U.S. Department of Energy instrumentation and controls technology research for advanced small modular reactors

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Abstract: Instrumentation, controls, and human-machine interfaces (ICHMI) are essential enabling technologies that strongly influence nuclear power plant performance and operational costs. The U.S. Department of Energy (DOE) has recognized that ICHMI research, development, and demonstration (RD&D) is needed to resolve the technical challenges that may compromise the effective and efficient utilization of modern ICHMI technology and consequently inhibit realization of the benefits offered by expanded utilization of nuclear power. Consequently, key DOE programs have substantial ICHMI RD&D elements to their respective research portfolio. This article describes current ICHMI research to support the development of advanced small modular reactors.

Keyword: nuclear energy; nuclear power plant; instrumentation and controls; human-machine interface; small modular reactor

1 Introduction

Instrumentation, controls, and human-machine interfaces are essential enabling technologies that strongly influence nuclear power plant performance and operational costs. The nuclear power industry is currently engaged in a transition from traditional analog-based instrumentation, controls, and human-machine interface (ICHMI) systems to implementations employing digital technologies. This transition has primarily occurred in an ad hoc fashion through individual system upgrades at existing plants and has been constrained by licenseability concerns. Although the recent progress in constructing new plants has spurred design of more fully digital plant-wide ICHMI systems, the experience base in the nuclear power application domain is limited. Additionally, development of advanced reactor concepts, such as Generation IV designs and small modular reactors, introduces different plant conditions (*e.g.*, higher temperatures, different coolants, etc.) and unique plant configurations (*e.g.*, multiunit plants with shared systems, balance of plant architectures with reconfigurable co-generation options) that increase the need for enhanced ICHMI capabilities to fully achieve industry goals related to economic competitiveness, safety and reliability, sustainability, and proliferation resistance and physical protection. As a result, significant challenges remain to be addressed to enable the nuclear power industry to complete the transition to safe and comprehensive use of modern ICHMI technology.

The U.S. Department of Energy (DOE) has recognized that ICHMI research, development, and demonstration (RD&D) is needed to resolve the technical challenges that may compromise the effective and efficient utilization of modern ICHMI technology and consequently inhibit realization of the benefits offered by expanded utilization of nuclear power. Consequently, several DOE programs have substantial ICHMI RD&D elements to their respective research portfolio. The objectives that can be achieved through execution of the defined RD&D are to provide optimal technical solutions to critical ICHMI issues, resolve technology gaps arising from the unique measurement and control characteristics of advanced reactor concepts, provide demonstration of needed technologies and methodologies in the nuclear power application domain, mature emerging technologies to facilitate commercialization, and establish necessary technical evidence and application experience to enable timely and predictable licensing.

This article discusses the ICHMI RD&D being conducted under a key DOE nuclear power program.

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Specifically, the Small Modular Reactor (SMR) Program has a dedicated research pathway to address ICHMI issues. An SMR is generally characterized by (1) an electrical generating capacity of less than 300 MW(e), (2) a primary system that is entirely or substantially fabricated within a factory, and (3) a primary system that can be transported by truck or rail to the plant site. These reactors can present lower capital costs than large reactors, allow for incremental additions to power generation capacity, and support multiple energy applications (*e.g.*, process heat, electricity). Additionally, SMRs can be introduced through phased construction of modules at a plant site to incrementally achieve a large-scale power park.

2 Advanced SMR R&D program overview

The overall program for supporting the development, demonstration, and deployment of SMRs consists two distinctly different elements: the SMR Licensing and Technical Support (LTS) Program and the Advanced SMR (aSMR) Research and Development (R&D) Program. The SMR LTS Program focus is on certification, licensing, and deployment of the most mature light-water-cooled SMR designs (*i.e.*, integral primary system reactors or IPSRs) through cost-shared partnerships with multiple reactor vendor/licensee teams. The aSMR R&D Program focus is on non-light-water-cooled high-temperature designs (*e.g.*, liquid metal, fluoride salt, gas) with activities to provide for the development of next-generation, advanced SMR concepts. However, provisions to support resolution of lessons learned from the certification and first-of-a-kind deployment of near-term SMR designs are also in place. Thus, the aSMR R&D program is principally an objective and “technology neutral” endeavor placing no particular preference on a specific design.

The primary goal of the aSMR R&D Program is the demonstration and deployment of advanced SMR designs that can provide safe, simple, and robust sources of energy to meet expanding needs for electricity, process heat, or other applications at an affordable price, including

(1) develop advanced SMR concepts that can achieve significantly enhanced performance and utility for a broader range of energy applications and
(2) develop transformational technologies that will enable the next generation of SMR designs to be deployed by 2030.

