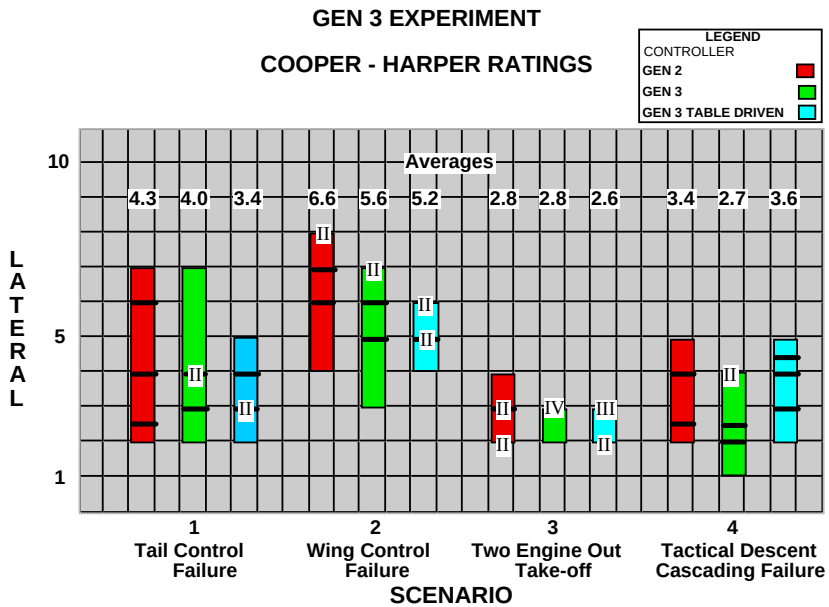
Integrated Neural Flight and Propulsion Control System (INFPCS)

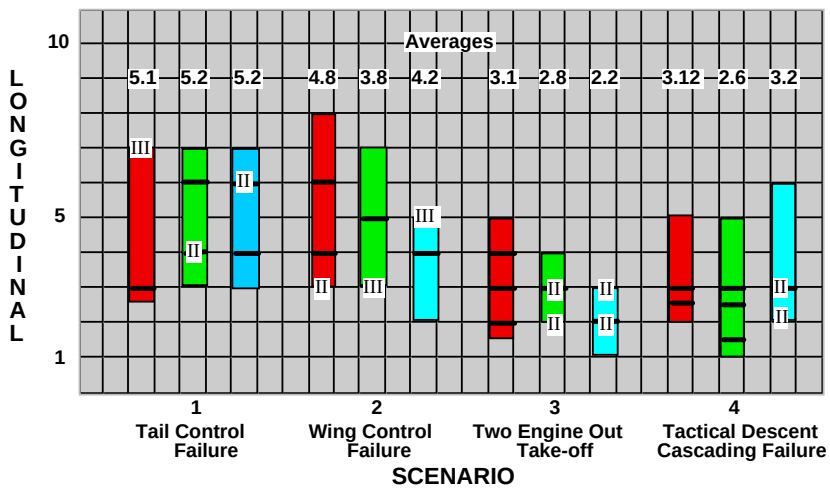
Daisy-Chained Control Allocation	*Lateral*	*Directional*	*Longitudinal*
Primary Flight Controls	Differential Ailerons	Rudder	Symmetric Elevators
Backup Flight Controls	Yaw-Based Roll Control	Differential Thrust	Symmetric Ailerons
Secondary Backup Flight Controls	- - -	- - -	Symmetric Thrust





