DEVELOPING "SMART" EQUIPMENT AND SYSTEMS THROUGH COLLABORATIVE NERI RESEARCH AND DEVELOPMENT: A FIRST YEAR OF PROGRESS

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Abstract

The United States Department of Energy (U.S. DOE) created the Nuclear Energy Research Initiative (NERI) in 1999 to conduct research and development with the objectives of: (1) overcoming the principal technical obstacles to expanded nuclear energy use, (2) advancing the state of nuclear technology to maintain its competitive position in domestic and world markets, and (3) improving the performance, efficiency, reliability, and economics of nuclear energy. The NERI program is now beginning its second year with increased funding and an emphasis on international participation.

Among the programs selected for funding was the "Smart Equipment and Systems to Improve Reliability and Safety in Future Nuclear Power Plant Operations". This program is a 36 month collaborative effort bringing together the technical capabilities of Westinghouse, Sandia National Laboratories, Duke Engineering and Services (DE&S), Massachusetts Institute of Technology (MIT) and Pennsylvania State University (PSU). The goal of the Smart-NPP program is to design, develop, and evaluate an integrated set of tools and methodologies that can improve the reliability and safety of advanced nuclear power plants through the introduction of "smart" equipment and predictive maintenance technology that ultimately aides in the reduction of construction, maintenance and operational costs.

To accomplish this goal the "Smart" Equipment program is:

1. Identifying and prioritizing nuclear plant equipment that would most likely benefit from adding smart features,
2. Developing a methodology for systematically monitoring the health of individual equipment implemented with smart features (i.e. "smart" equipment),
3. Developing a methodology to provide plant operators with real-time information through "smart" equipment Man-Machine Interfaces (MMI) to support their decision making,
4. Demonstrating the methodology on a selected component, and
5. Expanding the concept to system and plant levels that allow communication and integration of data among smart equipment.

This paper will discuss (1) the goals and significance of the program, (2) the significant achievements of the program's first year and the current direction for its continuing efforts and (3) potential cooperation with domestic nuclear and component manufacturing industries, and with international organizations.

Background - Smart-NPP Goals and Significance

The subject of the Smart-NPP program inevitably raises two questions. The first is "What do you mean by Smart Equipment?" To respond to this inquiry the Smart-NPP team established the following working definition:

> *"Smart equipment embodies elemental components (e.g., sensors, data transmission devices, computer hardware and software, MMI devices) that continuously monitor the state of health of the equipment in terms of failure modes and remaining useful life, to predict degradation and potential failure and inform end-users of the need for maintenance or system-level operational adjustments."*

With that established, the second question is "So how is smart equipment related to the future of nuclear power?" The second question is not so straight forward, but leads to the discussion of the goals and significance of the Smart-NPP program. The goal of the Smart-NPP program is to design, develop, and evaluate an integrated set of tools and methodologies that can improve the reliability and safety of advanced nuclear power plants through the introduction of "smart" equipment and predictive maintenance technology. When the methodology is completed and smart components and systems are deployed, costs associated with design, unit unavailability and maintenance should be significantly reduced in future nuclear power plants. This concept provides a unique system-level integration of plant maintenance information with real-time sensor data utilizing self-monitoring and self-diagnostic characteristics built into the equipment. The approach is based on a distributed software architecture to facilitate scaling up to enterprise-wide applications, and provides the ability to view real-time equipment performance and safety-related data from remote locations. The development of a Smart-NPP methodology is taking advantage of similar non-nuclear programs that are currently in progress.

The results of the Smart-NPP program have the potential to substantially change the way that nuclear power plants are designed and operated. Nuclear power plant design today is often constrained by the need for frequent access to equipment for inspection and repair. Further, redundancy and diversity of equipment are needed to ensure safety and reliability under a variety of conditions. When combined with the U.S. DOE NERI Risk-Informed program results, that move to a risk-based regulatory approach, the introduction of highly reliable ‘smart’ equipment and systems will allow plant designers to simplify plant designs without compromising reliability and safety. For example, normal operating systems employing smart components may supplement, or even replace, traditional safety systems such as Emergency Core Cooling or Emergency Feedwater. The smart features of the components may provide the basis for assuring that a non-safety system's availability is sufficient to meet Probabilistic Risk Assessment (PRA) goals and the demands of regulators. Such plant design innovation can potentially allow the use of less equipment resulting in more cost competitive and easier-to-construct power plants. Furthermore, the results of the Smart-NPP program will be useful to all reactor technologies (e.g., PWR, BWR, MHTGR, and PHWR), including new technologies that might be developed through other NERI projects (e.g., proliferation-resistant or low-output reactors).

