

# Monitoring System for Storm Readiness and Recovery of Test Facilities: Integrated System Health Management (ISHM) Approach

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## 1 ABSTRACT

Severe weather events are likely occurrences on the Mississippi Gulf Coast. It is important to rapidly diagnose and mitigate the effects of storms on Stennis Space Center's rocket engine test complex to avoid delays to critical test article programs, reduce costs, and maintain safety. An Integrated Systems Health Management (ISHM) approach and technologies are employed to integrate environmental (weather) monitoring, structural modeling, and the suite of available facility instrumentation to provide information for readiness before storms, rapid initial damage assessment to guide mitigation planning, and then support on-going assurance as repairs are effected and finally support recertification. The system is denominated Katrina Storm Monitoring System (KStorMS).

Integrated Systems Health Management (ISHM) describes a comprehensive set of capabilities that provide insight into the behavior—the health—of a system. Knowing the status of a system allows decision makers to effectively plan and execute their mission. For example, early insight into component degradation and impending failures provides more time to develop work around strategies and more effectively plan for maintenance.

Failures of system elements generally occur over time. Information extracted from sensor data, combined with system-wide knowledge bases and methods for information extraction and fusion, inference, and decision making, can be used to detect incipient failures. If failures do occur, it is critical to detect and isolate them, and suggest an appropriate course of action.

ISHM enables determining the condition (health) of every element in a complex system-of-systems or SoS (detect anomalies, diagnose causes, predict future anomalies), and provide data, information, and knowledge (DIaK) to control systems for safe and effective operation.

ISHM capability is achieved by using a wide range of technologies that enable anomaly detection, diagnostics, prognostics, and advise for control: (1) anomaly detection algorithms and strategies, (2) fusion of DIaK for anomaly detection (model-based,

numerical, statistical, empirical, expert-based, qualitative, etc.), (3) diagnostics/prognostics strategies and methods, (4) user interface, (5) advanced control strategies, (6) integration architectures/frameworks, (7) embedding of intelligence. Many of these technologies are mature, and they are being used in the KStorMS.

The paper will describe the design, implementation, and operation of the KStorMS; and discuss further evolution to support other needs such as condition-based maintenance (CBM).

## **MONITORING SYSTEM FOR STORM READINESS AND RECOVERY OF TEST FACILITIES: INTEGRATED SYSTEM HEALTH MANAGEMENT (ISHM) APPROACH**

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**Abstract:** The paper describes the concept, design, and implementation of a monitoring system that is rooted in recent advances in the area of integrated system health management (ISHM). The motivation for a monitoring system was to enable a safe and effective return to normal operations after damaging events such as Hurricane Katrina, as well as to improve readiness in preparation for such events. The system's uniqueness is derived from its architecture that embodies management of data, information, and knowledge (DIaK) distributed across elements of the system. The architecture also defines systems as networked intelligent elements with distributed processing capability, and enables systematic augmentation of monitoring capability as well a scalability to monitor additional systems. Furthermore, the monitoring system allows near real-time analysis; and includes databases that can be accessed for detailed visualization and analysis, as needed.

**Key words:** Diagnostics; Integrated System Health Management; ISHM; Condition-Based Maintenance; CBM; Prognostics; Health.

**Introduction:** Severe weather events are likely occurrences on the Mississippi Gulf Coast. It is important to rapidly diagnose and mitigate the effects of storms on Stennis Space Center's rocket engine test complex to avoid delays to critical test article programs, reduce costs, and maintain safety. An Integrated Systems Health Management (ISHM) approach is employed to integrate environmental (weather) monitoring, structural modeling, and the suite of available facility instrumentation to provide information for readiness before storms, rapid initial damage assessment to guide mitigation planning, and then support on-going assurance as repairs are effected and finally support recertification.

Integrated Systems Health Management (ISHM) describes a comprehensive set of capabilities that provides insight into the behavior—the health—of a system [1-3]. Knowing the status of a system allows decision makers to effectively plan and execute their mission. For example, early insight into component degradation and impending failures provides more time to develop work around strategies and more effectively plan for maintenance.

