1. Introduction

Since the mid of 1960s GE Nuclear Energy has built close to 60 nuclear reactor units (from BWR 2 to BWR 6 and ABWR). GE Nuclear Energy collaborates with the plant owners to maintain their facilities in support of effective and safe plant operation. One of the challenges in plant operation is that the design of the instrumentation and controls (I&C) for these BWRs are mainly based on the 1960’s and 1970’s analog technology. The rapid advancement of digital technology has rendered the analog technology obsolete. The consequences of the technological obsolescence are the scarcity of parts and personnel to maintain the existing equipment. Vendors discontinue the production of the older parts to meet current market needs [1]. Newer generations of engineers are less proficient with the older technology. An obvious solution is to upgrade I&C systems to modern technology. Such upgrades will be more critical as plants are looking into plant life extension. The huge financial benefits from plant life extension requires a pro-active and systematic approach in determining the strategy for the I&C upgrades [2]. The Neutron Monitoring System (NMS) and the Reactor Manual Control System (RMCS) in BWR I&C systems are prime candidates for upgrades because of their significant roles in the safety and operation of a BWR. The NMS is comprised of the following systems: (1) Source Range Monitor (SRM), (2) Intermediate Range Monitor (IRM), (3) Power Range Neutron Monitor (PRNM), and (4) Transverse In-core Probe (TIP). The SRM and IRM systems have moveable neutron detectors that monitor the level of reactivity during the startup or low power level of a BWR. The SRM initiates rod blocks or alarms and the IRM initiates a reactor scram, rod blocks or alarms if the reactivity level is too high. The
PRNM employs fixed in-core detectors known as Local Power Range Monitors (LPRM) to monitor local reactivity. The PRNM provides average values of the LPRM for core monitoring purposes. The PRNM initiates a reactor scram or rod block depending on the monitored reactivity levels. The TIP is a system with moveable detectors used to calibrate the LPRM. The RMCS obtains inputs from the Rod Position and Information System (RPIS) and provides controls for control rod movements. Due to their significance in the plant operation, these systems have often been upgraded in operating BWRs. GE-Hitachi has provided upgrades with the Nuclear Monitoring Analysis and Control (NUMAC) platform, which includes the Wide Range Neutron Monitoring (WRNM), Power Range Neutron Monitoring (PRNM) and the Rod Control Management System (RCMS). These systems represent a viable solution to potential I&C upgrades that would be required to support plant life extension. A summary description of each of these systems is provided in this paper.

2. Overview NMS and RMCS Retrofit

2.1 Key Considerations for I&C Upgrades

The GEH solution for upgrading the NMS and RCMS is based on the NUMAC platform. The NUMAC platform is a microprocessor-based system developed to replace the obsolete analog systems with a digital system that would be less vulnerable to future obsolescence. In addition to resolving the obsolescence issue, the upgrade of I&C provides other advantages, such as leveraging the technology to provide improved man-machine interface (HMI), accuracy, self-test and automatic calibration. An upgraded system will also improve plant safety, operation, system availability and reliability. Systems within the NUMAC platform have the following features:

a) Modular design for both hardware and software. This allows replacement of obsolete parts with minimal impact on the rest of the system.

b) Plug compatible with existing equipment at the panel level. This minimizes the need for any field wiring changes outside the panel that houses the existing equipment.

c) Qualified Parts, which means all components meet the quality, environmental, seismic and electromagnetic interference (EMI) qualifications.

d) Self-test capability to minimize the surveillance requirements and reduce mean time for repair.

e) Automatic calibration to minimize the maintenance requirements.

f) Improved Human Factors Engineering for ease of operation and reduced potential for operator errors.

g) Menu driven system that allows easy update of plant specific requirements, e.g., change in setpoints or other plant parameters.

h) Minimal installation time as the upgraded system must be completely installed during the allowed outage window.

Specific features of the WRNM, PRNM and RCMS are described below.

