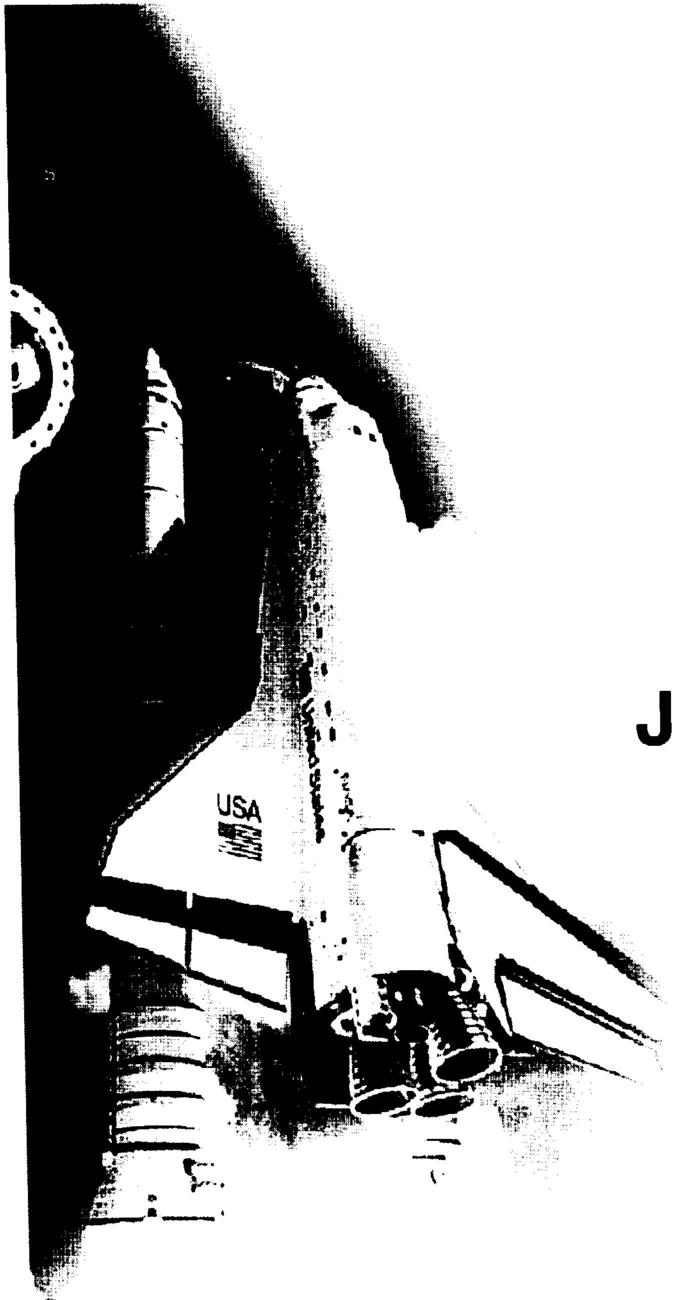


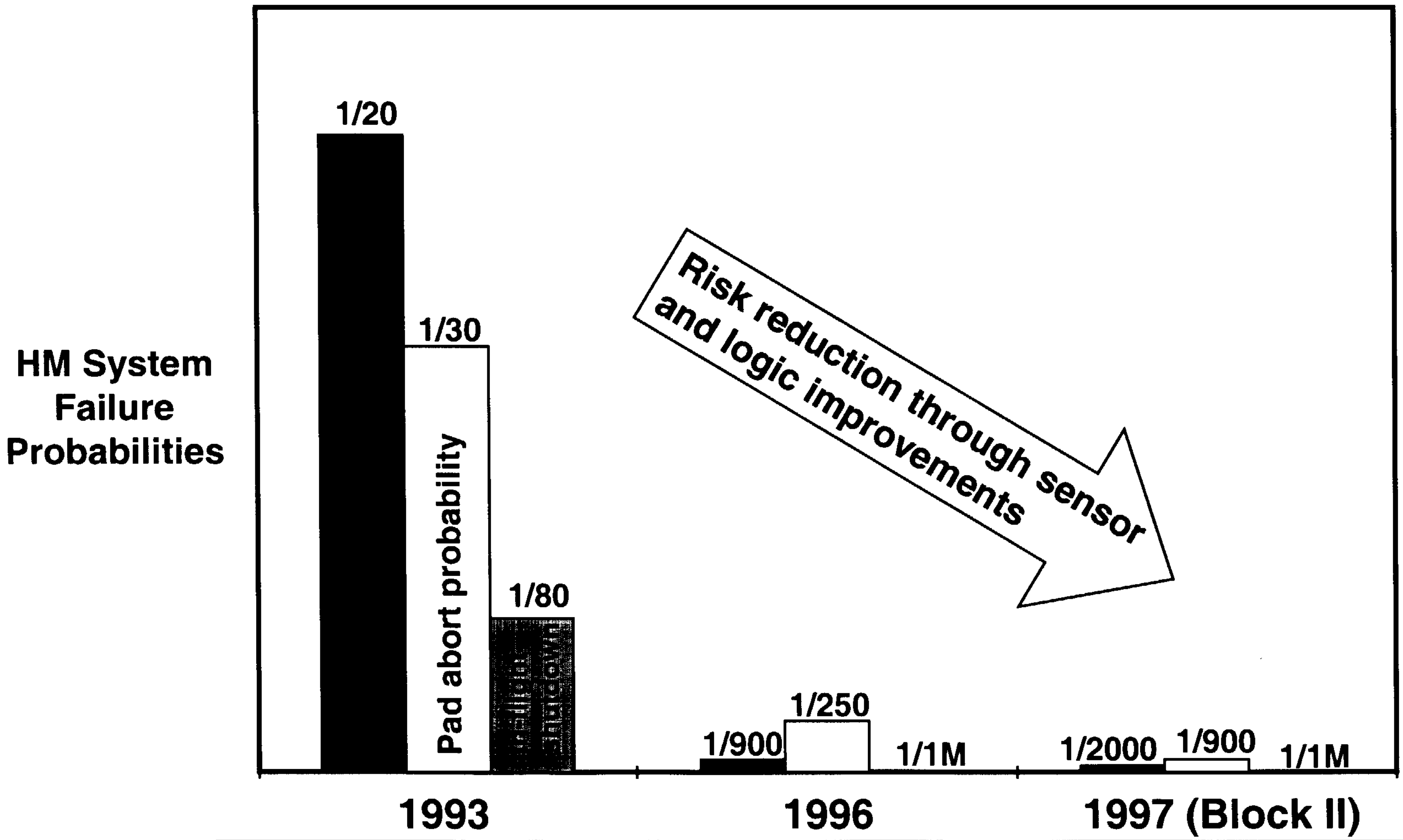
Joint Propulsion Conference 2000
Huntsville, Alabama
July 2000

John Plowden

Historical Background of SSME Advance Health Management Effort

- **Sensing and control systems have been continuously improved throughout the SSME program**
  - Essential for safety, reliability and maintenance
  - Sample improvements: Block II controller modifications, pressure sensor improvements, thermocouples, accelerometer installation software simplification, improved algorithms, etc.
  - Most recent results - sensors no longer drive abort probability
- **Advanced health management systems under evaluation in mid to late 90's**
  - In-house projects including lab and engine tested technologies
  - MSFC tasks
  - Industry surveys and study contracts
- **Maturity of technologies compared to possible benefits**

Sensor and Software Improvements



Sensors no longer dominate engine reliability

Early Advanced Health Management Development

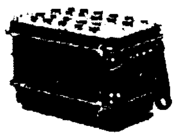
- **Three technologies chosen - best combination of benefits and maturity**
  - Real Time Vibration Monitoring System (RTVMS)
    - Fundamental measure of turbopump health
  - Optical Plume Anomaly Detection (OPAD)
    - Positive identification of engine wear, erosion, breakage
  - Linear Engine Model (LEM)
    - Key diagnostic tool for performance anomalies
  - All Successfully used in ground test program
- **Work initiated on overall software to combine inputs**
  - Identify problem in real time - added confidence in mitigation action
- **Hardware architecture studies conducted**

Final Health Management Configuration

- **Modified controller**
  - Synchronous vibration (rotor unbalance) redline
  - Add serial ports for communication with Health Management Computer
- **Separate Health Management Computer (HMC)**
  - One HMC per engine
  - Mounted in aft compartment
  - Includes advanced RTVMS, OPAD, LEM and overall software systems
  - Design for expandability
- **Phased approach for development and production**
  - Phase I - controller modification (development and production)
  - Phase IIA - develop RTVMS, OPAD, LEM and HMC including flight testing
  - Phase IIB - production of HMC

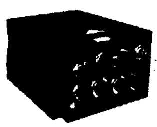
SSME Advanced Health Management System

Phase I

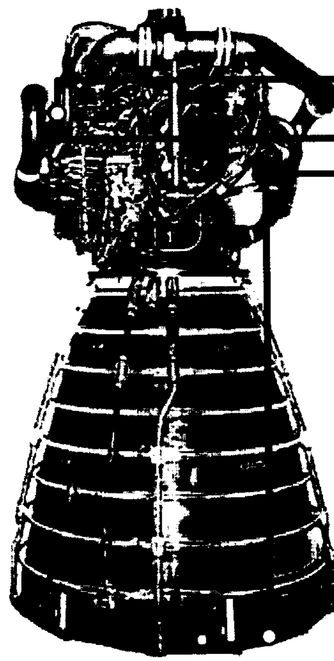


SSME Block II Controller Upgrade
- Vibration redline
- DCU memory
- Communication bus

Phase IIA



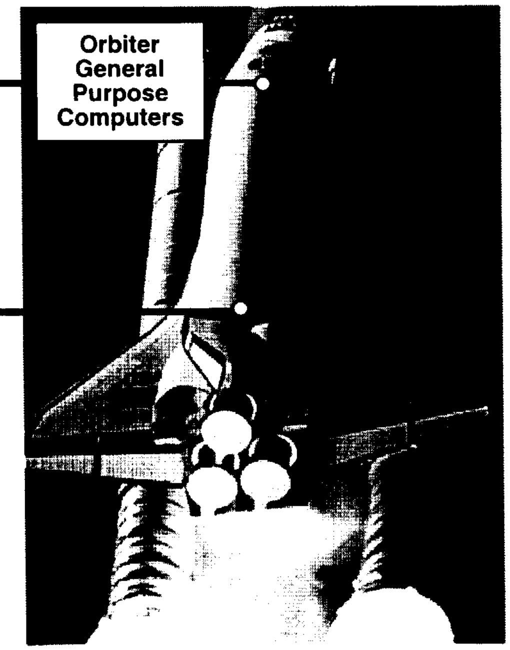
Protoflight Health Management Computer
- Design
- Development
- Vehicle integration
- Flight demo/monitor
- RTVMS, OPAD, LEM flight experiments