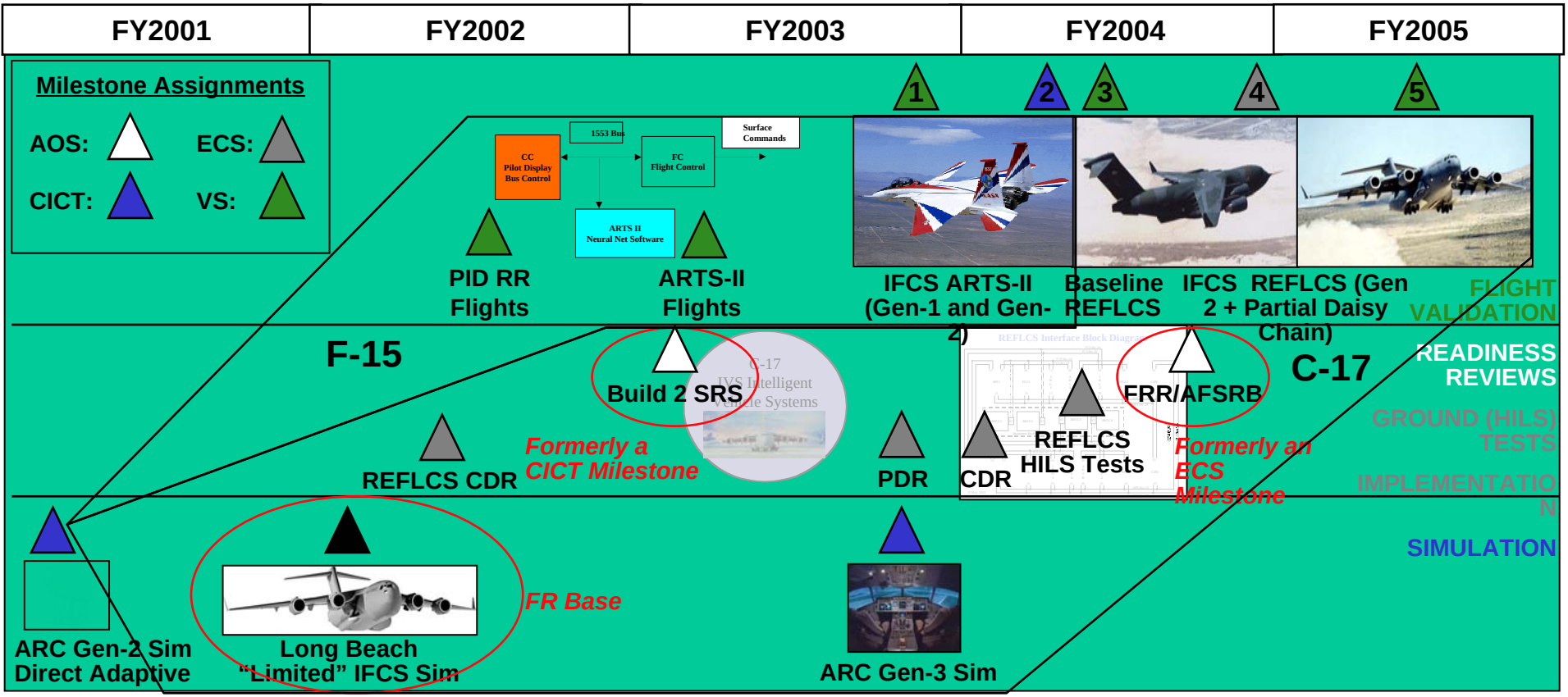
Cooper Harper Ratings for the Gen-3 Experiment





C17 Scenario	Scenario Characteristics: Winds 190 @ 10, light turbulence
Pitch axis	Full tail failure. Stabilizer failed at trim. 2 rudders, 4 elevevators failed at 0 deg.
Roll axis	2 ailerons and 8 spoiler panels failed at 0 deg.
Yaw axis	Two engines out on one side on takeoff, minimum climb speed + 10Kts.
Coupled failure	During tactical descent (failures on one side) • 23,000' : Stab frozen at trim • 20,000' : 2 Elevators frozen at 0 deg. • 17,000' : Upper rudder hard over • 15,000' : Outboard flap fails retracted • 14,000' : Aileron frozen at 0 deg. • 13,000' : Two outboard spoilers frozen at 0 deg. • When engines come out of reverse: Outboard engine seizes.