For these objectives, the aSMR R&D Program supports nuclear technology that enables the development and demonstration of new innovative SMR designs.

RD&D planning is guided by identification of technology gaps and challenges that could either inhibit the maturation of advanced designs or compromise the economic viability of SMRs as a class of plants. In addition, technology development opportunities that can facilitate improved economic competitiveness and enhanced safety are addressed as well.

The aSMR R&D Program defines technical research pathways and the associated activities to enable the achievement of technology advances that can significantly impact the timely, efficient, and cost-effective development of innovative SMR designs. These research pathways consist of the following five technical areas:

- SMR Assessment Methods;
- SMR ICHMI;
- SMR Materials, Fuels, and Fabrication;
- SMR Licensing Support; and
- SMR Advanced Concepts Evaluation.

Advanced SMRs face significant technical hurdles to design completion and commercialization due to the unique features and characteristics inherent to their compact designs. These features may include new fuels and materials of construction, tighter integration of primary system components within the primary system pressure boundary, the employment of modular fabrication techniques, or the use of long-life cores and advanced sensors and instrumentation.

3 DOE research on ICHMI technology for SMRs

The benefits of SMRs can include reduced financial risk, operational flexibility, and modular construction. Achieving these benefits can lead to a new paradigm for plant design, construction, and management to address multi-unit, multi-product-stream generating stations and to offset the reduced economy-of-scale savings. Fulfilling the goals of SMR deployment also depends on the resolution of technical challenges related to the unique characteristics of these reactor concepts. ICHMI (or ASI) technologies provide the foundation for what is the equivalent of the central nervous system of a nuclear power plant. Therefore, ICHMI RD&D can play a significant role in resolving challenges and realizing benefits specific to SMRs.

3.1 ICHMI research drivers for SMRs

ICHMI research drivers arise to resolve outstanding challenges and realize the prospective benefits posed by development and deployment of SMRs. These drivers translate into technology needs and innovation opportunities. The basis for identifying ICHMI challenges and the resulting RD&D needs can be categorized into three major elements. These three major elements as illustrated in Fig. 1 are (1) ICHMI issues that arise from the unique operational and process characteristics that are the consequence of fundamental design differences between advanced SMRs and previous or current large plants, (2) ICHMI technologies that can ensure and then further enhance the affordability of SMR plants, and (3) ICHMI technologies that can further expand the functionality of SMRs.

3.1.1 Unique operational and process characteristics

Small reactors have different process measurement needs from large light-water reactors (LWRs). For advanced SMRs with different coolants (*e.g*., gas, liquid salt, 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. Similarly, diagnostic measurements are different for reactors with different coolants.

The unique operational characteristics of most SMR designs arise from the dynamic behavior of each general reactor class and differences in plant configurations. 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. Plant configuration differences leading to unusual dynamic response may include integral placement of primary coolant system components, shared plant systems or resources among units, or 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. Additionally, various SMR concepts propose use of unconventional process system components that do not have well-established performance characteristics. Nontraditional and/or reconfigurable balance of plant configurations may pose control and condition monitoring challenges.

3.1.2 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 (O&M). 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.

