MSFC - 775

Pratt & Whitney Overview and Advanced Health Management Program

Presented To the University of Alabama IEEE
April 7, 2008

Calvin Inabinett

Pratt & Whitney Alabama Operations

Huntsville, AL

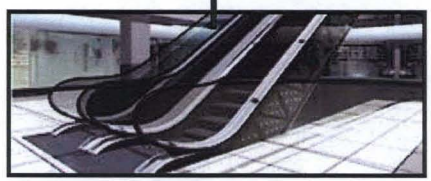
256-544-0754

PWR Is Part of United Technologies

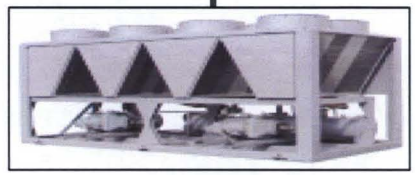
Pratt & Whitney
A United Technologies Company

United Technologies

Sikorsky

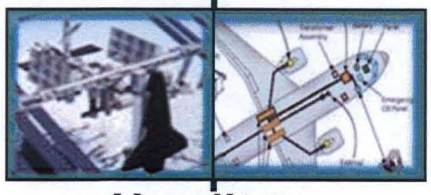


Otis



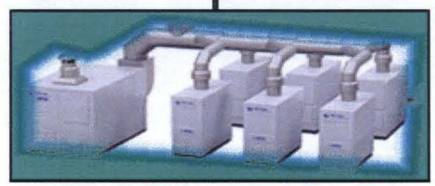
Carrier

UTC Fire & Security



Hamilton Sundstrand

Pratt & Whitney



UTC Power

Research Center

Hamilton Sundstrand Space Land Sea Rocketdyne

Pratt & Whitney Rocketdyne (PWR)

- Military Engines
- Commercial Engines
- Pratt& Whitney Canada (small gas turbines)
- Global Service Partners
- Power Systems

PWR Products

Pratt & Whitney
A United Technologies Company

Launch Vehicle Engines

Space Shuttle Main Engine

Delta II / RS-27A

Delta IV/ RS-68, RL10

Atlas V/ RD-180, RL10

Development Engines

CECE RL10

RS-18

RS-88

Attitude Control Propulsion

THAAD DACS

ABMD Integration

XSS-10

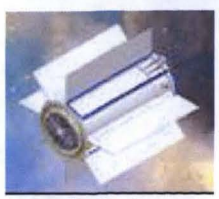
IPD

J-2S

MB-XX

RL-XX

Hamilton Sundstrand Power Systems

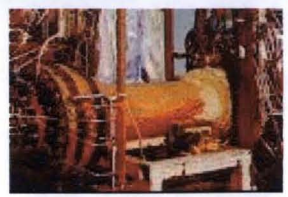


Radioisotope Power System

Power in Space and Distribution

Nuclear Power Conversion

Energy Systems



Energy Systems

Hypersonic Technologies

PWR – 3,700 Total Employees

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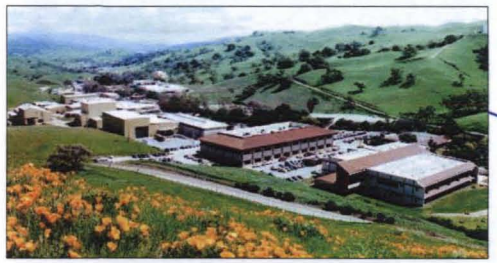
Canoga Facility (California)
1,100 Employees

