Integrated System Health Management: Pilot Operational Implementation in a Rocket Engine Test Stand

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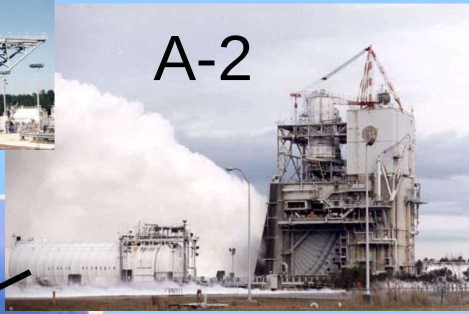
Outline

- Motivation
- Technology and Capabilities
  - Generic Architecture
  - ISHM Model
    - Embedded DIaK
    - Proximate Cause
  - VISE
  - Advanced Anomaly Detection
  - HADS
- ISHM Implementations
  - CSG Pilot Implementation
- ISHM Benefits
  - A3 Test Stand
  - Other facilities
- Conclusions

Support the rocket engine test mission with sustainable facilities that produce unquestionable measurements, affordably

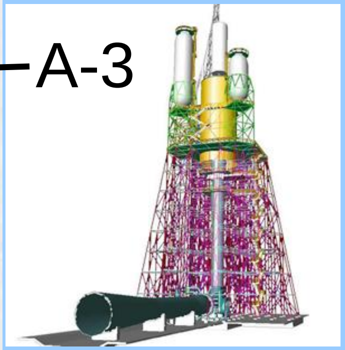
B-1/B-2

A-2



A-1

A-3



Others:
- High-pressure Gas
- Industrial Water

E-2

E-3

E-1

Requirements Driving ISHM

Through comprehensive, Integrated, and continuous vigilance and Analysis

- **Improve quality and safety.**
  - By more accurately understanding the state of a system.
- **Minimize**
  - Time to operational readiness.
  - Uncertainty.
  - Risk.
- **Minimize costs.**
  - Of configuration.
  - Of maintenance, repair, and calibration.
  - Of operations.
  - Of analysis.
- **Minimize downtime.**
  - By predicting impending failures.
  - By timely intervention.
  - By faster diagnosis and recovery.
  - By improving availability and reliability.

ISHM Objectives

- Use available SYSTEM-WIDE data, information, and knowledge (DIaK) to
  - Identify system state.
  - Detect anomaly indicators.
  - Determine and confirm anomalies.
  - Diagnose causes and determine effects.
  - Predict future anomalies.
  - Recommend timely mitigation steps.
  - Evolve to incorporate new knowledge.
  - Enable integrated system awareness by the user (make available relevant information when needed and allow to dig deeper for details).
  - Manage health information (e.g. anomalies, redlines).
  - Capture and manage usage information (e.g. thermal cycles).
  - Enable automated configuration.
  - Implement automated and comprehensive data analysis.
  - Provide verification of consistency among system states and procedures.

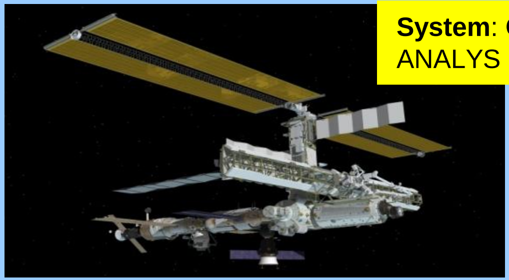
ISHM implementation is a problem of “management” of data, information, and knowledge (DIaK) focused on achieving the above objectives.

People-Based ISHM is Being Done Today

MOVE CAPABILITY TOWARD LEVELS 2 AND 1
DECREASE NEED FOR SUPPORT FROM LOWER LAYERS

International Space Station | **Rocket Engine Test Stand**

Layer 1
Vehicle/
Test Stand

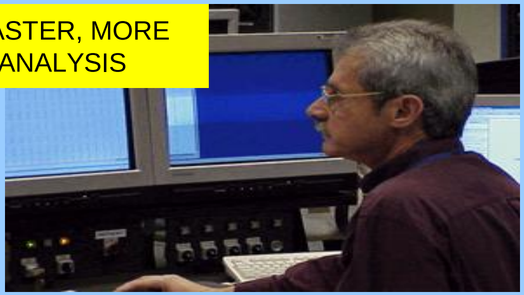


System: ON BOARD AUTOMATED ANALYS CAPABILITY

Signal threshold violation detection

Layer 2
Astronaut/
Test
Conductor

Operator: FASTER, MORE ACCURATE ANALYSIS



Added DIaK from on-board users.

Layer 3
Control
Room

Support: FASTER, MORE ACCURATE ANALYSIS
Decreased Need

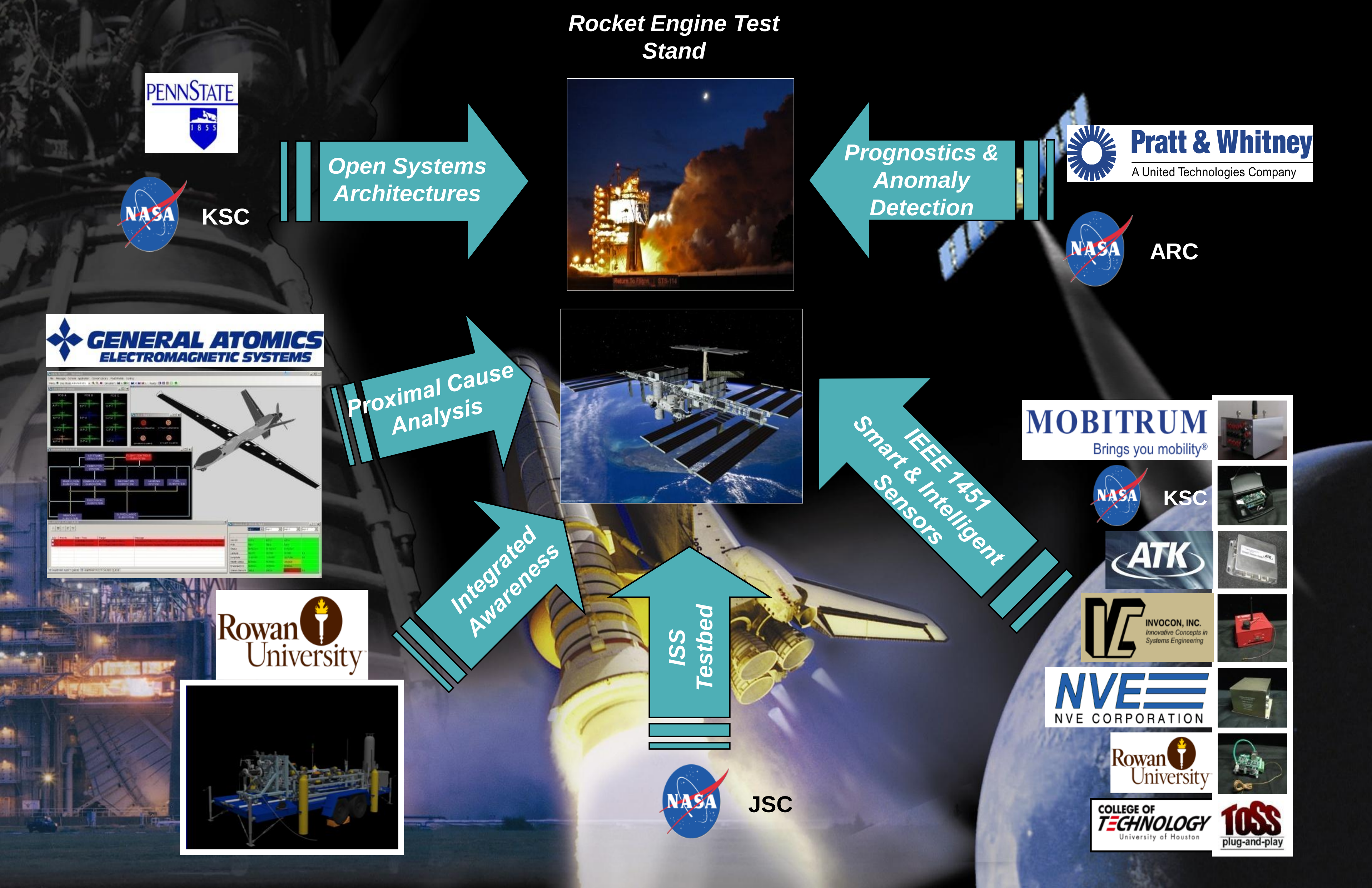
Added DIaK from broad group of experts.

Layer 4
Back
Control
Room

Support: FASTER, MORE ACCURATE ANALYSIS
Decreased Need

Added DIaK resources from larger community

John C. Stennis Space Center
ISHM Partnerships for Rocket Propulsion testing
A community of Expertise and Technologies



