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Nuclear Energy Research Initiative (NERI)

On-Line Intelligent Self-Diagnostic Monitoring For Next Generation Nuclear Plants Phase I Annual Report

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NUCLEAR ENERGY RESEARCH INITIATIVE (NERI)
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ANNUAL REPORT
FY 2000

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Abstract

The objective of this project is to design and demonstrate the operation of the real-time intelligent self-diagnostic and prognostic system for next generation nuclear power plant systems. This new self-diagnostic technology is titled, *On-Line Intelligent Self-Diagnostic Monitoring System (SDMS)*. This project provides a proof-of-principle technology demonstration for SDMS on a pilot plant scale service water system, where a distributed array of sensors is integrated with active components and passive structures typical of next generation nuclear power reactor and plant systems. This project employs state-of-the-art sensors, instrumentation, and computer processing to improve the monitoring and assessment of the power reactor system and to provide diagnostic and automated prognostics capabilities.

Accomplishments in FY 2000

Task 1: Design of Experimental Hardware and Software:

The project investigative focus was established by utilizing relevant Nuclear Regulatory Commission (NRC) Nuclear Plant Aging Program data to define which degradation mechanisms have the greatest applicability to tomorrow's nuclear platforms. An open architecture multi-module design SDMS architecture has been completed. System computing hardware has been configured and is operational in the laboratory.

Analytical Development: Preliminary examination of cavitation from a first principles perspective shows sufficient material exists to commence physics modeling studies. Work on other stressor - degradation correlations must wait for additional phase studies.

Task 2: Wireless Communication: Radio Frequency Modules and Sensors

Two radio frequency (RF) smart modules were fabricated and successfully deployed on the experimental test loop. A visual basic program running on the PC communicated with the reader (RS-232 link). The reader passed the data to the PC where it was displayed in graphical form. Both RF modules have onboard liquid crystal displays (LCD) for local status and diagnostic presentation. Each module has a unique address allowing for additional sensor modules to be linked to the system.

Task 3 and 4: Fabrication of SDMS Demonstration System and SDMS Test-Bed

The experimental test apparatus was received and the basic loop components and process instrumentation installed to allow component operational ranges (experimental envelope) to be verified. The test bed will simulate conditions experienced by low temperature reactor auxiliary systems. The "fouling meter" was demonstrated using an ultrasonic pulse-receiver and digital oscilloscope. Initial specifications were developed for the necessary semi-custom transducers that will be procured in Phase II. Initial pilot plant trials were performed. The updated system design and safety review for the Phase I as-built system were completed. An RF-multi-sensor module has been installed and tested using temperature and other system data. A draft standard operating procedure for initial trials has been completed.

Task 10: Project Management

The project activities were successfully accelerated to get the test bed system up and running to provide significant and reportable progress for the June program review. All Task 1- 4 milestones were completed to meet the planned schedule. Phase I was completed ahead of schedule and within budget constraints.

Executive Summary

The objective of this project is to design and demonstrate the operation of the real-time intelligent self-diagnostic and prognostic systems for next generation nuclear power plant systems. This new self-diagnostic technology is titled, *On-Line Intelligent Self-Diagnostic Monitoring System (SDMS)*. This project provides a proof-of-principle technology demonstration for SDMS on a pilot plant scale service water system, where a distributed array of sensors is integrated with active components and passive structures typical of next generation nuclear power reactor and plant systems. This project employs state-of-the-art sensors, instrumentation, and computer processing to improve the monitoring and assessment of the power reactor system and to provide automated prognostics capabilities.

The project scope is to develop and demonstrate advanced predictive technologies for a fault-tolerant health monitoring system. This system will be demonstrated on a test-bed that includes selected key elements found in next generation nuclear reactor systems.

The objectives of this project will be accomplished in three phases over a three-year period as described in the project management plan (PMP)¹. A total of eight tasks have been authorized. Phase 1, which initiates PMP Tasks 1, 2, 3, 4, and 10, is addressed in this annual report and is summarized here.

Significant project concepts and their potential for other applications:

- The “computer on a chip” component used for distributed data processing is significant as it gets data management down to the lowest possible level and is not affected by system level failure.
- The RF smart module is significant as the first wireless application of data management and collection in this type of environment.
- Intellectual property opportunities are high; one invention disclosure has already been submitted for a unique laser alignment tool as a result of this research direction.
- The Ford Motor Company and the U.S. Navy’s Office of Naval Research in their advanced amphibious assault vehicle watercraft development have indicated substantial interest based on this project concept.

Accomplishments in FY 2000

Task 1: Design of SDMS System Architecture and Demonstration System

This task has two components. The first component was the development of the SDMS project focus, computer architecture, and the associated evaluation methodologies that will then be evaluated and refined (Tasks 4 and 5). The second component was the design of a specific SDMS demonstration system to be fabricated in Tasks 2 and 3. The demonstration system is to be used in subsequent trials (Task 6) to validate the architecture and to demonstrate the effectiveness of this approach to health monitoring as applied to complex mechanical systems.

Task 1 Accomplishments:

The project investigative focus was established by utilizing relevant NRC Nuclear Plant Aging Program data to define which degradation mechanisms have the greatest likelihood to be present in tomorrow's nuclear platforms. The project focus is being documented in the Aging Phenomena Specification report, which is being developed and outlines the identified modes, mechanisms and related field stressors for study in this project.

The design of the SDMS architecture has been completed. The information processing and reporting hierarchy follows accepted nuclear plant taxonomy:

<u>Level 1: PLANT</u>	integrated systems perspective
<u>Level 2: SYSTEM</u>	common working fluid boundary definition
<u>Level 3: COMPONENT</u>	a specific process artifact (pump, filter, valve)

Commercial off the shelf software (COTS) utilized with an optimized process control (OPC) server module has been developed to allow inter-module open architecture communication. System computing hardware has been configured and is operational in the laboratory. The diagnostic processing requirements for lower (component specific) levels have been increased in light of the incorporation of a "computer on a chip" concept that will allow full diagnostic computation at that level. This concept will be developed further during Phase II. A graphical user interface (GUI) display has been designed and developed.

Analytical Development: Preliminary examination of cavitation from a first principles perspective shows sufficient algorithms modeling exists to commence physics modeling studies. Work on other stressor-degradation correlations must wait for additional phase studies.

Task 2: Wireless Communication: RF Modules and Sensors

This task is to complete the detailed design, fabrication, and testing for the advanced smart multi-sensor RF modules that will serve as the Level 3 (component) nodes in the SDMS hierarchy. The smart multi-sensor tag (SMST) will provide for wireless data communication links between distributed sensors and the Level 2 (system level) processing nodes.

