War-Winning Capabilities … On Time, On Cost

F-16 Engine Testing in the Failed State

A Summary of Lessons Learned

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U.S. AIR FORCE

Maj Desmond "Deuce" Brophy
Canadian Forces Exchange Test Pilot
416th FLTS, Edwards AFB CA
desmond.brophy.ca@edwards.af.mil

Outline

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2. Background
3. First “Flight” Sequence of Events
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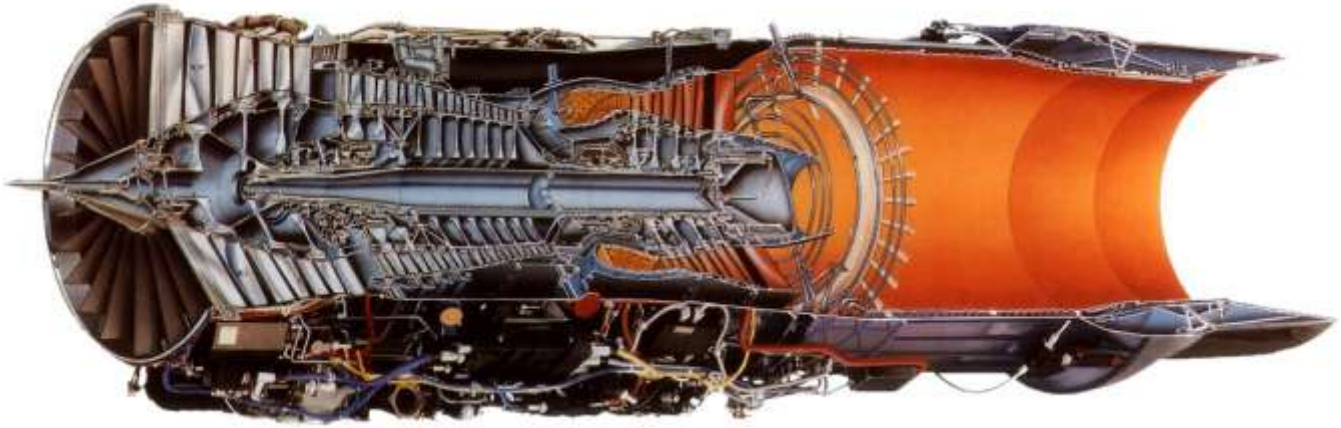
1. Overview of Test Objectives

Overview of Test Objectives



- **Operation controlled by Engine Digital Control (EDC) hardware and software**
- **EDC software upgrade designed to reduce:**
  - **Stalls in high altitude/low Mach regime**
  - **False stall detections**

Overview of Test Objectives

- **Demonstrate:**
  - **High altitude/low Mach performance**
  - **No adverse engine responses or operability produced by software update, including engine shutdown and airstarts**
    - **ie, testing in the '*FAILED STATE*'**