IFCS Schedule



5 Level 1 Milestones

VS 1 — F-15 837, **Gen-1** Class B Damage Adaptive Flight Tests (Build 2)

CICT 2 — F-15 837, **Gen-2** Class B Damage Adaptive Flight Tests (Build 3)

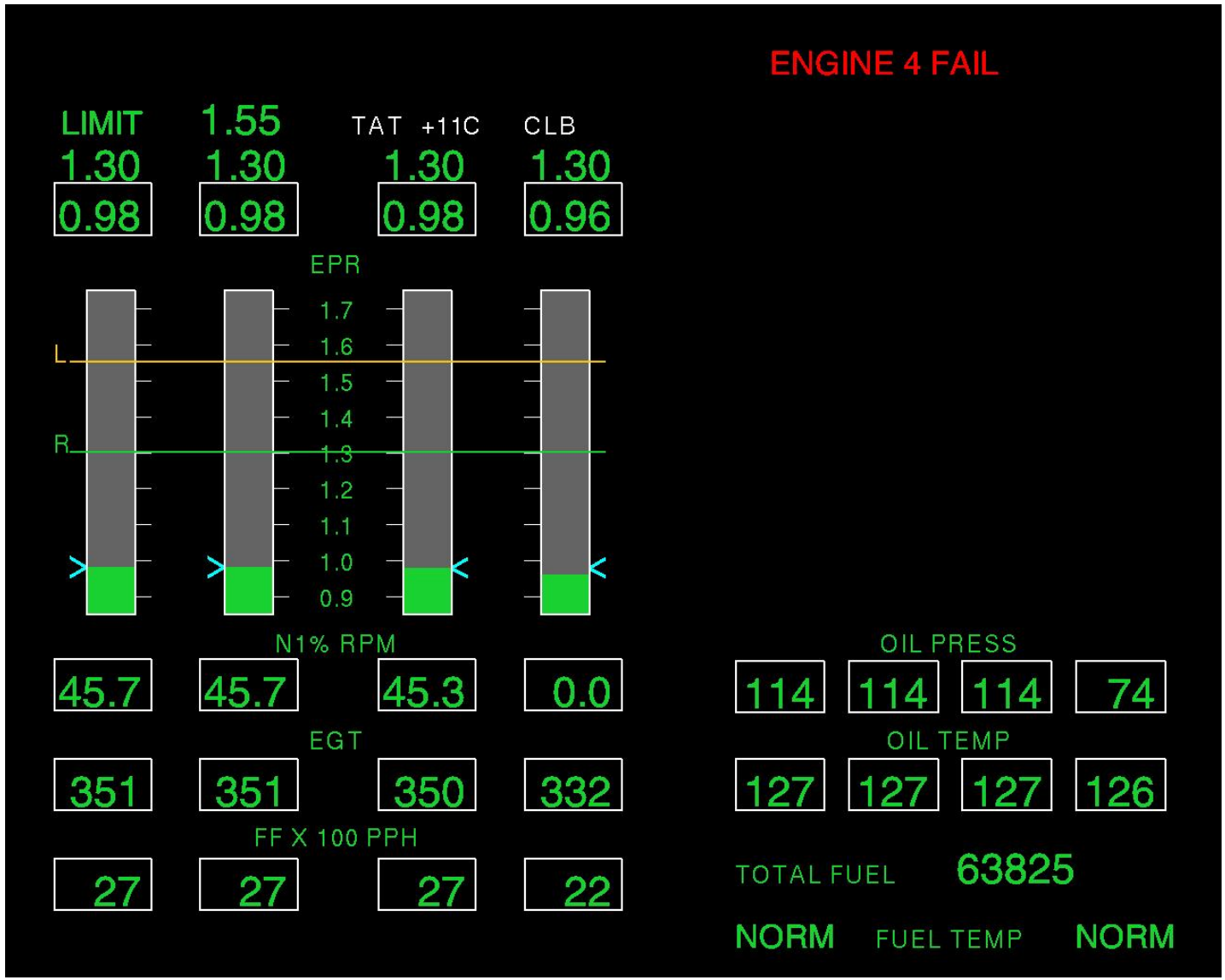
VS 3 — C-17 T1, **Conventional Controls** Class B REFLCS Flight Tests (Build 1)

ECS 4 — C-17 T1, **Gen-2 + Partial Daisy Chain** Class B Damage Adaptive Flight Tests (Build 2)

