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THE ROLE OF INSTRUMENTATION AND CONTROL TECHNOLOGY IN ENABLING DEPLOYMENT OF SMALL MODULAR REACTORS

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ABSTRACT

The development of deployable small modular reactors (SMRs) will provide the United States with another economically viable energy option, diversify the available nuclear power alternatives for the country, and enhance U.S. economic competitiveness by ensuring a domestic capability to supply demonstrated reactor technology to a growing global market for clean and affordable energy sources. Smaller nuclear power plants match the needs of much of the world that lacks highly stable, densely interconnected electrical grids.

SMRs can present lower capital and operating costs than large reactors, allow incremental additions to power generation capacity that closely match load growth and support multiple energy applications (i.e., electricity and process heat). Taking advantage of their smaller size and modern design methodology, safety, security, and proliferation resistance may also be increased.

Achieving the benefits of SMR deployment requires a new paradigm for plant design and management to address multi-unit, multi-product-stream generating stations. Realizing the goals of SMR deployment also depends on the resolution of technical challenges related to the unique characteristics of these reactor concepts. This paper discusses the primary issues related to SMR deployment that can be addressed through crosscutting research, development, and demonstration involving instrumentation and controls (I&C) technologies.

Key Words: Instrumentation, Controls, Modular, SMR, Deployment

1 INTRODUCTION

Energy security and the reduction of greenhouse gas emissions are two key national energy priorities that can be met in a sustainable manner through nuclear power. The development of deployable small modular reactors (SMRs) will provide the United States with another economically viable energy option, diversify the available nuclear power alternatives for the country, and enhance U.S. economic competitiveness by ensuring a domestic capability to supply demonstrated reactor technology to a growing global market for clean and affordable energy sources. Smaller nuclear power plants match the needs of much of the world that lacks highly stable, densely interconnected electrical grids[1]. These reactors can present lower capital costs than large reactors, allow for incremental additions to power generation capacity and support multiple energy applications (i.e., process heat). Additionally, SMRs can be introduced through phased construction of modules at a plant site to incrementally achieve a large-scale power park. Consequently, commitment of the full investment for a large plant would not be required up front and concurrent revenue generation would be facilitated throughout later phases of construction and commissioning.

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Achieving the benefits of SMR deployment requires a new paradigm for plant design and management to address multi-unit, multi-product-stream generating stations and to offset the reduced economy-of-scale savings. Realizing the goals of SMR deployment also depends on the resolution of technical challenges related to the unique characteristics of these reactor concepts. A comprehensive research, development, and demonstration (RD&D) program to coordinate collaborative efforts by industry and government can facilitate resolution of these needs. The basis for identifying I&C challenges and the resulting RD&D needs can be categorized into four major elements. These four major elements as illustrated in Figure 1 are 1) I&C issues that arise from the unique operational and process characteristics that are the consequence of fundamental design differences between new SMRs and previous or current large plants, 2) I&C technologies that can further enhance the affordability of new SMRs, 3) I&C technologies that can further expand the functionality of SMRs, and 4) I&C technologies that can enhance the safety, security and proliferation resistance.