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ISHM Capabilities

Integrated System Awareness

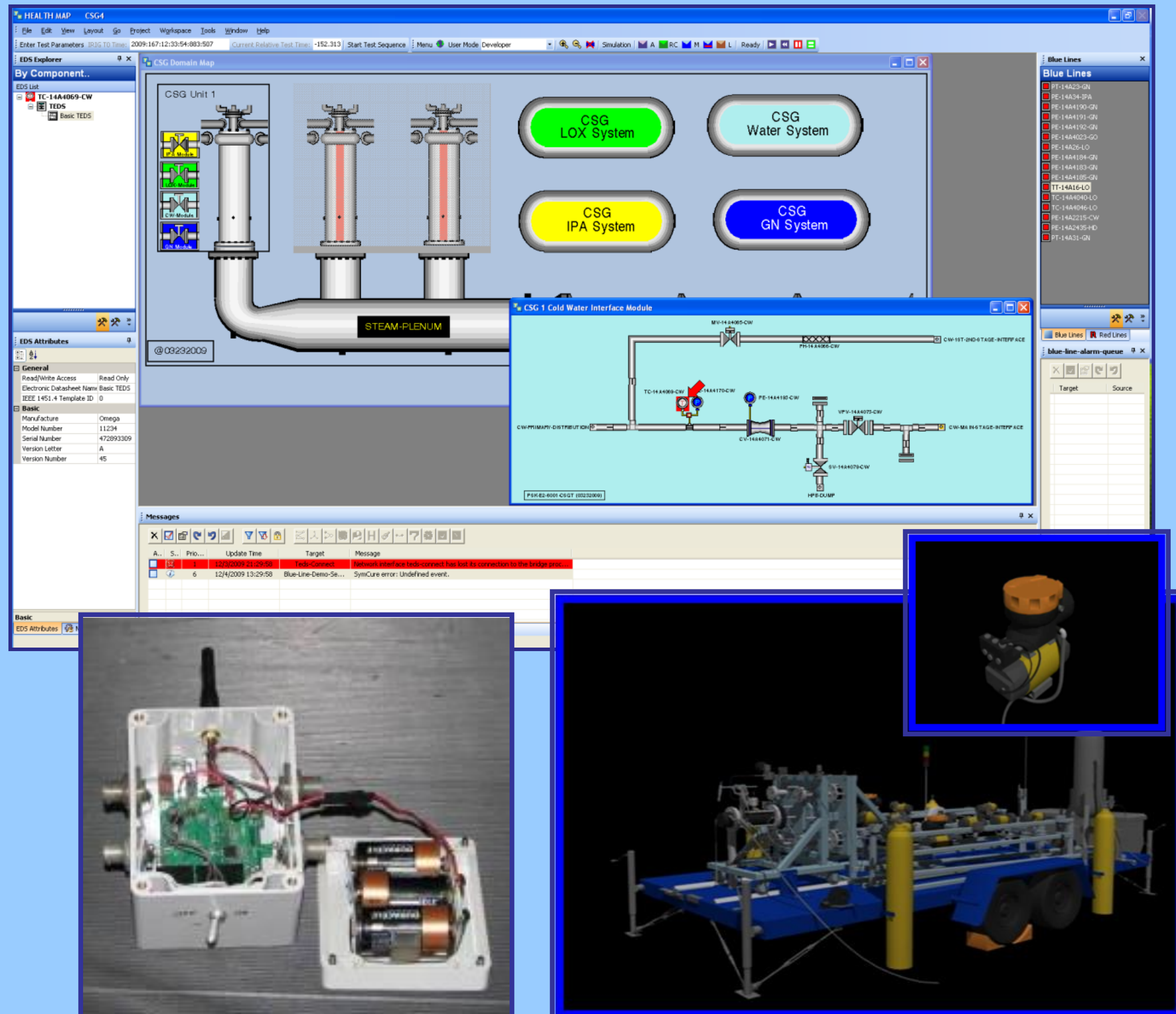
ISHM Development Environment

Health Assessment Database

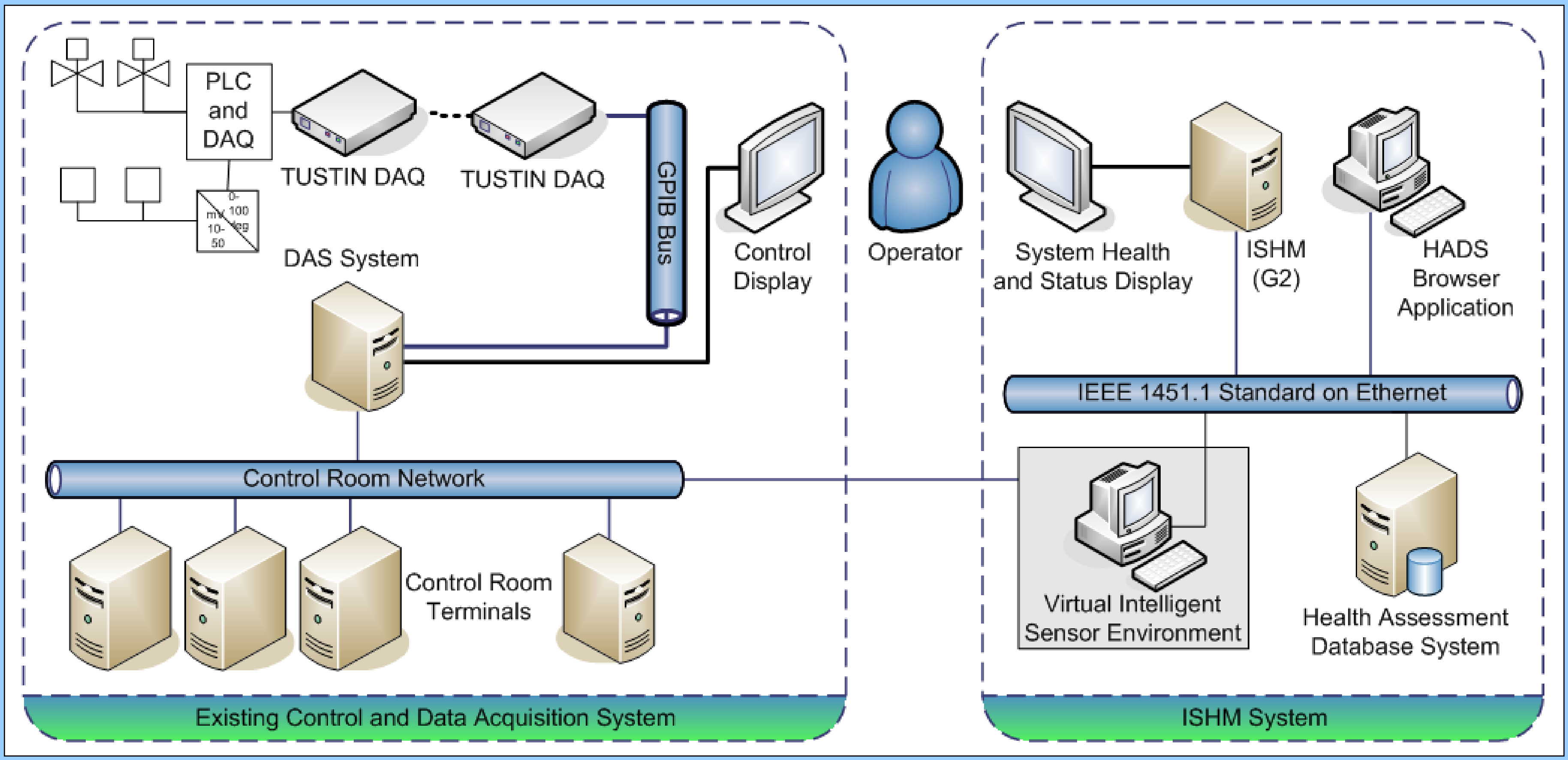
Anomaly Detection & Isolation

Integrated Predictive & Diagnostic Models

Intelligent Sensors



Generic ISHM System Configuration

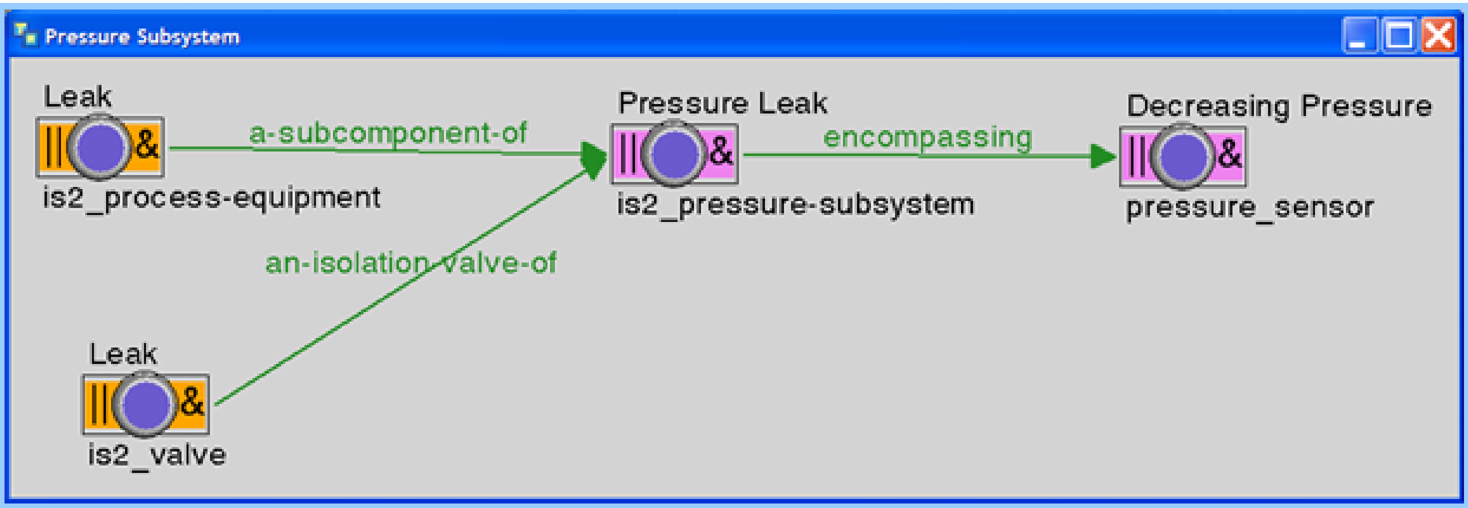


Failures Modes and Effects Analysis (FMEA) MIL-STD-1629A(2) NOT 3

ID #	Item-Functional Identification	Function	Failure Modes and Causes	Mission Phase-Operational Mode	Failure Effects			Failure Detection Method	Compensating Provisions	Severity Class	Remarks
					Local Effects	Next Higher Level	End Effects				

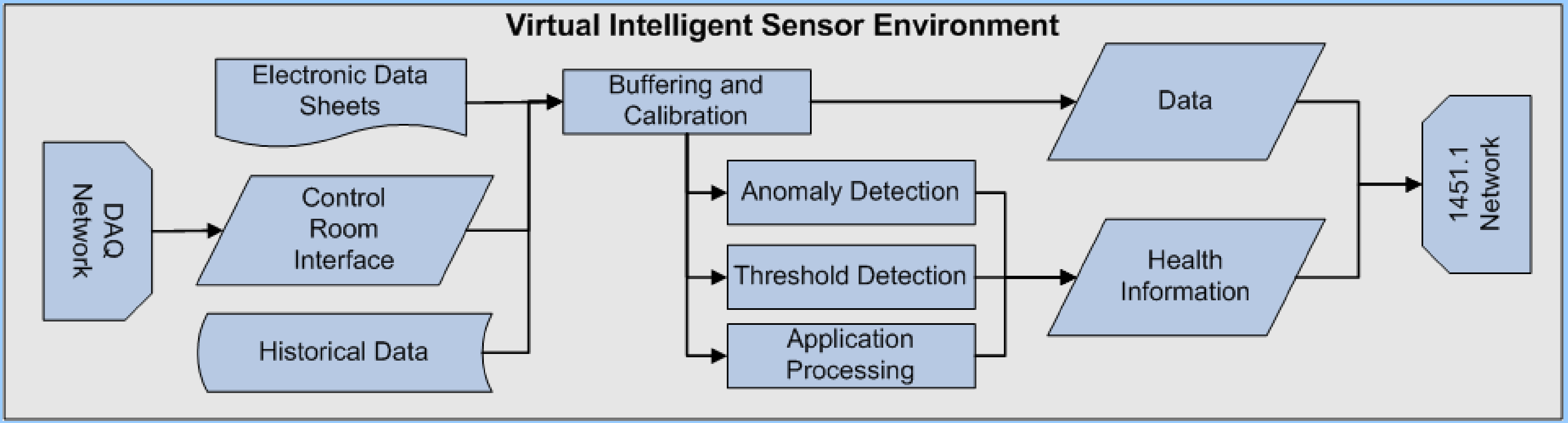
Failures Modes and Effects Analysis (FMEA)
MIL-STD-1629A(2) NOT 3

ID #	Item-Functional Identification	Function	Failure Modes and Causes	Mission Phase-Operational Mode	Failure Effects			Failure Detection Method
					Local End Effects Effects	Next Higher Level		
	Process Equipment	Fluid feed subsystem	Leak	Sealed subsystem maintaining pressure		Pressure leak	Decreasing pressure measurement	Identify sealed subsystem, and check pressure sensors for decreasing pressure.



Virtual Intelligent Sensor Environment

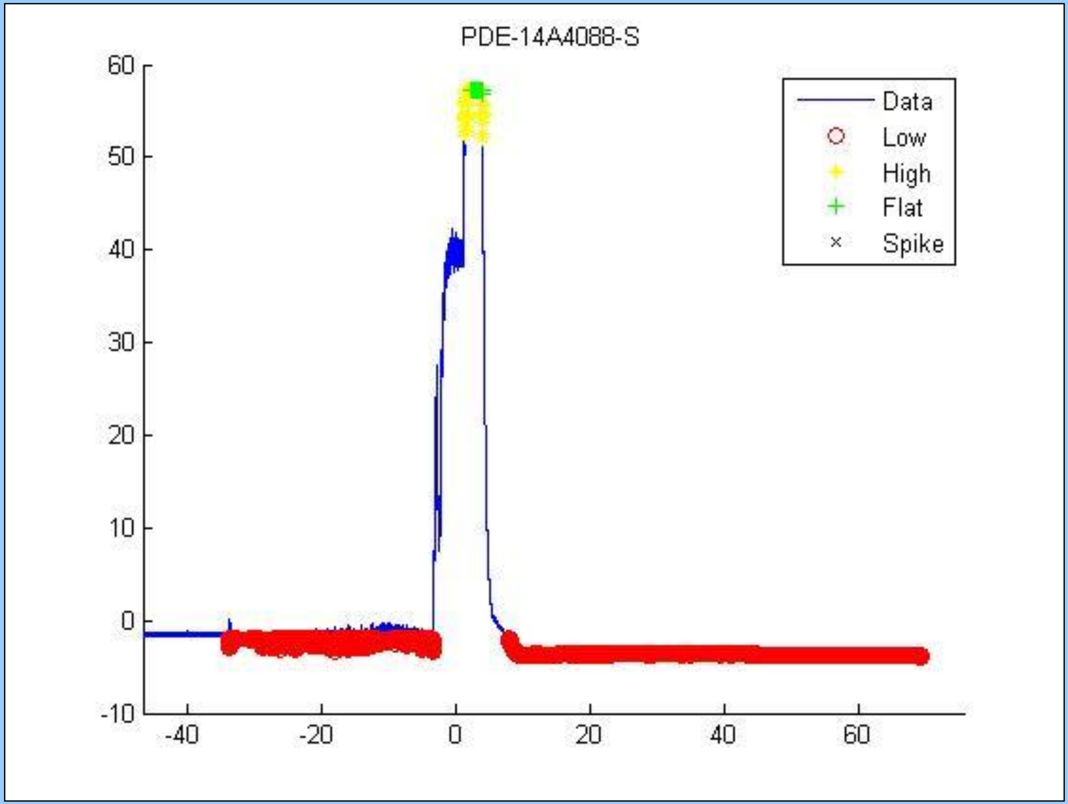
- Provides benefits of ISHM capabilities to existing data acquisition systems by adding Virtual Intelligent Sensor capability



Advanced Anomaly Detection

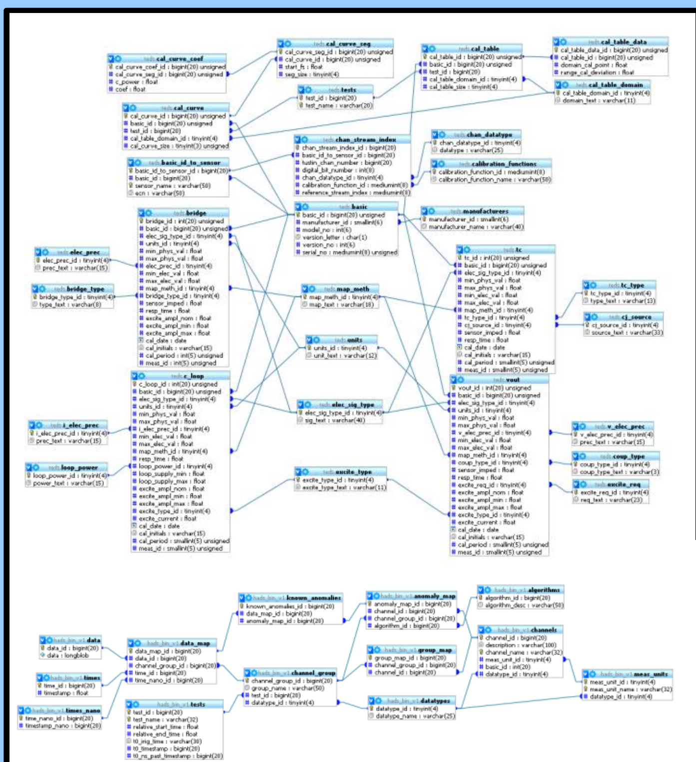
Anomaly algorithms used by VISE

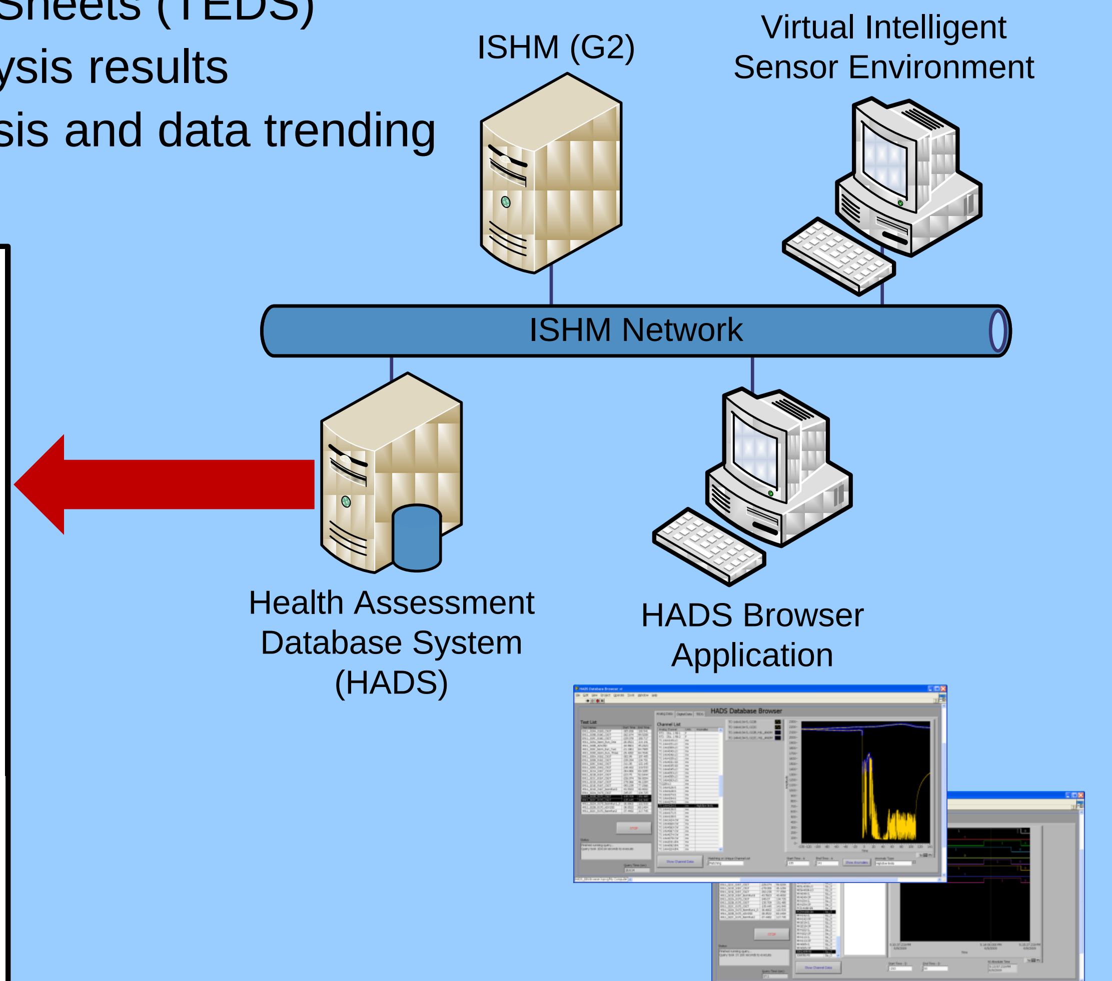
- Low physical limit exceedance detection
- High physical limit exceedance detection
- Flat line detection
- Impulse noise event/spike detection



Health Assessment Database System
HADS

- Health Electronic Data Sheets (HEDS)
- Repository of anomalies and algorithms
- Transducer Electronic Data Sheets (TEDS)
- Historical test data and analysis results
- Provides ease of data analysis and data trending

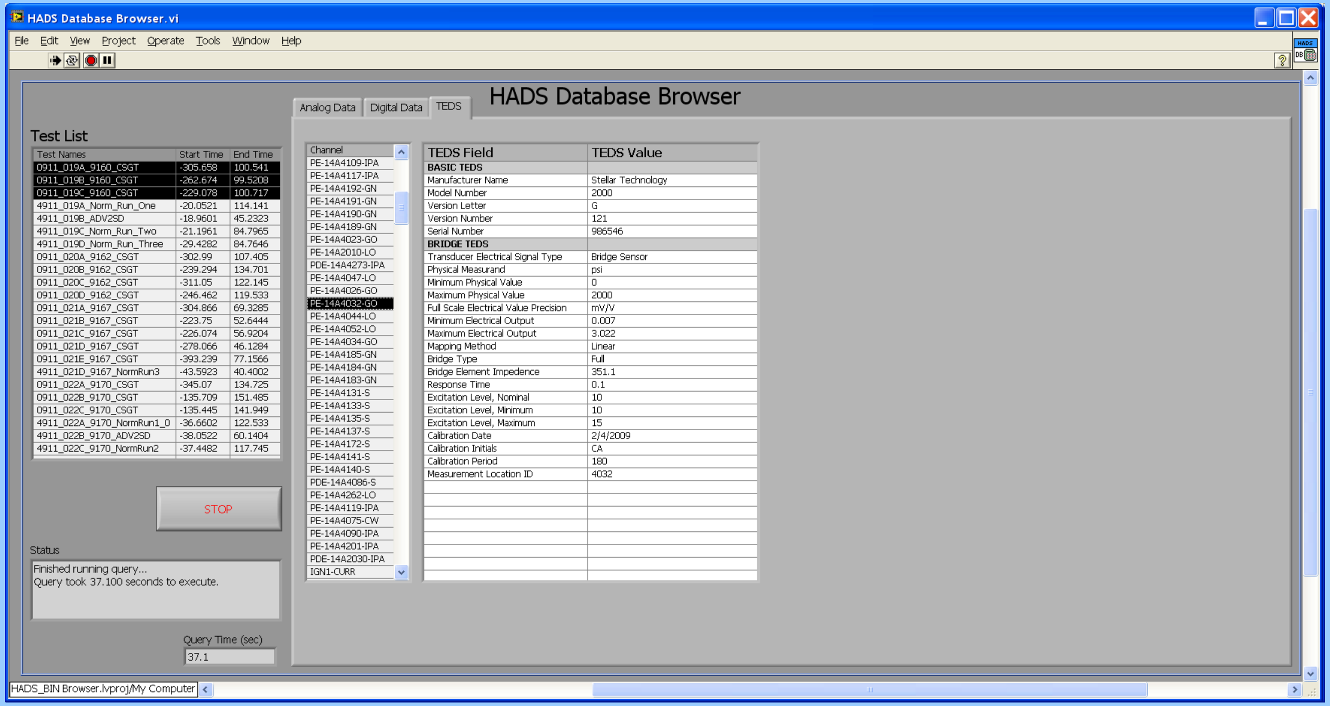




HADS Browser Application

HADS Browser Capabilities

- Allows longitudinal analyses and comparisons with previous test results
- Viewing usage statistics on monitored elements
  - cycle times on valves
  - mean time to failure
- Viewing anomalous events/data trends
- Viewing TEDS



