

DEVELOPING "SMART" EQUIPMENT AND SYSTEMS THROUGH COLLABORATIVE NERI RESEARCH AND DEVELOPMENT

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Abstract

The United States Department of Energy initiated the Nuclear Energy Research Initiative (NERI) 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. Fiscal Year 1999 program funding is \$19 Million, with increased funding expected for subsequent years, emphasizing international cooperation.

Among the programs selected for funding is the "Smart Equipment and Systems to Improve Reliability and Safety in Future Nuclear Power Plant Operations". This program is a 30 month collaborative effort bringing together the technical capabilities of ABB C-E Nuclear Power, Inc. (ABB CENP), Sandia National Laboratories, Duke Engineering and Services (DE&S), Massachusetts Institute of Technology (MIT) and Pennsylvania State University (PSU). The program's goal is to design, develop and evaluate an integrated set of "smart" equipment and predictive maintenance tools and methodologies that will significantly reduce nuclear plant construction, operation and maintenance costs.

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

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

This paper will discuss (1) detailed subtask plans for the entire program, including expected achievements, (2) preliminary results from the early program phases and (3) the program's relationship to other NERI programs being conducted by the same team.

A Brief NERI History

In January 1997, President Clinton requested that his Presidential Committee of Advisors on Science and Technology (PCAST) review the current United States energy research and development (R&D) portfolio, and provide a strategy to address the Nation's energy and environmental needs for the next century. In its November 1997 report, the PCAST Energy Research and Development Panel determined that assuring a viable nuclear energy option to help meet the United States' future energy needs is important, and that a properly focused R&D effort should be implemented.

In response to these recommendations the U. S. Department of Energy (U.S. DOE) established the Nuclear Energy Research Initiative (NERI). The NERI program was created to conduct nuclear-related R&D by fostering innovation and new ideas and to enhance cooperation among universities, U.S. DOE laboratories and the nuclear industry. The key technical objectives include:

- Addressing and helping to overcome the principal technical and scientific obstacles to expanded future use of nuclear energy in the U.S., including the issues involving resistance to proliferation, unfavorable economics and nuclear waste disposition,
- Advancing the state of nuclear technology to maintain a competitive position in overseas markets and a future domestic market,
- Promoting and maintaining nuclear science and engineering to meet future technical challenges, and
- Improving the performance, efficiency, reliability, economics, and other attributes to enhance nuclear energy applications.

In response to its subsequent solicitation announcement, the U.S. DOE received 564 pre-applications and 308 full applications for NERI funding. After a selection process, including a peer review element, 46 NERI awards were approved, with contract periods up to three years and contract amounts up to \$2.5 million. NERI funding for FY-99 totaled \$19 million and exceeds \$22 million for FY-2000. Funding is expected to increase in FY-2001 to approximately \$35 million, with a substantial fraction being designated for international NERI efforts.

Success of the ABB CENP/Sandia NL/DE&S/MIT Coalition

To respond to the NERI solicitation announcement ABB CENP, Sandia National Laboratories, Duke Engineering and Services and Massachusetts Institute of Technology (MIT) formed a coalition to propose programs primarily addressing the cost competitiveness of nuclear power through reducing capital cost (Reference 1). Submittal of proposals for the following three programs by the coalition resulted in all three being approved:

- "Smart Equipment and Systems to improve Reliability and Safety in Future Nuclear Plant Operations" (Sandia lead),
- "Risk-Informed Assessment of Regulatory and Design Requirements for Future Nuclear Power Plants" (ABB CENP lead),
- "The Development of Advanced Technologies to Reduce Design, Fabrication and Construction Costs for Future Nuclear Power Plants" (DE&S lead).

Additional organizations are participating in individual programs where specific areas of expertise are needed. 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. A brief description of the latter two programs is provided in the following paragraphs. The Smart Equipment program, subsequently referred to as the SMART-NPP program, is described in detail in the remainder of the paper.

Synopsis of Related NERI Programs

The Risk-Informed NPP program is aimed at revising costly regulatory and design requirements without reducing overall plant safety. Its two basic tasks are (1) Development of Risk-Informed Methods and (2) Strengthening the Reliability Database. The overall objective of the first task is to develop a scientific, risk-informed approach for identifying and simplifying deterministic industry standards, regulatory requirements, and safety systems that do not significantly contribute to nuclear power plant reliability and safety. The second basic task is to develop a means for strengthening the reliability database, along with the data collection and evaluation methods, that will be needed to evaluate the safety and reliability of future nuclear power plant designs. Reference 2 provides a complete description of this program.