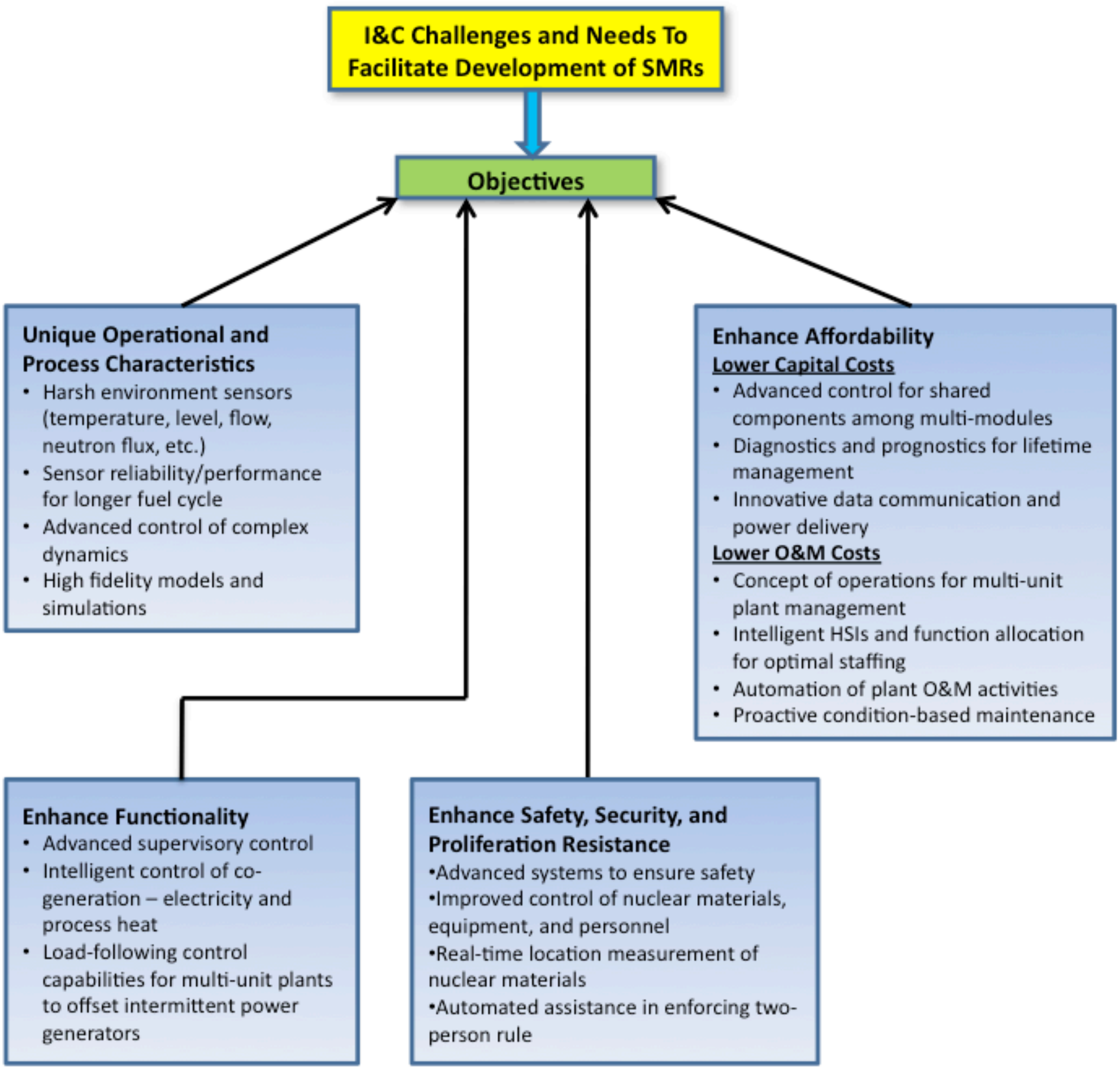

Figure 1. I&C approach for SMRs.

1.1 Unique Operational and Process Characteristics

Small and medium reactors have different process measurement needs than large Light Water Reactors (LWRs). For advanced SMRs with different coolants (gas, liquid salt, or liquid metals) operating at higher temperatures, the process measurement instrumentation needs to be both chemically compatible with the coolant as well as tolerant of the higher temperature. For example, no currently available fission chambers are capable of operating near-core in a very high-temperature gas-cooled reactor (VHTR), thus necessitating neutron flux measurement being located away from the core. Similarly, diagnostic measurements are different for reactors with different coolants. The ultrasonic imaging required to verify proper component or fuel element placement below the surface of liquid sodium remains commercially unavailable. Even several LWR-based SMR designs will have different sensor access requirements than loop type LWRs because they use an integral primary system reactor (IPSR) configuration. In addition, the larger amount of water in the downcomer region between the core and vessel in IPSRs greatly challenges the use of ex-vessel start-up flux monitoring, and locating the primary pumps within the reactor vessel limits accessibility for diagnostic measurements.

1.1.1 Models needed to understand dynamic behavior

Detailed knowledge of the dynamic behavior of the operational characteristics of SMRs needs to be represented in high-fidelity models and simulations. The unique operational characteristics of most SMR designs arise from the dynamic behavior of each general reactor class and differences in plant configurations (i.e., IPSR behave differently from loop designs, VHTRs behave differently from IPSRs, liquid metal reactors behave differently from VHTRs, etc.). Plant configuration differences include integral placement of primary coolant system components, shared plant systems or resources among units, and integrated, reconfigurable balance of plant systems for multiple co-generation products.

Some SMR concepts involve sharing resources and systems among units to further reduce the up-front costs. This degree of sharing can range from minor support or auxiliary systems (e.g., emergency coolant tanks, control stations, backup electrical power, etc.) to major primary or secondary systems (e.g., turbine-generators coupled with two or more units). Depending on the nature and degree of sharing among modules, there may be significant dynamic coupling that must be taken into account within the operational controls for the plant. The impact of shared resources and systems may only require supervisory coordination of demands or may result in more sophisticated control implementations to address unique dynamic behavior. However, these control considerations are uncommon in nuclear power operational experience and should be demonstrated. In addition, the regulatory implications of shared systems must be evaluated.

