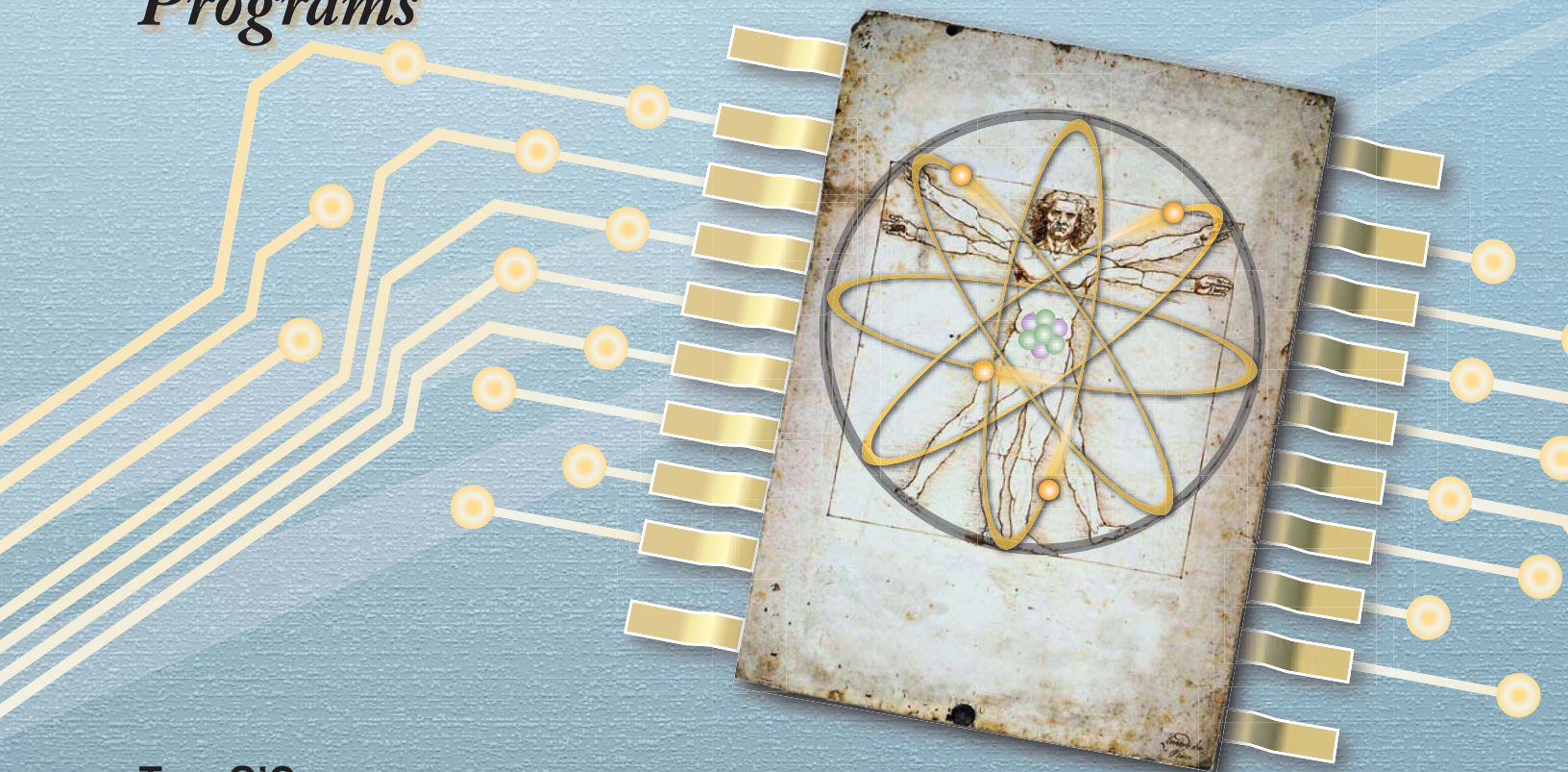


Technology Roadmap

Instrumentation, Control, and Human-Machine Interface to Support DOE Advanced Nuclear Energy Programs



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March 2007

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Additionally, the opinions and conclusions presented herein are those of the authors and do not necessarily represent the view or position of the Nuclear Regulatory Commission.

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Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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INL/EXT-06-11862

March 2007

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March 27, 2007

Date

EXECUTIVE SUMMARY

Instrumentation, Controls, and Human-Machine Interface (ICHMI) technologies are essential to ensuring delivery and effective operation of optimized advanced Generation IV (Gen IV) nuclear energy systems. In 1996, the Watts Bar I nuclear power plant in Tennessee was the last U.S. nuclear power plant to go on line. It was, in fact, built based on pre-1990 technology. Since this last U.S. nuclear power plant was designed, there have been major advances in the field of ICHMI systems. Computer technology employed in other industries has advanced dramatically, and computing systems are now replaced every few years as they become functionally obsolete. Functional obsolescence occurs when newer, more functional technology replaces or supersedes an existing technology, even though an existing technology may well be in working order. Although ICHMI architectures are comprised of much of the same technology, they have not been updated nearly as often in the nuclear power industry. For example,

some newer Personal Digital Assistants (PDAs) or handheld computers may, in fact, have more functionality than the 1996 computer control system at the Watts Bar I plant. This illustrates the need to transition and upgrade current nuclear power plant ICHMI technologies.

In 1997, the National Research Council conducted a study on the state of ICHMI technologies, referred to as digital instrumentation and control (I&C) systems, in nuclear power plants. This report reflected the state of current nuclear power plant ICHMI systems, a mixture of analog and hybrid technologies that faced obsolescence. The report also detailed the power of digital technologies and the advantages and the challenges involved in modernization of nuclear power plant instrumentation.

Unfortunately, the report issued in 1997 on the state of nuclear system instrumentation including existing deficiencies still largely reflects

On the State of ICHMI Technologies—National Research Council, 1997

Nuclear power plants rely on instrumentation and control (I&C) systems for monitoring, control, and protection. During their extensive service history, analog I&C systems have performed their intended monitoring and control functions satisfactorily. Although there have been some design problems, such as inaccurate design specifications and susceptibility to certain environmental conditions, the primary concern with the extended use of analog systems is effects of aging, e.g., mechanical failures, environmental degradation, and obsolescence.

The industrial base has largely moved to digital-based systems and vendors are gradually discontinuing support and stocking of needed analog spare parts. The reason for the transition to digital I&C systems lies in their important advantages over existing analog systems. Digital electronics are essentially free of the drift that afflicts analog electronics, so they maintain their calibration better. They have improved system performance in terms of accuracy and computational capabilities. They have higher data handling and storage capacities, so operating conditions can be more fully measured and displayed. Properly designed, they can be easier to use and more flexible in application. Indeed, digital systems have the potential for improved capabilities (e.g., fault tolerance, self-testing, signal validation, process system diagnostics) that could form the basis for entirely new approaches to achieve the required reliabilities. Because of such potential advantages, and because of the general shift to digital systems and waning vendor support for analog systems, the U.S. nuclear power industry expects substantial replacement of existing, aging analog systems with digital I&C technology. For the same reasons, designs for new, advanced nuclear power plants rely exclusively on digital I&C systems.

the current state of affairs for U.S. nuclear power plants. The lack of new plants, research, and consensus between the industry and the U.S. Nuclear Regulatory Commission has led to a near hiatus in advanced digital technology integration. With the expected deployment of new plants there is an urgent need to address both technological and regulatory issues so as to enable smooth incorporation of advanced ICHMI technologies.

ICHMI technologies are enabling technologies that affect every aspect of nuclear power plant and secondary plant operations. ICHMI subsystems and components include the following:

- Sensor subsystems that take physical measurements of plant pressure, temperature, flow, radiation, etc.
- Monitoring subsystems that monitor the signals and other information produced by sensors and evaluate that information to determine whether and what type of response may be needed, such as in diagnostics and prognostics applications.

- Control subsystems that process plant data, internal logic, and operator input to manage plant operations. Automatic functions within the control system are also growing in application. This area includes safety and non-safety systems.
- Communications subsystems that provide the path for data and information flow. This may consist of copper wire, fiber optic cable, and wireless mediums along with numerous data protocols.
- Human-Machine Interface (HMI) subsystems that provide the means for human interaction with the system including dials, knobs, computer displays, information fusion, electronic procedures, alarms, and indications.

Figure E-1 illustrates how these systems fit together within the context of reactor system operations. In the midst of information and digital technology growth, these systems represent some of the greatest areas for advancement in functionality, reliability, and process within plant operations.

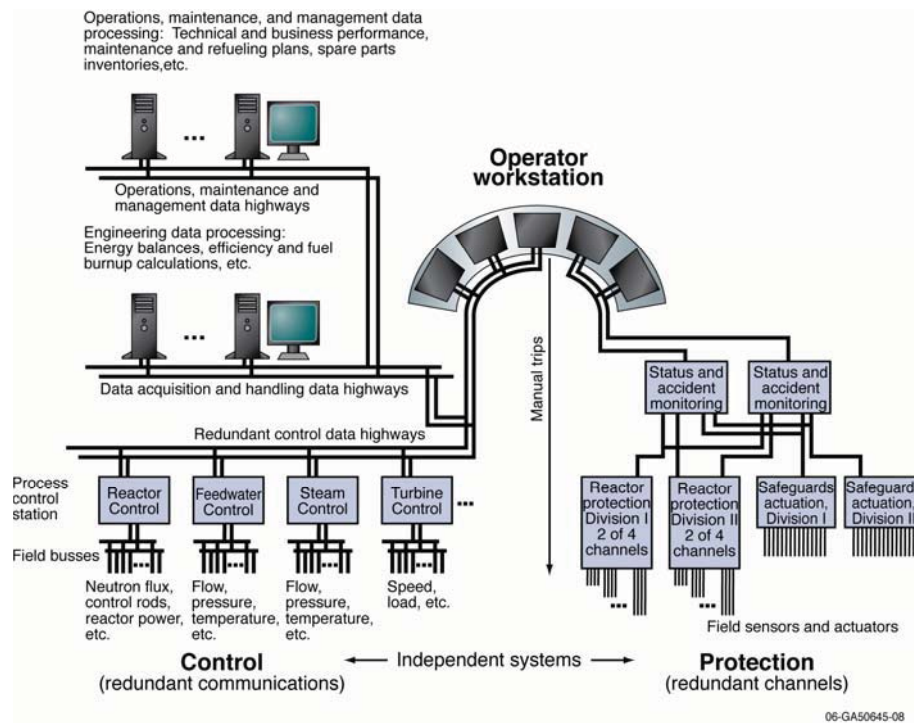


Figure E-1. Illustration of nuclear power plant ICHMI system (National Research Council, 1997).

New and advanced ICHMI technologies are already being applied in the U.S. in other industry sectors. However, their application to the nuclear industry is mainly being exercised in other countries. These applications areas have demonstrated tremendous gains in terms of efficiency of operations. U.S. plants are seeking to take advantage of these technological gains and have implemented digital system upgrades. Unfortunately, these upgrades have been limited in scope and have not leveraged the full benefit of digital systems due primarily to current U.S. Nuclear Regulatory Commission (NRC) licensing requirements. This issue of licensing of new ICHMI technologies continues to be a challenge in the U.S., which has the potential to impact rapid deployment for near-term (NP 2010) plants.

As the U.S. looks towards future advanced reactor systems in the Gen IV program, numerous challenges must be overcome not only to realize the full potential of digital system implementations, but also to field a new digital system. The analog and potentially hybrid systems currently implemented are not feasible for future plants because, in addition to the lack of analog system manufacturers, duplication of currently employed technologies will not achieve the desired performance and functionality gains for Gen IV and other advanced systems, the Next Generation Nuclear Plant (NGNP), and both small and fast reactors for the Global Nuclear Energy Partnership (GNEP).

Integration of new technology, however, comes with a price. ICHMI technology integration issues that must be addressed include the following:

- Software quality assurance
- System reliability in harsh environments (e.g., temperature, pressure, radiation)
- Common mode failure
- Human factors and new human error mode introduction
- Cyber security
- Applicability of commercial products for nuclear plant use.

The operating environment of a nuclear power plant introduces challenges not present in many other industrial environments. Thus, it is not realistic to assume that the simple integration of existing commercial products will be adequate to address issues such as those mentioned above. While research and development is required to address such issues, another aspect is U.S. NRC licensing. The U.S. NRC and industry must reach consensus not only on the introduction of existing digital technologies, but also on a method for introducing and integrating new technologies into plant operations on a broader scale.

Technology Roadmap on Instrumentation, Control, and Human-Machine Interface

This document was created to provide a systematic path forward for the integration of new ICHMI technologies in both near-term and future nuclear power plants and the reinvigoration of the U.S. nuclear ICHMI community and capabilities. As stated earlier, ICHMI technologies are an essential enabling element of nuclear power plant design, development, and operations. This roadmap proposes the establishment of a crosscut DOE program to address essential research on issues limiting near-term and future deployment of advanced ICHMI in current and future U.S. nuclear power plants.

International leadership in nuclear power research and development is a critical element in achieving U.S. energy security and addressing proliferation concerns. As such, the U.S. Department of Energy (DOE) Office of Nuclear Energy, Science, and Technology (DOE-NE) should lead the U.S. ICHMI activity. Such an activity will ensure availability of key enabling technologies supporting sustainable, safe, and effective application of nuclear power to meet future energy needs. Once established, this program would complement the activities currently within the “Gen IV Materials Crosscut Program” and leverage activities under the NGNP and GNEP programs.

The U.S. has been a leader in the advancement of nuclear sciences for energy production. It is a sobering fact, however, that the nation has lost the lead in technology innovation in the area of nuclear plant ICHMI. Foreign organizations and activities illustrating the gap include Électricité de France (EDF) with their N4 advanced control room, the digital ICHMI upgrade at the Biblis B plant in Germany, the fully digital Toshiba plant operating in Japan since 1995, and the advanced human-interface work being conducted at the Halden Reactor Project in Halden, Norway. Mitsubishi recently announced an advanced integrated digital control system for nuclear power plants. It is equipped with four 100-inch front panels and is designed to enable just one operator to handle the system. This system is planned for deployment to the Hokkaido Electric Power Company, No. 3 Tomari plant and is projected to be operational by December 2009. These overseas examples illustrate just how much technological nuclear capability and leadership the U.S. has lost over the past decade. A dedicated crosscut program in ICHMI is required to regain leadership in this area. This attitude is needed to re-establish the U.S. as pre-eminent in nuclear studies and, perhaps more importantly, to provide technology needed to guarantee national energy reliability and security.

Roadmapping Goals

The following are the programmatic goals of this ICHMI roadmap:

- Establish a DOE-led crosscut program in ICHMI
- Support programmatic objectives of the Gen IV development program and NGNP
- Support the reactor concept selection and demonstration process in Gen IV and other programs by providing ICHMI performance tradeoff analysis
- Optimize resource usage leveraging and coordinate crosscut needs while avoiding duplication between related ICHMI efforts

- Provide a programmatic path forward for the research and development of supporting ICHMI technologies needed for realization of Gen IV, NGNP, and GNEP.

