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Sensor Data Qualification for Ares

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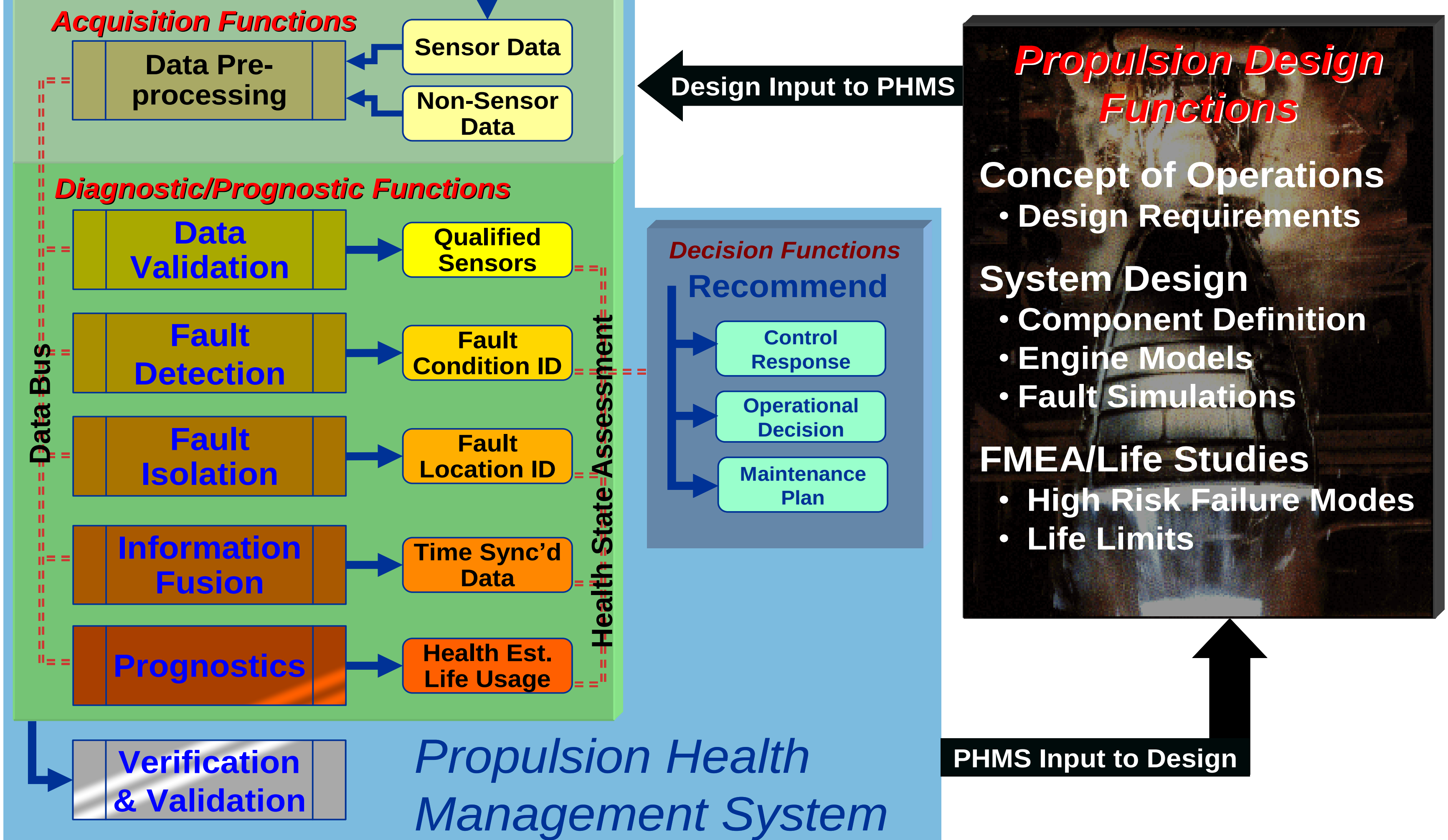
Outline

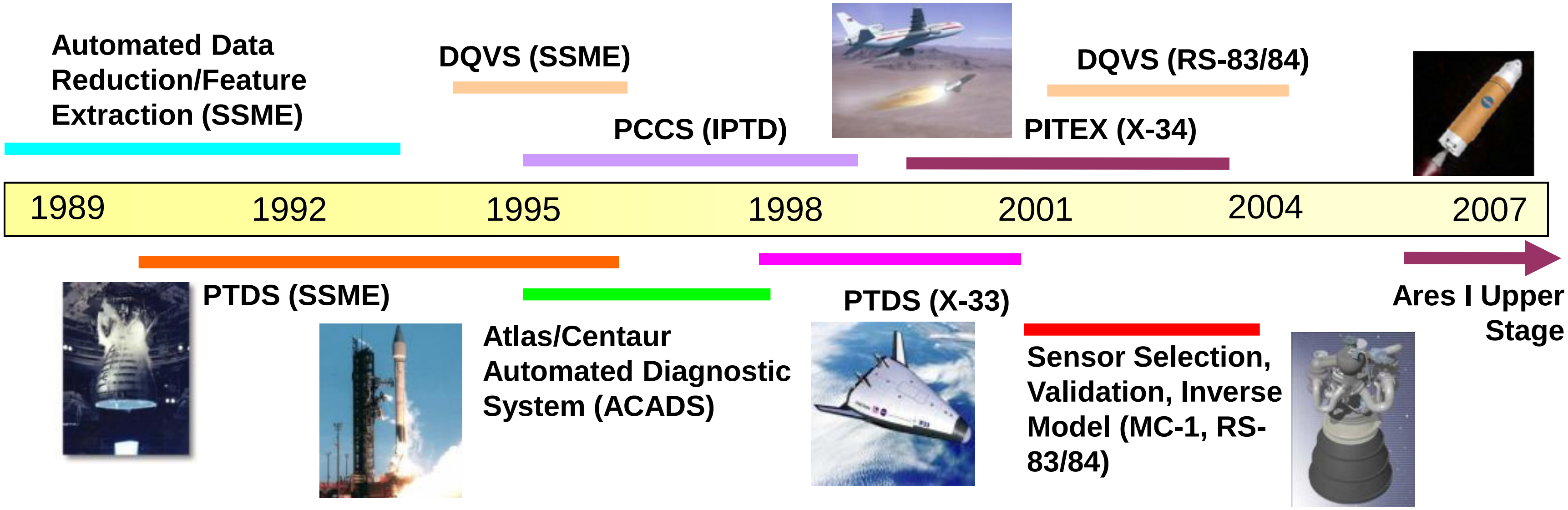
- ISHM Framework
  - GRC Historical Experience in Space Propulsion HM
  - Current Activities
- Sensor Data Qualification System
  - Description, applications to date, status and products
- Other ISHM Capabilities
  - Systematic Sensor Selection Approach (S4)
  - Sensors for ISHM
- Concluding Remarks
- References