Task 2 Accomplishments: Two radio frequency (RF) modules were fabricated and successfully deployed on the experimental test loop. The RF sensor module was wired to 12 separate sensors monitoring loop operational parameters such as temperature, flow, etc. The other RF module (known as the integrator or reader) was interfaced to a desktop PC. A visual basic program running on the PC communicated with the reader (RS-232 link) who then commanded the module to acquire sensor data and transmit the data back to the reader. The reader passed the data to the PC where it was displayed in graphical form. Both RF modules have onboard LCD displays for local status and diagnostic presentation. The two modules are fabricated into 7.6cm x 17.1cm x 5.7cm metal boxes. The module and reader communicate on a 916 MHz bi-directional link. The module has a unique address allowing for expansion of additional sensor modules.

Task 3 and 4: Fabrication of SDMS Demonstration System and SDMS Test-Bed Analysis and Preparation System 1 – Low Temperature Process Loop

The SDMS demonstration system will incorporate the architecture discussed in Task 1. This architecture is implemented within the three-level physical structure; the system will be designed to accommodate two distributed processing nodes (Level 2) up to eight SMST

(Level 3) and inputs up to 50 sensors. The process loop is designed to be analogous to low temperature pressurized water reactor (PWR) auxiliary systems, such as residual heat removal (RHR) component cooling water systems such as essential service water, and main and auxiliary condenser cooling systems. It will be used to demonstrate performance, diagnostic, and prognostic monitoring of nuclear components subjected to operations outside of their design basis envelope including misalignment, fouling, cavitation, chemical and biological corrosion.

Task 3 and 4 Accomplishments: The main system modules were integrated into the "NERI pilot plant." The "fouling meter" was demonstrated using an ultrasonic pulse-receiver and digital oscilloscope. Initial specifications were developed for the necessary semi-custom transducers that will be procured in Phase II. Initial pilot plant trials were performed. Basic sensors were tested and data recorded for temperatures, pressures and flow. Water conductivity was measured and recorded. The as-built system design and safety review for the Phase I system were completed. An RF-multi-sensor module has been installed and tested using temperature and other system data. A draft standard operating procedure for initial trials has been completed.

Task 10: Project Management

This task provides for interaction with the DOE NERI Program Office, program direction, internal review and coordination, including attendance at program and selected related scientific meetings.

Task 10 Accomplishments: Project activity was successfully accelerated with a substantial level of effort employed to get the test bed system up and running in order to provide significant reportable progress for the June program review. All Task 1- 4 milestones were completed to meet the planned schedule. Phase 1 was completed ahead of schedule and within budget constraints. The following items are notable:

- Dr. Bond attended and presented a paper entitled, *On-line Intelligent Self-Diagnostic Monitoring for Next Generation Nuclear Power Plants* at the NERI Workshop in San Diego on June 4, 2000. He also attended portions of the ANS meeting and presented the NERI Project Annual Assessments at DOE on June 6, 2000.
- The following papers were submitted for the ANS meeting, which will be held on November 12-16, 2000, in Washington, D.C. International Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human-Machine Interface Technologies (NPIC&HMIT 2000):
 - a. *On-Line Intelligent Self-Diagnostic Monitoring for Next Generation Nuclear Power Plants*, L.J. Bond, F.L. Greitzer, R.W. Gilbert, S.R. Doctor, and D.B. Jarrell. (See Attachment 3.)
 - b. ANS/ENS 2000 International Winter Meeting and Embedded Topical Meetings, *NERI – On-Line Intelligent Self-Diagnostic Monitoring Systems*, L.J. Bond, D.B. Jarrell, and R.W. Gilbert

**NUCLEAR ENERGY RESEARCH INITIATIVE (NERI)
DE-FG03-99SF9491
TECHNICAL PROGRESS REPORT
Fiscal Year 2000**

Title: Online Intelligent Self-Diagnostic Monitoring for Next Generation Nuclear Power Plants

Client: Pacific Northwest National Laboratory (PNNL), PO Box 999, Richland, WA 99352

PNNL Program Manager: Mr. Richard J. Meador

PNNL Principle Investigator: Dr. Leonard Bond

1 OBJECTIVE

Operating experience from U.S. nuclear power plants indicates that degradation of power plant performance in terms of unscheduled shutdowns, extensive maintenance, and operational efficiency occurs predominantly because of vibration, bio-fouling, and erosion/corrosion, and the effect of these mechanisms on the system. The objective of this project is to design and demonstrate the operation of intelligent or smart self-diagnostic and prognostic capabilities for next generation nuclear power plant systems. This new self-diagnostic technology is titled, *On-Line Intelligent Self-Diagnostic Monitoring System* (SDMS). This project provides a proof-of-principle technology demonstration for SDMS, where a distributed array of sensors is integrated within a pilot plant scale service water system that includes active components and passive structures. The project employs state-of-the-art sensors, instrumentation, and signal processing to improve the monitoring and assessment of the power reactor system and to provide prognostics capabilities. (For this effort, PNNL is the lead organization; there are no collaborators.)

The technical scope of the project includes:

- Designing and demonstrating an SDMS architecture that uses smart components, neural networks, and artificial intelligence
- Implementing the SDMS analytical methodology
- Developing advanced radio frequency (RF) module/multi-sensor units for condition monitoring
- Developing the detailed design and fabricating an SDMS computer demonstration system
- Validating the SDMS system capabilities through trial on a pilot plant scale service water system
- Providing an assessment of the potential economic impact of SDMS data analysis and software tools for improved efficiency of reactor operations, reduction of potential for unscheduled outages, reduction in maintenance activities, and extending reactor system design basis lifetimes when applied to a nuclear reactor system.

2 PROJECT TASKS – OVERVIEW

The task management work plan defines the following tasks:

To focus the project on relevant components and reactor system aging degradation mechanisms.

To specify the experimental apparatus, its configuration and instrumentation, to allow the selected components and degradation mechanisms to be fully exercised, measured, and analyzed.

To develop and codify computer architecture that is modular, allows a hierarchical diagnostic modeling approach, and is extensible to the inclusion of the full suite of degradation mechanisms. This extensibility must include all active and passive components, systems, and structures that will be found in the next generation of U.S. power reactors.

Develop the analytical methods and algorithms that will provide the diagnostic and prognostic processing to enable full condition based operations and maintenance including first-principals life-cycle asset management. It is necessary that a pragmatic solution be developed for applications to real world problems.

2.1 Task 1: Design of SDMS System Architecture and Demonstration System

This task has two components. The first component is the development of the SDMS computer architecture and the associated implementation methodologies that will then be evaluated and refined (Tasks 4 and 5). The second component is the design of a specific SDMS computer demonstration system to be fabricated in Tasks 2 and 3. The demonstration system will then be used in subsequent trials (Task 6) to validate the architecture and to demonstrate the effectiveness of this approach to health monitoring as applied to complex mechanical systems.