Catastrophic Redlines
Reside in Engine Controller

26% Reduction in Failure Probability

Phase IIB



Production Health Management Computer
- Expanded vibration monitoring
- Exhaust plume monitoring
- Engine model
- Expert systems
- Vehicle & System integration

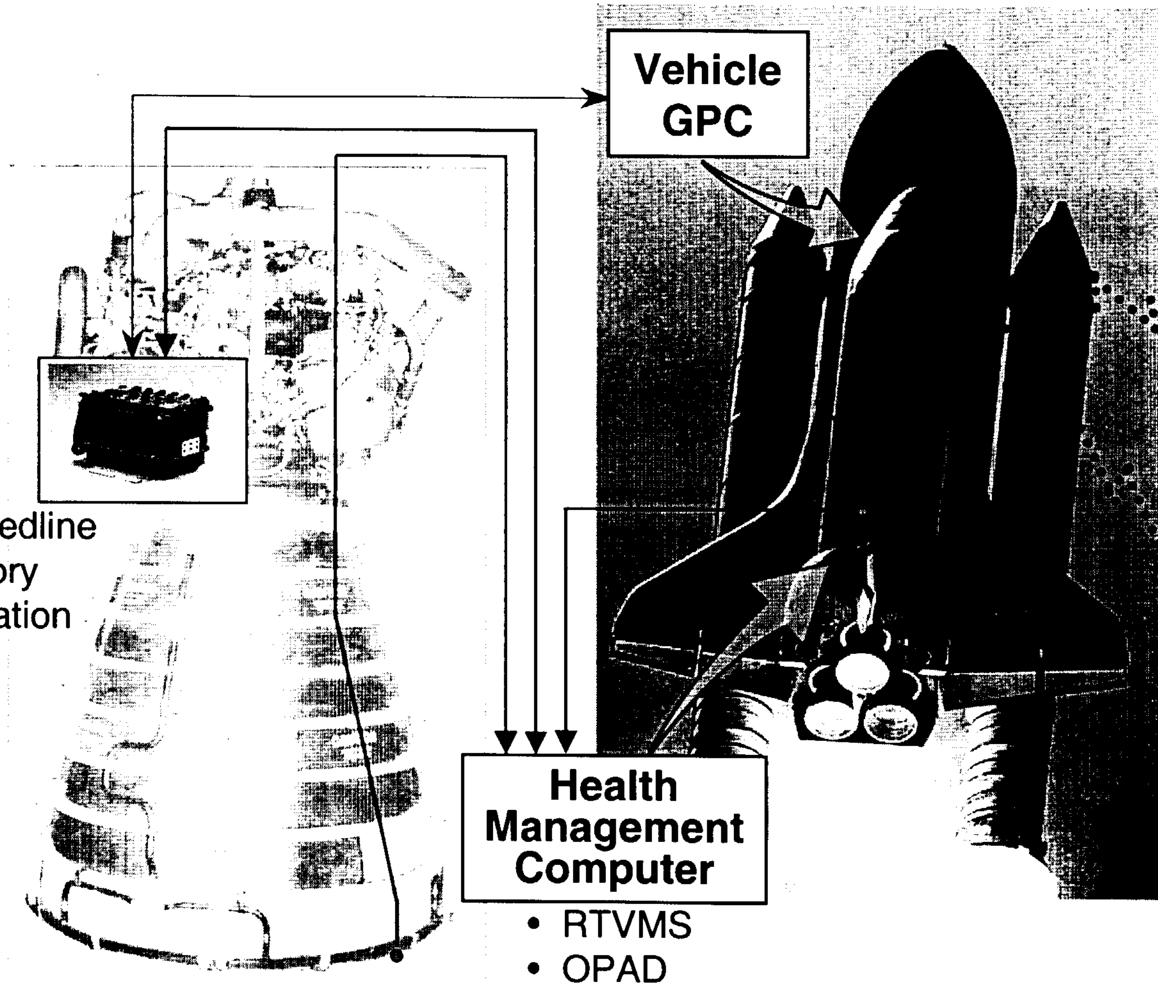
Engine Health & Advisories Recommend Action
Resides on Orbiter

Similar Risk Reductions Calculated for Phase II

System Architecture

SSME Controller

- Vibration Redline
- DCU Memory
- Communication Bus



Health Management Computer

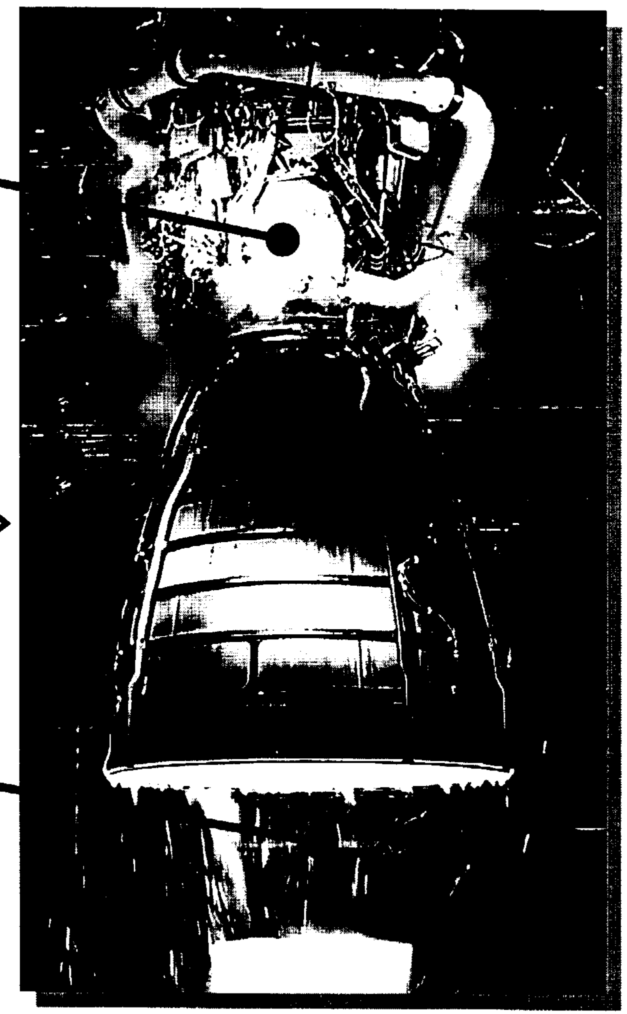
- RTVMS
- OPAD
- LEM
- Algorithm
- Shut down, throttle, MR command capability

MOD & Crew Ascent Situational Awareness

Informed Ground Maintenance

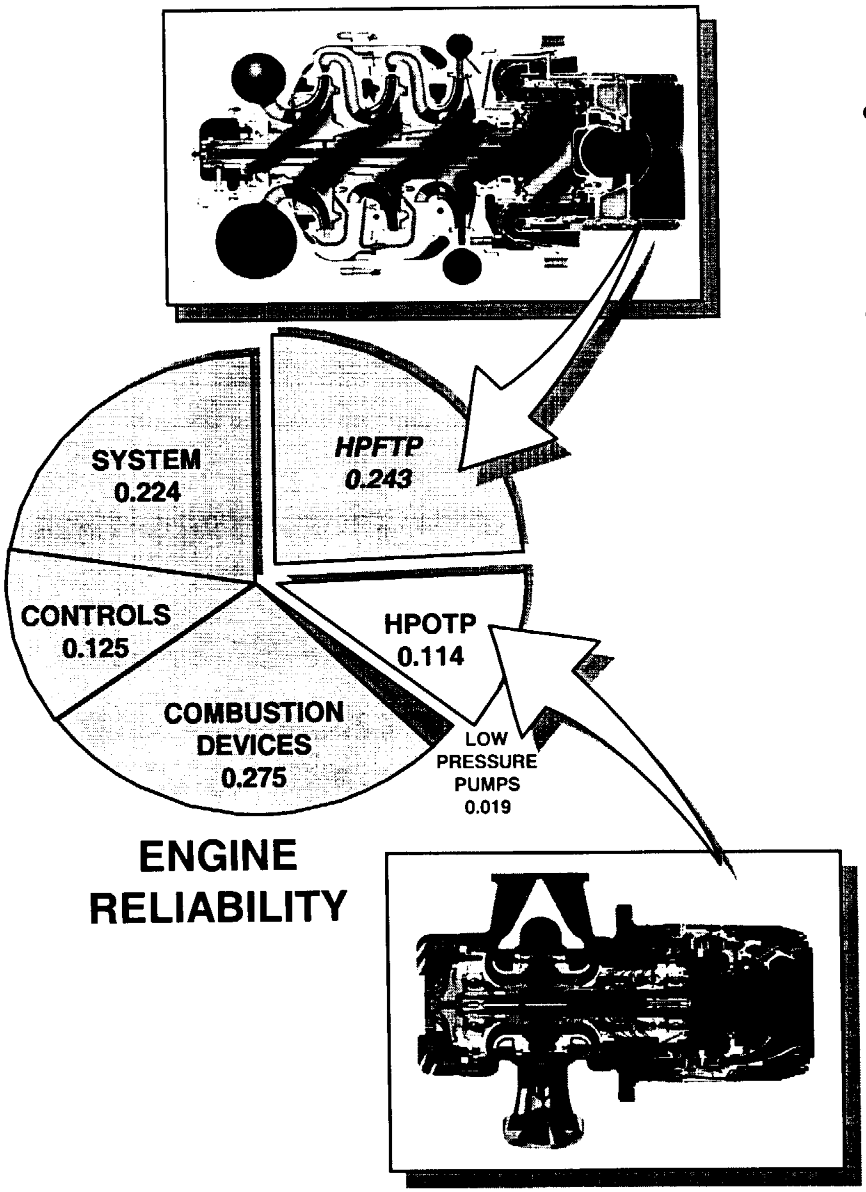
Health Management Features

- **Real-Time Vibration Monitor System (RTVMS)**
  - High Pressure Turbopump rotating hardware structural integrity
- **Linear Engine Model (LEM)**
  - Engine performance
- **Optical Plume Anomaly Detection System (OPAD)**
  - Engine wear, erosion, breakage