To meet the above programmatic goals and to develop an effective Gen IV program, the ICHMI activities must accomplish these key elements of success:

- Integrate and coordinate with program schedule and milestones for the other Gen IV focus development areas
- Leverage international activities and existing infrastructure outside of the existing Generation IV International Forum (GIF) collaborations
- Coordinate performance of common research among all DOE advanced nuclear initiatives.

Selection and scheduling of focused ICHMI activities should be tied to critical stages for NGNP and provide programmatic support in one or more of the following ways:

- Address critical parameters and processes
- Provide simulation to support design decisions and the construction planning process
- Evaluate the use of mature technologies within other application areas for use in nuclear power plants, including addressing issues relevant to U.S. NRC technology acceptance
- Explore emerging technologies for beneficial applications in the plant and similar U.S. NRC acceptance
- Engage vendors and end users in design, development, and evaluation of ICHMI and HMI technologies
- Link to other DOE and/or related industry programs to leverage concurrent research, development, and evaluation activities.

In coordination with other Gen IV and NGNP development, this crosscut plan for ICHMI will address the above goals and criteria.

FY 2007 Proposed Activities

The following FY 2007 immediate path forward activities are proposed:

ICHMI Initial Focus Areas and Funding Priorities

1. Crosscut ICHMI Program Establishment

- Establish a formal DOE-led crosscut ICHMI program. Currently ICHMI RD&D is neither a specified nor funded element of any GNEP, Gen IV, or NGNP program focus area. While DOE-led, this program will include an industry steering committee to encourage and leverage industry investment.

2. Harsh Environment Tolerant Sensor Project

- Investigate new sensor technologies to support the NGNP testing and operational environment. The operating and testing environments for advanced reactor systems are vastly different from today's systems. New sensor technologies are needed to support the evaluation and operation of plants in these new environments.

3. Regulatory Basis Development for NGNP ICHMI Technologies Project

- Develop methods and baseline assessments to support digital technology licensing. One area of this research is the development of technology-neutral performance-based measures to evaluate and assess suitability and limitations of proposed technologies.

4. NGNP Operational Concept Development Project (Demonstration and Deployment)

- Establish and evaluate roles, processes, procedures, interfaces, and operational concepts for operators. This area includes deriving the operational concepts, which will result in design requirements.

5. NGNP ICHMI Architecture Development Project

- Develop control system network architectures that not only integrate state-of-the-art hardware and software, but also allow for the investigation of the application of increased automation as an element of system operation.

6. ICHMI Technology Assessment and Gap Analysis Project

- Perform state-of-the-art assessment and gap analysis to focus specific research needs. This initial project listing represents a first attempt at assessing programmatic needs. A more rigorous analysis of the current state of the art is required to identify promising technological developments and gaps in research.

Program Administration and Integration

A program administration model is required to begin planning and implementation of the Research Design and Development (RD&D) recommendations of this roadmap. A number of requisite conditions must be addressed to effectively integrate this plan with broader DOE Gen IV and NGNP system development and demonstration objectives:

1. The implementation plan and schedule should enable progress and support critical decisions during design stages of the reference systems and technologies
2. The implementation plan and schedule should be manageable under the same program management plan as the Gen IV systems development and procurement programs and thus integrated within this program
3. The plans for implementing these RD&D recommendations require a physical reference plant such as NGNP to proceed beyond the conceptual design stage

4. Out-year planning must be tied to critical stages of technology development and deployment for ICHMI systems that support critical stages of technology deployment for NGNP
5. Plans for technology transfer to support procurement and interactions with system vendors and suppliers must be developed over the design cycle of the reference systems.

The timeline of the reference next generation nuclear plant project (Weaver et al. 2006) is shown in Figure E-2. The project programmatic elements provide a suitable starting point for conceptualizing the scope of plant design activities and schedule that ICHMI activities must address and support. This includes design, construction, testing, and operation of nuclear energy production systems, certification and licensing, power conversion, and associated balance of plant.

Deliverables to Support Gen IV (Specifically NGNP Critical Milestones)

The following deliverables are recommended for the crosscut program, not necessarily for the initial effort:

- Technology research and development plans to support conceptual design decisions, alternatives, evaluations, and licensing issues associated with instrumentation, controls, and human-machine interaction that must be addressed

- Development of specifications for instrumentation, controls, and human-machine interaction design
- Preparation of request for proposal for instrumentation systems, controls systems, and human interface systems in support of the nuclear system, hydrogen production facility, power conversion, energy transfer, operations, and licensing
- Completion of the conceptual design and tradeoff analysis studies based on prototype requirements specifications
- Licensing strategy and technological review methodology.

Acquisitions strategy support for instrumentation, controls, and human-machine interaction systems.

ICHMI Research Drivers

- *Longest lead time for development of a needed capability*
- *Largest potential benefit(s) in terms of supporting near-term NGNP program decisions*
- *Significant potential to impact technical and functional requirements of the NGNP conceptual design*
- *Potential to significantly improve life-cycle efficiency or affordability of the technology.*

Next Generation Nuclear Plant Project

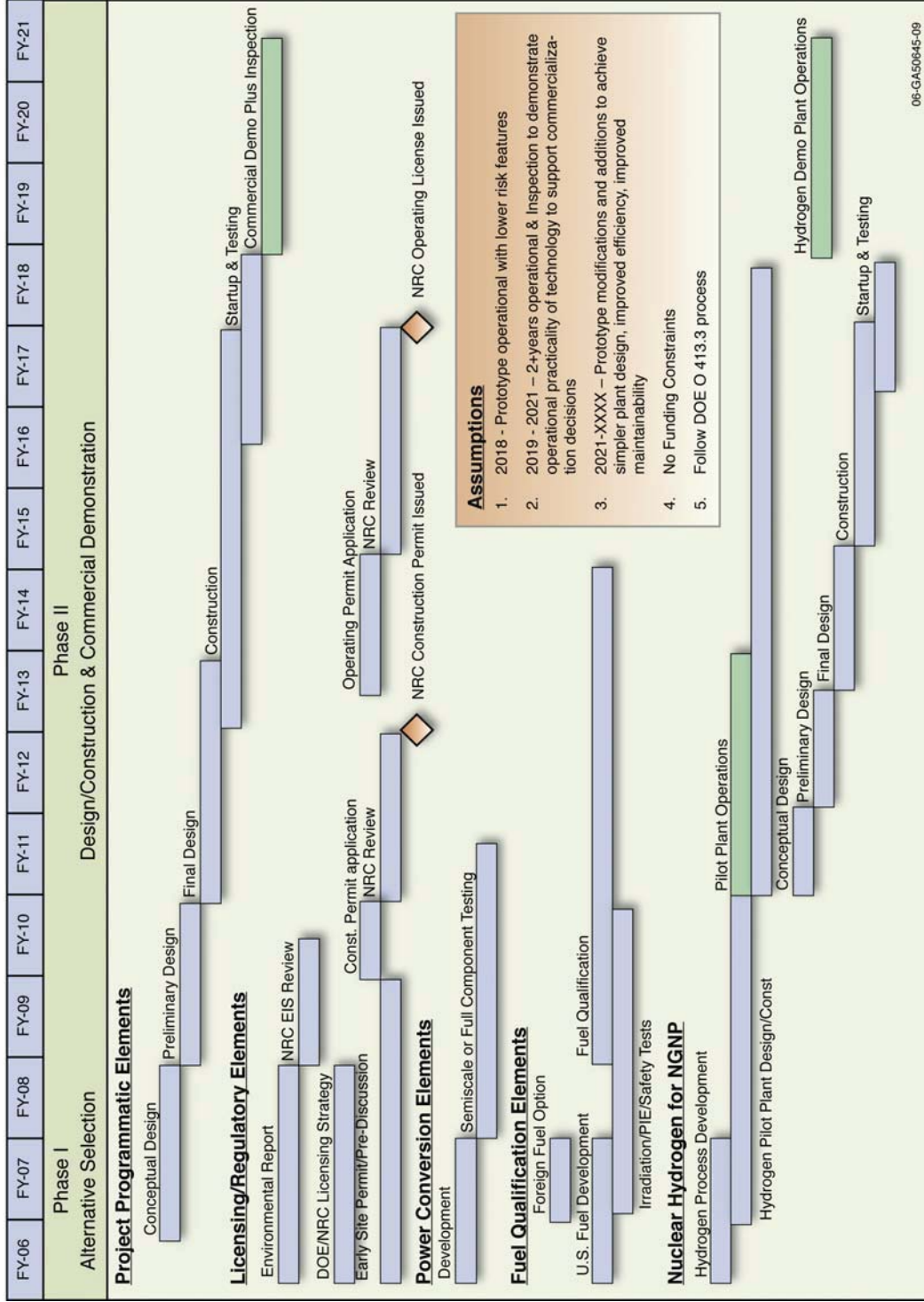


Figure E-2. NNGNP Project timeline.



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Technology Roadmap on Instrumentation, Control, and Human-Machine Interface to Support DOE Advanced Nuclear Power Plant Programs

1. INTRODUCTION

This report provides the rationale for the ICHMI Technology Crosscut Program by identifying programmatic goals related to ICHMI technologies for the Generation IV (Gen IV) and Next Generation Nuclear Plant (NGNP). This report identifies and describes a variety of program needs and goals related to ICHMI, challenges to accomplishing these goals, and the technological needs and innovations that will be necessary to overcome these challenges. Foremost, this roadmap establishes a prioritized set of initial activities for a comprehensive program plan for RD&D activities to support the design and demonstration needs of the Gen IV and NGNP programs.

The Instrumentation, Controls, and Human-Machine Interface (ICHMI) technologies shown in Figure 1-1 represent core crosscutting subsystems that are an essential element within advanced nuclear power plant (NPP) research, development, and demonstration (RD&D) programs. ICHMI RD&D is needed to achieve a sustainable capability for the safe and effective application of nuclear power in both future and existing plants. An ICHMI crosscut program should be an integrated element within the U.S. Department of Energy, Office of Nuclear Energy, Science, and Technology (DOE-NE) portfolio for advanced nuclear power plant research.

The overarching goal of an ICHMI roadmapping effort (of which the present project represents the initial phase) is the creation of a dynamic ICHMI technology development plan

and program that will enable and maximize the performance of Gen IV nuclear power plants while minimizing the potential for ICHMI systems to become an impediment in NPP design, construction, and operation. A primary outcome of the roadmapping process is a preliminary technology development plan and schedule that addresses the ICHMI challenges that must be overcome to practically and economically deploy advanced nuclear power plants in the U.S. A roadmap is especially timely because the RD&D effort for long lead-time ICHMI technologies needs to begin in order to reduce the potential for key technologies becoming a critical path item that could then affect the timeline for deployment of Gen IV nuclear power systems.

The ICHMI RD&D roadmap provides a plan that, if implemented, reduces the possibility of future plants being limited by obsolete, low-functionality, labor-intensive ICHMI technology due to the lack of technological maturity or ability to be licensed. In addition, ICHMI RD&D increases the future use of automation and modern control rooms in order to achieve reduced staffing and attains greater use of information to enable advanced asset management programs for currently operating reactors. ICHMI RD&D also enables the production of other advanced nuclear power plant technologies that will improve sensors and monitoring in order to achieve higher fuel burnup and stable operation at a higher operating temperature.

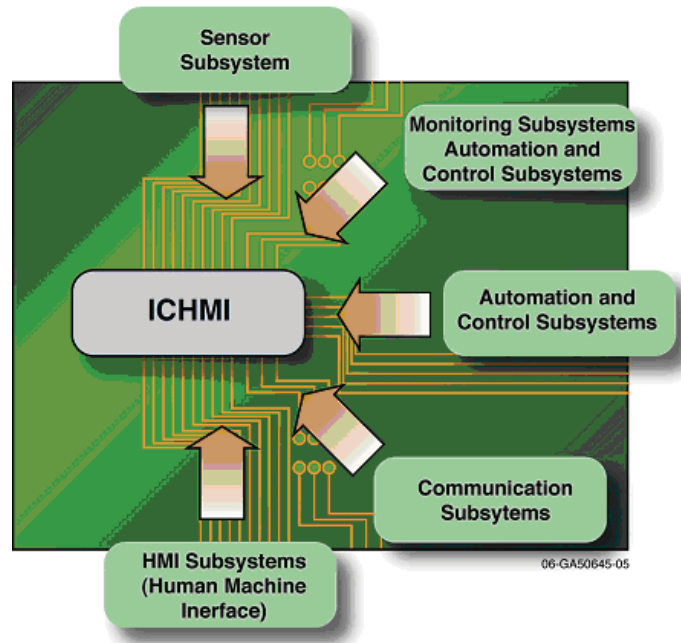


Figure 1-1. The ICHMI technologies essential core crosscutting subsystems.

1.1 Objectives

ICHMI Road Map Goals

- *Establish a crosscut program for ICHMI*
- *Identify and assess the technical and regulatory gaps that have the potential to significantly impact the design, development, and licensing of Gen IV and NGNP plants*
- *Provide ICHMI performance tradeoff analysis for Gen IV reactor concept selection*
- *Establish ICHMI RD&D research priorities and schedule to support the realization of Gen IV, NGNP, and GNEP*
- *Optimize and leverage ICHMI RD&D efforts in order for DOE and industry to fully realize the potential for advanced nuclear facility operation.*

A primary objective of the RD&D roadmap is to identify and assess the technical and regulatory gaps that have the potential to significantly impact the design, development, and licensing of Gen IV and NGNP plants. While this roadmap anticipates ICHMI technological progress and makes informed projections of what is likely to be available from other highly reliable industries, a comprehensive, in-depth technology progression assessment has not been performed. Development of a more thorough and strategic assessment of worldwide, high-reliability ICHMI technology development is recommended as the next phase in the development of a nuclear power ICHMI strategic technology roadmap.

An additional objective of the RD&D roadmap is to identify the steps required to implement the advanced ICHMI technologies and methods that would be derived from the proposed DOE-NE program. This includes both design/technology tradeoff analysis and research prioritization. When looking towards effective deployment, a path forward for building the ICHMI technology vendor infrastructure needs to be included in the technology implementation plan.

The RD&D roadmap scope is to be integrated with ongoing DOE research efforts and specifically seeks to address the ICHMI related technology issues directly affecting the technical and commercial success of Gen IV, NGNP, and GNEP Programs. The roadmap timeframe and schedule is linked to that of the NGNP program, which is considered as an early deployment of a Gen IV system.

1.2 Background

ICHMI technologies provide enabling capabilities that strongly influence plant performance and operational costs. In most existing nuclear power plant designs, the incorporation of ICHMI technologies was addressed in the final phase of the design process, resulting in a fragmented system design adapted to the structure and performance limitations of the nuclear systems and the balance of the plant, rather than planned and developed as an integral design activity intended to optimize the overall system performance. Although this “add-on” approach has not prevented safe operation of existing modern nuclear power plants, it constrains the achievement of plant management efficiencies and leads to higher required operational and maintenance staffing levels. It also creates a need for more highly specialized skill sets among the nuclear plant staff. Much of the ICHMI technologies that are available and licensable for new nuclear power plants are based on dated technologies with limited functionality. To achieve the performance-based economic, sustainability, security, and safety goals of the Gen IV and NGNP programs, timely and focused research and development on needed ICHMI technologies must be completed early in the design phase and in close coordination with other design activities. This will enable technology demonstration on reference systems, testbeds, certification, and licensing. Early ICHMI technological development will also enable the necessary maturation that must take place in order to develop confidence in the new technology’s ability to perform reliably over its planned service life.