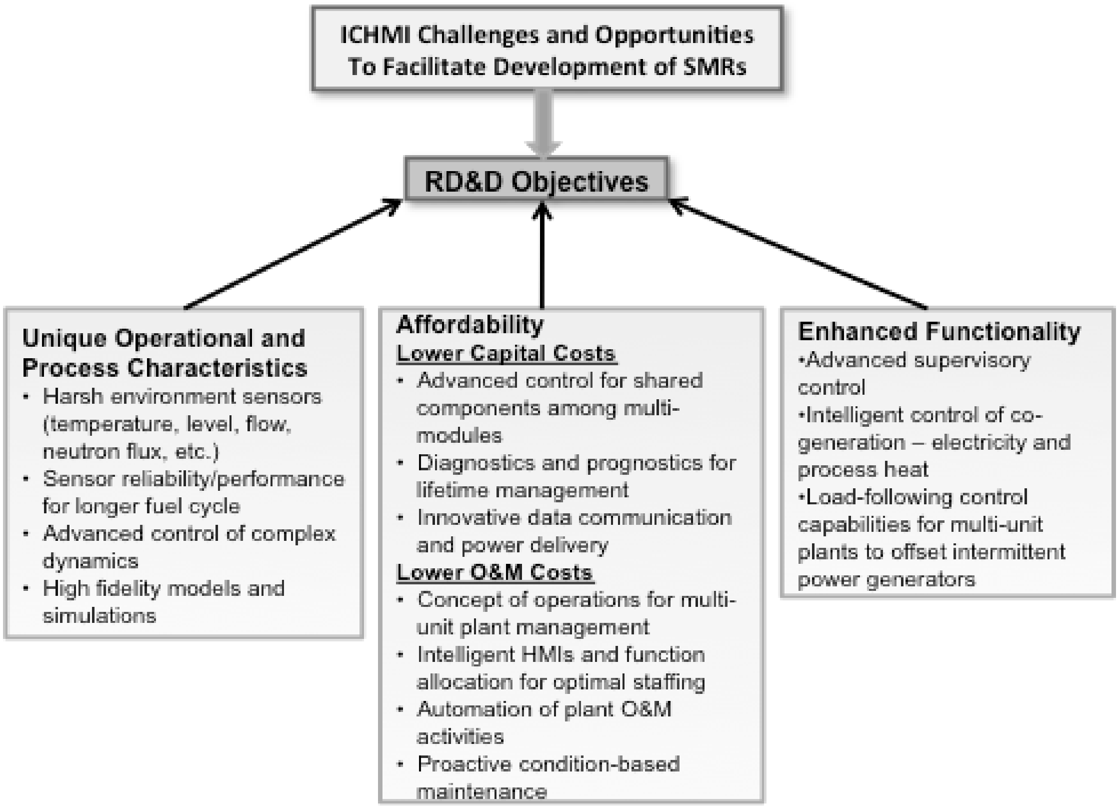

Fig. 1. SMR RD&D drivers for ICHMI technologies.

However, reduction in cost for capital equipment tends to increase the significance of ICHMI costs, which do not tend to scale with size. Thus, effective use of advanced technology to minimize cable runs and consolidate functions in highly reliable systems can contribute to managing up-front costs for ICHMI. Selection of innovative technologies may also provide some benefit in reducing the fabrication, installation and inspection costs, financing costs, and 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 help contain these costs and ensure economic viability.

3.1.3 Enhanced functionality

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 be out of service for a planned outage or unplanned trip. Effective plant management through advanced control and predictive maintenance capabilities enhances this benefit. The expected impacts are minimization of 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. 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 respond to dynamic coupling of different production systems (*e.g.*, turbine-generator for electricity, thermal systems for desalination or hydrogen production) enable automatic reconfiguration of balance of plant. 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. Needed capabilities address managing demand allocation, system reconfiguration, and dynamic transitions among multiple co-generation products.

3.2 Needs and challenges for ICHMI technology research

Based on consideration of the drivers related to the benefits and challenges of SMRs, corresponding technology needs and innovation opportunities are identified. The needs and opportunities identified for advanced SMR development and deployment that should be addressed through RD&D into ICHMI technologies can be organized according to four subactivity areas. Based on high-level technology groupings, these areas are defined as follows: Sensors and Measurement Systems, Diagnostics and Prognostics Methods, Plant Operations and Control, and ICHMI Architectures and Infrastructure.

Sensors and measurement systems present the primary source of technology gaps for advanced SMR concepts. There simply exist no viable, commercially available sensing capabilities that can directly measure some key parameters given the harsh environments, chemically different coolants, and unique configurations of many advanced concepts. Failing an advance in the technology, indirect measurements, with their attendant uncertainties leading to greater safety margins and less efficient operation, constitute the principal option, thereby limiting designs. Addressing the need for direct sensing capabilities can remove design constraints and enable improved efficiency while reducing the uncertainties built into margins.

Diagnostics and prognostics capabilities provide a technical means for enhancing affordability of SMRs over their lifetime. Advanced diagnostics and prognostic systems have the potential to reduce labor demands arising from currently required periodic equipment surveillance and inspection, thereby reducing manpower demands. Additionally, these systems can significantly reduce risks to safety and investment protection due to a greater understanding of precise plant equipment conditions and margins to failure. Also, development of diagnostic and prognostic methods allows evidence to be developed to support a science-based justification for extended plant lifetime.

Regarding plant operations and control, innovative concepts of operation and advanced human-automation collaboration are aspects of control room operations and human factors engineering that can contribute to enhanced affordability of SMRs through optimal performance and reduced O&M costs. Effective use of human resources based on advanced human-automation collaboration can enable O&M cost containment through reduced staffing requirements. Flexible plant management through new operational concepts to support a variety of product demand scenarios can facilitate highly efficient, effective use of multiple small units. In addition, control of SMRs will benefit from a high degree of automation to enable efficient operations while minimizing the need for a large operational staff. This is especially true for multiple SMR units in a multi-modular nuclear plant.