Active Controller Synchronous Vibration Redline

Phase I, Task #1



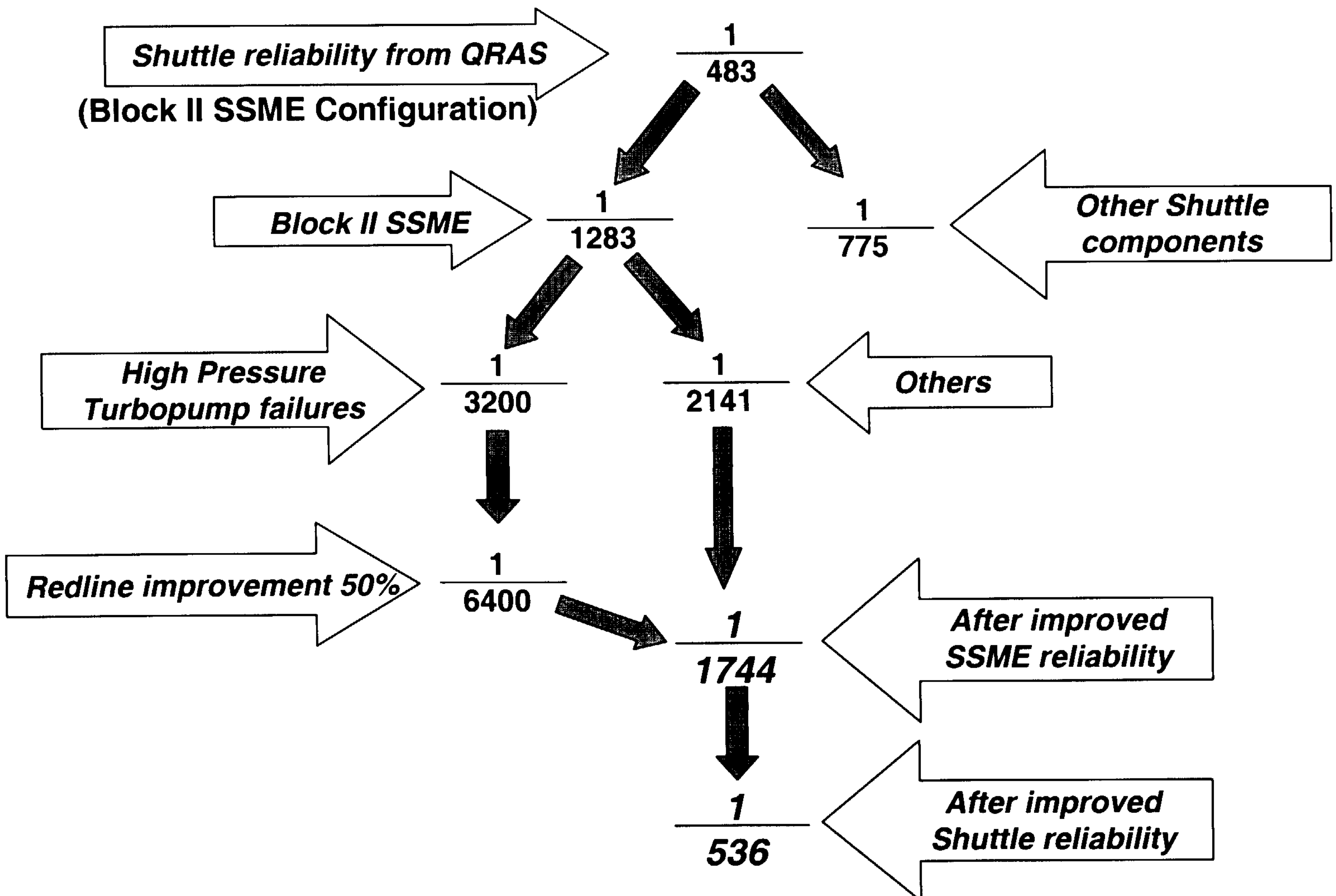
- High Pressure Turbopumps are a significant part of engine reliability
- Consequences of a turbopump failure are severe
- Vibration is a fundamental measure of SSME turbopump health
  - Quickest, most sensitive
  - Detects critical failure modes (blades, bearings, impellers, etc.)
- Vibration redlines have prevented engine failures

Real Time Synchronous Algorithm

Status of Algorithm Verification Testing

- **Real Time Vibration Monitoring System (RTVMS) in operation since Oct 1996 at SSC**
  - Monitor mode and active redlines
  - No anomalies in over 200 tests
- **RTVMS experiment flown on STS-96**
  - Flawless operation (monitor mode)
- **Testing algorithm on all tests since return to flight**
  - Playback of dynamic data

Reliability Improvement Tree



SSME Failure Probability Reduced 26%
Shuttle Failure Probability Reduced 9.8%

HMC Advanced RTVMS Benefits

Phase IIA, Task #2

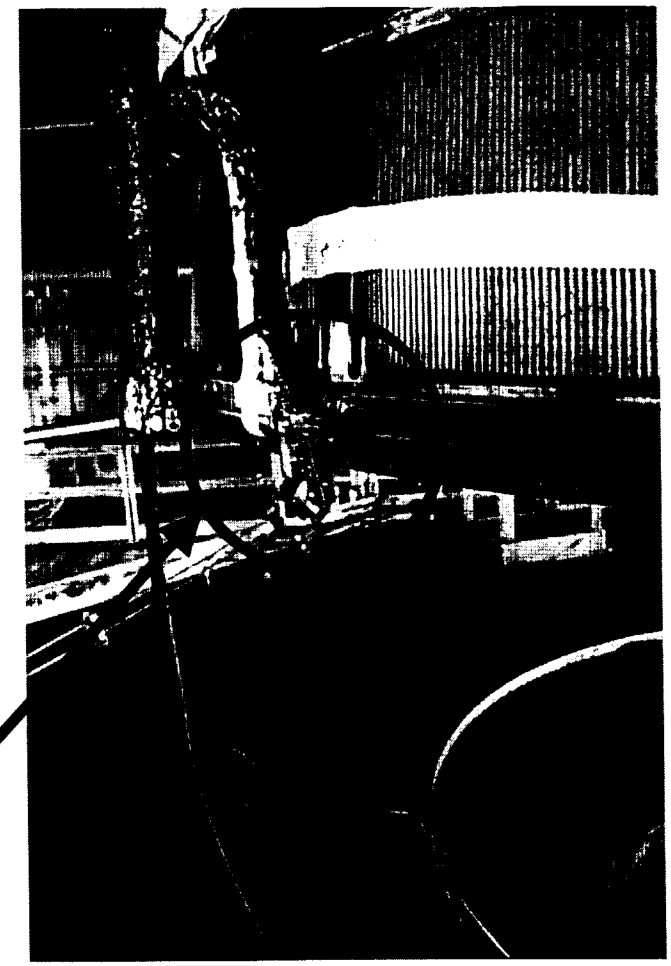
- **HMC RTVMS will monitor numerous discrete frequencies**
  - Harmonics of synchronous (2N, 3N) for indications of rub
  - Blade wake frequencies (4N, 6N, 8N) for indications of impending failure
  - Bearing-related frequencies (cage, ball spin, inner race and outer race) to determine bearing health
  - Sub-harmonic resonance and sub-synchronous whirl
- **Non-linear algorithms are used to distinguish between rotating and non-rotating related phenomena**
- **Digital data acquired by RTVMS will be stored on the HMC**
- **HMC RTVMS supports future upgrades**
  - Additional sensor inputs
  - Cavitation detection
  - Active signature phase correlation

Advanced RTVMS in the HMC provides much greater insight into turbopump health

Optical Plume Anomaly Detection (OPAD)

Phase IIA, Tasks #3

- Monitor of engine wear, erosion, breakage
- Proven in ground test program
- Early warning compared to conventional measurements
- Key to eliminating inspections in the future
- Phase II, Task #3 - Experimental flight (HDT) prior to HMC flight



OPAD system tested on development engines 0523 and 0525

OPAD Benefits

Phase IIA, Task #3

- **Used in support of engine tests at SSC since 1989**
- **Demonstrated capability to detect the following constituents which are indicative of failure events and maintenance actions**
  - Palladium - Turbopump honeycomb seal erosion
  - Aluminum - Turbopump impeller rubbing pump housing
  - Copper - Main combustion chamber erosion, baffle erosion
  - Silver - Turbopump seal wear
  - Iron, Chromium - Bearing wear (440C)
  - Iron, Nickel, Cobalt, Chromium, Manganese - Structural failure
  - Calcium - RKDN HPFTP bearing cage wear
  - Titanium - Impeller rub
  - Blade material identified indicating blade fracture
- **Data has been invaluable during failure investigations (Blade failure, impeller rub)**
- **System operates in Real-Time (200hz sample rate)**

OPAD is an extremely sensitive, non-intrusive technique for assessing engine health