The legacy power plant ICHMI has produced architectures that are more amenable

to hardwired, stove-piped systems and interface structures, rather than functionally integrated, interlinked digital system architectures. As such, modern control architectures already in use in the U.S. outside the nuclear community represent a radical departure from traditional nuclear power plant ICHMI architectures. Introducing ICHMI technological advances in the U.S. through upgrades at existing nuclear power plants has been slowed by a variety of factors, including regulatory uncertainty, inadequate cost justification and recovery, piecemeal system upgrades, and simple organizational inertia. In 1997, the National Research Council conducted a study on the state of ICHMI technologies, referred to as digital instrumentation and control (I&C) systems, in nuclear power plants. This report reflected the state of current nuclear power plant ICHMI systems, a mixture of analog and hybrid technologies that faced obsolescence. The report also detailed the power of digital technologies and the advantages and the challenges involved in modernization of nuclear power plant instrumentation.

The findings of the NRC emphasize that the U.S. nuclear power industry is not evolving to use the full capabilities and characteristics of the available ICHMI technologies. As a result, the nuclear power industry has not realized the benefits that these technologies afford. The technology development described for this crosscut program is intended to rectify this situation.

Major advances in moving to digital systems and advanced control rooms are occurring, particularly at new plants in Asia. A fully digital ICHMI system is reported to have been developed in Japan and it has been in use with an advanced light water reactor (LWR) simulator since 1995. Mitsubishi recently announced an advanced integrated digital control system for nuclear power plants derived from this effort (Mitsubishi 2006). It is equipped with four 100-inch front panels and is designed to enable just one operator to handle the system. This system is planned for deployment to the Hokkaido Electric Power Company, No. 3 Tomari plant and projected to be operational by December 2009. Korean groups have developed a design for a fully digitized sequence of events

On the State of ICHMI Technologies—National Research Council, 1997

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The industrial base has largely moved to digital-based systems, and vendors are gradually discontinuing support and stocking of needed analog spare parts. The reason for the transition to digital I&C systems lies in their important advantages over existing analog systems. Digital electronics are essentially free of the drift that afflicts analog electronics, so they maintain their calibration better. They have improved system performance in terms of accuracy and computational capabilities. They have higher data handling and storage capacities, so operating conditions can be more fully measured and displayed. Properly designed, they can be easier to use and more flexible in application. Indeed, digital systems have the potential for improved capabilities (e.g., fault tolerance, self-testing, signal validation, process system diagnostics) that could form the basis for entirely new approaches to achieve the required reliabilities. Because of such potential advantages, and because of the general shift to digital systems and waning vendor support for analog systems, the U.S. nuclear power industry expects substantial replacement of existing, aging analog systems with digital I&C technology. For the same reasons, designs for new, advanced nuclear power plants rely exclusively on digital I&C systems.

system in NPPs as well as several other digital systems. Électricité de France (EDF) has their N4 advanced digital control room coupled with multiple levels of automation. The Biblis B plant in Germany has conducted a full digital ICHMI upgrade as well.

In the U.S., major advances are being made in plant modernization with digital reactor protection systems. Heckle and Bolian (2006) conclude that “digital technology provides significant benefits to utilities... modern systems provide functional upgrades and solve reliability and maintenance problems.”

The benefits of digital systems are illustrated by the fact that candidate Generation III + plants, considered for deployment under the DOE NP 2010 program, are adopting digital technologies as the basis for their nuclear plant ICHMI systems. However, the application of more advanced functionality available with digital technologies has been constrained, and the realization of full advanced digital system capabilities is hindered by (1) the desire for

assured licenseability and (2) the risk management approach of using proven technology while maintaining a strong evolutionary connection with conventional ICHMI architectures.

The Current Situation

- the U.S. nuclear power industry is **not evolving** to utilize the full capabilities and characteristics of the available ICHMI technologies.
- **Major advances in moving to digital systems and advanced control rooms are occurring, particularly at new plants in Asia.**
- ... the application of more advanced functionality available with digital technologies [sic in nuclear plants] **has been constrained**, and the realization of full advanced digital system capabilities **is hindered**...

2. PROGRAMMATIC CONTENT

2.1 Generation IV Nuclear Plants

Gen IV nuclear energy systems are comprised of the nuclear reactor, its energy delivery or conversion systems, and the necessary facilities for the entire fuel cycle, from ore extraction to final waste disposal.

Information and digital technologies, including their application to control systems architectures, intelligent sensors, wireless communications, advanced HMI, and related applications, have developed tremendously over the past 30 years. The technological advances are used by many other industries requiring process control to increase efficiency, production, and safety while lowering operations and maintenance (O&M) costs. It is also realistic to believe that such technologies will be required to support NNGP operations and fuel-cycle activities. This involves more than simply the transition of capabilities used in analog ICHMI technologies employed in plants today into a digital form. It will require functionally advanced digital hardware, software, sensor systems, and different staffing and operational philosophies in order to achieve the economics and operational goals set for Gen IV plants.

As time and resources are of the essence, the recommended RD&D activities must focus on and enable the programmatic goals of the broader Gen IV initiative.

Achieving these goals will require advances in reactor fuels and materials and fundamentally different plant concepts. It will also depend on the program's ability to integrate original technologies in many of these areas in the final developed detailed designs. The following subsections discuss ICHMI needs relative to the Gen IV goals above and identify some key issues pertaining to each. This discussion is not exhaustive and a more thorough treatment of specific technology needs and objectives for ICHMI is presented in Appendix A.

Figure 2-1 illustrates the Gen IV programmatic Metrics, Criteria, Goals, and Goal Areas as stated in the 2002 Gen IV Technology Roadmap. These metrics are used as a standard for comparison between the candidate Gen IV systems. A similar categorization has been applied to the ICHMI technologies with the objective of determining the contribution of ICHMI technologies to the high-level goal areas of System Sustainability, Economics of Deployment and Operation, Safe and Reliable Operations, Proliferation Resistance, and Physical/Cyber Protection. Figure 2-2 illustrates a parallel diagram detailing potential metrics for ICHMI technology comparison.

2.1.1 Sustainability

In terms of an ICHMI system, sustainability refers to the ability to maintain system functionality in the midst of rapid technology change, which will occur over the course of the facility's life cycle.

Sustainability includes both issues related to the physical performance of technology as it ages, or becomes obsolete, as well as considerations for how to best support effective human performance with the systems. Consider, for example, the effect of digital technologies replacing the analog control systems in plant control systems. Prime drivers for their replacement are the promise of added functionality, efficiency of newer systems, and growing difficulties in finding replacement parts for aging systems. With such sweeping instrumentation changes comes the need to address the effects on the human operators and to plan for technology replacement that enhances human performance during plant life-cycle planning.

To maintain the functionality of the system over time, the system must be able to be adapted to respond to needed change and designed to be

4 Goal Areas	8 Goals	15 Criteria	24 Metrics
Sustainability	SU1 Resource Utilization	SU1-1 Fuel Utilization	<ul style="list-style-type: none"> Use of Fuel Resources Waste Mass Volume
	SU2 Waste Minimization and Management	SU2-1 Fuel Utilization	<ul style="list-style-type: none"> Heat Load Radiotoxicity
		SU2-2 Environmental Impact of Waste Management and Disposal	<ul style="list-style-type: none"> Environmental Impact
	Economics	EC1 Life Cycle Cost	EC1-1 Overnight Construction Costs
EC1-2 Production Costs			<ul style="list-style-type: none"> Production Costs
EC2 Risk to Capital		EC2-1 Construction Duration	<ul style="list-style-type: none"> Construction Duration
		EC2-1 Overnight Construction Costs	<ul style="list-style-type: none"> Overnight Construction Costs
Safety and Reliability	SR1 Operational Safety and Reliability	SR1-1 Reliability	<ul style="list-style-type: none"> Forced Outage Rate
		SR1-2 Worker/Public - Routine Exposure	<ul style="list-style-type: none"> Routine Exposures
		SR1-3 Worker/Public - Accident Exposure	<ul style="list-style-type: none"> Accident Exposures
	SR2 Core Damage	SR2-1 Robust Safety Features	<ul style="list-style-type: none"> Reliable Reactivity Control Reliable Decay Heat Removal
		SR2-2 Well-Characterized Models	<ul style="list-style-type: none"> Dominant Phenomena-Uncertainty Long Fuel Thermal Response Time Integral Experiments Scalability
	SR3 Offsite Emergency Response	SR3-1 Well-Characterized Source Term/Energy	<ul style="list-style-type: none"> Source Term Mechanisms for Energy Release
		SR3-2 Robust Mitigation Features	<ul style="list-style-type: none"> Long System Time Constants Long and Effective Holdup
Proliferation Resistance and Physical Protection	PR1 Proliferation Resistance and Physical Protection	RR1-1 Susceptibility to Diversion or Undeclared Production	<ul style="list-style-type: none"> Separated Materials Spent Fuel Characteristics
		PR1-2 Vulnerability of Installations	<ul style="list-style-type: none"> Passive Safety Features

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Figure 2-1. Gen IV programmatic metrics, criteria, goals, and goal areas used for comparison.

Sustainability
<ul style="list-style-type: none"> - ICHMI operational lifecycle - Upgrade/replacement criteria and requirements - Staffing models and operator roles - Licensing and certification requirements
Economics
<ul style="list-style-type: none"> - Level of system automaton - Self-monitoring and self-maintaining capability - Fleet-wide O&M integration and support requirements
Safety and Reliability
<ul style="list-style-type: none"> - ICHMI system reliability and availability - Operator performance under new and increasingly complex environments - Human and system error modalities - Procedural requirements - Operator qualification and training requirements - Level of automated operator support (system automation and augment operator needs)
Proliferation Resistance and Physical/Cyber Protection
<ul style="list-style-type: none"> - Ability to tag and active monitoring of all aspects of the fuel cycle - Physical access control measures to prevent/alert/mitigate threats - Cyber security controls for digital control, monitoring, and information systems - Event mitigation and recovery controls for physical/cyber protection

06-GA50645-11

Figure 2-2. Goal areas and system metrics for ICHMI system comparison.

receptive to new technology insertion, including potentially new and different process control and human interface technologies. The system must also have the ability to modify methods used in plant automation and be open to inclusion of new and more highly modular plant control systems. Several of the issues which arise with system sustainability and the changing dynamic of the plant system are:

- *Design for technology replacement and upgrade.* A significant limitation in current nuclear energy ICHMI systems is the lack of a flexible design configuration that allows for new technology insertion, replacements, and upgrades. Hurdles and impediments to technology sustainability must be addressed to assure long-term technology integration into Gen IV systems. A case in point is the

use of wireless ICHMI technologies expected to greatly improve design flexibility and cost saving.

- *Staffing models and roles.* Changing and updating system technology can affect staffing models (onsite versus fully remote operations) and staffing roles (increased automation and use of intelligent monitoring systems).
- *Licensing and certification.* Advances in system technology raise questions regarding the applicability of current certification and licensing standards and processes applied to enable deployment of new systems. As aging systems are replaced with newer technologies, processes that are technology neutral must be available to support their integration in Gen IV systems, and these

approaches must be part of a robust regulated environment.

2.1.2 Economics

An overarching goal of economics is to maintain the reliability and availability of the system at costs that are competitive with other energy generation sources over many years of expected service. Maintaining system reliability and availability while managing costs requires improved control system performance, which is achieved through greater automation, decreasing unplanned and preventive maintenance, and providing technology, methodologies, and interfaces that support effective human performance. To promote low life-cycle O&M costs for ICHMI systems, the following issues must be addressed:

- *Automation.* Future nuclear energy systems may employ different kinds and a much greater degree of automation than in current and near-term nuclear energy systems. Automation has the potential to perform many routine and planned activities in modern plants, thereby reducing the staffing requirements in future systems.
 - *Self-monitoring, self-maintaining systems.* Improvements attendant to greater automation call for more online monitoring, diagnostics, and prognostics systems to follow the performance and assess the condition of plant systems. Self-maintaining and correcting technologies may also be able to reduce demands for manual performance of calibration, testing, surveillance, and potentially some scheduled maintenance activities. Enhanced diagnostics and prognostics that better monitor and predict system performance, including future condition trends and remaining safe-life, over its life cycle can enable more effective O&M strategies to be deployed. Some of these advanced capabilities will closely depend on the decisions made in other design areas. For example, enhanced prognostics will require good characterization of degradation modes of selected materials and components.
 - *Fleet-wide O&M integration.* ICHMI systems must support fleet-wide monitoring and management of structures, systems, and components. Economies of scale on a fleet-wide basis must provide for the ability to centralize monitoring and management of hardware through information exchange from plant systems to new integrated monitoring facilities.
- Different ways of achieving cost and performance objectives may have attendant impacts on the role and activities of human operators. Recognizing that technology can change the requirements for human performance, the following must also be addressed in design:
- *Operator's skills.* Fewer manual activities by the operator may be required in a more highly automated system. Consequently, operator knowledge and skills can degrade over time due to infrequent use. There is a need to balance the advantages of increased automation with the potential for a long-term, systematic drop in the skill levels of operational staff in future ICHMI systems.
 - *Monitoring.* Automation especially changes the nature of the role and activities of human operators from frequent engagement and interaction with plant systems to one of more passive monitoring and vigilance. Future systems must address this change in activities and include characteristics in design that promote cognitive engagement and in-the-loop activities to ensure operators are able to develop and maintain situation awareness with more advanced ICHMI systems.
 - *Over-reliance upon automation.* Automated systems employ logic and computer code that may be ill understood or unavailable to operators. As a result, out-of-the-loop performance may occur, and a potential result is situations where human operators overly depend on automation and may be unable to intervene in off-normal system operations. Such over-reliance or lack of ability to intercede is paradoxical but an inherent risk in highly automated system activities and system interfaces. The new

designs should address methodologies that support potential operator intervention.

2.1.3 Safety and Reliability

Future energy systems must meet general design criteria established for ensuring safety and reliability of existing nuclear energy production systems, yet new and different means may be used to accomplish this purpose. A technology-neutral framework is envisioned for licensing and verifying approaches used to ensure advanced plant safety, and the following elements are needed to accomplish this goal:

- *Highly reliable and available systems.* ICHMI technologies are needed that are highly reliable and have been qualified for the performance environments envisioned for Gen IV systems. Information is needed that can be accessed by operators at all levels of system performance (component, train, system, etc.) to ensure the expected performance and availability of service systems is delivered during all modes of plant operation.
- *Need for human reliability and performance.* The complexity of a multi-modular control system and the addition of possible co-located hydrogen production in the balance of plant operations will change the human contributions to system reliability. In systems that are more complex than technologies currently in use, the sources of risk may shift from activities that are predominantly and currently manual to other modes of human performance (cognitive) and other kinds of errors, which may expose new system vulnerabilities that require attention. More highly automated systems change the opportunity for and kinds of impact that human performance may have on system safety and reliability.
- *Procedure and training development.* New systems may require different operator skills and knowledge. Thus, it is important that personnel receive adequate training and become accustomed to different procedures for new system operations. Such procedures

and training need to be defined within the context of advanced systems.