2.2 Wide Range Neutron Monitor System (WRNM)

2.2.1 WRNM System Description

Currently, most BWRs use four Source Range Monitors (SRMs) and eight Intermediate Range Monitors (IRMs) to provide approximately 10 decades of neutron flux for coverage in
startup and intermediate ranges. The SRM and IRM detectors have to be inserted into the reactor core during shutdown and withdrawn after startup to preserve their limited life using non-Class 1E drive/retract mechanisms. In addition, range switches are used for linear IRM output to switch between decades during power ascension.

These old analog systems are difficult to operate, requiring operators to manage the range switches to avoid inadvertent reactor trips. The mechanisms for the detector insertion and retraction present challenging maintenance practices with ALARA concerns. A stuck detector would lengthen an outage and delay plant startup. The non-1E mechanism also presents a challenge for the plant to demonstrate compliance to regulations regarding post accident monitoring. [3]

To resolve these design and operational issues with the present SRM/IRM system, a new fixed detector system, WRNM, was developed to replace the SRM/IRM systems. The WRNM uses fixed location in-core regenerative breeder detectors. The WRNM monitors approximately 11 decades of neutron flux over the startup, intermediate, and power ranges. Use of regenerative sensors permits permanent in-core locations corresponding to present "full in" detector positions. The use of a single detector for both SRM and IRM functions eliminates the need for the SRM and IRM transitions. Due to the coverage in the power ranges, the WRNM also provides automatic verification of the overlap that is required for IRM and APRM. The fixed detectors also eliminate the need for the drive mechanisms for the SRM/IRM. In addition to eliminating maintenance and radiation dose issues associated with the drive mechanisms, the removal of the drive mechanisms also eliminate the undervessel interferences and other space issues associated with this machinery. The vertical position of the WRNM detectors will be the same as the IRMs in their fully inserted condition. A further simplification of the new system is to use only 8 WRNM channels (2 trip systems with 4 channels per system) to replace the 12 combined SRM and IRM channels.

The number and locations of the sensors have been analytically and experimentally demonstrated that it can provide sufficient flux level information under the most limiting bypass and sensor failure conditions. Although there are fewer channels, the WRNM system enhances core coverage during fuel loading because it provides 8 channels, two per quadrant of core coverage, whereas the SRM only has 4 channels, one per quadrant of core coverage. The WRNM uses the microprocessor based NUMAC control room monitors to calculate reactor parameters. It provides both counting and mean square voltage (MSV) modes of operation and automatic switching of the IRM ranges. The level based trip in the MSV ranges has been changed to a rate based period trip, thus eliminating the need for range switches. This allows the operator to focus on the rod movements and reactivity response as opposed to manipulating the range switches to avoid a scram. Consequently, the WRNM provides significant improvement in terms of operation and ease of maintenance. Figure 1 provides a comparison between the SRM/IRM and the WRNM systems.

### 2.2.2 WRNM Channel Configuration

The WRNM system utilizes eight WRNM channels to monitor the core. Each WRNM channel consists of the following components:

a) The sensor is housed in a dry tube in the vessel.

b) The sensor is connected by coaxial cable to a preamplifier that is located outside the primary containment in the Reactor Building.
c) The preamplifier provides a signal output to the control room monitor (WRNM chassis) that processes the flux signals. The NUMAC WRNM chassis, located in the control room, provides high voltage detector polarizing power, receives input from the preamplifier, provides local visual displays and fiber optic output to a remote Operator Display Assembly, provides discrete outputs to various alarms and trips via a Trip Auxiliary unit, provides analog outputs to recorders and plant computer and provides a serial output to plant computers.

d) The Operator Display Assembly (ODA) located in the operator benchboard provides displays of various measured and set parameters. In addition, recorders also show reactor power information.

e) Fiber optic transmission cable module between NUMAC chassis and Operator Display Assembly.

f) Associated qualified interconnecting cabling.