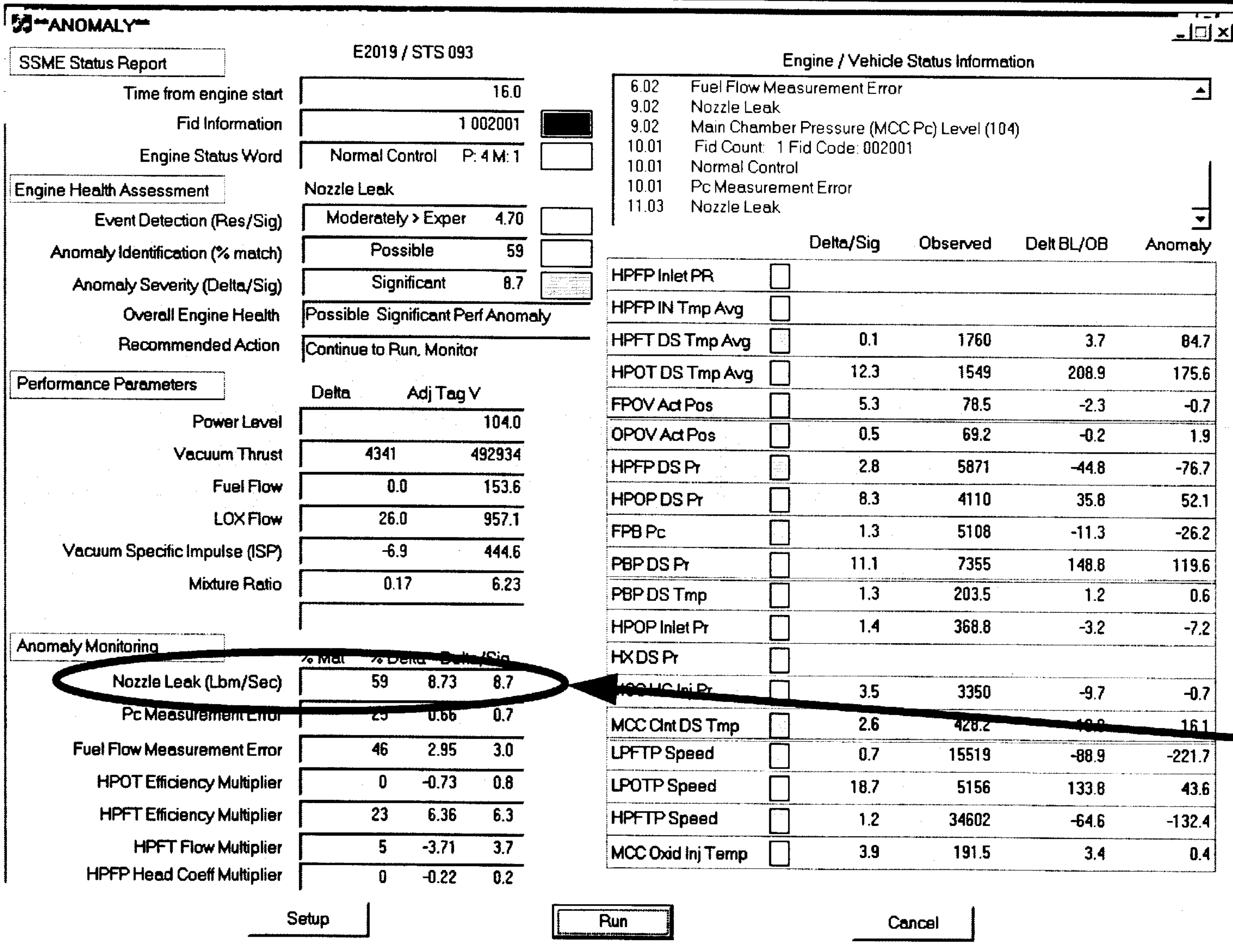
SSME Advance Health Management

SSME Linear Engine Model

- LEM is a system and major component level diagnostic tool
- Originally developed as a post test/flight anomaly diagnostic tool in mid 80's
- Based on partial derivatives of influence coefficients from SSME Power Balance Model
- Compares observed slice of data with pre-determined baseline slice
- Potential anomalies matched for direction and magnitude to minimize difference between baseline and observed data
- Quality of match rated from 0 to 100%
- Modified to run in real time

Linear Engine Model (LEM) Benefits

Phase IIA, Tasks #4



STS-93 Engine 3 LEM screen

STS-93 Nozzle leak detected with development LEM

Health Management Computer(*HMC*)

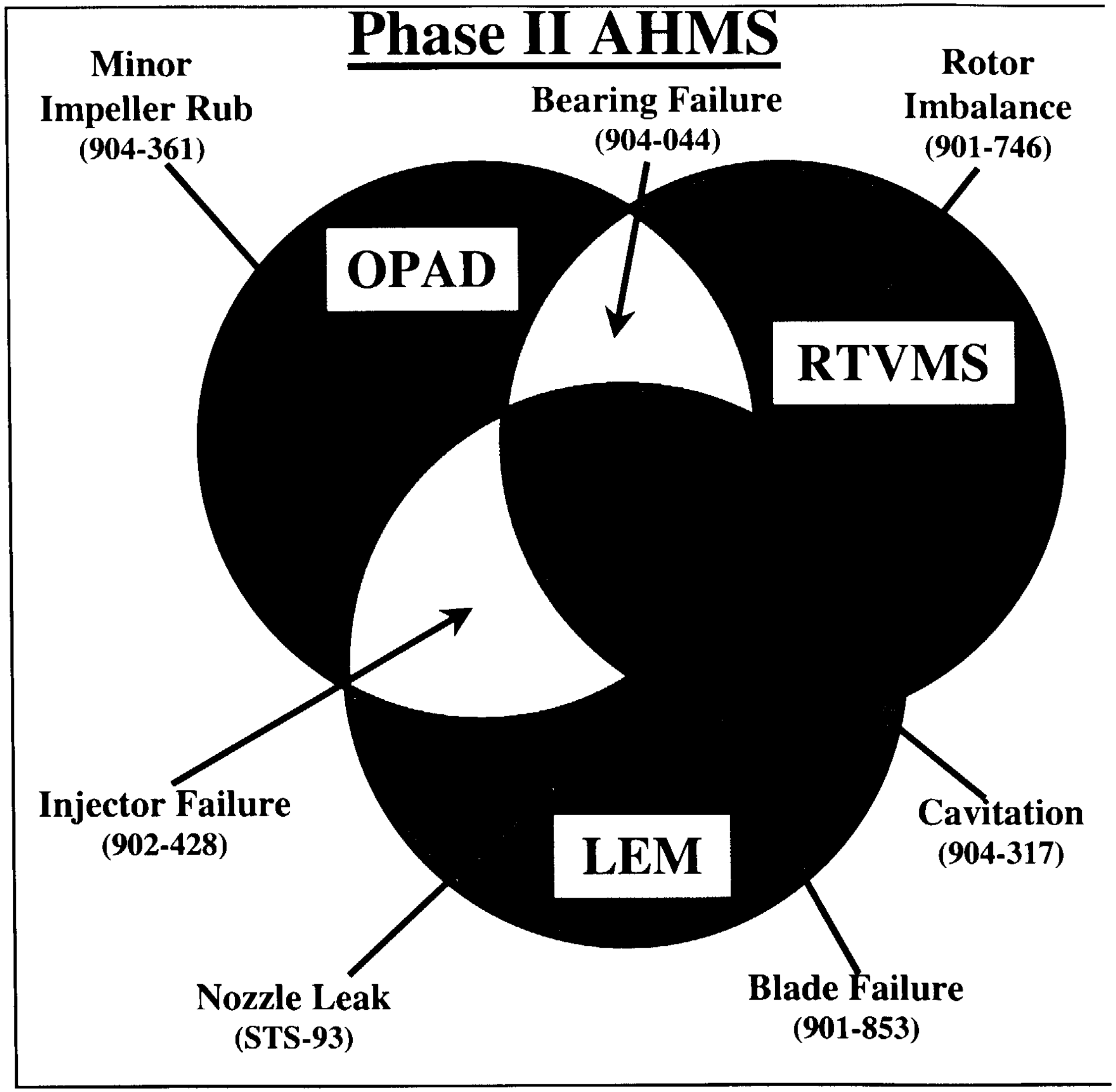
Phase IIA, Task #2

- **HMC - MSFC in-house effort**
  - System controller and mass memory
  - Advanced real-time vibration monitoring system (RTVMS)
  - Optical plume anomaly detection (OPAD)
  - Linear engine model (LEM)
  - Spare capacity for upgrades
- **Key Design Assumptions**
  - “Do no harm” fail safe design
  - RTVMS, OPAD and LEM are single string, post test diagnostic tools
  - Maximize use of off-the-shelf hardware while maintaining reliability

SSME Advanced Health Management

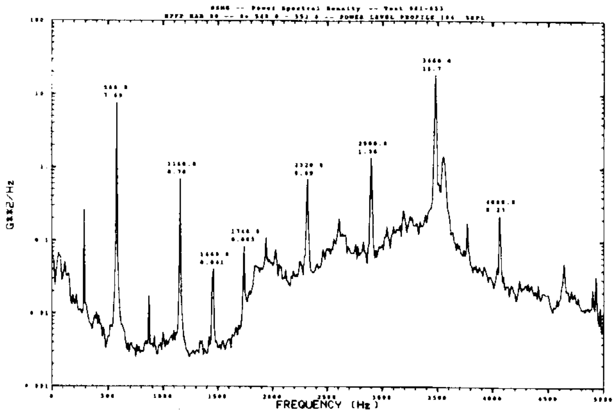
Integrated Health Management Computer Benefits

- **Multiple diagnostic technologies**
  - Increase detection likelihood
  - Increase confidence in results
- **Requirements definition in Phase IIA**
- **Finalized expert system in Phase IIB**