Analog Data – 3 tests, multiple channels
Digital Data – 2 tests, 1 channel

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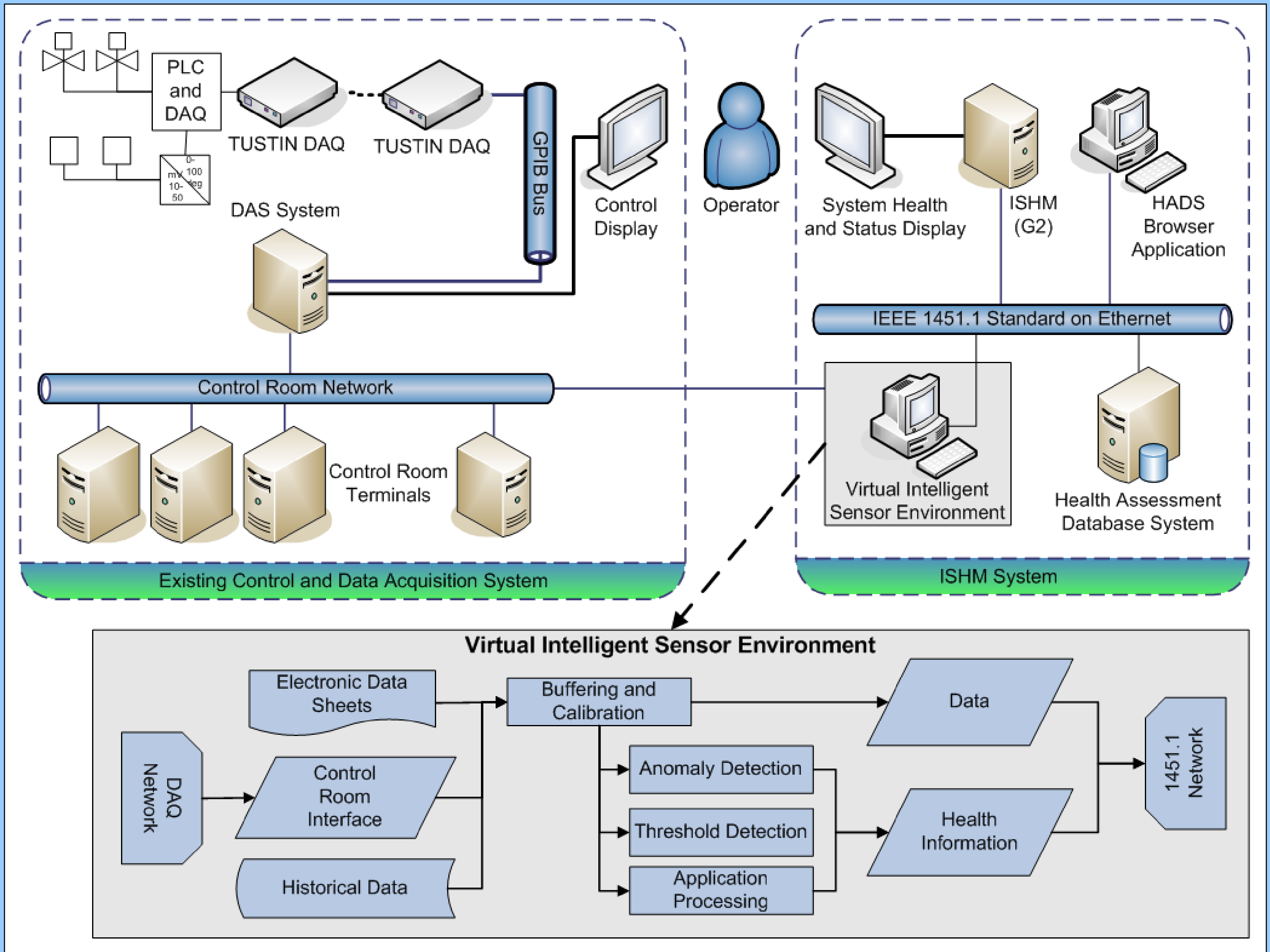
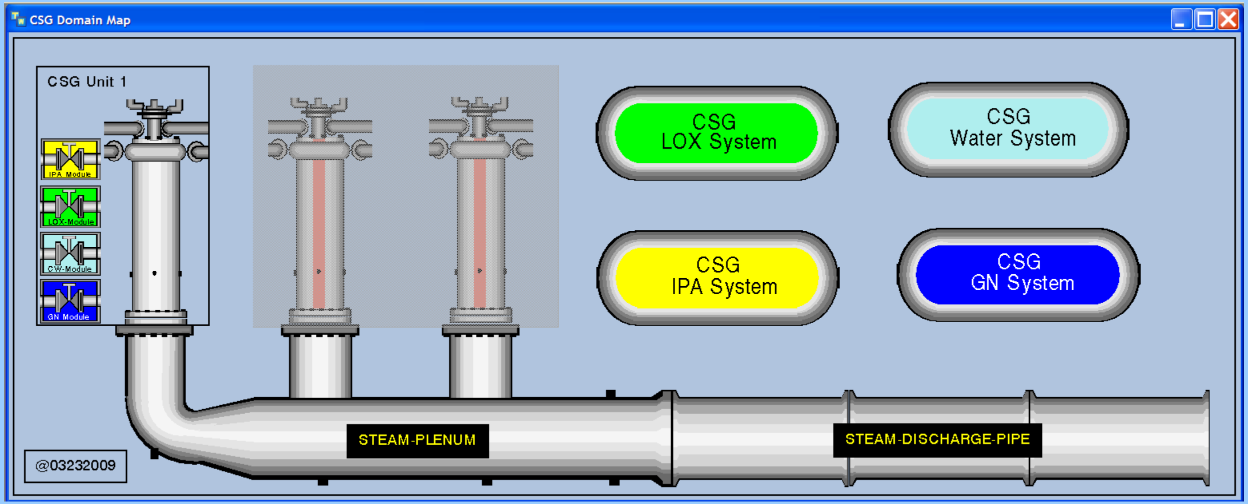
ISHM Pilot Implementation for Chemical Steam Generator (CSG)

- Complete an end-to-end ISHM Domain Model for the CSG program focused on sensor verification & validation for the facilities and test article
- Demonstrate near real time streaming of test data
- Operate on data streams in near real-time using anomaly detection algorithms implemented with two assets:
  - VISE
  - G2-based ISHM model
- Validate the CSG ISHM Domain-Model before, during, and after testing (3 test days).

CSG Architecture



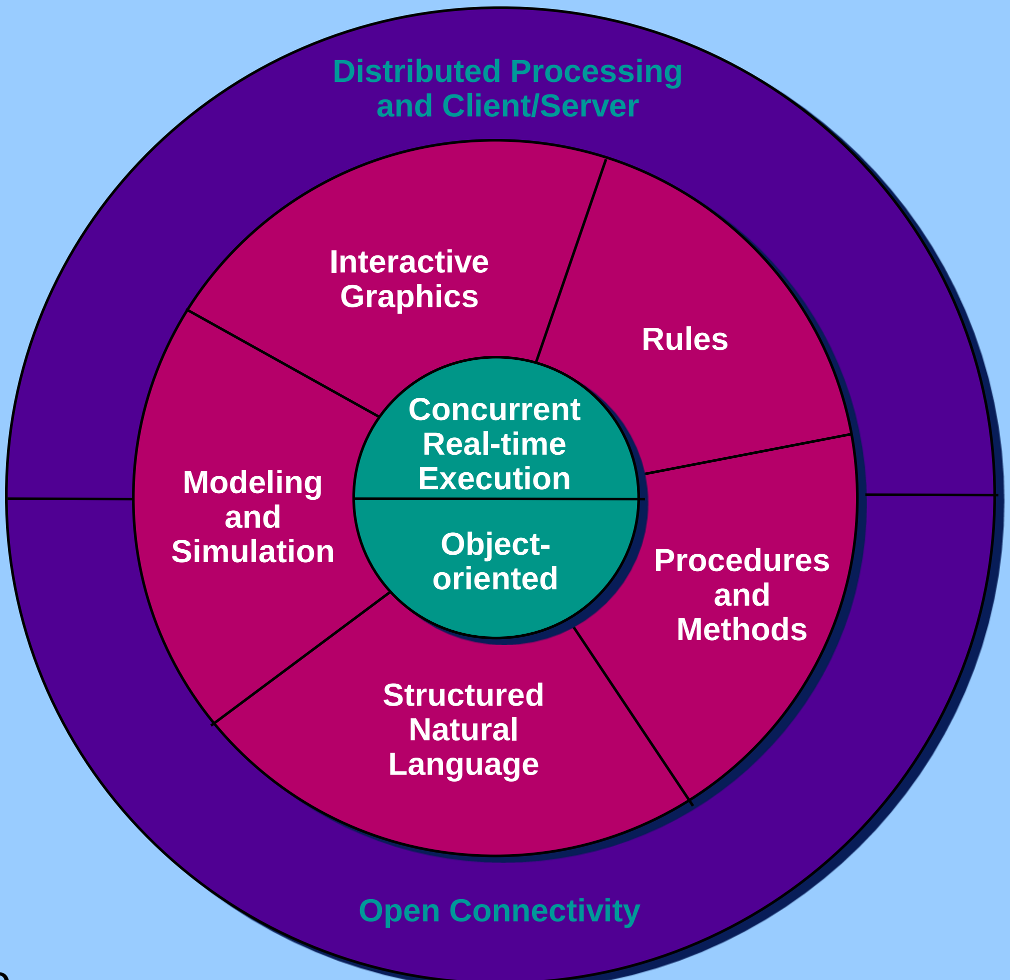
CSG ISHM Domain Model:
Top Layer View



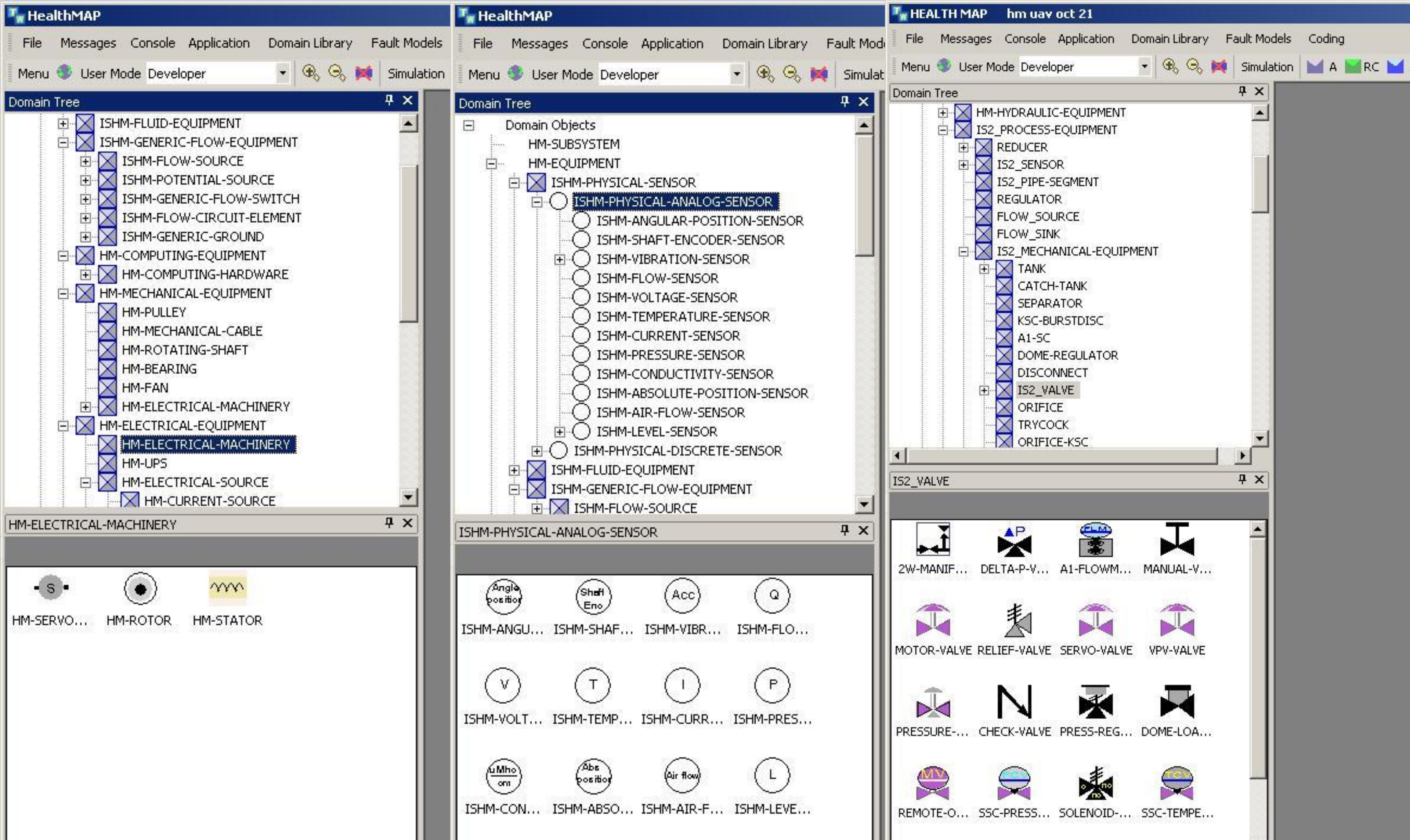
ISHM Domain Model
Top Layer

G2/Optegrity Software Environment

- Object Oriented Graphical Programming Platform
- Rules Based Reasoning
- Model Based Reasoning
- Graphical Modeling
- Decision Trees
- Procedural Reasoning
- State Transition Diagrams
- Workflow Engine
- Real Time Process Modeling/Automation
- Causal Event Propagation Modeling
- Cause/Effect Modeling
- Fuzzy Logic
- Neural Networks
- Flexible, Structured Natural Language Interface