- *Need for an augmented cognitive system.* Responsibilities for human operators in a highly automated environment will primarily be monitoring (checking the system status) and detecting (recognizing that something is not operating normally in the system). In addition, these actions may need to be performed under off-normal conditions in context of information overload or complexity (simultaneously monitoring the status of multiple reactors). Thus, developing a system that can automatically and actively monitor operator workload and performance and adjust the degree of automation to match the needs of the situation may be beneficial.

2.1.4 Proliferation Resistance and Physical Protection

ICHMI technologies contribute to plant and fuel-cycle security, and some of the new technologies that may be envisioned have the potential to alleviate the current cost burden of security programs.

After the events of September 11, 2001, requirements for physical security have grown in importance and in cost. In addition to advances in technological aspects of Gen IV plant and fuel design, enhancements in technology are also needed to assure physical plant security. This includes material protection, inventory accountability and tracking, personnel identification and verification, remote assessments of the facilities, deterrence, and mitigation. Cyber security of plant systems must also be assured. Today these requirements impose a tremendous financial burden on nuclear utilities. ICHMI advancements offer increased flexibility and new approaches to meeting the safeguards and security requirements for new systems, and can include the following features:

- *Traceability and monitoring of all aspects of the fuel cycle.* ICHMI technologies coupled with operator decision support systems provide the ability to identify, tag, and monitor activities and components

throughout all aspects of the fuel cycle. This ability provides greater accountability for nuclear materials and personnel and can potentially reduce the physical burden of such security activities.

- *Access control.* As stated earlier, world events over the past few years have forced an elevation of the security posture at plants. To meet the new security requirements, physical barriers have been erected, the number of security guards has been increased, and new policies and procedures implemented. To a large extent, this new posture reflects the desire (1) to prevent access to unauthorized individuals, (2) to alert the security force should access occur, and (3) to mitigate or slow unauthorized progress after a breach. Security factors must be a design consideration for any new nuclear plant or support facility. ICHMI should be a prime component for implementing access control measures, increasing the efficiency of such measures, and decreasing the cost burden of current system designs. Supporting technologies for access control could include:
 - Plant situational assessment and monitoring systems
 - Anomaly and change detections systems (video, audio, etc.)
 - Intrusion detections systems
 - Automated response systems
 - Advanced means of user identification
 - Physical access control and tracking systems.
- *Cyber security and protecting digital and physical systems.* Technology transition will see the implementation of cross-connected digital systems. The demand for information flow between plant components and between the operations, engineering, and business elements in facility operation, combined with the migration toward digital systems, has brought tremendous benefit in terms of situation awareness for plant operations. This

aspect of information flow is only expected to grow. These conditions with a modern system architecture introduce the potential for vulnerabilities to cyber intrusion. Next generation control system architectures must be designed to address these potential vulnerabilities from both the prevention and mitigation perspectives. This will require technological solutions and human centric systems design. Multiple cyber security studies demonstrate that the lead cause of security failure within a system is not a failure of technology, but is human centric in nature, involving either a failure to understand the nature of the problem or the result of flawed practices employed in the implementation.

The preceding discussion is intended to describe how the application of ICHMI technologies and a program of RD&D are integral to achieving the programmatic goals of the Gen IV Nuclear Program. The ICHMI considerations must be incorporated into and become an active part of the programmatic wider execution.

2.2 Next Generation Nuclear Plant

While the Gen IV nuclear power plant programmatic objectives discussed previously addressed issues at a broad scale, the programmatic issues associated with the design, development, and testing of NGNP are more pressing, due to the potential near-term deployment horizon. Targeting high-efficiency electricity, process heat delivery, and nuclear-assisted hydrogen production, the NGNP project will develop and demonstrate a first-of-its-kind very-high-temperature, gas-cooled nuclear system.

A key programmatic issue for the NGNP is risk management, including risk area identification, risk quantification, and risk mitigation, through all phases from design to deployment. The importance of risk management within the development of the associated new technologies only highlights the need for active and integrated ICHMI programs incorporated

early into the NGNP program. ICHMI technologies will be needed, especially in the areas of sensors, monitoring, measurement, diagnostics, and prognostics, early in the design process to validate and quantify nucleonics methods, thermal-hydraulic properties, and material characteristics. Current areas of concern include but are not limited to the following:

- Fuel qualification and safety case performance
- Material performance at high temperature (900-950°C)
- Thermal aging
- Metallic materials irradiation qualification
- Material corrosion and oxidation
- Flow and heat transfer measurement and verification (physical measurement and computational fluid dynamics [CFD] software code validation)
- Monitoring for management of “balance of plant” systems.

These concerns just represent the nuclear power production side. Large-scale hydrogen production and process heat technologies are perhaps even less mature and more ill-defined. Significant RD&D is still needed to evaluate laboratory pilot technologies for selection of nuclear heating engineering-scale demonstration technologies. As such, ICHMI will be essential for providing the technical basis for milestone decisions on design and materials selection supporting hydrogen production and process heat delivery.

While the above areas address to a large degree individual subsystem concerns, ICHMI plays an even greater role in the integration and operation of these subsystems within the whole facility. The NGNP design includes the coupling of both high efficiency electricity and nuclear-assisted hydrogen production. This design consideration presents previously unaddressed challenges in terms of implementation, controllability, and safety case consideration. Additionally, during the design and development process, material and engineering consideration

will likely drive plant controllability requirements, including control-system functionality and human-activity requirements.

In addition to addressing technology and engineering challenges, the NGNP design must also fulfill U.S. Nuclear Regulatory Commission (NRC) licensing requirements. The NRC has previously conducted advanced reactor design reviews for the Modular High-Temperature Gas-Cooled Reactor (MHTGR) and the Pebble Bed Modular Reactor (PBMR), neither of which has yet been constructed. In terms of ICHMI for advanced reactor plants including near-term plants, significant challenges exist in licensing. This has been exemplified by the PBMR (SECY-01-0207) and, more recently, by the challenges facing the nuclear industry in migrating from analog safety systems to entirely digital safety systems (Heckle and Bolian 2006). NRC concerns regarding digital systems include the potential for common-mode failures caused by software errors, the complexity of systems due to unique configurations, and the inability to “prove” software to be free of errors (U.S. NRC 2006 RIC, March 7-9, 2006).

Beyond purely technical considerations are concerns related to joint system operations: the integration of hardware, software, and human activity. Operational concepts such as passive safety, hydrogen production, and a “100 person” plant are vastly different from the current paradigms. A strong technical basis with quantifiable evidence is likely to be required for the licensing of any new digital or advanced system control concept. Therefore, ICHMI research followed by system verification and validation (V&V), are needed early in the design phase to address these potential licensing stumbling blocks. Without a well-planned and integrated roadmap for ICHMI, the programmatic elements discussed above may potentially fail to meet their objectives and milestones.

2.3 Goals, Challenges, and Needs

Achieving the goals of the Gen IV and NGNP Programs is subject to overcoming ICHMI technology challenges that could lead to costly,

complex, inefficient engineering solutions coupled with associated schedule delays. Without a comprehensive, systematic crosscut program to provide the technological advances and capability

demonstrations necessary to resolve challenges in a timely, cost effective, and efficient manner, these programmatic goals may not be fully realized.

3. RECOMMENDED RESEARCH AND DEVELOPMENT

This section proposes initial project focus areas and discusses the basis for this ICHMI research. The particular tasks identified represent high-value tasks with potentially long lead times and schedule implications for the NGNP. Note this list represents only a first iteration in response to ICHMI research drivers. The objective is to establish a high-level research plan and specify a set of initial high-priority research projects. Once funding is available for plan execution, a detailed implementation plan will be developed for each project.

ICHMI Initial Focus Areas and Funding Priorities

1. Crosscut ICHMI Program Establishment

- Establish a formal DOE-led crosscut ICHMI program. Currently ICHMI RD&D is neither a specified nor funded element of any GNEP, Gen IV, or NGNP program focus area. While DOE-led, this program will include an industry steering committee to encourage and leverage industry investment.

2. Harsh Environment Tolerant Sensor Project

- Investigate new sensor technologies to support the NGNP testing and operational environment. The operating and testing environments for advanced reactor systems are vastly different from today's systems. New sensor technologies are needed to support the evaluation and operation of plants in these new environments.

3. Regulatory Basis Development for NGNP ICHMI Technologies Project

- Development of methods and baseline assessments to support digital technology licensing. One area of this research is the development of technology-neutral performance-based measures to evaluate and assess suitability and limitations of proposed technologies.

4. NGNP Operational Concept Development Project (Demonstration and Deployment)

- Establish and evaluate roles, processes, procedures, interfaces, and operational concepts for operators. This area includes deriving the operational concepts, which will result in design requirements.

5. NGNP ICHMI Architecture Development Project

- Develop control system network architectures that not only integrate state-of-the-art hardware and software, but also the investigation of the application of automation as a greater element of system operation.

6. ICHMI Technology Assessment and Gap Analysis Project

- Perform state-of-the-art assessment and gap analysis to focus specific research needs. This initial project listing represents a first attempt at assessing programmatic needs. A more rigorous analysis of the current state of the art is required to identify promising technological developments and gaps in research.

ICHMI Research Drivers

- *Longest lead time for development of a needed capability*
- *Largest potential benefit(s) in terms of supporting near-term NGNP program decisions*
- *Significant potential to impact technical and functional requirements of the NGNP conceptual design*
- *Potential to significantly improve life-cycle efficiency or affordability of the technology.*

In addition to technical projects, a key component to ICHMI integration is the establishment of a formal DOE-led crosscut ICHMI program. A centralized program is essential to provide the close coordination and development of activities with specific support for NGNP realization. This will include the further refinement and specification of research gaps and development needs. The goal of a centralized program is not to control all advanced I&C and HMI RD&D, but instead to leverage such efforts across different programs.

The roadmap presented in this document is revision one in a continual update and focusing process. The objectives of NGNP and advanced system nuclear programs will not be

achieved without a strong coordination and leveraging of cross-organizational activities. A DOE-led Crosscut ICHMI program is essential. Industry by itself will neither accomplish nor likely even attempt the level of research risk required for achieving the goals of next generation nuclear power.

Research Plan Development

This roadmap recommends RD&D pathways to provide a system of integral capabilities needed for DOE to develop and deploy Gen IV nuclear energy systems. The recommendations presented here are derived from numerous studies, reports, and workshops focused on digital ICHMI and human-machine interaction.

Gen IV Instrumentation, Control, and Human-machine Interaction Technology Needs

(ref: A Technology Roadmap for Generation IV Nuclear Energy Systems)

- *Instrument and sensors to support monitoring/prediction of nucleonics, of heat transfer, and of flow patterns through the core for model development, validation, and operational control*
- *Corrosion and embrittlement detection/measurement/monitoring technologies to support new material evaluation*
- *Instrumentation and controls for helium system purification, control of inventory, and in-service monitoring of interactions between helium and the materials it contains*
- *Instrumentation and test rigs to support the qualification of high-temperature alloys*
- *Balance of plant control for applications such as thermo-chemical processes, dedicated electricity production, or cogeneration at temperatures well above present state of the art*
- *Mechanical and electrical controls/actuators/sensors for new system components, such as valves, heat exchangers, steam reformers, turbines, etc.... that are required for the new designs*
- *Analysis and demonstration of passive safety features to include not only equipment, but process, procedures, and people*
- *Identification and characterization of plant features that influence human performance in operations and maintenance*
- *Collection of quantitative criteria to enable effective comparisons of Gen IV systems and inform design decisions*
- *Flexible, risk-informed regulatory tools for licensing advanced systems*
- *Development of a method for determining the amounts, locations, and characteristics of materials, at each phase of the fuel cycle development and in real time, including information from in-line and offline monitoring instrumentation.*

Drawing upon these and additional sources, this roadmap was developed by an interdisciplinary team of subject matter experts from industry, academia, and national laboratories. A series of focused workshops was arranged to facilitate discussions and identification of technical needs specifically for this roadmap (U.S. DOE Nuclear Energy, *ICHMI Roadmap Development Workshops*).

The result was generation and progressive refinement of recommended RD&D topics and issues that, if addressed in a concerted coordinated

manner, reduce programmatic risk to the Gen IV and NGNP programs and also support critical decisions and activities in the construction of Gen IV demonstration systems.

The six initial recommended RD&D activities are based upon specific research drivers for successful accomplishment of Gen IV and specifically NGNP project schedules. The next section will provide the rational and greater detail for these specific activities. On a broader scale, eight topical areas are identified as focal points for ICHMI R&D efforts.

KEY RESOURCES USED TO DERIVE ICHMI RESEARCH REQUIREMENTS

- *IAEA Technical Meeting: Cyber Security of Nuclear Power Plant Instrumentation, Control, and Information Systems, Idaho Falls, ID Oct 17-20, 2006.*
- *Workshop on "Technology Roadmap on ICHMI to Support DOE Advanced Nuclear Power Plant Programs," Reno, NV, June 2-3, 2006.*
- *International Workshop On Future Control Station Designs And Human Performance Issues In Nuclear Power Plants, OECD Halden Reactor Project (HRP) and NEA/CSNIS Special Expert Group On Human and Organisational Factors (SEGHOFF), Halden Norway, May 2006.*
- *Advanced Reactor Licensing: Experience with Digital ICHMI Technology in Evolutionary Plants, U.S. Nuclear Regulatory Commission, NUREG/CR-6842, 2004.*
- *Workshop on Human Performance in Advanced Control Rooms, INL-PNNL hosted, Seattle, April 6-7, 2004.*
- *Instrumentation, Controls, And Human-Machine Interface (ICHMI) Technology Workshop, DOE-NE sponsored, Gaithersburg, Maryland, May 2002.*
- *A Technology Roadmap for Generation IV Nuclear Energy Systems, GIF-002-00, 2002.*
- *Legal and Financial Issues Related to Exelon's Pebble Bed Modular Reactor (PBMR), U.S. NRC SECY-01-0207, November 2001.*
- *"Instrumentation and Control System Failures in Nuclear Power Plants," Brill, R. W., International Symposium on Software Reliability Engineering, San Jose, CA, Oct 8-11, 2000.*
- *Modern Instrumentation and Control for Nuclear Power Plants: A Guidebook, IAEA Tech Report 387, 1999.*
- *Digital Instrumentation and Control Systems in Nuclear Power Plants: Safety and Reliability Issues: Final Report, National Research Council, 1997.*

3.1 First Phase Technical Tasks

A few specific technical tasks needed are identified in this section. These tasks are representative, high-value tasks with long lead times that have potential schedule or configuration implications for NGNP. Later phases of these tasks should be performed in close coordination with the selected NGNP vendor team.

