32p

Propulsion IVHM

Extreme Environment Instrumentation

Power IVHM

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Space Transportation Technology Workshop /IVHM:

Propulsion & Power IVHM Technologies

AGENDA

- **Why**
- **What**
- **Propulsion IVHM**
  - **Vision**
  - **Capabilities/Research**
  - **Selected Projects**
    - X33
    - X34
    - AHMS
    - Smart Self Healing Propulsion Systems
    - Extreme Environment Sensors
- **Power IVHM**
  - **Vision**
  - **Capabilities/Research**
  - **Selected Projects**
    - EMAs
- **Summary**

WHY?

Goal Driven Space Transportation

Goal 9: Low-Cost Space Access

- Reduce the payload cost to low-Earth orbit by an order of magnitude, from $10,000 to $1,000 per pound, within 10 years and by an additional order of magnitude within 25 years.
- Increase the mission safety by two orders of magnitude within 10 years and four orders of magnitude within 25 years

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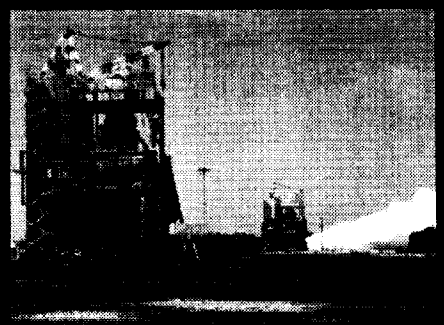
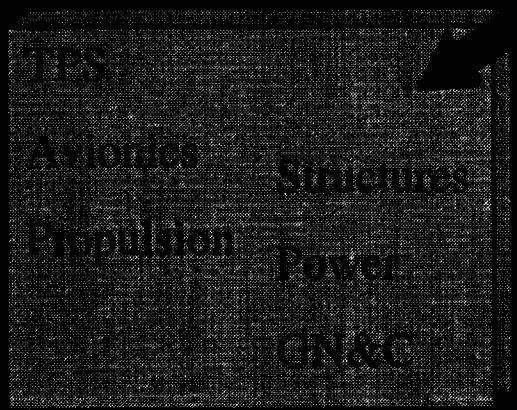
WHAT?
IVHM Vision



Test Facility

Control Rooms

Ground Processing Facility



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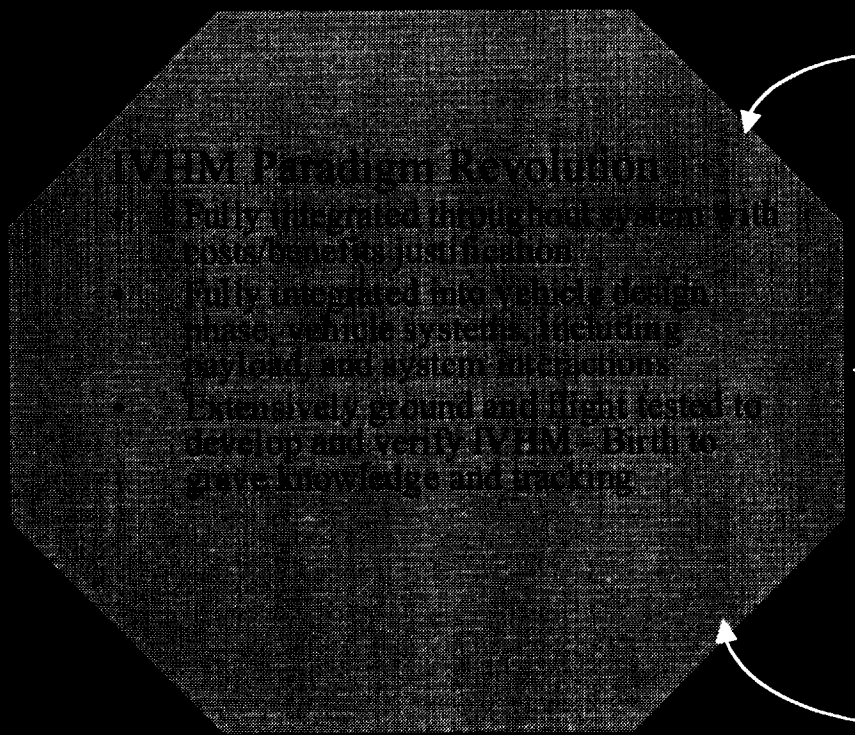
WHAT?
Paradigm Shift



Projected IVHM Impacts

- **20x Ops and Maintenance Reductions**
  - Condition Based Maintenance
  - 100% Vehicle IVHM Coverage Integrated With Autonomous Control
  - Automated Ground Processing and Mission Control Systems
- **Reduced Development Time and Costs**
  - Integrated Tools that Facilitate Rapid Analysis and Design of Highly Reliable, Cost-Effective Vehicles
- **10x Reliability Improvements**
  - Improved real-time fault management and fault modeling
  - Increase sensor redundancy throughout system (10 to 100x)
- **15% Weight Reductions**
  - Wireless and Nano Electronics
  - Real-Time Margin Management

PROPULSION IVHM Vision

1st Generation

2nd Generation

- Major LRU coverage, limited integration
- Maintenance and operations focused
- In-flight and post-flight analysis
- Smart components - Turbopumps, nozzles...
- Advanced materials knowledge

3rd Generation

- Integrated into design
- Complete system coverage
- Reliability, maintenance and operations focussed
- Intelligent Propulsion System: real-time analysis fully integrated with accommodating controls, intelligent maintaining systems

Distributed Architectures

IVHM System Design Tools (including sensor placement)

Physics-based models (including failure modeling)

Smart microsensing

High Temp Electronics/ Instrumentation

Hazardous condition monitoring

Auto generation of maintenance and ops procedures

Multifunctional/embedded sensor systems

Advanced Diagnostic and Prognostic and Control Techniques

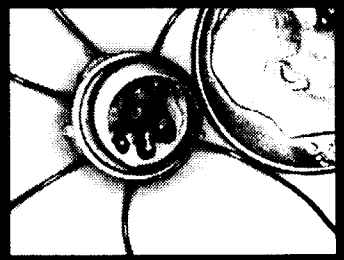
- neural networks
- fuzzy logic
- genetic and evolutionary algorithms

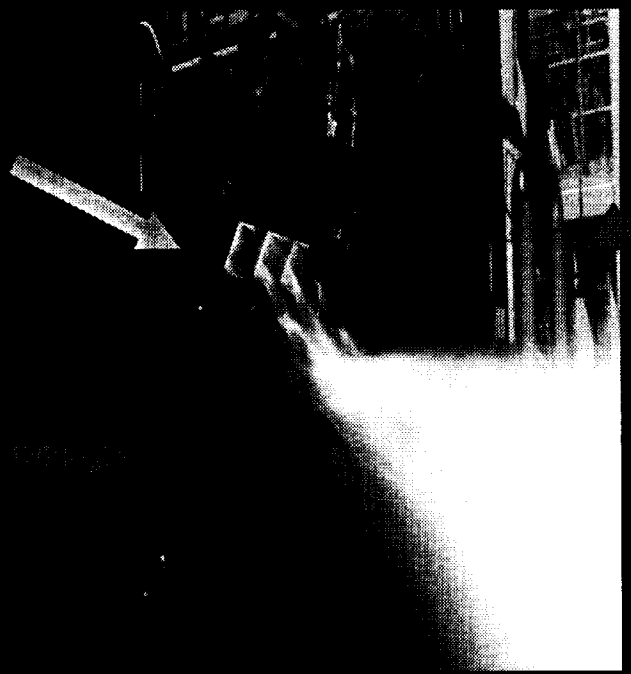
Fully photonic avionics & instrumentation

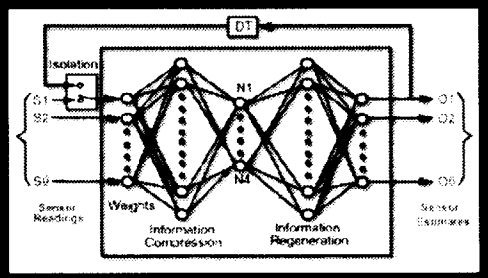
Wireless Operations

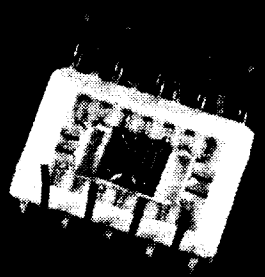
Smart components/structures

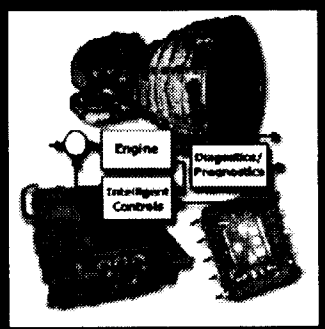
PROPULSION IVHM Vision

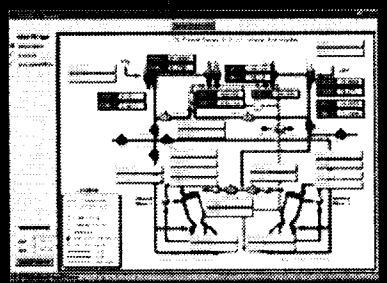


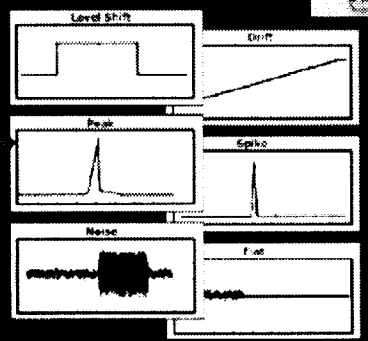












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PROPULSION IVHM

Capabilities/Research

Propulsion IVHM works within a distributed vehicle IVHM architecture

Propulsion IVHM life cycle approach extends inherent engine reliability and reduces costs

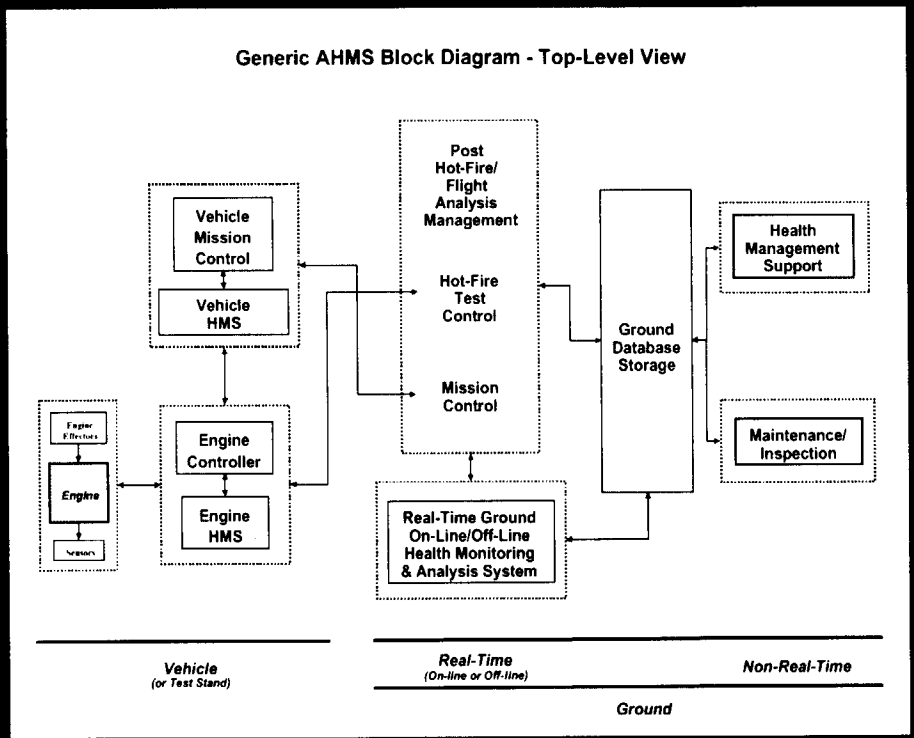
Propulsion IVHM is embedded

Flight –

- Instrumentation
- Avionics
- Controls
- Intelligent components

Ground Elements

- Advanced ground processing
- Maintenance reduced
- Paperless Systems
- Smart Software
- Smart GSE



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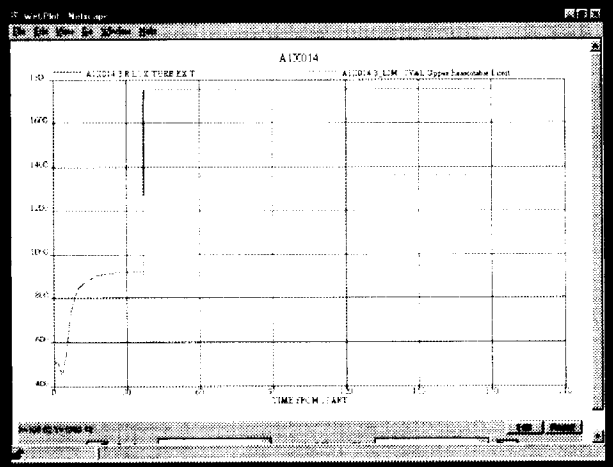
PROPULSION IVHM

Projects: X-33 Post-Test Diagnostic System

PTDS analysis and viewing system infra-structures are in place and validated; user training conducted at Rocketdyne

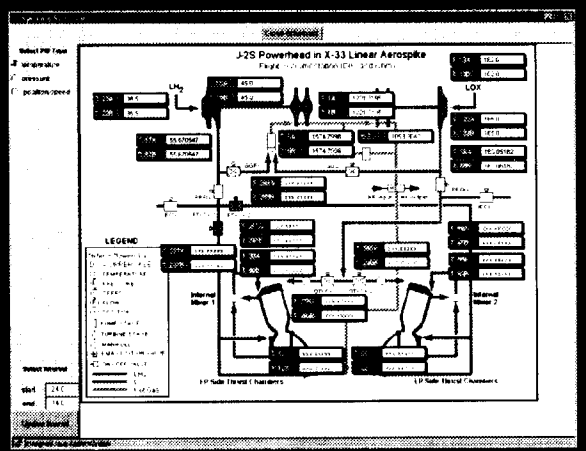
Highlights

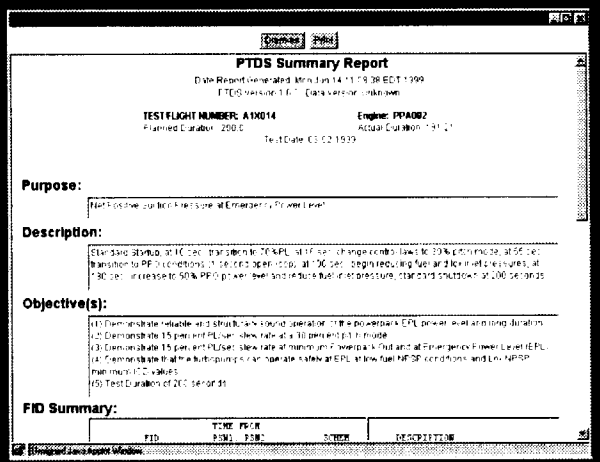
- **Has successfully analyzed all powerpack and engine firings**
- **Rocketdyne estimates order of magnitude reduction in flight turnaround time**