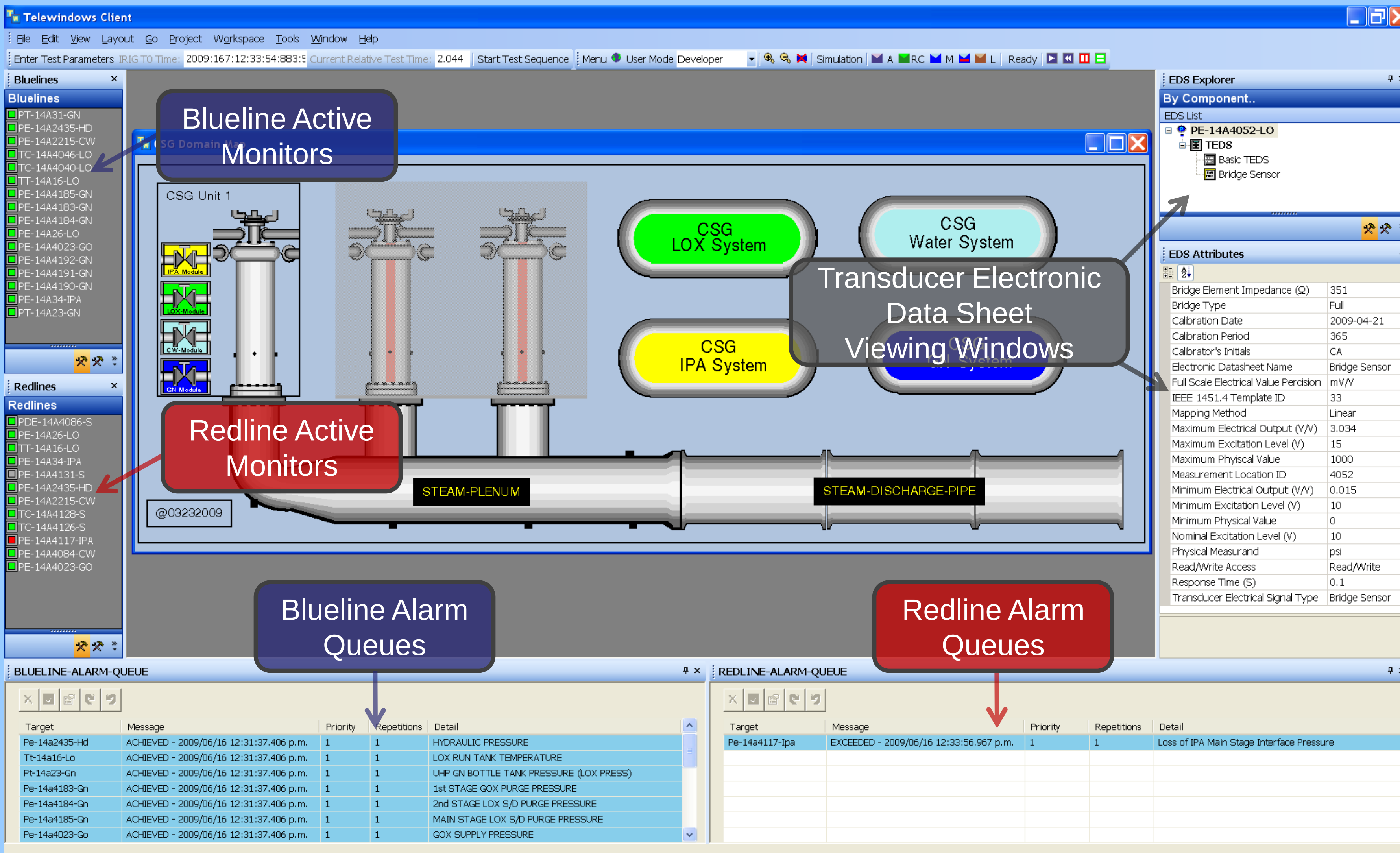


HM Domain Modeling - Palettes



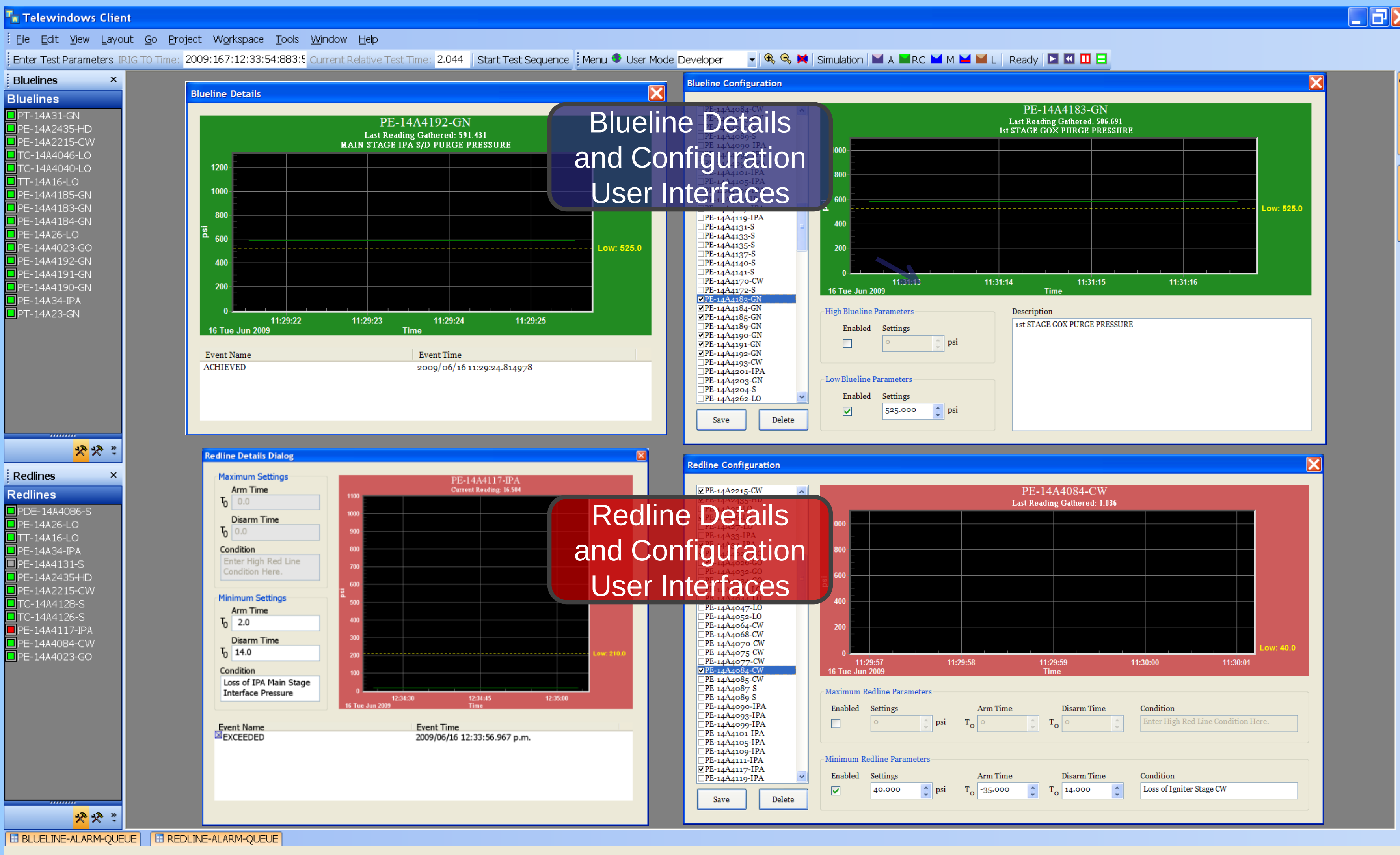
CSG ISHM Domain Model:

User Interfaces



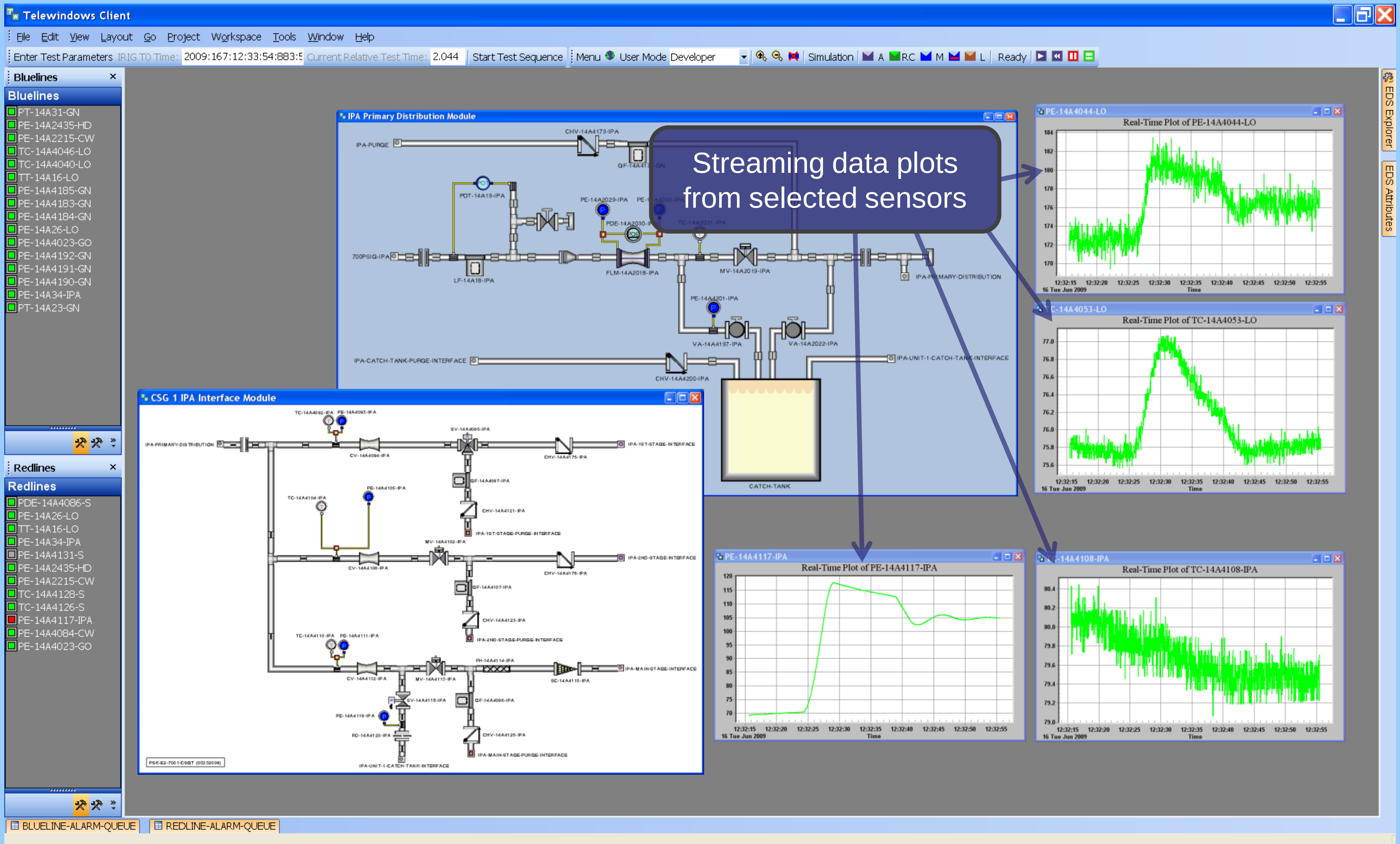
CSG ISHM Domain Model:

Blueline/Redline User Interfaces



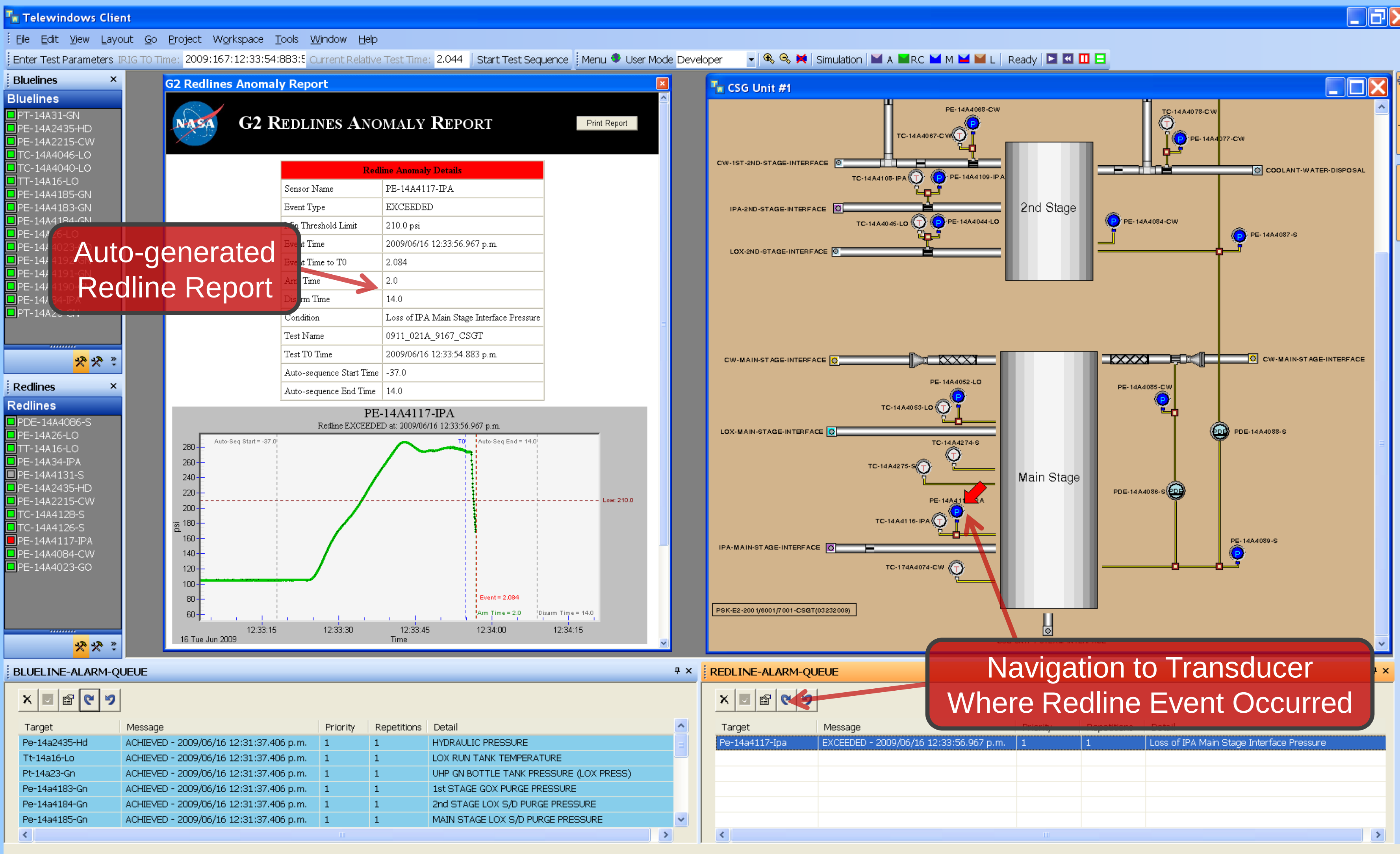
CSG ISHM Domain Model:

Transducer Data Plots

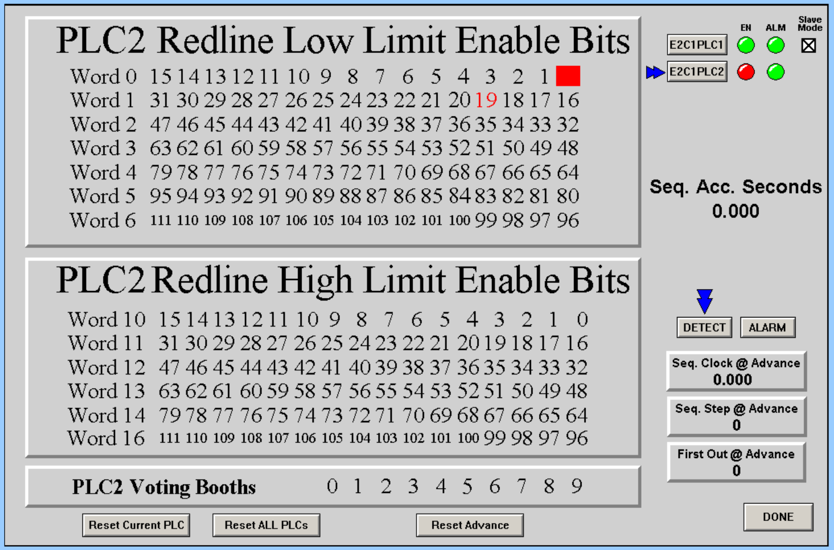


CSG ISHM Domain Model:

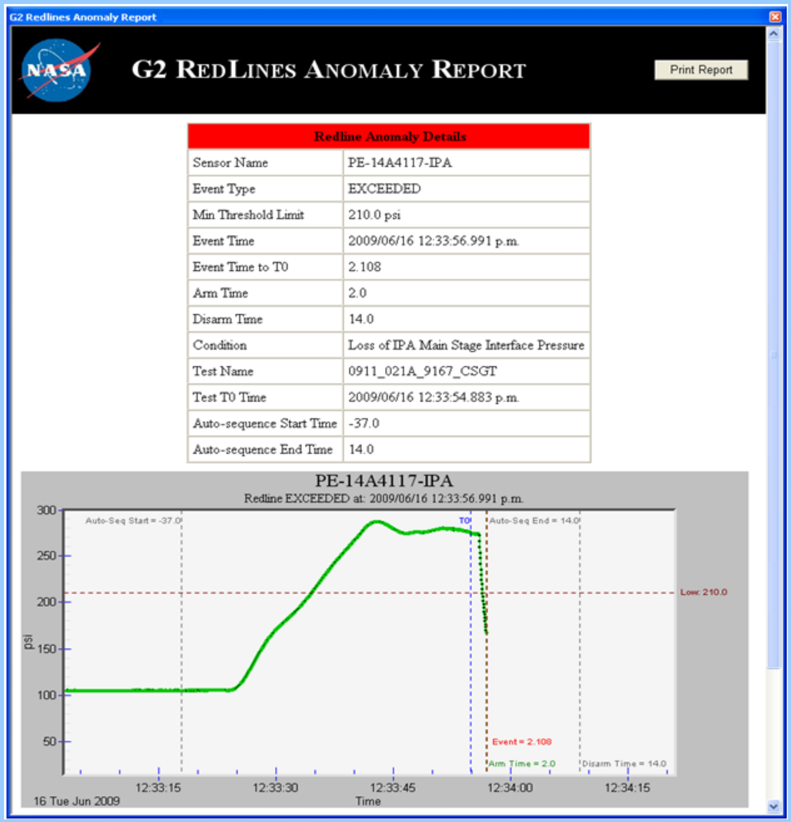
Redline Event Handling



Example Redline Handling



VS.