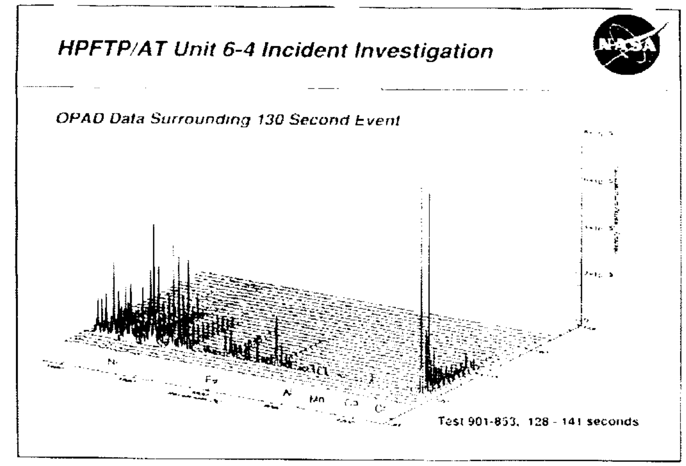


Integrated Health Management Computer Benefits

Test 901-853 Blade Failure

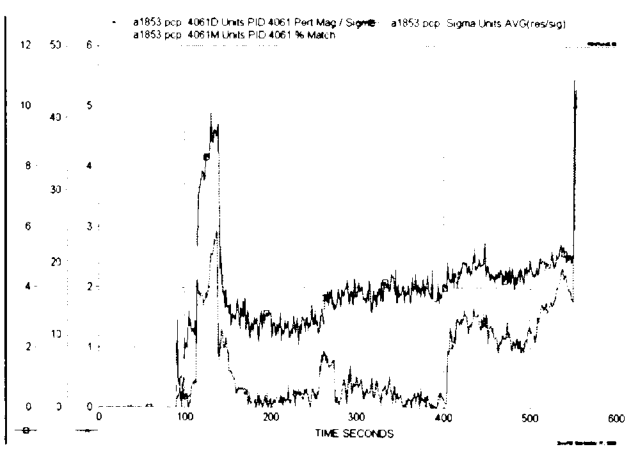


RTVMS - High unbalance and rubbing

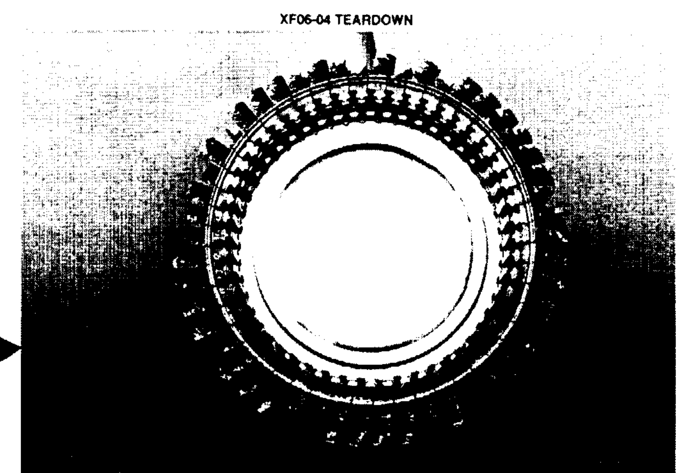


OPAD - Blade material in plume

HMC Integrates Output - Fuel Turbine Failure



LEM - Turbine performance degradation

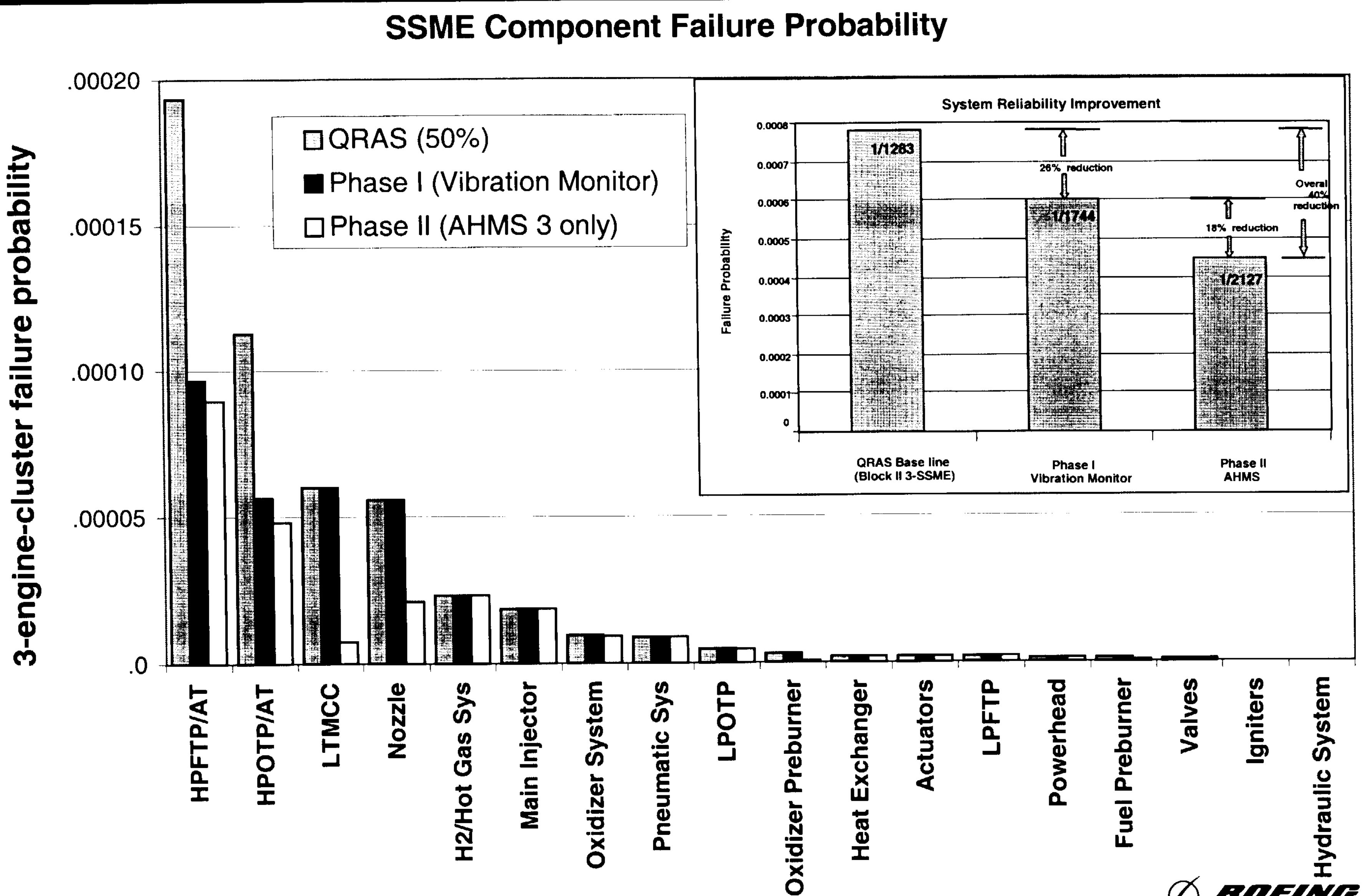


Integrated Health Management Computer Benefits

Reliability Assessment Overall Plan

- **Joint MSFC / Rocketdyne team formed composed of SSME Systems experts**
- **Team utilized broad database for evaluation of potential failures**
  - FMEA
  - Hazards
  - Past hot-fire testing failures
- **Potential failures assessed for ability to be detected and mitigated**
- **Systems experts evaluation combined with QRAS analysis to quantify overall failure probability reduction**

Integrated Health Management Computer Benefits
Quantified Reliability Assessment



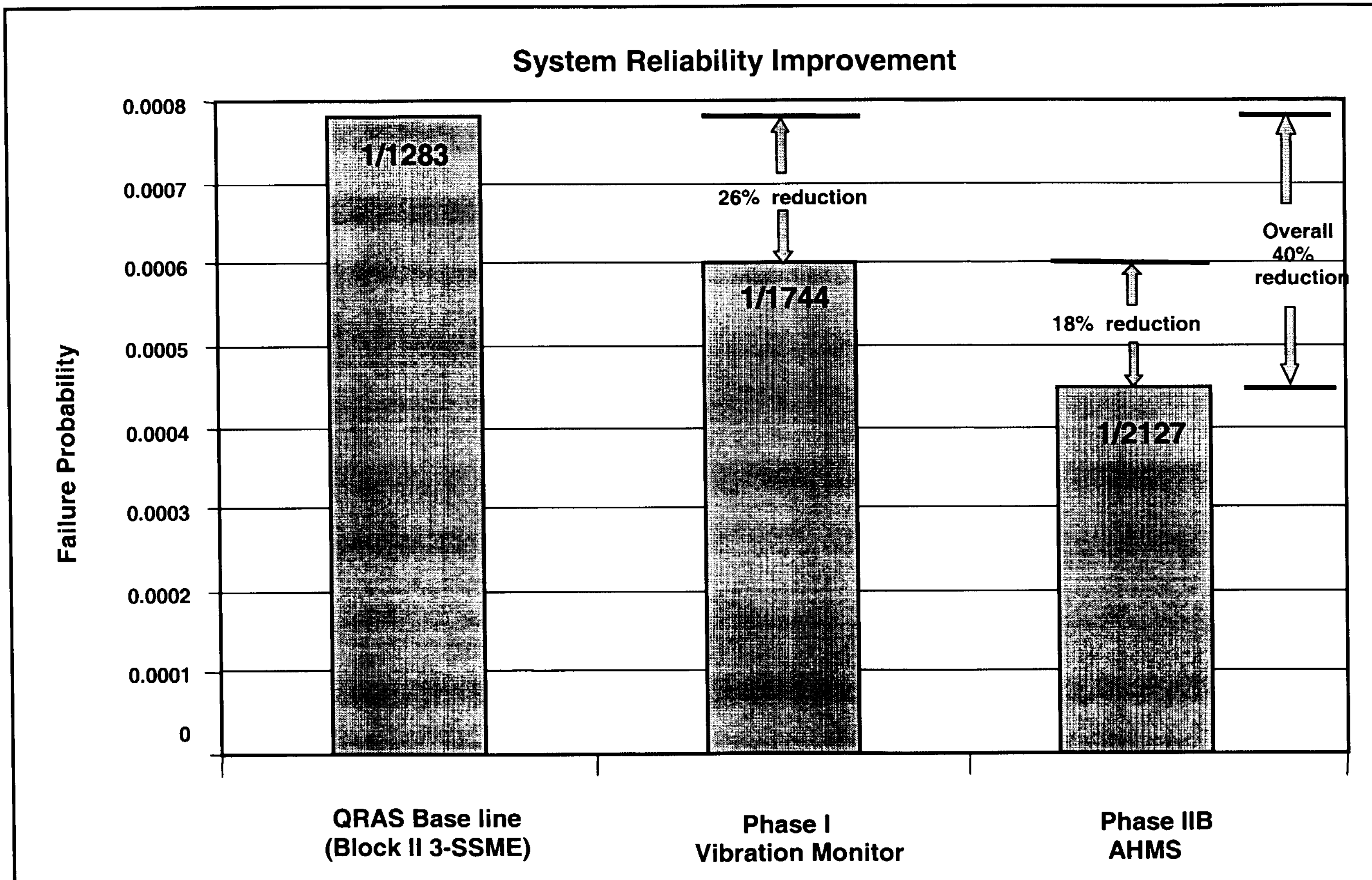
SSME Advanced Health Management

Summary

- **Phase I synchronous vibration redline reduces SSME failure probability by 26% using demonstrated reliability and QRAS approach**
- **MSFC and Rocketdyne systems and component experts performed estimate of reliability gain of Phase II AHMS with HMC**
    - Approach utilized assessment of potential to mitigate FMEA failure modes combined with QRAS reliability
- **Overall SSME failure probability reduction potential of 40% for combined Phase I (26%) and Phase II AHMS (18%)**
    - Assessment is conservative
    - Any potential vibration related Phase II to Phase I overlap offset by QRAS ignoring 100+ failure modes which can be mitigated