Comprehensive Plotting and Interactive Statistics

Interactive Schematics





Data Review Ready Reports

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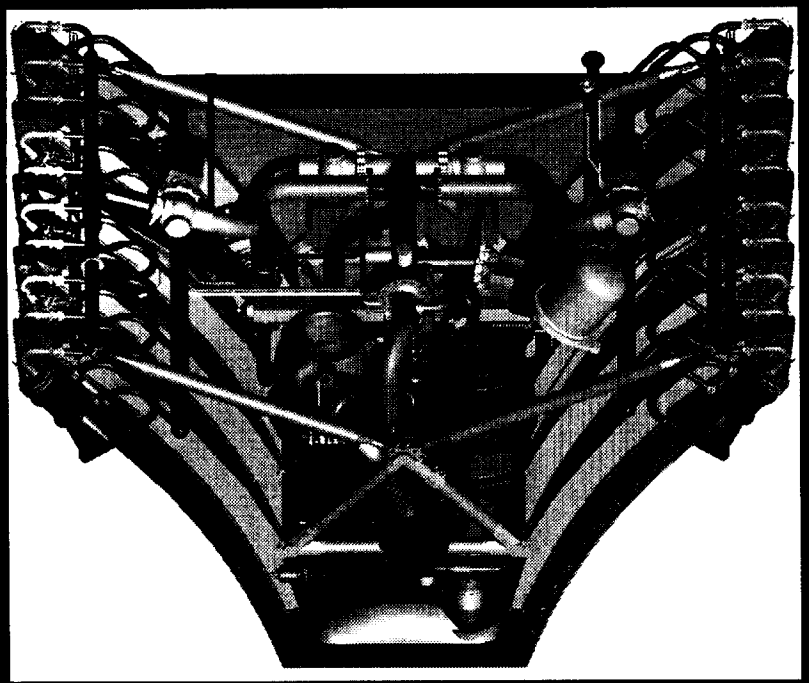
PROPULSION IVHM

Projects: X-33 Post-Test Diagnostic System



All Components Covered

- Sensors
- Gas Generator
- LOX turbopump
- Fuel Turbopump
- Valves, Actuators, Ducts
- Nozzles, Thrust Chambers

Analyses Performed

- Component Performance Predictions
- Statistical Characterization
- Life Tracking
- ICD Exceptions/Margin Analysis
- Model-Based Fault Detection

Web-Based GUI

- View Reports
- View Interactive Schematics
- View Predefined Plot Packages
- Generate/Annotate Plots on Request
- Perform Complex Statistical Analyses

Available Reports

- Summary Report
- Systems Report
- Margin Report
- Life Tracking Report
- Events Report
- Component Reports

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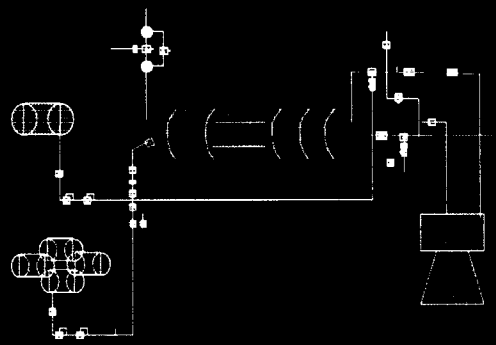
Projects: X34 NITEX

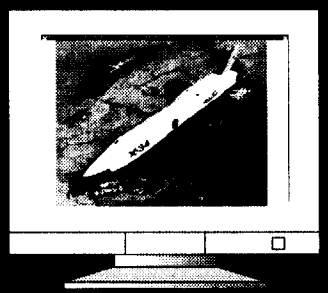


- Vehicle Sensor Data
- Vehicle Status
- Phase Information
- GSE Data

IVHM Flight System

- Records
- Processes
- Tags
- Telemeters

Telemetry



- Databases
- Tracks
- FDI, Predicts
- Maintenance Actions
- Checkout

Ground Link

IVHM Ground System

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PROPULSION IVHM

Projects: X34 NITEX

The IVHM Vision and How NITEX Relates

Green = Potential

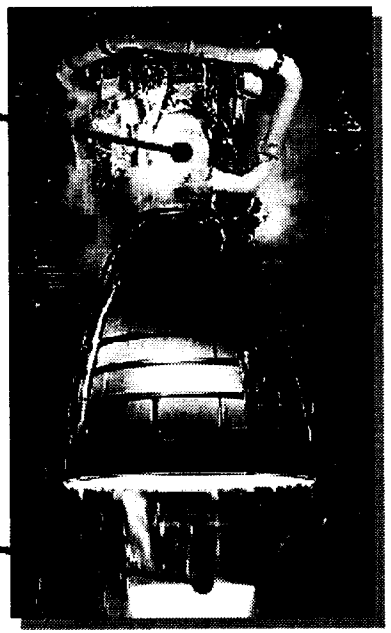
IVHM Vision / Long Term Objectives

- **Enhanced vehicle safety and reliability**
  - Modern sensing systems
    , *prediction*
  - Reliable, accurate health diagnosis and prognosis
- **Reduced ground processing of reusable vehicles**
  - In flight system checks
  - Automated ground servicing and checkout
  - Informed maintenance scheduling system
- **Autonomous operation in flight and on the ground**
  - Reduced workload for ground controller team
  - *Predicting and adapting to sub-system degradation and failure real-time in flight and on the ground*

PROPULSION IVHM
Projects: AHMS

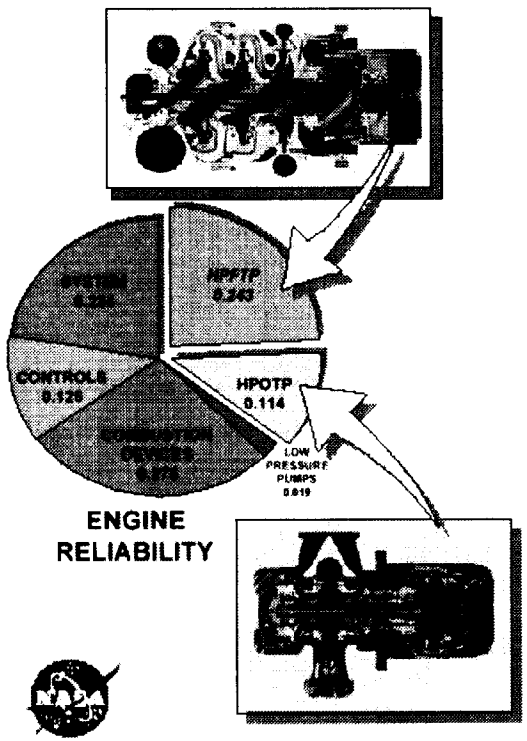
Advanced Health Monitoring Features

- **Marshall Space Flight Center (MSFC) Developed Real-Time Vibration Monitor System (RTVMS)**
  - **High Pressure Turbopump rotating hardware structural integrity**
- **Boeing-Rockedyne Developed Linear Engine Model (LEM)**
  - **Engine performance**
- **MSFC Developed Optical Plume Anomaly Detection System (OPAD)**
  - **Engine wear, erosion, breakage**



PROPULSION IVHM
Projects: AHMS

Active Vibration Monitoring System



- 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

BOEING

PROPULSION IVHM
Projects: AHMS

Linear Engine Model
(LEM)

- Real time monitoring of engine performance and anomalies
- Console tool for Mission Operations Directorate Booster Operator
- Identification of between flight maintenance requirements
- Potential for adaptive throttling or shut down commands

Engine Performance

SSME Maintenance

JSC MOD Booster Console

KSC Turnaround Operations

Real-time multiple failure risk mitigation tool for ground and flight

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BOEING

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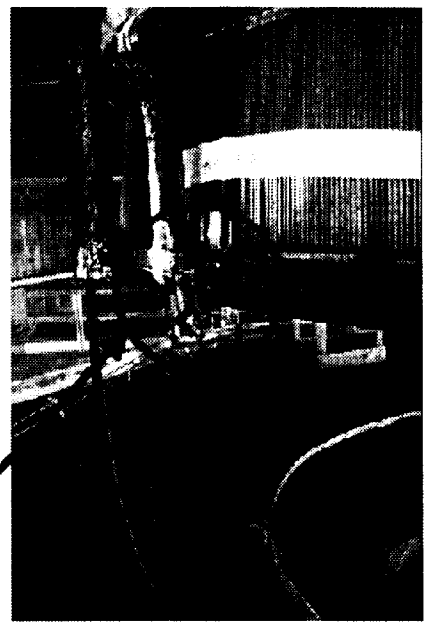
Optical Plume Anomaly Detection
(OPAD)

- Sensitive Monitor of engine wear, erosion, breakage
- Technology proven in ground test program
- Early warning compared to conventional measurements
- Diagnostic Tool for eliminating additional inspections requirements
- Experimental flight demonstration in work

OPAD Flight system tested on development engine



BOEING

PROPULSION IVHM

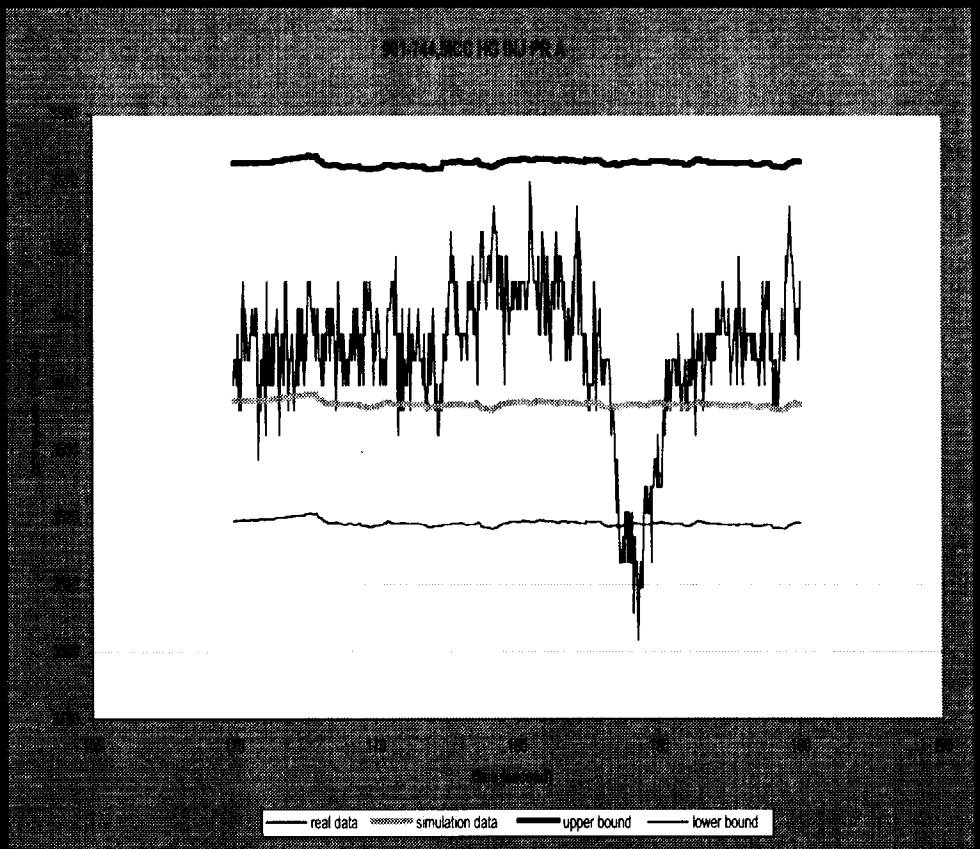
Projects: Smart Self Healing Propulsion Systems

Objective: Diagnostic Solutions that

- Do not require exhaustive enumeration of faults
- Cover steady-state and transient operation
- Address test-to-test variability
- Explicitly handle model and measurement uncertainties
- Provide Confidence in Diagnostic System Output
- Provide Instrumentation Selection Guidance

Model-based monitoring algorithm

- Uses dynamic simulation of the SSME
- no false alarms on 8 nominal SSME data sets
- 10 successful isolations on 13 off-nominal SSME data sets



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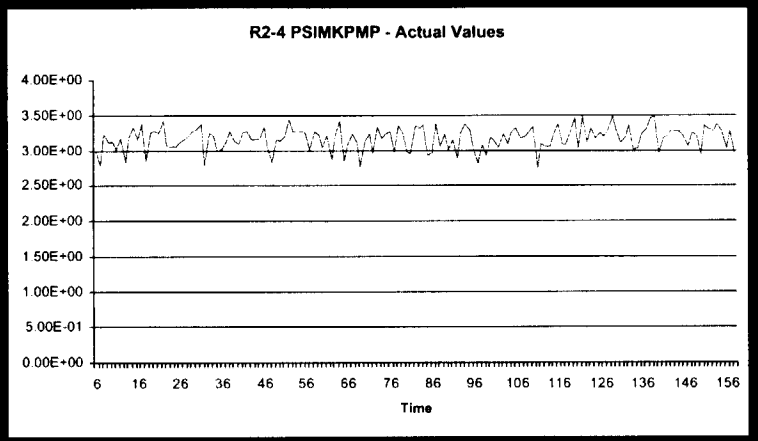
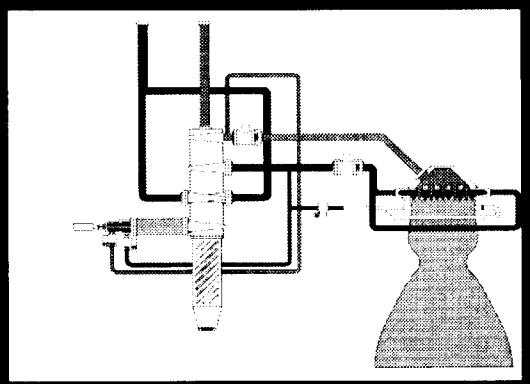
PROPULSION IVHM

Projects: Smart Self Healing Propulsion Systems



Engine Diagnostics via Data Reduction

- Comprehensive linearity analysis has been completed for Fastrac Engine
- Various versions of algorithm (incorporating 1st and 2nd order effects) have been successfully demonstrated on historical data



Will Fly as Part of X-34 NITEX

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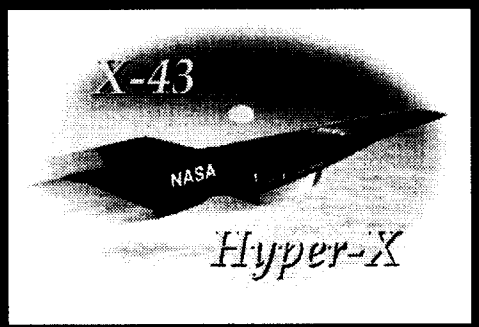
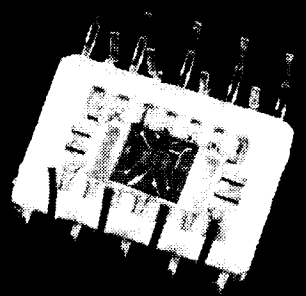
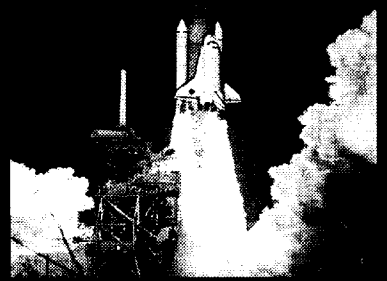
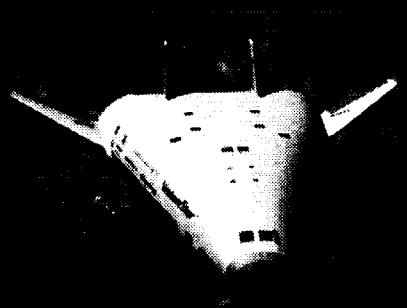
PROPULSION IVHM