A major contributor to high Operations and Maintenance (O&M) costs are maintenance practices that rely heavily on time consuming procedures. This includes periodic overhaul or replacement of parts is based primarily on historical maintenance records, without regard to the actual “health” of a component or system. The Smart-NPP results are providing a blueprint for creating the capability to predict system performance and remaining useful life with high confidence, based on predictive or condition-based maintenance methods that utilize current and projected conditions of critical components and subsystems to predict their time to failure. This requires understanding how an entire history or profile of sensor information, given specific environmental and operating conditions, relates to component or system wear and age. Such practices allow overhaul and repair to be performed only when necessary to prevent failure and provide a capability for assessing the risk of delaying indicated maintenance tasks. Maintenance methods that predict system performance while utilizing the maximum useful life of subsystems and components represent an innovative and cost saving approach to O&M activities. The overall reduction of the inventory of required plant safety equipment will likely produce an additional O&M benefit due to reduced surveillance testing requirements in Technical Specifications.

Summary of Smart-NPP Accomplishments and Project Plan

The Smart-NPP team is presently embarking on the second year of its three year program with high expectations of realizing a demonstration health monitoring system tied to both a physical, real-world system and a virtual machine simulation by the year's end. A complete description of the project plan for each of six tasks is provided in Reference 1, while Figure 1 provides a project schedule for task activities for the entire program duration. The following is a summary of the significant achievements realized during the past year. These are further explained, along with other achievements, in the following section.

- Developed system/component criteria to establish priorities for smart equipment application and used them to prioritize both PWR and BWR systems
- Based on the prioritization, selected a high energy, horizontal, centrifugal pump as a demonstration component for a Health Monitoring System (HMS)
- Developed an architecture for a HMS using Bayesian Belief Networks (BBNs) to determine failure probability information based on sensor data and conditional probabilities
- Procured the use of a pump lube oil system to supply real-world data to the HMS
- Created the design for a virtual machine for the selected pump to supply simulated reliability and sensor data to the HMS
- Reviewed state-of-the-art pump diagnostics and assessed failure modes of the pump to provide the basis for establishing an optimum health monitoring plan
- Reviewed and assessed sensor technology to develop criteria for sensor element selection and sensor system architecture
- Reviewed smart equipment MMI technology currently being used in other industries to support creation of an MMI prototype
- Established industry contacts for potential cooperative working arrangements

Results and Future Direction of Smart-NPP Tasks

The following sections provide a description of the first year's Smart-NPP results and plans for the remainder of the project organized by the six Smart-NPP tasks.

<u>Task 1: System Evaluation and Prioritization Study</u>

This initial Smart-NPP task has been completed during the first project year. The results are (1) a methodology for systematically evaluating plant structures, systems and components (SSCs) to determine those that would benefit most from application of smart equipment concepts, (2) selection of a demonstration component and (3) an optimum health monitoring plan for the selected component, including identification of its failure modes.

A set of weighted selection criteria were developed focussing on SSC performance and cost/benefit. Key criteria include:

- a high failure rate
- well-known failure modes
- availability of accessible locations allowing sensor installation and data acquisition
- sufficiently long repair time to cause significant lost generation

Table 1
Weighted Results with PWR Data for the System/Component Prioritization

System/Component	Points From I	Points from II	Total Points
Main Turbine	37.9	19.8	57.7
Main Generator	35.2	18.5	53.7
SG Feedwater Pump	27.7	20.8	48.5
Reactor Coolant Pump	27.3	19.3	46.6
Charging Pump	24.0	21.1	45.1
Heater Drain Pump	22.2	15.7	37.8
Auxiliary/Emergency Feedwater System	3.7	10.0	13.7
Diesel Generator	3.1	9.3	12.5
Circuit Breakers	2.9	7.9	10.8
Service Water System	2.5	7.7	10.2
Steam Generator	5.5	4.3	9.8
Main Steam System	6.5	2.6	9.1
Transformer	3.5	3.4	6.9
Control Rod System	4.5	2.4	6.9
Main Feedwater System	5.3	1.6	6.8
Condenser	3.5	1.4	4.9
Circulating Water System	1.6	3.0	4.5
RHR and Low Pressure Safety Injection System	1.0	2.7	3.7
Pressurizer	1.4	1.9	3.3
Condensate System	1.6	1.5	3.1
High Pressure Safety Injection System	0.8	1.5	2.3