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. Proposed improvements point towards meaningful reductions in the length of time and total cost of the design, procurement, construction, installation and testing cycle for future nuclear power plants. The work is focusing on developing a Product (or plant) model, a Productivity (or schedule) model and a Process (methods and practices) model. In parallel to the model development an initial set of benchmarks are being developed to allow assessment of proposed practices and techniques to reduce capital costs. Reference 3 provides a more complete description of this program.

Smart-NPP Goals and Significance

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.

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. 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 includes a distributed software architecture that allows scalability 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 will take advantage of non-nuclear programs that are currently in progress. When the methodology is completed and smart components and systems are deployed, costs associated with design, plant unavailability and maintenance will be significantly reduced in future nuclear power plants.

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 is often restricted 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 Risk-Informed program results that move to a more 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 Emergency Core Cooling or Emergency Feedwater safety systems, obviating the current degree of safety system redundancy. 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 inefficient and costly 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 will provide a blueprint for creating the capability to predict system performance with high confidence, based on predictive and 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 Smart-NPP Project Plan

The research project will begin with a system evaluation and prioritization study that will identify and prioritize nuclear plant equipment that would most likely benefit from the addition of 'smart' features. Advanced sensor technology will be evaluated to determine its adequacy for implementing smart features. An optimum equipment health-monitoring system will be developed for individual pieces of smart equipment. The health monitoring system will include a "virtual machine" capability to simulate equipment behavior over future time intervals in order to evaluate the overall benefits to system performance by incorporating smart features into the design.

Methodologies will be developed for consolidating and presenting the data obtained from 'smart' equipment as readily understandable health information for the smart plant. A strategy will be developed for providing the smart equipment information to plant operators, maintenance personnel, and plant management that is integrated with existing Man-Machine Interface (MMI) systems. For example, this may include capabilities for success path monitoring of safety systems.

The results of the Smart-NPP program would be unconvincing if limited to paper-only methodological results. Thus the equipment health-monitoring methodologies will be combined with the operator interface methodologies to develop a demonstration of the smart system. A specific result from this task will be a detailed, documented example of how to apply smart features to a specific nuclear plant component and how that may be extended to variety of equipment types. A design methodology allowing communication and integration among the smart components, control room systems, and plant operators will also be provided. A physical test bed will be used to conduct selected parts of the demonstration.

While it is obviously beneficial to perform health monitoring on individual pieces of equipment, the ultimate goal is to develop methodologies to combine health-monitoring information into a plant-wide system. This extension will improve operations and facilitate predictive maintenance on a plant-wide scale. Thus in addition to providing a demonstration example, the Smart-NPP program will expand the concept of smart equipment to system and plant levels. This effort will look beyond systems that improve the reliability and safety of specific pieces of equipment, and determine how to integrate such systems plant-wide.

Figure 1 provides a project schedule for the task activities for the entire program duration.

Detailed Plans for Smart NPP Activities

The following sections provide a brief description of each of the Smart -NPP project activities.

System Evaluation and Prioritization Study

The initial Smart-NPP activity will develop a methodology for systematically evaluating plant equipment and systems to determine an optimum health-monitoring plan. Due to limited resources, it will be necessary to prioritize the equipment at a nuclear power facility to identify those that will derive the greatest benefit from application of smart equipment technology. Similar criteria will be used in the Smart-NPP program itself to prioritize candidate components for selection of a demonstration component. Weighted prioritization criteria will be developed that include historical data indicating contribution to lost operational availability and potential contributions to capital cost reduction via contributions to the other NERI programs.

Based on the rankings of subsystems important to system availability, a methodology will be developed to identify critical equipment and failure modes. Equipment criticality will be identified using a reliability centered maintenance (RCM) methodology. Failure modes and root cause data from maintenance optimization projects and root cause assessments of nuclear plant equipment will contribute to this effort. These failure causes represent the primary targets for additional sensors to help detect incipient failures thus making the equipment 'smart'. Current health monitoring philosophies will be investigated to generate a plan for integrating individual signals into a system that gives an overall picture of the health of a system or component. The selected demonstration component will serve as an example application of the resulting optimal health monitoring plan.