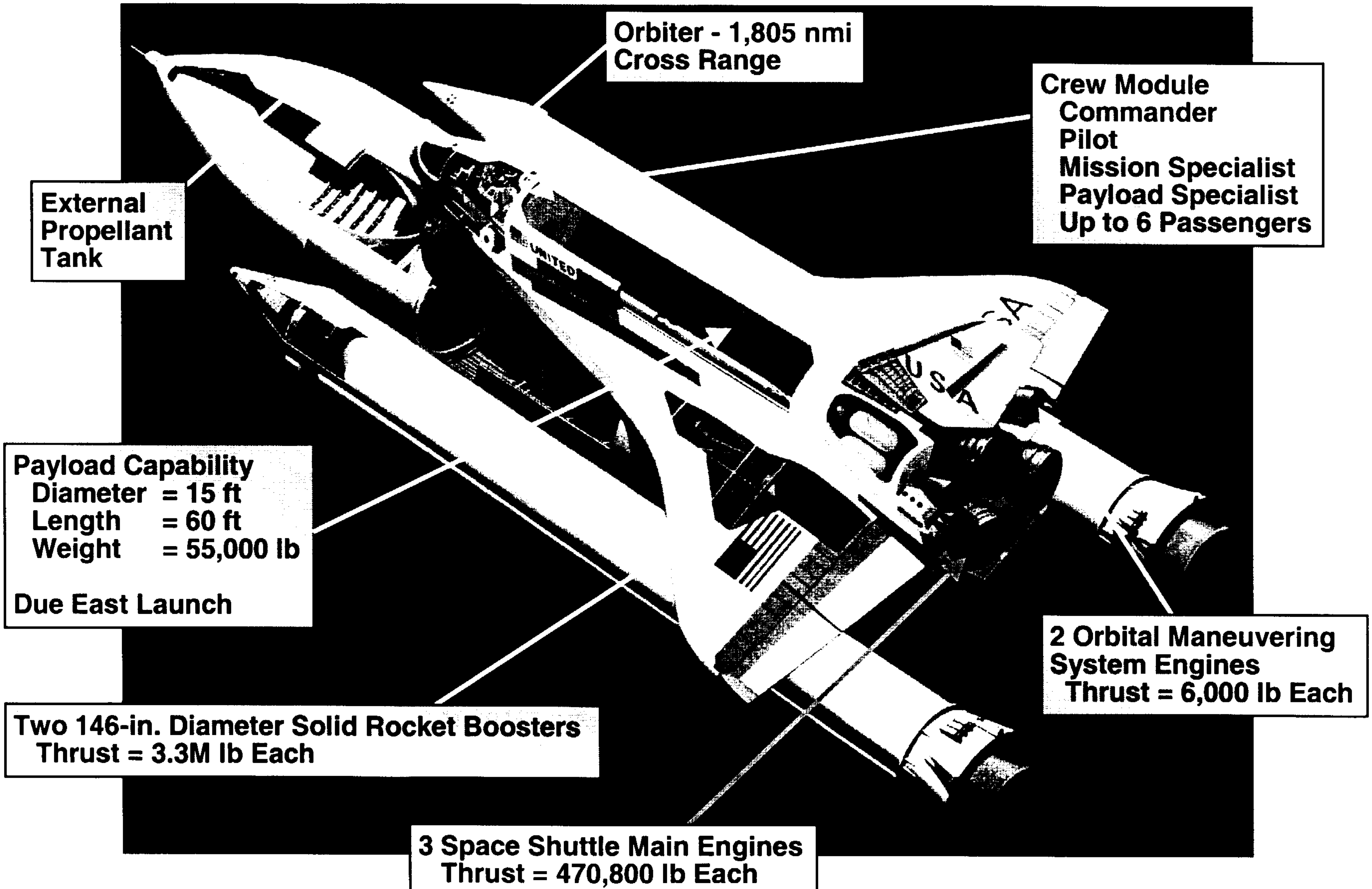
SSME Advanced Health Management

Reliability Improvement

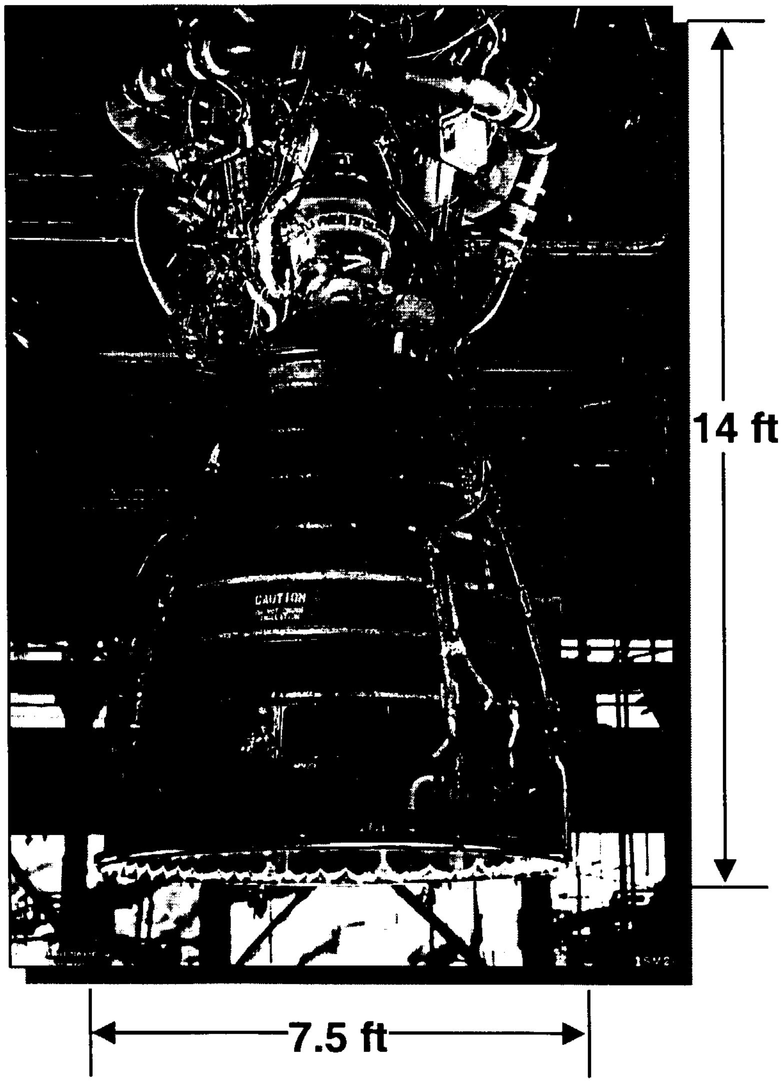


Back up

Space Shuttle

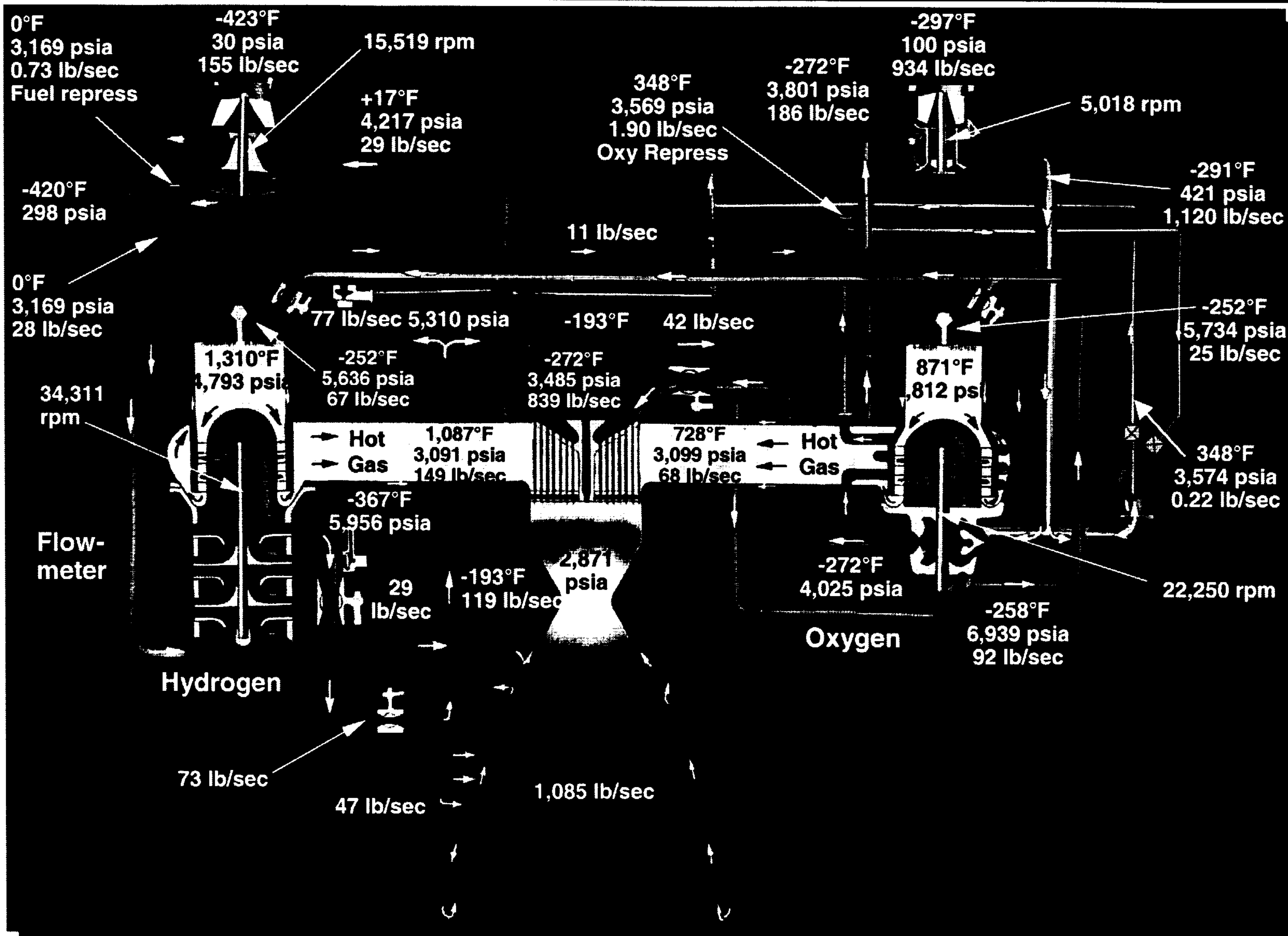


SSME Is the First Reusable Large Liquid Rocket Engine



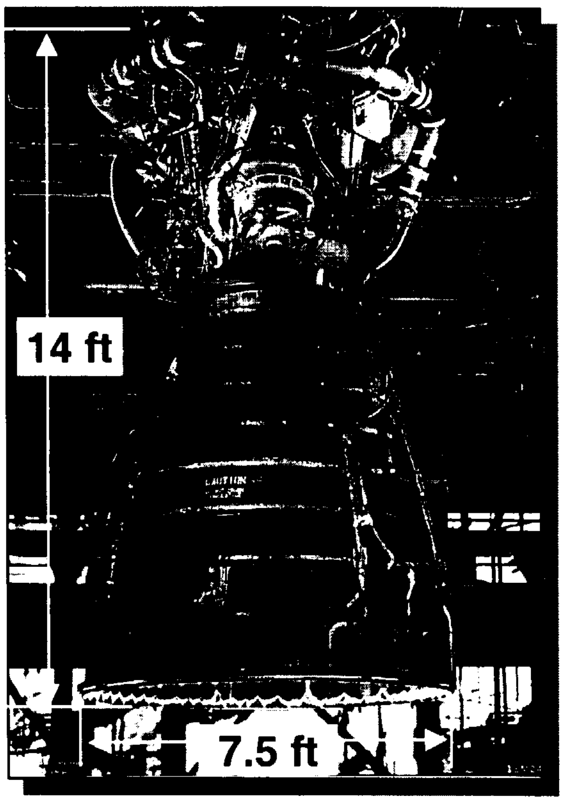
• Propellants	Oxygen/ Hydrogen
• Rated power level (RPL) 100%	470,800 lb
• Nominal power level (NPL) 104.5%	491,900 lb
• Full power level (FPL) 109%	512,900 lb
• Chamber pressure (109%)	3,008 psia
• Specific impulse at altitude	452 sec
• Throttle range (%)	67 to 109
• Weight	7,480 lb
• Total program hot-fire time (April 2000)	> 2,821 starts > 911,664 sec