2.2 Task 2: Wireless Communication: RF Modules and Sensors

This task is to complete the detailed design, fabrication, and testing for the advanced smart multi-sensor RF tag modules that will serve as the Level 3 (component level) nodes in the SDMS hierarchy. The smart multi-sensor tag (SMST) will provide for wireless data communication links between distributed sensors at Level 3 (component level) and Level 2 (system level) processing nodes.

2.3 Task 3: Fabrication of SDMS Demonstration System

The SDMS computer demonstration system will incorporate the architecture discussed in Task 1 accomplishments. This architecture is implemented within the three-level physical structure; the system will be designed to accommodate two distributed processing nodes (Level 2), up to eight SMSTs (Level 3), and inputs up to 50 sensors.

2.4 Task 4: SDMS Test-Bed Analysis and Preparation: System 1 – Low Temperature Process Loop

The low temperature process loop is designed to simulate low temperature pressurized water reactor (PWR) reactor systems, such as residual heat removal (RHR), component cooling systems such as essential service water, and main and auxiliary condenser cooling systems. The pilot plant scale service water treatment system test bed will simulate conditions experienced by low temperature systems. It will also demonstrate the ability to monitor performance of a component, such as a pump, which may be subjected to fouling or corrosion mechanisms that are chemically or biologically induced for proper operation.

2.5 Task 5: SDMS Demonstration System: Initial Testing

This task will consider the initial testing of the SDMS computer demonstration system, hardware and software. The initial testing will include verification of the performance of the sensor suite, the interfaces to the four sets of Level 3 SMST units, the RF-wireless links, the two Level 2 distributed processing nodes, and Level 1 central SDMS unit. The testing process will be performed as an integrated part of the development program for the SDMS computer demonstration system. As the performance testing of the sensors, instrumentation and computer hardware (operating with basic data displays) is completed; attention will then focus on an initial software validation trial.

The initial integrated system testing will culminate in a series of commissioning tests. These will test and validate the integration and implementation of the complete hardware/software system to form the SDMS architecture and the distributed processing capabilities defined under Task 1.

2.6 Task 6: SDMS Demonstration System Trials Series 1 & 2

Following completion of the fabrication initial testing, which will confirm satisfactory operation and implementation of both the hardware and software in the SDMS computer demonstration system, attention will turn to performing a series of formal trials developed using the design of experiments methodology.

Trial 1 (data for training neural nets, process model development and data base verification) will provide a range of data with trends that can be used to test and validate the SDMS system. Trial 2, a repeat of protocols developed under Trial 1, will be designed and developed to test, exercise features in the SDMS architecture, and to validate the performance and effectiveness of this approach to integrated system monitoring and prognostics using advanced instrumentation and software. The final component of this task is to perform an analysis of the data generated, and to evaluate the performance of the SDMS computer demonstration system.

2.7 Task 7: SDMS Test-bed Analysis and Preparation: System 2 - High Temperature Process Loop

This task has been eliminated.

2.8 Task 8: SDMS Demonstration System: Trials Series 2

This task will be combined with Task 6, and implemented as a second series of trials performed on the low temperature process loop.

2.9 Task 9: SDMS Implementation of Economic Impact Analysis: Cost of Ownership

The reverse osmosis (RO) water treatment unit considered in Tasks 4 through 6 would be used as the test-bed for the economic assessment tools in the SDMS software package.

The economics of the process are controlled by 1) adjustment of process parameters to minimize the rate of fouling and maximize the permeate flux; 2) process optimization for the process/cleaning cycle; 3) variation of intervals for filter replacement; and 4) costs of system operation, system component maintenance, replacement, and repair.

Process data from Tasks 6 and 8, together with the relevant economic inputs, will be used as the basis for testing of the economic analysis tools.

The second component of this task will be the extrapolation to model components or subsystems for a model nuclear power reactor. This analysis will be used to develop the economic case, in terms of the potential impact on plant efficiency, cost of operations, and potential for improved safety in relation to considering the development of the SDMS architecture, methodology, and systems for use in next generation nuclear power plants.

The final component of this task is to perform an analysis of the data generated and an evaluation of the performance of the SDMS computer demonstration system. It is expected that some modification, adjustments, and improvements will be developed during this part of the project.

2.10 Task 10: Project Management

This task will provide for interaction with the DOE NERI Program Office, program direction, internal review and coordination, including attendance at program and selected related scientific meetings. It will also provide for preparation of the necessary monthly, quarterly, and annual reports.

3 PROJECT TECHNICAL OBJECTIVES BY PHASE

3.1 Phase 1

The Phase 1 (year 1) project technical objectives include:

- Initiate Tasks 1, 2, 3, 4, and 10
- Design and demonstrate of SDMS architecture
- Initiate implementation of SDMS methodology on laboratory test loop

- Design advanced RF module/multi-sensor units
- Design SDMS demonstration system
- SDMS performance demonstration through baseline measurements and data analysis on a pilot plant scale water treatment system.

3.2 Phase 2

The Phase 2 (year 2) project technical objectives include:

- Complete Tasks 1 and 4; continue Tasks 2, 3, and 10; and initiate Tasks 5, 6, and 9. Internally the plan is to complete Task 2 and 3 in Phase 2.
- Complete implementation of SDMS methodology on laboratory test loop
- Fabricate advanced RF tag/multi-sensor units
- Fabricate SDMS demonstration system
- SDMS performance demonstration through a developing program of measurements and data analysis for a pilot plant scale water treatment system
- Non-destructive degradation and stressor recognition models will be tested and verified on the test loop.

3.3 Phase 3

The Phase 3 (year 3) project technical objectives include:

- Complete Tasks 2, 3, 5, 6, 9, and 10. SDMS performance will include full duration run-to-failure testing with verification of accuracy of first-principles prognostics.
- Assess SDMS economic impact on nuclear power plant systems operation, maintenance and design basis life extension.

4 PHASE 1 TASK DETAILS AND ACCOMPLISHMENTS

A summary of activities and accomplishments is given in this section of the report. Further details are provided in an integrated form as the conference proceedings papers (Bond et al. 2000a&b)^{2,3} given as Attachment 3.

TASK 1: Design of SDMS System Architecture and Demonstration System - Detailed Description

To ensure that this research is fully responsive to the needs of the next generation of power reactors in the U.S., this subtask will focus on selected system components and associated aging phenomena that are important to nuclear power plant operation and are, at this juncture,

unresolved. Material pertaining to the frequency and critical nature of nuclear industry faults will be drawn from the Nuclear Regulatory Commission's (NRC) Nuclear Plant Aging Research (NPAR) Program and will utilize the risk-based evaluation approach used therein.

This subtask will produce the research area of focus by specifying the components and the degradation mechanisms that will be examined. A test plan for the project will then be developed from this specification.

Develop and codify the SDMS computer architecture that allows flexibility and extensibility in the software to be produced by this project. This architecture will build on the foundation established in the DSOM II (Jarrell et al. 1997)⁴ diagnostic programming by incorporating a more extensive modular process for diagnostics and prognostics. The incorporation of radio frequency communications protocols will be another major advance by providing a fault-tolerance to this architecture.