Note: Points from I are derived from performance-based criteria including availability
Points from II are derived form cost/benefit criteria

A study of failure rates and failure modes considered data of SSC contributions to forced outages. This study used the NRC MORP 2 Database for Monthly Reports between 1990 and 1999 for 14 PWR and 13 BWR units. SSCs were ranked based on their fraction of the total forced outage time (based on occurrence frequency and mean outage duration). Individual failure modes were similarly ranked for the SSCs with the highest forced outage contributions. This quantitative data was combined with qualitative team assessments of instrumentation feasibility and cost/benefit to result in a SSC prioritization, which is shown in Table 1 for PWRs. The entire results of this effort are captured in the Task 1 deliverable report (Reference 5). The significant result of this effort was identification of rotating machinery, including pumps, as the primary contributors to forced outages in LWRs. This conclusion, coupled with their application in both charging and feedwater systems, led to the selection of a high energy, horizontal, centrifugal pump as the demonstration component for the Smart-NPP project.

The other Task 1 effort explored the nuclear industry's transition from traditional time-based and corrective maintenance methods to Reliability Centered Maintenance (RCM), including application of Condition Based Maintenance (CBM). Methods for monitoring component health being developed in the Smart-NPP program directly support the transition to CBM. Typical pump failure modes were identified and are described fully in Reference 5. Current pump diagnostics however are often limited to characterizing casing vibration via portable sensors. Integration of advanced diagnostic methods including vibration analysis, rotor dynamics modeling, infrared thermography, motor monitoring, lubrication assessment, acoustic monitoring and performance parameter measurement will be critical to developing an optimum HMS for a pump. Other issues identified as critical to the effectiveness of an HMS include (1) sensor adequacy and location, including potential use of "smart" sensors, (2) data acquisition, particularly with respect to assessing the benefits offered by wireless data transmission and (3) selection of algorithms and intelligent processing systems to process the data into useable information. The full results of the optimum HMS evaluation are provided in Reference 5.

Task 2: Sensor Technology and Installation Analyses

Task 2 has featured three somewhat independent aspects of smart equipment development during the first project year. These are (1) sensor selection criteria, (2) use of plant system modeling to support sensor development and (3) a technology assessment of MMI techniques being employed in smart equipment applications in other industries. A deliverable report for the MMI technology assessment has been issued (Reference 6), while a combined report for the first two activities is currently being produced.

Criteria for sensor selection have been developed for both sensor elements and sensor system architectures. Key criteria identified pertaining to sensor elements are (1) the ability to indicate component state based on either the physics of failure mechanisms or a Failure Modes and Effects Analysis (FEMA), (2) the ability to withstand the local environment (e.g., temperature or radiation effects), (3) accuracy and (4) reliability. The criteria identified for a sensor system architecture include (1) flexibility, (2) a web-based design including compatibility with the IEEE 1451 standard, and (3) a wireless data communications network. Of particular note is the potential for wireless data communications to minimize concerns associated with installation feasibility and the cost of wired communication networks. Based on current industry direction, it is recommended that smart equipment networks be compatible with the Bluetooth wireless protocol, which is emerging as an industrial standard.

For high-energy pumps, diagnostic technology in today’s nuclear plants is quite dated. Rotor/bearing dynamic modeling has proven effective in extending the effectiveness of a limited number of sensors in today's pumps. To support development of smart equipment, the failure modes identified in Task 1 were addressed via rotor/bearing dynamics modeling. This effort is resulting in recommended enhancements in sensor placement and sensor development. Additionally, dynamic modeling is being calibrated with pump operating data to provide an array of “virtual” sensors that can aggressively assess the condition of equipment and supply input data to the HMS BBNs. An effort is underway to determine how to best integrate the pump dynamic modeling with the virtual machine pump model.

The MMI technology assessment investigated smart equipment applications in other industries for potential use in nuclear power plants. The technology assessment identified various techniques for presentation of smart equipment and predictive maintenance information, including display and warning techniques. An example of smart equipment MMI is provided in Figure 2. Another result of the investigation was the potential use of smart equipment in control applications. The aerospace industry uses *agents* to both sense and control a dynamic environment to accomplish a predetermined goal. This has the potential in future nuclear plants to move smart equipment from the realm of only monitoring to that of automatic control.