Existential System

Advanced System (WRNM)

**FIG: 1 Comparison between SRM/IRM and WRNM Systems**

### 2.2.3 WRNM Experience

The WRNM system was first installed in an operating BWR in 1987. To date, 25 BWRs worldwide have installed the WRNM. The WRNM is also installed in the ABWR at Lungmen, with scheduled startup in the later part of this decade. It is also one of the required NMS systems for the ESBWR, the new generation of BWR. Although the installation of the WRNM is considerably involved, with work from the refuel floor, under reactor vessel, inside the containment, and with signal path from the containment penetration all the way to the control room, most installation can be accomplished within the outage window, typically approximately 14 days. Successful operational history of the WRNM and its enormous potential advantages suggests that this system can play a significant role in supporting the mission of plant life extension for the rest of the BWRs. Figure 2 presents a picture of an installed WRNM system at one of the panels.
2.3 Power Range Neutron Monitor System (PRNM)

2.3.1 Description of Current System

The current PRNM in most BWRs is a 6-channel system comprised of different assemblies for APRM, LPRM, flow units, and power supplies (see Figure 3). The system also interfaces with the RCMS via a two-channel Rod Block Monitors (RBM) to provide rod block when necessary. The system is comprised of over 30 types of modules, totaling about 600 total for a plant. The display is based on meters, lights and recorders. The system receives inputs from LPRM and the recirculation flow transmitters and performs core-averaging functions in the APRM. The averaged power level is compared with the absolute core average neutron fluxes and flow biased power based trips to determine if there is a need for protective actions, such as reactor scram or rod blocks. The APRM are inputs to the Reactor Protection System (RPS) that is based on a one-out-of-two-twice logic. Since the RPS has two trip systems, the APRMs are arranged to provide two trip channels per RPS trip system. Since the RPS is a fail-safe system, any failure in the APRM or associated equipment would contribute to a trip signal to the RPS, resulting in a half-scram with any equipment failure. Therefore, the current system provides multiple challenges in terms of maintenance and operation. In addition, as a result of the thermal hydraulic instability event at the La Salle plant in 1986, the NRC required all US BWR to have a long-term stability solution to meet the requirements of General Design Criterion 12.[4] This imposed a new functional requirement to the PRNM.

FIG: 2 NUMAC WRNM in a BWR 4

1 BWR 6 and new plants do not have RBM.
resulting in a modification to the existing PRNM. Although it may be possible to provide a relatively simple modification to the existing system to satisfy the stability solution, the long-term solution for the PRNM, in terms of obsolescence, maintenance, operation, and regulatory issues can be addressed with the implementation of the NUMAC PRNM.

### 2.3.2 Configuration of PRNM

As in the case of the WRNM, the NUMAC PRNM System provides significant simplification over the existing system. The NUMAC PRNM is a 4-channel system comprised of the following in each channel (see Figure 3):

- a) Average Power Range Monitor (APRM) chassis
- b) Two-out-of-Four Logic Voter
- c) Low Voltage Power Supplies (LVPS)

In addition, the NUMAC PRNM also has a two-channel RBM for rod block functions. The RBM is non-divisional and is supported by its only interface units and low voltage power supplies. The LVPS for the RBM is identical to that for the APRM. Consequently, the system is reduced to only 4 different types of assemblies with about 12 types of modules and about 180 modules total for a plant. The reduction in the types and total number of modules greatly simplifies the burden on maintenance.

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FIG: 3 Block Diagram of Current PRNM for a BWR
The APRM receives inputs from the LPRM and flow transmitters and performs the core averaging functions. The flow-biased calculation is also performed in the APRM. Digital filtering is performed on the LPRM signals so that the system is not susceptible to the spiking of the LPRM signals as the current system. The digital filtering also ensures that the system is not susceptible to the various noise issues experienced in the current system.

The long-term stability solution is also performed in the APRM as software based function. For example, the Oscillation Power Range Monitor (OPRM) determines the reactor stability by monitoring the behavior of the LPRM and initiated trips based on stability algorithms based on the period, amplitude, and growth rate of the LPRM signals.

All trip signals from the APRM are sent to each of the Two-out-of-Four Voters via fiber optic cables. The Voters provides input to the RPS and would initiate a reactor trip when two of the four voters initiate a trip signal. As opposed to the current system, a single channel trip would not result in a half-scram. Therefore, the Two-out-of-Four Voters eliminate the PRNM as a contributor to reactor half-scram.

The APRM contains redundant high voltage power supplies for the energization of the LPRM. The redundancy improves the reliability and availability of the system. It also allows the system to perform on-line diagnostics of the LPRM (i.e., I/V curves). This is a powerful tool that significantly reduces the maintenance tasks for the system.