Failures of system elements generally occur over time. Information extracted from sensor data; combined with system-wide knowledge bases and methods for information extraction and fusion, inference, and decision making, can be used to detect insipient signs of future failure. If failure does occur, it is critical to detect it, find out what failed, and suggest a course of action.

ISHM enables determining the condition (health) of every element in a complex system-of-systems or SoS (detect anomalies, diagnose causes, predict future anomalies), and provide data, information, and knowledge (DIaK) to control systems for safe and effective operation.

ISHM capability is achieved by using a wide range of technologies that enable anomaly detection, diagnostics, prognostics, and user interfaces for integrated awareness and advice for control. Technology areas include: (1) anomaly detection algorithms and strategies, (2) fusion of DIaK for anomaly detection (model-based, numerical, statistical, empirical, expert-based, qualitative, etc.), (3) diagnostics/prognostics strategies and methods, (4) user interfaces, (5) advanced control strategies, (6) integration architectures/frameworks, (7) embedding of intelligence. Many of these technologies are mature, and they are being used in the KStorMS. References [4-14] describe concepts, technologies, and various implementations of ISHM capability.

**Concept of Operations (ConOps):** The Katrina Storm Monitoring System (KStorMS) is designed to provide condition information on a continuous basis for the following facilities: E-Complex, B-Complex, A-Complex, High Pressure Industrial Water Facility (HPIW), High Pressure Gas Facility (HPGF), and the Cryogenics Facility. The concept of operation is represented in Figure 1. ISHM domain models of the facilities are software models that include data, information, and knowledge (DIaK) needed to assess the condition of a facility. The ISHM Domain Models (ISHM-DM's) use data from sensors to determine anomalies or potential anomalies for any configuration reflecting specific phases of operation; be it stand-by, pre-storm, during storm, post-storm, and recovery.

As per Figure 1, data from new wind and structural deformation sensors, along with data from existing facility sensors, are streamed to facility ISHM-DM's; where health assessments are carried out automatically. During normal system operation, the KStorMS makes users aware of anomalies to ensure that critical functions are available and safe. The KStorMS also helps prepare for storm conditions by providing current health information and confirmation of pre-storm configuration. During storms, the KStorMS continuous to operate as permitted by availability of power and network communications. During storms, data and health information might not be available for immediate analysis, but it is stored for delayed (in-depth) analysis. Post storm, the KStorMS provides support for recovery by continuously assessing condition of system elements, thus enabling more efficient planning for recovery. For instance, the KStorMS will indicate if specific sensors are suspect of having failed, or if a sealed subsystem is leaking; providing a graphical immersion that pinpoints the location of suspect elements.

Figure 1. Monitoring System Concept of Operations (ConOps)

**System Description:** The KStorMS consists of the following subsystems:

1. Information architecture.
2. Facility Architecture.
3. Facility Structural and Wind Measurement Systems.
4. Data and Sensor Validation.
5. Health Assessment Data System (HADS)

### SYSTEM DESIGN/IMPLEMENTATION

Wind and Structural sensor data acquisition added to existing facility and test stand sensors and data acquisition and archiving system.  
ISHM Domain Models for facilities and test stands implemented with corresponding integration of structural models.



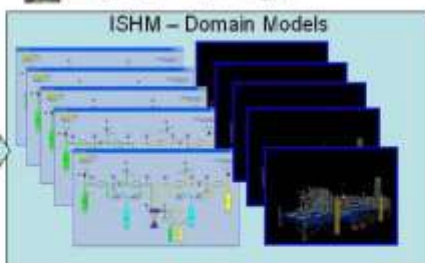
### NORMAL SYSTEM OPERATION

KSMS consoles are available in TCCs and EOC; also network accessible.  
KSMS continuously verifies integrity and availability of KSMS functions.  
Provides status condition of facilities and test stands, and stores information logs.



EXISTING FACILITY SENSORS & DAS

ADDED SENSORS (Wind, Structural)



### DURING STORM

KSMS provides real-time assessment of health and state of facilities to control rooms, Ride-Out crews, EOC, and others.  
Provides critical status alerts.