At a minimum, the software structure must meet the following requirements:

1. Modular construction that allows the main program to continue running despite functional failure of any module except the central system supervisor.
2. Extensibility of the construction such that additional degradation phenomena and component elements can be added without restructuring the basic code design.
3. Provide a RF module interface that will allow a real time communication process for test system parameters if required.

This task will also develop the SDMS analytical methods and algorithms necessary to provide accurate first-principles diagnostic and prognostic processing for the test loop components and associated aging phenomena. A new in-depth component level diagnostics and prognostics (D/P) will be generated. The D/P programming will be such that a hierarchical reporting structure will provide health status starting at the component level, the systems level and finally at the plant level. Algorithms will include rule-based logic, fuzzy logic, and directed neural net determinations based on several different qualitative input forms. A graphic front end (human-computer interface) will be designed to clearly identify the stressor levels encountered, the active mechanism and rate of degradation, and the projected life under the existing conditions.

Functional testing of the software will be done at the diagnostic and prognostic sub-module level, full diagnostic module, and total program levels.

The SDMS demonstration test rig design subtask will identify the experimental apparatus, its configuration and instrumentation, necessary to allow the selected components and associated aging phenomena to be fully exercised, measured, and analyzed. A low temperature test loop will be designed to provide real world data on the components and associated degradation mechanisms. This test loop must provide test conditions that are representative of an actual reactor system environment. Components will be specified based on their ability to provide the appropriate (pressure, temperature, flow, vibration, etc.) conditions and to produce the selected degradation stressors required by the testing. Standard operational and advanced laboratory instrumentation will be specified, procured, and installed on the test rig. A full commissioning acceptance test will be developed and administered to provide a performance baseline for subsequent analysis and proof of concept.

Task 1 Accomplishments

Design of SDMS System Architecture: The design of the SDMS architecture has been completed. Commercial off the shelf software (COTS) has been purchased. An optimized process control (OPC) server module has been developed to allow inter-module open architecture communication. System computing hardware has been configured and is operational in the laboratory.

Project Focus and Demonstration System Definition: The project degradation focus was established by utilizing relevant Nuclear Plant Aging Program data to define which mechanisms have the greatest application to tomorrow's nuclear platforms. The project focus is being documented in the Aging Phenomena Specification, which outlines the identified modes, mechanisms, and related field stressors for study in this project.

The experimental test apparatus was received and the basic loop components and process instrumentation installed to allow component operational ranges (experimental envelope) to be verified.

Analytical Development: Preliminary examination of cavitation from a first principles perspective shows sufficient material exists to commence physics modeling studies. Work on other stressor-degradation correlations must wait for additional funding to be received (Phase II).

The diagnostic processing requirements for lower (component specific) levels have been increased in light of the incorporation of a "computer on a chip" concept, which will allow full computation at that level. This concept will be developed further during Phase II.

A graphical user interface (GUI) display has been designed and developed, and an example screen is shown as Figure 1.

Figure 1. SDMS Software Interface

5 TASK 2: WIRELESS COMMUNICATION: RF MODULES AND SENSORS – Detailed Description

Complete Fabrication of Smart Multi-Tasking RF Module Units

- Task 1 Architecture Review -- Examine the proposed architecture outlined in Task 1 (Design of SDMS System Architecture and Demonstration System).
- RF Telemetry Module and Main System Module Design and Fabrication --Design and construct the RF telemetry modules and a "main system module" (MSM), which will acquire the sensor information from the remote telemetry modules. The MSM will also contain its own local computer, which will aid in the design and development of the system in lieu of main system being constructed and operational. This local computer will also provide an easy means to interface the MSM to the main system with conventional serial, parallel, or local area network (LAN) connections. Finally the telemetry module will be able to format the sensor data to a form that is easily interfaced to the main system prior to sending it over the hardwired communications link.

Initiate Design, Validation & Functional Testing

- RF Telemetry Design Requirements -- Determine the optimum RF communication frequency, distance, and the total number of RF telemetry modules which will be required to communicate all of the sensor data required to the main system. It is anticipated that up to three RF telemetry modules will be designed, fabricated and tested, each with the ability to ascertain the status of as many as 15 external sensors. It is also assumed that power to energize the RF telemetry modules will be readily available, thus alleviating the need to develop battery operated, low power modules.
- Establish Sensor and RF Module Interfaces -- Sensors will be interfaced to the three distributed RF telemetry modules. These sensors will be specified and procured on other tasks. It is anticipated that the RF telemetry modules will be able to accept sensor-input signals from a variety of sensors. Available interfaces will include analog, digital, serial, and 0-20 mA current loop connections.
- Smart Multi-Sensor RF Module Communication Link Testing -- Complete laboratory testing will be performed on the smart multi-sensor RF module communication links. This task will include testing of all RF and hardwired communication links, interfaces, and communication protocols. Data formats will be checked for compatibility with the main module. Acquisition rates, data integrity, and communication distances and rates will be verified.
- RF Telemetry System Functional Testing -- Demonstrate the RF telemetry system showing its functionality and capabilities

Task 2 Accomplishments

- Two RF modules were fabricated and successfully deployed on the experimental test loop. The sensor module (known as a RF module) was wired to 12 separate 4-20 mA loop sensors such as temperature, flow, etc. The other RF module (known as the integrator or reader) was interfaced to a desktop PC. A visual basic program running on the PC communicated with the reader (RS-232 link), who then commanded the module to

acquire sensor data and transmit the data back to the reader. The reader passed the data to the PC, where it was displayed in graphical form. Both RF modules have onboard LCD displays for status and diagnostic presentation. The two modules are fabricated into 7.6cm x 17.1cm x 5.7cm metal boxes. The module and reader communicate on a 916 MHz bi-directional link. The module has a unique address allowing for expansion of additional sensor modules. The electronics block diagram is shown as Figure 2.

Figure 2. Electronics Block Diagram

6 TASK 3: FABRICATION OF SDMS DEMONSTRATION SYSTEM - Detailed Description

The SDMS computer demonstration system will incorporate the architecture discussed in Task 1. This architecture is implemented within the three-level physical structure; the system will be designed to accommodate two distributed processing nodes (PCs - Level 2), up to eight smart multi-sensor modules (SMST -Level 3), and inputs from up to 50 sensors. This task will implement the three-level SDMS architecture consisting of the following:

- one main work station
- two distributed processing nodes, two PCs, one wired LAN, and one RF LAN
- four - eight RF-module multi-sensor modules
- 50 sensors (max)

Complete Design, Fabrication & Testing of Process Loop

This task completes the design, fabrication and testing for the SDMS system and related pilot plant.