De Soto Facility (California)
1,250 Employees



San Jose Facility (California) 35 Employees
Decommission 2007

120 Employees
Kennedy Space Center (Florida)

140 Employees
Alabama Operations (Huntsville)

235 Employees
Stennis Space Center (Mississippi)

880 Employees
West Palm Beach (Florida)

PWR Alabama Operations

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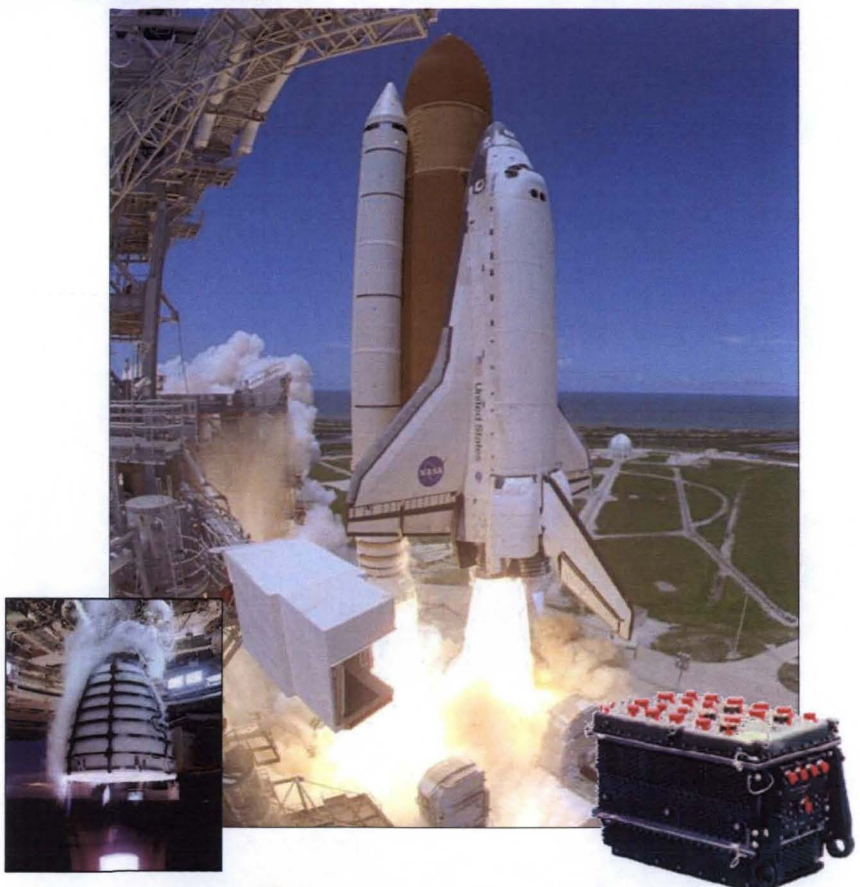

SSME Project Support

- Provides project support functions
- System Engineering / Management
- Configuration and Business Management

Advanced Programs

- Concept Development & Market Shaping
- Campaign Strategy
- Proposal Development & Capture

PWR Alabama Operations

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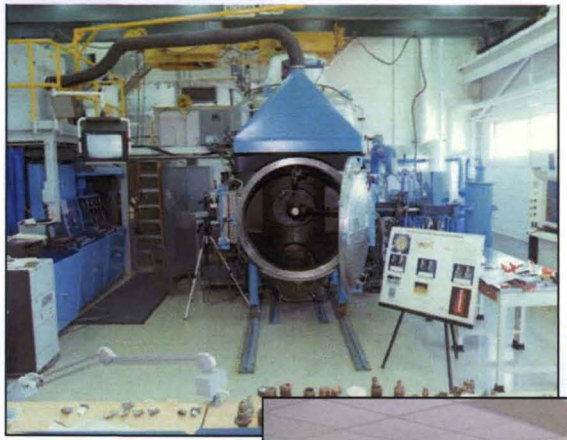
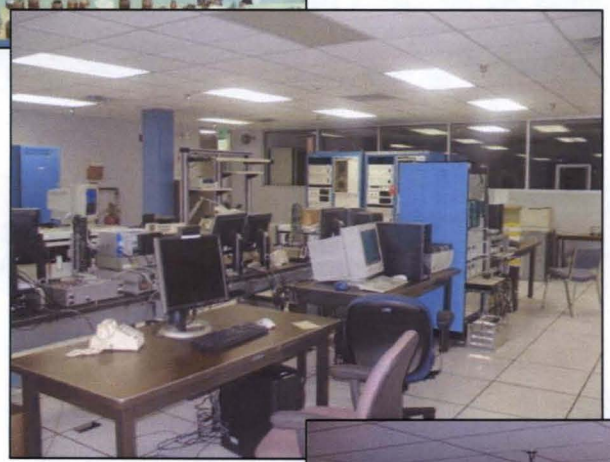


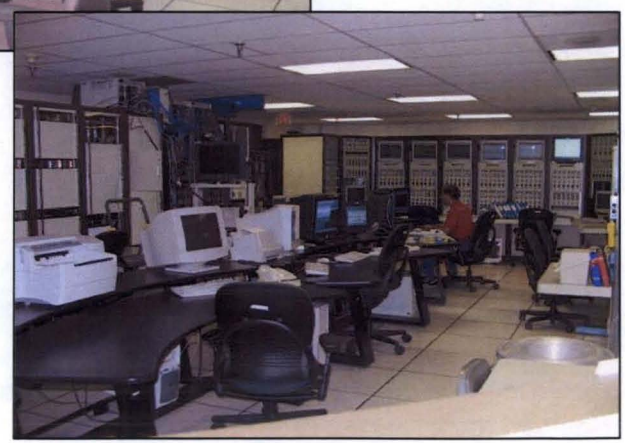
Materials Lab

- Assist in Developing and implementing Advanced Process Improvements
- Develop Improved Manufacturing Processes for Canoga Park
- Work On-Site with MSFC Personnel
- Process Flight Development Hardware