Sensor Technology and Installation Analyses

The sensor technology and installation task focuses on evaluating the availability and adequacy of sensor technology needed to implement 'smart' equipment in future nuclear power plants. The criteria governing the selection of a particular sensor set are its ability to indicate the state of the system and withstand the local environment. As sensor capability is state-dependent, characterization of failure modes and causes on critical components must be identified, tabulated, and evaluated for detecting impending or potential equipment failure effectively. An assessment of existing sensor effectiveness will be conducted leading to a matrix of sensor (and associated diagnostic) effectiveness for the critical components. Innovative use of existing or recently developed sensor technology will be examined for suitability, resulting in an equipment-sensor matrix that will also serve to identify sensor technology needs.

For the smart equipment concept to be successful, accurate plant system modeling is needed. Representative system models, used by nuclear steam supply systems Original Equipment Manufacturer (OEM's) in plant design, will be reviewed and enhanced. Operating functional models of the specific component selected for demonstration will also be reviewed. A pilot system model and associated component model will be exercised to demonstrate their interaction and effectiveness for assisting in smart equipment sensor selection and development.

Advanced sensor technologies will be evaluated for use in commercial nuclear applications. This effort will evaluate application of networked, digital sensors, including consideration of wireless networking. Methods for verifying sensor integrity will be investigated as a necessary part of condition-based maintenance. Sensor technology evaluations will consider application of the Intel "RAD-HARD" Pentium chip in smart equipment for nuclear power applications. This breakthrough could allow microprocessor-based sensors to be used for in-containment equipment where the concept was not previously feasible due to the radiation environment. A methodology for performing sensor installation feasibility studies will be developed and applied to the selected demonstration component.

Man-Machine Interface

To ensure that trained operators can readily interpret the health status of the smart plant, methodologies are needed for consolidating smart equipment data into effective end-user information. To meet these requirements, original research and development will be combined with results from

other tasks to produce state-of-the-art recommendations for smart equipment MMI. A smart equipment MMI technology assessment will explore current methods of aggregating sensor data and real-time presentation of probabilistic information from smart equipment in other industries. The virtual simulation capabilities and the component demonstration will offer opportunities for MMI prototyping. A demonstration of proposed displays and of the methodology for their development will be provided.

Equipment Maintenance and Reliability Simulation ("Virtual Machine") Capability

This task will develop a capability to simulate equipment behavior over future time intervals in order to evaluate the overall benefits to system performance by incorporating smart features into the design. A major issue in developing the smart machine concept for nuclear power plant equipment is the unavailability of a test bed that can provide rapid turn-around for test results. Real equipment, no matter how well suited for the smart machine concept, experiences failures and repairs at a rate that is far too slow to fully support design and optimization of the smart machine system. For example, rules must be developed and tested to allow the smart system to "learn" the equipment being monitored and for making "repair/do not repair" recommendations. For these reasons, a means of simulating equipment behavior is required. In effect, a "virtual machine" is needed that can realistically generate the same failure, inspection, and repair events that real equipment experiences.

Object oriented design principles will be applied to give the virtual machine properties, methods, and events that allow it to mimic the reliability, inspection, and maintenance characteristics of real equipment. The virtual machine has at least three possible uses in the Smart-NPP program:

1. Rapid testing and optimization of the rules that govern smart equipment decision making,
2. Estimating the gains, in terms of increased availability, of applying the smart equipment concept to specific components, and
3. Providing a capability for projecting actual machine performance as an integral part of the smart machine system

Smart Equipment Health Monitoring System

Developing methods for taking sensor data from the component monitoring and translating it into information about 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, and predictions of likely failure modes and causes.

The following types of analysis will be evaluated for diagnosing and predicting equipment health from sensor data:

- *Trend analysis* requires holding a history of a particular sensor reading and extrapolating it to project when that sensor reading may reach a critical threshold,
- *Regression analysis* employs methods such as least squares to fit previous sensor data (input) to a variable indicating equipment health (such as wear fraction),
- *Analytical equations*, such as the Arrhenius equation, power curves, or exponential functions, can be used to estimate component life as a function of input stressors (such as temperature),
- *Expert systems* include neural networks, rule-based systems, and/or Bayesian Belief Networks (BBN) to predict equipment health from a large number of sensors.

Specific monitoring plans for components such as piping, tanks, pumps, turbine/generators will be developed. For each component-monitoring plan, a sensor(s) will be identified along with the relationship between the sensor readings and the component health.