- Integrated SDMS Demonstration System Design -- Complete and review the integrated design for SDMS computer demonstration system, including integration with low temperature process loop. Include:
 1. hardware-software system from Task 1
 2. complete flow loop analysis
 3. process analysis and sensor identification from Task 4.
- SDMS Workstation Fabrication and Testing -- Develop detailed designs for completion of fabrication, integration and testing of main SDMS workstation for application to the low temperature process loop. Review and complete sensor selection, which will include an ultrasonic thickness gage/pulse-receiver and analog to digital (A/D) card or digital oscilloscope for operation with one distributed preprocessing node and which will be used as a fouling meter working with a digital oscilloscope.
- Design preliminary testing program for integrated SDMS computer demonstration system.

Complete Preliminary Tests for SDMS Demonstration System

This task will develop the methods to be used for testing the SDMS.

- Initiate test and integration of two distributed processing nodes, with main SDMS processing unit.
- Initiate test and integration of RF-module multi-sensor modules, with distributed processing unit and sensors. Include testing of interfaces and all connections, between modules and system sensors.

Task 3 accomplishments are integrated with those for Task 4 and are reported at the end of Task 4.

7 TASK 4: SDMS TEST-BED ANALYSIS AND PREPARATION: SYSTEM 1 – LOW TEMPERATURE PROCESS LOOP-Detailed Description

The low temperature process loop is designed to be analogous to low temperature PWR reactor systems such as RHR, condensate and such component cooling systems as service water, and main and auxiliary condenser cooling systems. The test bed will simulate conditions experienced by low temperature systems. It will also demonstrate the ability to monitor performance of a component, such as a pump, for proper operation, and the filtration system, which may be subjected to fouling, or corrosion mechanisms that are chemically or biologically induced.

Complete Low Temperature Process Loop Analysis

This task will include identification of key components, “process” mechanisms, parameters to sense, and selection of a sensor suite. Complete initial flow loop design and selection of components.

Complete Preliminary Testing

The SDMS and pilot plant water treatment system will be integrated, and a series of trials performed.

Task 3 and 4 Accomplishments

1. The main system modules were integrated into the “NERI Service Water Pilot Plant.” The system is shown in Figure 3. Procurements and accomplishments include:
 - a. Two 100-gallon capacity, liquid storage tanks with secondary containment stands and support frame for mounting mixers.
 - b. 5.5m x 5.5m secondary containment berm for housing skid platforms, including rubber matting for reduction of vibration.
 - c. Two skid platforms, a pump section and a reverse osmosis (RO) section were designed and purchased.
 - d. A PC has been received and configured; this unit now forms the system master unit. Two additional PCs have been configured for operation as the distributed processing nodes.
 - e. Instrumentation for measurement and control of pH, conductivity and salinity has been procured and received. These units are adaptable and have an RS232 interface for multiplexing data to a PC at some point in the future.
 - f. The wired and wireless LAN has been established to provide communication between the three processing levels in the system.
 - g. The first RF-multi-sensor module has been installed and tested using temperature and other system data.
 - h. The “fouling meter” was demonstrated using an available ultrasonic pulse-receiver and digital oscilloscope. Initial specifications were developed for the necessary semi-custom transducers that will be procured in Phase II.
 - i. Initial system integration was completed, and initial pilot plant trials were performed.
 - j. Basic sensors were tested and data recorded for temperatures, pressures and flow.
 - k. Water conductivity was measured and data recorded.

Figure 3. PNNL-NERI service water pilot plant

2. The development of standard operating procedures for varying specific system conditions and measurement of the parameters of interest is underway. The initial trials used tap water. In Phase II, testing will be developed using salt-water solutions and will include both filter cleaning and fouling.
3. The updated system design and safety review for the Phase I as-built system were completed.
4. A draft standard operating procedure for initial trials has been completed.
5. An on-going literature review continued to develop the knowledge base needed for preparation of a paper for submission to a refereed journal.
6. A presentation was prepared and made at the DOE NERI Workshop and Annual Meeting, San Diego on June 4, 2000, and a second extended annual review presented to DOE on June 6, 2000.
7. The proceedings paper for the ANS meeting, Nuclear Plant Instrumentation, Washington, D.C., November 13-17, 2000 was completed (Bond et al. 2000a)². An abstract for the NERI Success Session was submitted and the paper accepted (Bond et al. 2000b)³.

8 TASK 10: PROJECT MANAGEMENT

This task will be on going for the duration of the project. This task will provide for interaction with the DOE NERI Program Office, program direction, internal review and coordination, including attendance at program and selected related scientific meetings. It will also provide for preparation of the necessary monthly, quarterly, and annual reports.

Perform Project Management

Manage the project and mitigate risk to accomplish the following:

- Project Status Meetings will be held monthly.
- Design Reviews will be accomplished as appropriate and in a timely manner.
- Areas of high IP potential will be discussed with the Product Line Manager, Principal Investigator, Project Manager, and Project Task Leaders as they develop. Project organization is shown in Attachment 1.

Milestone Plan

The baseline Milestone Plan for this project is incorporated into the project management plan (PMP) by reference. This plan outlines the work breakdown schedule (WBS) for this project in the form of a Gantt chart. This plan was delivered to the customer as part of the first Technical Progress Report. The Milestone Plan will be maintained as part of the remaining Technical Progress Reports delivered to the customer. [Updated version given as Attachment 2.]

Technical Progress Reports

Quarterly Technical Progress Reports will be delivered to the customer. They will provide a narrative summary of items of interest and incorporate a marked up version of the milestone deliverable plan, and a listing of tasks/milestones with the planned due date and actual completion date.

Topical Reports for Each Phase

Upon completion of each phase, a Topical Report will be delivered to the customer to report the results of the corresponding phase.

Final Technical Report

A complete project technical summary will be provided to the customer in the form of a Final Technical Report to be included in the Phase 3 Topical Report.

Internal Deliverables

Project Task Leader status updates will be provided, by the end of each quarter, to the Project Manager for inclusion in the Technical Progress Report.

Task 10 Accomplishments

1. Accelerated activity was the result of a significant level of effort to get the test bed system up and running to provide notable progress for the June program review.
2. Dr. Bond attended and presented a paper entitled, *On-line Intelligent Self-Diagnostic Monitoring for Next Generation Nuclear Power Plants* at the NERI Workshop in San Diego on June 4, 2000. He also attended portions of the ANS meeting and presented the NERI Project Annual Assessments at DOE on June 6, 2000.
3. The following papers were submitted and accepted for the ANS Meeting, which will be held November 12-16, 2000, in Washington, D.C.
 - a. International Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human-Machine Interface Technologies (NPIC&HMIT 2000): *On-Line Intelligent Self-Diagnostic Monitoring for Next Generation Nuclear Power Plants*, L.J. Bond, F.L. Greitzer, R.W. Gilbert, S.R. Doctor, and D.B. Jarrell.
 - b. ANS/ENS 2000 International Winter Meeting and Embedded Topical Meetings, *NERI – On-Line Intelligent Self-Diagnostic Monitoring Systems*, L.J. Bond, D.B. Jarrell, and R.W. Gilbert
4. The Task 1 milestone to complete SDMS demonstration design was accomplished to meet the planned schedule.
5. The Task 2 milestone to complete fabrication of smart multi-tasking RF module units was accomplished to meet the planned schedule.
6. An independent safety review of the use and placement of components of the NERI flow loop in the laboratory was found to have safety & health issues adequately addressed.
7. The Task 4 milestone to complete low temperature process loop analysis was accomplished to meet the planned schedule.