### POST STORM

KSMS provides tools for assessing status of facilities for near-term re-entry and subsequent remediation actions.  
Supports assessment of mitigation actions and impacts.

## 6. Facility ISHM Domain Models.

Systems Architecture: Figure 2 shows how systems associated with the KStorMS is organized. The architecture shows four blocks that correspond to different physical locations where information is managed. The Facility Block encompasses structural deformation and wind measurements at the facility (e.g. test stand), and streaming of the measurements to a database in the Control Room Block (Facility HADS). The Control Room Block incorporates measurements from the system (e.g. pressures, temperatures, etc. from existing sensors used in the operation of a test stand) into the Facility HADS. The Facility HADS updates the Site Wide HADS at the Stennis Data Center (SDC Block). The G2® [4] Server has the ISHM-DM's of each facility, and uses the information and measurements in the Site Wide HADS to perform the monitoring activities. The G2 Server also stores monitoring results in the Site Wide HADS. User interfaces are at the Emergency Operations Center (EOC) Block. A Telewindows® Client software is used for real-time monitoring, while a HADS Browser will be used for (in-depth) analysis as needed. Other web applications might also use the data and information in the Site Wide HADS. Other user interfaces can also be setup in other locations in the Stennis Network, if desired.

Site-wide Architecture: site wide monitoring is done from the EOC building. Note that monitoring from other stations on the Stennis Network can also be easily implemented. The Storage Area Network (SAN), located at the Data Center provides isolation for the systems at the facilities so that these systems are not visible from outside their private domains.

Facility Structural and Wind Measurement Systems: Structural deformations at key structural elements in the facilities are measured using fiber optic strain gauges (FOSG's). Wind velocity is measured using ultrasonic devices. These are both robust technologies. FOSG's are being used for the first time at Stennis. The purpose of these measurements is to determine when excessive (anomalous) deformations in structural elements supporting critical systems occur. In turn, deformations are correlated with wind measurements, and with outcomes from monitoring the existing facility sensors in the context of a facility ISHM-DM.