2. Background

F-16 Engine Testing in the Failed State

AFFTC

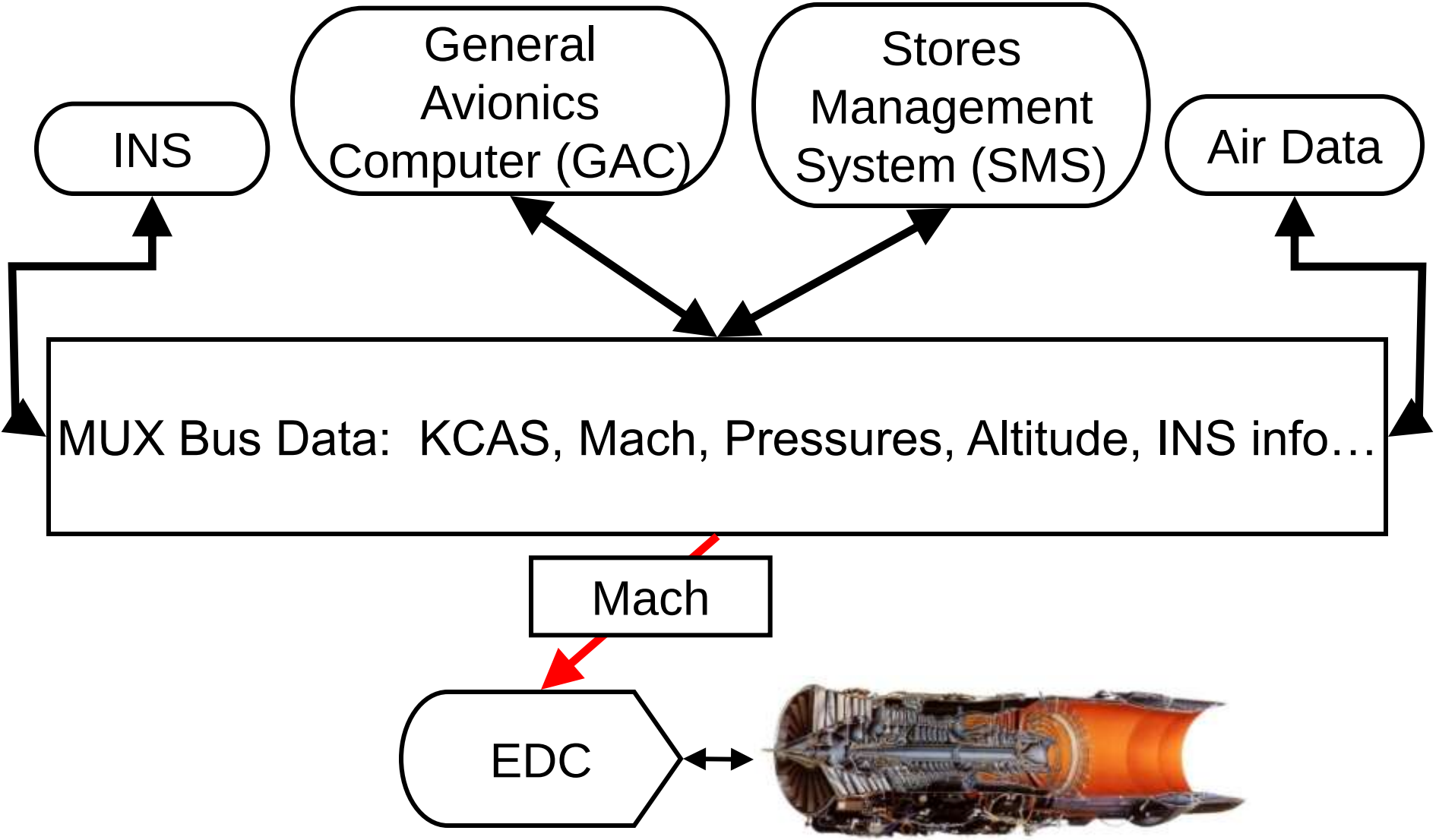
F-16 Engine Testing in the Failed State

F-16 Engine Testing in the Failed State

Hydrazine-Powered Emergency Power Unit (EPU)