Block IIA
SSME Propellant Flow Schematic
104.5% of RPL



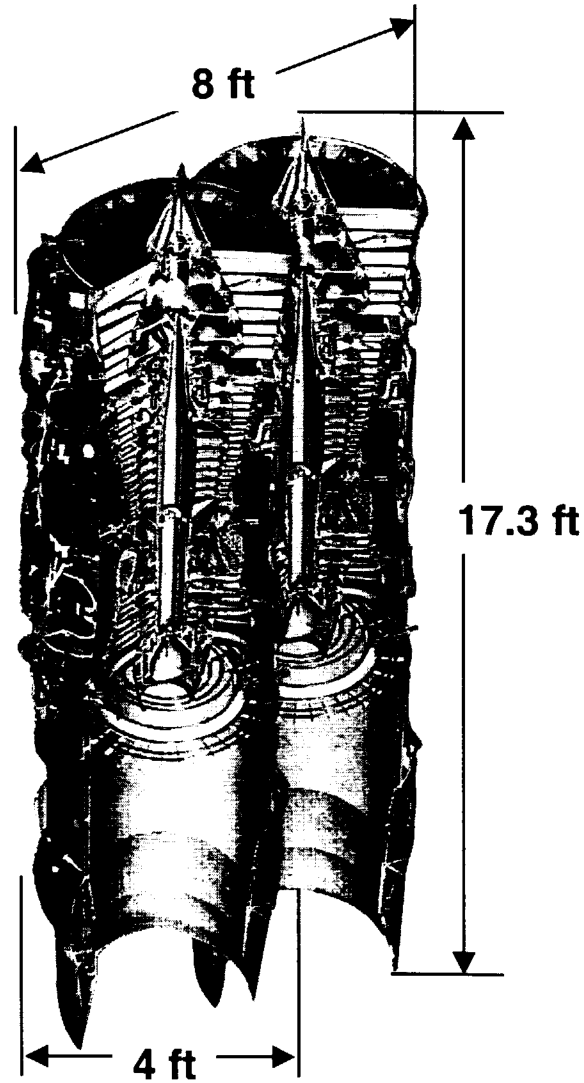
Rocket Propulsion Systems Place Greater Demands on the Hardware

- Leads to more stringent requirements



Weight 7,400 lb
SSME

500,000 lb
Thrust



Weight 7,300 lb (2)
Turbojet Engine
(2 ea on F-15)

50,000 lb (2)
Thrust
Full After Burner

Advanced Health Management Tasks

Phase I

- **Task #1: Modify SSME Controller**
  - Reliable real-time turbopump synchronous vibration <u>redline</u> capability
  - New standard high speed serial interface for external communication
  - Deliverables - 20 flight SSME controllers (deliveries through 2008)

Phase IIA

- **Task #2: Develop and Fly Protoflight Health Management Computer (HMC)**
  - Includes advanced Real Time Vibration Monitoring System (RTVMS), Optical Plume Anomaly Detection (OPAD), Linear Engine Model (LEM)
  - Deliverables - 2 "protoflight" units, 1 brassboard
  - Fly a single HMC monitoring a single SSME
- **Task #3: OPAD Flight Experiment**
  - Single OPAD box monitoring a single SSME
- **Task #4: LEM as MOD Tool**
- **Task #5: Phase IIB Requirements Definition**

Vibration Redline Benefit Assessment

Based on Hot-fire Experience

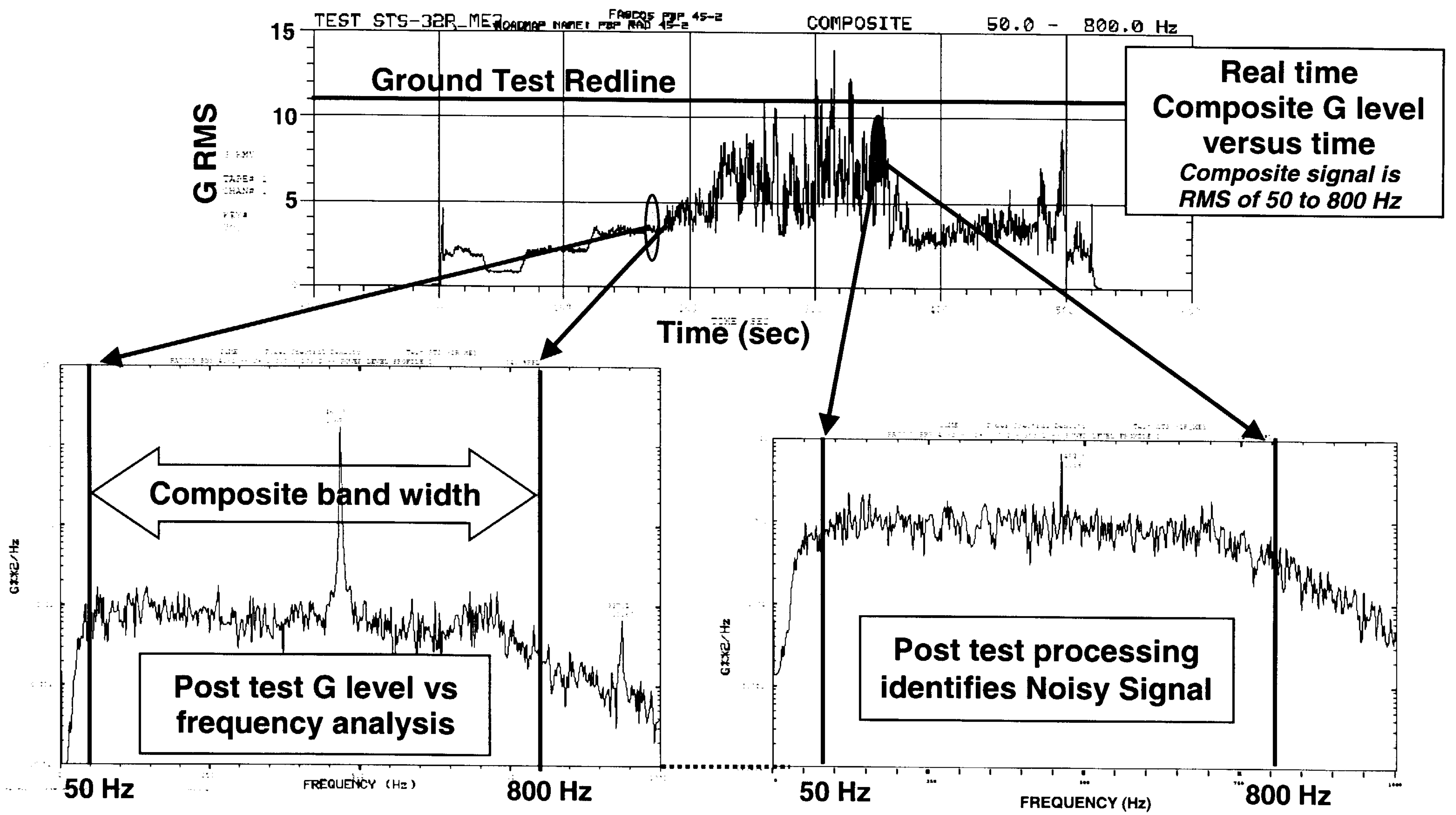
- **Total hot-fire vibration cut-off database evaluated**
  - Database reduced to 34 applicable vibration related premature cuts
  - 21 catastrophic failures
    - 13 preventable by vibration redline
- **Calculation of vibration redline effect**
  - Reduce high pressure pump catastrophic failure probability by approximately half
    - (13 preventable/21 catastrophic) vibration related failures
    - Remaining failures in total historical database not vibration related

Risks in Activating Redlines

- **Accelerometer signal integrity / interpretation of signal**
  - Primary reason for not previously activating vibration redline
    - Initial efforts focused on accelerometer and cable improvements
    - Hardware reliability still unacceptable (STS-32)
  - RTVMS solves signal integrity problem
    - Algorithm identifies erroneous signal
    - Controller and algorithm reliability confirmed with test data
- **Redline limit amplitude**
  - Determine proper redline based on hot-fire experience