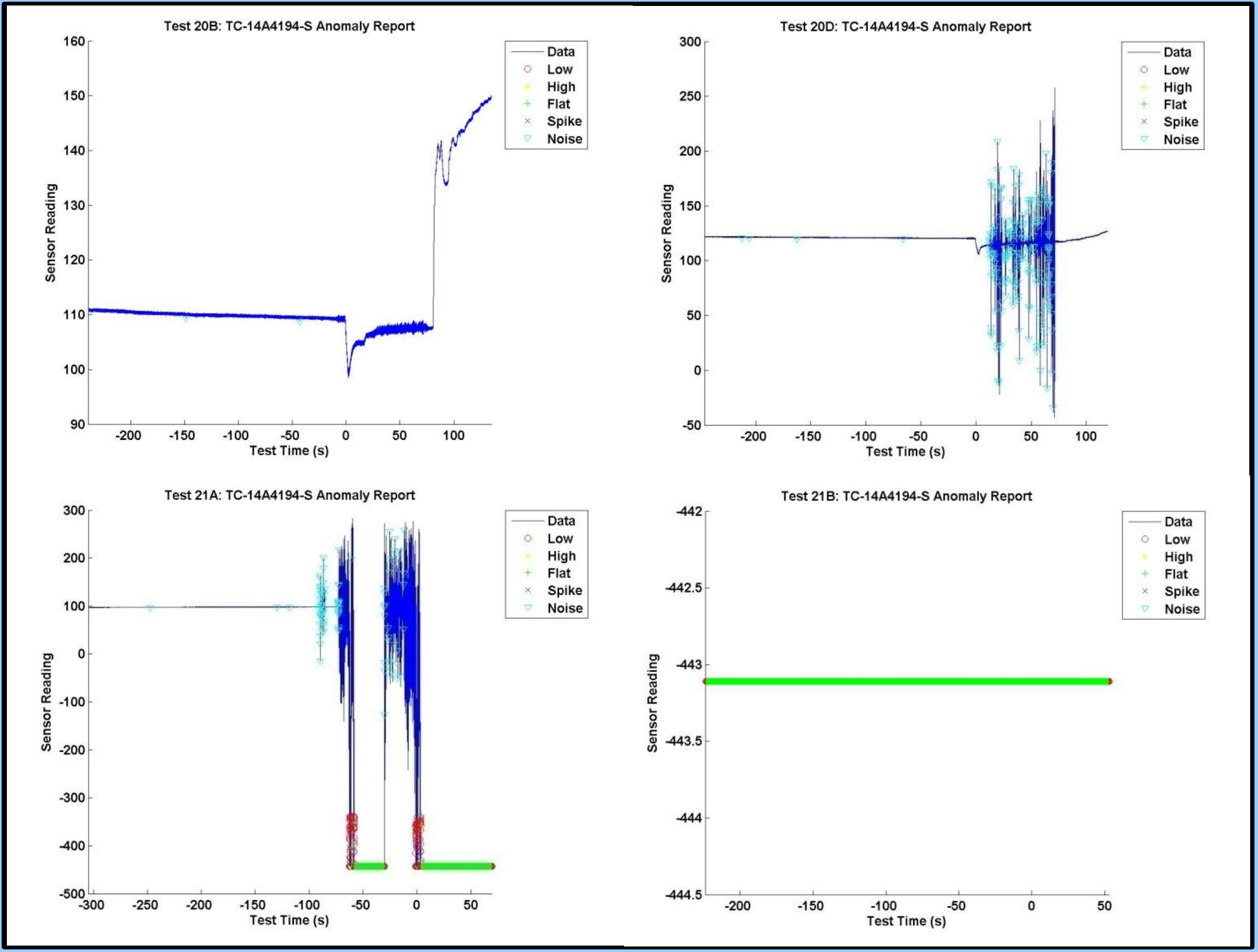
E2 Control Room Redlines UI

- Requires extensive expertise in interpreting events
- Analysis of events takes considerable time and effort
- Only viewed by selected personnel at control room facility

ISHM CSG Model Redlines UI

- Provides easily recognizable details of events
- Immediately accessible to all personnel at control room facility, hardcopy printouts allow for ease of distribution and record keeping
- Additional event and test parameters and associated data are depicted

CSG Anomalies Detected



- Evidence of TC degradation detected by VISE anomaly detection
- Advanced notification to determine the health of the whole system before beginning a test

Transducer Anomaly Report Graphs for one sensor in four consecutive tests.

Key Implementation Objectives/Results

- **Support for test readiness**
  - Bluelines (time savings and improved reliability)
    - Fast and accurate setting of bluelines.
    - Fast and accurate identification of violations and relevant hardware.
  - TEDS (time savings and improved reliability)
    - Immediate identification of sensors.
    - Immediate availability of specifications and calibration information.
    - Immediate identification of sensor locations in the diagram.
- **Support during test**
  - Redlines
    - Fast and accurate setting of redlines (time savings and improved reliability).
    - Fast and accurate identification of violations and relevant hardware (time savings, improved reliability, quicker response to safety critical issues, and faster analysis).
  - Immediate viewing of trends for any sensor or signal (improved reliability).
- **Support for rapid return to test**
  - On-line analysis.
    - Re-stream data to simulate tests at any time (faster and better analysis).
  - Advanced post-test analysis and data review
    - View data windows for multiple sensors, involving multiple tests (improved understanding of system).

Improvements for the Next CSG Test Program

The following improvements, requested by the test director and test conductors, will be in place for testing in September, 2010.

- Continuous checking of all sensor values for violations of thresholds defined by any desired criteria (e.g. sensor specifications, operational requirements from the Test Request Document).
- Valve state verification.
- System state verification at test stages as specified by the Test Request Document.
- System interlocks verification as specified by the Test Request Document.
- Usage capture.
  - Valve cycling.
  - Tank thermal cycling.
- Post test quick-look analysis (immediate and accurate understanding of test results and any issues):
  - Select sensor sets and time windows for viewing trends from the current test or from across multiple tests.
  - Select redline occurrences and view details, including identification of relevant elements in the diagram.
  - View all anomalies an descriptions, and identify relevant elements in the diagram.
  - Proximal Cause Analysis

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Benefits to A3
(and to other facilities)

- Improve assessment of test readiness—availability, reliability, configuration.
- Assist in verifying conformity of system states throughout the test, as per the Test Request Document.
- Improve information flow to operator during test.
- Improve post-test data review and analysis: accurate, fast, and comprehensive understanding of test results and test stand issues (including analysis across multiple tests).
- Improve safety: awareness of system condition, faster and accurate identification of safety issues.
- Automatic generation of reports.
- Capture safety critical events.
- Capture usage information.
- Capture anomaly information.
- Improve efficiency and effectiveness of PSM and RCM activities.
- Create and maintain a comprehensive database incorporating health information.

Extending ISHM to A-3
(and other facilities)

- Steps needed to extend CSG model to full-up A-3 configuration
  - Implement three-unit skid to prepare for 9-skid A-3 design
  - Incorporate leak detection, advanced valve anomaly management and other improvements in anomaly detection
  - Integrate with SSC configuration management
  - Develop ConOps
  - Use ISHM system for long-term benefits
    - Increase understanding of CSG reliability
    - Condition-Based Maintenance (CBM)
    - Reliability-Centered Maintenance (RCM)
    - Process safety management (PSM)

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A-3: ISHM Will Reduce Risks and Enable Sustainable/Affordable Operations

- A-3 has a high degree of complexity and its operation will present a substantially more difficult challenge than any system before. The number of data and signal streams to be monitored and reasoned about will be overwhelming. Testing might be seriously limited without the support from an ISHM capability.

48+ VESSELS AS OPPOSED TO 3-4 IN EXISTING STANDS.
321+ MORE SENSORS THAN IN EXISTING STANDS.

A-3: ISHM Will Reduce Risks and Enable Sustainable/Affordable Operations

- A3 Will involve safe, accurate, and reliable synchronized-operation of multiple systems (27 CSG's, Steam Water System, IPA System, LOX System, LH2 System, Purge Systems, Industrial Water, Hydraulic System, Diffuser System, Test Chamber System).
  - Will require automated monitoring and analysis capability to achieve the appropriate degree of confidence for test readiness in a timely and affordable manner.
  - Will require improved approach to manage bluelines and redlines.
  - During tests, it will require awareness about a system one order of magnitude larger than typical test stands.
  - Will require improved analysis tools for accurate and fast assessment of test results, anomalies, and safety issues.

Summary

- ISHM Capability can be implemented without disturbing normal operations of a system. The only things needed are: (1) the data stream, and (2) information describing all elements in the system (P&ID's, specifications records, calibration records).
- A sound methodology for ISHM implementation has been validated in an operational setting.
- The implementation provides for systematic augmentation of the capability to meet user needs.
- Feedback from test conductors and test director has been very positive, and all became engaged in defining needed updates.
- Expertise and tools reside at the center, but capable industry partners are also available to support fast deployments and long term operations.
- The ISHM capability will make possible a more effective use of predictive models from the Analysis and Simulation Group. Quick access to relevant data and anomalies will make analysis with predictive models more effective and accurate. Also, predicted measurements will be used to detect anomalies, diagnose causes, determine effects, and predict future anomalies.

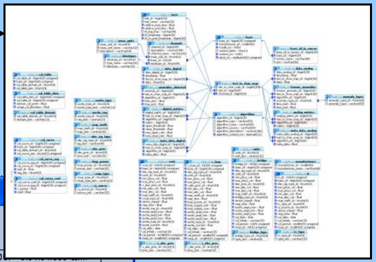
The difference between having ISHM capability and not having it is analogous to using a Windows computer connected to a network (WWW) as opposed to a DOS computer without network capability … SIGNIFICANT DIFFERENCE IN DATA, INFORMATION, AND KNOWLEDGE AVAILABILITY; AND IN AWARENESS THROUGH USER INTERFACES

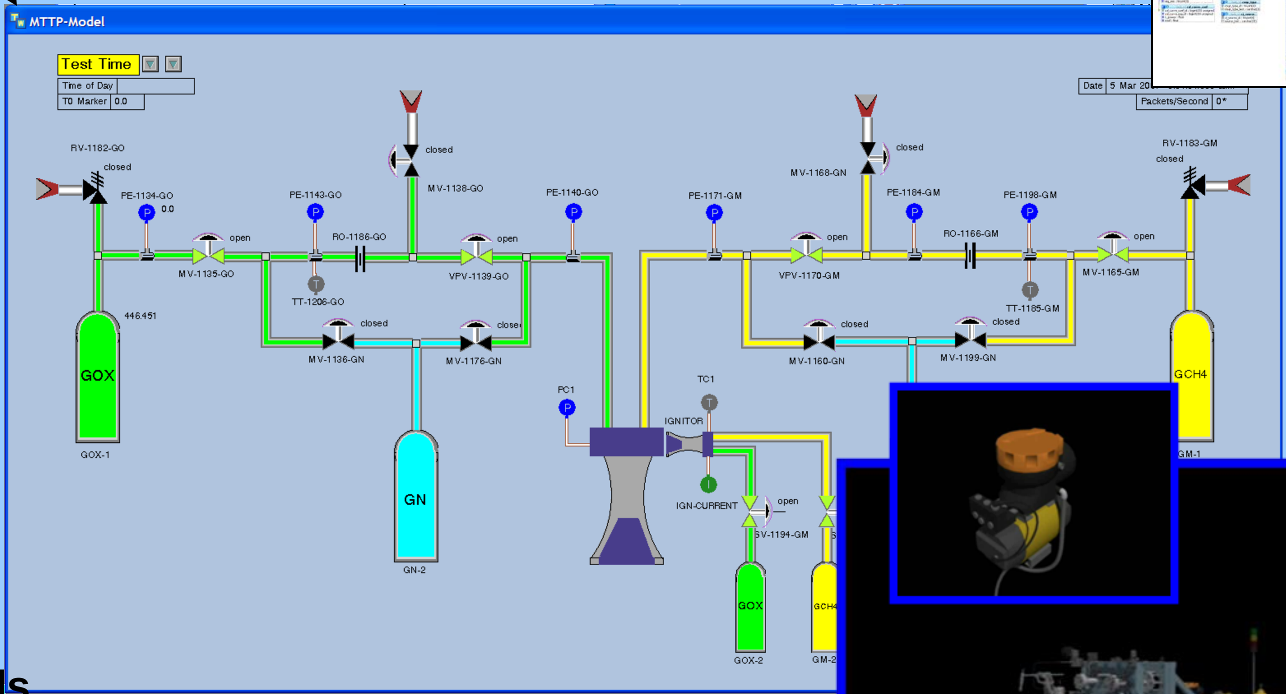
Backup Slides

Snapshot of SSC ISHM Capabilities

ISHM Models (Embedded Data, Information, and Knowledge):
Object-oriented model

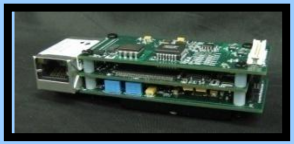
Health Assessment Database:
Health Electronic Data Sheets (HEDS)
Repository of anomalies, algorithms,
Transducer Electronic Data Sheets (TEDS),
Historical Test Data



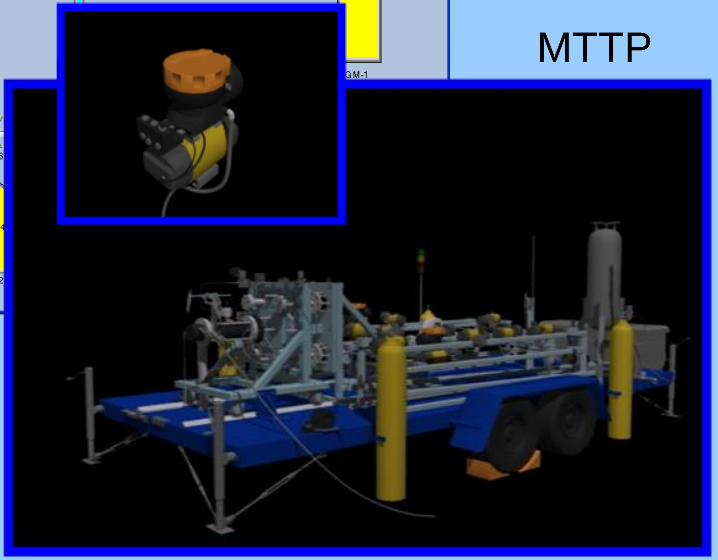


Anomaly Detection:
Sensor faults, leaks, etc.