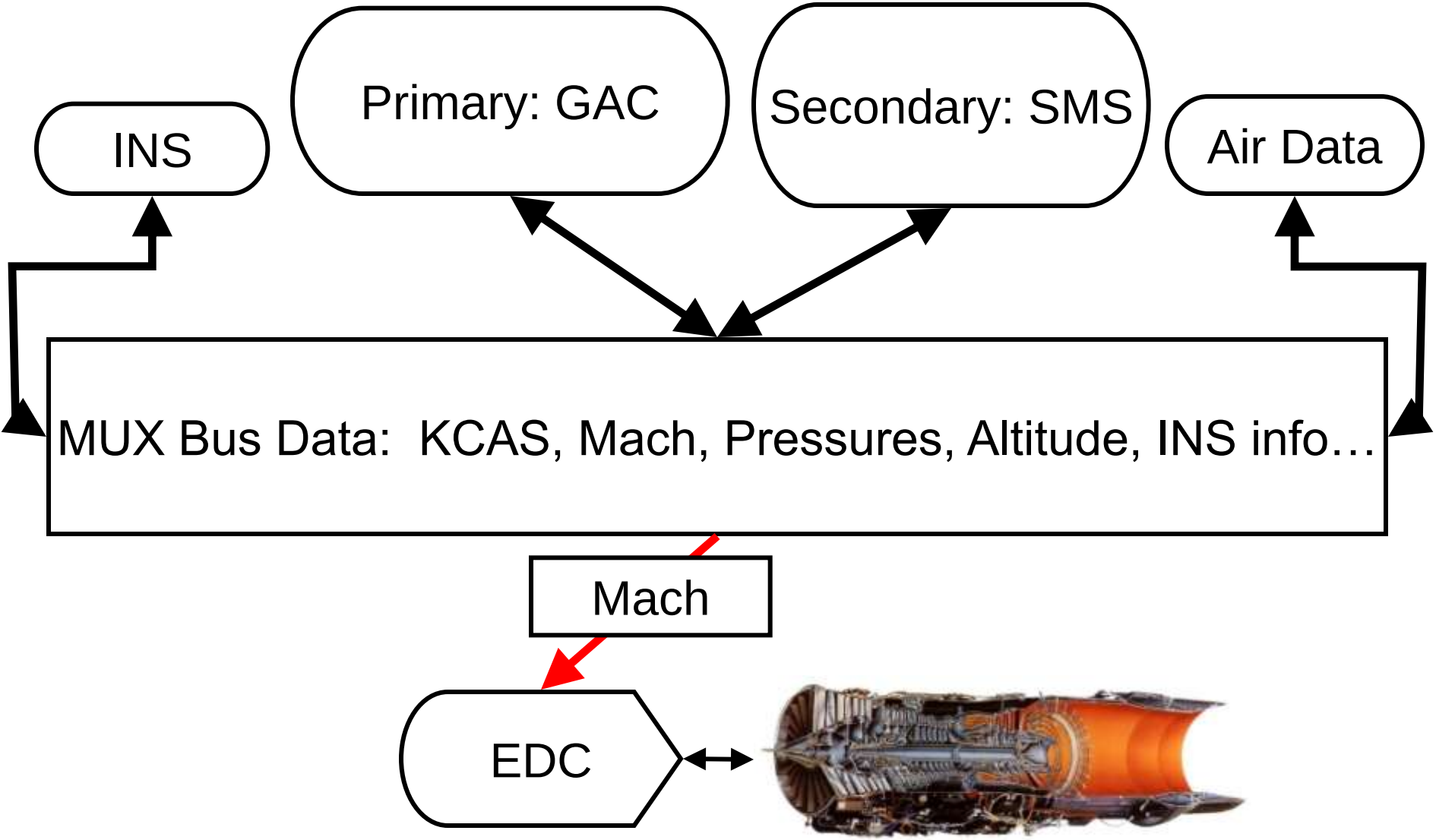
- **Partial hydraulic power**
- **Emergency electric power**
  - ***Only Emergency Electrical bus is powered***

Simplified MUX Bus Flow



GAC vs GACK

MUX Bus Controllers



MUX Bus Controllers

SMS 'designed' to take over MUX bus control when:

1. **GAC fails**
2. **EPU powering Emergency Electric bus**
   - **When the engine isn't operating!**
   - **GAC falls offline (load shedding)**

Engine Operating Modes

- **Primary (PRI) Mode**
  - **Max thrust and stall protection**
  - **Robust airstart envelope**
  - **AB available**
  - **Full nozzle control**

Engine Operating Modes

- Primary (PRI) Mode
  - Max thrust and stall protection
  - Robust airstart envelope
  - AB available
  - Full nozzle control
- Secondary (SEC) Mode
  - EDC Failure
  - Possible engine failure during SEC reversion
  - Reduced stall protection and thrust (No AB)
  - Reduced airstart envelope
  - Nozzle stuck closed

3. First “Flight” Sequence of Events

First Flight Leadup

- EDC software tested in integration lab
  - Including failed state testing with SMS as 2^Y MUX bus controller
- Flight-test proven EDC hardware
  - F-15 ‘sibling’ project
- Robust ground runs in test aircraft
  - MAX/MIL/Idle transients, etc
  - NO failed state testing

First Flight *Plan*

- Normal ground ops
- MIL thrust takeoff
- Heart of envelope throttle transients and Mach sweep
- Airstart test points
  - Heart of envelope
  - High/slow edge of envelope

First Flight *Reality*

- **Normal Start**
- **GAC failure due to internal hardware fault**
- **INS data dumps**
- **Control room reports MUX bus flooded with ‘noise’**
  - **Including critical safety of flight/test parameters**
- **10 mins into trouble shooting**
  - **Engine reverts to SEC**

Flight cancelled- back to the old drawing board!