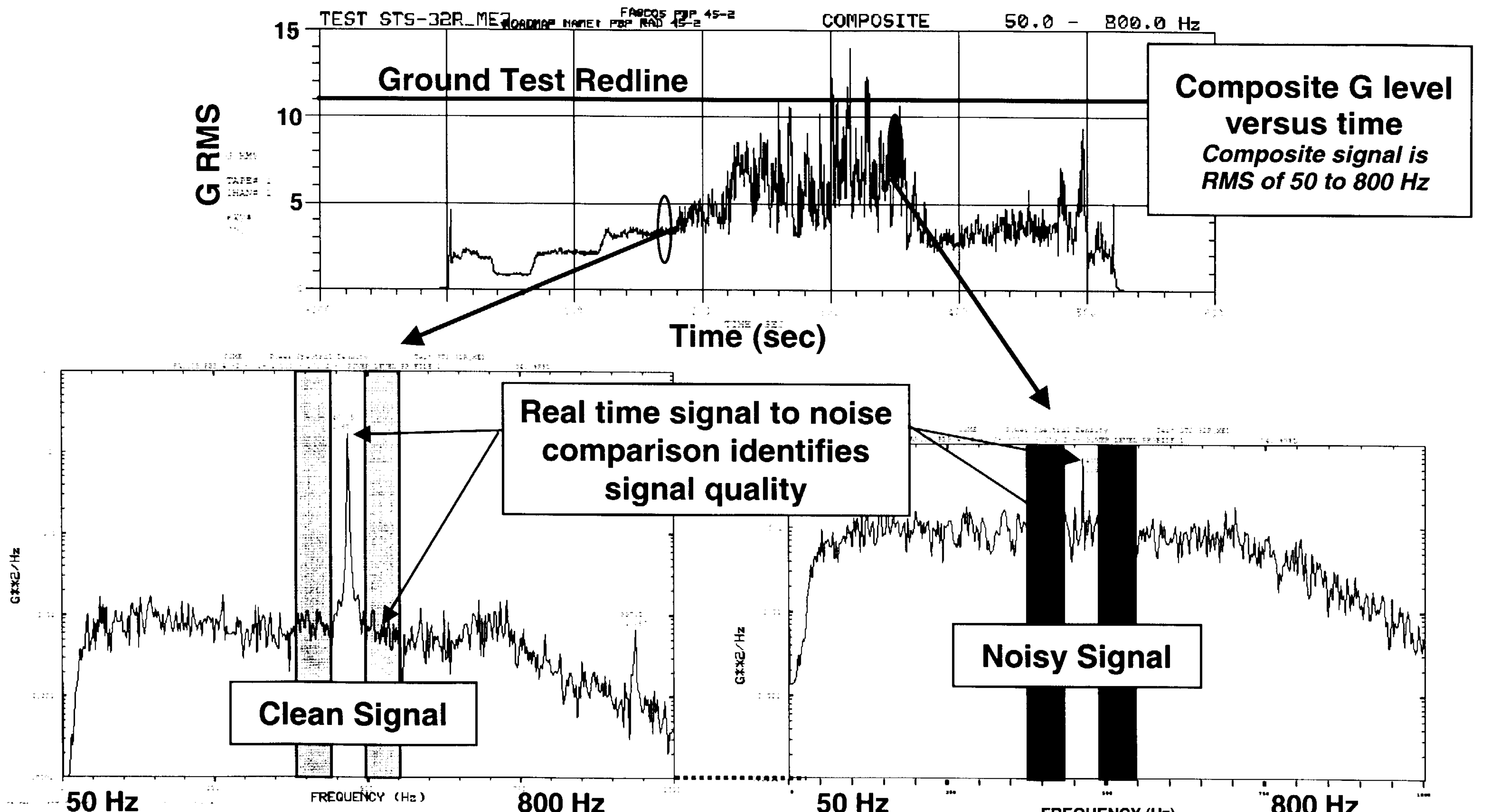
STS-32R Noisy Signal Problem

Historical Real Time Redline Could Not Distinguish Noisy Signal



RTVMS Identifies Signal Integrity

Real Time Signal to Noise Comparison



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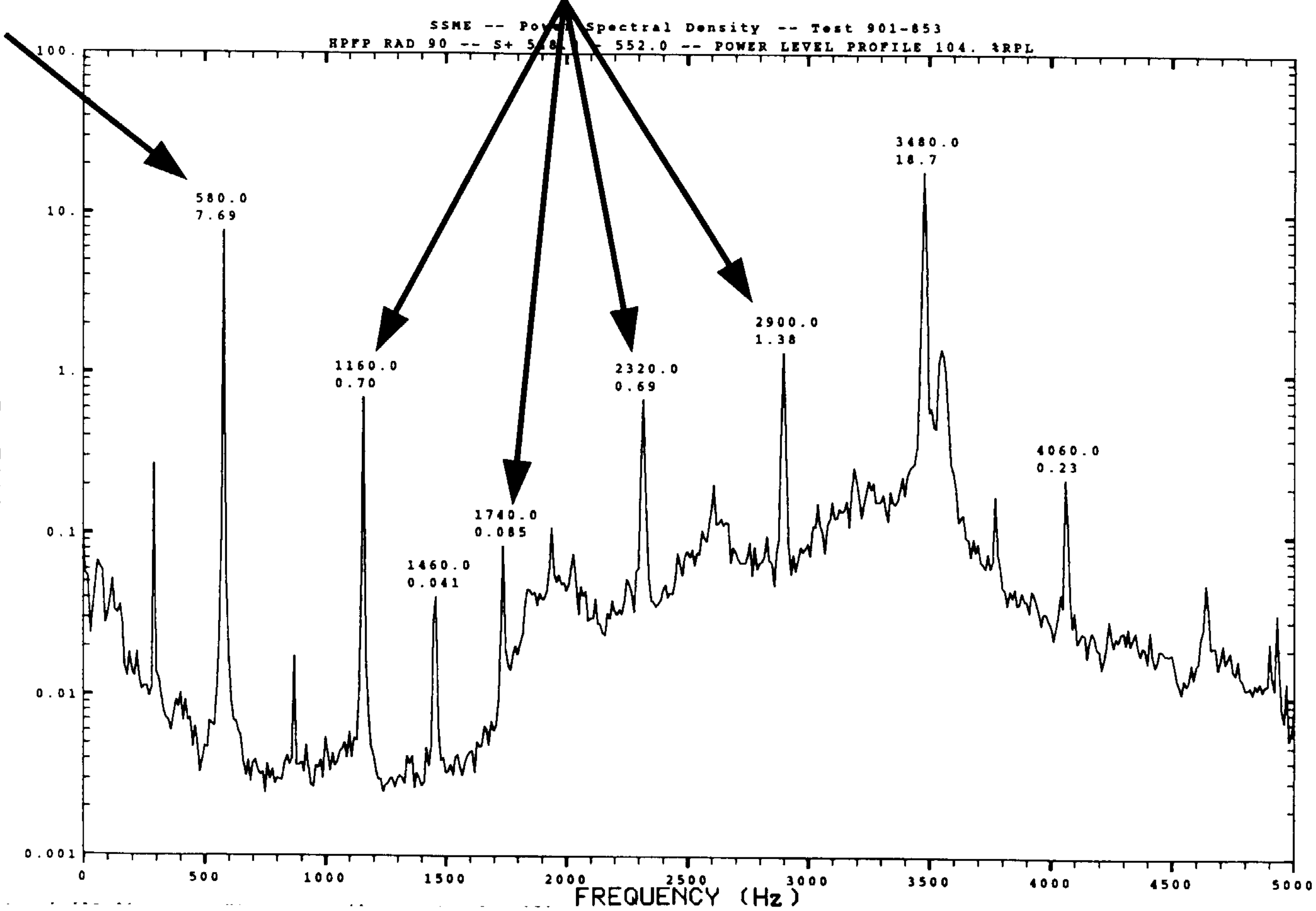
HMC RTVMS Benefits

HPFTP/AT Blade Problem Indicated by RTVMS - Test 901-853

Multiples of synchronous
(rubbing indicators)

Synchronous
(unbalance)



Sample OPAD Data Chart

Blade Failure Test 901-853

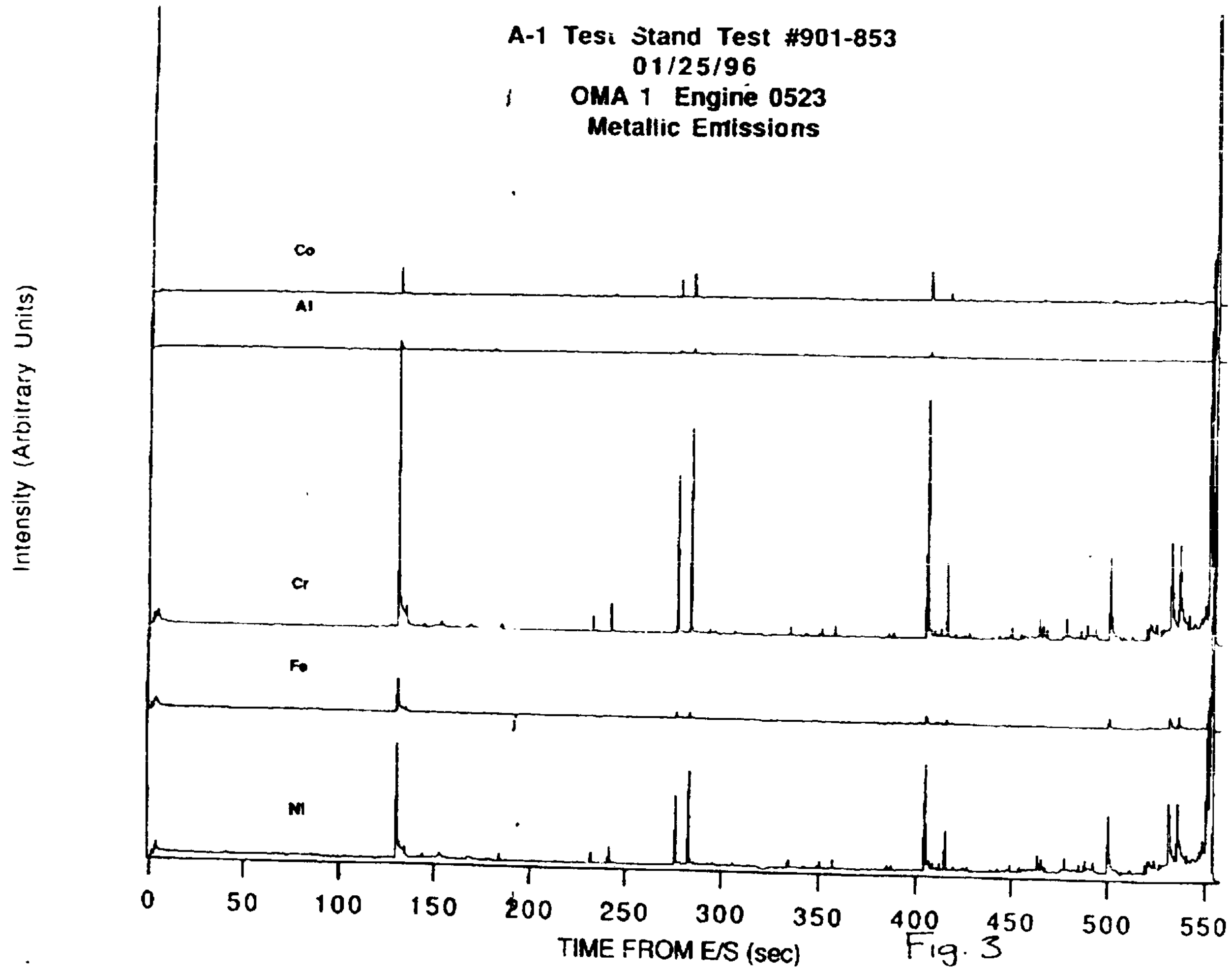


Fig. 3

Blade material indications correlate with vibration data

Integrated Health Management Computer Benefits

Phase IIA, Task #5

- **System Identifies Impending Failures and Significant Performance Cases**
- **Example: 901-853 HPFTP/AT Turbine Blade Failure**
  - Initial Failure Event Detected at 130 seconds (109%RPL)
    - Well Below Standard Redline Criteria
    - Easily Detected by OPADS, RTVMS, LEM
  - Multiple subsequent events also detected
    - Standard Redlines never exceeded
    - Observer initiated Shutdown
    - Turbine Hardware Severely Damaged
- **HMC Algorithm will detect gross anomalies and recommend Reduced Throttle Level (<100%)**
  - Probability of Catastrophic Failure reduced for Damaged Engine

Integration of HMC results will improve Situational Awareness and provide Failure Mitigation Options

Integrated Health Management Computer Benefits

Initial Reliability Assessment - Conclusions

- **Majority of mainstage FMEA failure modes <u>detectable</u> by Phase II AHMS**
- **Greater than 150 failure modes had a score of 3 or higher**
  - Significant rating for one system, minor rating for all three systems, etc.
- **Dozens of failure modes had a score of 6 or higher**
  - Significant rating for two systems, moderate rating for three, etc.

Integrated Health Management Computer Benefits

Additional Benefits Yet to be Quantified

- **MSFC/Rocketdyne systems experts team also reviewed potential for all mainstage FMEAs to cause off-nominal performance (e.g. mixture ratio)**

- **Team assessed ability of Phase II AHMS to mitigate off-nominal performance**
  - 85 failure modes identified as having mitigation potential with regard to off-mixture operation - detailed evaluation in work
  - Need to coordinate efforts to quantify benefits with MOD

- **OPAD provides additional data to assess engine health for real-time safety, post-flight maintenance decisions and potential inspection reduction efforts**
  - Benefits of Phase II AHMS with regard to operability not yet assessed in detail by MSFC / Rocketdyne operability improvement team

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