3.1.1 ICHMI Technology Development Assessment

A principal underlying requirement for an efficient Gen IV ICHMI technology development program is a suite of up-to-date assessments of ICHMI technology development. The capability assessments will describe the as-is situation of ICHMI technologies worldwide that are available to support Gen IV system deployment and identify areas where developmental activities are needed. This type of comprehensive, international study has been undertaken previously under the aegis of the National Science Foundation in the early 1990s (White et al.), but the information is highly dated and limited to those technologies already adopted into nuclear power plants. Other organizations (e.g., IAEA, NRC) have also produced limited scope surveys of emerging ICHMI technologies of interest to the nuclear power industry (IAEA Technical Report 387, NUREG/CR-6888 & NUREG/CR-6812). However, no recent assessment has had its primary focus on overall lifecycle O&M cost reduction or been of a depth sufficient to enable creation of an efficient Gen IV ICHMI technology development plan. The technology capability assessments should be performed with a combination of commercial system vendors as well as ICHMI experts from the international, national laboratory, and university communities. These assessments will provide the basis for identifying the gaps between current capabilities and future expected ICHMI technology needs.

3.1.2 Regulatory Basis for NGNP ICHMI Technologies

The licensing process, embodied in the Code of Federal Regulations and supported by the

NRC's Standard Review Plan (NUREG-0800), is undergoing a significant update to support the first round of license applications for new nuclear power plants. The current regulatory framework for licensing nuclear power plants, including licensing of instrumentation, control and protection systems, as well as human factors engineering in nuclear power plants, has not been implemented yet. As a result, it is unclear whether the new framework will provide the methods or strategies needed to address ICHMI systems for NGNP or to facilitate the licensing of innovative digital system architectures that will likely be used in Gen IV plants. In addition, since current regulations and safety review guidance are based on experience with LWR technology, changes (e.g., enhancements or exceptions) may be necessary to appropriately address NGNP and Gen IV issues (e.g., non-LWR concepts, multi-unit applications, and optimized staffing). As part of the initial activity under this roadmap and in conjunction with NGNP planning and conceptual design activities, an evaluation of the current regulatory framework and licensing processes related to ICHMI technology is necessary. This evaluation will assess the impact of current regulations (e.g., the General Design Criteria) and regulatory guidance (e.g., the Standard Review Plan and associated regulatory guides) on the design and implementation of NGNP ICHMI systems. The expected outcome includes development of a recommended approach to ICHMI system licensing as an element of an overall NGNP licensing strategy; determination of the ICHMI system requirements and technical justification for responding to and improving current regulations; and identification of needed RD&D to resolve open regulatory issues.

3.1.3 Harsh Environment Tolerant Sensor Development

All of the principal NGNP process sensors will require significant technological advances to perform under its high temperature and high radiation environment. The sensor suite used for existing commercial NPPs was developed during the 1950s and 1960s, and there has been little requirement for fundamental advancement since then. While the specific design for the NGNP remains unsettled, its general operational

parameters are well known. Hence, RD&D should begin immediately on the primary reactor and thermal variable measurement suite as these technologies have long lead times throughout their development cycle and thus have the potential to be design and schedule restrictive to the NGNP.

The NGNP relies on high temperatures to achieve its high thermodynamic efficiency. Measurement of high process temperatures is necessary for reactor control, balance of plant control, and to determine reactor status. While work on a full set of environmentally tolerant measurements would ideally begin in FY 2007, temperature remains the primary reactor and thermal system variable. It is, therefore, recommended to lead off the harsh environment tolerant sensor development effort with thermometry.

The higher NGNP temperatures, as compared to current generation light water reactors, will result in more rapid deterioration of the temperature transducers with attendant drift in calibration. Further, the less frequent refueling outages of next generation plants decrease thermometer calibration opportunities as compared to current generation nuclear power plants. The requirement for high-accuracy measurement combined with the inevitable drift in the material properties of temperature transducers results in high value being placed on temperature measurements that depend on invariant, fundamental phenomena.

3.1.4 NGNP ICHMI Architecture Development

The required functions, if not their plant-specific details, of the NGNP control and protection systems are already well known. Further, desirable ICHMI architectural characteristics are evident, such as the ability to make diverse and redundant measurements, flexibly reconfigurable information networking, and high security against external threats. Consequently, the system architecture technology development can efficiently begin immediately. Further, even in the merely evolutionary LWRs ICHMI upgrade technology is not incorporating greatly advanced operational functionality.

ICHMI development is proving to be schedule restrictive and has in the recent past delayed several new plant start-ups.

Defining a high-reliability ICHMI architecture requires planning for the functional and physical arrangement of the ICHMI system components as well as understanding the control and protection concepts for the reactor. The system architecture design begins with determining the necessary functions that the control and protections must perform and augmenting that list with the additional desirable properties and functions of an optimized plant control network. The control system functions are then allocated to particular hardware, which is mapped into the plant. In parallel, or in a repeated design revision cycle, the control system is configured for maximum plant reliability incorporating diversity, redundancy, and adaptability.

A program of RD&D is recommended that will involve the participation of industry, academia, national laboratory, and international (i.e., GIF member) partners to develop candidate NGNP ICHMI architectures. The development activities will emphasize new ICHMI architectures that incorporate the best features from current ICHMI designs, proven performance in other fields of power generation (e.g., fossil energy supply systems), and address new functionality and physical requirements of NGNP systems.

This task will create a conceptual design for a robust, secure, fault-tolerant, highly reliable ICHMI architecture for the NGNP to maximize system availability while minimizing the requirements for constant human interaction. ICHMI system goals will include sufficient real-time health monitoring diagnostics to enhance reliability prediction and condition-based maintenance for operational efficiency. The products of these RD&D activities will be performed and delivered to support key design activities and critical decisions in the NGNP program.

3.1.5 NGNP Operational Concept Development Project (Demonstration and Deployment)

As noted in Section 3.2.7, new models of human system interaction and analysis tools are emerging that can support performance optimization of new reactors. However, before such concepts can be effectively applied to new designs, several tasks must be accomplished.

First, the various levels of control that are appropriate in nuclear plant control system must be defined. “Levels of control” refers to the relative roles and responsibilities of human and automation agents in the performance of a specific function or task. While levels of control have been defined and implemented in some industrial domains, such as aviation, they have not been defined and validated for nuclear plant operations. Furthermore, the differences in process demands and dynamics do not permit simply adopting models developed in other industries.

Second, once an appropriate levels-of-control model has been identified, analysis and design tools must be developed to support identification of appropriate levels of control for various plant functions/tasks under specific operational conditions. Function/tasks are analyzed using “function allocation” methods, which define the criteria and decision bases for making function assignments to specific levels of control.

Third, the ICHMI and user interface requirements for each level of control must be specified to support the proper integration and communication between human and automation agents.

A program of physical and simulation-based human-in-the-loop research is recommended that involves participation of the NGNP project, industry ICHMI vendors, and the operations and engineering staffs of nuclear utilities, national laboratories, and university personnel to carry out applied research on human-centered automation design. Using a number of existing facilities and developing additional capabilities needed to support design and development studies, the research program would address issues that can significantly impact the direction and final design

of control facilities and capabilities for the NGNP. The issues to be addressed include the following:

- Technical approaches to achieve multi-module control and significantly reduce main control room staffing requirements
- Role of the operator in NGNP operations and proof of operational concepts
- Hierarchy of interface development to support functional-oriented, symptom-oriented, and task-oriented system design to address operational and safety considerations
- Technologies that can be used to achieve fleet-wide system management and distributed control of assets.

These activities will make use of available research testbeds in the U.S. and abroad and leverage existing capabilities. These tasks will produce (1) technologies that can be transferred to industry and other Gen IV partners to support concept development, design decisions, and interface technologies and (2) development methods that can form the basis for system design for the NGNP and other Gen IV (i.e., GIF-sponsored design) systems.

3.2 Recommended RD&D Focus Areas

The following eight focus areas have been identified for investigation under this crosscut program effort (Figure 3-1). Each area represents an essential element for advancing ICHMI technologies in nuclear power plants and is required to resolve the challenges and needs discussed in Section 3. The RD&D focus areas are as follows:

1. Sensors and electronics for harsh environments
2. Uncertainty characterization for diagnostics/prognostics applications
3. Quantification of software quality for high-integrity digital applications
4. Intelligent controls for nearly autonomous operation of advanced nuclear plants
5. Plant network architecture

6. Intelligent aiding technology for operational support
7. Human system interaction models and analysis tools
8. Licensing and regulatory challenges and solutions.

The significance of each of the recommended RD&D focus topics derives from three sources:

1. Current open-issues thought to hinder the implementation of advanced technologies, methods, and techniques
2. Gen IV and NGNP reactor concept design requirements that introduce unique measurement needs, environmental stress conditions, and control demands
3. Evolving concept-of-operation considerations related to greater automation/autonomy, extended operational cycles, reduced maintenance and operations staffing, and multi-modular configurations.

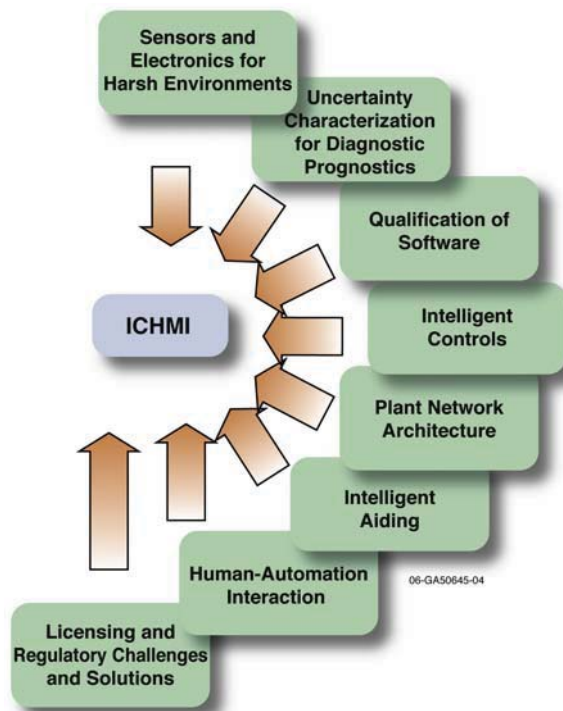


Figure 3-1. Focus areas identified for investigation under this crosscut program effort.

3.2.1 Sensors and Electronics for Harsh Environments

Accurate process and plant-state knowledge representation is essential for safe and reliable plant operation. Advanced reactor systems, such as those in the Gen IV program, envision primary operating temperatures near 1000° Celsius and concepts that use gaseous or molten liquid metal coolants. These designs are being developed to combine the co-production of hydrogen or process heat and electricity through possibly direct-conversion methods.

Higher temperatures are a primary instrument stressor effectively making much of the established LWR instrumentation base inappropriate for such applications. Further, measurement system technology throughout many process industries is moving toward microprocessor-based “smart” sensors. Both commercial availability and increased functionality are driving the nuclear industry to adopt this new instrumentation with its deeply embedded digital technology. Moreover, a direct consequence of the higher accuracy and reliability measurement capability is enabling plants to increase their output by operating nearer component physical limits, hence reducing the set-point margins. However, the harsh environments that the transduction element and its nearby associated electronics must endure are a severe impediment to the adoption of the advanced technology within containment for the proposed advanced NPP (Gen IV) designs.

Smart instrumentation shows promise for providing higher reliability, including self-diagnostics features and higher fidelity measurements with automatic calibration features, while minimizing plant downtime and plant component replacement costs. However, achievement of these desirable features necessitates reliable electronics operating at higher temperatures and in higher radiation areas than those encountered in current plants. Particular research tasks supporting this topic would include development of higher temperature tolerant sensors and harsh environment tolerant electronics.

3.2.2 Uncertainty Characterization for Diagnostics and Prognostics Applications

In industries outside of nuclear power, well-implemented diagnostics and prognostics systems have provided predictions of maintenance requirements and identification of incipient failures. This capability provides both economic and safety benefits for plant operation. However, to achieve these benefits, the uncertainties associated with the estimation of diagnostic information and projection of failures must be addressed. The Nuclear Regulatory Commission has indicated that the application of advanced diagnostic and prognostic techniques for extending surveillance and maintenance intervals is only acceptable if the capabilities and limitations (i.e., uncertainties) of those methods can be determined.

Research activities recommended in this area include:

- Development of uncertainty analysis techniques for data-driven diagnostic models
- Development and validation of degradation models for key nuclear plant components
- Investigation of the strengths and weaknesses of advanced inverse algorithms for diagnostics
- Development of testing protocols for quantification of uncertainty in diagnostic and prognostic modules.

3.2.3 Quantification of Software Quality for High-Integrity Digital Applications

The current reliance on qualitative indications of software quality often leads to high development and implementation costs for safety-related digital systems and a need for more direct performance-based evidence that the software will perform its intended functions on demand under every circumstance. The safety-critical nature of nuclear control operations requires a systematic approach to software quality assessment. The first and often most crucial element in developing a software-based system is to define the necessary

and complete set of system requirements and correctly translate those into the associated software specifications. Systematic approaches for designing and evaluating functional requirements and software specifications need to be developed and demonstrated to support quantification of software quality.

One research activity that could contribute to achieving this capability is the development of techniques for expressing requirements in mathematical or graphical forms that are more amenable to analysis, review, and demonstration of systematic approaches for the translation of requirements into specifications, such as when using sequence-based specification and formal language techniques.

A second aspect of the development of software-based systems that could benefit from more rigorous methods is high-integrity software validation testing. Model-based statistical testing has demonstrated success in the computing industry and should be investigated through application to a nuclear power demonstration. In addition, fault-seeding approaches and testing programs using massively parallel computers, such as those using inexpensive personal computers, have shown promise and could be developed further.

Key to this technical area is developing consensus methodologies and identifying acceptance criteria that can enable predictable reviews by the U.S. NRC.

3.2.4 Intelligent Controls for Nearly-Autonomous Operation of Advanced Nuclear Plants

In delivery of Gen IV nuclear power plants there are tremendous economic incentives to increase automation and self-monitoring so as to limit operational cost, increase plant output, and minimize downtime. Intelligent control concepts that are self-diagnosing, self-correcting, self-validating, and autonomous, and that have increased responsibility and authority, are needed to provide the desired capabilities.

The smaller reactor thermal output of the NGNP, combined with its likely future deployment in multi-reactor plant configuration, provides further motivation towards decreasing the reactor staffing level through increasing automation. Additionally, the overall limited operational experience with non-LWR plants encourages the adoption of more intelligent controls, thereby reducing plant reliance on approaches that depend on operator performance.

Advanced control algorithms have undergone continued development for non-nuclear industrial applications over many years and similar concepts may have applicability in nuclear power applications. While the demonstration of advanced algorithms on selected nuclear plant systems has value, a greater benefit can be gained by a more comprehensive effort to establish candidate control system architectural frameworks, with functionally hierarchical structures that can facilitate intelligent, autonomous control of NGNP plants.

This research could consist of several individual projects performed sequentially or in parallel, which focus on multi-system slices to build an over-arching, whole-plant control architecture. Research activities that can support this development could involve comparative evaluation of the capabilities and limitations of advanced control algorithms for large-scale complex system control, demonstration of control structures that incorporate captured expertise for self-maintenance and command validation, and development of approaches to integrate control, decision, diagnostic, and prognostic capabilities in the context of supervisory control.