Some SMR designs, such as the IPSR and other advance designs, use unconventional process system components that do not have well-established performance characteristics. For example, helical coil steam generators (HCSGs) with tube side boiling differ from conventional steam generators (SGs) with shell side boiling. Thus boiling is on the tube-side where the inventory is small. The result is the need for tight tube-side inventory control to avoid dryout. With the array of bundled helical tubes, flow-induced vibrational effects have to be investigated and addressed through control approaches utilizing surveillance and diagnostics information. Finally, the nature and impact of long-term degradation of the tube bundles has to be determined and addressed.

For SMR concepts that involve passive process systems, the impact of those systems on operability and plant performance needs to be evaluated to ensure proper consideration in control and safety requirements. For example, behavior under natural circulation and determination of need for indirect control options in off-normal situations.

Unconventional and/or reconfigurable balance of plant configurations may pose control and condition monitoring challenges. Designs with multiple steam generators present the opportunity for level oscillations that may exhibit limit cycle behavior. These potential effects have to be addressed in control schemes.

1.1.2 Implications of unique operational and process characteristics

The unique operational and process characteristics listed above will require either significant development or redesign of the process monitoring and component diagnostic instruments to satisfy the prospective harsh environments and unique measurement demands. These operational differences need to be understood and stimulated to support the design and testing of control systems and process diagnostics. Additionally, the performance of controls, diagnostics, prognostics, sensors, communications, and other elements of the integrated I&C system architecture need to be demonstrated using virtual and physical testbeds. However, these testbeds are not generally available so they must be developed or adapted for this use from other resources.

1.2 Enhanced Affordability

Two factors for the economic competitiveness of SMRs that can be notably affected by design and implementation are the up-front capital cost to construct the plant and the day-to-day cost of plant management, including operations and maintenance. The former cost is primarily dependent on the size and complexity of the components that must be fabricated and the methods of installation. A simplified design, smaller components, and modular fabrication and construction are among the characteristics of SMRs that can reduce this cost. Selection of innovative technologies may also provide some benefit in reducing the fabrication, installation, inspection costs, financing costs, and operations and maintenance (O&M) costs. Fuel costs tend to be stable and, in contrast with other energy sources, they are a minor component of the operational costs. The most significant controllable contributor to day-to-day costs arises from O&M activities, which are heavily dependent on staffing size and plant availability. Efficient, effective operational approaches and strategic maintenance can influence these costs.

1.2.1 Capital Costs

Capital cost reductions compared with conventional large reactors are anticipated for SMRs due to smaller size and fewer components. Although costs associated with I&C systems are typically not a significant contributor to capital expenses for nuclear power plants, they may constitute a proportionally larger fraction of capital costs for SMRs. Essentially, costs for sensors, cable runs, controls and interface equipment may not be as sensitive to savings resulting from reduced unit size, especially if multi-modular plants require independent, dedicated control rooms for each unit. Thus, there is benefit to ensuring that more highly integrated system architectures utilizing modern technologies are employed. Traditional I&C architectures were based on segregated or “stove-piped” systems and required extensive cable runs. Current upgrades and Generation III+ I&C systems involve greater integration and more common communication interconnections (e.g., multiplexing or networking).

The greatest capital cost contribution from I&C systems arises from cable installation. The trend toward more effective, efficient operation and maintenance will require many additional sensors beyond the number of nuclear and process sensors at a conventional nuclear power plant. These additional sensors will be needed to enable monitoring of real-time process variables, structural components, movable equipment, portable devices, and warehouse/inventory areas, but will exacerbate the cabling complexity and cost. Wireless or shared wire communications capabilities could substantially reduce the cabling cost but a number of technology and security issues must be resolved.

Extensive digital technology use and integrated designs can optimize the I&C architecture of a plant and reduce inventory requirements. While modern wireless communications technology can minimize cabling needs, guaranteeing the integrity of safety significant functions and ensuring the necessary communications reliability pose challenges to taking full advantage of these potential benefits. Most wireless communications currently being installed at nuclear power plants are for non-real-time information systems (e.g., parts tracking). To develop wireless alternatives to costly hardwired cabling for real-time, on-line monitoring, a demonstration of a high-reliability, secured wireless communication system for continuous data transmission is necessary. This is especially true if wireless communications are used for transmission or measurement and control data as part of the plant control systems.