4. Ramifications

A Stunning Realization

- **Airstart testing=**
  - **EPU- ON**
  - **GAC offline**
- **GAC failure in chocks inadvertently provided ground test of avionics in the failed state...**
- **And revealed some major issues with aircraft, avionics, and engine!**

Ramifications

- **INS dump**
  - **Complicates flame out landing execution**
- **MUX bus ‘noise’**
  - **Monitoring of critical parameters in control room impeded**
- **Engine reversion to SEC**
  - **Worst case= engine failure / unable to restart engine**
  - **Best case= long, ‘hot’ landing**

5. ‘Investigation’ Results

‘Venerable’ F-16 Engine Test Aircraft

AFFTC

- **Several test modifications over last two decades**
  - **Engine testbed**
  - **Flight control system testbed**
  - **Avionics testbed**
- **Block 25 F-16 subsequently modified to Block 40**
- **Formerly, *INS* was secondary MUX bus controller (vice SMS)**

‘Venerable’ F-16 Engine Test Aircraft

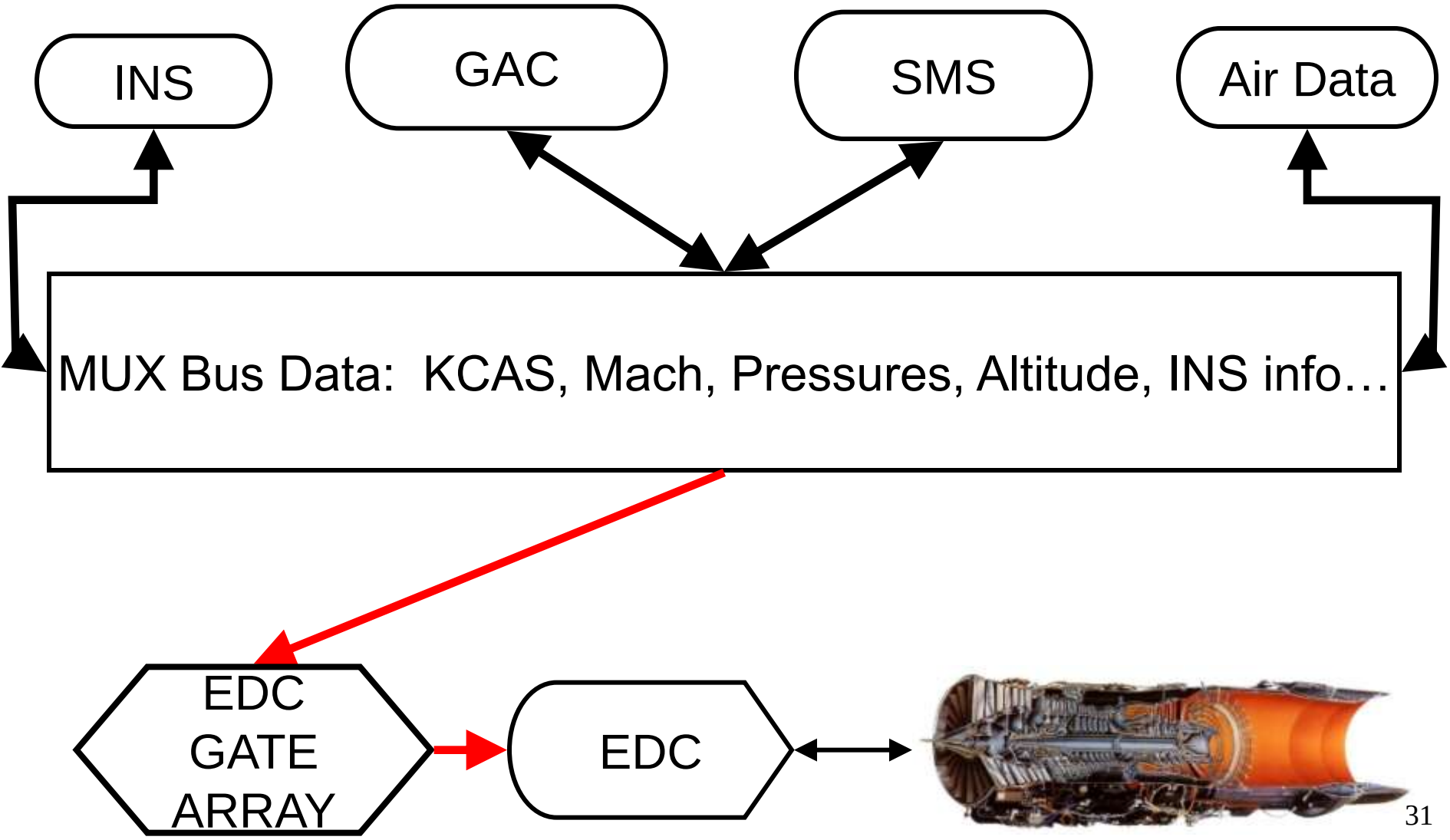
- **INS modification designed such that:**
  - **Would NOT attempt 2y MUX bus control**
  - **Hard wired to aircraft battery during load shedding**
- **Reality:**
  - **INS ‘fighting’ with SMS for 2y MUX bus control**
    - **‘Garbage’ and ‘Noise’ on bus when GAC offline**
  - **Electrical failures resulting in INS dump when transferring to battery power**