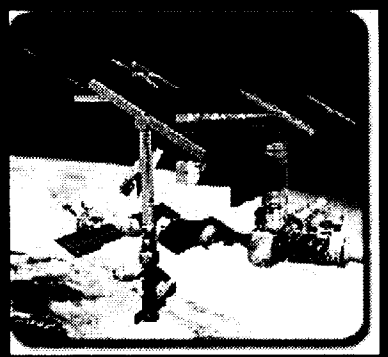
Projects: Extreme Environment Sensors











CWRU

NASA

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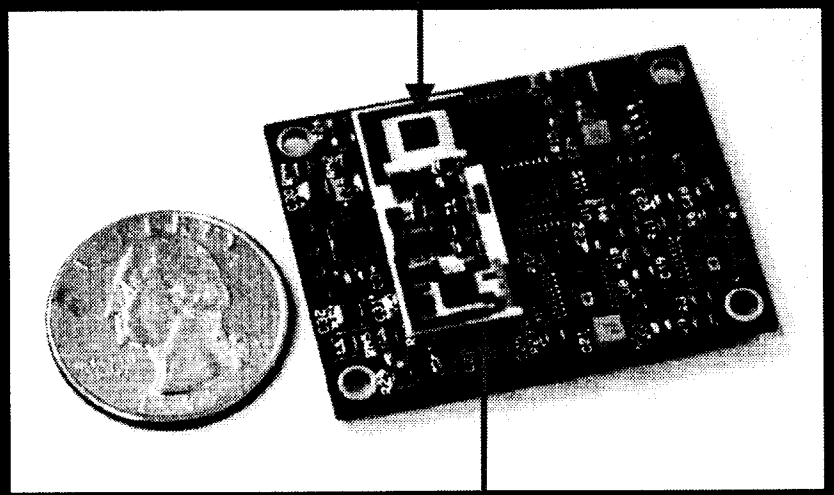
PROPULSION IVHM

Projects: Extreme Environment Sensors

Shuttle system hardware (H2 Sensor with Electronics)



H2 and O2 Sensor with Electronics

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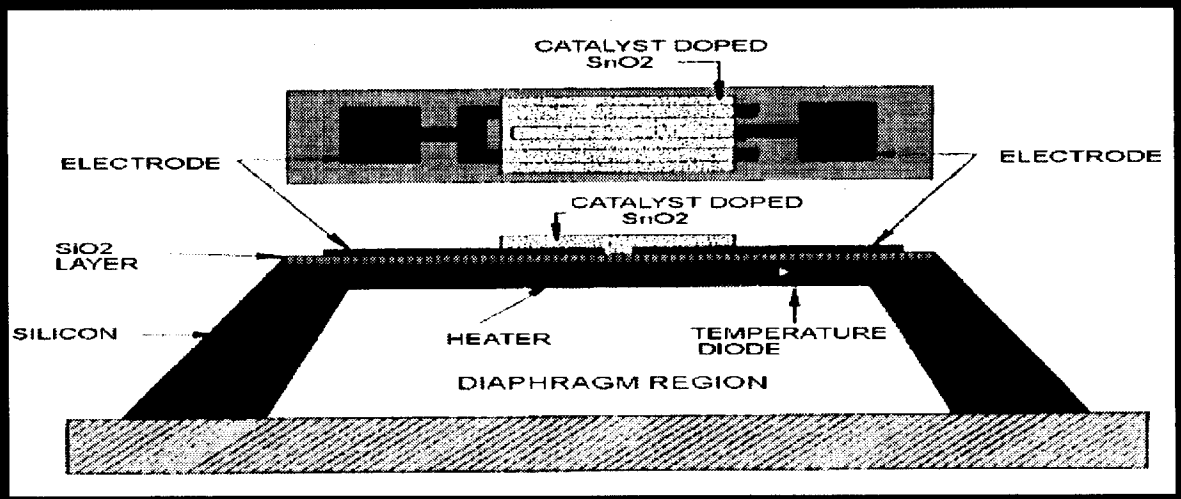
PROPULSION IVHM

Projects: Extreme Environment Sensors

- Microfabricated for minimal size, weight and power consumption
- Micromachined to minimize power consumption and improved response time
- Temperature detector and heater incorporated into sensor structure
- Nanofabrication of Tin-Oxide to increase sensor stability

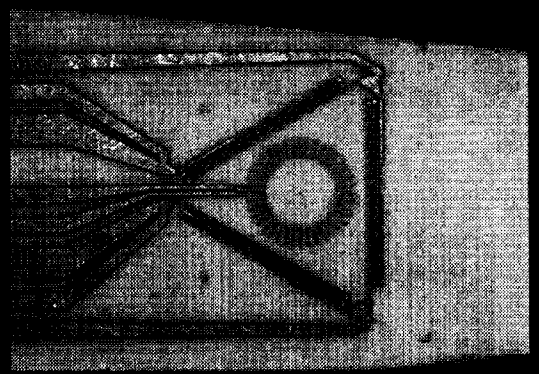


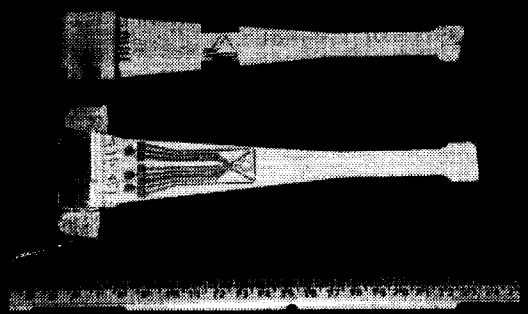
PROPULSION IVHM

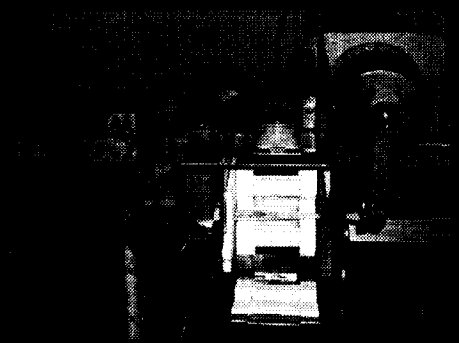
Projects: Extreme Environment Sensors

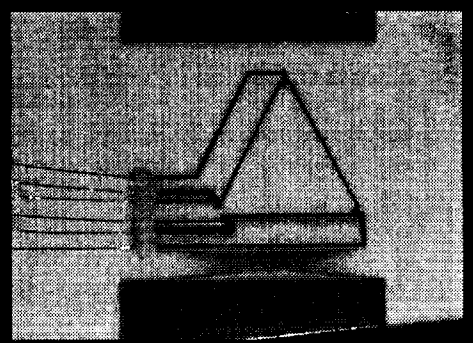
Multiple Measurements

- Strain Magnitude & Direction
- Heat Flux
- Surface Temperature
- Flow Velocity Magnitude and Direction









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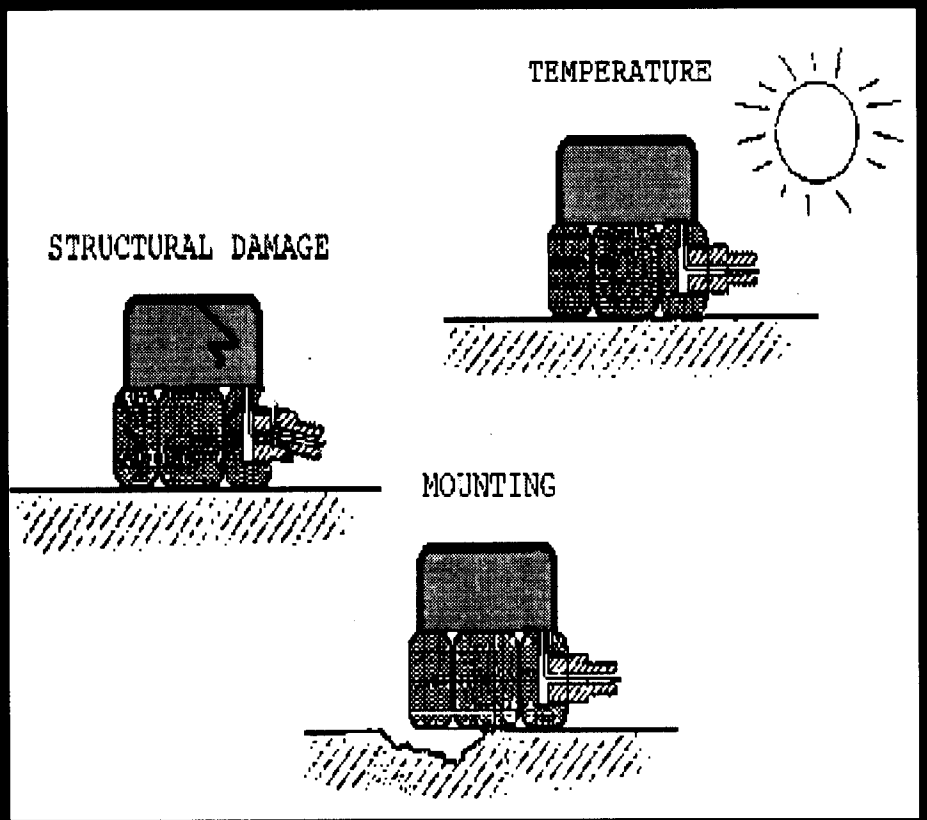
Projects: Extreme Environment Sensors

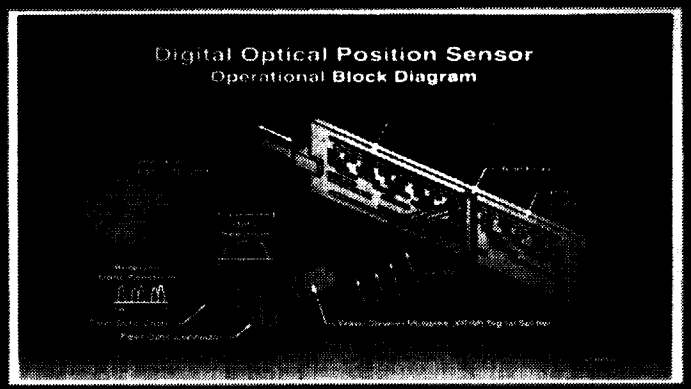


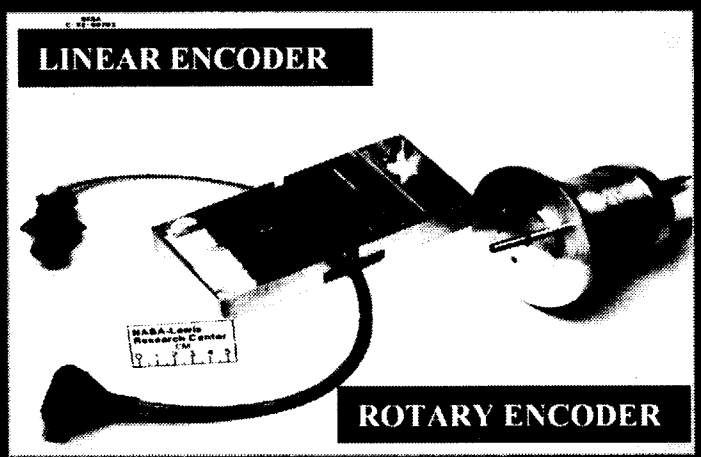
- Detects accelerometer mounting problems (i.e. torque) and structural damage
- Collects diagnostic information and acceleration data concurrently
- Increases accuracy of accelerometer data by 10X during temperature fluctuations
- No additional hardware required, accomplished by using active sensing methods
- Research to be conducted on in-situ calibration

PROPULSION IVHM

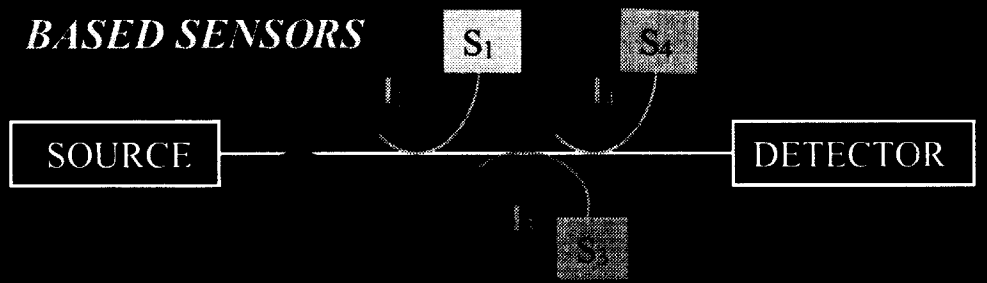
Projects: Extreme Environment Sensors

DIGITAL SPECTRAL ENCODERS

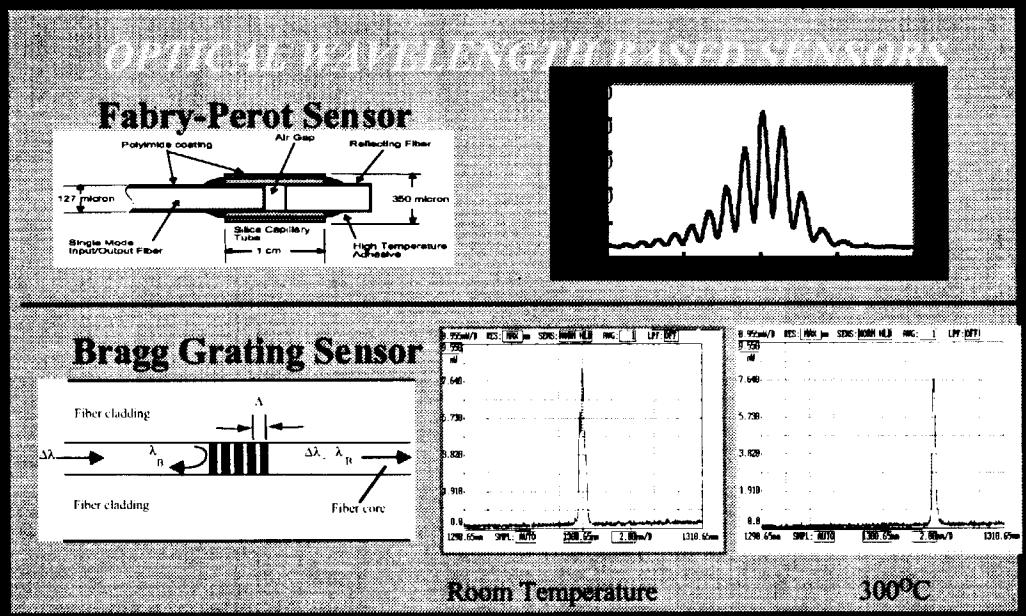




ANALOG SPECTRAL BASED SENSORS



OPTICAL WAVELENGTH BASED SENSORS



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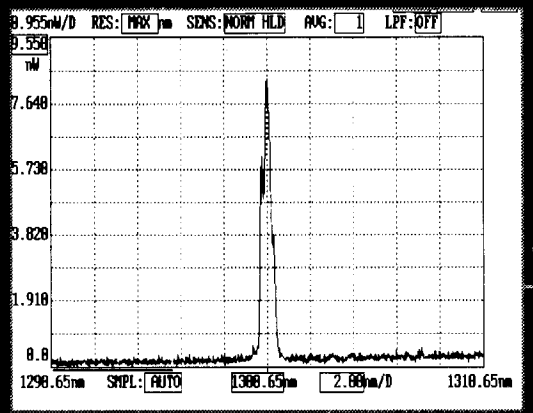
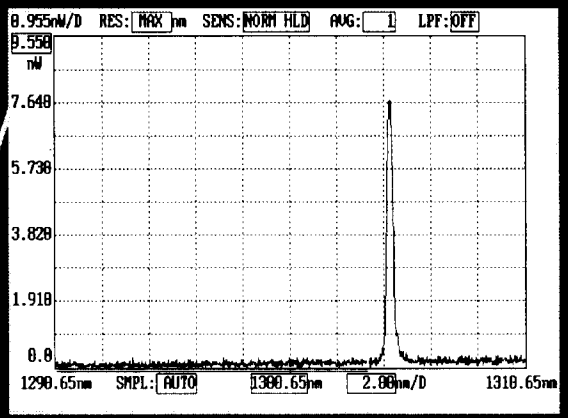
PROPULSION IVHM