1.2.2 Plant Operations and Maintenance Costs

Plant O&M costs are driven by a number of factors including plant availability, efficiency of power conversion, staffing requirements, etc. The unique design and operational features of SMRs can affect of each of these cost elements, positively or negatively. Appropriate I&C can help mitigate negative impacts and enhance positive impacts. For example, the operation of a nuclear power plant is labor intensive. The O&M staff at a plant consists of operator teams for each shift at each unit and the maintenance staff can involve a large number of technicians and specialists. The current industry average for O&M staff is roughly one person per every two megawatts of generated power. SMR designs must be able to meet or improve on this ratio to be cost competitive, independent of the number of reactor modules needed to achieve a comparable power output. Meanwhile, the maintenance staff requirements for an individual reactor module may decrease due to a simplified design but the volume of work might increase as the number of systems to be serviced increase proportionally with the number of units on site. Additionally, the workload could also be affected by an increase in the percentage of time each year spent with one or more units at the plant in outage as multi-modules rotate refueling. New advances in I&C capabilities provide the possibility of much deeper knowledge of the status and condition of a nuclear power plant, which can be exploited to improve the effectiveness and efficiency of plant personnel. The industry success over the past couple of decades in reducing plant O&M staffing levels by roughly a factor of four is primarily the result of lessons learned coupled with improved I&C technology and functionality. Continued improvement in I&C systems and applications, coupled with the operational characteristics of SMR designs, can support further enhancements in O&M performance.

Ensuring high availability depends on avoiding unnecessary plant or unit trips and minimizing the outage time for refueling and maintenance. The first condition is supported by highly reliable automated control systems that are fault tolerant and sufficiently robust to handle an extensive range of plant transients. For highly automated intelligent control systems, the robustness that can be achieved may include anticipating (and avoiding) accident conditions and responding to off normal or degraded conditions (e.g., plant component degradation or failure) through power runbacks and adjustments in control goals or methods. The former characteristic requires a detailed understanding of the dynamic behavior of the SMR, the availability of diagnostic information on the plant state, and robust control capabilities that integrate the knowledge of plant state with decision-driven intelligent control. The latter characteristic also requires state knowledge as well as condition information for components and equipment to enable robust supervisory control that can respond to events and conditions by adjusting demands and/or adapting the control strategy.

Plant availability is also influenced by fuel cycle demands. Most SMR designs promote extended refueling intervals. The LWR-based designs typically anticipate 3-4 year cycles by eliminating the mid-cycle shuffling of fuel assemblies. More advanced concepts with high conversion ratio designs anticipate core lifetimes of 20-30 years. In those cases, the outage frequency will be driven by inspection and maintenance needs. Thus, there is a need to have a well-founded understanding of the condition of plant components and equipment and a basis for detecting incipient failure (to avoid scrams and unplanned outages). Minimizing maintenance demands can be facilitated by intelligent integrated I&C systems that support plant-wide diagnostics and prognostics. In addition to improving plant availability, optimized maintenance also has the prospective benefit of reducing staff demands so that staff reduction goals for SMRs can be achieved.

Automated, intelligent control can contribute to improved efficiency of power production by ensuring that control actions closely and rapidly track load demands. Additionally, improved knowledge of plant state can be facilitated through highly reliable, accurate sensors and possibly innovative measurement techniques (e.g., more direct measurement of key parameters, drift free first principle measurements, analytic measurement based on data fusion). With improved state knowledge and tighter control, operating margins can be reduced and more power can be generated.

Finally, advancement in the use of digital technology and innovative techniques, such as intelligent automation and prognostics, is needed to achieve the staffing reductions that are necessary to ensure the desired cost competitiveness of SMRs. For example, a highly automated plant control system, which incorporates advanced control algorithms and diagnostics, can assume responsibility for almost all normal operational control activities ranging from startup through full power operation and can also incorporate automatic responses to anticipated operational occurrences. These gains can be even more dramatic for SMR designs that take advantage of inherent dynamic responses to simplify operation. Reductions in maintenance staff require a comprehensive transition from preventive or periodic maintenance to predictive, condition-based maintenance. Effective, timely maintenance is enabled by the capability to measure key indicators and to accurately determine the condition of components or processes through diagnostic and prognostic functions. Thus, suitable measurement technologies are needed and a well-founded understanding of the monitored component or process is necessary.

1.3 Enhanced Functionality

The new SMR designs can provide the benefit of sustained output from a plant composed of multiple modules. By building a large power park of many SMR modules, the plant has the advantage of only losing a small percentage of its power output should one unit go out of service for a planned outage or unplanned trip. This is especially important when the SMR is being used to provide the primary power for an isolated community or installation or where continuity of mission is critical. Effective plant management through advanced control and predictive maintenance capabilities enhances this benefit. The expected impacts are minimizing unplanned shutdowns and optimization of maintenance demands through condition determination (monitoring) and stress reduction (control).