MUX Bus Communication Issues

The SEC Reversion

- **Software under test using recently upgraded EDC hardware**
  - **Flight tested**
  - **Operationally fielded**
- **Hardware upgrade**
  - **MUX bus data collected via ‘Gate Array’**
  - **Goal to enhance performance of future EDC**

The SEC Reversion



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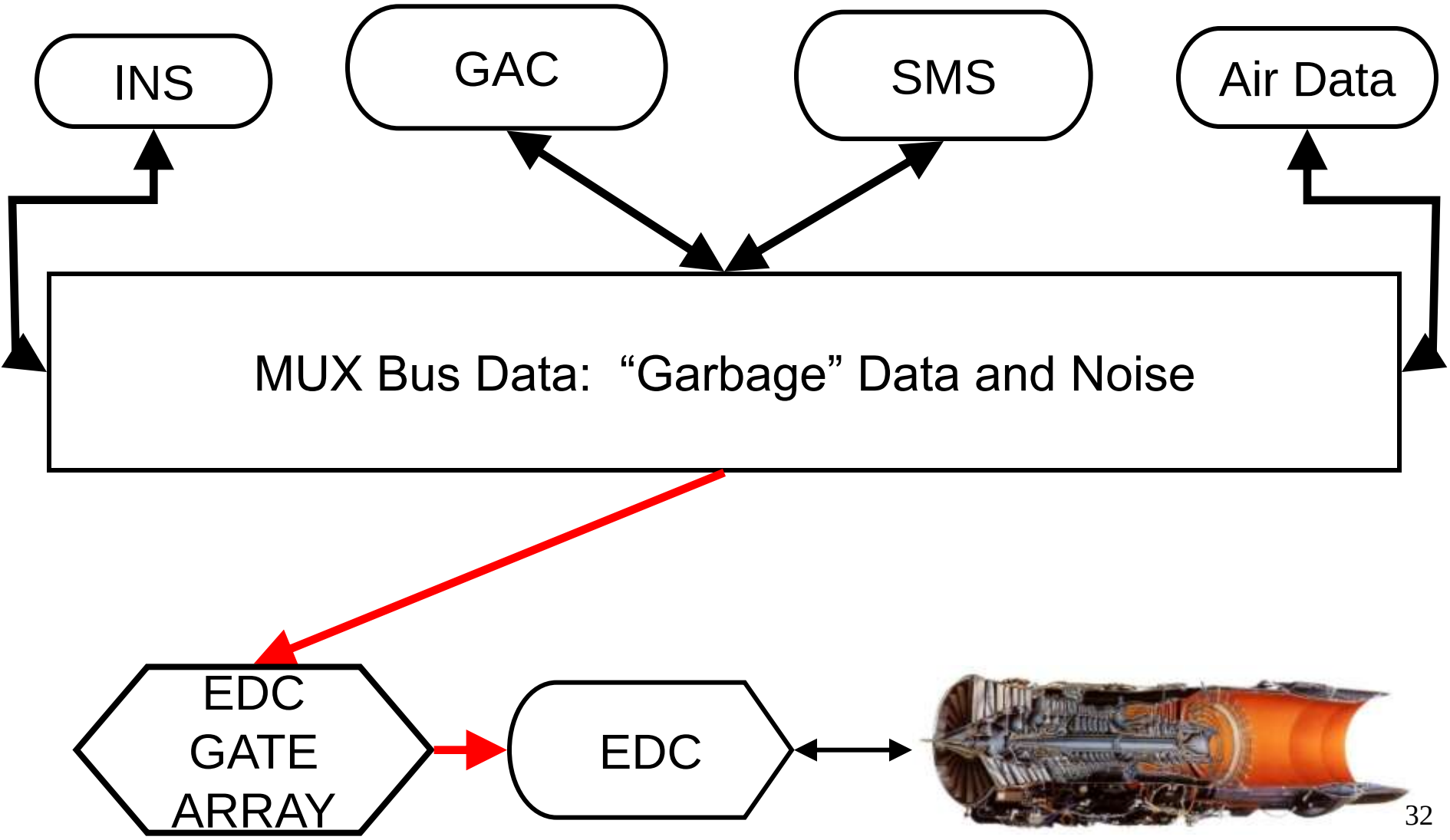