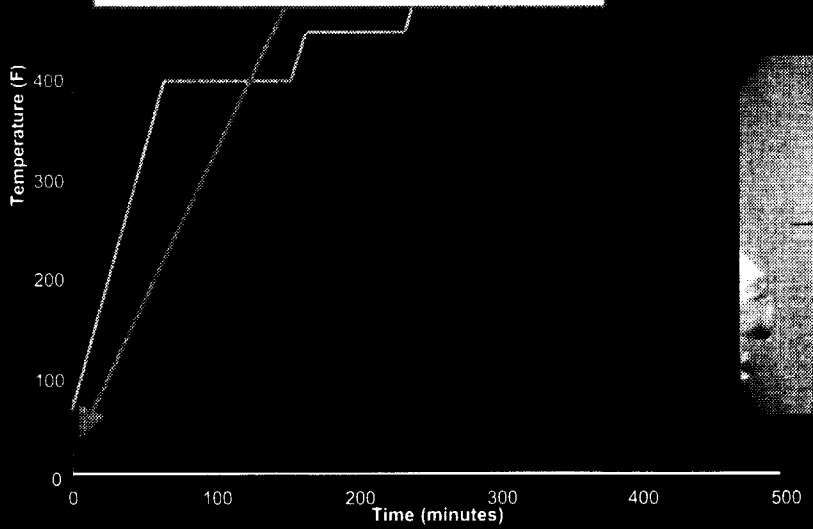
Projects: Extreme Environment Sensors

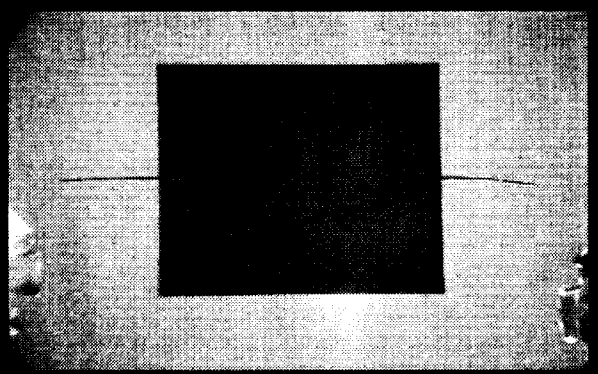
Room Temperature



600°F







Embedded Fiber Optic Sensors

Space Transportation Technology Workshop /IVHM:

Propulsion & Power IVHM Technologies

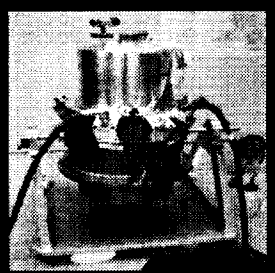
POWER IVHM Vision

Objectives

- Maximize safety
- Minimize costs
- Maximize dispatch reliability

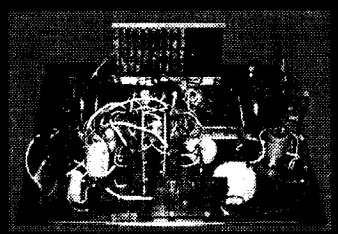
Approach

- Minimize human involvement in power system operations
- Monitor component health
- Manage redundancy



Automate

- Incipient failure detection
- Time-to-failure estimation
- Optimal load management



Space Transportation Technology Workshop /IVHM:

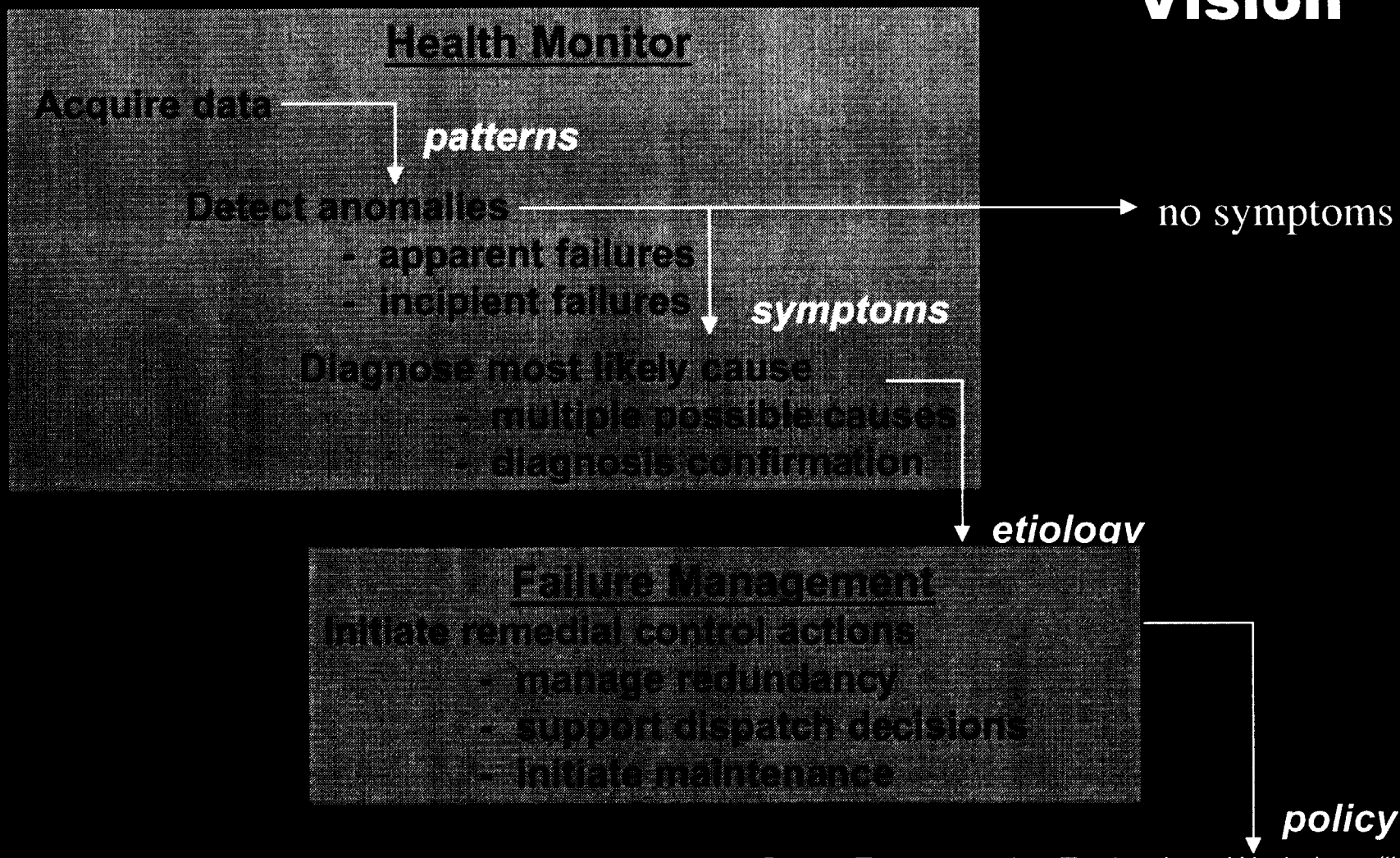
Propulsion & Power IVHM Technologies

POWER IVHM Vision

Responsiveness & Dependability

- **System Flexibility & Operability**
  - Autonomous optimal load management accomplishes in-flight redundancy
- **System Reliability**
  - Optimal load allocation during partial failures in generation or distribution provides the most functional redundancy for equipment still operating.
- **Maintainability**
  - Automated failure cause diagnosis eliminates costly manual diagnosis when identifying faulty electrical equipment.

POWER IVHM Vision



Space Transportation Technology Workshop /IVHM:

Propulsion & Power IVHM Technologies

POWER IVHM
Capabilities/Research

Develop advanced architecture

Develop expert automated agents continued

- Flywheel energy storage systems
- Power distribution control centers
- Power converters
- Distribution network wiring
- Generators

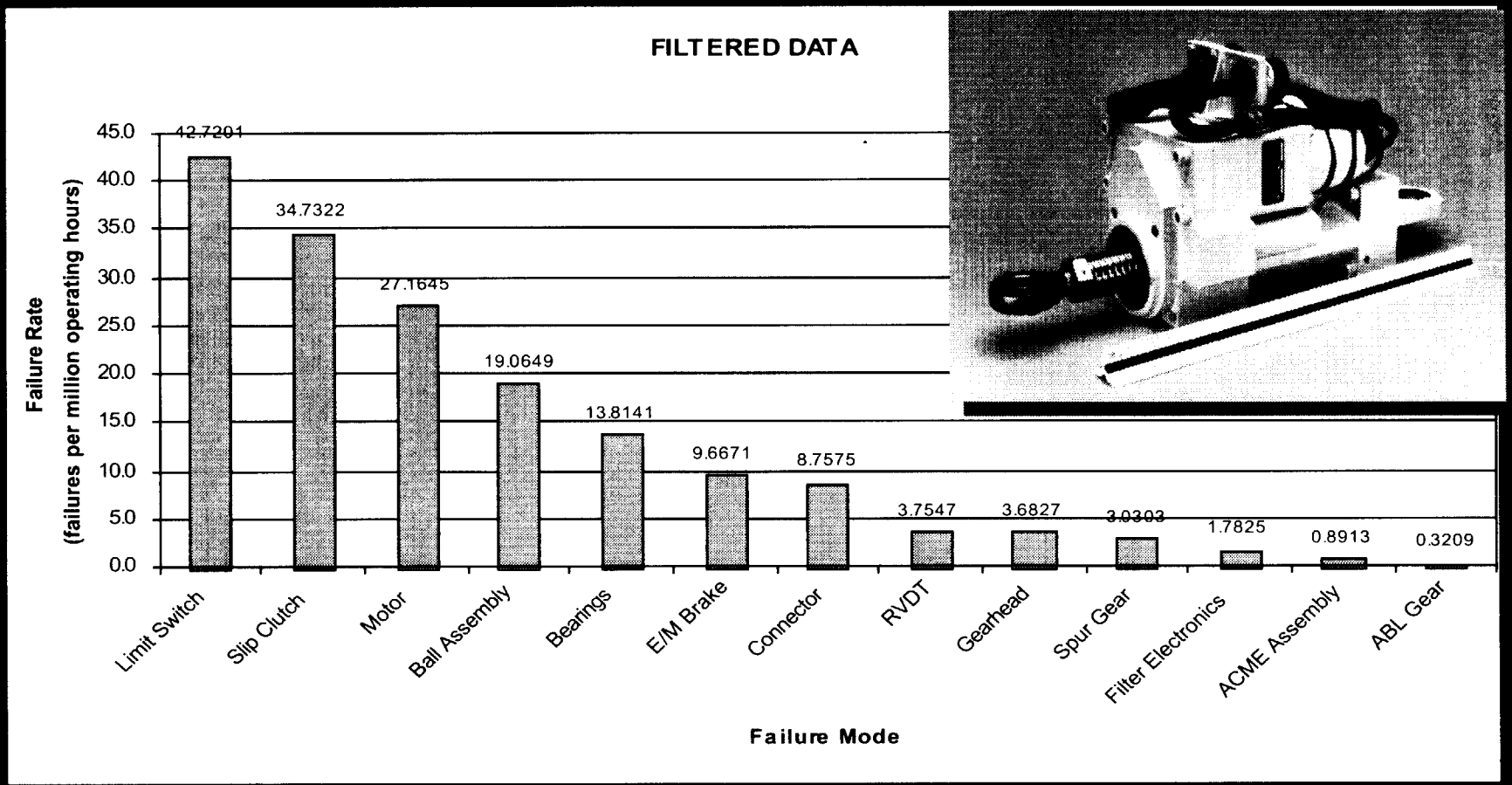
Develop expert automated agents that are competent in:

- Planning
- Scheduling
- Optimal load management

Demonstrate using a RLV power system test-bed.