In the next project year the sensor technology and installation task focuses on evaluating advanced sensor technology for applications supporting smart equipment use in nuclear power plants. A methodology for performing sensor installation feasibility studies will be developed and applied to the horizontal, centrifugal pump. Future MMI work will concentrate on developing a smart equipment display set and display features with the end result being a prototype display set for the pump demonstration facility. A human factors validation will assess usability of this MMI from both an operations and a maintenance perspective.

Task 3: Equipment Maintenance and Reliability Simulation ("Virtual Machine") Capability

The efforts of Task 3 are developing a virtual machine for the centrifugal pump with the capability to simulate equipment behavior, such as failures, maintenance (including inspection and repair activities) and user-defined sensor signals. The virtual machine supports design and testing of the HMS, allows evaluation of the benefits of incorporating smart features and provides a platform for realistic demonstrations. Figure 3 illustrates the overall architecture of a HMS with a virtual machine simulating an actual plant component.

The virtual machine depicted in Figure 3 consists of three primary components: a reliability module, a scheduling module and a simulation engine. The reliability model identifies failure modes and their relationships including maintenance impact and effects of aging, based on historical data supplemented with engineering judgement. The scheduling module defines schedules for equipment use and maintenance. The simulation engine generates the components behavior (e.g. state changes) based on inputs from the scheduling module and reliability model and provides it as input to the Computerized Maintenance Management System (CMMS) and the HMS software.

During the first project year the reliability and scheduling module designs have been completed for the centrifugal pump and the simulation engine is nearly completed. An overall HMS architecture integrating the virtual machine, BBNs and MMI is being developed. Software design for the alpha version of all components of the virtual machine has begun and will be completed during the second project year.

Task 4: Smart Equipment Health Monitoring System

Developing methods for taking sensor data from the component monitoring and translating it into information relative to the equipment's health is the heart of the Smart-NPP program. Equipment health can include information about predicted lifetime of the equipment, estimated percentage wear out on various components, recommendations for preventive maintenance activities, predictions of likely failure modes and causes and cost impact of maintenance-related decisions.

A significant accomplishment early in the first project year was the decision to follow the smart equipment methodology outlined in Reference 4. This previous work at MIT provides a structure for developing comprehensive sensor networks and analysis of the resultant data to create an intelligent diagnostic and maintenance advisory system. Adoption of this methodology has provided direction for development of the demonstration HMS. Specifically fault trees have been constructed providing a functional decomposition of the centrifugal pump. Starting at the highest level of "pump failure" the fault trees break down pump subsystems until individual cause-consequence branches are identified.

Also of importance to the HMS development is the endorsement of Bayesian Belief Networks as the engine needed to capture the expertise relating sensor data to system states through the use of conditional probabilities. The BBN approach was selected because (1) it has been shown to work better than rule-based and neural network systems, (2) it is very flexible and tolerant of complexity and (3) it is available on personal computer with a convenient user interface (Reference 4). The HUGIN BBN shell has been selected for use on the project and an initial canned demonstration of its application has been completed. The effort to populate the conditional probabilities based on input from pump and maintenance experts has been initiated. Development and population of the BBNs for the centrifugal pump will continue throughout the next project year.

Two additional activities will be conducted as part of this task during the upcoming year. One is to determine effective data reduction and presentation methods that preserve the essence of the needed information. The second is to determine how to effectively utilize historical reliability centered maintenance (RCM) data, equipment failure reports, and root cause assessments to optimize sensor placement, monitoring techniques, and data processing for the centrifugal pump. Potential incorporation of maintenance data with the sensor data to aid in the prediction of component health will be investigated.

Task 5: Sample Application of Health Monitoring System

Perhaps the most significant accomplishment of the Smart-NPP program to date is the selection of high energy, horizontal, centrifugal pumps as a demonstration component. This pump is used in both charging and feedwater systems for PWRs and was selected based on the criteria established in Task 1. Its selection has allowed subsequent program activities, such as the virtual machine design, to focus methodological developments on a specific application.