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1. Meador, R.J., Bond, L.J., Project Management Plan for On-Line Intelligent Self-Diagnostic Monitoring System for Next Generation Nuclear Power Plants, Rev 1, April 2000.
2. Bond, L.J., Greitzer, F.L., Gilbert, R.W., Doctor, S.R., Jarrell, D.B. *On-Line Intelligent Self-Diagnostic Monitoring for Next Generation Nuclear Power Plants*, International Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human-Machine Interface Technologies (NPIC&HMIT 2000):
3. Bond, L.J., Jarrell, D.B., Gilbert, R.W., *NERI – On-Line Intelligent Self-Diagnostic Monitoring Systems*, In Proceedings of the ANS/ENS 2000 International Winter Meeting and Embedded Topical Meetings.

4. Jarrell, D.B., Meador, R.J., *Decision Support for Operations and Maintenance (DSOM) – Twentynine Palms Final Report, Vol. I*, PNNL-11582, June 1997.

FINANCIAL STATUS REPORT

(Long Form)

(Follow instructions on the back)

1. Federal Agency and Organizational Element to Which Report is Submitted Oakland Operations Office		2. Federal Grant or Other Identifying Number Assigned By Federal Agency DE-FG03-99SF9491		OMB Approval No. 0348-0039	Page 1 of 1
3. Recipient Organization (Name and complete address, including ZIP code) Pacific Northwest National Laboratory, PO Box 999, Richland, WA 99352					
4. Employer Identification Number 31-4379427		5. Recipient Account Number or Identifying Number PNNL Project No. 30344		6. Final Report PHASE 1 ☒ Yes ☐ No	7. Basis ☐ Cash ☒ Accrual
8. Funding/Grant Period (See instructions) From: (Month, Day, Year) 9/1/99		9. Period Covered by this Report From: (Month, Day, Year) 8/30/02		9. Period Covered by this Report To: (Month, Day, Year) 8/31/00	
10. Transactions:		I Previously Reported		II This Period	
a. Total outlays				III Cumulative \$497,883	
b. Refunds, rebates, etc.					
c. Program income used in accordance with the deduction alternative					
d. Net outlays (Line a, less the sum of lines b and c)				497,883	
Recipient's share of net outlays, consisting of:					
e. Third party (in-kind) contributions					
f. Other Federal awards authorized to be used to match this award					
g. Program income used in accordance with the matching or cost sharing alternative					
h. All other recipient outlays not shown on lines e, f or g					
i. Total recipient share of net outlays (Sum of lines e, f, g and h)					
j. Federal share of net outlays (line d less line i)					
k. Total unliquidated obligations					
l. Recipient's share of unliquidated obligations					
m. Federal share of unliquidated obligations					
n. Total federal share (sum of lines j and m)					
o. Total federal funds authorized for this funding period					
p. Unobligated balance of federal funds (Line o minus line n)					
Program income, consisting of:					
q. Disbursed program income shown on lines c and/or g above					
r. Disbursed program income using the addition alternative					
s. Undisbursed program income					
t. Total program income realized (Sum of lines q, r and s)					
11. Indirect Expense		a. Type of Rate (Place "X" in appropriate box) ☐ 9 Provisional ☐ 9 Predetermined ☒ Final ☐ Fixed			
		b. Rate		c. Base	
				d. Total Amount 192,061	
				e. Federal Share	
12. Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation:					
13. Certification: I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purpose set forth in the award documents.					
Typed or Printed Name and Title Leonard Bond, Program Manager				Telephone (Area code, number and extension) 509-375-4486	
Signature of Authorized Certifying Official Walter W. Laity				Date Report Submitted 9/29/2000	

Cost Performance:

Figure 4. Phase 1 Cumulative Expenditure Summary

ATTACHMENT 1

NERI SDMS PROJECT ORGANIZATION

Project Organization Chart

ATTACHMENT 2

DE-FG03-99SF9491
PNL Project No. 30344

ATTACHMENT 2

DE-FG03-99SF9491
PNNL Project No. 30344

ID	Task Name	2000												2001												2002															
		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
23	Milestone 6.2.2: Complete SDMS Demonstration System 1 Series 2 data analysis																																								6/28
24	Task 9: SDMS Implementation of Economic Impact Analysis: Cost of Ownership																																								6/28
25	Subtask 9.1: Complete development of economic analysis software																																								12/31
26	Subtask 9.2: Complete trials with SDMS economic analysis software .																																								6/28
27	Task 10: Project Management																																								
28	Subtask 10.1: Perform Project Management																																								8/30
29	Subtask 10.1: Deliver Milestone Plan																																								1/18
30	Subtask 10.3: Deliver Technical Progress Reports																																								1/18
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																																									5/31
42	Subtask 10.4: Deliver Topical Reports for each Phase																																								9/15
																																									9/14
																																									8/30
46	Subtask 10.5: Deliver Final Technical Report																																								8/30

Project: 30344 DOE NERI 3rd qtr rpt.
Date: Thu 8/31/00

Task
Split

Progress
Milestone

Summary
Rolled Up Task

Rolled Up Split
Rolled Up Milestone

Rolled Up Progress
External Tasks

Project Summary

Attachment 3

ON-LINE INTELLIGENT SELF-DIAGNOSTIC MONITORING FOR NEXT GENERATION NUCLEAR POWER PLANTS

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Keywords: monitoring, instrumentation, prognostics

ABSTRACT

This paper describes a novel approach and reports preliminary results of initial testing of a technology demonstration for an on-line intelligent Self-Diagnostic Monitoring System (SDMS) for possible use in next generation nuclear power plants. The SDMS will detect, monitor, and diagnose various degradation precursors and resultant mechanisms, and their effects on reliability and service life. The goal of this project is to provide the proof-of-concept demonstration for SDMS technology, including novel software architecture, distributed data processing and the use of wireless smart multi-sensor modules.

1. INTRODUCTION

There is a growing need to develop and demonstrate technologies that can predict the remaining service and safe life for key elements in our national civil infrastructure (Bond 1999). Operating experience from U.S. nuclear power plants indicates that degradation of power plant performance, as evidenced by unscheduled shutdowns, extensive maintenance and reduced operational efficiency, occurs to a large extent because of vibration, bio-fouling, and erosion/corrosion mechanisms. The goal of this project is to provide the proof-of-concept demonstration for SDMS technology.