The APRM also sends LPRM signals to the RBM so that the RBM can determine the local flux response and initiates rod blocks when the flux signals exceeds pre-determined limits, indicating a high rate of reactivity increase. The RBM chassis is also the communication path between the NUMAC PRNM and the process computer. The PRNM can download all LPRM, APRM, and RBM signals effectively to the process computer. It can also receive calculated gain factors of the LPRM and APRM based on the LPRM calibration from the process computer. Automating the transfer of the gain factors reduces the potential for human error from the manual inputs of the current system.

Each APRM and RBM provides output to an ODA at the control room bench board, similar to the WRNM. The ODA is a self-contained graphics display mounted at the operator’s console that provides APRM, LPRM, OPRM, and recirculation flow information to the plant operator. The ODA provides both “bar graph” and digital representation of the primary signals, as well as status information for the APRM/RBM channel. Bar graph representations also include trip point markers for both the fixed and flow-referenced trip setpoints. More information is made available to the operator with the ODAs than is presently offered by the existing operator display panels.

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2 BWRs with large cores may require more than one APRM chassis per channel for the required LPRM inputs.
2.3.3 PRNM Experience

The PRNM system was first installed in an operating BWR in 1996. To date, 24 BWRs worldwide have installed the PRNM. The PRNM is also installed in the ABWR at Lungmen, with scheduled startup in the later part of this decade. It is also one of the required NMS systems for the ESBWR, the newest generation of BWR. Although the installation of the PRNM is considerably involved, with complete removal of all the equipment in 5 panels and the rearrangement in the control room bench board for the ODA, most installation can be accomplished within an outage window of approximately 14 days. The shortest installation period has been less than 10 days. The interface between the PRNM and other plant systems is the cause of most installation issues for the PRNM. However, careful review of the interfaces and collaboration with involved plant personnel during the design phase of the upgrade project would minimize the impact on these interface issues. The successful operational history of the PRNM and its enormous potential advantages suggest that this system will play a significant role in supporting the mission of plant life extension for the rest of the BWRs. Figure 5 presents a picture of an installed PRNM system in a BWR 4 plant.
In summary, the NUAMC PRNM System provides neutron flux information used for monitoring the average power level of the reactor core, monitoring the local power density distribution associated with the withdrawal or insertion of a control rod, and for protecting the core against local average power transients when the reactor power is in the power range. It is a significant improvement over the currently installed system.

2.4 Rod Control Managements System (RCMS)

2.4.1 Reactor Control Function

In reactor vessels, control rods are used to regulate the level and distribution of flux activity within the reactor core. This is accomplished by moving control rods according to a predetermined pattern and sequence. Improper rod position can result in uneconomic fuel consumption or, worse, possible damage to the fuel and fuel assemblies. To prevent inadvertent operator errors, reactor performance and rod positions are constantly monitored by systems that either give an alarm demanding operator attention or completely block rod movement until the error has been corrected.

To accomplish the rod control function, the system takes in rod position input and input from operator for the demand of rod movement, evaluates it against other system inputs, such as the RBM or Rod Worth Minimizer (RWM), and allows or prohibits rod movements accordingly. The rod movement is accomplished by sending the demand signal to the hydraulic control units (HCU) for the Control Rod Drive (CRD) system.
The rod control function is accomplished by the following systems:\(^3\):

1) Rod Position Indication System (RPIS) that provides inputs on the vertical location of the rod. Reed switches are used to detect rod positions. The inputs from the reed switches are multiplexed and processed by probe mux cards that are arranged and controlled by the file control processors to provide an efficient means of sending the rod position data to the Rod Drive Control System (RDCS) and the Operator Control and Display System (OCDS) in the control room.

2) Rod Drive Control System (RDCS) that provides the signals to the HCU to initiate rod movement. This system takes inputs from the RPIS and evaluates it against other plant inputs, such as permissive from the Rod Worth Minimizer, power level and RBM from the PRNM. It has an Analyzer that evaluates the conditions of the HCU and a Fault Map that will report any failure of the HCU that would prohibit rod movement. The Power Gate of the RDCS sends signals to energize or de-energize the direction control valves of the HCU for rod movement if all conditions are satisfied. Due to the limitation of the technology at the time, timers are used to limit the duration of a control signal to the HCU.