ISHM Development Process

ISHM development in "parallel" with the overall requirements and system development is Essential for Safe, Affordable & Reliable Operation



System Health Management Heritage



- **Automated Data Reduction / Feature Extraction – SSME and Atlas/Centaur, and Post Test Diagnostics System (PTDS) for SSME and X-33**
  - Significantly reduced time to analyze test data from weeks to days
- **Data Quality Validation System – SSME and RS-83/84**
  - Demonstrated feasibility of analytical redundancy based sensor validation
- **Propulsion IVHM Technology Experiment (PITEX) – X34**
  - Demonstrated real-time fault detection for complex propulsion system
- **Propulsion Check Out and Control System (PCCS) for Integrated Propulsion Technology Demonstrator (IPTD)**
- **Inverse Model based Sensor Selection – RS-83/84**
  - Capability to optimize sensor suite for fault detection and isolation

Current Propulsion System HM Activities in NASA Exploration Systems Programs

- Exploration System Mission Directorate
  - Constellation Program
    - Ares Launch Vehicle
      - Upper Stage
        - Avionics
        - J2-X
        - TVC

- **Sensor Data Qualification**
  - Provide a validated analytical redundancy-based methodology for on-board data qualification of sensors with application to various Upper Stage subsystems
- **J-2X Redline & Calibration Studies**
  - Develop software tools supporting Monte Carlo simulation/analysis of redline sensor system and calibration of engine from engine test data.
- **Fault Detection Notification and Response for Ares I US Thrust Vector Control**
  - Support development of integrated upper stage abort detection, caution & warning, redundancy management, and functional fault analysis for fault testability and diagnostics

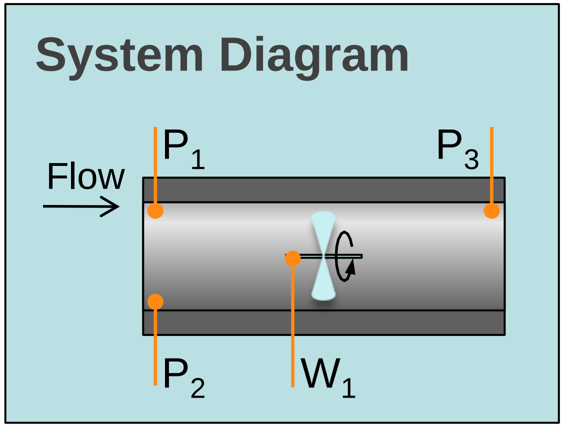
Sensor Data Qualification Justification

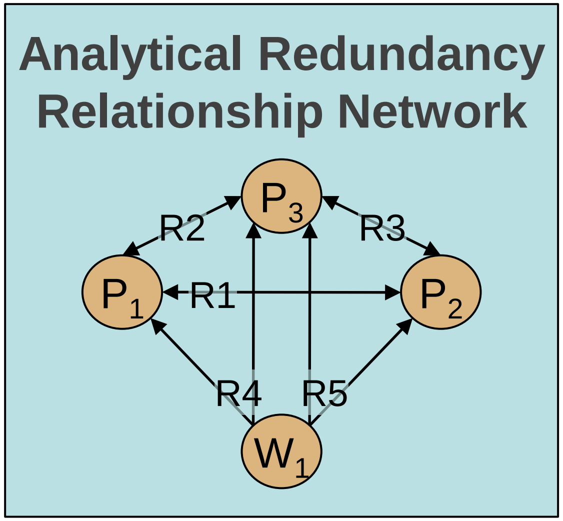
- **What is SDQ?**
  - A mathematical approach for using redundant information within a group of sensors to assess the validity of individual measurements
- **Why qualify data?**
  - Decisions need to be made on the flight critical data in real-time and on-board the vehicle.
- **What are the current approaches to onboard qualification of data?**
  - Only reasonableness limits are employed on all flight critical sensors
  - Some redundant channel checking performed on flight control parameters
  - In limited cases, driven by necessity, analytical redundancy has been applied with algorithm development tailored to a specific set of sensors.
- **What are the issues we are trying to address?**
  - Algorithm development in a concurrent engineering environment
  - Modular flight software and generic algorithm design paradigm
  - Deterministic real-time execution with static data tables that are verifiable
  - Application of analytical redundancy to heterogeneous sensor set
  - Need to ensure that analytical redundancy networks provide proper response to actual sensor faults AND do not incorrectly fail sensors during off-nominal system operation.

Sensor Data Qualification (SDQ) Diagnostic Approach

♦ The Process

Acquire Data from sensors to be qualified and from other sources to determine system operating mode





Onboard Sensor Monitoring

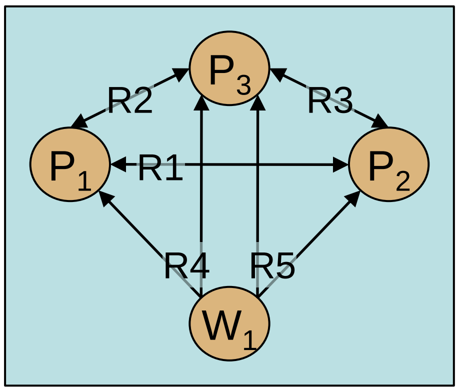
Acquire Data

Sensor Data Qualification (SDQ) Diagnostic Approach

- **The Process**

Acquire Data from sensors to be qualified and from other sources to determine system operating mode

Estimate output of each sensor using known/derived relationships with other sensors



$$\text{R1:}\quad \hat{P}_{1,1} = P_2$$

$$\text{R2:}\quad \hat{P}_{1,2} = C_{2,2} P_3 + C_{2,1}$$

$$\text{R3:}\quad \hat{P}_{2,3} = C_{3,2} P_3 + C_{3,1}$$

$$\text{R4:}\quad \hat{W}_{1,4} = C_{4,2} \left(P_1 - P_3\right)^{1/2} + C_{4,1}$$

$$\text{R5:}\quad \hat{W}_{1,5} = C_{5,2} \left(P_2 - P_3\right)^{1/2} + C_{5,1}$$