Intelligent Sensors: IEEE Standard+Health

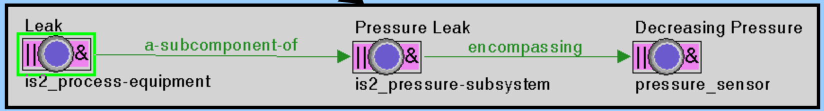


MTTP



Embedding of Predictive Models

Proximate Cause and Effects Determination

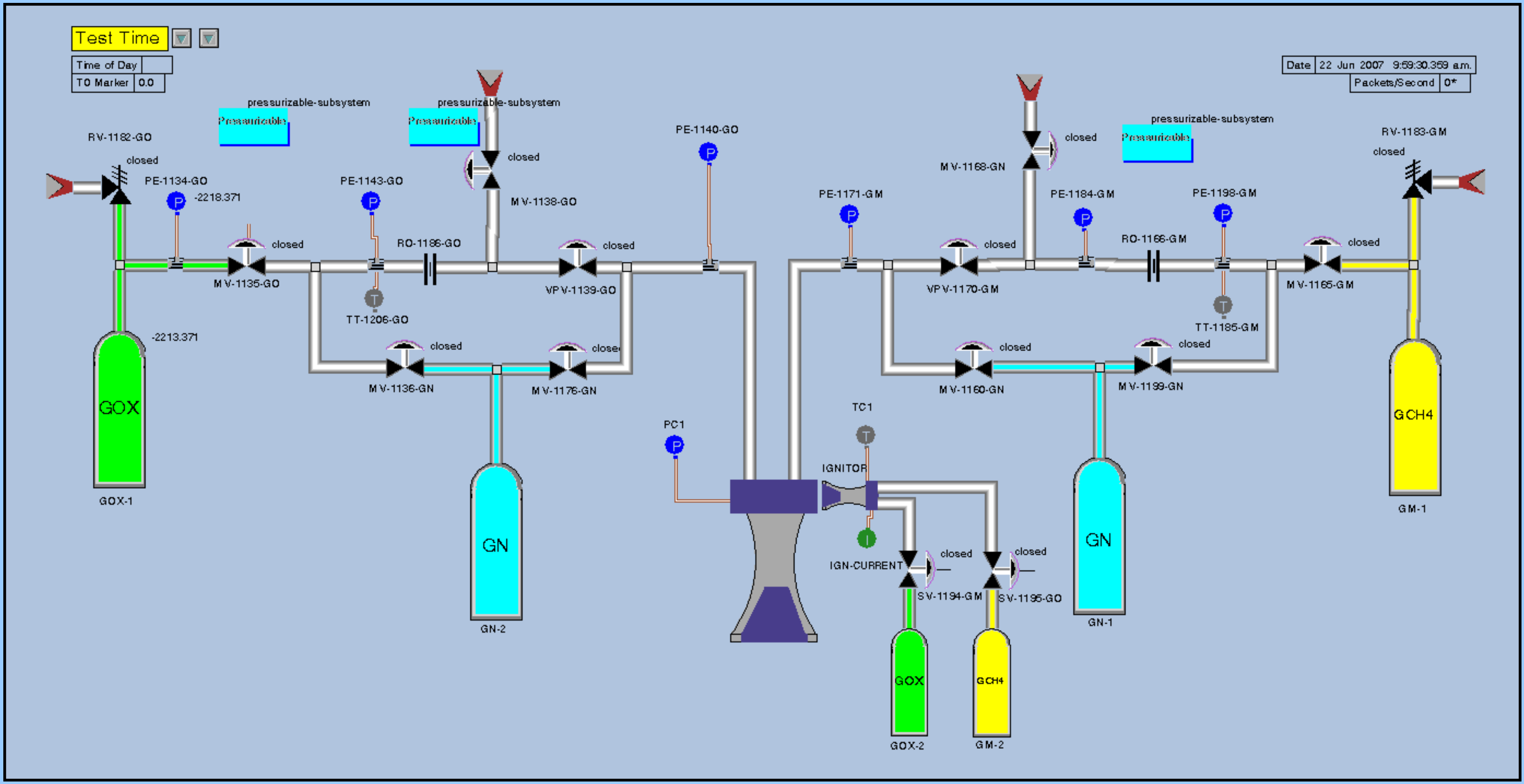


Integrated Awareness:

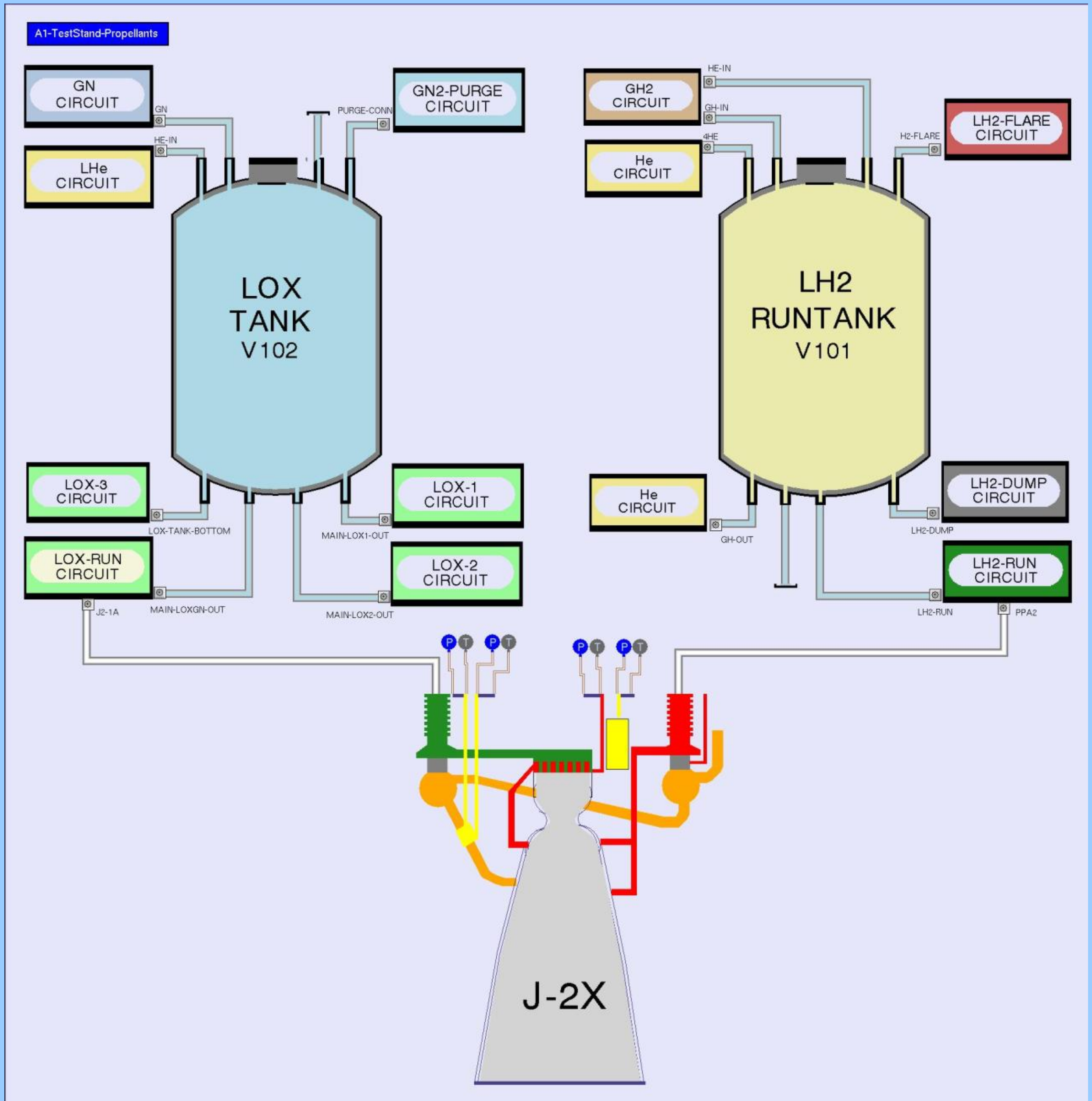
3-D Health Visualization

Elements of an ISHM System:

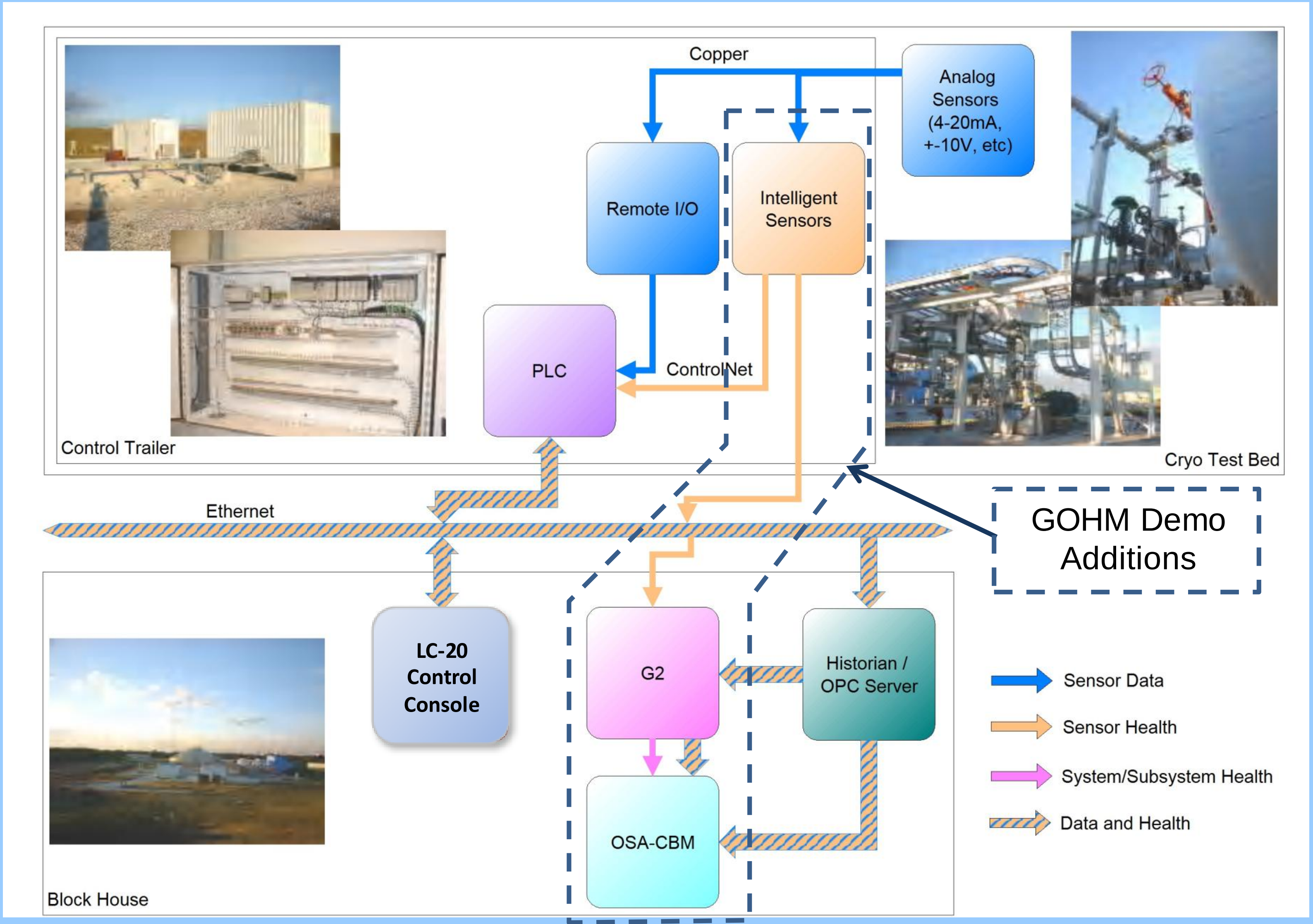
ISHM Model - Proximate Cause Analysis



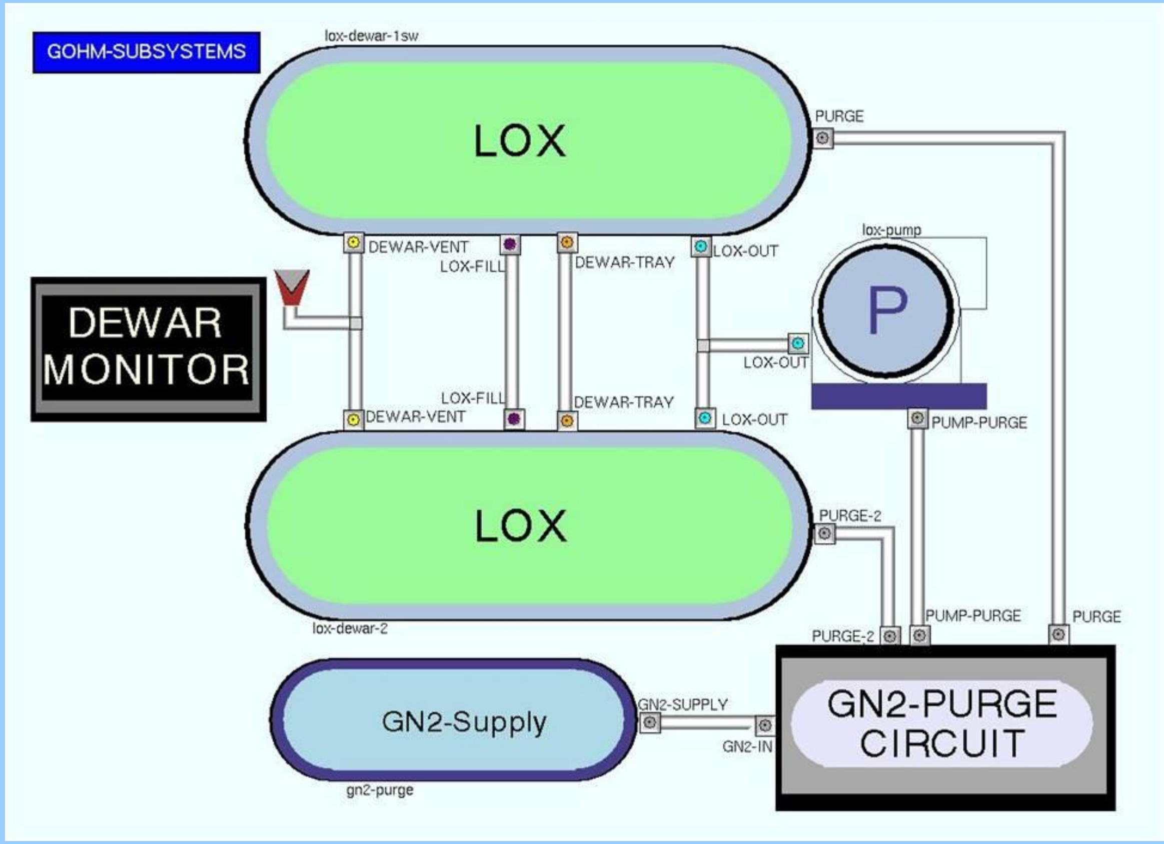
A1 and J2-X ISHM MODEL



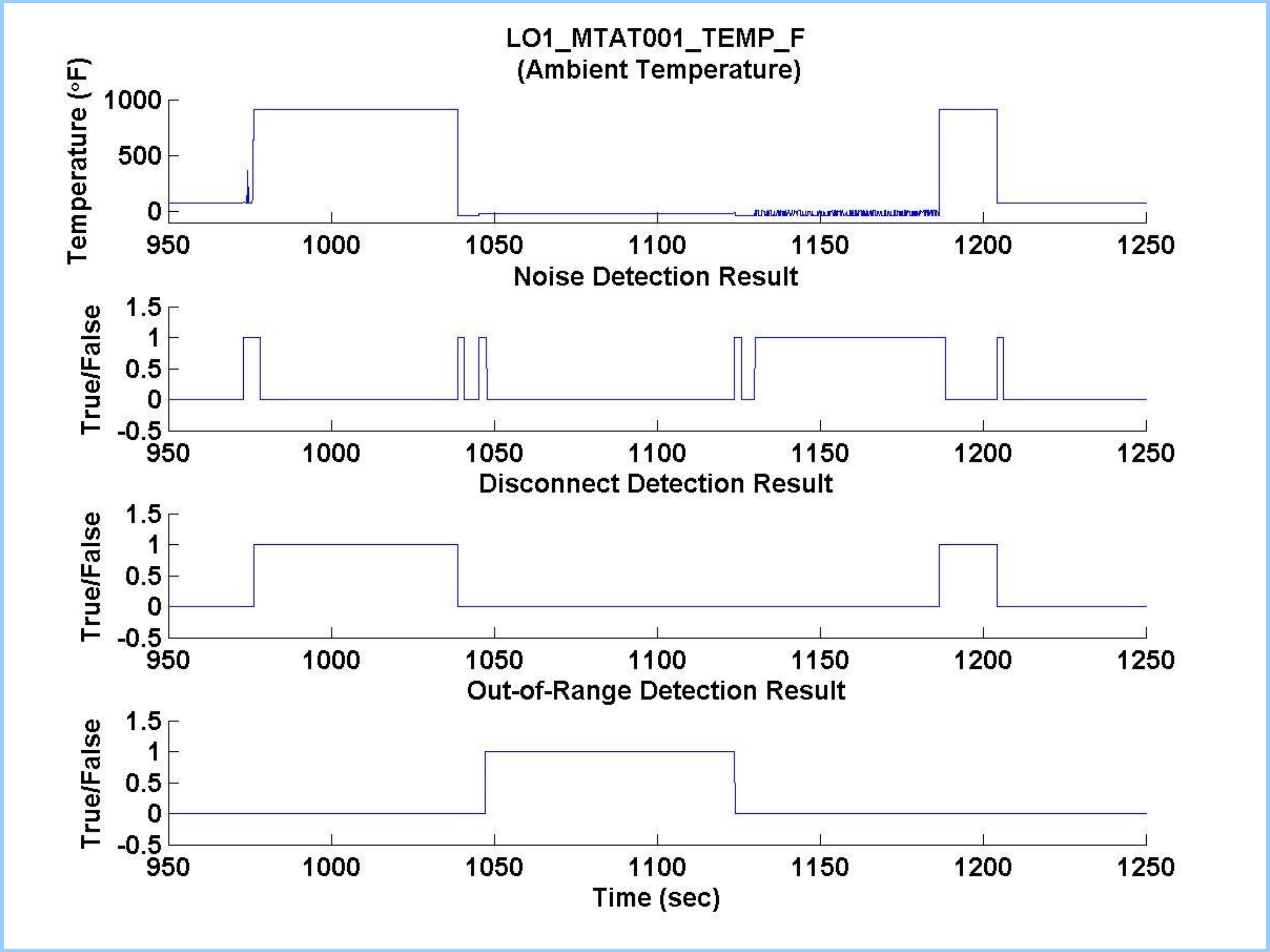
Launch Center 20 at KSC
ISHM Pilot Implementation
Validation During a LOX Pump Test



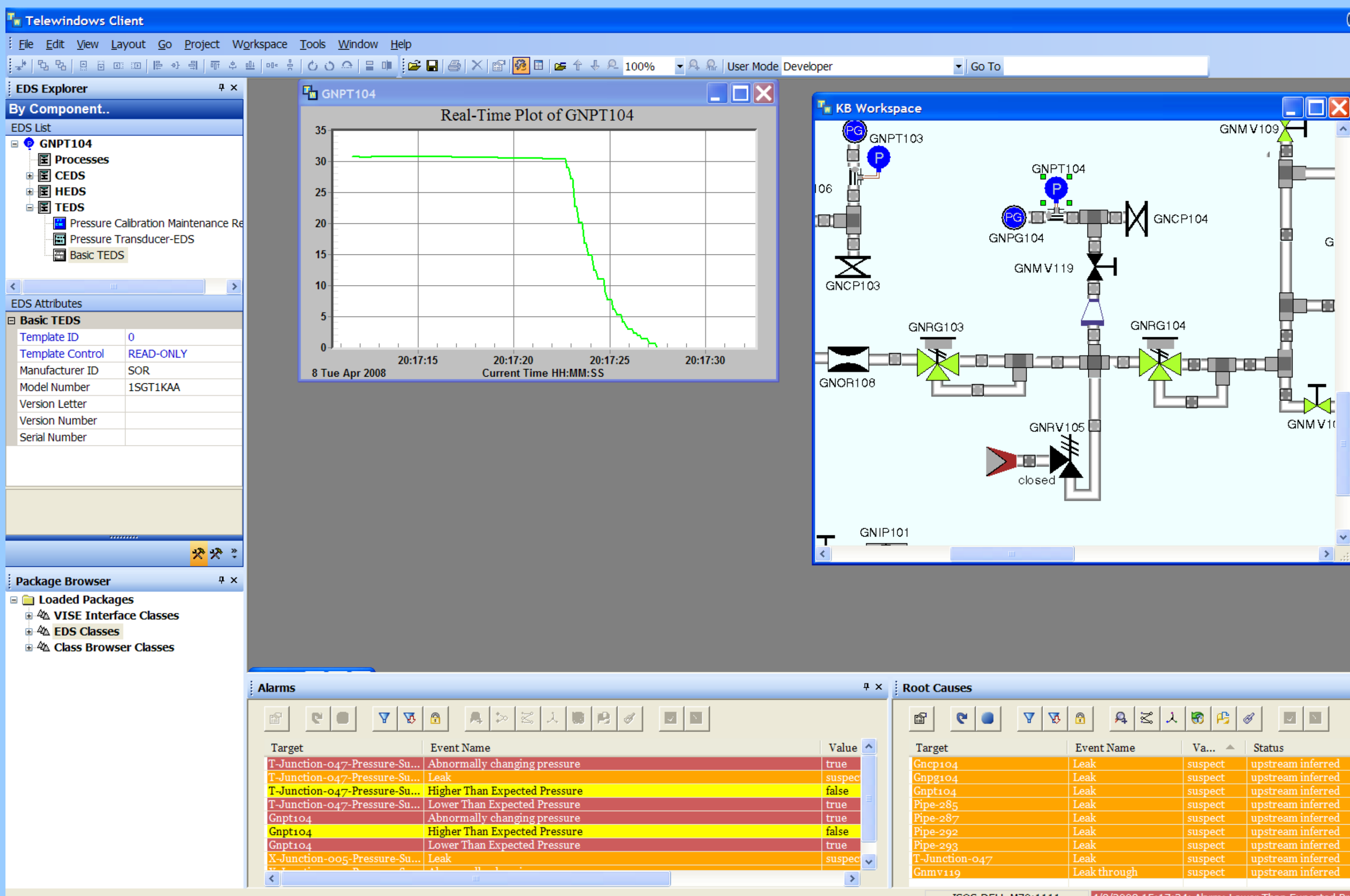
Top level view of the ISHM model of the Launch Complex 20 Facility at NASA Kennedy Space Center



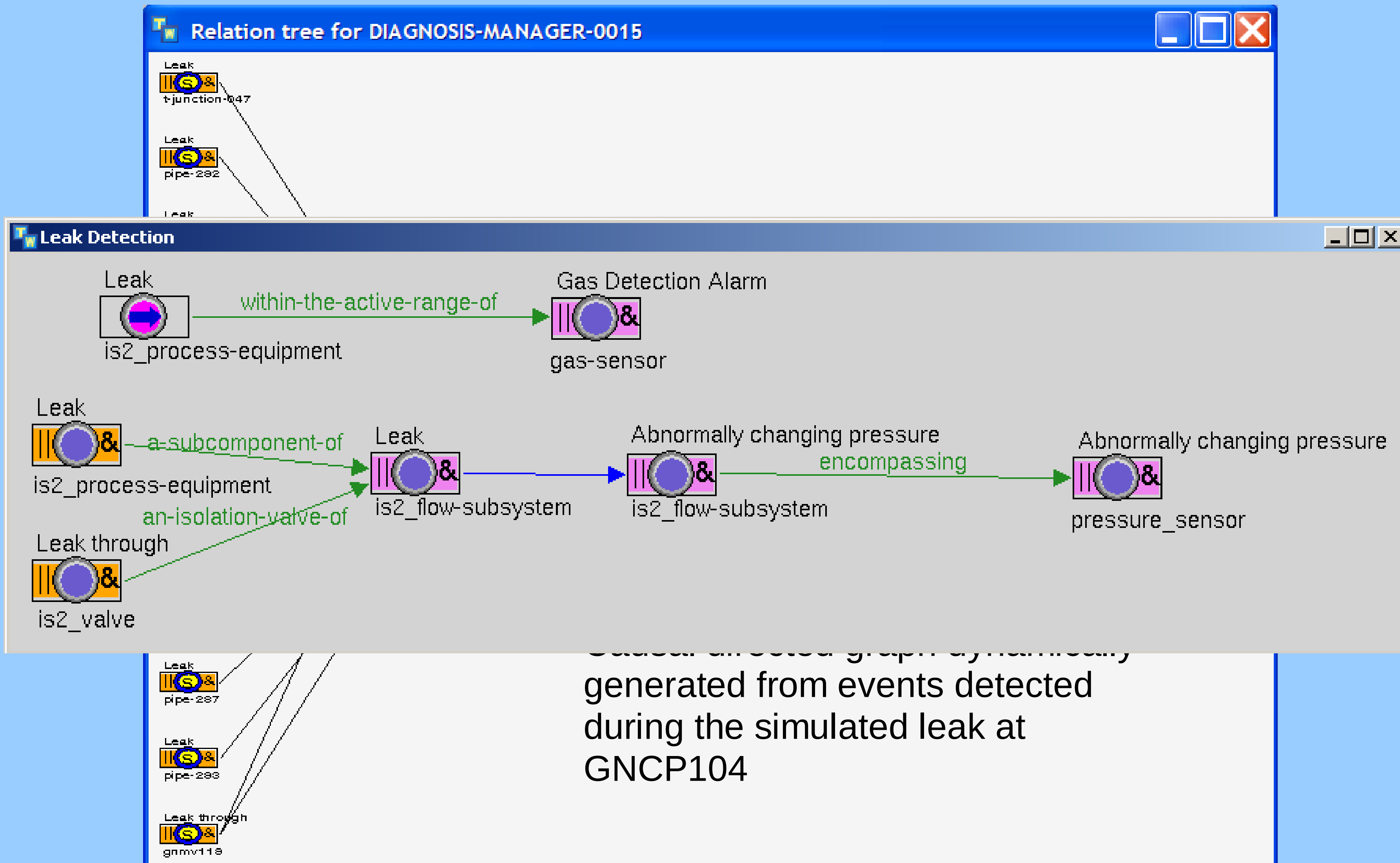
Sensor anomaly indicators detected by an intelligent sensor during a pump test using the LC-20 facility at NASA Kennedy Space Center



Screenshot of the ISHM model of the LC-20 facility at KSC showing detection of a valve leak created by opening the valve manually



Expanded causal-directed graph generated by the detection of a leak in the subsystem where a valve was opened manually (injected leak)

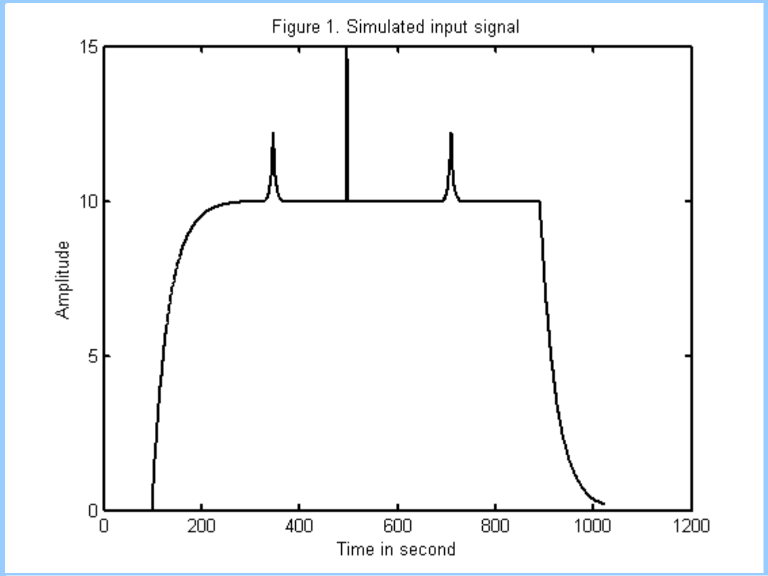


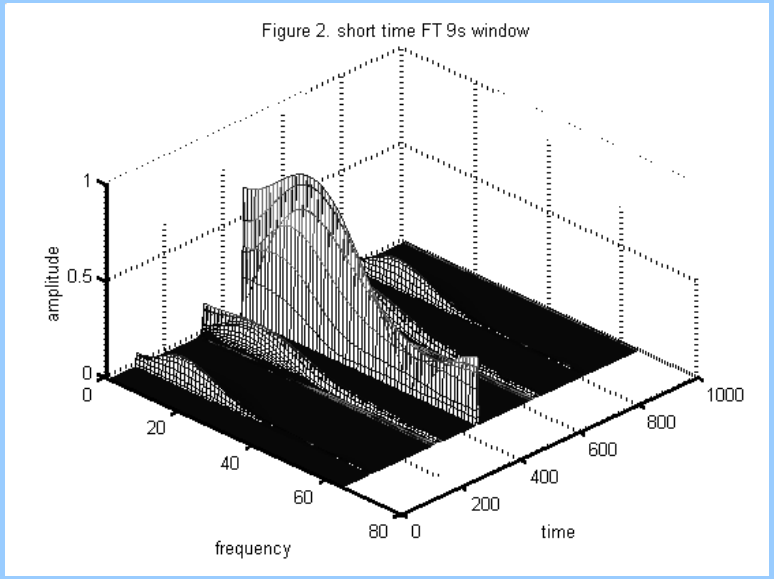
Causal-directed graph dynamically generated from events detected during the simulated leak at GNCP104

List of Anomaly Detection Capabilities

Anomaly/Behavior	Demonstrated Cause	Detection Approach
Leaks (pipes, valves, etc.)	Various	Checking for pressure leaks using the concept of Pressure Subsystems.
Valve state undetermined	Defective feedback sensor Controller failure	Determines valve state by checking consistency of command, feedback, open/close switches, and pressure conditions upstream and downstream.
Valve oscillation	Fluid contamination in hydraulic supply	Compare running standard deviation of command versus feedback.
Valve stuck	Fluid contamination in hydraulic supply Seat seizure	Feedback remains horizontal while command changes.
Excessive noise, spikes, etc.	Interference	Running standard deviation exceeds set limits. Thresholds violations during short time spans (compared to sensor time-constant).
Degradation	Wear, aging	Trend detection using curve fitting and determination of time-constants.
Prediction-Measurement mismatch	Various	Use predictive model (e.g. from Modeling & Analysis Group) to predict sensor values and compare with measurements.