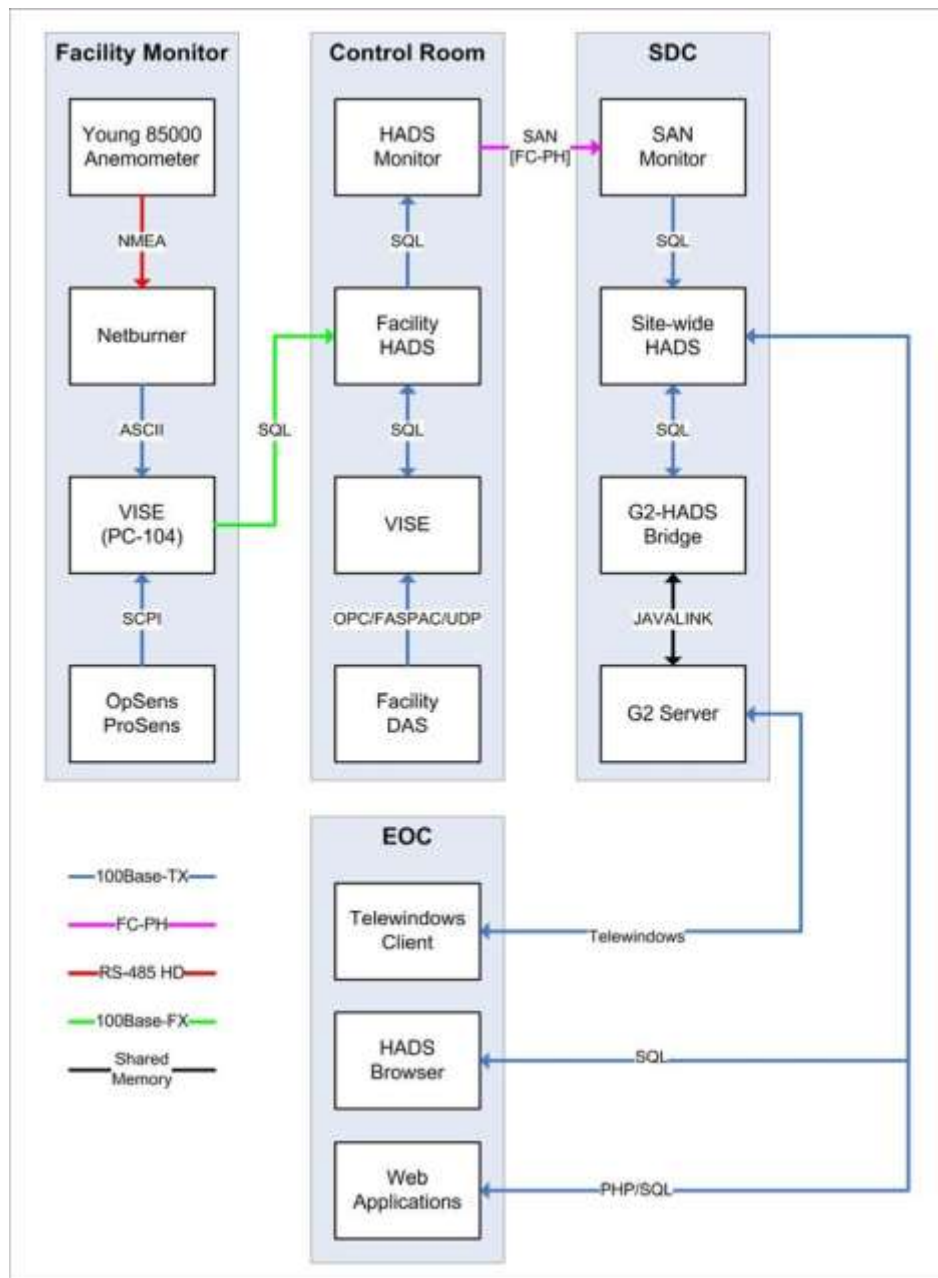
The Facility Monitor Block in Figure 2 shows the elements of the structural and wind measurement systems, encompassing the FOSG system and the anemometer. Both are connected to a PC-104 computer used to configure, control, and collect measurements; and stream measurements to the Facility HADS in the Control Room Block. The FOSG system consists of the gauges and a signal processing box, which is managed by the PC-104 computer. Figure 3 shows a photo of the "as-built" hardware to measure structural deformations and wind velocity.

*Deformation Measurements:* Deformations of structural elements supporting critical systems are measured using the FOSG's. FOSG's were installed in structural members supporting liquid oxygen (LOX), liquid hydrogen (LH2), and Nitrogen tanks and piping. Deformations in these members can be indicators that tanks and pipes might suffer excessive misalignments and stresses. Deformation measurements can also be used to validate structural deformation models that might be created in the future. This is especially important for the A3 Test Stand. These measurements are correlated with wind measurements and anomalies determined in the ISHM-DM.

*Wind Velocity Measurements:* Anemometers were installed to provide local wind velocity that can be correlated with strain measurements and anomalies determined in the ISHM-DM.

Figure 2. StorMS Systems Architecture





### Figure 3. Structural and Wind Measurement Systems

Data and Sensor Validation: Data and sensor health are validated using the Virtual Intelligent Sensor Environment (VISE). VISE capability resides in the Facility Structural Monitor Block and the Control Room Systems Monitor Block of Figure 2. The VISE performs signal processing and sanity checks to help determine if measurements are indeed believable, and if sensors show signs of anomalies. The VISE increases credibility in the KStorMS, by avoiding use of corrupted data and helping detect faulty sensors.

One copy of the VISE is embedded in the PC-104 computers (Structural and Wind Measurement Systems); which also includes interfaces to the anemometer and the FOSG measurements system. A second VISE is in a computer at the Control Room; this computer includes an interface to the facility data acquisition system (Facility DAS). Depending on the facility, this interface might use a specific protocol: UDP in the E complex, FASPAC in the A and B complexes, and OPC in the HPGF.