Controller Software Lab

- Software Project Management
- Requirements Definition/ Analysis
- Software Implementation
- Hardware Design
- System Management



Hardware Simulation Lab

- Verification and validation (V&V) of the SSMEC software in a hardware-in-the-loop environment
- Delivery of the SSMEC software for test and flight
- Anomaly resolution in support of engine test and flight

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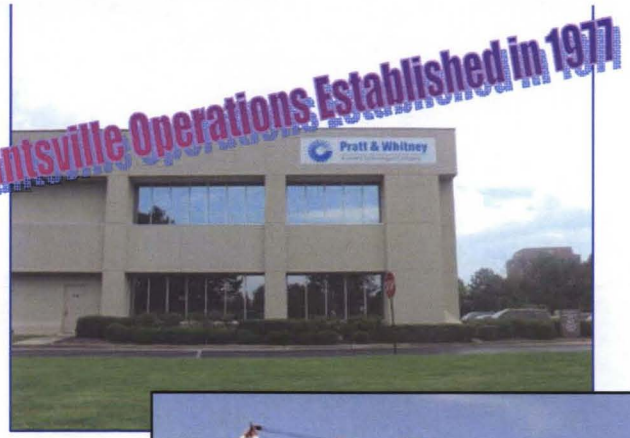

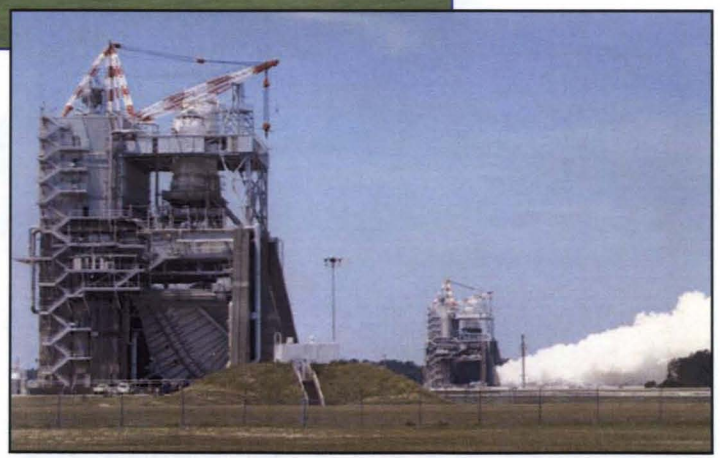

- The original SSME Hardware Simulation Laboratory (HSL) was developed in the mid to late 1970's with Rocketdyne assuming operation on April 1, 1977.
- 1st Flight of the SSME Block I Controller Software 1981
- The MSFC Technology Support Team was formed in 1984 to support the Labs in developing and implementing new technologies for propulsion
- The MSFC Project Support Team was formed in 1986 to support the SSME Program in Huntsville and provide better customer integration.
- The current HSL, also known as the Block II HSL was brought on-line in September 1988 to support the Block II engine controller software V&V.
- Technology Test Bed (TTB) at MSFC was created for the testing of highly instrumented engines to provide a deeper understanding of SSME operation (1986 to 1995).

- 1st Flight of the SSMEC Block II Controller Software 1992
- CSL relocated from Canoga Park to Huntsville 1995
- 1st Flight of the SSMEC Advanced Health Management System (AHMS) Software in 2006

PWR Alabama Operations: A Rich History… Surrounded by Great Accomplishments!

Pratt & Whitney
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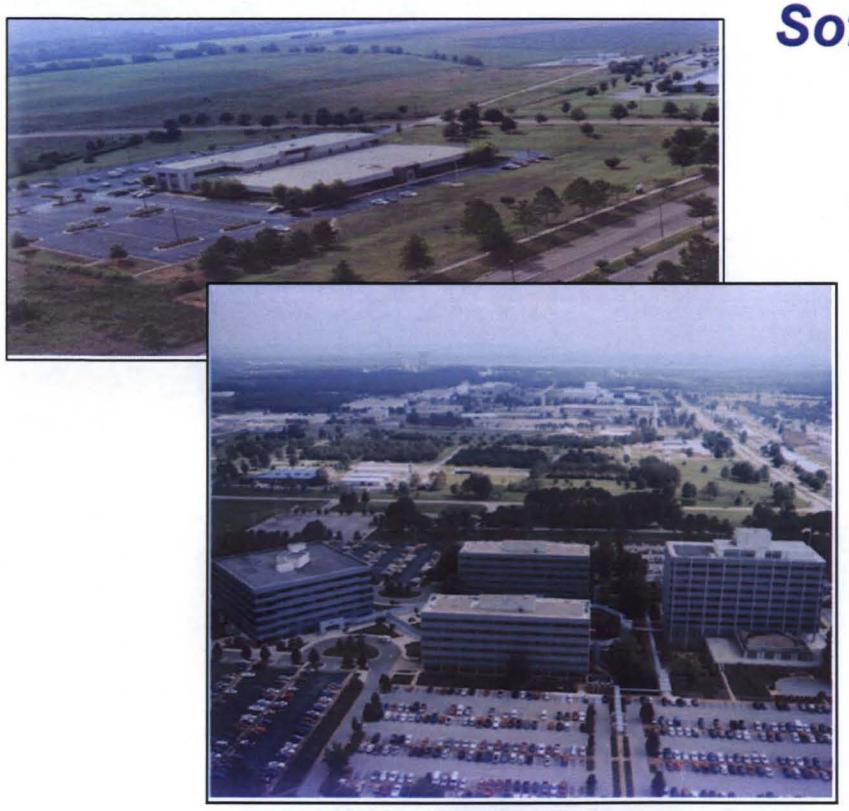