3) Hydraulic Control Unit receives signals from the RDCS and controls the directional control valves for rod movement. The system uses a transponder card for each control rod to control the signal to the directional control valve and monitor the HCU status. The transponder cards are arranged in branches with a Branch Amplifier for signal conditioning.

4) Rod Worth Minimizer (RWM) monitors and controls the movement of the control rods at low power. The RWM prevents the withdrawal of an out of sequence control rod during startup that could result in an unacceptable neutron flux excursion.

5) Operator Control and Display System (OCDS) is comprised of the rod select module that allows the operator to select individual rods for rod movement and a core map that indicates the position of each rod in the core.

2.4.2 Rod Control Managements System (RCMS)

Each of the subsystems listed above has its own unique design. The complexity of the rod control function is compounded by the less than optimal integration of these subsystems. The interdependence between the systems would result in an inability to move the control rods when needed. Furthermore, obsolescence in one of these systems would affect the entire rod control functions. For these reasons, GEH has introduced a new Rod Control Management System (RCMS) that integrates all these subsystems to provide optimal rod control functions.

The RCMS replaces the existing RDCS, RWM, and Operator Control and Display, and portions of the RPIS and HCU with one fully integrated system that provides redundancy and expanded capability for maintenance and operations, e.g. rod stroking and scram timing. The redundancy within the RCMS allows continued system operation in case one of the components fails. Figure 6 provides a pictorial presentation of the new system that is comprised of the following:

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\(^3\) The “rod control systems” in BWR are dependent on their vintage with different names of the system for each type of plants. The systems shown here are representative of a BWR 5.
1) The Transponder cards and Branch Amplifiers of the HCU are replaced with the new Micro-Logic Transponder cards and Branch Amplifiers with improved reliability and alarms and diagnostic capability. In addition, a new Transponder card cover is also available.

2) The Probe Mux Card and File Control Processors of the RPIS are replaced to allow faster inputs to the system. The faster input rate is required to support the system to operate in a position feedback mode as opposed to a timer mode in the old design. The position feedback feature ensures that the rod will stop at the targeted location.

3) RCMS Controllers are used to process the inputs from the RPIS, Transponder cards, Branch Amplifiers, other plant inputs, and the Main Control Room (MCR) Controller from the Main Control Room. The RCMS communicates with Transponder cards and Branch Amplifiers via the two RCMS Interface Units. The MCR Controller transmits the rod select input from the control room. The RCMS Controller is a dual controller unit that performs parallel data processing and performs cross compare. Alarms will be initiated if the cross compare shows a disagreement between the controllers. The RCMS Controller performs all rod control function, including the RWM. It provides additional capability such as rod prompting, pre-loading of rod sequences, continued operation with bypass or failure of a Transponder card or Branch Amplifier, automatic rod drift suppression, and intelligent rod substitute position. A 20-inch Liquid Crystal Display (LCD) touch screen is provided as a maintenance display for the RCMS.

4) The RCMS Interface Unit is a single processor unit that provides inputs to the RCMS Controller from the Transponder cards, Branch Amplifiers and other plant data for the RCMS processing.

5) The RCMS Interface Unit controls the power module as the power source for the Branch Amplifiers, stabilization valves and annunciators.

6) The MCR Controller is a dual controller, similar to the RCMS Controllers. It takes plant data inputs from the control room, from the RCMS Controller, and from the rod select module and provides displays in the control room. The MCR Controller obtains plant data input from the MCR Interface Units, a similar arrangement as the RCMS Controller and the RCMS Interface Units.

7) The HMI in the control room is comprised of a large 40-inch LCD displaying the full core map, and two 20-inch LCD with touch screen capability. One of the LCD’s is used for rod select and the other is for status display. These two LCD’s serve as a backup display for each other. These displays and the diagnostic and prompting capability provide excellent HMI that would reduce the potential for operator errors for rod movement. In addition, the system allows all CRD surveillance and maintenance functions, e.g., rod exercise; rod flushing, can be performed directly from the rod select module in the control room.