Onboard Sensor Monitoring

Acquire Data → **ESTIMATE**: System behavior with onboard model

Sensor Data Qualification (SDQ) Diagnostic Approach

♦ The Process

Acquire Data from sensors to be qualified and from other sources to determine system operating mode

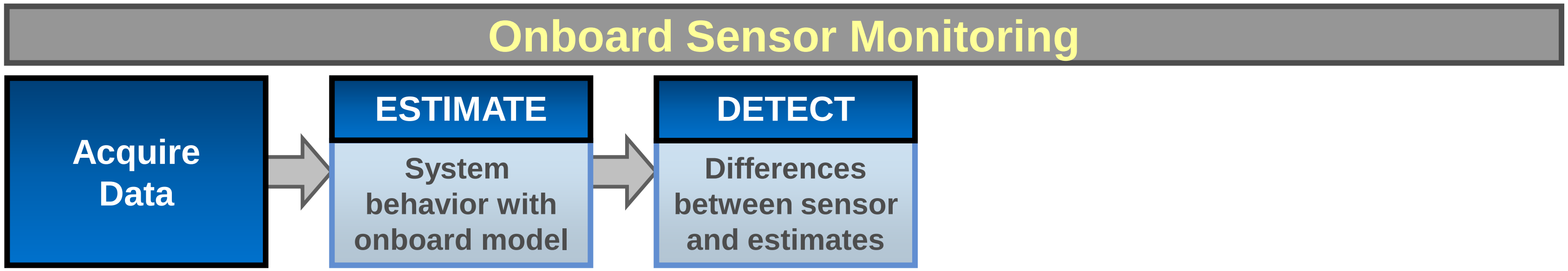
Estimate output of each sensor using known/derived relationships with other sensors

Detect and flag breakdown of any relationships during current cycle by comparing residuals (i.e., difference between measurement & estimate) to pre-defined thresholds

$$\text{if } \left|\hat{P}_{1,1} - P_1\right| \le T_1, \text{ then R1} = \text{qualified, else R1} = \text{failed}$$

$$\vdots$$

$$\text{if } \left|\hat{W}_{1,5} - W_1\right| \le T_5, \text{ then R5} = \text{qualified, else R5} = \text{failed}$$



Sensor Data Qualification (SDQ) Diagnostic Approach

♦ The Process

Acquire Data from sensors to be qualified and from other sources to determine system operating mode

Estimate output of each sensor using known/derived relationships with other sensors

Detect and flag breakdown of any relationships by comparing residuals (i.e., difference between measurement & estimate) to pre-defined thresholds

Decide if sensor has failed based on number and frequency of failed relationships

Bayesian Analysis-based Voting Table (Example)

No. Active ARRs for a Signal	No. Failed ARRs Required to Disqualify the Signal
3	3
4	4
5	4

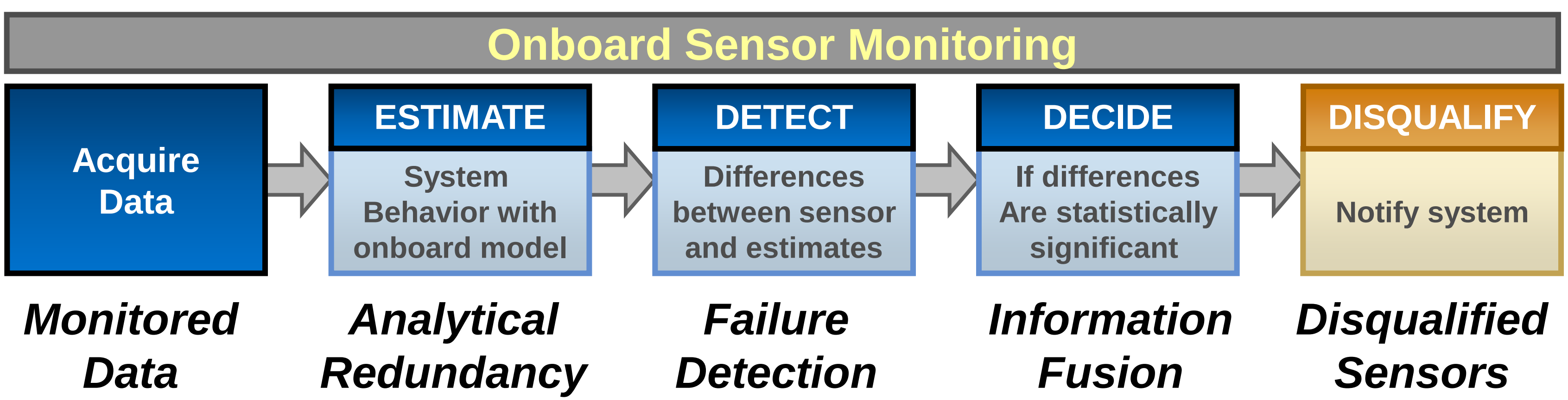
+ Persistence

Onboard Sensor Monitoring

Acquire Data → **ESTIMATE**: System Behavior with onboard model → **DETECT**: Differences between sensor and estimates → **DECIDE**: If differences are statistically significant

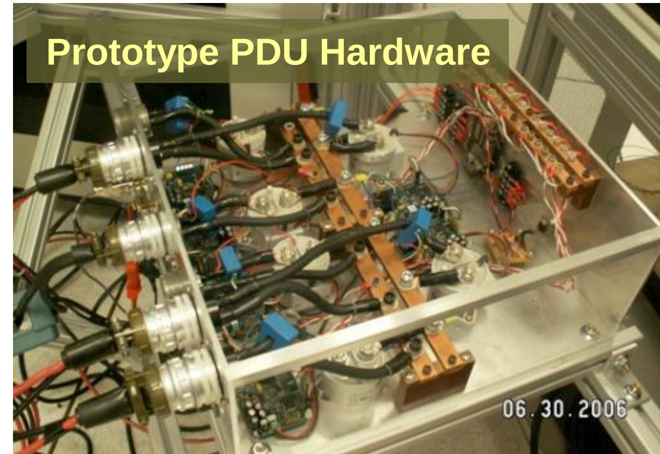
Sensor Data Qualification (SDQ) Diagnostic Approach