The VISE processes each stream of data (data streaming from each sensor) by multiple algorithms to determine the following:

1. Operational limit violations.
2. Flat line.
3. Excessive noise level.

Timing for the wind and structural measurement systems is provided by a precision clock in the PC-104 computer, which streams measurements and validation outcomes into the Facility HADS in the Control Room. Timing for the measurements streamed from the Facility DAS is provided by the DAS and is synchronized to IRIG-B.

Health Assessment Data System (HADS): The Facility HADS is a database that contains the following information:



1. Configuration of the facility represented in the Facility ISHM-DM. Configuration information is stored as a Transducer Electronic Data Sheet (TEDS) for each sensor and component, and adheres to templates in the IEEE 1451.4 Standard for Smart Sensors and Actuators.
2. Measurements that are continuously streamed from each facility at an approximate update rate of once per second.
3. Condition information.
  - a. Sensors and Component anomalies.
  - b. Leaks.
  - c. Suspect excessive structural deformations.
  - d. Interlocks occurrences (configuration changes when unsafe conditions occur).

Facility ISHM Domain Models (ISHM-DM'S): ISHM-DM's include DIaK needed to make health assessments, and provide awareness and immediate information about the system health and current configuration. ISHM-DM's constitute the foundation of the monitoring capability, and were developed using a toolkit denominated ISHM Model Building Toolkit (IMBT), which is the result of a collaboration effort between NASA SSC and General Atomics. Description of the toolkit and multiple applications can be found in references [15-22].

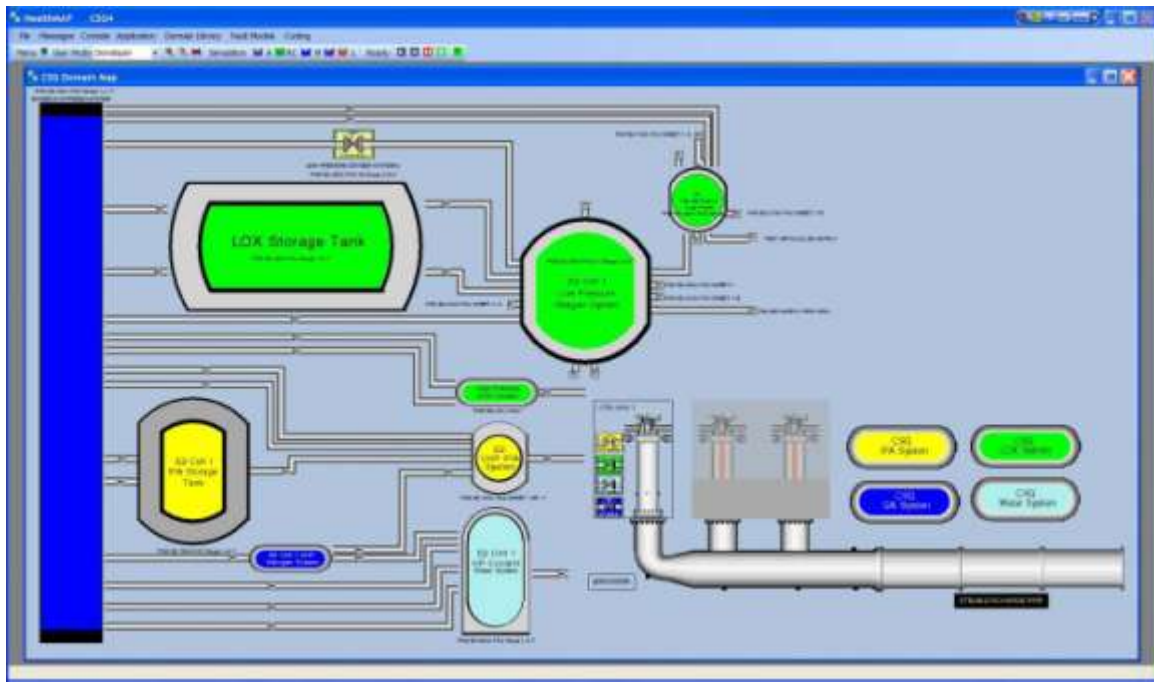
DM's of subsystems deemed critical for the storm monitoring application were developed. In general, they include hydrogen, oxygen, nitrogen, and helium subsystems. The DM's are modular, and all are defined using generic objects of the IMBT, and use resources also available in the IMBT. These DM's can be systematically augmented and refined to accommodate new strategies and technologies to improve the health management capability; be it anomaly detection, diagnosis, prediction of future anomalies, or improvements in user interfaces for integrated awareness.