This paper reports on Phase I of the project. Four central tasks for Phase I of the project are:

- 1) focusing the project on appropriate problems,
- 2) the design and construction of the SDMS software architecture and implementation methodology,
- 3) the design and fabrication of an SDMS demonstration system, and
- 4) the validation of the basic SDMS instrument set on the test-bed system.

The type of system selected for the test-bed was a nuclear plant service water system, which is recognized as a key risk component with requirements for monitoring and prognostics (Vo et al. 1994). The test-bed includes a reverse osmosis filter unit, heat exchanger, pumps, and other common service water loop components. The test-bed is being used to evaluate the integrated diagnostic-prognostic (D/P) capabilities of the SDMS for fouling, vibration, and other high-priority component degradation mechanisms. The pilot system test loops, D/P software, wireless multi-sensor data transmission, and a distributed data processing concept are being developed to demonstrate the SDMS advanced real-time on-line monitoring, data processing, and root-cause diagnosis.

The SDMS system is designed to employ intelligent sensors to provide an evaluation of the operation of nuclear plant components, and to monitor their health status and diagnostic

needs. The SDMS architecture and data acquisition system combine data from a comprehensive sensor suite that measures parameters traditionally considered to be discrete in terms of process operation, monitoring, control, and Nondestructive Evaluation (NDE). For the test-bed, a combination of advanced distributed smart sensors and wireless Radio Frequency (RF) Tag data transmission is being implemented (Gilbert et al. 1999). A hierarchy of both locally distributed and central processing is employed. The SDMS analysis of data obtained from the test-bed operation utilizes an extension of the unique capabilities of the Pacific Northwest National Laboratory (PNNL) diagnostic/prognostic methodology found in the Decision Support for Operations and Maintenance (DSOM) system (Jarrell and Meador, 1997). Diagnostic capabilities have now expanded to levels that can detect emerging conditions that, if allowed to continue, could lead to system or component inefficiencies or failure.

2. BACKGROUND

At PNNL there is a growing thrust in the science and technology used to predict the remaining service and safe life for complex structures and systems (Bond, 1999), and in particular the sensors and measurements needed for predictive engineering (Bond et al. 1999). PNNL was the lead Laboratory for the Nuclear Regulatory Commission's Nuclear Plant Aging Program, a 60 million dollar research effort conducted from 1983 through 1993. PNNL has participated in researching the relationship between maintenance and reactor safety since the beginning of this program (Olson et al. 1985). This hardware-oriented NRC program was designed to understand and manage aging of safety-related structures, systems and components (SSC's) used in nuclear power plants in the United States. The program produced over 150 technical reports on various aging issues and numerous technical papers to document the results. A summary report prepared by Subudhi (1995) was used to focus the PNNL NERI study on relevant next-generation reactor issues. The Subudhi (1995) report summarizes all the research findings that are currently being used by the nuclear power industry and other government agencies to guide the state-of-the-art, in monitoring, measurement, control and prognostics.

3. PROJECT FOCUS

This section documents the process by which the PNNL NERI team selected the specific reactor plant mechanical systems and components as well as the associated degradation mechanisms to investigate.

3.1 Focus Methodology

The method used to select specific components and associated degradation mechanisms was:

- 1) to research the existing history of failure events and construct a profile of safety significant reactor component failures,
- 2) to extract and inventory components from the high-consequence, high-failure-rate events,
- 3) to determine which of these components and component environments could be reasonably simulated in the laboratory within the allotted budget, and
- 4) to select degradation mechanisms that were still unresolved and/or prevalent in today's generation of reactors.

Of specific interest Subudhi (1995) examines the following areas: 1) failure experience data sources, 2) aging reliability models, 3) aging of mechanical components, and 4) aging of fluid systems.

These topics are particularly relevant to creating the knowledge base that allows us to make an appropriate study topic choice. The resultant choice maximizes the increase in safety and

reliability that our research contribution will make to the next generation of U.S. reactors. Specific attention was given to the literature that described mechanisms of degradation for service water systems, methods for detecting and monitoring degradation, and predicting the future requirements for monitoring the residual life of critical nuclear plant components. (Blahnik et al. 1992, USNRC, 1986, Leeds and Lam 1988).

Subudhi (1995) states: "A critical element in the qualification of equipment is determining how the environmental and operational stressors affect equipment during normal operation." To this end, this NERI project is the next logical step in the pursuit of this understanding.

3.2 Focus Results

A summary of the chosen components, their respective degradation mechanisms, and stressor agents to be applied in this project are:

Table 1 Project Focus Summary

Component	Degradation Mechanisms	Stressor Agent
Centrifugal Pump	Cavitation, Vibration, Erosion, Corrosion	Flow throttling, Misalignment, Suspended Solids, Acidity, Cl
Reverse Osmosis Filter	Fouling,	Suspended Solids, Chlorine
Heat Exchanger	Fouling, Corrosion, Erosion	Suspended Solids, Chlorine, High flow velocity

The goal of this project is to provide a significant increase in reactor safety system reliability by developing methodologies that will integrate or devise new ways to measure and correlate stressor intensity, degradation rate, performance levels, and remaining useful service life for these categories of components. More component specific information on guidelines for aging management of pumps and heat exchangers was found in Booker et al. (1994a) and Booker et al. (1994b).

4. SELF-DIAGNOSTIC MONITORING SYSTEM (SDMS)

4.1 Design of the Computer Architecture

The project software architecture and diagnostic approach is an extension of the design of the DSOM II program (Jarrell 1999, Jarrell and Meador 1997). This program is founded on condition-based maintenance (CBM) and incorporates all the critical functional aspects of nuclear plant interactive information infrastructure. Four unique features highlight the design of the computer hardware and software approach:

- 1) A total infrastructure interface is used to provide unique views of the recorded data to each segment of the functional infrastructure. For example, the same poor performance of a component might show up as an alert or alarm to an operator, a failed instrument to a maintenance technician, off-nominal performance alert to an engineer, and as an incremental loss of revenue to the plant administrator.
- 2) The central focus is on measurement and correlation of basic stressors (temperature, pressures, alignment, etc.) rather than purely on process degradation as is found in other approaches. Once identified, the stressor is then linked to the rate of degradation of the physical attributes of the component. By contrast, most diagnostic programming attempts to infer diagnosis from operational parameters only. The stressor identification approach

implicitly enhances operator understanding and participation in the root cause analysis process for machinery degradation and failure.

- 3) Utilize the results of number 1 above, to project and produce an accurate first-principles prognostic on remaining useful life.
- 4) The system is being designed to exhibit advanced fault tolerance capability. This is being accomplished through the use of distributed intelligent agents, literally multiple artificial intelligence computers at all three levels of the computational hierarchy, and by the use of multiple independent communications pathways. RF tagging technology will be used to accomplish greater communication reliability, remote information transfer from a hostile environment, as well as layered information access from a plant, system, and individual component interface perspective.