Additionally, the provision of multiple product streams enables effective utilization of the energy content of the heat generated by the reactor. For example, the lower end waste heat can be used to support district heating, desalination, or low-grade industrial process heat applications. High temperature heat can be used for product generation such as hydrogen production to provide an alternate use when the full output of the plant is not needed for power production. Essentially, the plant could be reconfigured to meet demand. For example, electrical power could be the exclusive product during high demand periods and some units could be switched to hydrogen production during overnight, low demand periods. Integrated process diagnostics and advanced control to anticipate downstream upsets and response to dynamic coupling of different production systems (e.g. turbine-generator for electricity, thermal systems for desalination or hydrogen production) enables automatic reconfiguration of balance of plant.

1.3.1 New paradigm

In the past, large nuclear power plants were designed to be base loaders (due to their large unit capacity) that for the most part ignored the system dynamics associated with external energy sources and loads on the electric grid. This approach, while sound for the early generation nuclear power plants, will not be adequate for the small modular nuclear reactors being designed today to operate cooperatively with renewable energy sources. The size and location of these new reactors, coupled with an increase in the percentage of renewable energy generators on the same grid, will force a change in the reactor controls paradigm. The time varying nature of renewable energy sources such as solar and wind generators is manifested as fluctuations in voltage and frequency on the power grid. Without appropriate highly reliable automated controls, the variations in these external generators will result in the reactor tripping off the grid.

In addition to the development of models for this new class of small modular nuclear reactors, that will capture internal components such as the turbine control system (including the steam line and bypass valves), the reactor (including the neutron flux of the reactor core, temperature and pressure of the coolant), reactor protection system, and the generator, complementary models for emerging renewable energy sources must also be developed. The objectives are to develop these plant models of small modular reactors and complementary models for solar and wind generation stations that will be operating on the same grid in order to ascertain changes in the plant controls/protection philosophy and to determine reasonable limits of renewable energy sources.

1.3.2 Implications of enhanced functionality

Multi-unit control with significant system integration and reconfigurable product streams has never before been accomplished for nuclear power, and this has profound implications for system design, construction, regulation, and operations. Demonstration of the technology required to effectively operate a grouping of small reactors as a single plant is needed. Development of multi-modular plant management and supervisory control should address strategies for coordinated use of shared systems and managed transitions among plant configurations (e.g., phased commissioning of units or flexible system arrangements for selection among co-generation options). These strategies include supervisory control approaches for managing demand allocation, system reconfiguration, and dynamic transitions among multiple co-generation products.

1.4 Enhanced Safety, Security and Proliferation Resistance

Because there are several different SMR designs, there are many different safety system designs. Many SMR designs exhibit a high degree of passive safety using convection cooling systems and/or the use of moderators and fuel elements that have a negative temperature coefficient. In the case of convection cooling systems, decay heat following the shutdown of the reactor can be safely removed. Using negative temperature coefficients in the moderators and fuels keeps fission reactions under control. While many SMR designs have a high degree of passive safety, I&C technologies can help assure this high degree of passive safety is maintained [2].

Physical security and proliferation resistance must be an integral part of SMR design and implementation. I&C technologies must have a significant role in providing an enhanced level of security against the ever changing threat environment. I&C technologies can also play a role in reducing the cost associated with the more traditional human based solution currently used at existing nuclear power plants. New technologies must be developed to minimize the likelihood of attack (physical and cyber) and mitigating the consequences of attempted attacks. Automated monitoring of real-time video images provides the ability to watch staff and visitors in facilities to confirm authorization for access to facilities. Customized vision recognition algorithms could also assist in the enforcement of the two-person rule.

The logical focus is on technologies that enable timely information on the location and movement of nuclear material. Security assurance requires timely information on the location and movement of nuclear material, and proliferation resistance also requires timely information on the location and movement of nuclear material. There is an overlap and synergism between measurements that support these objectives [3].

1.5 Key I&C Research Needs for SMRs

Nuclear power I&C technology is a broad discipline that encompasses many technical aspects that include measurement, control, monitoring, and human-system interaction. To account for the breadth of the discipline, the I&C research needs for SMRs are characterized in terms of key technical focus areas. This discussion does not exhaustively identify the prospective research needs but provides covers of several keys issues organized according to measurements, diagnostics and prognostics, control and plant operations, and I&C architecture and infrastructure (e.g., communications, power, interfaces, and shared components).