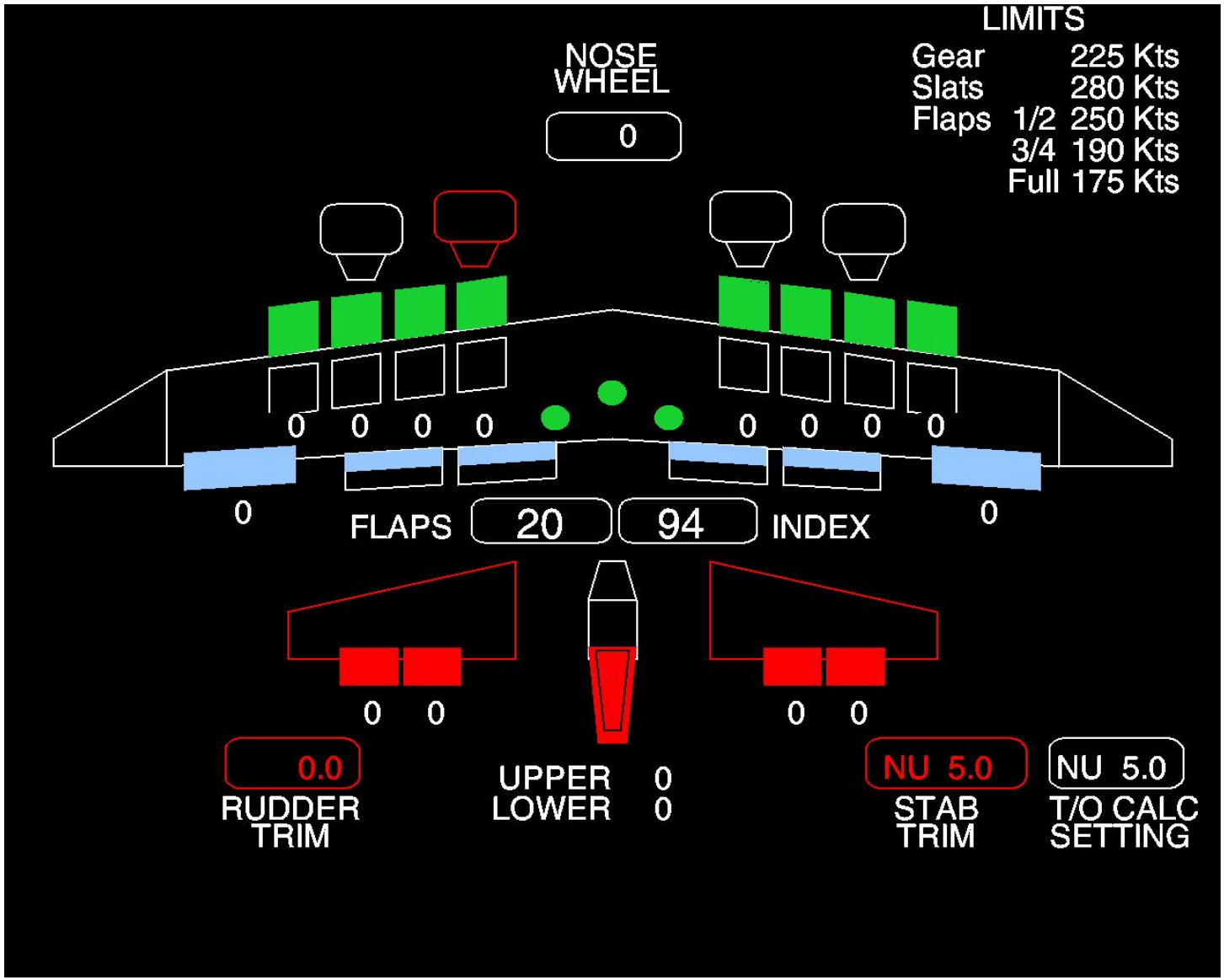
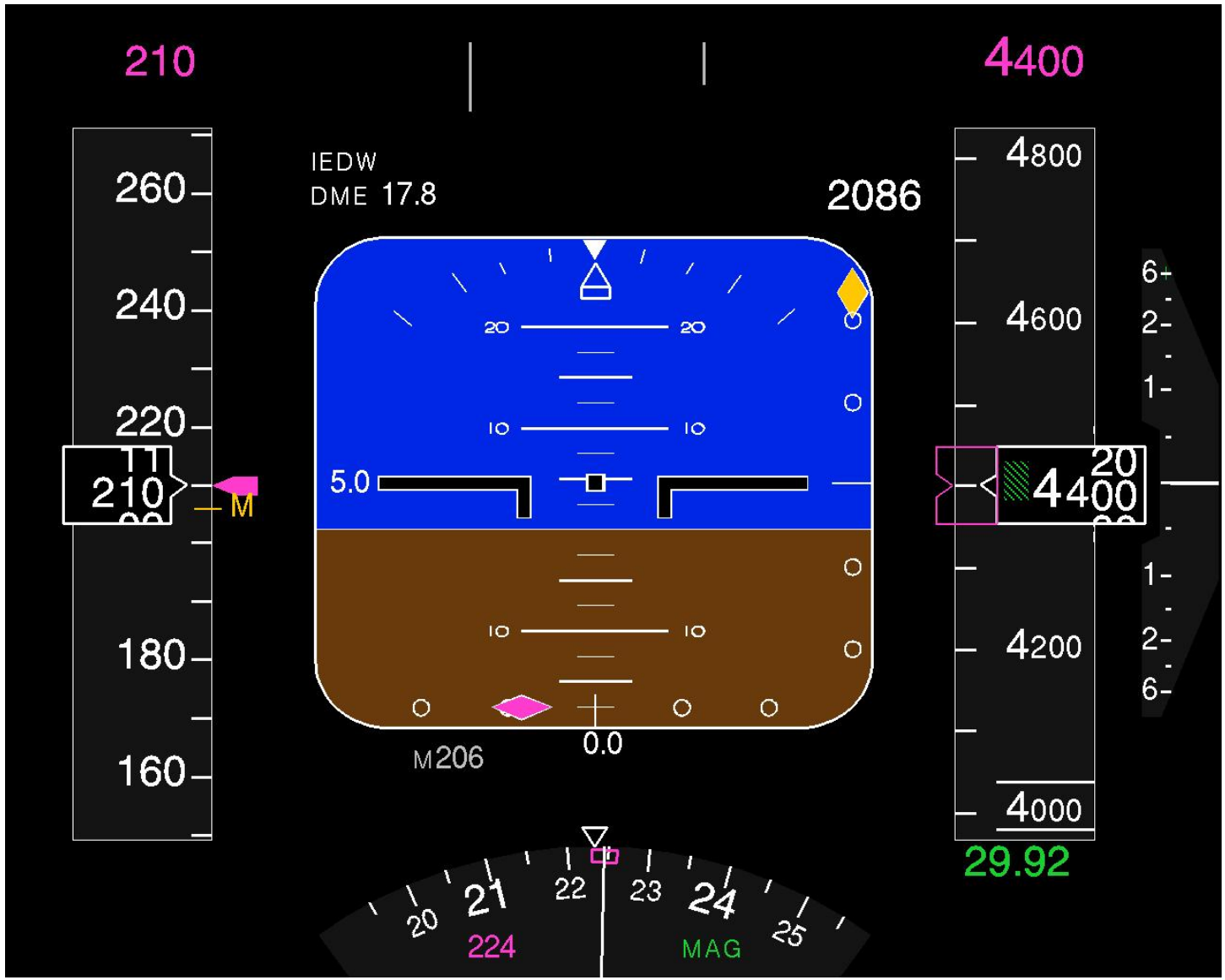
VS 5 — C-17 T1, **Gen-2 + Partial Daisy Chain** Class A Damage Adaptive Flight Tests (Build 2)

Note: "Partial Daisy Chain" is a prescribed control allocation scheme for surfaces only (does not utilize propulsion control)

Upper EICAS Display



Lower EICAS Display



Primary Flight Display