The software was created in a modular structure to allow efficient construction of special purpose modules for specific applications tasking. The overall NERI computer software configuration is shown in Fig. 1.

Figure 1 Computer Software Modular Configuration

Figure 2 Functional Hierarchy of NERI Diagnostics

5. DIAGNOSTICS AND PROGNOSTICS

An overview of the diagnostics and prognostics modules design is shown in Fig. 2. The purpose of the diagnostician is to turn plant data (temperatures, pressures, flows, levels) into diagnostic and prognostic conclusions regarding the behavior and health state of the monitored components (fouling, leaks, cavitation, residual life).

The system operates on four tiers starting with simple calculations of efficiency down through advanced algorithms for determining degradation root cause and useful residual life. Results determined at each level are passed on to the next for additional manipulation and output conclusions.

5.1. RF Multi-Sensor Modules

Wireless sensor technologies are an increasingly attractive approach to many common sensor-networking requirements (Manges 2000). PNNL is developing families of smart multi-sensor RF tag based units for use in predictive engineering/prognostics (Gilbert et al. 1999). The RF sensor tag is a platform based upon using RF tags connected to a central reader.

The RF tag modules have their own unique address and will respond to commands from the reader. They also have the capability to report autonomously to the reader. At short range (< 200 feet) 916 MHz bi-directional links are being utilized based upon RF transceivers operating in conjunction with onboard microcontrollers. The microcontrollers provide intelligence for RF data encoding/decoding and data storage into nonvolatile memory. Data can either be stored along with associated clock/calendar or uploaded directly. The tags to which the sensors are connected are able to accommodate several different interface types (analog, digital, and 4-20 ma). The tags also have output capability for controlling actuators. The tags onboard the microcontroller can be used for performing local health diagnostics and low-level control. The reader can be interfaced to any existing higher order computer over a serial link.

6. SERVICE WATER PILOT PLANT

The SDMS test loop is an approximate 1/10-scale replica of a nuclear plant service water system. In the laboratory, two 100-gallon water tanks simulate the ultimate heat sink and provide a surge volume for the system. Tank level and outlet temperatures are measured to provide a check value on pump net positive suction head (NPSH) for the full open valve

configuration. Ball valves (not shown on the diagram) are used throughout to allow flow circuit shifting while providing throttling capability and nearly zero flow restriction in the full open position. The system is completely fabricated in stainless steel (304 and 316) with the exception of the system supply tanks, supply piping to the main loop, and drain piping to the sewer, which are all PVC.

A 12 kW heater bank (to be installed in Phase 2) will be located in the pump suction line to allow elevation of the suction temperature as a method of inducing cavitation in the circulation pumps and to exercise the heat exchanger. Appropriate valves are also available in the pump suction lines for that purpose as well. Two 5 horsepower, vertical, 3450 RPM, fifteen-stage centrifugal pumps allow modest flow (nominal flow 28 GPM) at relatively high pressure (360 psig maximum). The #1 pump is powered by a variable frequency drive (VFD) to allow wide changes in test flow and pressure with varying system resistances. A third pump in a horizontal configuration will be added in Phase 2 for alignment and imbalance stressor testing. The existing pumps can be run individually or in parallel to sustain the necessary flow and pressure conditions for simultaneous test runs. A heat exchanger (Phase 2) will be placed in the loop between the pump discharge and the RO filtration station. This will be used to measure fouling and erosion phenomena and to maintain inlet temperatures to the RO filter below its design maximum (50 C). The filter station consists of two parallel reverse osmosis (RO) banks of three filter elements each. The unit will be used to study both fouling and back flush operations of a normal service water strainer, or RO purification filter.

6.1 Man-Machine Interface (MMI)

The interface is patterned after the "point and click" hierarchical information retrieval system designed by PNNL engineers for the DSOM project. The top screen, shown as Fig. 3, presents the operator with sufficient information to monitor normal unfaulted system operation. The vertical column on the left provides (from top to bottom): 1) system information that, when coupled with the reduced information set on the screen, allows a complete system overview, 2) navigation from one screen level to the next, 3) alarm and alert notification and acknowledgement, and 4) a selection of the operating mode. Navigation to a more detailed station or component level, or time histories of any observable parameter can be obtained by direct mouse click as well.

7. PILOT PLANT TRIALS

The Pilot Plant trials in Phase 1 were designed to accomplish five tasks: 1) the fabrication of the NERI pilot plant service water system, 2) the system integration, including installation of basic sensors and system controls, 3) testing of the SDMS/MMI software, 4) testing of the data communication RF-Multi-sensor modules and LAN network, and 5) initial operation of the digital fouling meter.

The Phase 1 NERI pilot plant service water system is based on two semi-custom component modules. One module consists of the six reverse osmosis filter modules and the other contains the two main system pumps. These elements were connected with the requisite tanks, pipe, valves and sensor measurement ports as shown in the MMI display shown as Fig. 3. A suite of sensors that measures basic pressures, temperatures and flow were put into the system. Initial pressure, flow, and filter functional testing was performed. The pumps were operated to give an operating pressure of about 200 psi at the filter input. The filters gave a permeate flow of pure water – the mass-flow and conductivity of which were measured. Initial testing of the RF multi-sensor tag operation was performed using thermocouples and a calibrated temperature block.

Figure 3 NERI Phase I Man-Machine Interface

This was then expanded to also consider system pressure data. In both cases directly measured and RF transmitted data were in close agreement. The hardware and software for two distributed data processing nodes were integrated into the system, and in one case is being developed using a new computer on a single chip. Initial functionality was demonstrated in terms of data transmission to the main SDMS hardware unit. Initial testing consisted of two hours of continuous operation, with the permeate flux recycled into the feed water. Data were measured at 10-minute intervals and system parameters were measured. For example, a feed water temperature rise of approximately 10° C was seen, as the mass flow, pressures, pH and conductivity were monitored concurrently at four locations. All sensors were seen to operate within specified ranges. In addition, preliminary data were measured with a semi-custom fouling/cleaning meter. This employs ultrasonic transducers set onto the outside of the filter housing. Trials were performed to enable optimal frequency selection and geometry. A designed series of trials are being developed to verify the functionality of a set of standard operating procedures for the system. The results will be documented and reported for filter and pump operation, including flow-head characteristics, fouling, and cleaning.

8. CONCLUSIONS

The SDMS architecture designed and implemented on pilot plant Service Water System. A fault-tolerant communication design was developed. Novel RF Multi-sensor tags were

designed, built, and tested. A novel fouling/cleaning monitor is being implemented. Initial trials on the system are in progress.

ACKNOWLEDGMENTS

The DOE-NERI program supported this work. PNNL is operated for the U.S. Department of Energy by Battelle under Contract DE-AC06-76RLO 1830.

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