3.2.5 Plant Network Architecture

Gen IV NPPs have large, complex data networking needs with high-security and extreme reliability. Further, the networking requirements change as plant demands change from supporting configuration and material accountability during initial plant acceptance testing, to ad hoc networking for component diagnostics as equipment operates and wear occurs, to flexible reconfigurations that enable lifetime upgrades as technology inexorably advances. The capacity for

change must effectively facilitate adaptation for failures, such as a wire being accidentally cut or a deliberate wireless attack on the plant. Well-designed, fully digital control and information systems are necessary to exploit the capabilities of modern networking and computing technologies. Operational cost reductions through activities, such as empowering the maintenance staff with ubiquitous plant component status and maintenance procedures, are made practical through well-designed and implemented information networking. Further, a strong motivation exists to employ open protocol communication networking, where multiple vendors provide components that seamlessly interact. Demonstration of compliance with the networking protocol is thus critical for adoption of multi-vendor system elements.

Testing and evaluation capabilities are needed to investigate communication performance and security issues and to support development of an optimal plant network. The testing capability would optimally be based on a testbed facility augmented by a virtual testbed association consisting of distributed, interconnected physical and simulated elements. This can be realized through incremental capability and component additions from individual projects over several years.

Key elements that can be added or enhanced through research activities involve testing constructs for network elements that demonstrate performance characteristics, such as time response, interoperability, cyber-security, and environmental compatibility.

3.2.6 Intelligent Aiding Technology for Operational Support

This research topic addresses the research need to define where intelligent aiding in support of plant operations is needed. Candidate technologies will be evaluated for their ability to deliver this intelligent aiding. The research should include the development and refinement of design prototypes and the development of general design principles. Additional output should be guidelines for the validation of the usefulness of an intelligent aid.

3.2.7 Human System Interaction Models and Analysis Tools

Human system interaction and human factors must be a key consideration in any upgrade or paradigm of operation shift. Considerations include the integration of plant automation, new information systems, new procedures, and any other aspect that changes the human-machine interaction expectation. This topic addresses the development of new models of human-automation interaction based on emerging control technologies, such as automation that adapts to operator workload. Models should be defined and methods of analysis for allocation of functions, including dynamic allocation, should be formalized. The user interface requirements for each model should be specified. A test program should be included to evaluate concepts.

3.2.8 Potential Licensing Challenges and Solutions

Approaches are needed to license ICHMI technologies for the operation of Gen IV, NGNP,

and GNEP facilities. The experiences gained from the NP2010 program in ICHMI licensing will be relevant to the case of Gen IV systems, but due to the substantial changes in operating environment and in operations themselves, much of the licensing guidance may not be applicable. Gen IV systems will employ much greater connectivity between reactor modules, employ newer and more kinds of automation, and rely to a much greater extent on digital technologies even for safety systems. Technology-neutral and perhaps performance-based approaches are needed that permit the selection of best available technologies for eventual qualification, methods for their qualification, and approaches that can be used for system maintenance, including upgrades and replacement. These approaches will ensure that the most suitable technologies can be fielded in Gen IV systems and that strategies for upgrade and replacement are sound.

4. ICHMI CROSSCUT PROGRAM RATIONALE

Achieving the performance goals of the Gen IV and NNGP Programs is encumbered by ICHMI technology challenges that can potentially lead to costly, complex, and inefficient engineering solutions with resulting associated schedule delays. Without a comprehensive, systematic crosscut program to provide the technological advances and capability demonstrations to resolve those challenges in a timely, cost effective, and efficient manner, the Gen IV and NNGP programmatic goals are at risk. The purpose of this section is to establish the technical basis for the ICHMI Technology Crosscut Program by identifying key ICHMI technical challenges and relating them to NNGP or Gen IV programmatic goals. More details on the goals, challenges, and technical needs for advanced ICHMI are provided in the appendices.

To facilitate a systematic presentation of the issues, the challenges and technological needs are organized in terms of a series of framework structures based on key programmatic, implementation, and utilization structures. These framework elements are Operations, Environmental, Regulatory, Investment, Technology, and Infrastructure. These interrelated elements are further explained in the appendices.

4.1 Life-Cycle Cost Advantage

4.1.1 Operations and Maintenance

Operating nuclear power plants to economically and safely produce electricity throughout the plant lifetime is the chief function of the utilities engaged in the nuclear power industry. The net cost of power from present generation nuclear power plants is currently competitive with, or lower than, other generation resources. The largest component of the day-to-day costs for nuclear power plant operation today, as will likely be the case for Gen IV plants, is O&M, and this is dominated by plant staffing costs. This contrasts dramatically with fossil plants, where the quotidian costs are principally those for fuel. Operational efficiencies in areas such as maintenance and security are thus

proportionally more important to the nuclear power industry.

ICHMI's primary impact on operational cost is by making each member of the plant staff more effective and efficient. Improved ICHMI has been a key element in progressively driving down plant staffing levels and costs from two persons per megawatt towards a current industry level of one-half person per megawatt. In Gen IV and multi-unit NNGP deployments, this ratio will need to be further reduced in order to enable nuclear to remain the low-cost electricity/energy generator. While it is common for adjacent nuclear reactors to share some systems, the smaller reactor size of the NNGP will, in many deployments, necessitate much deeper system integration for financial viability. Multi-reactor control grouping has never before been accomplished, and this has profound implications for system design, construction, regulation, and operations. Providing the technology required to effectively operate a grouping of small reactors, which would be considered a single plant, is thus an important NNGP programmatic goal.

Maintenance reductions will take place largely through more intelligent instrumentation supporting widespread plant diagnostics and prognostics with on-line component health monitoring, ubiquitous information networking, and optimized human-machine interaction designs that enable maintenance staff to proactively address equipment maintenance issues before they significantly impact plant operations. An operational shift from preventive to predictive maintenance will thus increase safety and reduce O&M costs. Operations labor reductions will rely upon developing highly integrated, intelligent control (potentially to the point of limited autonomy), providing optimal operation of multi-unit plants and management of dynamic transitions among multiple co-generation products. The technology pillars upon which O&M labor cost reduction rest remain unproven in the nuclear power domain, and these capabilities are at widely varying levels of development in other industries.

Plant component health information needs to be ubiquitous in Gen IV designs to support optimized maintenance scheduling and minimization of non-productive information access activities by plant staff. Advanced information access needs to be intelligently structured to support appropriate personnel actions and to minimize human error rates and impacts, as well as to incorporate lessons learned during the plant operation. Further, plant health and performance information needs to be accessible by off-site experts in order to ensure both optimal responses to abnormal and off-normal conditions as well as to enable transfer of lessons learned by one plant throughout the industry.

4.1.2 Availability

Achieving very high plant availability (> 95%) is required to make the economic case for Gen IV and NGNP plants. In the U.S., LWR plant availability has increased steadily for the past 25 years to the point where unplanned trips are rare events and refueling outage length tends to be limited by fuel and major component manipulation. Even so, of the remaining unplanned trip events, roughly one-third of the remaining trips are ICHMI-related (U.S. NRC Licensee Event Report Database). Acquiring the experience necessary to achieve this level of availability (capacity factor) has taken many years of concerted effort by financially motivated utilities. The NGNP will have a significantly different technology suite than existing LWRs. Major control concepts, such as trip avoidance methodologies and event management procedures, are yet to be developed for either the new designs or multi-unit operation. The control challenges are particularly acute for reconfigurable balance-of-plants featuring electricity generation, process heat delivery, and hydrogen production. Avoiding the multi-year learning curve required previously (for single-unit, single purpose plants) to achieve optimal operation and high capacity factor is a principal challenge for the NGNP.

Providing accurate process and plant-state knowledge is core to achieving efficient plant operation and effective maintenance. Gen IV plants employ higher temperature processes,

which are required to achieve higher plant thermal efficiencies and to allow for process heat delivery and hydrogen production. Higher temperatures are a primary instrument stressor effectively making obsolete much of the established LWR instrumentation base currently used, for example, temperature, neutron flux, and position measurement. High-temperature reactors have previously been forced to position primary thermal variable measurements at locations away from the reactor core and coolant loop and develop methods to estimate the in-core process variables. This has required approaches that provide sufficient engineering margins to accommodate the resultant uncertainties. High-temperature, environment-tolerant sensor development is thus a principal challenge that must be addressed in order to enable efficient NGNP operation.

4.2 Sustainable Energy Generation

4.2.1 Rapid Technological Obsolescence

ICHMI technology has advanced more rapidly than some other disciplines important to future NPPs. Unfortunately, while most industries have been able to apply the new technology to improve reliability, efficiency, and safety of production, the nuclear industry in the U.S. has been particularly slow to do so, not least because there have not been new plants constructed. ICHMI equipment integrated today will have a relatively short *useful* lifetime in terms of maintainability and adaptability. Taking the personal computer (PC) as an example, the lifespan of a household computer is estimated to be between two and six years. The lifespan consists of two specific elements: the functional lifespan and the useful lifespan. The functional lifespan describes how long the computer system will actually operate as designed, which is a function of system reliability. The useful life describes the capability of the computer to perform desired functionality including interfacing with other systems, which refers to its capability to adapt to changing functional requirements, such as the capability to upgrade software. While the PC example does not

precisely reflect nuclear plant ICHMI equipment, there are definite parallels between the lifespans of both types of equipment.

Nuclear systems and support systems do not need to be upgraded for technology's sake, but they must support the ability to deploy and implement required incremental upgrades (software and hardware), which can be expected to occur several times over the course of a nuclear plant's expected life.

Traditional ICHMI architectures are functionally stove-piped and thus not amenable to piecemeal upgrading into an integrated system. The digital system architectures currently available from vendors for Gen III+ plants are intended to expediently meet present-day minimal information needs, while avoiding the regulatory uncertainty likely to occur from more advanced technology usage. Current concepts are not structured or intended for the significantly increased informational requirements for optimal operation of Gen IV plants and thus become obsolete rapidly.

From a financial viewpoint, component obsolescence is a continuing burden on the maintenance of current generation LWR plants. Hence, Gen IV ICHMI systems need to be considered in terms of functional modules and designed for easy replacement and upgrading several times during the plant lifetime. As cable pulling now costs \$3000 – \$6000 / meter for safety-related cable, such costs dominate ICHMI capital costs, and ease of installation needs to become a prominent system design feature. Likewise from a regulatory viewpoint, the regulatory process must support the pace of needed ICHMI upgrades and maintenance processes.

4.2.2 Infrastructure Development

As a result of the relatively dormant state of the nuclear industry in the U.S. over the past several decades, aspects of needed infrastructure have weakened considerably. With respect to the development of ICHMI systems to support Gen IV plant design, three infrastructure goals must be addressed. The first is to provide an adequate number of *trained and qualified*

personnel to support all aspects of Gen IV ICHMI systems, including design, testing, licensing, operation, and maintenance. The second is to ensure state-of-the-art *methods and tools* to provide the technical foundation to support the development and validation of Gen IV ICHMI applications. The third is to ensure that adequate *facilities* exist for the testing, validation, and proof of advanced ICHMI technology concepts.

State-of-the-art methods and tools are emerging in the digital ICHMI communities that provide new means to analyze, design, and test advanced systems. State-of-the-art computer-based engineering tools enable designs to be rapidly developed and tested in a way that is traceable for both engineering change purposes as well as for regulatory reviews. However, adaptation of state-of-the-art computer-based engineering tools for use in the nuclear power domain in either the design or regulatory spheres has yet to be accomplished in the U.S.

Demonstration of new technology in the nuclear domain in the U.S. remains a significant hurdle that inhibits adoption of advances already deployed in other industries. In many industries involving complex human-machine systems, such as aviation, petro-chemical, maritime, and rail, facilities exist that provide national testbeds focused specifically for that industry's R&D needs. Of particular importance in the nuclear power arena, an ICHMI testbed would provide the capability for developing a technical basis for licensing new technology via demonstration. A limiting factor in the development of advanced ICHMI technologies for Gen IV plant applications is the lack of a national facility to provide needed testbeds.

4.3 Safe and Reliable Operation

Although digital technology has proven to be very reliable in other industries, no accepted means currently exist for characterizing or quantifying the reliability of the software element of digital systems for potential use in U.S. nuclear power plants. Qualifying software for NPP safety and control applications is difficult since internationally acceptable standards, procedures, and methods are not yet available.

The NRC's regulations and safety review guidance reflect the current concepts of operations used in today's plants. For example, the current definition of crewmember roles and responsibilities reflects the staffing approaches used in older, less automated plants. New technology has created tremendous functionality, but this functionality has come with the price of increased system complexity. Coupled with multi-million lines of computer code, the level of complexity is rapidly outstripping the plant staff's ability to assess system performance and conduct troubleshooting outside of black box component replacement. Improved tools and methods for evaluating digital system reliability are vital to adopting and licensing advanced ICHMI technologies in NPPs.

The regulatory and licensing processes are significant elements of bringing advanced plants online. The current regulatory framework for licensing nuclear power plants, including licensing of instrumentation, control and protection systems, and human factors engineering in nuclear power plants, has evolved significantly since the first nuclear power plants were licensed. ICHMI aspects of the design certification reviews were based largely on process rather than detailed design, thus Design Acceptance Criteria (DAC) were used. DAC are a form of Inspection Testing Analysis and Acceptance Criteria (ITAAC) that addresses whether the specific deployment conforms to the design. This means that a considerable amount of effort remained post certification. New plants currently being considered for the U.S. will be licensed under a new regulatory process (10 CFR Part 52) that has not yet been fully implemented.

The current licensing basis in the Code of Federal Regulations (e.g. General Design Criteria) is based upon use for LWR designs. Advanced reactors, such as the NGNP, will have significantly different accident and operational performance characteristics. An integrated approach, including ICHMI, needs to be developed to allow the NRC to establish an appropriate licensing basis for Gen IV reactors.

Considering required unit level safety-related and control instrumentation, the potential for exponential growth of equipment and related

operational requirements quickly becomes apparent. Though conceptually this problem can be mitigated by the clever use of automated digital systems, use of computers in safety-related systems introduces a new set of challenges that must be considered, e.g., common cause failure. As a consequence, a high priority instrumentation issue is the need for a "grass roots" synergistic approach to the design of an ICHMI system for advanced and multi-unit nuclear power plants that involves consideration of control, instrumentation, and the regulations associated with safety-related instrumentation systems.

4.4 Minimize Financial Risk

The primary challenge facing new nuclear generation of any kind is related to capital investment costs when compared with those for other types of power generation. ICHMI conditions that could challenge the achievement of competitive investment for the Gen IV nuclear option are cost of cable installation, higher lifecycle costs for nuclear ICHMI components, high threshold for market entry of new and improved components and systems, and investment protection for ICHMI systems and components. Further, application of advanced ICHMI diagnostic and prognostic technology would provide significant enhancements in capital investment protection to reduce the potential for costly, long-plant outages during recovery from damaged equipment.

Small numbers of digital system sales to date have not presented ICHMI vendors with a sufficient market to allow RD&D budgets to be increased to meet future nuclear power industry demands for more advanced and dedicated technologies. In fact, actual nuclear orders are a very small percentage (less than 5%) of original equipment manufacturer (OEM) sales orders and are at risk for reduction based on lack of future market. This is of particular concern for Gen IV, where even the first-of-a-kind demonstration units remain more than a decade away. This long time-line effectively prevents instrumentation OEMs from commercializing the new and specialized ICHMI components required in technology demonstrations.