Health-monitoring systems often require processing enormous amounts of data. Effective reduction of this data that preserves the essence of the needed information is critical. Various methods of data

reduction will be investigated including: (1) low-level data manipulation, (2) filtering via signal-processing techniques, (3) non-parametric methods, (4) cluster analysis, (5) feature extraction algorithms to detect shifts, peaks, spikes etc. (6) correlation analysis and multiple regression testing, and (7) sensor fusion.

The effective utilization of historical reliability centered maintenance (RCM) data, equipment failure reports, and root cause assessments to optimize sensor placement, monitoring techniques, and data processing will be evaluated. Potential incorporation of maintenance data with the sensor data to aid in the prediction of component health will be investigated.

Sample Application of 'Smart' System

This task will identify and implement an application of the concept of 'smart' equipment. This task was initially intended to build off a separate ongoing activity for a non-nuclear manufacturing facility. It has been redirected to a demonstration application of smart technology on a typical nuclear power plant component, to assure relevance of the findings to the NERI program.

The 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. This task will help develop the design methodology needed to allow communication and integration among the smart components and prototype control room systems. Furthermore, this application will provide the test bed to help refine the virtual machine capability.

Enterprise Level Health Monitoring

This task will develop a methodology that combines equipment-health information from individual machines 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 machine, system, and plant levels,
2. Provide historical performance and maintenance data required for analyzing reliability, spares, and maintenance conditions,
3. Store machine, system, and plant configuration models and simulation data,
4. Support data requirements of selected reliability and maintenance analysis techniques.

Significant Results to Date

Though the Smart -NPP program began only six months ago, the project team has achieved significant results.

Ranking of PWR and BWR Components

Nuclear power plant systems and components that are potential candidates for smart equipment monitoring were prioritized with respect to their contribution to lost plant availability based on data extracted from an industry database (for selected plants from 1990 to 1999). A ranking was established for both U.S. PWR and BWR plants, the results of which are shown in Table 1. For the most significant contributors, a ranking of the individual causes that contribute to lost operational availability was also made. Criteria have been developed to select potential demonstration components from these lists of smart equipment candidates.

Selection of a Demonstration Component and Test Bed

A major accomplishment of the Smart-NPP program to date is selection of high energy, horizontal, centrifugal pumps as a demonstration component. This pump is used in both charging and feedwater systems for PWRs. This component was chosen based on the criteria established in the previous activity, including contribution to unavailability, historical data on failure causes and mechanisms and potential relevance to capital cost reduction. Its selection allows subsequent program activities to focus methodological developments on this example application.

Another important milestone is identification of a related test bed. A pump oil lube test system, which is available at Penn State, will be utilized for actual instrumentation and testing of a subsystem typical of the selected centrifugal pump. In addition, the team has created a basic structure of the intended demonstration system as shown in Figure 2.

Selection of a Basic Smart Equipment Methodology

Another significant early accomplishment of the team is 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 data provided from them to create an intelligent diagnostic and maintenance advisory system. Adoption of this methodology has provided direction to identification of critical failure modes and development of an optimum health monitoring plan.

Of particular importance is the endorsement of Bayesian Belief Networks (BBN) as the engine needed to capture the expertise relating sensor data to system states for the health monitoring system. The BBN has been shown to work better than rule-based and neural network systems. The BBN approach is very flexible, tolerant of complexity and available on personal computer with a convenient user interface. The success of this effort will be measured by how well the parameters governing the relationship between the sensor input and the equipment health can be identified.

Table 1 Systems/Components Rank According to Contribution to Total Forced Outage Length

Rank	PWR Ranking	BWR Ranking
1.	Auxiliary/Emergency Feedwater System	Feedwater System
2.	Circuit Breakers	Main Turbine
3.	Diesel Generator	Condenser
4.	RCP	Main Generator
5.	Service Water System	Transformer
6.	Steam Generator	Diesel Generator
7.	Main Turbine	Recirculation System
8.	Main Steam System	Main Steam System
9.	Transformer	Electrical Systems
10.	Generator	Switch Yard
11.	Control Rod System	Coolant Injection System
12.	FW System	Condensate System
13.	Circulating Water System	Drywell
14.	Condenser	Instrumentation - Air Supply
15.	RHR and LP Safety Injection System	Reactor Water Cleanup System
16.	Pressurizer	Steam Extraction System
17.	Condensate System	Cont. Isolation System
18.	HP Safety Injection System	Reactor Protection System
19.	SG Feedwater Pump	Circulating Water System
20.	Heater Drain Pump	
21.	Charging Pump	