Software Processing Cell

We Were The First ….

- ❑ To develop software for the first digitally controlled rocket engine
- ❑ To create MSFC first automated hardware-in-the-loop simulation environment
- ❑ To develop the first man-rated health management system

Longevity….

- ❑ Hardware Simulation Lab is the longest running sole-sourced MSFC contract (30+ years)
- ❑ Longest running government-owner / contractor-operated facility at MSFC
- ❑ Over 345 SSME Flights and over 1,000,000 seconds on test stand with zero turnbacks

Space Shuttle Main Engine (SSME)
Advanced Health Management System

The First Active Health Management System Ever Deployed on a Rocket Engine

AHMS Project Overview

- **The AHMS Project - Upgrade Existing SSME Flight Controller**
  - Incorporate High Pressure Turbopump Synchronous Vibration Redline
  - Add External Communications Interface for Future Applications
  - Double Memory Capacity and Utilize Radiation Tolerant Memory Devices
  - Eliminate Controller Memory Retention Batteries - Replace with Electrically Erasable Programmable Read Only Memory (EEPROM)
  - Team
    - NASA – Marshall Space Flight Center (MSFC)
    - Pratt & Whitney Rocketdyne (PWR), Inc. (SSME Prime)
    - Honeywell International (Controller Supplier)

Space Shuttle Main Engine Controller

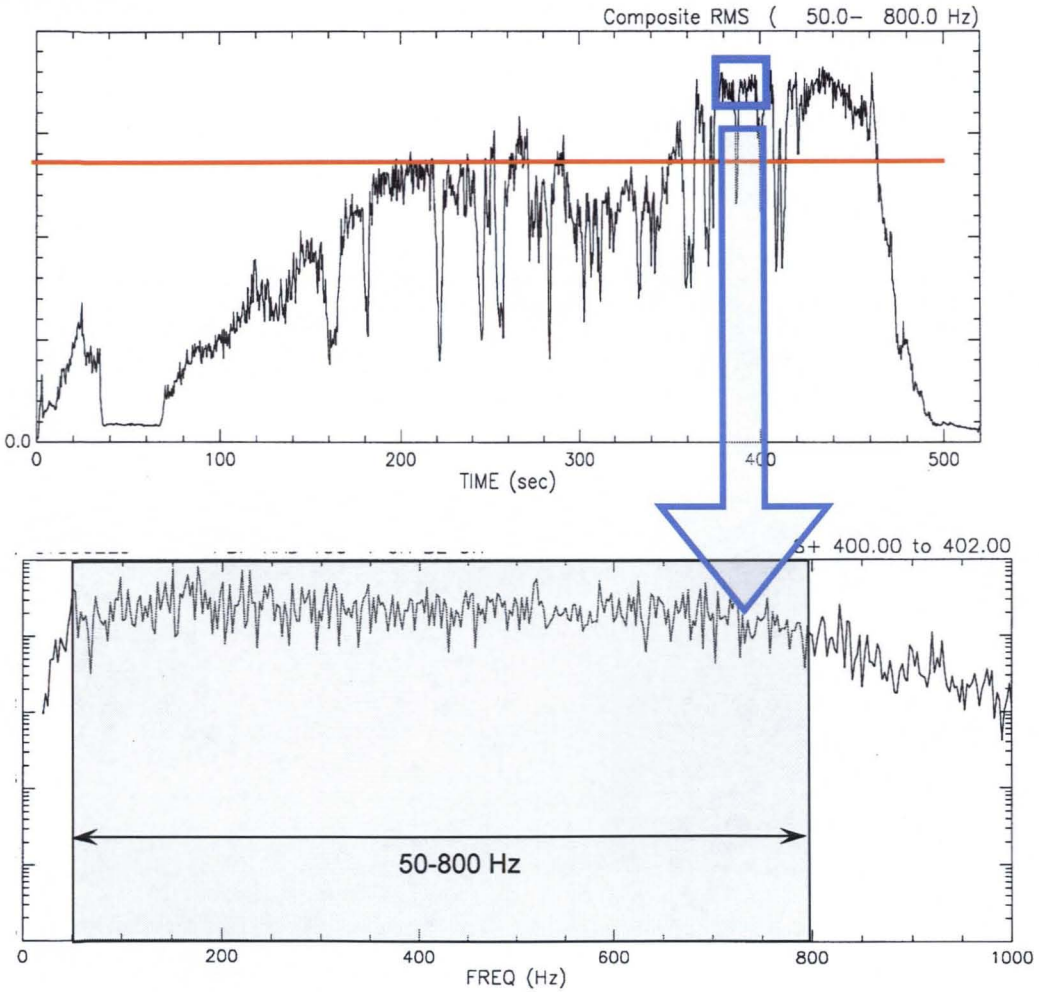
Phase 1 Synchronous Vibration
Redline Overview