Another important milestone has been the identification of a related test bed. The Smart-NPP team concluded that a software only demonstration using the virtual machine could be perceived as doing little to address real world problems in developing a HMS. For example, data acquisition may be much more difficult from an actual sensor network, compared with simulated sensor data acquisition. To address this concern, a pump lube oil test system at Penn State University (see Figure 4) will be utilized for instrumentation and testing of an actual subsystem typical of the selected centrifugal pump. The virtual machine will simulate the remainder of the pump to allow testing of a HMS for the entire component as described in Task 3. A basic structure of the integrated demonstration system is shown in Figure 5. The current goal is to make this a web interface to allow testing and demonstration of the HMS at a variety of locations.

The eventual HMS demonstration will help develop the methodology for systematically evaluating equipment to determine how best to improve its reliability. In addition, it will provide an opportunity to evaluate and optimize ‘smart’ equipment and predictive maintenance strategies and support the MMI validation.

Task 6: Enterprise Level Health Monitoring

This task will develop a methodology that combines equipment-health information from individual components into overall plant-health information. It will expand the health-monitoring concept to system and plant levels, allowing communication and integration of data among the smart equipment, as well as control room systems and plant operators. An advanced information system architecture will be designed to support data transfer and storage at the enterprise scale.

The system will be designed to:

1. Provide data and configuration information required for interpreting and displaying real-time sensor and health data at the component, system, and plant levels,
2. Provide historical performance and maintenance data required for analyzing reliability, spares, and maintenance conditions,
3. Store component, system, and plant configuration models and simulation data,
4. Support data requirements of selected reliability and maintenance analysis techniques.

Though this task is not scheduled until the third project year, consideration is being given to the system and enterprise HMS as the component level work is being carried out.

Cooperation with Industry Initiatives and International Organizations

The Smart NPP program has generated significant interest with component manufacturers, specifically for pumps, and with nuclear industry organizations. Conversely, the Smart-NPP team realizes the potential benefit of such cooperation and is encouraging mutually beneficial participation in the program. Pump companies who have been in contact with the team include Flowserve, Goulds, Ingersoll-Dresser and Textron. Industry contacts currently include the EPRI Monitoring and Diagnostic Center and the EPRI Nuclear Maintenance Application Center Pump Users Group. Working arrangements with some of these organizations are expected in the next project year.

Additionally, there is a mutual interest regarding international participation, partly because the U.S. DOE is encouraging international cooperation with NERI projects. For the Smart-NPP program particular interest has been expressed by Korean nuclear organizations and potential working arrangements are being pursued.

Coordination with Other NERI Programs

The coalition of Westinghouse, Sandia National Laboratories, Duke Engineering and Services and Massachusetts Institute of Technology (MIT) have three NERI funded programs primarily addressing various facets of improving the cost competitiveness of nuclear power through reducing capital cost. Though contractually independent, the three programs are being conducted cooperatively to take full advantage of the synergy that exists between these different facets of nuclear R&D. The Risk-Informed NPP program is aimed at revising costly regulatory and design requirements without reducing overall plant safety by (1) developing risk-informed regulation methods and (2) strengthening the reliability database. The Development of Advanced Technologies to Reduce Design, Fabrication, and Construction Costs for Future Nuclear Power Plants program is integrating (1) advances in information technology in design methods and tools, (2) designs for constructability and (3) collaborative work practices that link project organizations. Both programs have recently completed their first year's task and are proceeding with the remainder of their initiatives.

An effort to systematically integrate the three NERI programs was initiated during the past year. This included (1) identifying information or methods planned to be developed in one program that could significantly benefit the tasks planned for another program, (2) identifying interfaces between programs that currently are not being coordinated, but could produce a synergistic benefit if better coordinated, (3) identifying administrative coordination improvements and (4) assigning individuals from each program to communicate with each other to accomplish coordination of the identified areas. This is intended to be an ongoing process and will be modified over time as the direction, accomplishments and needs of each project are more clearly defined.

Summary

The results of the "Smart Equipment and Systems to Improve Reliability and Safety in Future Nuclear Power Plant Operations" program have the potential to substantially change the way that future nuclear power plants are designed and operated. By providing the capability to predict future component and system performance with high confidence, the development of smart equipment will help improve the cost competitiveness of nuclear power by (1) providing substantial operations and maintenance savings and (2) reducing capital costs by allowing front-line systems in normal operation to supplement or even replace dedicated safety systems.