Summary

The "Smart Equipment and Systems to Improve Reliability and Safety in Future Nuclear Power Plant Operations" program was selected for the U.S. DOE's NERI funding. The program's goal is to design, develop and evaluate an integrated set of "smart" equipment and predictive maintenance tools and methodologies that will significantly reduce nuclear plant construction, operation and maintenance costs by:

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 pieces of equipment implemented with smart features (i.e. "smart" equipment),
3. Developing a methodology to provide plant operators with real-time information through "smart" equipment MMI to support their decision making,
4. Demonstrating the methodology on a targeted component and/or system,
5. Expanding the concept to system and plant levels that allow communication and integration of data among smart equipment.

The results of the SMART-NPP program have the potential to substantially change the way that nuclear power plants are designed and operated. Restrictions on nuclear power plant design for frequent access to equipment for inspection and repair and redundancy and diversity needed to ensure safety and reliability may be eliminated while maintaining acceptable safety and availability. The Smart-NPP results will also provide a blueprint for creating the capability to predict system performance with high confidence, based on predictive and condition-based maintenance methods that utilize current and projected conditions of critical components and subsystems. This can result in substantial operations and maintenance savings for future nuclear power plants.

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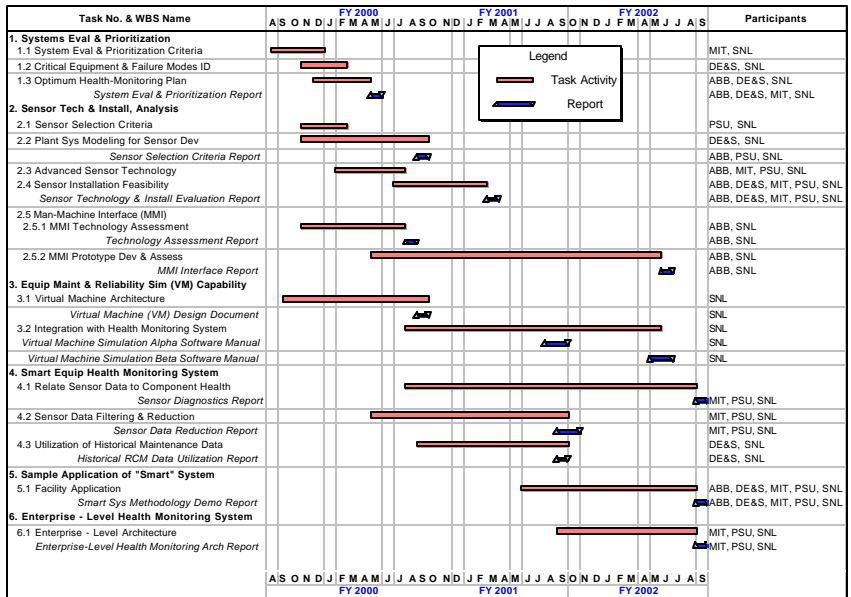


Figure 1 Smart-NPP Schedule for FY99 though FY2001

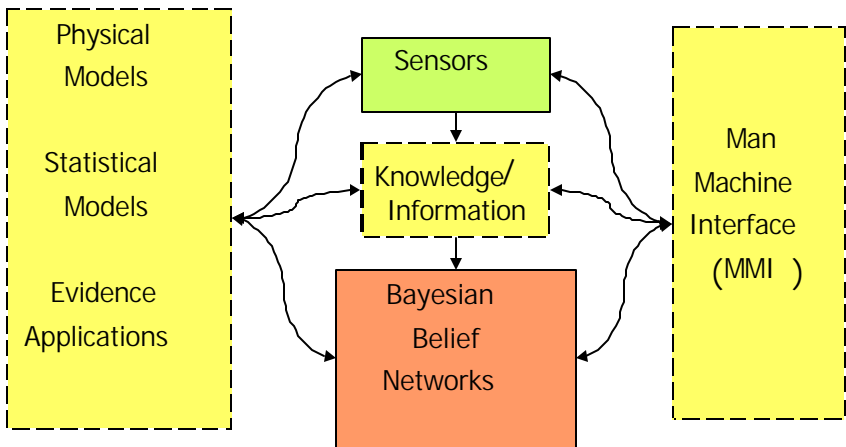


Figure 2 Structure for the Smart Equipment Demonstration System