- **What We Had**
  - Flight Accelerometer Safety Cutoff System (FASCOS)
    - Data acquisition: 3 High Pressure Oxidizer and 3 High Pressure Fuel Pump accelerometers
    - Redline voting logic: 3 of 3 or 2 of 2 qualified sensors over 5 controller cycles (5 20 msec cycles ==> 100 msec)
  - FASCOS is an analog redline based on 50-800 Hz composite amplitude
  - FASCOS is unable to distinguish between real pump distress and a noisy accelerometer signal
  - FASCOS has never been active for flight
  - An active high pressure turbopump vibration flight redline has been a long sought-after capability for the SSME Project and the Shuttle Program

Redlines provide engine cut off if limit is exceeded, but health management requires knowledge of system condition to determine appropriate mitigation action

Example of Potential Redline Cut-off

Historical Real Time Redline <u>Could Not</u> Distinguish Noisy Signal



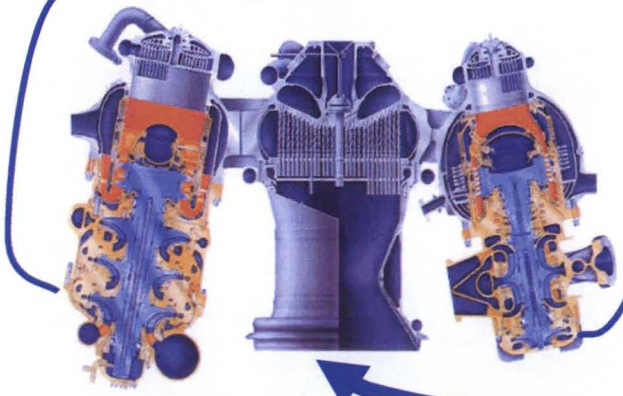
STS-32 Power Spectral Density @ 400 seconds

- **All three accelerometers on the HPOTP during STS-32 had failed (cable damage)**
- **Composite level (at top left) indicates a violation of the FASCOS redline limit**
- **PSD (at bottom left) indicates a noisy accelerometer**
  - FASCOS does not examine spectral content
  - FASCOS cannot determine exact nature of high vibration level
- **FASCOS misinterprets high vibration level and would vote to shutdown**
- **Had FASCOS been active, Engine 3 would have been erroneously shutdown**

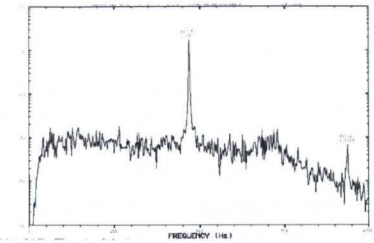
AHMS Phase 1 System

Synchronous Vibration – System Solution

High Pressure Pumps vibration and speed signals from sensors sent to engine Controller for processing



Engine Control filters and converts analog signals to digital data for further processing



Real-Time Spectral Analysis (Fast Fourier Transforms) Performed to detect and measure pump synchronous frequency

Engine Control Adjusted
- Sensor Disqualifications
- Engine Shutdown

Active during flight – requires significant system reliability

Sensors used:

3 HPFTP accelerometers

2 HPFTP speed sensors

2 HPOTP accelerometers

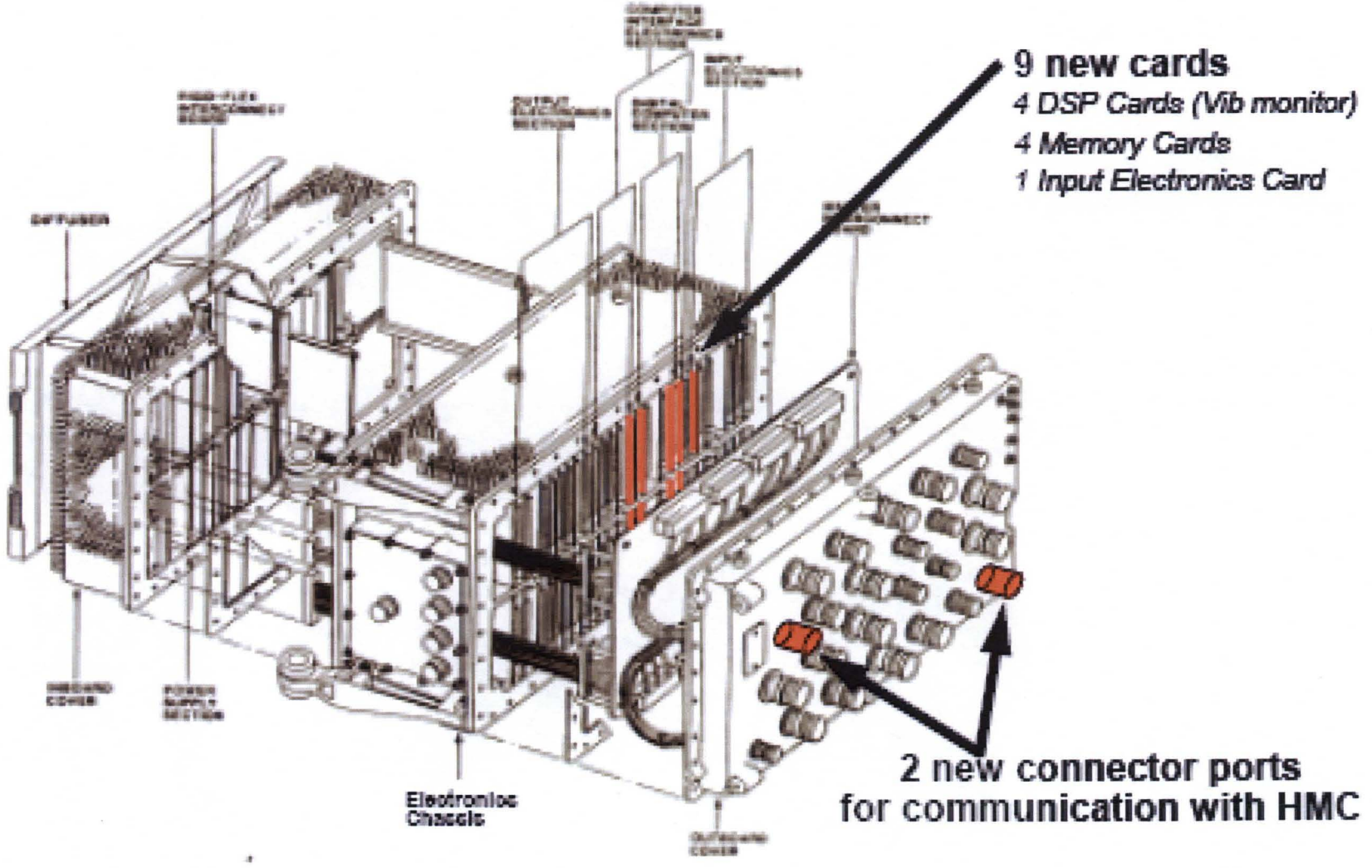
Data acquired at 10,240 samples per second

– 50 msec time slice results in 512 data samples per slice

– Frequency resolution of 20 Hz

HPOTP – High Pressure Oxidizer Turbopump HPFTP – High Pressure Fuel Turbopump

AHMS – Controller Design Solution



Phase 1 Synchronous Vibration

- **New AHMS Phase 1 Synchronous Vibration Redline**
  - Data processing
    - All sensors are processed in real-time by utilizing Digital Signal Processing (DSP) technology
    - HPFTP speed used to locate HPFTP synchronous frequency
    - Main Combustion Chamber pressure used to estimate search band for HPOTP synchronous frequency
      - No HPOTP speed probe
      - Increased frequency range used to evaluate synchronous frequency
        - Most prominent harmonic in measurable frequency range
  - Qualification logic
    - Algorithm incorporates validation logic to qualify the 6 accelerometer signals
      - Logic passes synchronous and background noise levels through threshold limit checks in combination with cross-accelerometer comparisons
      - Only qualified sensors used to determine the health of the turbomachinery
      - Disqualified sensors will be deactivated from the redline voting logic
        - Once disqualified, no longer eligible for use during that flight