Upon completion of its first year, the Smart-NPP program is well on its way to achieving the program's goal of designing, developing and evaluating a health monitoring system for a nuclear plant component. Significant achievements this year include:

- Selecting a high energy, horizontal, centrifugal pump, based on SSC prioritization criteria, as a demonstration component for a HMS
- Developing a HMS architecture using Bayesian Belief Networks to relate sensor data to failure probability
- Creating a combination of real-world and simulated input data for the HMS through use of a pump lube oil system and creation of a virtual machine, respectively

- Reviewing and assessing sensor and smart equipment MMI technology as precursors to creating the demonstration system
- Establishing industry contacts for potential cooperative working arrangements

The Smart-NPP team is continuing to make progress, with an eye toward making the best use of industry and international cooperation to extend the potential results of the program.

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4. M.W. Golay, C. W. Kang, "On-line Monitoring for Improved Nuclear Power Plant Availability and Operational Advice", Department of Nuclear Engineering, MIT, February 1998.

5. Mammar Maghraoui, Bilge Yildiz, et al, System Evaluation and Prioritization Report (Task 1), SMART-NPP-I-2-00, June 2000.

6. C. Frank Ridolfo et al, Smart Equipment MMI Technology Assessment Report (Task 2), SMART-NPP-I-3-00, July 2000.

Figure 1: Smart-NPP Schedule for FY99 though FY2001

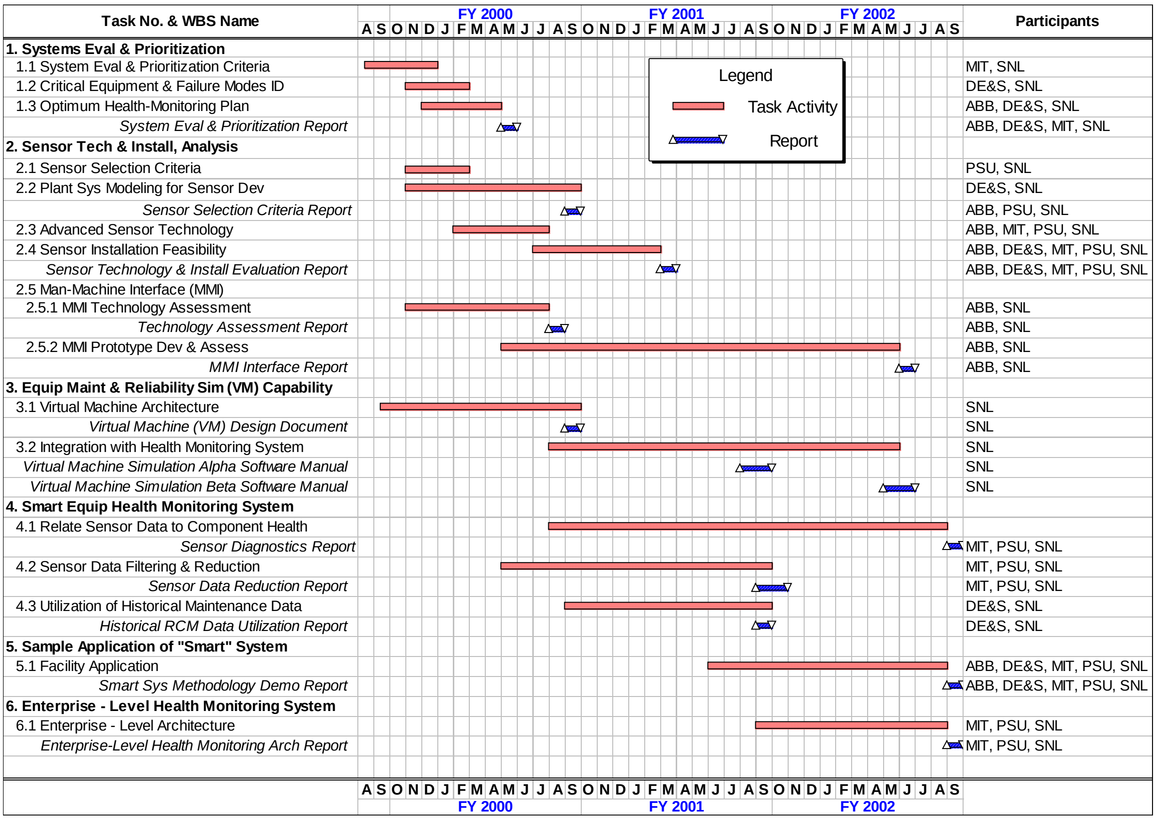

Figure 2: Example Man-Machine Interface for a Smart Component

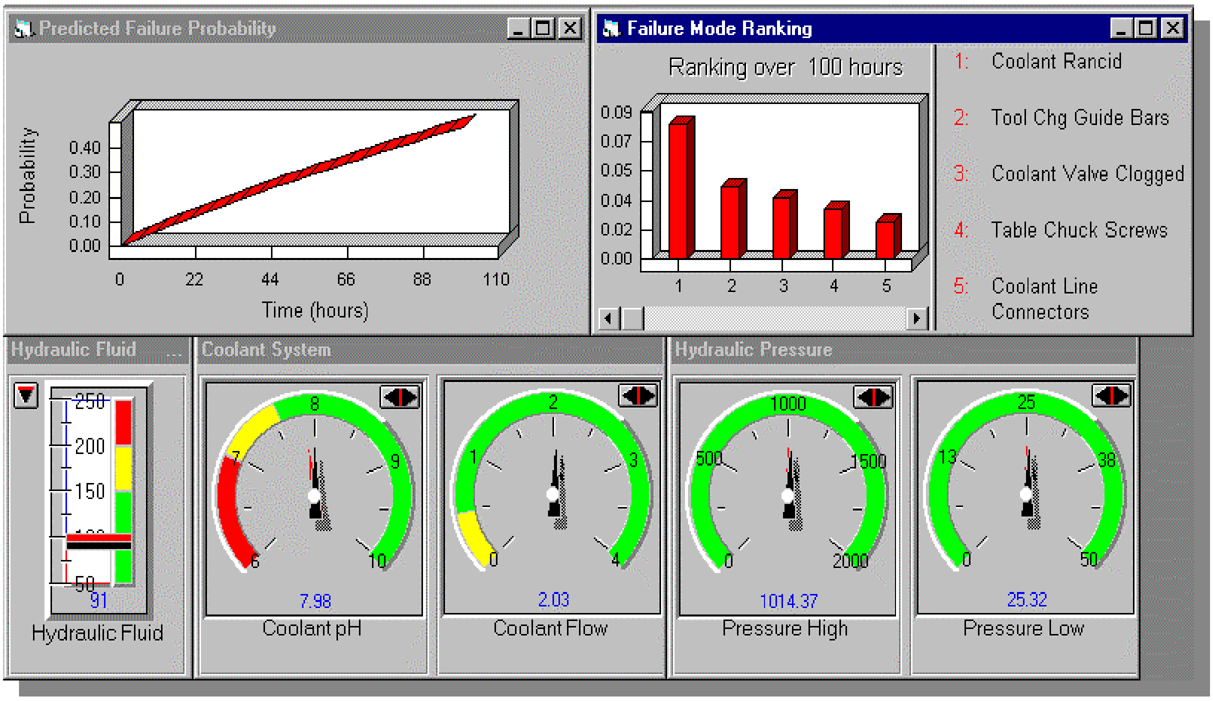

Figure 3: Health Monitoring System Linked to a Virtual Machine

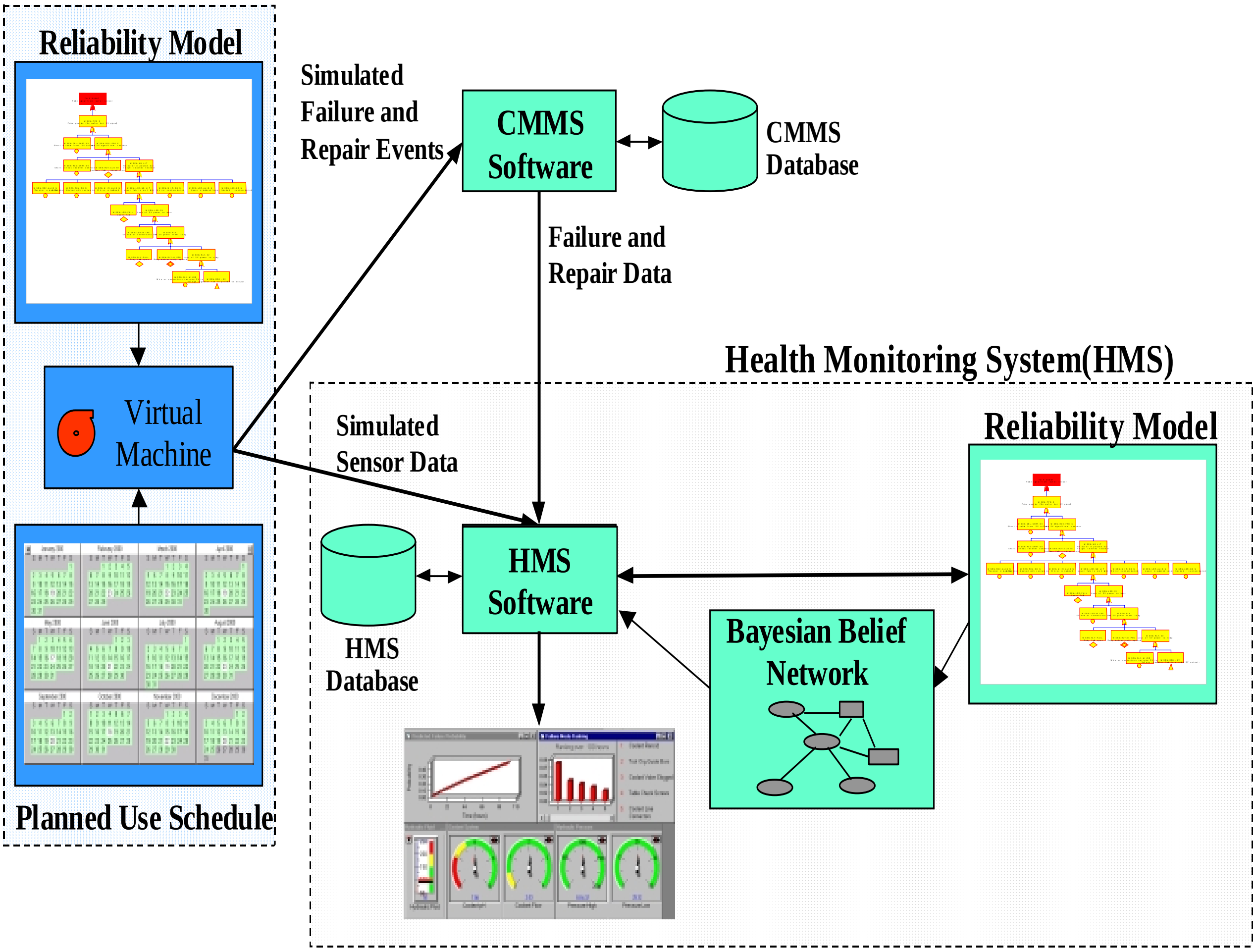

Figure 4: Pump Lube Oil System at Penn State University

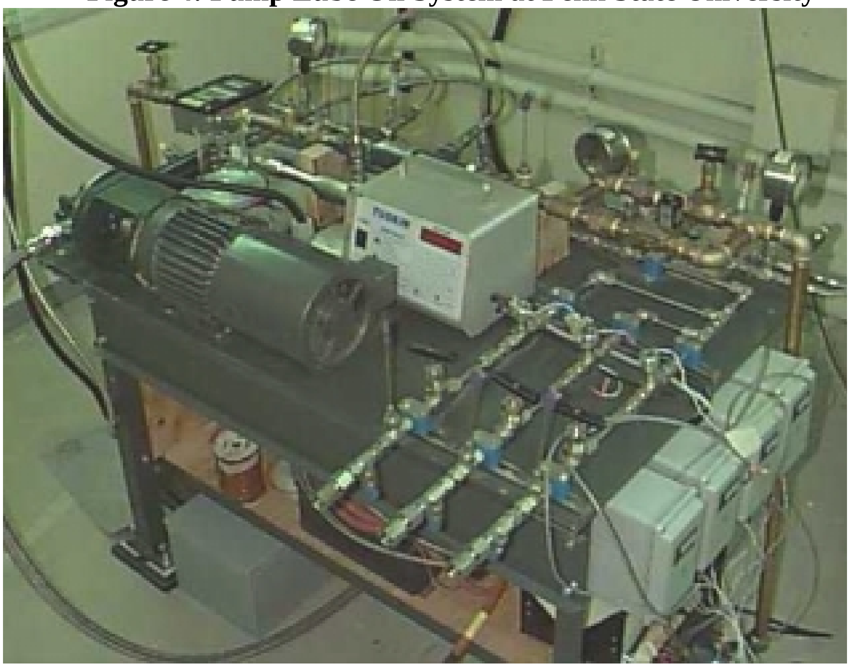

Figure 5: HMS Linked to a Virtual Machine and Physical System