1.5.1 Measurements

The instrumentation development needs for SMRs have both common elements independent of the reactor type and specific elements relevant to certain reactor types. The most probable near-term SMR is expected to be an integral primary system reactor (IPSR), which incorporates the reactor core, steam generator(s), and pressurizer into a single, common pressure vessel. An IPSR has many features in common with conventional pressurized-water reactors (PWRs), but its integral nature necessitates several measurement technology differences.

Under an International Nuclear Energy Research Initiative (I-NERI) collaborative project with counterparts from Brazil, an investigation of instrumentation needs for IPSRs was conducted [4]. It was determined that measurement of certain key parameters can best be accomplished using in-vessel sensors that require development and demonstration. These in-vessel measurement capabilities include flux/power, primary flow, reactor coolant system temperatures, primary water inventory, steam generator water inventory, and steam generator stability. As an additional consideration, SMR concepts include provisions for extended operational cycles and longer maintenance intervals. Thus, sensors developed for these plants must be capable of long-term operation without requiring maintenance intervention to address drift or degradation due to environmental stress.

1.5.1.1 Neutron flux measurements

An IPSR features a larger water gap between the core and reactor vessel, which causes the flux levels outside the vessel to be sufficiently low enough to restrict the use of ex-vessel ion chambers for start-up monitoring and flux profiling. A highly ruggedized neutron detector capable of withstanding high temperature and high radiation needs to be developed with the associated radiation hardened electronics.

1.5.1.2 Level and flow measurements

Also, since the pressurizer is integral to the reactor vessel and vessel penetrations are restricted, conventional PWR-type temperature-compensated differential pressure-based level measurements are not feasible. The lack of an external primary coolant loop for an IPSR also alters the nature of the heat balance measurements across the core. As the primary flow measurements place the highest value on measurement reliability and response time as opposed to absolute accuracy, alternate instrumentation approaches appear useful such as applying pumping power signature diagnostics coupled with neutron noise analysis as a primary flow measurement.

1.5.1.3 Thermometry

The lack of an external primary coolant loop for an IPSR implicates alternate instrumentation approaches to thermometry. For example, obtaining accurate measurements from long lead wire thermocouples will be challenging. Resistance Temperature Detectors (RTDs) should be considered as an alternative. . The longer fuel cycles and service intervals envisioned for SMRs provide a strong incentive to develop drift free, first principles measurement technologies. In conventional PWRs, the coolant temperature measurement instrumentation is calibrated during each refueling outage. Technologies such as Johnson noise thermometry that are immune to the progressive deterioration of the sensing element are important to a successful, cost effective SMR deployment.

1.5.1.4 Beyond IPSR

SMR concepts for longer-term deployment will tend to have harder neutron spectra to increase their ability to achieve deeper burns and convert long-life actinides. The immediate instrumentation challenges of these liquid metal or salt cooled or gas cooled reactors relate to sensors for harsh environments (e.g., higher temperatures, harder neutron flux).

1.5.2 Diagnostic and prognostics

To meet the goals for safe, secure, and economic operation of SMRs, the application of advanced automated diagnostics and prognostics techniques will be required. Integrated within digital I&C architectures, advanced diagnostics and prognostic systems have the potential to extend the interval between maintenance outages through better equipment condition monitoring, reduce labor demands for equipment surveillance, and significantly reduce risks due to a greater understanding of precise plant equipment conditions and margins to failure.

Fundamental studies have been supported through DOE university research programs for applications of on-line condition monitoring and prognostics to nuclear energy systems. The need is now to validate prognostic capabilities and demonstrate how they can be integrated with highly automated intelligent control to give safe and optimal plant operation. Integration of multiple sensor data through data fusion can provide signals for advanced control of actuators and prediction of system element remaining life. The use of prognostics can provide for a proactive approach to operations and maintenance that reduce unplanned outages, optimize staff utilization and, give smart self-diagnostic systems that operate with high reliability.

For prognostics to be effective and to determine whether there is chance of system recovery, it is necessary to understand the key degradation mechanisms and associated stressors that may significantly affect plant performance and safety and to formulate damage models for key plant components under different operational conditions. Ultimately, it will be necessary to demonstrate the integration of all elements needed to enable the vision of advanced real-time monitoring and prognostics for a SMR, including the interfaces to advanced automated control systems to support normal operation, off-normal response, and operation under degraded conditions.

1.5.2.1 Remote monitoring of coolant pumps

Traditional reactor coolant monitoring methods using conventional instrumentation is not feasible in SMRs because these components are located within the reactor pressure vessel (RPV). Traditional vibration measurement techniques using accelerometers becomes extremely difficult because of the inaccessibility of the pumps and their relatively harsh environment.