- **The Process**
  - **Acquire Data** from sensors to be qualified and from other sources to determine system operating mode
  - **Estimate** output of each sensor using known/derived relationships with other sensors
  - **Detect** and flag breakdown of any relationships by comparing residuals (i.e., difference between measurement & estimate) to pre-defined thresholds
  - **Decide** if sensor has failed based on number and frequency of failed relationships
  - **Disqualify** sensor and notify system/user



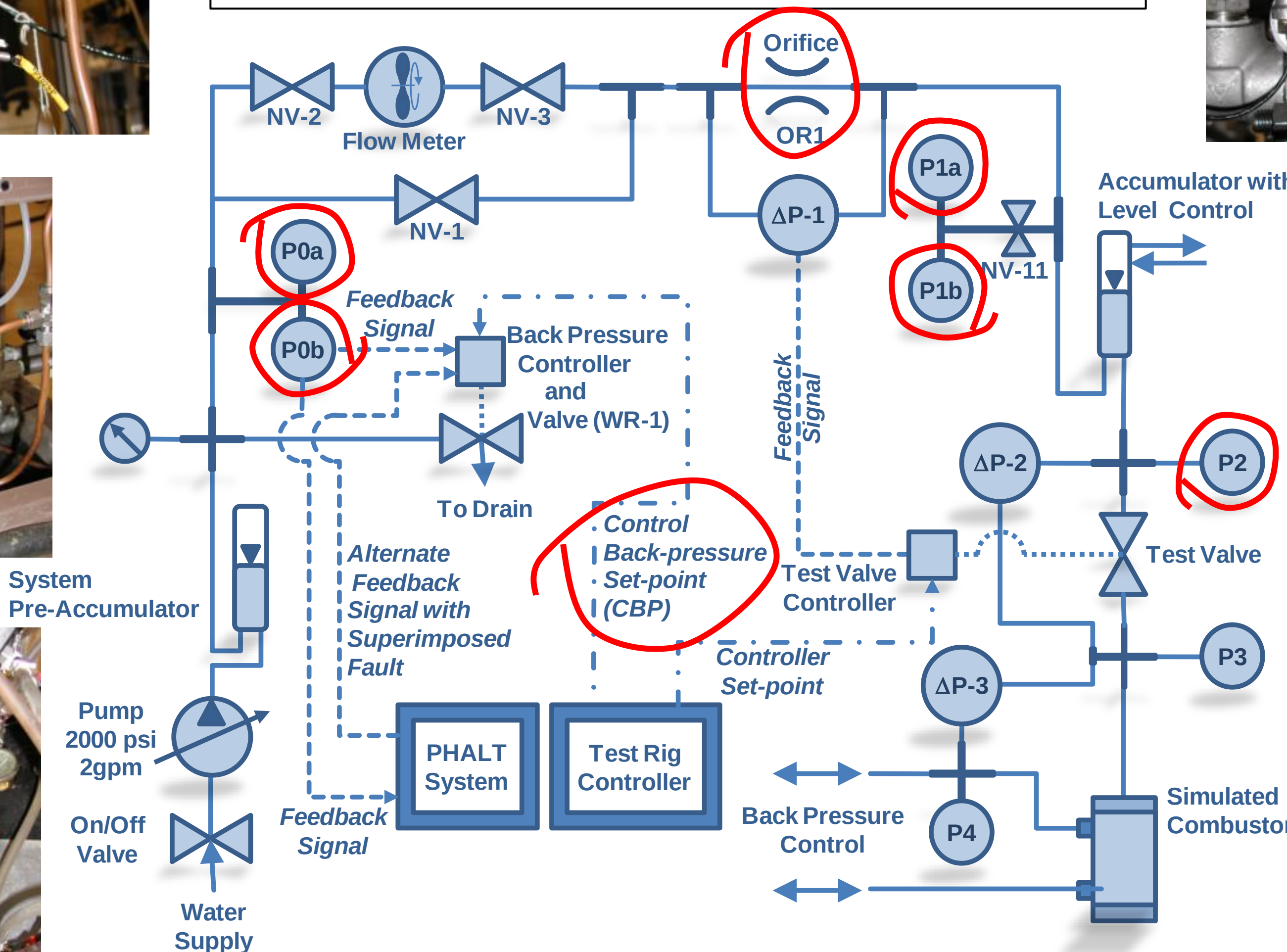
SDQ Proof-of-Concept Design Studies

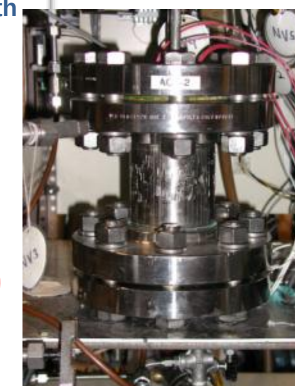
- Demonstrated proof-of-concept for ***analytical redundancy-based*** data qualification methods using test-beds relevant to Upper Stage Subsystems.
- Demonstrated real-time hardware-in-the-loop system SDQ with deterministic execution in the presence of hardware simulated sensor and system faults
- Performed SDQ on signals with …
  - multiple sensor failures – concurrent and sequential
  - bias faults on a closed-loop control feedback sensor
- Identified abnormal system operation in lieu of failing all sensors
- Characterized real-time (onboard) implementation and execution of prototype code



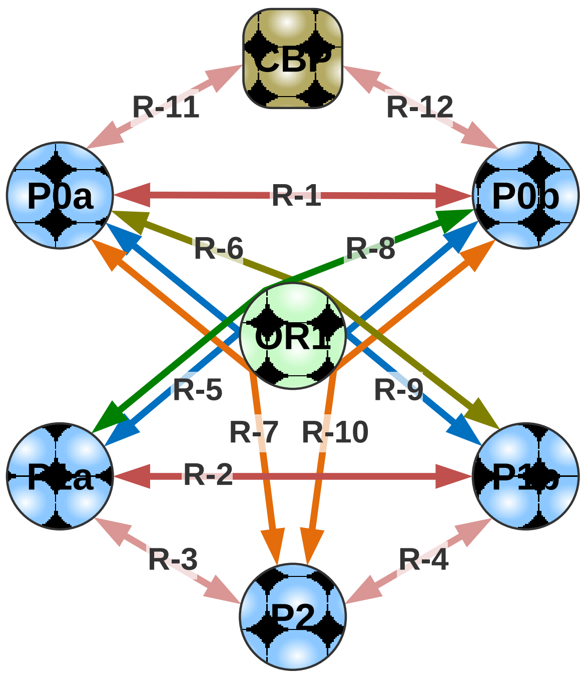
FASTR Schematic

- Up to 600 PSI supply with water as working fluid
- Characteristic of pressure levels on the low-pressure side of the SSME feed system.