POWER IVHM

Projects: Smart EMA Agent



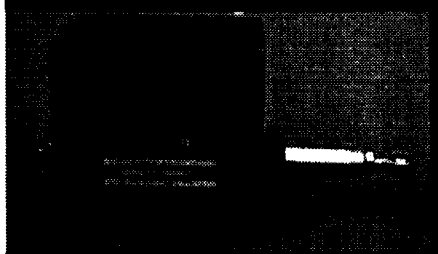
Space Transportation Technology Workshop /IVHM:

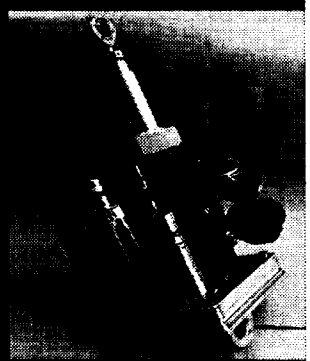
Propulsion & Power IVHM Technologies

POWER IVHM

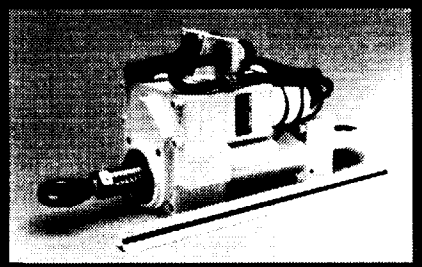
Projects: Smart EMA Agent

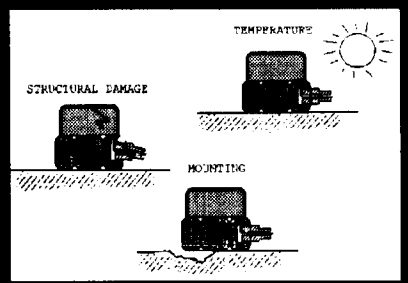
Item / Measurement	Windings	Bearings	Friction Surfaces
Differential Torque	Low	Medium	High
Vibration	Low	High	Medium
Temperature	Medium/High	Medium	Medium/Low
Voltage/ Current	High	Medium/Low	Medium/Low

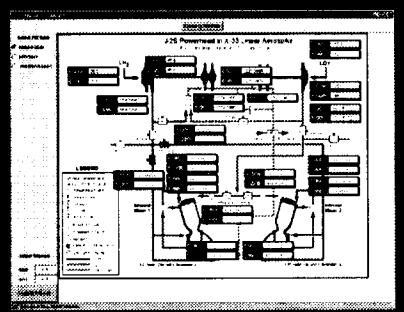


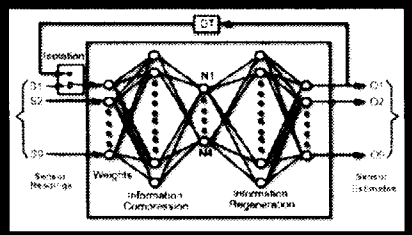


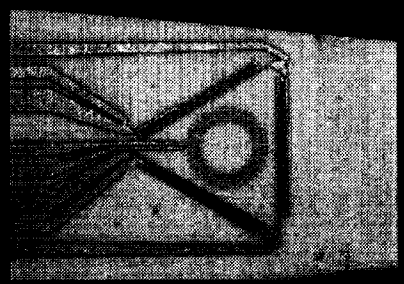
Summary

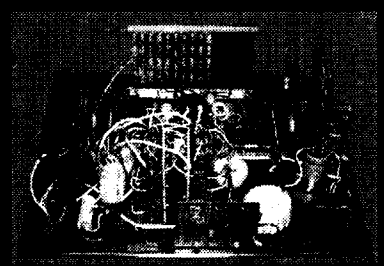












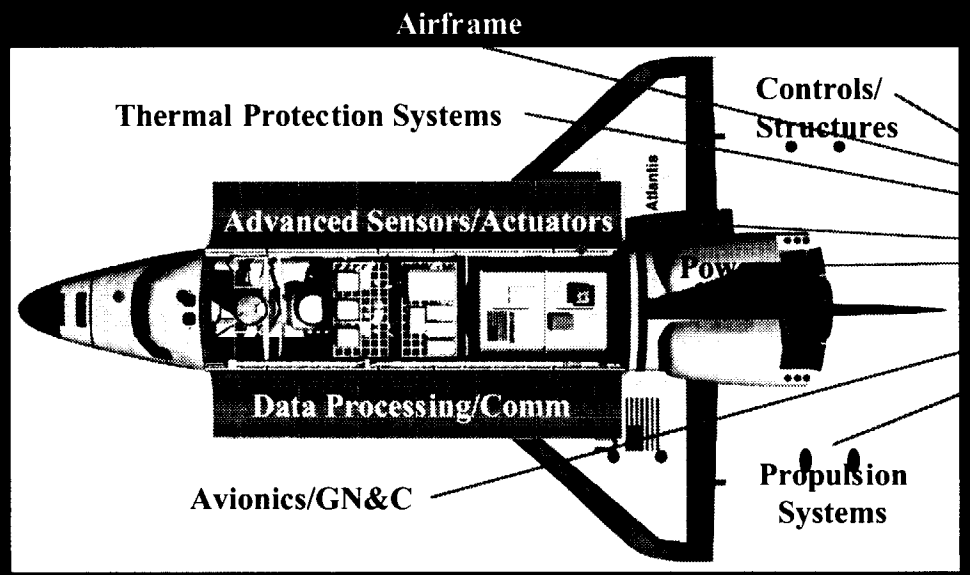
Space Transportation Technology Workshop /IVHM:

Propulsion & Power IVHM Technologies

IVHM Systems Engineering & Integration Office

NASA Ames Research Center
POC: Kevin Flynn
650-604-4062
kflynn@mail.arc.nasa.gov

Collect, process, and integrate information about the health of a launch system including the vehicle, subsystems, components, sensors, and ground support systems to make informed decisions and take appropriate actions to ensure the success of a mission



- Anomaly detection and isolation
- Recovery/Reconfiguration
- Component degradation detection

Intelligent Executive

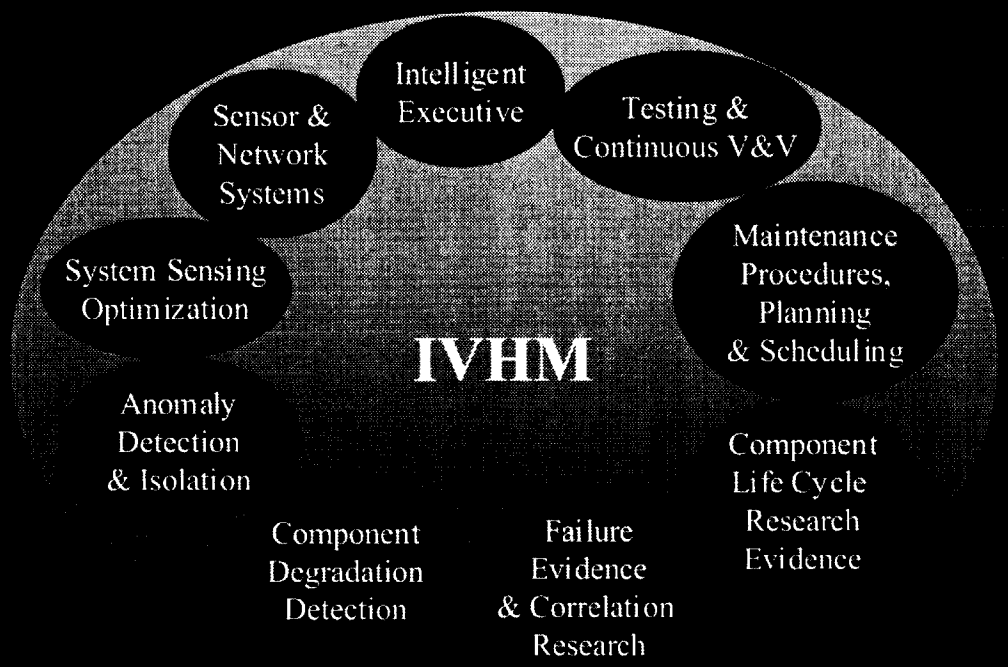
- Data fusion
- Model-based controllers
- Autonomous Software Agents

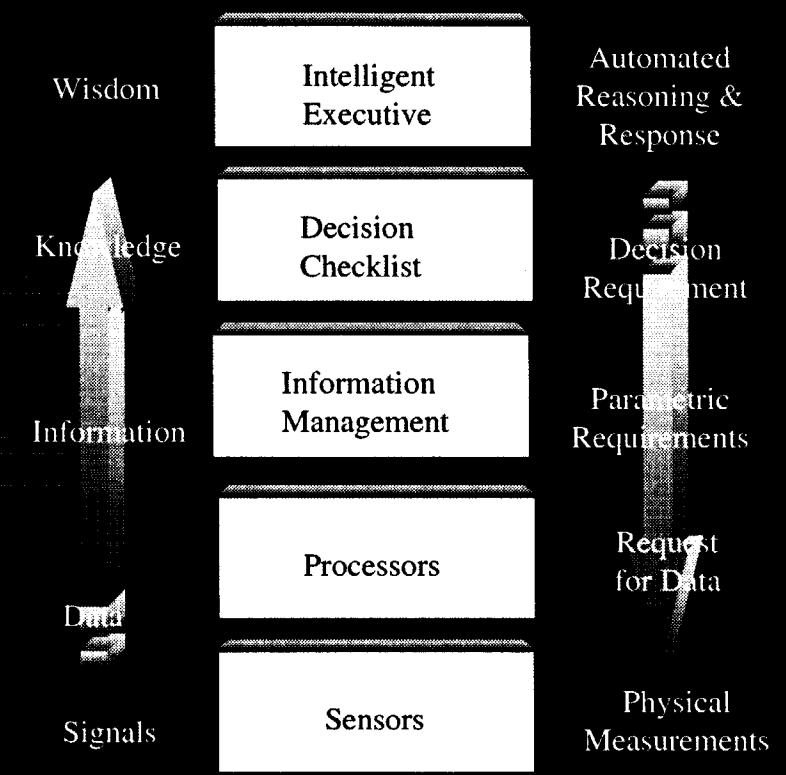
Informed Operations & Maintenance

- Planning and Scheduling
- Maintenance Procedures
- Testing

The Union of Advanced Hardware and Software -
Providing higher reliability, with greater robustness, at lower costs

Integrated Vehicle Health Management:
IVHM

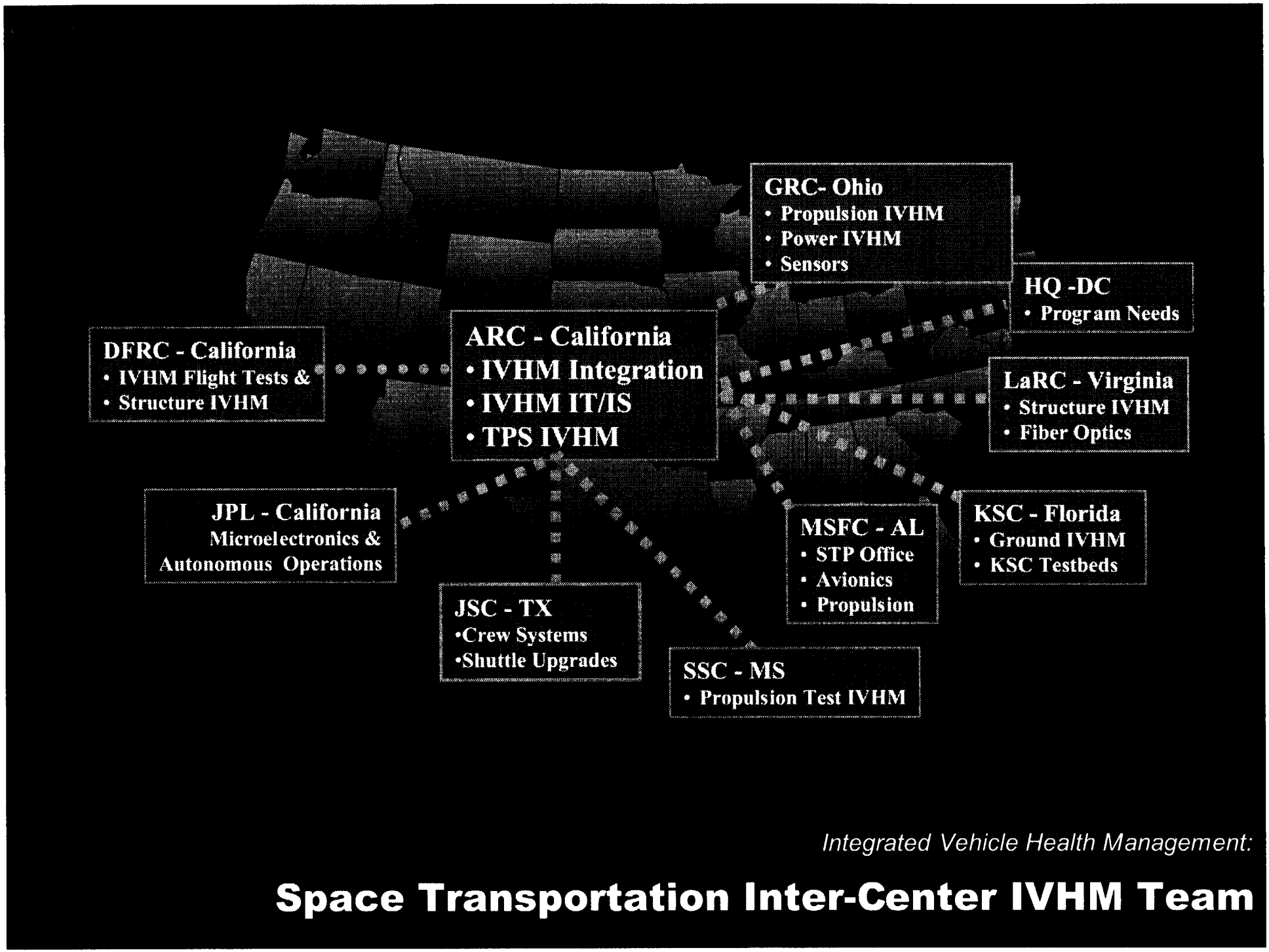




SE&I helps these IVHM pieces work together to meet the goals

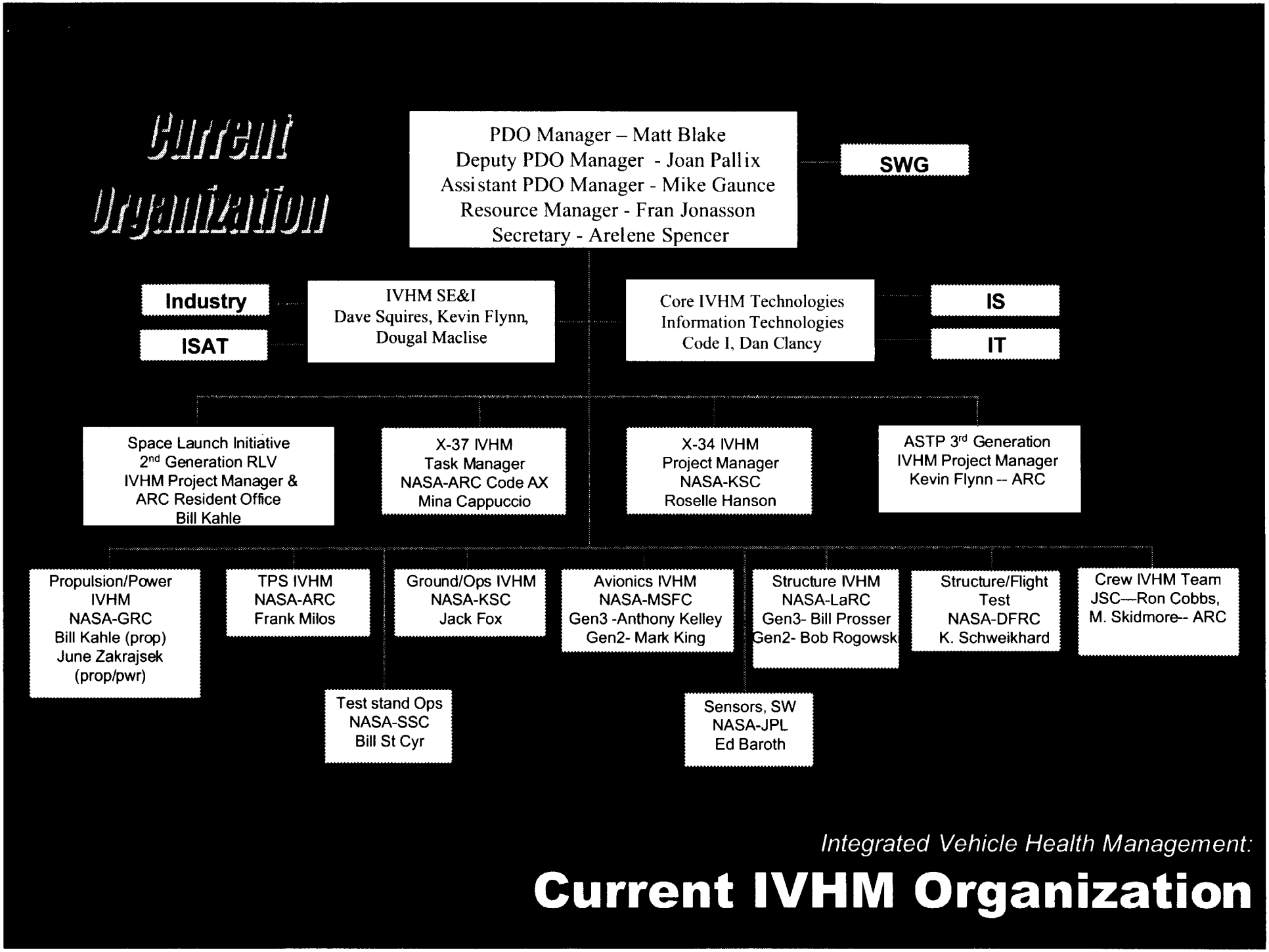
Integrated Vehicle Health Management:

IVHM: Convert Data into Knowledge



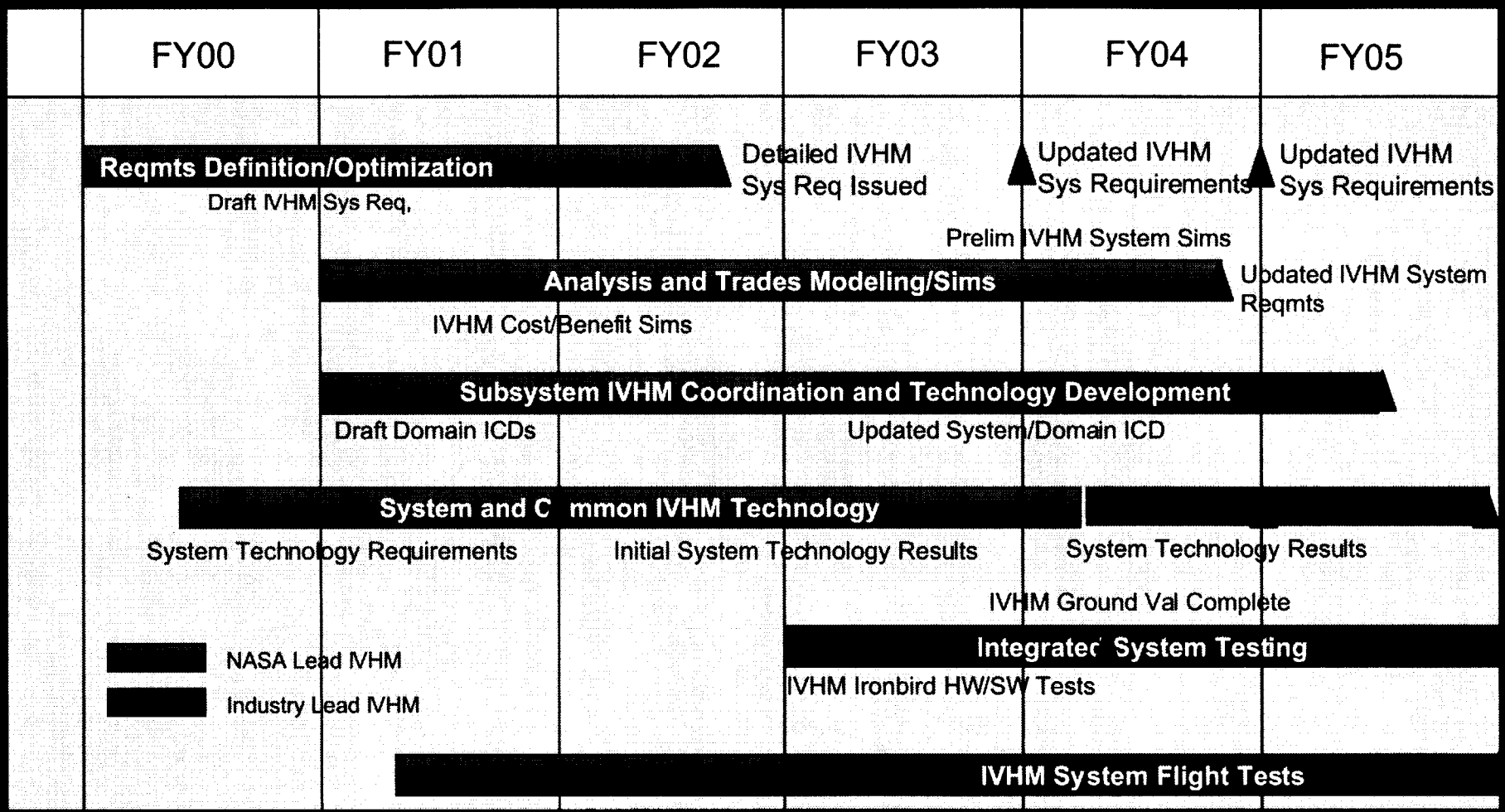
Integrated Vehicle Health Management:

Space Transportation Inter-Center IVHM Team



Integrated Vehicle Health Management:

Current IVHM Organization



Integrated Vehicle Health Management:

IVHM Systems Integration Project

IVHM Technologists at other NASA centers

ISAT
- **IVHM, new ISAT discipline**
- **Safety& Reliability**
- **Economics**
- **Performance effects**

MSFC
- **2nd gen, SE&I**
- **3rd gen, ASTP**
- **Operability branch**

LaRC
- **Maintainability branch**

ARC
- **Systems Analysis branch**
- **Space Transportation Projects Office**
- **System Engineering division**
- **IT directorate**
- **Thermal Physics branch**
- **Space payloads branch**

Industry
- **Boeing (Seal Bch) NRA 8-27**
- **DSI International (eXpress modeling tool)**
- **USA (providing shuttle data)**

Integrated Vehicle Health Management:

IVHM SE&I Working Relationships

Integrated Vehicle Health Management:

IVHM SE&I Simplified Process Model

Business Driven Requirements

Param	Reqmt	Measured
DDT&E	$xxxxM	xxxx
Schedule	32 months	xxxxx
Duration	10 years	xxxxx
Ps	95%	xxxx
xxxx		
xxxxx		

Feedback Loop

Feedback Loop

Reqmts Modeling

DOORS, RTM Requirements Object Oriented Modeling and Dependencies

Management & Traceability

System/subsystem/ sensor reqmts

System Logic Flow Path

Interface Reqmts

Ops Scenarios

ISAT System Descriptions

CONOPS Discrete Model

Maggio/Squires Reliability Data

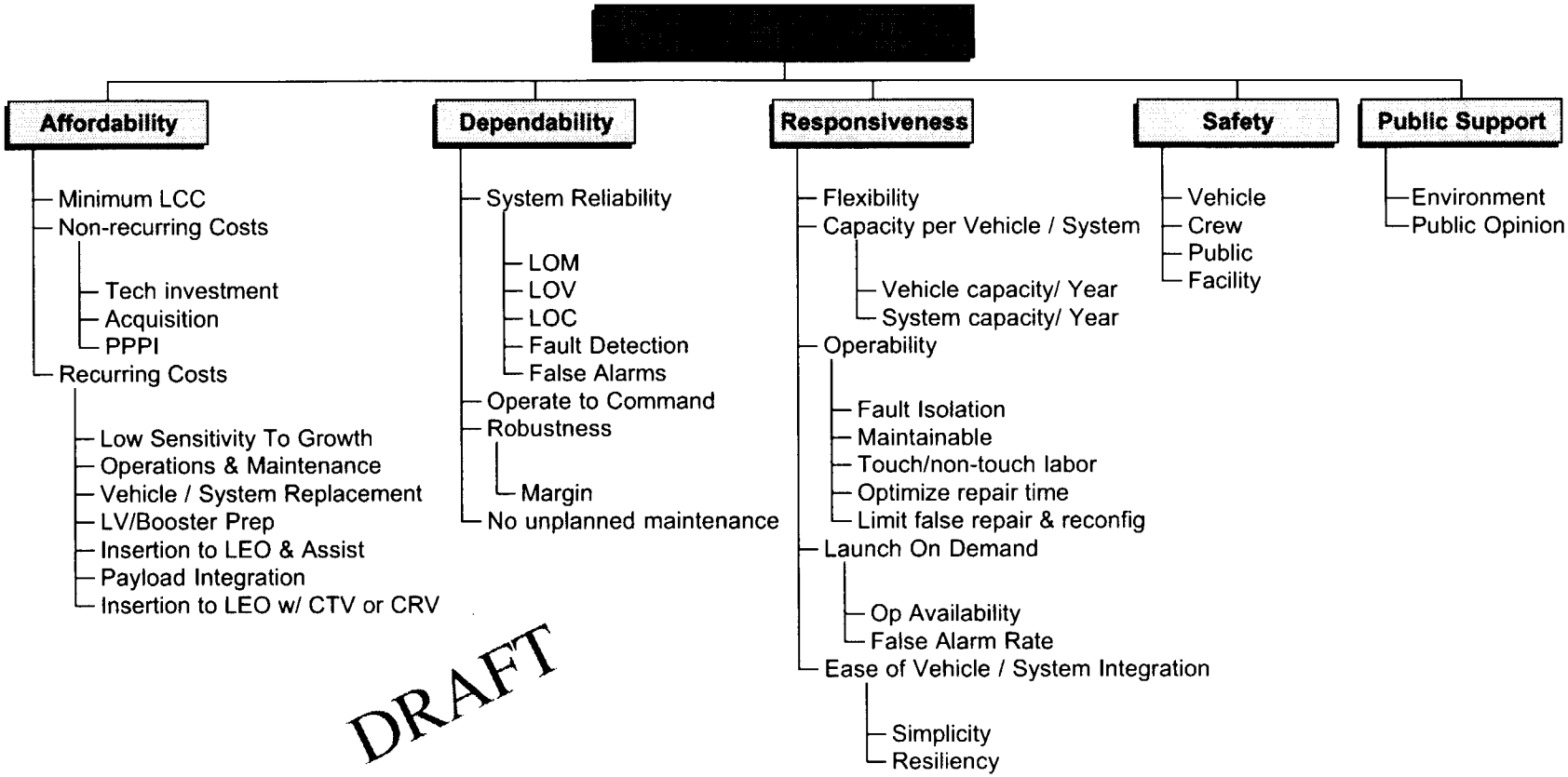
Squires IVHM Event Descriptions

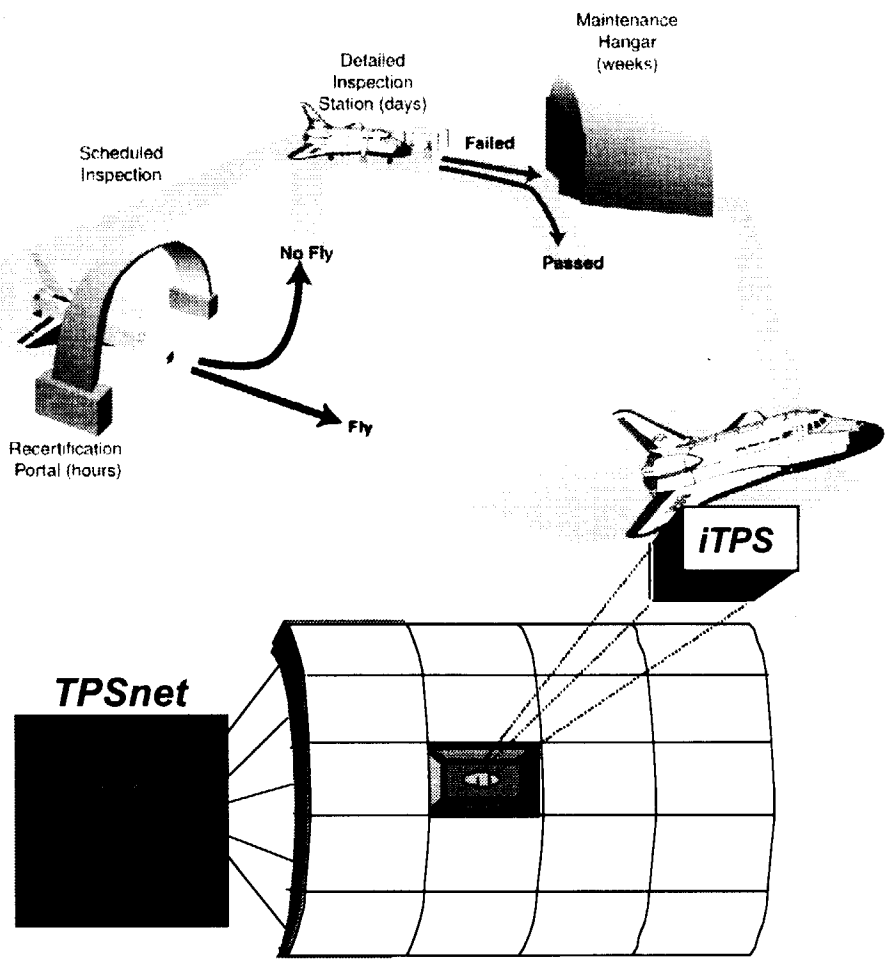
Shaw/Flynn Cost Analysis

eXpress Int. Diagnostics Models

Price

Cost/Schedule Earned Value Tracking


[redacted]
Affordability
Minimum LCC
Non-recurring Costs
Tech investment
Acquisition
PPPI
Recurring Costs
Low Sensitivity To Growth
Operations & Maintenance
Vehicle / System Replacement
LV/Booster Prep
Insertion to LEO & Assist
Payload Integration
Insertion to LEO w/ CTV or CRV
Dependability
System Reliability
LOM
LOV
LOC
Fault Detection
False Alarms
Operate to Command
Robustness
Margin
No unplanned maintenance
Responsiveness
Flexibility
Capacity per Vehicle / System
Vehicle capacity/ Year
System capacity/ Year
Operability
Fault Isolation
Maintainable
Touch/non-touch labor
Optimize repair time
Limit false repair & reconfig
Launch On Demand
Op Availability
False Alarm Rate
Ease of Vehicle / System Integration
Simplicity
Resiliency
Safety
Vehicle
Crew
Public
Facility
Public Support
Environment
Public Opinion
DRAFT