Electrical Signature Analysis (ESA) appears to be a useful method for monitoring these pumps. ESA has the advantage of being able to monitor signals anywhere along the pump power cable. Thus, ESA transducers can be placed in any convenient location and do not need to be inside the RPV. This ease of application is the biggest advantage of using ESA for monitoring the reactor coolant pumps. Other advantages include no additional RPV penetrations and ease of replacing the ESA transducers in the event of transducer malfunction. For SMRs, the ESA system would consist of three parts, a current or voltage sensor, a signal processor to analyze the data and control the sensor, and a transmitter to transmit the sensor information to the condition monitoring system.

1.5.2.2 Remote monitoring of control rod drive motors

Condition monitoring of the control rode drive motors would be performed using a very similar transducer to that of the reactor coolant pumps. The main difference between the applications is that the reactor coolant pumps typically operate under steady state conditions while control rods drive motors operate only periodically. Thus the analysis methods will be completely different. It is probable that the reactor motor coolant pump electrical signatures will be analyzed almost exclusively in the frequency domain. Time domain analysis is more likely to yield useful descriptors of the control rod drive motor condition.

1.5.2.3 Monitoring steam generator tubes and reactor internals

Like the reactor coolant pumps and the control rod drive motors, the steam generators are located within the RPV in many SMR designs making traditional monitoring using accelerometers difficult. The proximity of the steam generators to the reactor core may allow neutron noise to be an effective tool for measuring steam generator tube vibration. Neutron noise analysis uses fluctuations in the external core neutron flux measurements to extract information on motion of the components inside the RPV. These fluctuations are caused by changes in neutron flux absorption, scattering, and moderation due to motion of the reactor internal components.

1.5.3 Controls and plant operations

Modern nuclear power plants have moved toward greater automation but still rely on human interaction for supervision, system management, and operational decisions. More importantly, the human is also given the responsibility to serve as the last line of defense should I&C system failure prevent automatic plant protective measures from actuating, particularly in the case of prospective common cause failures that could disrupt multiple safety-related systems. In contrast, SMR objectives for reduced staffing imply highly automated plant control with greatly reduced reliance upon on-site highly skilled staff for interactive operational control under normal conditions and immediate intervention for event management.

Highly automated intelligent control involves more than simple automation of routine functions. It implies the detection of conditions and events, determination of appropriate response based on situational awareness, adaptation to unanticipated events or degraded/failed components, and reevaluation of operational goals. To enable plant operations based on a reduced staff, the control system for a SMR must be capable of fulfilling these higher level supervisory and decision functions. The automation and intelligence incorporated in the SMR control system can range from automated control systems that perform simple transition among predefined operational strategies and functional configurations based on detection of triggering events, to nearly autonomous control systems that can perform control, detection, decision, reconfiguration, and self-maintenance independently based on human permissives.

Highly automated, intelligent control capabilities have not been demonstrated for nuclear power plant operations and there is limited experience in other application domains. Thus, an investigation of the state-of-the-art for control technology is necessary. Given the identification of the state-of-the-art and an understanding of the SMR requirements and application constraints, a definition of the needed degree of automation and intelligence can be developed in the context of near-term and long-term capabilities. Subsequently, these findings can be used to determine technology gaps regarding techniques for control and decision, methods for identifying plant state and system performance, and functional architectures that can integrate control, diagnostics, and decision capabilities. Additionally, a determination of the technology maturity can guide demonstration activities to establish readiness for use in nuclear power plants.

Research, development, and demonstration are needed to facilitate a transition strategy from the modest automated control systems of the Generation III+ plants to highly automated intelligent control systems. For near-term SMRs, development and demonstration of robust supervisory control for an IPSR can be performed. The lessons learned can be extended to more general application for other reactor designs. For longer term SMRs, research focused on developing control, monitoring, and decision capabilities and a suitable architectural framework will permit evolution from the supervisory control foundation to a more comprehensive automated intelligent control system.

1.5.4 Operational infrastructure

An effective I&C infrastructure supports effective SMR operations and maintenance. While many components of this advanced infrastructure are not commercially available at present, all necessary components can be achieved through engineering RD&D efforts. For example, reducing cable installations using wireless or shared wire communications and power scavenging techniques reduces the up-front capital cost to construct a SMR plant. Using advanced robotics and remote handling, some routine maintenance may be conducted between scheduled shutdowns.

1.5.4.1 Communications

Cable configuration changes and cable replacement over the power plant lifetime is a significant cost for all reactors. The technology for communications from the sensing elements to the control logic is rapidly evolving. In many industries, wireless mesh networking is beginning to replace conventional point-to-point wiring. In addition to much lower cost, properly designed, deployed, and maintained wireless networks feature increased reliability as they are not subject to disruption of the transmission medium (e.g., a severed cable) and inherently fail to alternate communication paths as individual elements (e.g., nodes) are damaged.