4.5 Proliferation Resistance, Physical Security, and Cyber Protection

New technologies are not only required to address the technological challenges of physical plant operation, but design and implementation considerations must also consider the current global conditions. Proliferation resistance and physical protection are cornerstones for Gen IV designs. New ICHMI technologies that support secure operations must be developed and implemented. Current NPP security staffs can be larger than operational staffs. Advanced ICHMI technologies have a significant role in reducing the cost and enhancing the capabilities for NPP security. New technologies must be developed that counter current and developing physical security and cyber security threats by minimizing the likelihood of attack and mitigating the consequences of attempted attacks.

Likewise, ICHMI technologies can also be instrumental for strengthening the proliferation resistance of advanced reactor designs. For example, ICHMI techniques developed for anomaly detection and on-line condition monitoring of critical equipment are often used to implement advanced O&M strategies, such as machine condition monitoring (MCM) and condition-based maintenance (CBM). However, realizing that these monitoring technologies are designed to detect and interpret anomalies without being limited to how the anomaly entered into the monitored systems (e.g., by physical degradation or inappropriate operation), there has been an increasing interest in using these techniques for detecting operations supporting nuclear proliferation objectives, as these unauthorized operations also manifest themselves as abnormal process behaviors or anomalies. Such an operations accountancy approach of nuclear activities via process monitoring can significantly complement the traditional safeguards approach based on nuclear material accountancy. For example, through process monitoring of electricity generation, it is possible to detect whether a (target) pebble in a Pebble Bed Modular Reactor (PBMR) has been removed from the core abnormally early in order to support nuclear

proliferation purposes. This ICHMI process monitoring approach for proliferation detection is particularly important in those nuclear reactor designs with continuous refueling while in operation, such as the PBMR and CANDU reactors. Thus, online condition monitoring technologies originally designed to significantly improve O&M can also be used for supporting nuclear nonproliferation objectives with anticipated similar returns.

While a significant body of work is available in anomaly detection and research continues in this area due to its strong potential for improving reliability, efficiency, and safety of production in many industries, including nuclear, the application of these techniques for nuclear nonproliferation objectives has just been initiated. Much work is needed to adapt and validate their potential within the advanced nuclear reactor design concepts being developed under NGNP and Gen IV programs. This is an ICHMI RD&D area of potentially significant payoff to DOE for addressing its nuclear nonproliferation objectives; however, this effort needs to be integrated early with other design activities in order to obtain highest returns. One reason is that it is important to understand early how a given reactor concept can be (overtly or covertly) misused to support proliferation activities and how these activities manifest themselves (e.g., through process variable changes).

Given this information, optimized ICHMI platforms (i.e., sensors and algorithms) can then be designed to detect them on-line. If no cost-effective process monitoring solutions can be designed that assure adequate observability and transparency of proliferation-related anomalies, changes to the original reactor design may need to be considered in order to address the identified vulnerability regarding nonproliferation objectives. A case in point is that the IAEA, recognizing this synergy, has already initiated efforts to share and transfer ICHMI technologies between its department of nuclear energy, where most of these ICHMI techniques are developed, and its department of safeguards, where nuclear nonproliferation measures are devised and installed.



5. IMPLEMENTATION PLAN AND SCHEDULE

5.1 Program Administration

An ICHMI RD&D program needs to be initiated in a timely fashion so as to potentially avoid programmatic and schedule impacts for both the Gen IV and NGNP programs. The primary issues that must be resolved are the technology gaps posed by unique measurement, control, and interaction demands of non-LWR designs and the technology readiness of enhanced ICHMI capabilities to enable significantly improved performance and resource usage. In essence, early action is needed to prevent ICHMI from becoming a critical path item for NGNP or an inhibiting factor in realizing the potential of Gen IV designs. Thus, the focus of the ICHMI RD&D program involves technology gaps, technology maturity, and technology experience. The first objective is to identify and eliminate technology gaps that may constrain measurement, monitoring, control, or protection. The second objective is to ensure technology maturity so that needed methods, tools, equipment, or other products are commercially available with a robust infrastructure. The third objective is to demonstrate performance and resolve licensing and usage uncertainty for digital and advanced digital system functionality.

A program administration model is required to begin planning and implementation of the RD&D recommendations of this roadmap. The recommended administrative structure for the ICHMI Science and Technology Program follows the framework established by other DOE-NE crosscut programs. This includes an ICHMI RD&D Program Manager (IRPM) to administer and oversee the technical activities of the program. Primary responsibilities of the IRPM may include program management, project administration, coordination of technical reviews, progress tracking support, and working with DOE-NE to ensure integration of tasks with the overall Gen IV and NGNP program activities. This position could be supported by an ICHMI Advisory Committee (IAC), which is composed of key technical experts. Serving in an advisory and review capacity, the IAC provides input to

detailed planning and update of the roadmap, an interface to the ICHMI community, recommendations on RD&D prioritization and project selection, and assessment of technical progress. The IRPM also can serve as a Generation IV ICHMI National Technical Director (NTD) in working with DOE-NE staff to establish program elements that are consistent with and supportive of Gen IV and NGNP, as well as other DOE-NE nuclear power programs. ICHMI work packages and detailed program elements are based on DOE-NE guidance and funding.

- *NGNP is conducting conceptual design research.... ICHMI research, however, is not an integrated element of this research.*
- *Now is the time to commence integrated ICHMI research within the NGNP and GNEP programs.*
- *ICHMI technology gaps have the potential to delay NGNP employment.*
- *Off-the-shelf ICHMI technologies do not exist or are not qualified (licensable) for advanced nuclear systems.*

5.2 Programmatic Considerations and Schedule Planning

A number of requisites must be addressed to effectively integrate the implementation of the ICHMI Science and Technology Program roadmap with broader DOE Gen IV system development and demonstration objectives:

1. The implementation plan and schedule should enable progress and support critical decisions during design stages of the reference systems and technologies
2. The implementation plan and schedule should be consistent with the program

management plan for the Gen IV systems development and procurement programs and thus manageable as an integrated element within this program

3. The plans for implementing many of these RD&D recommendations require a physical reference plant such as NGNP to proceed beyond the conceptual design stage
4. Out-year planning must be tied to critical stages of technology development and deployment for ICHMI systems that support critical stages of technology deployment for NGNP
5. Plans for technology transfer to support procurement and interactions with system vendors and suppliers must be developed over the design cycle of the referent systems.

Figure 5-1 displays the graphical timeline of the reference next generation nuclear plant project (Weaver et al. 2006). The project programmatic elements provide a suitable starting point for conceptualizing the scope of plant design activities and schedule that the ICHMI RD&D activities must address and support. This includes design, construction, testing, and operation of nuclear energy production systems, certification and licensing, power conversion, and associated nuclear hydrogen production.

To effectively support the objectives of the Gen IV and NGNP programs, the ICHMI RD&D makes the following recommendations:

- The plan and schedule for the RD&D elements of this roadmap need to be focused toward application to a suitable reference technology such as NGNP
- Planning assumptions of the current RD&D recommendations must be validated
- A prioritized schedule of activities needs to be developed and associated costs estimated
- A technology licensing and transfer plan must be generated to support system development and procurement strategies.

Key steps for accomplishing these actions are further summarized below.

5.2.1 Applying ICHMI RD&D Recommendations to NGNP

The RD&D recommendations of this roadmap are not strictly limited to specific nuclear heat production technologies—that is, the physical form of the nuclear reaction and heat transfer processes. The different reactor concepts being developed by the Gen IV International Forum (GIF) each embody different technologies and may require fundamentally different techniques and methods accordingly, to achieve process monitoring and control. As the U.S. demonstration technology of the Gen IV concept, the NGNP should serve as the reference technology for the RD&D identified for this program. Currently NGNP is conducting conceptual design research for both the Nuclear and the Hydrogen Systems. ICHMI research, however, is not an integrated element of this research. Now is the time to commence integrated ICHMI research within the NGNP program. A critical step in managing the implementation of this roadmap is to confirm that the specific requirements related to the NGNP high-temperature gas reactor concept are adequately addressed by the ICHMI technology and methods development recommendations. ICHMI technology gaps have the potential to delay NGNP employment. Off-the-shelf ICHMI technologies to support the unique aspect of NGNP operations either do not exist or are not qualified (licensed). Thus, an up-front assessment by the IAC and NGNP stakeholders is needed to ensure that near-term ICHMI RD&D activities are appropriately focused.

5.2.2 Validation of Planning Assumptions

Much of the information used in developing this roadmap and, hence, most of its ICHMI RD&D recommendations, are based upon planning assumptions about future nuclear energy production objectives. These include assumptions throughout regarding economic, investment, safety, and other over-arching objectives that underpin much of the inquiry about the specific needs and objectives of the corresponding ICHMI technologies that must also be developed. The planning assumptions must be validated against specific NGNP and other related program

objectives prior to further development of longer term RD&D roadmap plans and schedules.

5.2.3 Prioritized Schedule of Activities

Based upon the technical program identified in Section 3 of this report, the recommended focus areas should be further analyzed and developed to (a) ensure that their basis, drawn from the various Gen IV reactor systems concepts, appropriately addresses the specific challenges and needs embodied in the NGNP high-temperature gas reactor concept; (b) mesh with the overall NGNP schedule; (c) address technology transfer and licensing planning to ensure implementation through procurement; and (d) support critical decisions in the Gen IV program.

5.2.4 Evaluation of a Technology Crosscut

Crosscut programs have been successfully used by different industries and within the federal

government to leverage investments to the extent practical to support a variety of programs. The programmatic objectives of this Science and Technology roadmap are intended to focus first upon the needs of the Gen IV program. However, many of the needs of this program overlap with the needs of other programs, since they all share common requirements for system instrumentation, monitoring, and control. Some of the other DOE-sponsored programs are also being conducted in a time frame that may allow technology developed for Gen IV systems to be deployed elsewhere, and vice versa. Establishing a technology working group as an element of the IAC, with the intent of identifying and characterizing shared needs across several DOE programs, provides a systematic means of identifying opportunities for leveraging through cost-sharing, technology transfer, and communication to support the most efficient utilization of resources.

Next Generation Nuclear Plant Project

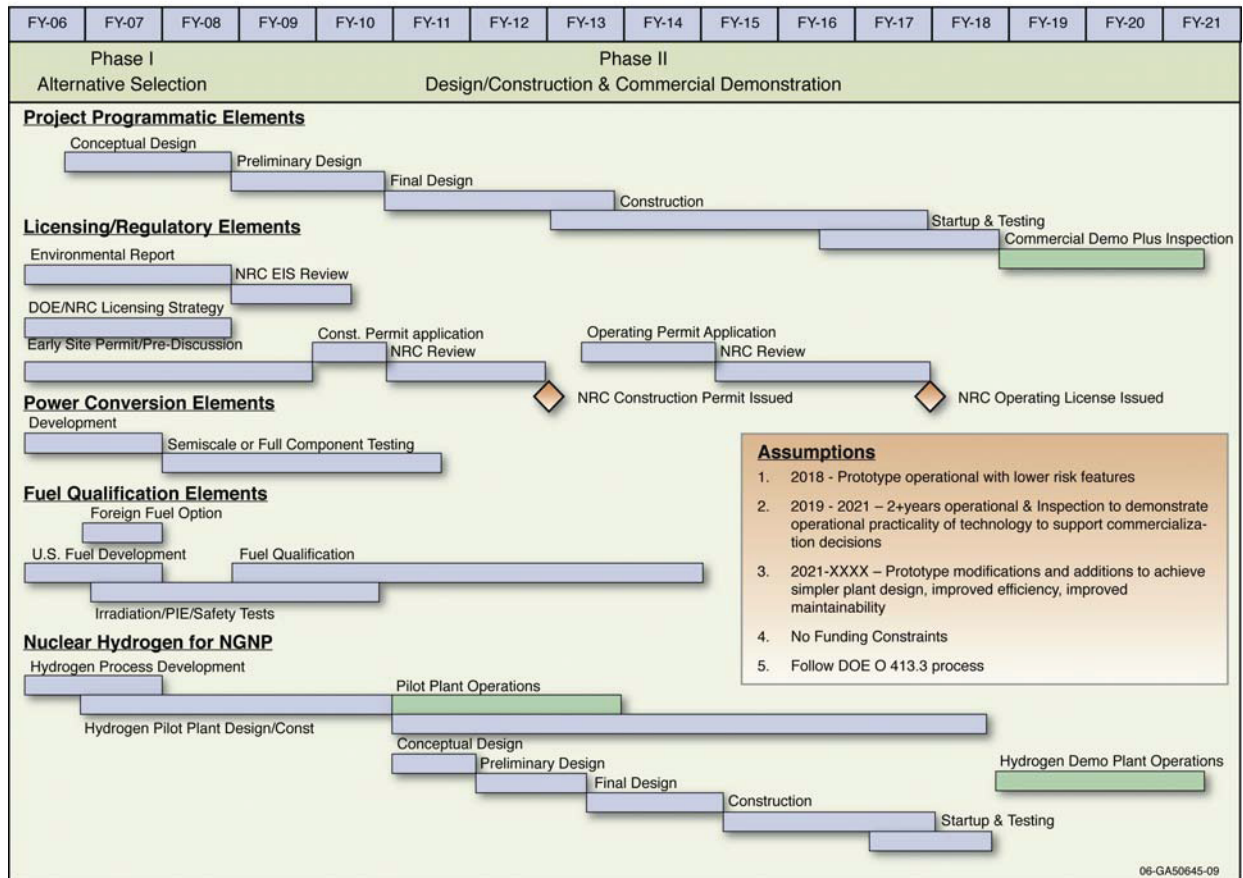


Figure 5-1. Graphical timeline of the reference next generation nuclear plant project.

6. POTENTIAL COLLABORATIONS AND PROGRAMMATIC CROSSCUTS

The requirements for provision of reliable, state-of-the-art ICHMI systems to support and enable the Gen IV program provide significant opportunities for potential collaborations and crosscutting activities across both DOE programs and wider ICHMI activities.

6.1 DOE – NE Gen IV and GIF

Within the Gen IV program and Generation IV International Forum (GIF) activities, there is an established “Materials Crosscut” that is looking at materials for the various systems, materials aging and degradation, and systems issues, including the requirement for expanded “on-line condition monitoring” rather than periodic inspections. Complementing the materials activities there is an emerging effort focused on NDE for next generation NPPs, which includes on-line condition-based maintenance (CBM), diagnostics, and prognostics (Roney 2006). Opportunities also exist to leverage supporting materials studies under Gen IV, including those being performed at the Idaho National Laboratory (INL) Advanced Test Reactor (ATR). These activities require sensors for harsh environments, communications networks, and operator interface capabilities that overlap with needs and requirements for what are normally considered to be plant ICHMI and O&M interests.

The ATR has the potential to become a test bed for ICHMI, as well as a facility to support a wider range of material and sensor studies in NGNP and Gen IV system environments. Programmatically, NERI, I-NERI, Gen IV materials crosscut, and GIF partnerships form a core of activities that can be mutually leveraged by the proposed Gen IV ICHMI cross cut.