FASTR-1 SDQ ARRN*



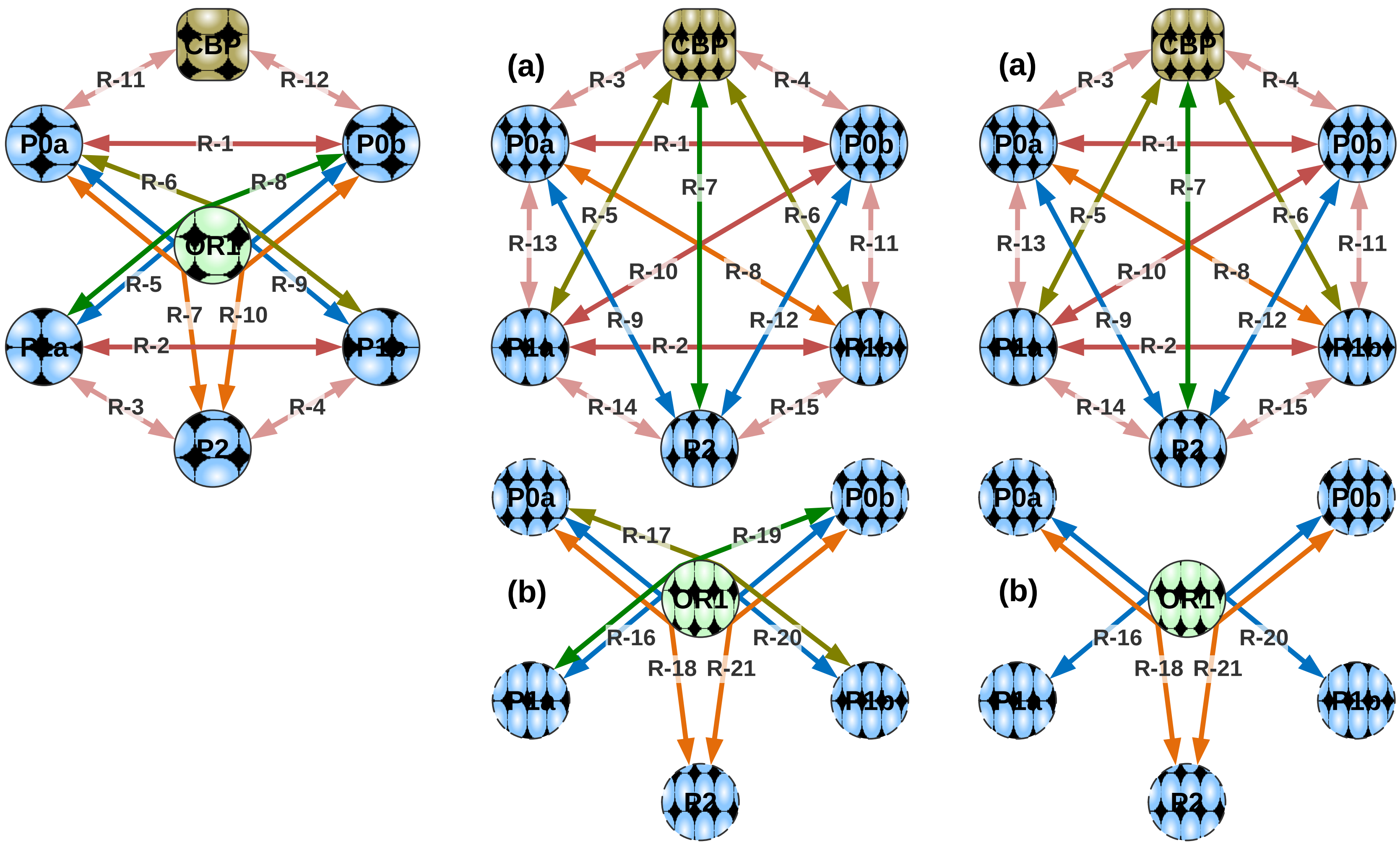
ARRN Diagram

ID	Measurement Estimation Equations
R-1	P0a = P0b
R-2	P1a = P1b
R-3	P1a = a + b*P2
R-4	P1b = a + b*P2
R-5	OR1 = a + sign(P0a-P1a)*b*$(\lvert P0a-P1a\rvert)^{1/2}$
R-6	OR1 = a + sign(P0a-P1b)*b*$(\lvert P0a-P1b\rvert)^{1/2}$
R-7	OR1 = a + sign(P0a-P2)*b*$(\lvert P0a-P2\rvert)^{1/2}$
R-8	OR1 = a + sign(P0b-P1a)*b*$(\lvert P0b-P1a\rvert)^{1/2}$
R-9	OR1 = a + sign(P0b-P1b)*b*$(\lvert P0b-P1b\rvert)^{1/2}$
R-10	OR1 = a + sign(P0b-P2)*b*$(\lvert P0b-P2\rvert)^{1/2}$
R-11	CBP = a + b*P0a
R-12	CBP = a + b*P0b

*Analytical Redundancy Relationship Network

SDQ ARRNs

FASTR-1* | FASTR-2 | FASTR-3



SDQ Results for Test Series 2
P1a & P1b Common Cause Failure

Test Number	Fault Description	FASTR-1		FASTR-2		FASTR-3	
		SDQ Output	Cycles	SDQ Output	Cycles	SDQ Output	Cycles
TS2_01	Blocked Sensing Port — Positive Level Shift	**P1a** **P1b** OR1 **Suspended**	70	P1a P1b OR1 **Abnormal**	---	**P1a** **P1b** **Suspended**	70
TS2_02		**OR1**	18	**P1a** **P1b** OR1 **Suspended**	18	**P1a** **P1b** **Suspended**	18
TS2_03		**OR1** P1a	5	OR1 P1b P1a **Abnormal**	---	**P1a** **P1b** **Suspended**	6
TS2_04		**OR1**	13	P1a **P1b** **OR1** **Suspended**	16	**P1a** **P1b** **Suspended**	17