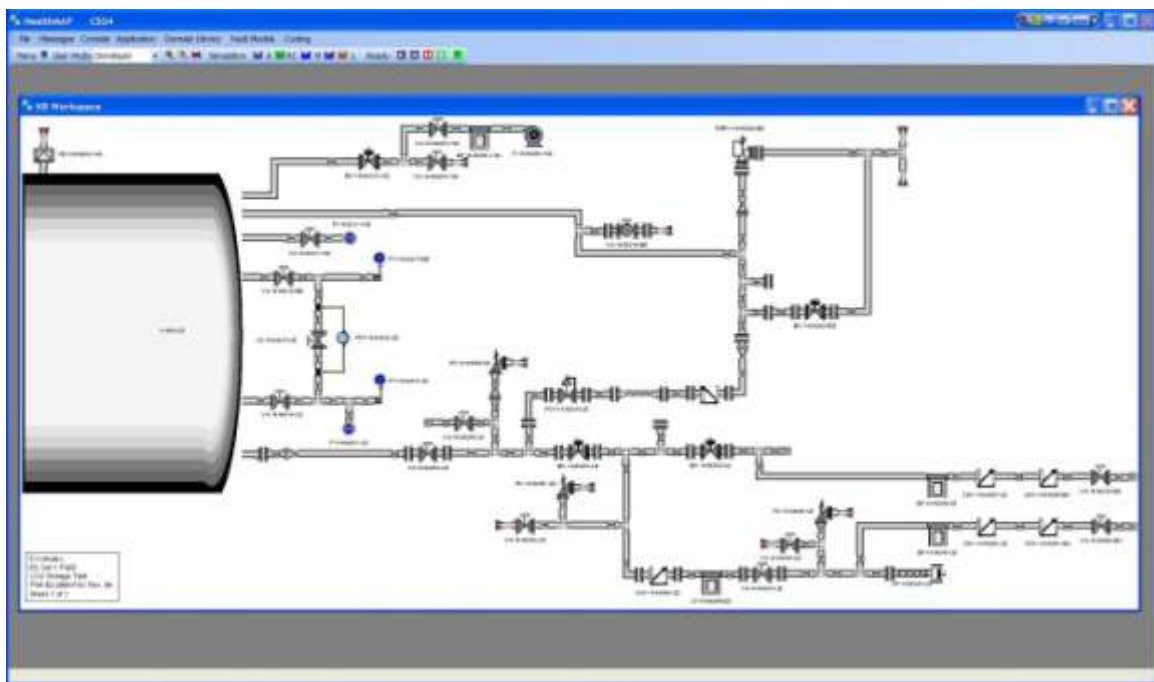
DM's are created from Piping and Instrumentation Diagrams (P&ID's). Each element (sensor or component) in a P&ID is represented as an object in the DM. These elements include attributes such as "measurement value," for a sensor, "condition," and Transducer Electronic Data Sheet or "TEDS." Relationships with other elements such as belonging to a subsystem, or connection to another element are also part of the knowledge-base of the DM. Relationships provide context to apply rules and procedures focused on determining condition.

DM's include user interfaces to navigate the domain and access information about any subsystem or element, showing graphically the physical configuration of a system, replicated from P&ID's. An example top level user interface is shown in Figure 4, and a detailed one is shown in Figure 5. Clicking on a subsystem allows to navigate to a detailed diagram identifying all elements of the system. A menu tool is also available to browse the DM.

Figure 4. Top Level DM showing subsystems.

Figure 5. Detailed DM of a LOX Subsystem.





DM's include windows that display warnings and fault conditions that the ISHM-DM detects (Figure 6). Warnings and faults are associated with elements in the DM. Clicking on an element associated with a warning or fault takes the user to the element in a window showing a detailed DM of the subsystem where the element is located.