Short-Time Fourier Transform Segmentation

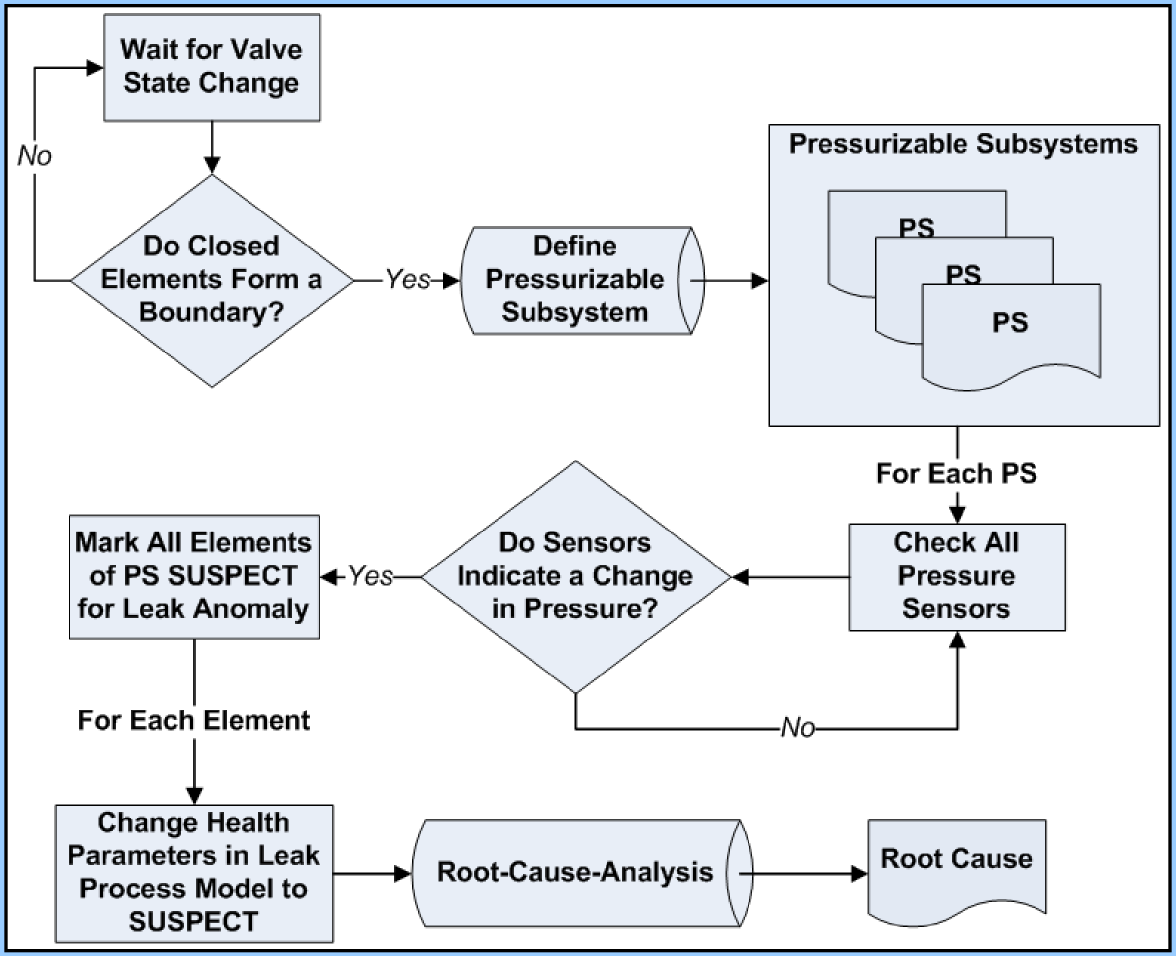




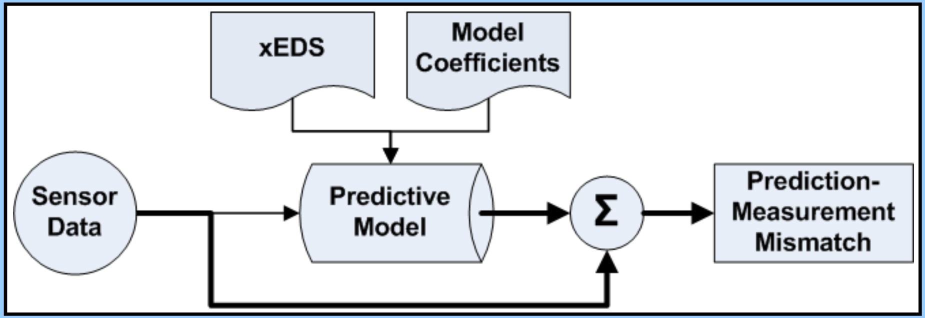
Determining Valve-State

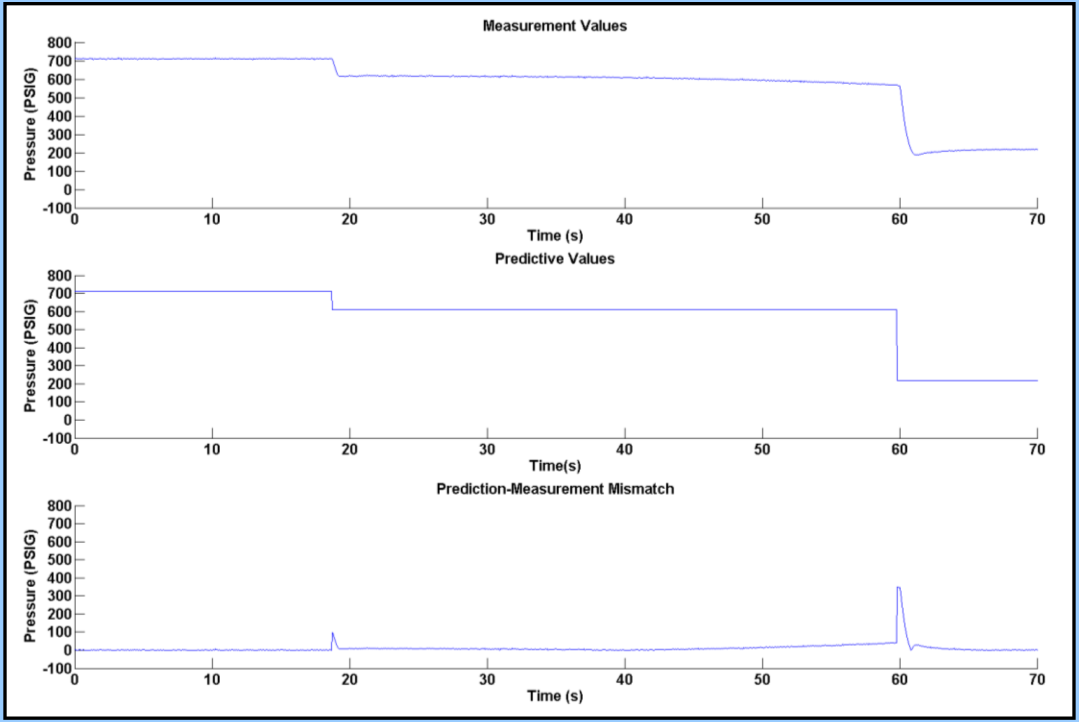
Valve State	**Command**	**Feedback**	**Open limit**	**Closed Limit**	**Associated Sensors**
Open	Open	Open	True	False	Agree with model
	Healthy				
Closed	Closed	Closed	False	True	Agree with Model
	Healthy				

Checking for Pressure Leaks



Runtime Predictive Modeling



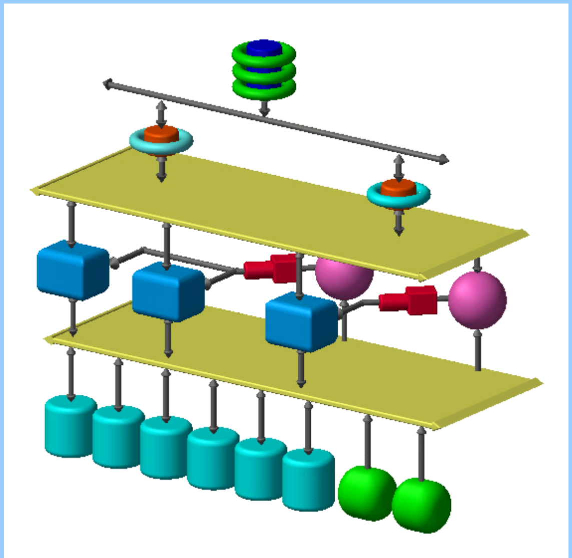


Electronic Datasheets

- Electronic Data Sheets (EDS)
  - Transducer Electronic Data Sheets (TEDS)
    - Calibration
  - Health Electronic Data Sheet (HEDS)
    - Quality of data
    - Codified fault conditions and system phases
    - Key detection algorithms w/ parameters
  - Component EDS (CEDS)
    - Manufacturing details
    - Engineering data
    - Traceability
  - Other EDS

Intelligent Sensors

- Smart sensor
  - NCAP (Go Active, Announce)
  - Publish data
  - Set/Get TEDS
- Intelligent sensor
  - Set/Get HEDS
  - Publish health
- Detect classes of anomalies using:
  - Using statistical measures
    - Mean
    - Standard deviation
    - RMS
  - Polynomial fits
  - Derivatives (1^{st}, 2^{nd})
  - Filtering—e.g., Butterworth HP
  - FFT—e.g., 64-point
  - Wavelet Transforms (segmentation)
  - Algorithms for
    - Flat
    - Impulsive (“spike”) noise
    - White noise
  - Other (ANN, etc.)

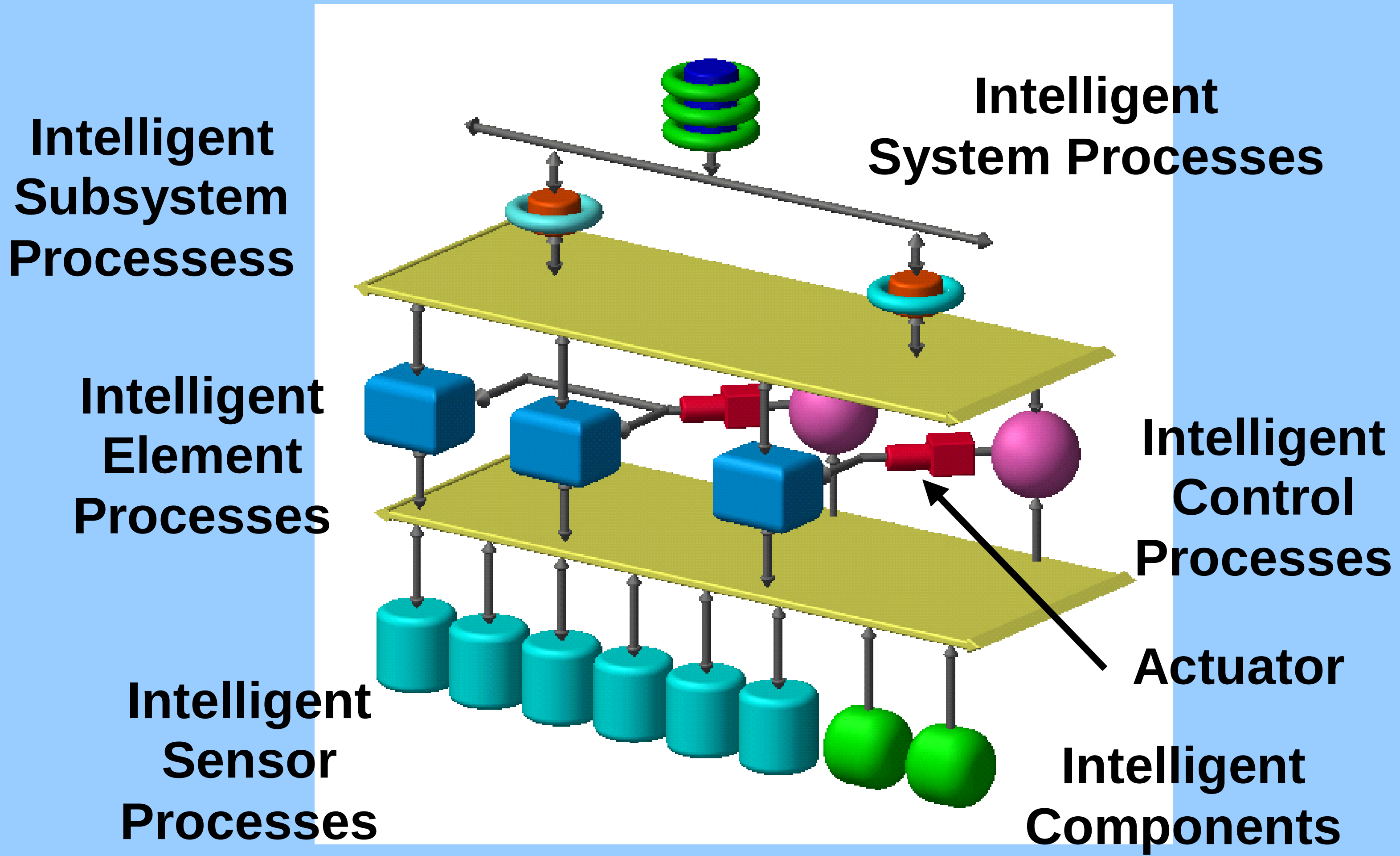


Intelligent Sensors have embedded ISHM functionality and support ***Smart Sensor*** standards

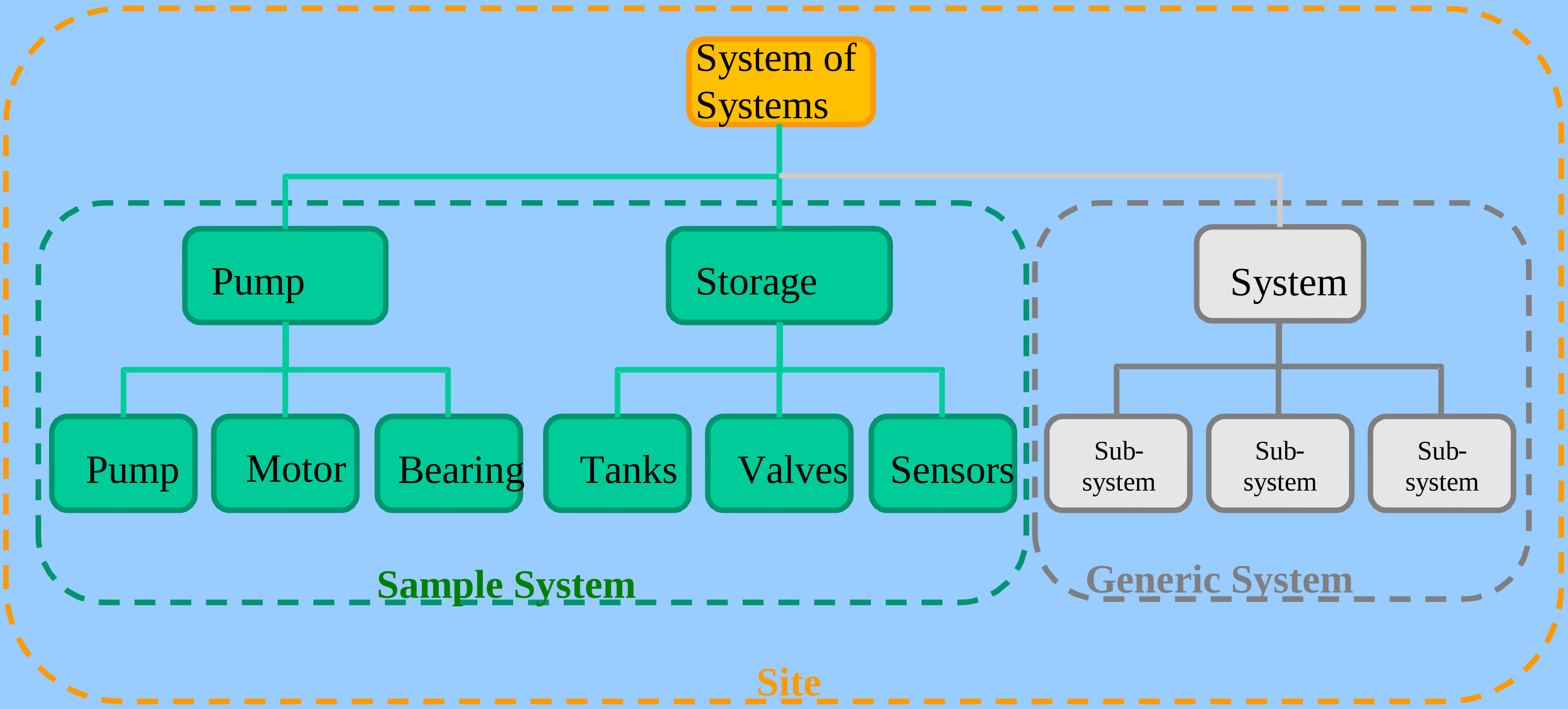
Concepts - Paradigm

- System of connected (networked) intelligent elements.
  - Standards for Plug&Play and Interoperability.
- Compartmentalized DIaK.
- ISHM Subsystem definitions are dynamic, based on current process analysis needs?
- ISHM Subsystems use resources from their intelligent elements, and improve the elements' own health assessment.

Data, Information, and Knowledge Management Architecture for ISHM (Information Architecture)



Classic architecture describing how systems are built



Detection and Confirmation of Anomalies
Consistency Checking Cycle