The fourth subactivity area addresses the infrastructure to support ICHMI technology development and the architectural elements that constitute the necessary plant ICHMI systems. Immediate development activities can provide tools for representing the SMR systems of interest and establish a common resource to facilitate an efficient RD&D program. Longer-term research addresses architectural innovations that enable needed capabilities (*e.g.*, measurement, monitoring) to be implemented under adverse conditions (*i.e.*, harsh environments) and within imposed application constraints (*i.e.*, limited wired interconnections).

3.3 DOE research activities under the ICHMI research pathway

The ICHMI research pathway is comprised of nine technical projects that were started in mid-2012. The objective of the projects is to address identified technology gaps, resolve challenges that constrain the development and deployment of advanced SMR concepts, and expand technical capabilities to enable enhanced benefits to be realized from innovative applications. The identification of technology needs, challenges, and opportunities was based on documented assessments from prior ICHMI technology workshops and roadmaps,[1–4] technical input from subject matter experts and stakeholders, and findings from the DOE SMR Workshop held in Washington, DC, in June 2010.[5] The selection of the projects was based on a rational prioritization approach that emphasized RD&D into specific technology needs that are unique to SMRs (*e.g*., multi-modular plant management, highly automated control, and specific measurement and monitoring techniques that enable optimal staffing, efficient operation, and effective asset usage).

Two projects are ongoing under the Sensors and Measurement Systems subactivity. These are Johnson Noise Thermometry (JNT) for Drift-free Temperature Measurements and In-vessel Optical Measurements for Advanced SMRs. Regarding the JNT project, periodic maintenance demands to ensure sensor calibration are a significant source of O&M burden and cost. Developing a fundamental measurement of a critical parameter (temperature) can enhance operational efficiency and reduce maintenance demands. JNT does not drift over time, so it can provide a dependable, accurate temperature measurement that minimizes the need to perform periodic maintenance.

The in-vessel optical measurement project will develop concepts and evaluate enabling optical-based sensing and monitoring approaches along with advanced sensor materials that can survive the process extremes of SMRs. Advanced SMRs have fundamental design differences compared to traditional large plant designs. These differences require unique sensing technologies to enable in-situ measurement of key parameters in difficult-to-access locations under harsh conditions. Nearly all required structural and process information for reactors with transparent coolants (*i.e.,* gas, salt, water) can be gathered optically. However, key issues must to be resolved, such as environmental robustness of sensing elements, engineered optical access and mounting techniques, and demonstrated technology readiness.

The Diagnostics and Prognostics Methods subactivity involves two projects. These are Prototypic Prognostic Technique Demonstration for SMR Passive Components and Enhanced Risk Monitors with Integrated Equipment Condition Assessment. The basis for the first of these projects arises because traditional in-service inspection approaches used with LWRs are difficult to apply for assessment of SMR component degradation given the different coolant environments, temperatures, and accessibility. Physics-based prognostics facilitate estimation of the remaining lifetime of generally inaccessible SMR structures and components, some of which may be reach a degraded condition during extended operational cycles. There is a need to demonstrate methods to determine the remaining lifetime of passive internal components and, thereby, avoid unnecessary component replacement while contributing to a science-based justification for extended plant lifetime. Development of prognostic methods requires that issues specific to advanced SMRs are addressed, such as monitoring in-pool or in-vessel components to reduce the requirement for in-service inspection, accounting for uncertainties in advanced material behavior by detecting high-temperature degradation phenomena, and resolving measurement challenges associated with extreme coolant environments.

The risk monitor project is based on employing condition monitoring techniques to provide condition indicators for key active equipment. Such indicators can reflect evolving degradation and support identification of incipient failure. These capabilities are especially important for hard-to-access, in-vessel active components that would otherwise require time-consuming, labor-intensive inspection during outages. Incorporation of condition knowledge into operational risk monitors can enable real-time decisions about stress relief for susceptible equipment while supporting effective maintenance planning. The capability to actively address the normal, abnormal, and deteriorating states of plant equipment through degradation-based reliability models can permit SMRs to meet aggressive availability, safety, and economic goals.