DM's include knowledge and procedures focused on determining condition. The following capabilities are available:

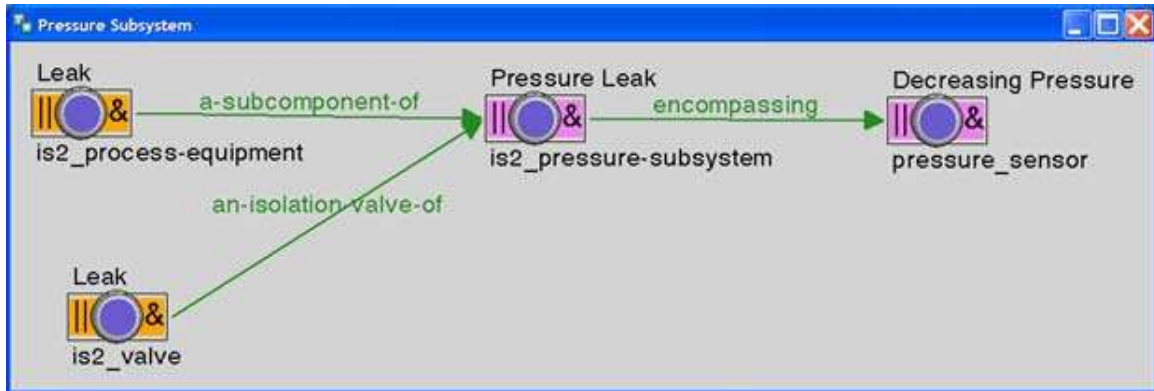
1. Sensor anomalies detection.
2. Structural deformation and wind event detection.
3. Automated, continuous, and comprehensive leak detection on isolated subsystems.
4. Valve state verification whenever a valve command is initiated or if a sensor on a valve is suspect of being anomalous.
5. Interlocks event detection.

Figure 6. Multiple informational windows for anomalies and configuration.

DM's are defined by "intelligent objects" where DIaK is compartmentalized and managed; and also include other elements as described below.

*Sensor Objects:* Sensor objects include the following attributes: measurement, time stamp, anomalies, and TEDS. Measurements can be displayed graphically to visualize trends. TEDS are uploaded from the HADS, and can be displayed at any time. This provides immediate access to sensor specifications. Sensor objects representing thermocouples, pressure sensors, and others are included in the DM. Figure 6 shows viewing of TEDS windows for a sensor object.





*Component Objects:* Component objects have the following attributes: anomalies and component electronic data sheet (CEDs). CEDs are uploaded from the HADS and can be displayed at any time. This provides immediate access to component specifications. Component objects in the DM's include valves, pipes, tanks, etc.

*Sensor Anomalies Detection:* Sensor anomaly indicators are initially determined at the VISE. These indicators are monitored to try to predict when a sensor might be about to fail. Occurrence of the following indicators is displayed for operator review:

1. Operational limit violations.
2. Flat line.
3. Excessive noise level.
4. Sensor not consistent with valve state verification (see section below).