However, wireless communication networks with the extreme reliability required for nuclear power plant safety and control have yet to be developed; producing this technology will have a significant impact on the economic viability and overall reliability of SMRs. The research and development path for enabling this advancement in reactor communications technology would be to first develop candidate network architectures, transceivers designs, and communication protocols suitable for use in SMRs power plants and then to demonstrate and evaluate these communications technologies in surrogate environments. Assault by typical plant RF environments, atypical interference, and attempted cyber-intrusion would be used to assess the system robustness and vulnerability to various stressors.

1.5.4.2 Power scavenging

By using modern power scavenging techniques, cable runs could be significantly reduced by minimizing the need for many of the power cables to various sensors. In recent years, novel electronics for the management and application of scavenged power to localized electronic systems have been developed. A reactor environment should provide an ideal source of energy for both thermal and mechanical scavenging technologies. However, power scavenging techniques have not yet been applied to a nuclear environment. Successfully applying these techniques will influence the economic viability of SMRs over its long operational life.

1.5.4.3 Radiation tolerant, high temperature electronics

The I&C subsystem will consist of sensors, actuators, wiring, and electronics. Radiation will have an effect on each of these components. With the longer fuel cycles proposed for SMRs, higher accumulated irradiation doses are expected on electronic components before components may be replaced during a scheduled maintenance activity. High doses of ionizing radiation cause significant changes in the characteristics of semiconductor electronic devices. The response of integrated circuits may be understood in terms of the combined response of individual transistors. However, in complex circuits the analysis can be difficult because of the large number of possible bias configurations and circuit paths. Before reaching the dose at which functional failure is observed, significant changes in circuit parameters may be observed. For example, circuit speeds usually decrease although certain timing paths may speed up for some total dose levels, input and output voltage switching points will change, output drive capability can decrease significantly, and the frequency range over which a circuit will operate can reduce.

Radiation exposure complicates the utilization of COTS semiconductor components. Radiation tolerance is rarely if ever required for applications outside of military, aerospace, and nuclear industry applications. Without detailed process knowledge, radiation tolerance is impossible to simulate. Radiation tolerance can change without notice whenever the manufacturer makes minor process changes.

Fortunately, there are a variety of nonexclusive techniques that can be implemented to overcome the lack of commercially available radiation tolerant, high temperature electronic devices. These techniques include (1) the addition of localized shielding for sensitive components, (2) moving the sensitive components further from the reactor where technically feasible, (3) design Application Specific Integrated Circuits (ASICs) using silicon-on-insulator (SOI) techniques, (4) design ASICs using modern complementary metal–oxide semiconductor (CMOS) processes, and (5) fault tolerant circuit design techniques.

1.5.4.4 I&C testbeds

Test and development platforms are needed to support the RD&D activities identified for key I&C technologies and to facilitate generation of the data required to validate a spectrum of simulation models. The harsh environments, unique measurements, sophisticated diagnostic and prognostic methods and innovative control strategies necessitate the use of simulated and physical testbeds. Existing facilities at national laboratories and universities would enable a "virtual" testing facility to be created. Proof-of-principle development of laboratory prototypes and demonstrations for near-term SMR concepts should be accommodated by existing capabilities with modest modifications to address unique conditions or capabilities required for SMR research needs. However, more complex and longer-term needs as well as integrated demonstrations of research products may require extensive adaptation of existing resources or the development of new testbeds to allow scaled demonstration of advanced I&C components and techniques.

2 CONCLUSIONS

This paper has identified several RD&D areas that must move forward to accomplish the safe, economic, and proliferation resistant deployment of SMRs. Some of these areas arise from the unique operational and process characteristics that are the consequence of fundamental design differences between SMRs and current large plants. Other I&C technologies must be developed to further enhance the affordability of new SMRs by achieving lower capital and O&M costs by reducing staffing and maintenance requirements via innovative concept of operation strategies, intelligent human-system interfaces and functional allocation. The functionality of SMRs can be expanded through the development of advanced supervisory control capabilities that enable sophisticated operational approaches such as intelligent control to facilitate automated load following for multi-unit plants to offset the grid impact of intermittent power generators such as wind turbines or photovoltaic arrays. Advanced I&C technologies can have a significant role in providing an enhanced level of safety and can enhanced the level of security against the ever-changing threat environment while reducing the cost associated with more human intensive measures currently used for nuclear power plant protection.

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