The Plant Operations and Controls subactivity consists of four ongoing projects. These are Concepts of Operation for Multi-Modular SMR Plants, Framework for Human-Automation Collaboration, Supervisory Control of Multi-Modular SMR Plants, and Impact of Active Control on Passive Safety Characteristics of Advanced SMRs. To ensure economic viability through containment of O&M costs, multi-modular SMR plants require definition of nontraditional concepts of operation to address unique operational scenarios. These scenarios can involve considerations such as distribution of load-following demand among multiple units, transition among different product streams, and high levels of automation with humans in supervisory roles. The issues and implications of innovative operational concepts for multi-modular plant configurations have not been evaluated in detail. Alternate concepts of operation and staffing models need to be developed and demonstrated to enable multi-unit SMR plant concepts to achieve flexible, efficient operations. In addition, an investigation of the impact of these concepts on human roles and responsibilities is needed to resolve regulatory uncertainty about licensability.

Current regulations that establish minimum staffing requirements for each unit provide a driver for the human-automation collaboration project. These requirements are based on traditional operational models and limited automation. High staffing levels pose the threat of unsustainable O&M costs for SMRs on a per megawatt basis. To enable optimal staffing, the focus of this research is a framework that balances automation and human involvement to support personnel situational awareness. A key consideration is the identification and demonstration of innovative approaches to automation, such as adaptive automation. More flexible automation can lead to effective integrated human-automation teams, which can support staffing goals and unique operational scenarios for SMRs.

Regarding the supervisory control project, highly automated, intelligent control capabilities have not been demonstrated for nuclear power plant operations and there is limited experience in other safety-critical application domains. Supervisory control provides a means for the integration of control, decision, and diagnostics to support extensive automation. The targets for automation include operational management of highly complex plants, dynamic management and control of multiple product streams from a plant, and coordinated management of multiple modules. Specifically, control strategies and methods need to be developed within a flexible functional architecture to supervise multi-unit plants, accommodate shared systems or resources, and enable flexible co-generation operational regimes.

Advanced SMR concepts promise to improve safety through passive characteristics based on intrinsic design features. Passive features can perform more reliability than active systems because of their reliance on natural phenomena. The presence of active systems, whether due to design or regulatory requirements, poses the potential that their action could affect the behavior of passive characteristics. The impact of active control on passive safety characteristics has not been adequately investigated and requires integrated treatment. The project investigating the impact of active control on SMR passive safety characteristics will evaluate the potential for active control actions to compromise the performance of passive safety features.

The ICHMI Architectures and Infrastructure subactivity currently consists of one ongoing project: Modeling Tools for Dynamic Behavior Simulations of SMRs. Advanced SMR concepts likely will go through great variety of configurations of reactors and heat loads to explore useful and cost-effective applications of modular plants designs. The safety and control evaluations of various concepts depend on an understanding of system dynamics, necessitating a number of mathematical models. Several different organizations and researchers may be involved in evaluating the concepts and developing advanced technology and methods. A basic library of models and common simulation environment is needed to facilitate efficient research, establish a common basis for comparison, and minimize the potential for duplicative modeling efforts. Thus, this project will effectively support a range of research activities requiring dynamic behavior simulation; modeling tools should provide easily reconfigurable modules, use a commonly available and familiar simulation environment, and reduce data input to typically available system-level plant data.

4 Conclusions

Energy security and the reduction of greenhouse gas emissions are two key energy priorities that can be met in a sustainable manner through nuclear power. The development of deployable small modular reactors (SMRs) can provide the United States with another economically viable energy option, diversify the available nuclear power alternatives for the country, and enhance economic competitiveness by ensuring a domestic capability to supply demonstrated reactor technology to a growing global market for clean and affordable energy sources. Achieving these objectives requires technology development. As part of its research portfolio, DOE recognizes that ICHMI technology development is necessary to resolve impediments to the realization of SMR deployment.

A comprehensive SMR research effort addresses key needs and challenges to enable optimal technology solutions. In particular, technical advancements and demonstration of technological maturity must move forward to effectively realize the safe, economic, and effective deployment of SMRs. Consequently, the aSMR R&D Program is proceeding with a set of ICHMI research projects. Key RD&D areas include sensors and measurement systems, diagnostics and prognostics methods, plant operations and control, and ICHMI architecture (*e.g.*, communications, power, interfaces, and shared components) and infrastructure. As noted, some RD&D drivers arise from the unique operational and process characteristics that are the consequence of fundamental design differences between SMRs and current large plants. Other ICHMI technologies must be developed to further enhance the affordability of new SMRs by achieving lower 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 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. Finally, advanced I&C technologies can have a significant role in providing an enhanced level of safety and can enhance 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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