8) The system uses Ethernet for internal and external communications, thus providing a standard protocol to plant process computer and other external devices.
2.4.3 RCMS Experience

The RCMS is a new system and is currently under development. The first RCMS installation is schedule for spring of 2008 in a BWR 5. Effort is under way to complete the design of the RCMS for BWR 6 and earlier BWRs. Since the ABWR and ESBWR employ a different type of CRD system, the RCMS will not be implemented in the newer generations of BWRs. However, the technology of the RCMS, e.g., HMI, are based on the ABWR design.

3. Support for Plant Life Extension

The three systems presented in this paper represent the continued evolution of the NUMAC product line in support of the BWR operation. These systems have been or are being implemented in operating BWRs for various reasons. In terms of plant life extension, these systems are most certainly solutions that may be used to support plant life extension. One of the goals of the NUMAC product line is to be able to manage obsolescence. This is accomplished by applying modular design, common modules, progressive improvements in response to industrial changes, and by adherence to the design basis of the plant. The modular design allows a minor change to a module if a component within the module becomes obsolete. Modules that perform the same functions, e.g., Computer Processing Unit (CPU), are used within the same platform. Therefore, resolving the obsolescence in one case will resolve the issue for the entire platform. As changes are inevitable in the I&C world, it is necessary to continue to update the product line and leverage the changes. The RCMS is a prime example of the changes in the NUMAC product in that Ethernet as opposed to point-to-

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4 Clockwise from the top: 40-inch core map; panel for RCMS controller, maintenance display and RCMS interface units; Transponder card/covers; Probe Mux and File Control Processor; Rod Select Display.
point fiber optic is used for communication within the system. Reference 2 also shows an example of the CPU upgrade for NUMAC. However, whatever changes or modification of the design is required for any I&C system in a BWR, it is necessary to maintain the design basis of the system and the plant. Therefore, maintaining the design basis of the plant is part of the design task for I&C. All these elements are required for GEH to support plant life extension in the I&C area.

4. Summary and Conclusions

GEH is the industry leader in Boiling Water Reactor (BWR) technology with over 50 years of experience in the nuclear industry. GE offers a wide range of products and services including Instrumentation and Control systems that ensure the safe operation and maintenance of the plant, while bringing greater efficiency and output. The NUMAC (Nuclear Measurement Analysis and Control) product line is a family of digital instruments designed to improve plant performance. The design concept of NUMAC has proven to be in concert with the mission of plant life extension.

LIST OF ACRONYMS

1. ABWR – Advanced Boiling Water Reactor
2. APRM – Average Power Range Monitor
3. BWR – Boiling Water Reactor
4. CPU – Computer Processing Unit
5. CRD – Control Rod Drive
6. EMI – Electromagnetic Interface
7. GE – General Electric
8. GEH – General Electric Hitachi
9. HCU – Hydraulic Control Unit
10. HMI – Human Machine Interface
11. I&C – Instrumentation and Control
12. ICPS – Ion Chamber Power Supply
13. IRM – Intermediate Range Monitor
14. LCD – Liquid Crystal Display
15. LPRM – Local Power Range Monitor
16. LVPS – Low Voltage Power Supply
17. MCR – Main Control Room
18. MSV – Mean Square Voltage
19. NMS – Neutron Monitoring System
20. NRC – Nuclear Regulatory Commission
21. NUMAC – Nuclear Measurement Analysis and Control
22. OCDS – Operator Control and Display System
23. ODA – Operator Display Assembly
24. OPRM – Oscillation Power Range Monitor
25. PRNM – Power Range Neutron Monitor
26. RBM – Rod Block Monitor
27. RCMS – Rod Control Management System
28. RDCS – Rod Drive Control System
29. RMCS – Reactor Manual Control System
30. RPIS – Rod Position Information System
31. RPS – Reactor Protection System
32. RWM – Rod Worth Minimizer
33. SRM – Source Range Monitor
34. TIP – Transverse In-core Probe
35. WRNM – Wide Range Neutron Monitor

REFERENCES