Shuttle/2nd Gen Smart TPS

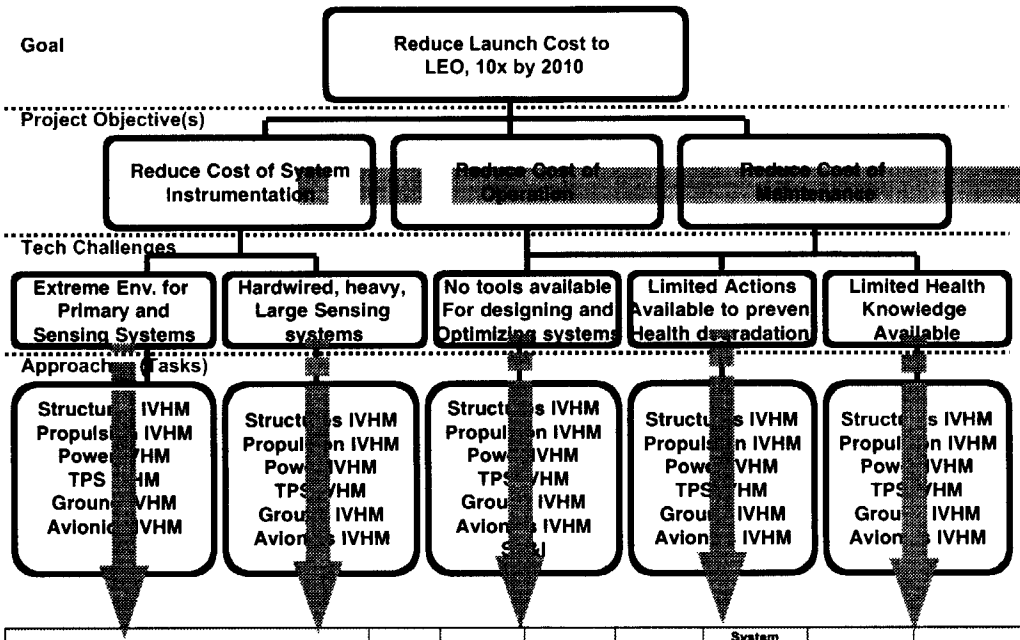
- Saves thousands of hours of inspection (touch and non-touch)
- Eliminates the need for set up of scaffolding
- Eliminates the need to disassemble the vehicle to inspect for subsurface defects
- Enabling for 24 hour turnaround 3rd gen goal

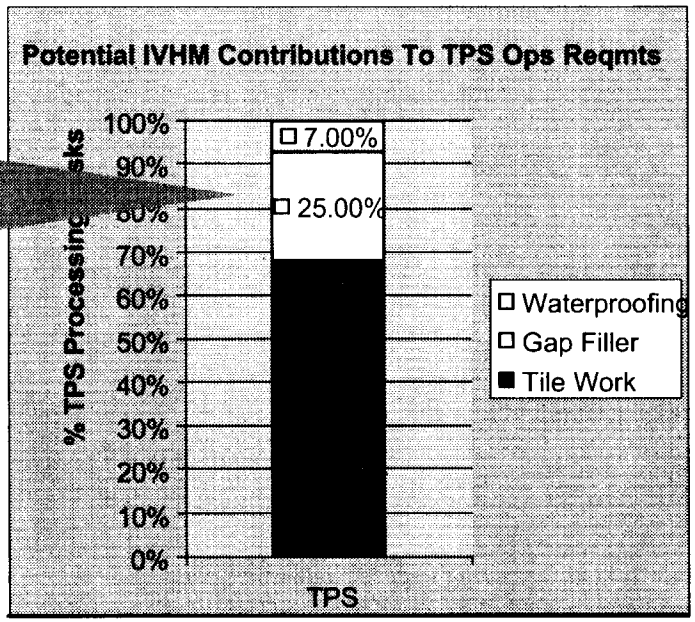
Integrated Vehicle Health Management:

Example of an IVHM technology: TPS IVHM

- Evolvable architecture

TPS IVHM Example





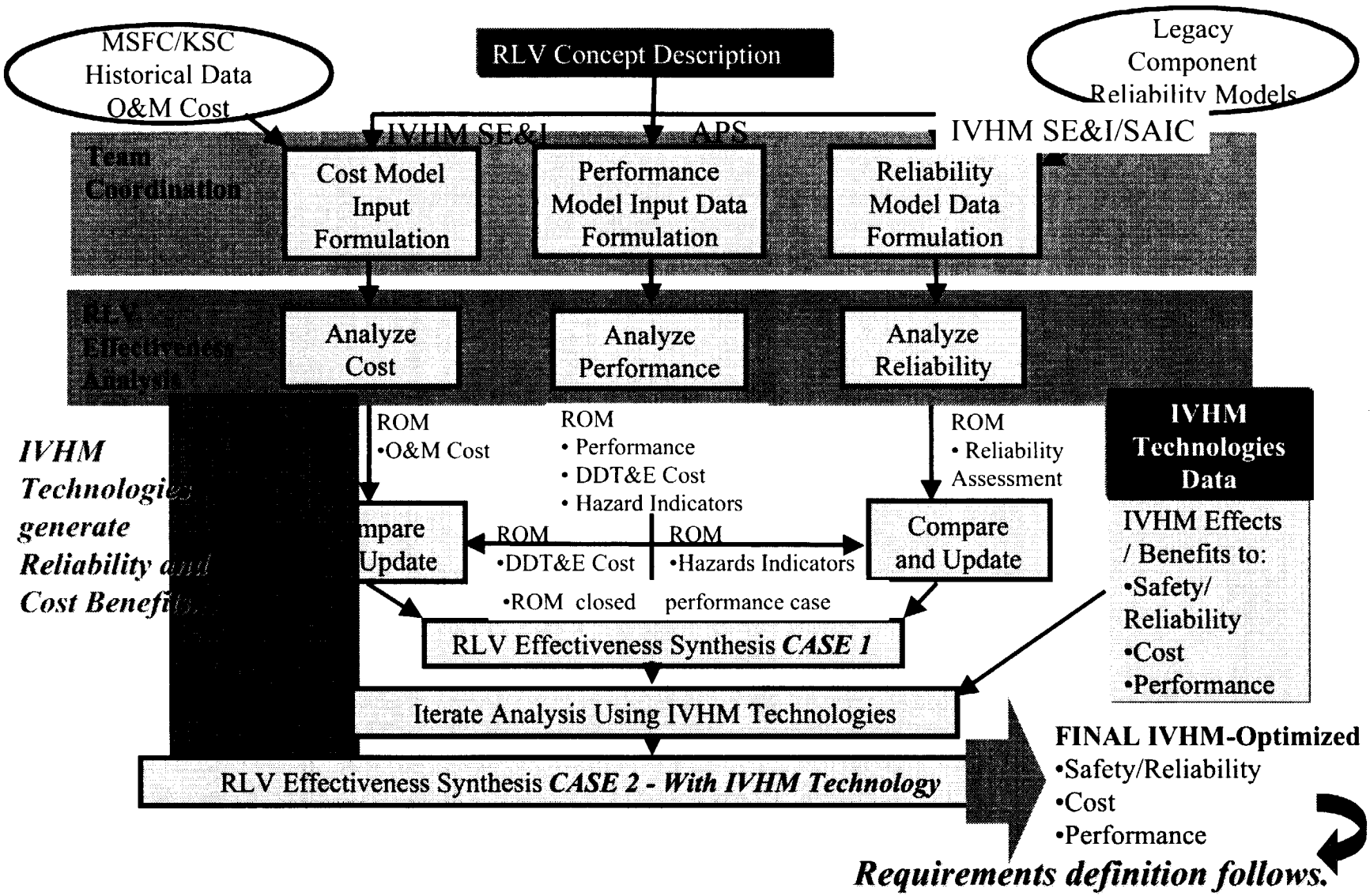
Technology	Use for Ref.	Weight reduction	Vehicle Cost Reduction	Ops Cost Reduction	System Reliability Improvement	Safety Improvement	Current Funded Program
IVHM							
Avionics IVHM							
Distributed Architecture/RHNs	a	0/+	0	0	+	0	X33,2nd
FO Network	a	+	0	-	0	+	X33,2nd
Advanced Instrumentation	r	+	0	+	+	+	2nd
TPS IVHM							
Advanced MEMs For On-Board Gap and Overheat	a	0	0	+	+	+	X37, Shuttle, 2nd Gen?
On-Board Neural Network TPS Sensor Models	a	0	0	+	+	+	X37, Shuttle, 2nd Gen?
TPS Smart Sensor and Validation Algorithms	a	0	0	+	+	+	X37, Shuttle, 2nd Gen?
Ground Based Hand-Held NDE/NDI	a	0	0	+	+	+	X37, Shuttle, 2nd Gen?

34,000 hrs/flow x 25% (gap filler/barrier) = 8,500 hrs/flow (Touch)
30,000 hrs/flow x 25% = 7,500 hrs/flow (Non)
64,000 hrs/flow x 25% (Total labor) = 16,000 hrs/flow
$3.05M/flow x 25% = $7.0M/Flow

Demonstrate Repeatability on RLV IVHM Airframe Testbeds

Integrated Vehicle Health Management:

IVHM SE&I manages traceability to program goals



Integrated Vehicle Health Management:

Interim IVHM Analysis Approach

Technology Plan Linked to Reliability Analysis

IVHM ROM Component Reliability Effectiveness Assessment

			Baseline Risk		Risk Mitigation thru IVHM
Subsystem	**FYI: Baseline Failure Probability and Technology used for Reference For Probability #'s from ISAT; Total ISAT vehicle failure probability is 1 in 282**	**Components (Vehicle Technology From *ISAT* Reference Vehicle Description under development)**	**Your assessment of Component Failure Probability *without IVHM* (N, L, M, H)**	**Severity Of Failure (N, L, M, H)**	**Name of Gen2 *IVHM* Technologies To be Applied to Subsystem/ Components**
Main Propulsion	1 in 617 (SSME Block II)	(Six RS2100 Engines full-flow staged combustion cycle, SSME BlockIII Combustion chamber uses A286 Tubes and Titanium honeycomb jacket, [illegible] is gas-gas coaxial, 3250 psi chamber pressure; High-pressure [illegible] drive			
		Hi-press. Fuel (LH2) Turbopump	H		
			H		
			M		
			M		
			H		
			M	H	
			L	H	

IVHM Reliability Benefits Assigned to Subsystems / Components

Technology Assignments From Agency Team

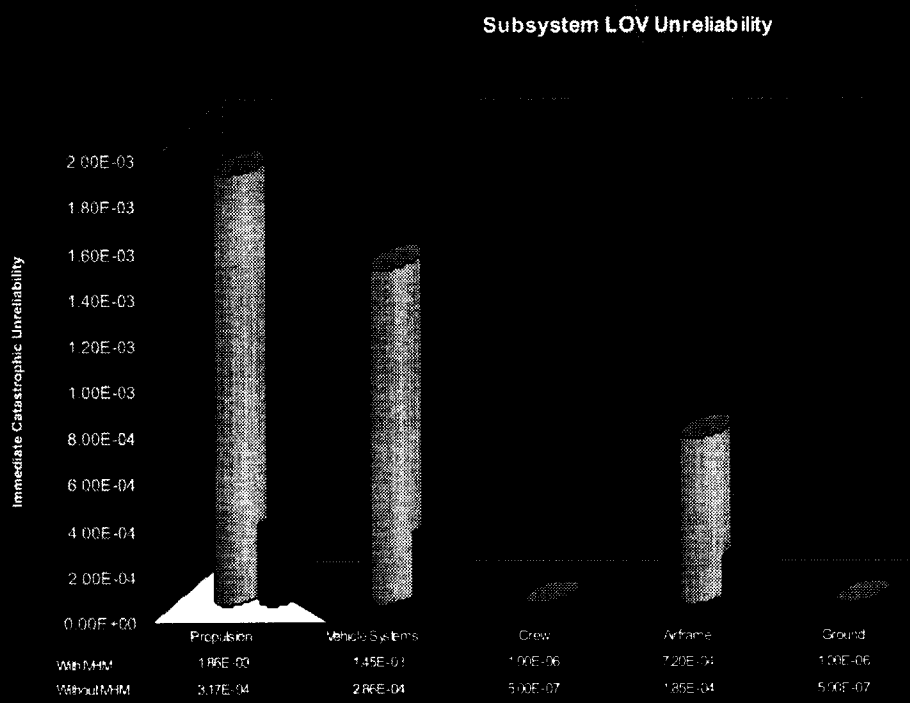
Technology Name	Gas for Ref.	Weight reduction	Vehicle Cost Reduction	Ops Cost Reduction	System Reliability Improvement	Safety Improvement
Propulsion Systems						
Reduced Cryo Toward Architecture	f	0	0	0	+	+
[illegible]	f	+	+	+	+	0
Warning Flight Control Data Loss	f	+	0	0	0	0
High Speed Wide optics Web Sys for Aviation	f	+	0	0+	0	0
Subsystems Flight Systems						
? Powered Landing	a	0	0	0	+	+
? Parachute and docking system	a	0	0	0	+	+
? Terminal adapter	a	0	0	0	+	+
? Autonomous GNSS algorithms for all mission phases	f	0	0	0	+	+
? Advanced alert and landing	a	0	0	0	+	+
Intelligent control systems						
? Adaptive control	a	0	0	0	+	+
? Advanced Model Based/Self-Reasoning	a	0	0	+	0	0
? Reconfigurable Flight Controls	r	0	0	0	+	+
? Fault Tolerant Controls	f	0	0	0	+	+
? Neural network based systems	f	0	0	0	+	+
Oversight Activities Activities						

IVHM Technologies Applied to Risk.