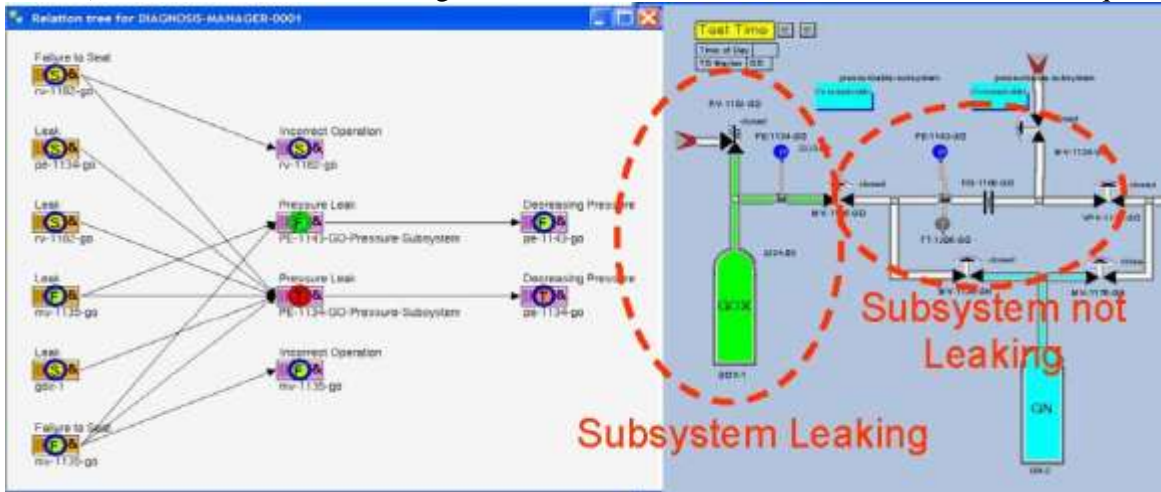
*Structural Deformation and Wind Event Detection:* Structural deformations beyond those observed during normal operating conditions are displayed for operator review. Sensor location and a measure of excess deformation is described, along with respective wind conditions [this capability was not yet implemented at the time this document was prepared].

Figure 7. Root Cause Tree to diagnose and determine consequences of a leak detection event.

*Leak Detection:* The ISHM-DM monitors for leaks in isolated subsystems within which pressure should be maintained. The leak detection methodology is generic, and applies to a class of subsystems (isolated subsystems). At initiation, the DM determines automatically which subsystems are isolated. Every "n" seconds (user definable), the system looks for pressure sensors in each isolated subsystem and checks if pressure is changing beyond a set limit. If pressure is changing, then a leak event for the subsystem is activated. The leak event feeds into the root-cause tree for leaks, at the node "leak" for "isolated subsystems." As a result, all elements of the isolated subsystem become suspect of leak, and all pressure sensors should be seeing changing pressure. If leak detection sensors are present, their input can also be incorporated to reduce the set of suspect elements. Figure 7 shows a root-cause tree where the central node is a leak event in an isolated subsystem. Figure 8 shows the instantiation of the tree in Figure 7 to a specific subsystem. Note that as a result of the leak, each element of the system is determined to be suspect or not leaking. The tree automates determination of causes for the leak and effects of the leak.

Figure 8. Instance of a leak in a particular isolated subsystem, showing a diagram detailing the status of each element associated with the leaking subsystem.

*Valve State Verification:* A valve state verification process is part of the ISHM-DM. This is done by checking consistency among valve sensor data (open limit switch, close limit switch, position feedback) and commands; considering also information on the health of the sensor and the quality of



its data (given that all sensors are “intelligent” elements). This capability allows to ensure that the valve state is determined correctly, and to help determine valve anomalies such as “valve-stuck,” or sensor or command anomalies.

*Interlocks (and redline/blueline) Event Detection and Reporting:* Interlock events occur when conditions indicate that the system must be taken to a safe configuration state. Figure 9 shows an example of a redline event that automatically produces a report. The user interface also allows immediate navigation to the sub-diagram where the redline sensor is located.

User Interfaces for Operators: User interfaces are available at the Data Center and the EOC. There are two types of user interface: (1) Real-Time Monitoring User Interface, and (2) Off-Line Monitoring User Interface.

*Real-Time Monitoring User Interface:* These interfaces are directly in the ISHM-DM, whereby the user is made aware of events as they occur, and can navigate through the model to look for additional information or details.

Figure 9. Redline occurrence detection, reporting, and identification in detailed diagram.

*Off-Line Monitoring User Interface:* These interfaces are to the HADS, whereby the user can analyze historical information going back in time, and also use external tools for additional analysis.

**Conclusion:** The KStorMS described represents a departure from typical approaches to monitoring and condition-based maintenance. It provides continuous vigilance about the condition of each element in a system, by implementing an architecture and technologies that embody DIaK distribution across system elements. Moreover, KStorMS incorporates approaches to analyze conditions of elements based on process models where multiple elements are involved; thus considering consistency checking integrated across elements involved in the same process.

At this time, the implementation is not complete. Final user interfaces are being developed, and some functions are being refined.

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