Comparison of Detection Statistics for FASTR ARRNs

Test Series	No. Tests	FASTR-1			FASTR-2			FASTR-3		
		Green	Yellow	Red	Green	Yellow	Red	Green	Yellow	Red
1	13	***100%***	***0%***	***0%***	62%	38%	0%	92%	0%	8%
2	4	0%	25%	75%	0%	25%	75%	***100%***	***0%***	***0%***
3	2	***100%***	***0%***	***0%***	***100%***	***0%***	***0%***	***100%***	***0%***	***0%***
4	2	0%	0%	100%	0%	0%	100%	***50%***	***0%***	***50%***
5	8	50%	50%	0%	50%	13%	38%	***75%***	***25%***	***0%***
Combined	29	66%	17%	17%	48%	24%	28%	***86%***	***7%***	***7%***

SDQ Summary

- **Investigated Alternate Analytical Redundancy Relationship Networks (ARRNs) for Qualification of Flow and Pressure Sensors**
  - Qualified heterogeneous sensors in ARRN consisting of five (5) pressure measurements and one (1) flow measurement
  - Trained ARRNs using test data with “real-world” measurement variations
  - Tested detection capabilities using hardware simulated faults
  - Demonstrated capability/limitations in detecting multiple concurrent and sequential sensor failures.
- **Lessons Learned**
  - Use of significantly less certain measurements to qualify more certain measurements can degrade qualification accuracy.
  - Use of ARRs that are not truly independent can result in an ARRN that is prone to incorrect detections & network suspensions.
  - Lack of sufficient relationships can result in missed detections.

Sensor Selection and Optimization

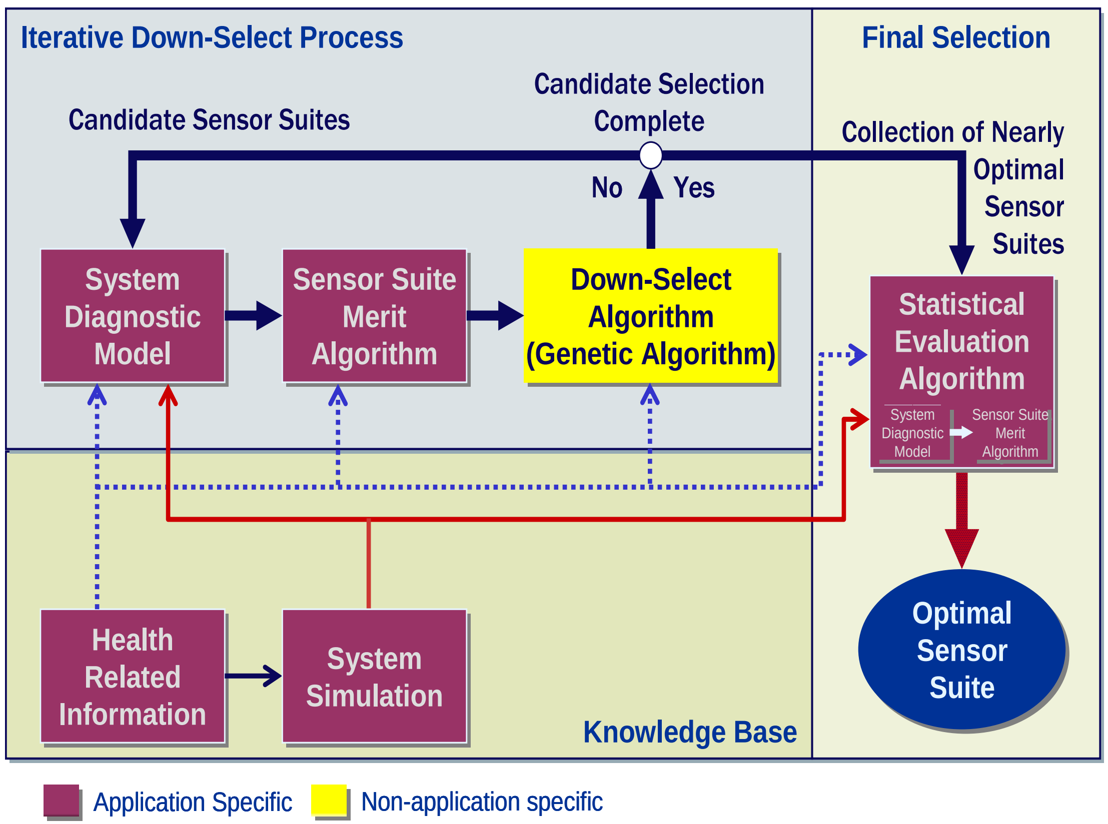
Systematic Sensor Selection Strategy (S4)

- Quantitative approach for reducing sensors to the “minimal necessary set”
- Proactive means of circumventing the costly addition of sensors after the system design has been finalized
- Efficiently searches large, complex solution spaces
- Incorporates critical FMEA and risk information

S4 Applications

- PWR J2X engine for Ares Upper Stage
- Rocketdyne RS-83 and RS-84 engines
- Advanced sensors for turbine engines

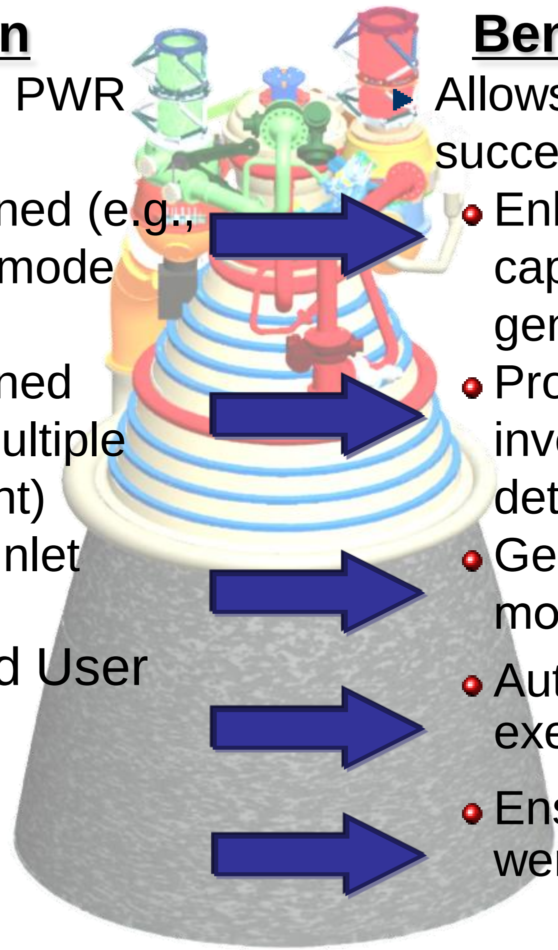
S4 Framework



J-2X Engine Fault Detectability Study

Objective:

- Develop S4 detectability database for critical faults using large set of candidate J-2X sensors



GRC Contribution

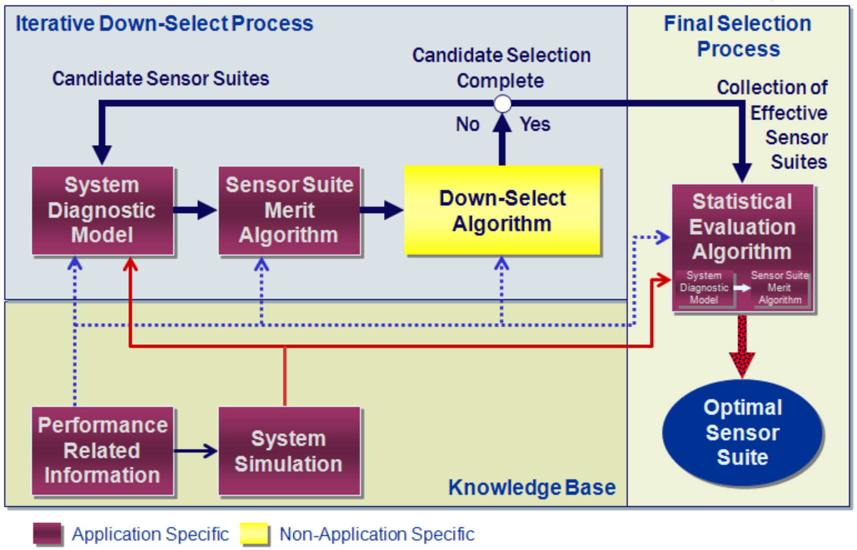
- Added new capabilities to PWR J-2X Real-Time Model
  - Simulation of user-defined (e.g., off-nominal) operating mode profiles
  - Simulation of user-defined faults (bias and drift, multiple sequential or concurrent)
  - Variation of propellant inlet conditions
- Developed Excel-based User Interface
- Provided independent verification of results

Benefit to J-2X Program

- Allows J-2X program to successfully meet milestones
  - Enhances overall simulation capability and reduces time to generate simulation data
  - Provides mechanism for investigating propagation and detectability of complex faults
  - Generates results that are more "flight-like"
  - Automates simulation setup, execution, and analysis
  - Ensures simulation results were generated correctly

Systematic Sensor Selection Strategy for J-2X Test Data Reduction

Systematic Sensor Selection Strategy



Systematic Sensor Selection Strategy is used to analytically verify that J-2X test sensor suite will meet test data reduction goals

- Accurately characterize J-2X engine operation over multiple operating states
- Calibrate each engine to meet thrust & mixture ratio targets
- Enable detection of off-nominal engine component operation which might result in faulty calibration
- Support engine model calibration for specific engine configurations
- Ensure that acceptance of production J-2X engine systems is based on reliable test data

Data Reduction Process

Collect Sensor Data

Flow Rates	Pressures	Shaft Speeds	Temperatures	Etc.

Qualify Sensor Data

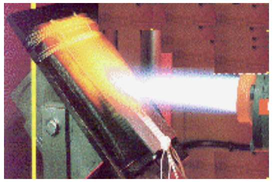
Range/Rate Checks	Statistical Checks	Comparison Checks	Analytic Redundancy Relations

Determine Engine Component Performance Characteristics

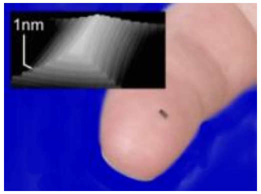
Direct calculations from individual functions	Mathematical system level solution methods

- **OPERATION IN HARSH ENVIRONMENTS**
- **ALL-IN-ONE SHOP FOR HARSH ENVIRONMENT SYSTEM APPLICATIONS**
- **RANGE OF PHYSICAL AND CHEMICAL MEASUREMENTS**
- **HARSH ENVIRONMENT MICROSYSTEMS TECHNOLOGY**
- **INCREASE DURABILITY, DECREASE THERMAL SHIELDING, IMPROVE IN-SITU OPERATION**
- **ENABLE EXPANDED MISSION PARAMETERS**

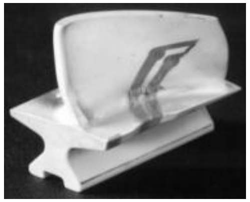
World Recognized Accomplishments



1998 R&D 100 Award



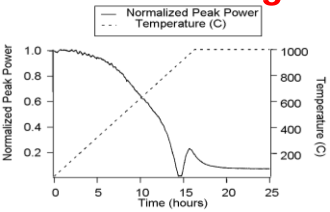
2004 R&D 100 Award



1995 R&D 100 Award

1991 R&D 100 Award

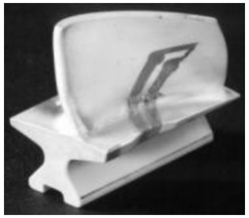
Range of Physical and Chemical Sensors for Harsh Environments and Intelligent Systems



High Temp Fiber Sensor Operation

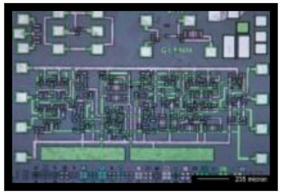
Self Diagnostic Accelerometer

High Temperature Pressure Sensor

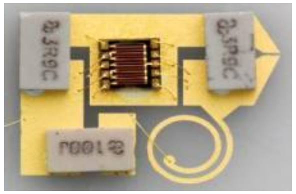


Thin Film Sensors

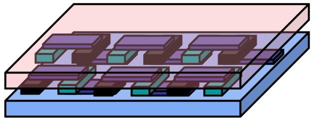
High Temperature Electronics and Wireless