Integrated Vehicle Health Management:

Technology Plan Linked to Reliability Analysis

Draft Data for Illustration Purposes Only

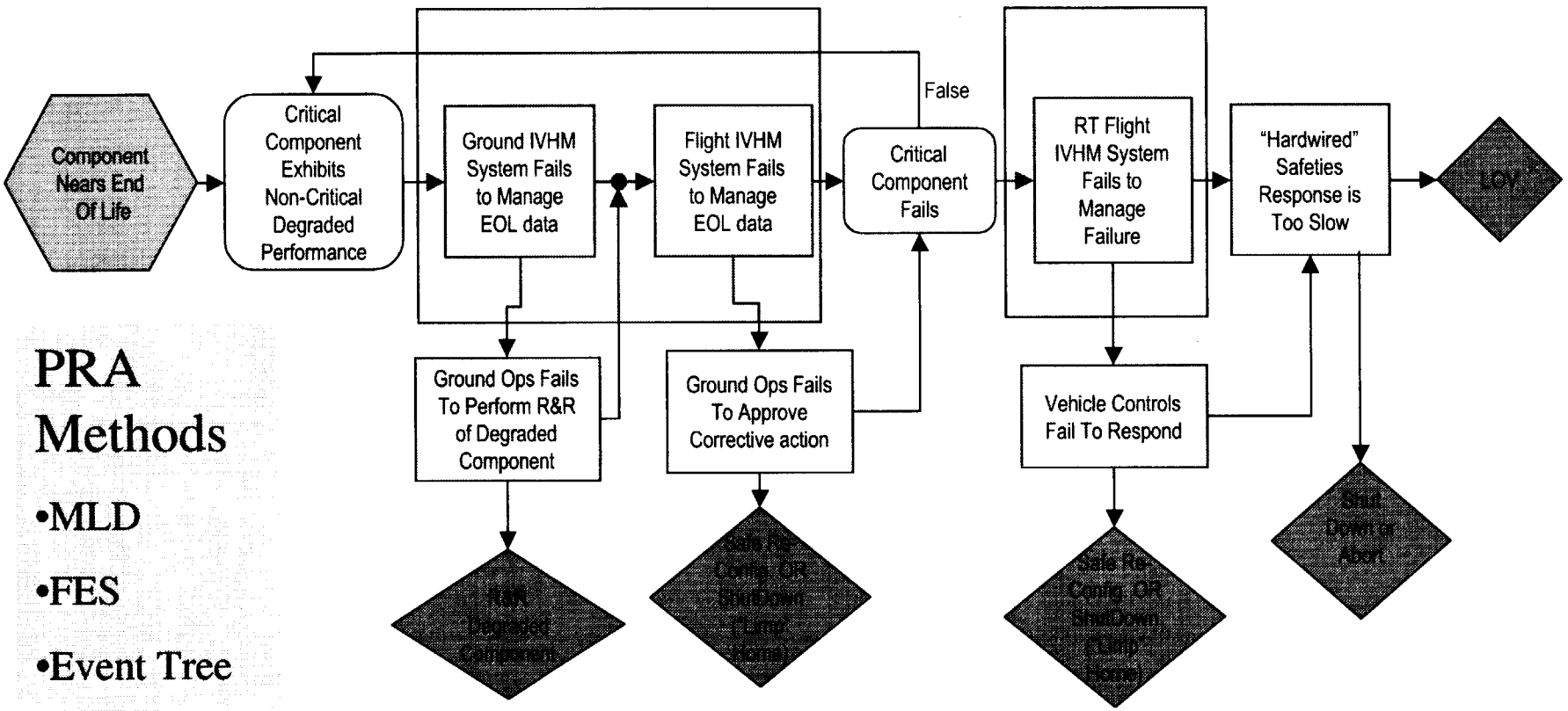


Subsystem/IVHM Technology ICU	ICU-RLV Alone	ICU-RLV w/ IVHM	1/ICU-RLV Alone	1/ICU-RLV w/ IVHM
Propulsion	1.86E-03	3.17E-04	537	3158
Engine	1.62E-03	2.44E-04	617	4095
Feed System	3.52E-05	6.40E-06	28409	156250
Main Propellant Containment	1.92E-04	6.40E-05	5208	15624
RCS and OMS	1.39E-05	1.99E-06	71942	503594
Vehicle Systems	**1.45E-03**	**2.86E-04**	**688**	**3502**
Avionics	1.00E-04	3.55E-05	10000	28182
Actuator Power	1.13E-03	1.62E-04	882	6174
Actuators & Control Surfaces	2.16E-04	8.64E-05	4630	11575
Purge Vent and Drain	1.00E-06	4.29E-07	1000000	2333333
Flight Termination	1.00E-06	2.50E-07	1000000	4000000
Other	1.00E-06	1.00E-06	1000000	1000000
Airframe	**7.20E-04**	**1.85E-04**	**1389**	**5412**
Thermal Protection	6.19E-04	1.55E-04	1616	6464
Airframe Structure	1.00E-04	2.97E-05	10000	33636
Undercarriage	1.00E-06	3.33E-07	1000000	3000000
Crew	1.00E-06	5.00E-07	1000000	2000000
Personnel Provision (N/A)	1.00E-06	5.00E-07	1000000	2000000
Ground	1.00E-06	5.00E-07	1000000	2000000
Total	**4.03E-03**	**7.87E-04**	**248**	**1271**

Integrated Vehicle Health Management:

LOV Reliability Analysis Providing IVHM Subsystem Allocations

TOP LEVEL IVHM GENERIC FUNCTIONAL EVENT SEQUENCE
(Payload-Only Mission Scenario)



PRA Methods

- MLD
- FES
- Event Tree
- Fault Trees

Integrated Vehicle Health Management:

How does IVHM effect Failure Modes?

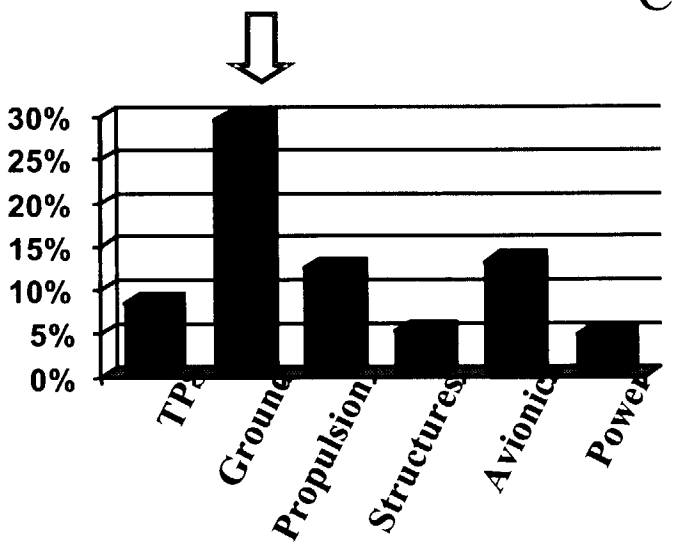
Launch Ops
Vehicle Processing
Process Eng
Recovery Ops
Fixed Support
Facility O&M
Base Support
Propellant Mgt.
GSE Spares

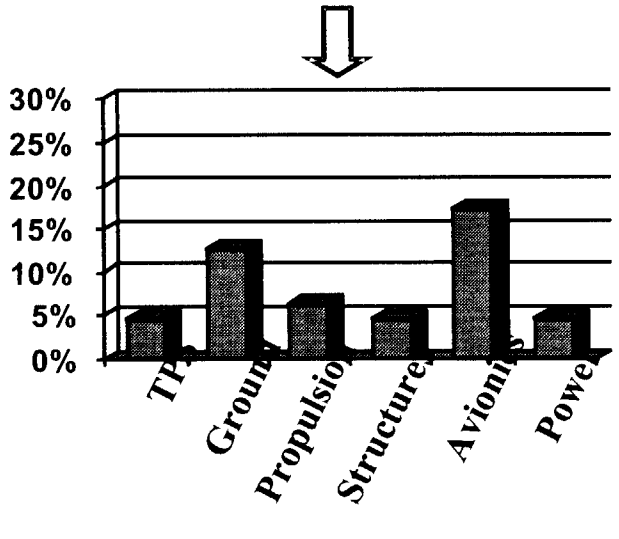
73 % Reduction in cost due to IVHM

50 % Reduction in cost due to IVHM

Flight Ops
Flight Planning
Mission S/Ware
Simulation/Training
Mission Control O&M
System Integration
Payload Analysis
Crew Ops
Fixed Support
General Mgt.
Network Support

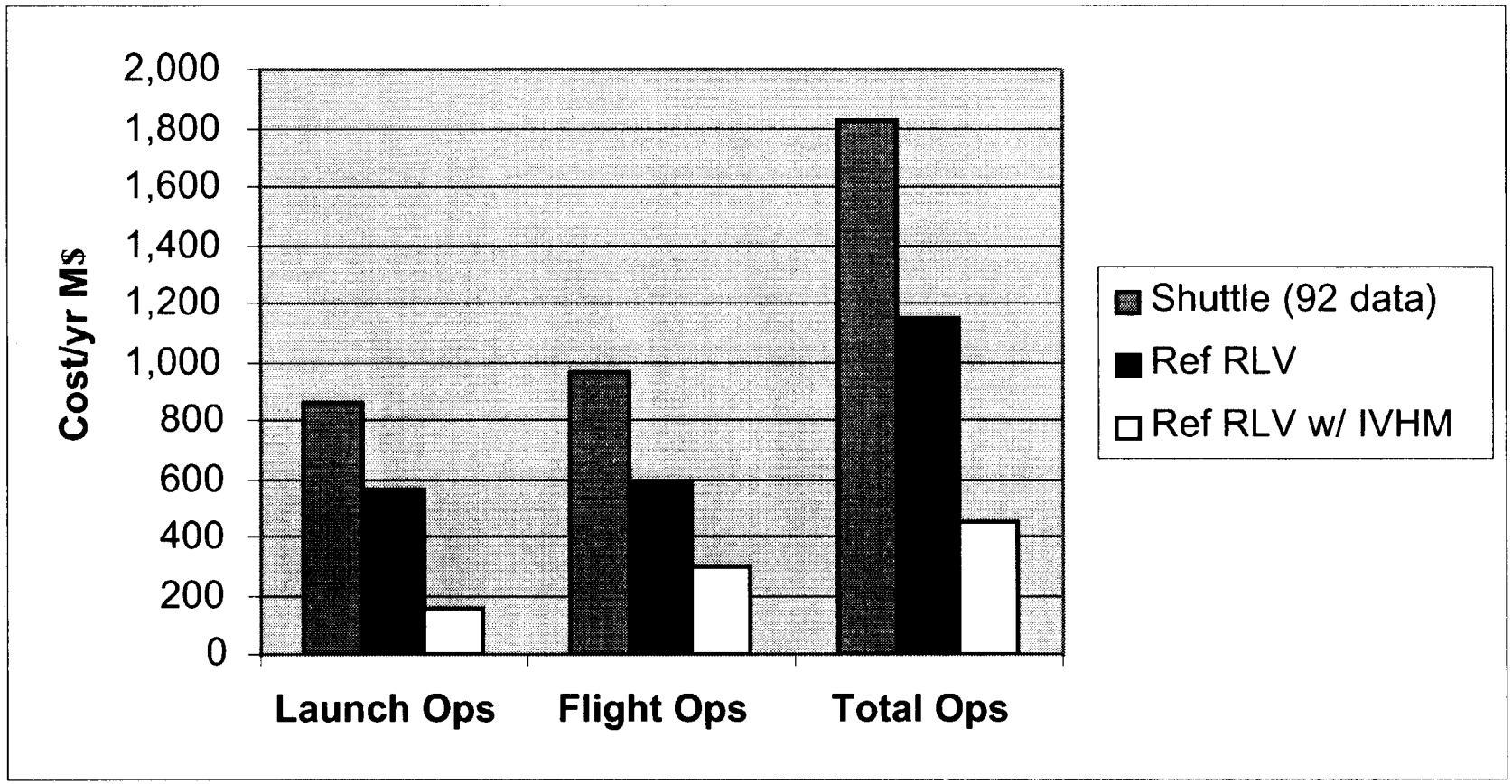
IVHM Technology Categories





Integrated Vehicle Health Management:

Ops Cost Savings due to IVHM



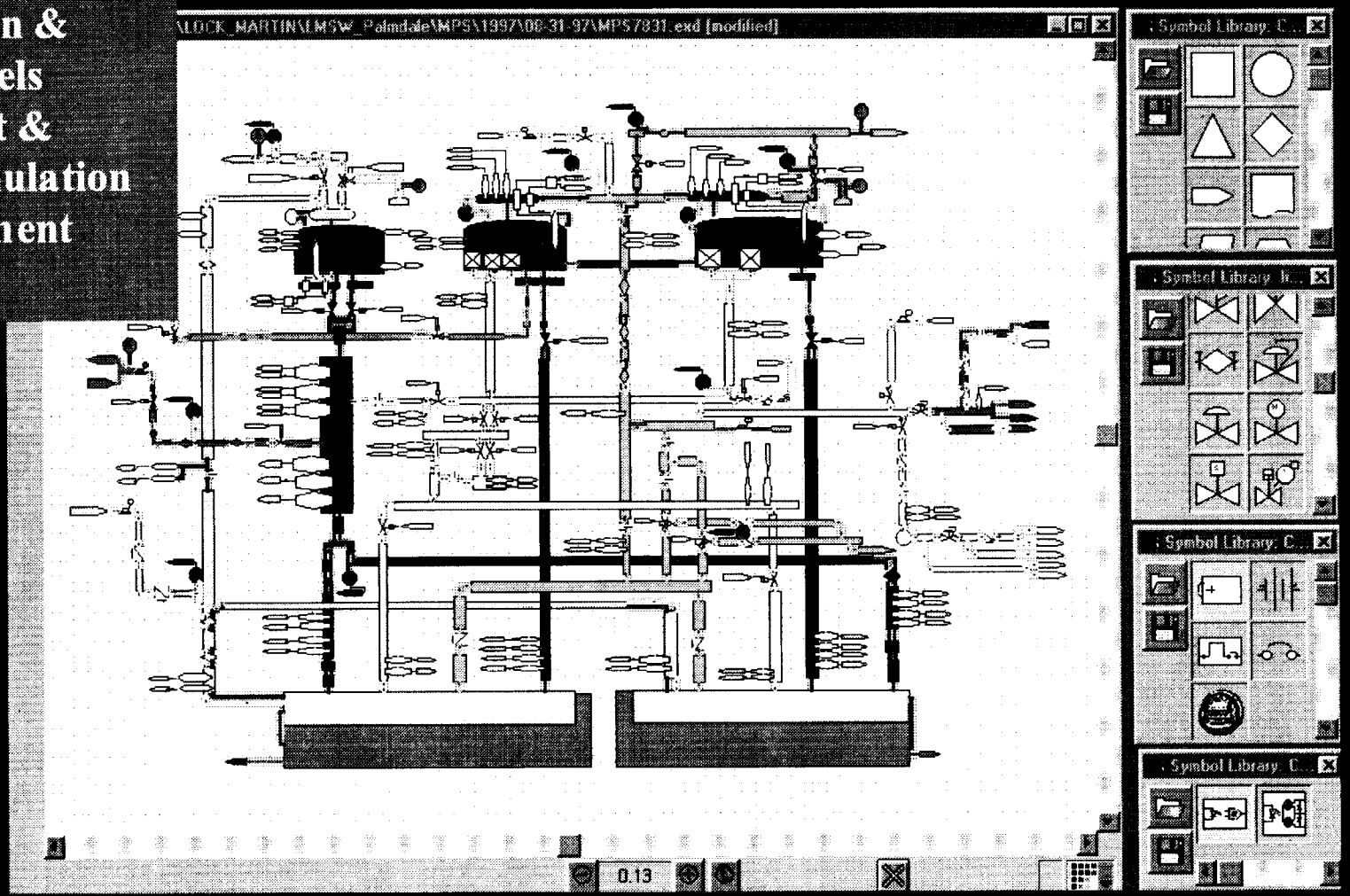
Comparison For Demonstration Purposes Only

Integrated Vehicle Health Management:

Operations Cost/yr Comparison

eXpress modeling tool

- **Operability models**
- **Fault detection & isolation models**
- **Life cycle cost & reliability simulation**
- **Sensor placement optimization**



Integrated Vehicle Health Management:

IVHM Modeling with DSI International

Provide IVHM Technology descriptions

Provide input to Operations Modeling/Ops processes

- Operability
- Testability
- Maintainability
- Availability

Support development of IVHM+Subsystem Failure Event Models

- Isolation of subsystem failures
- Detectability of IVHM false positives

Support life cycle cost and reliability optimization using eXpress

Support IVHM technology DDT&E cost estimating

Flow IVHM Requirements to 2nd gen SE&I and IVHM development tasks

Integrated Vehicle Health Management:

In summary: Functions of IVHM SE&I