The SEC Reversion

- Gate array recognized presence of ‘garbage’ data via BIT parity error logic
- Misinterpreted this as a EDC hardware failure vice MUX bus problem
- EDC shut down causing reversion to SEC ‘as designed’

Aircraft Avionics Failures Driving Engine into Failure Mode!

6. Recommendations

1. If planning airborne tests in the failed state, conduct ground tests in the failed state

- Emulate avionics failed state conditions
- Activate EPU

2. Heavily modified test aircraft can generate surprises

- Lab tests used ‘standard’ block 40 F-16 avionics and architecture
- Actual test aircraft had been significantly modified in ways that affected testing in the failed state
- Operationally representative test aircraft?
- Critical review of all system modifications and ground testing essential

3. Never believe “that’s impossible!”

- **Initially, manufacturer categorically denied any link between GAC failure and SEC reversion**
- ***Subsequent* lab tests consistently reproduced the problem in presence of MUX ‘noise’**

4. The system under test may be the least of the worries

- **EDC software worked as designed, flawlessly**
- **Safety issues caused by EDC hardware, which was not the system under test!**

5. Take a cautious approach towards systems integration

- Good reason to have engine operation 'separated' from avionics
- Highly integrated designs:
  - Vectored thrust example
    - Flight control laws and computers
    - Air data systems
    - MUX buses
    - Engine operations and control laws

6. External safety oversight is critical

- Team eager to control MUX bus noise and ‘get flying’
  - Reduce MUX bus loading via test GAC software
  - Treat symptom
- Oversight directed team to get the root cause before any more flights

7. Test points near the edge of the envelope hold other surprises

- Mach 2 run aborted at 1.8 due to airframe vibration
- Tail hook found slightly out of rig tolerance
- Appears as though aircraft hadn't been at this part of the envelope in two years

Epilogue

- **INS problems corrected**
- **‘Clean’ MUX bus data, even in failed state**
  - **Therefore no SEC reversion concern**
- **Smooth flow of airstarts, throttle transients, and Mach sweep test points**
- **EDC software performed flawlessly, as designed**
- **Deficiency Report generated for design of EDC Gate Array / MUX bus interaction**

Questions and Wrap Up