World Record High Temperature Electronics

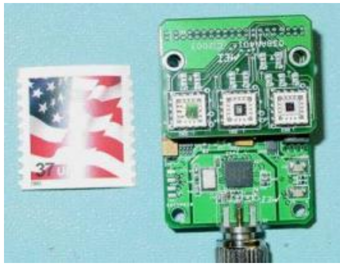


High Temperature RF Components



Energy Harvesting Thin Film Thermoelectrics

Long Term Vision: High Temperature "Lick and Stick" Systems

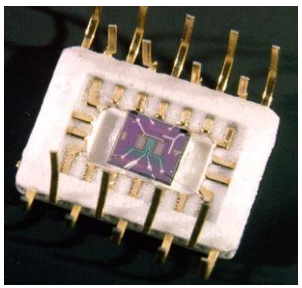


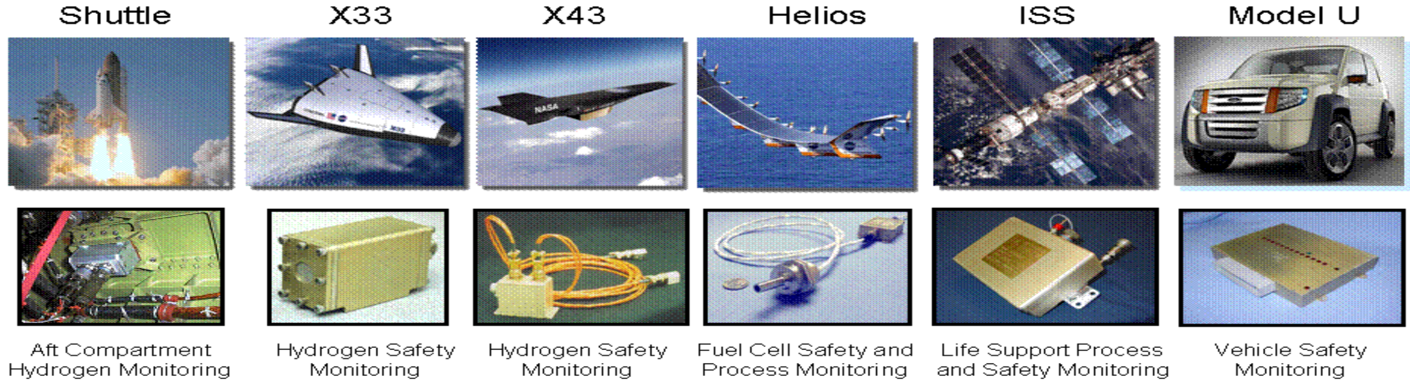
• *Hydrogen Sensor Technology*

- **MICROFABRICATED USING MEMS-BASED TECHNOLOGY FOR MINIMAL SIZE, WEIGHT AND POWER**
- **HIGHLY SENSITIVE IN INERT/OXYGEN ENVIRONMENTS, WIDE CONCENTRATION RANGE DETECTION**

MATURE TECHNOLOGY IMPLEMENTED, E.G., ON THE ISS

NASA 2003 TURNING GOALS INTO REALITY SAFETY AWARD	1995 R&D 100 AWARD WINNER

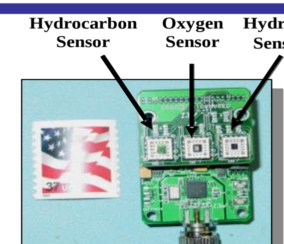




"Lick And Stick" Leak Sensor System

- **CONFIGURATIONS INCLUDE THREE SENSORS, SIGNAL CONDITIONING, POWER, AND TELEMETRY IN A SINGLE PACKAGE**

H_2 COTS SYSTEM SCHEDULED FOR CLV IMPLEMENTATION



Micro-Fabricated Gas Sensors for Low False Alarm Fire Detection

NASA 2005 TURNING GOALS INTO REALITY AA'S CHOICE	2005 R&D 100 AWARD WINNER

- **MEMS-BASED CHEMICAL SPECIES AND PARTICULATE SENSORS ORTHOGONAL DETECTION SIGNIFICANTLY REDUCES FALSE ALARMS**

CEV FIRE AND ENVIRONMENTAL MONITORING

Prototype Smart Space Fire Detection System

CWRU

MEI Makel Engineering Inc.

Concluding Remarks

- **NASA Glenn is developing key technologies for access to space propulsion system ISHM**
  - Sensor Data Qualification (SDQ) to ensure that critical flight operations are based on validated data
  - Systematic Sensor Selection Strategy (S4) to determine "optimal" sensor suite for Fault Detection and Isolation
  - Harsh environment electronics/sensors and chemical sensors support system health assessment.
- **SDQ, S4 and sensor technologies being applied to NASA Exploration System programs**
  - SDQ approved by Ares Upper Stage Chief Engineer for onboard qualification of flight critical sensors.
  - S4 used to analytically verify that J-2X test sensor suite will meet test data reduction and engine calibration goals
  - H_2 sensor (mature technology) demonstrated on ISS, COTS version scheduled for Ares implementation
- **NASA interested in further technology maturation and application opportunities**

References

- **Overview:**

  - Melcher, Kevin J.; Maul, William A.; Garg, Sanjay: " Propulsion Health Management System Development for Affordable and Reliable Operation of Space Exploration Systems," AIAA-2007-6237, NASA TM-2007-215034. Prepared for the AIAA SPACE 2007 Conference & Exhibit, Sept. 18-20, 2007.

- **Sensor Data Qualification:**

  - Maul, W.A.; Melcher, K.J.; Chicatelli, A.K.; and Johnson, S.B.: "Application of Diagnostic Analysis Tools to the Ares I Thrust Vector Control System," AIAA-2010-3451, NASA TM-2010-216333. Prepared for the AIAA Infotech@Aerospace 2010 Conference & Exhibit, Atlanta, GA, April 20-22, 2010.
  - Maul, W. A.; Melcher, K. J.; Chicatelli, A. K.; and Sowers, T. S.: "Sensor Data Qualification for Autonomous Operation of Space Systems," Proceedings of the American Association for Artificial Intelligence 2006 Fall Symposium on Spacecraft Autonomy, October 13 15, 2006. AAAI Technical Report FS-06-07: 59-66.
  - Wong, E.; Fulton, C.E.; Maul, W.A.; and Melcher, K.J.: "Sensor Data Qualification System (SDQS) Implementation Study," NASA TM-2008-215241, Prepared for the 2008 International Conference on Prognostics and Health Management, Denver, CO, October 6-9, 2008.

- **ISHM for the J-2X:**

  - Sowers, T.S.; Santi, L.M.; and Butas, J.P.: "Selection of Sensors for J-2X Test Data Reduction", Prepared for the Joint Army-Navy-NASA-Air Force (JANNAF) Interagency Propulsion Committee meeting, December 8-12, 2008.
  - Maul, W. A; Kopasakis, G.; Santi, L. M.; Sowers, T. S.; Chicatelli, A. K.: "Sensor Selection and Optimization for Health Assessment of Aerospace Systems," AIAA 2007-2849, May 2007.

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