Phase 1 Synchronous Vibration
Redline Overview

- **New AHMS Phase 1 Synchronous Vibration Redline (cont'd)**
  - Redline is active from Engine Start (E/S)+5 sec until engine cutoff
  - Redline Voting Logic
    - Engine shutdown requires a 3 of 3 vote (2 of 2 if one sensor disqualified)
      - Must have 2 consecutive strikes on a ***qualified*** accelerometer to issue individual accelerometer vote
      - Must have 3 ***simultaneous*** qualified accelerometer votes (2 votes if one accelerometer is disqualified) to issue engine shutdown command
    - "Hold down" Health Monitoring
      - From E/S+5 sec until ~E/S+6.0 sec, engine shutdown can be initiated by one qualified accelerometer exceeding threshold
        - One accel may exceed threshold prior to other accels – limited timeframe might prevent proper shutdown if all accels are required to exceed threshold
        - Consistent with other redlines on engine

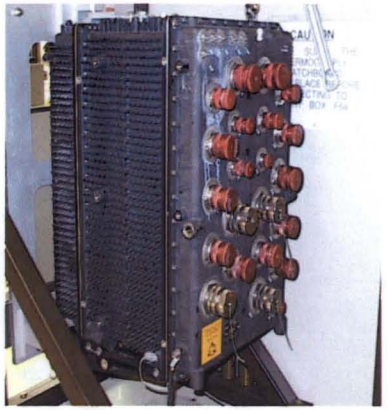
Alabama Operations Contributions

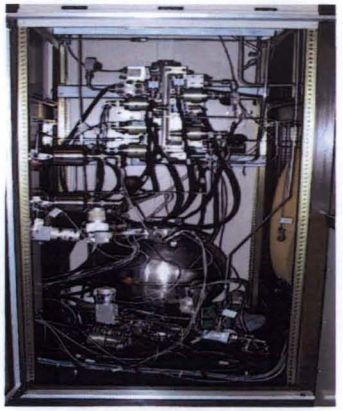
- **Software Development Activity**
  - Controller Software Development
    - Design and develop two Computer Software Configuration Item (CSCI) to execute in a Digital Signal Processor
    - Developed a real-time operating system
    - Upgraded existing core CSCI to command and control DSPs
  - Software Test Tools Development
    - Design and develop real time test environment
    - Integrate new test insertion tool into an existing facility
    - Develop a Data Reduction tool
    - Further enhance automation of testing

Alabama Operations Contribution

- **Hardware Development Activity**
  - Design and Test Custom Multi-layer Circuit Boards for use in the Fault Emulation Unit
  - Logic design performed using VHDL
  - Lay out power system for lab hardware
  - Work lab issues with software developers and software testers
  - Interface with Engine Systems personnel with performance of Engine hardware components
  - Perform off nominal testing with new engine hardware

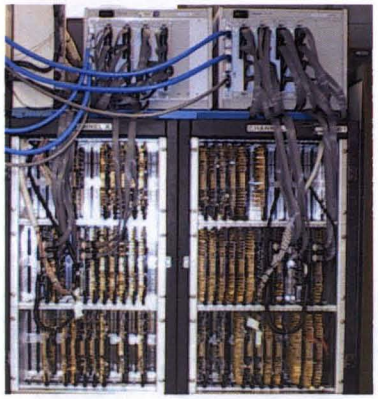
Hardware in The Loop Lab





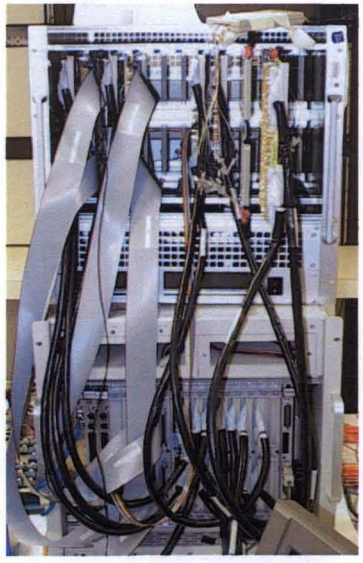
- High fidelity real-time hardware in-the-loop test environment using real-time engine models
- Utilizes flight type hardware
  - Actuators, transducers, solenoids, igniters
  - Flight type SSME controller
- Unique SW developed to provide automated testing capability
  - Hardware switching
  - Fault insertion
  - Data recording/reduction/analysis
- Supports hardware integration, anomaly resolution and provides a high fidelity test environment

AHMS HWIL Lab Upgrades



AHMS Brass-Board Controller

- Functionally equivalent unit
- Interfaces with other lab tools



Fault Emulation Unit (FEU)

- Playback historical data
- Insert analog data
- Insert digital data
- Automated, script-based verification

CADS III

- More data output options
- PC Based
- Facilitate future PC software delivery

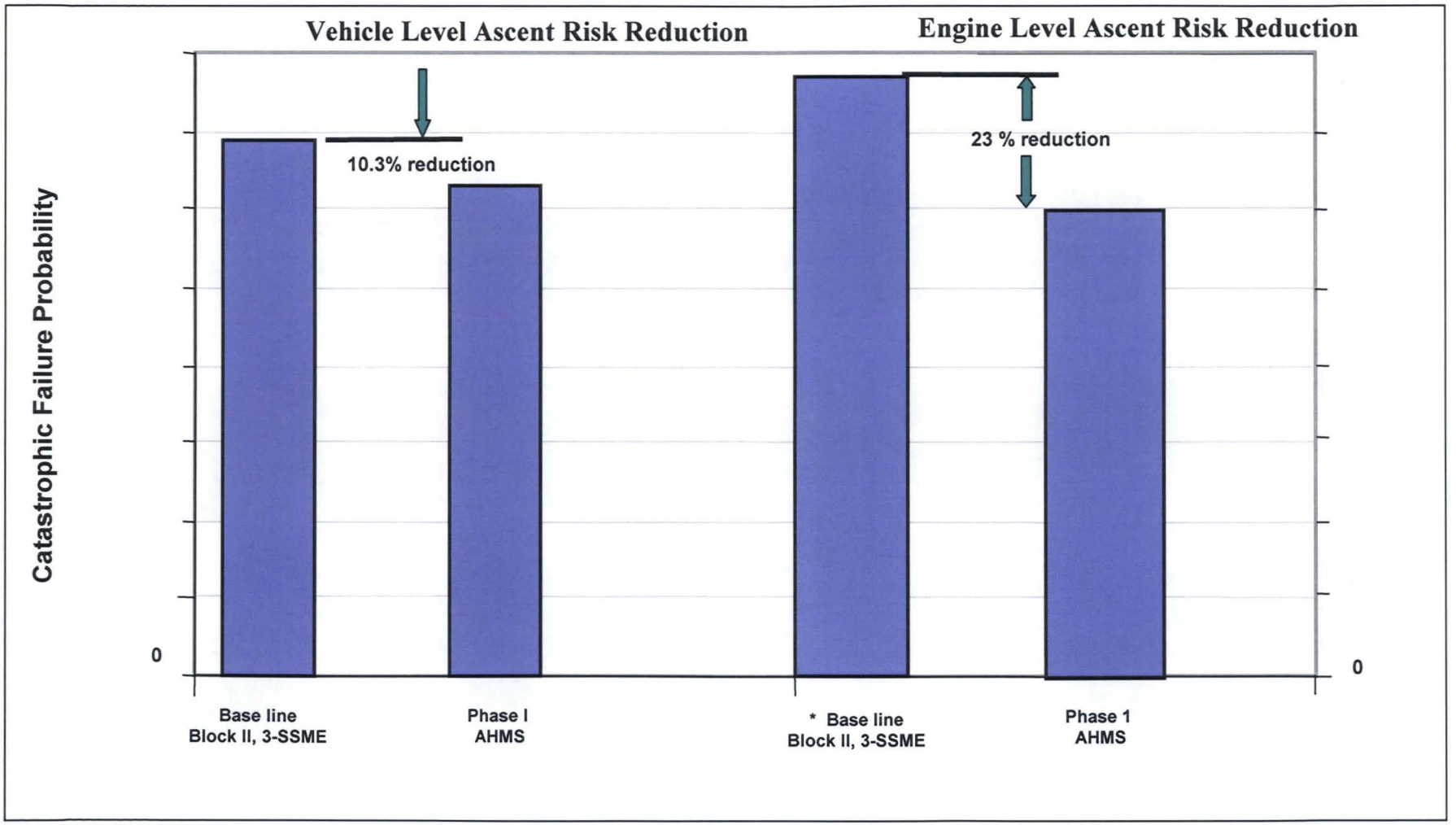
Logic Analyzer

- Low level analysis of DSP activity
- Captures 40 times more data than legacy system

Alabama Operations Contribution

- **Algorithm Test Tool and Historical Playback Effort**
  - Executed test cases utilizing data from 7 different Non-AHMS engine tests
    - **3 faulty LOX sensors**
    - **3 faulty Fuel sensors**
    - **1 faulty Fuel pump**
    - **Utilized a new S/W technique that allows for capture of all Algorithm parameters evaluated in determining engine health**
    - **Test data was used to baseline performance of Algorithm**
  - Executed 39 simulations with various software and requirement modifications to support multiple proposed algorithm changes

SSME Reliability Enhanced using AHMS



AHMS Phase 1 Phase-in

- **1st Flight - 1 AHMS controller in monitor-only mode, 2 Block II controllers**
  - Accomplished on STS –116 on 12/9/2006
- **2nd Flight - 1 AHMS controller in redline-active mode, 1 AHMS controller in monitor-only mode**
  - Accomplished on STS –117 on 6/8/2007
- **3rd Flight - 3 AHMS controllers in redline-active mode**
  - Accomplished on STS –118 on 8/8/2007

All Space Shuttle Missions Are Now Using the AHMS System For A Higher Reliability Launch System