6.2 NP2010, NGNP, and GNEP

The Nuclear Power 2010 Program is a DOE-industry cost-shared effort to reduce the regulatory, technical, institutional, and economic uncertainties associated with the licensing and

Industry Issues of Concern and Potential Areas for Research Collaboration

- *Potential for software common mode failure including diversity and defense-in-depth and critical design reviews*
- *Qualification and acceptance of commercially available equipment and platforms including generic pre-qualification of safety equipment and platforms*
- *Risk-informed insights on regulatory issues*
- *Qualification of human-system interfaces (HSIs) for accident mitigation*
- *Qualification for HSI capabilities such as automation, soft controls, computer-based procedures, computerized operator support systems*
- *Scope and rigor for human factors engineering activities*
- *Minimum inventory of fixed position and continuously available indicators and controls*
- *EMI/RFI test levels*
- *Digital ICHMI architectures*
- *Digital system specific technical specifications that allow taking advantage of the capabilities made possible by digital technology*

construction of new nuclear plants, advanced light water systems, of the Generation III + vintage. Through successful completion of the NP2010 program activities, competitive Generation III + designs will become available to the commercial market and a more viable business case will be established to bring new and more advanced nuclear generating capacity online. Digital systems with some limited levels of functionality are expected to be deployed in NP2010 plants.

Meeting the ICHMI and sensor/model validation capabilities and needs for advanced nuclear programs such as NGNP and GNEP offers ideal early opportunities to develop, test, and deploy advanced control, instrumentation, on-line condition-based monitoring, diagnostic, and prognostic capabilities. These capabilities can then be developed further and deployed to meet the needs of other Gen IV systems.

6.3 Nuclear Industry, EPRI, and NRC

The NRC is committed to licensing digital technology in safety system applications. The U.S. Nuclear Regulatory Commission Digital Safety System Research Plan (U.S. NRC Adams Access ML061150050) defines the research activities planned for FY 2005 through FY 2009 and describes the background, technical issues, and on-going and planned activities to meet the challenges of implementing digital technologies in nuclear systems that are important to safety. It outlines current and future research into several areas of emerging ICHMI technology and applications that will be used in the new NPPs and advanced or Gen IV plants.

Specific challenges of regulating digital technologies fall into several areas. One area of focus is the development of methodologies for identifying digital system faults and their potential impact on digital ICHMI system performance. This area needs to address the unique failure modes and complexity associated with digital systems. For example, complete testing of digital ICHMI systems is impractical due to their complex design and operation. This necessitates tools and methodologies that may complement the more traditional testing strategies.

Another area of focus is the evaluation of digital system reliability. State-of-the-art methods for assessing digital system reliability are relatively undeveloped. Quantitative measures of digital system reliability are available for digital system hardware, but methodologies for evaluating software reliability are not well defined. However, comprehensive use of fault injection techniques and life cycle process and

product metrics may reduce software reliability uncertainties.

Another area of focus is the difference between digital equipment and analog equipment in susceptibility to environmental conditions such as electromagnetic compatibility and microelectronic vulnerabilities. For example, digital equipment responds to electromagnetic interference differently from analog equipment. However, environmental qualification techniques specifically designed for digital systems can complement existing environmental qualification processes.

In order to address existing and anticipated ICHMI regulatory issues, the NRC research plan involves a series of tasks grouped into the following four areas: (1) System Aspects of Digital Technology, (2) Software Quality Assurance, (3) Risk Assessment of Digital ICHMI Systems, and (4) Emerging ICHMI Technology and Applications. This research will support the development of review guidance for NRR for these new and improved technologies, which will be applicable to both current reactors retrofits and new advanced reactors.

The NRC also has an ongoing program examining the human factors and human performance aspects of new reactors and new technology. In order to develop technical bases upon which new review guidance can be established, this program examines trends in reactor technology, ICHMI, human system interfaces, and design and evaluation methods. Topics being addressed in this research include the role of personnel and automation, staffing and training, normal operations management, disturbance and emergency management, maintenance and change management, plant design and construction, and HFE methods and tools. The NRC is currently prioritizing needed research in each area and will use the results to guide future activities.

The NRC and industry have been collaborating on the identification of regulatory issues, and ultimately research needs to address the construction and licensing of new reactor plants. Along this line, the NEI Digital I&C and

Human Factors Working Group has been formed. This Working Group (WG), Figure 6-1, is composed of various task forces and focus groups designed to address the implementation and licensing challenges of near-term ICHMI issues:

- I&C Technical Issues Task Force
- Human Factors Task Force
- Digital PRA Task Force
- Cyber Security Focus Group
- Licensing Process Focus Group.

The Working Group, Task Forces, and Focus Groups include industry leadership (utilities, suppliers, consultants, Electric Power Research Institute (EPRI), and NEI). For each of these five groups under the WG, there is a Technical Working Group that includes both Industry and NRC representation.

The EPRI-ICHMI Program has also been working with its member utilities, domestic and international, and other stakeholders in the nuclear power industry. EPRI activities seek to enable more cost-effective operation and maintenance, to take advantage of improvements possible with digital technology, and to maintain or enhance safety. This program applies to operating and future plants (Gen III+). There are still several challenges that must be addressed and several opportunities that should be exploited. In many cases this requires additional RD&D work.

Much of the work needed to support advanced ICHMI for operating Gen III+ plants also applies to Gen IV, NGNP, GNEP, and other future programs and opens up the opportunities for collaboration between the programs. U.S. and foreign utilities' experience from digital modernization of ICHMI controls rooms should be leveraged to support Gen III+ and other advanced plant programs.

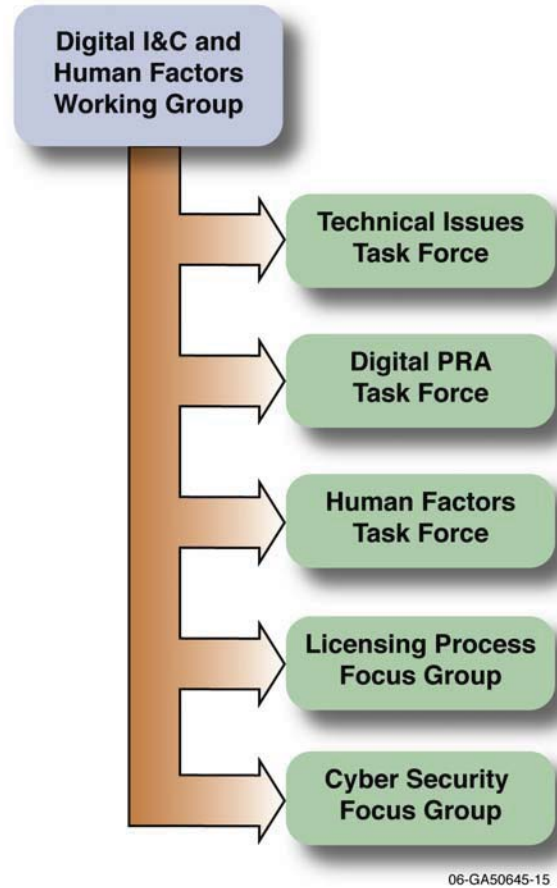


Figure 6-1. Organization of the NEI Digital I&C and Human Factors Working Group.

Examples of some of the challenges being addressed by EPRI are as follows:

- Potential for software common mode failure, including diversity and defense-in-depth and critical design reviews
- Qualification and acceptance of commercially available equipment and platforms including generic pre-qualification of safety equipment and platforms
- Risk-informed insights on regulatory issues
- Qualification of human-system interfaces (HSIs) for accident mitigation
- Qualification for HSI capabilities such as automation, soft controls, computer-based procedures, computerized operator support systems

- Scope and rigor for human factors engineering activities
- Minimum inventory of fixed position and continuously available indicators and controls
- EMI/RFI test levels
- Digital ICHMI architectures
- Digital system-specific technical specifications that take advantage of the capabilities made possible by digital technology.

Examples of some of the opportunities for enhanced functionality and reductions in O&M costs being addressed by EPRI include the following:

- On-line monitoring for calibration interval extension
- On-line monitoring, early fault detection, diagnostics, and prognostics
- Wireless technology
- Fleet-based and centralized monitoring and diagnostics support
- Simplification of the ICHMI architecture to reduce the amount of equipment needed
- Increased use of standardization and automation
- Use of smart field devices for control and diagnostics
- Improved access and analysis to real-time plant data and other data to enhance performance
- Effective simulation and modeling for improved designs and training
- Better use of information technology and visualization.

Through input to the NEI Digital ICHMI and Human Factors Working Group, EPRI provides the technical basis to address generically regulatory issues for modernizing operating plants and for new plant combined construction and licensing (COL) applications. Providing this

technical basis, in some cases, will require new RD&D activities.

6.4 Basic Science

As the nuclear power community looks to advanced systems (NGNP and Gen IV), new operating conditions and materials will be encountered. Developing a more basic science activity in sensors, sensors materials, and applications in harsh environments is needed to demonstrate sensors and measurement technologies that provide data required to validate advanced simulations for new systems.

A wider community already exists that is addressing fundamental sensor and other issues associated with deployments in harsh environments. To support the activities of DOE-NE, the DOE-Office of Science is looking at possible opportunities. There is growing interest in more fundamental science programs that will support the technology programs being developed by DOE-NE. Details for this are still being developed, but potential exists for research that can support all DOE advanced reactor programs (Gen IV, NGNP, and GNEP) and provide opportunities to engage a wider talent base outside that with current links to nuclear programs. One example is the National Science Foundation's (NSF's) work to establish cooperative activities in materials research between U.S. investigators and their counterparts abroad (NSF 2006). These activities form an element in the emerging "Materials World Network" with priority interests including high-performance structural ceramics and high-performance structural composites, both of which are relevant to Gen IV materials and ICHMI needs.

6.5 IAEA

The activities of the IAEA Nuclear Power Division provide a forum for information exchange and document development that reports best practices and fosters international exchanges. Activities include a Technical Working Group on NPP Control and Instrumentation, the 21st meeting of which will be held May 2007. A recent draft IAEA Report has also addressed the "Potential for sharing nuclear power infrastructure between countries" (IAEA, 2006). Opportunities exist for

the U.S. to participate and for the U.S. ICHMI community to leverage these on-going activities.

6.6 Global Digital ICHMI and Advanced Control Room Experience

Advanced Digital ICHMI has received significant attention in other countries. For example, a digital ICHMI system for a nuclear power plant has been reported as operating with an advanced light water reactor simulator since 1995. Mitsubishi has recently announced an advanced integrated digital control system for nuclear power plants derived from this effort (Mitsubishi 2006). It is equipped with four 100-inch front panels and designed to enable just one operator to handle the system. This system is planned for deployment to the Hokkaido Electric Power Co., No. 3 Tomari plant and to be operational in December 2009. The level of advanced functionality to be delivered is not yet fully known.

Earlier experience at the Lungmen NPP, which has modern ICHMI and control room, has now been reported openly in the literature (Chuang and Chou 2005). Organizations including the Halden Project, Norway, have developed control room simulators for advanced NPPs. However, no advanced digital control room simulator system for an NPP is currently available in the U.S. Other industries in the U.S. are developing and deploying automated chemical process control systems using digital systems. Guidelines for such systems are well established (CCPS 1993).

Opportunities exist to leverage GIF partner capabilities, including major efforts in ICHMI in South Korea, through Gen IV, I-NERI and GNEP, to leverage experience. Major sensor challenges remain to be addressed for the harsh environments in NGNP and other Gen IV systems, systems needed to support GNEP, as well as the associated

systems for delivery of both hydrogen and process heat.

6.7 Standards Community

The Institution of Electronic and Electrical Engineers (IEEE), International Electrotechnical Commission (IEC), and other organizations are working to develop a new generation of codes and standards for both the new systems and advanced digital ICHMI systems. The U.S. is strongly engaged and opportunities exist to participate in the development of guides, codes, and standards which incorporate and leverage global best practice.

6.8 System Health and Wider ICHMI Community

There is a growing technical community studying “system health monitoring” and better prediction of plant/system life and remaining life. Opportunities exist to leverage and build on earlier efforts in GIF and other countries, such as the aging materials evaluation and studies by non-destructive techniques (AMES-NDT) – a European network Project focused on NPP needs (Dobmann et al. 2001). There is also a diverse range of material aging, structural health monitoring, and damage mechanics investigations in gas turbine and other communities outside the nuclear power community (Larsen et al. 2005, Chang 2003, Pusey 2005). The wider material aging and degradation, system structural health, and machinery monitoring efforts in the U.S. are receiving extensive support from activities that include DARPA, the DOD (Army, Navy, Air Force), and NASA.

In looking to better life-prediction capabilities, the state of technology outside the nuclear community has recently been assessed and is summarized as Table 6-1 (Howard 2005). Opportunities exist for the nuclear community to leverage these existing and emerging capabilities.

Table 6-1. Diagnostic (D) and prognostic (P) technology maturity matrix.

Technology Classification	AP	A	I	NO
Basic Machinery (motors, pumps, generators, etc.)	D		P	
Complex Machinery (Helicopter Gearboxes, etc.)		D	P	
Metal Structures	D		P	
Composite Structures			D&P	
Electronic Power Supplies (Low Power)		D	P	
Avionics and Controls Electronics	D		P	
Medium Power Electronics (Radar, etc.)		D		P
High Power Electronics (Electric Propulsion, etc.)				D&P

AP – technology currently available and proven effective
A – technology currently available, but V&V not completed
I – technology in process, but not completely ready for V&V
NO – no significant technology development in place

7. CONCLUSION

The objective of this report is to illustrate the essential role that Instrumentation, Controls, and Human-Machine Interface (ICHMI) technology will play in the RD&D of advanced NPPs. Numerous issues have been discussed which currently present barriers for realizing the potential gains for integrating new ICHMI technologies. More precisely, this report has identified a variety of specific program needs and goals related to ICHMI, predicted challenges to the accomplishment of the goals, and described the technological needs and innovations necessary to overcome these challenges.

Related to these programmatic needs, the roadmap establishes a comprehensive program plan for RD&D activities to provide the necessary technological advances that will enable the goals to be fulfilled. ICHMI technologies are dynamic and often driven by other industries outside the nuclear field. This document is an initial effort to capture dynamic requirements that will need revision as NGNP, GNEP, and Gen IV activities develop.

The overarching goal of an ICHMI roadmapping effort, of which the present project represents the initial phase, is reinvigoration of the U.S. nuclear ICHMI community and capabilities. This reinvigoration will occur through the creation of a dynamic ICHMI technology development plan and program that enables and maximizes the performance of Gen IV nuclear power plants while minimizing ICHMI system potentials that impede their design, construction, and operation.

This initial document has the following programmatic goals:

- Establish a DOE-led crosscut program in Instrumentation, Control, and Human-machine Interaction
- Support programmatic objectives of the Gen IV development program and NGNP
- Support the reactor concept selection and demonstration process by providing ICHMI performance trade-off analysis

- Optimize resource usage leveraging, and coordinate crosscut needs while avoiding duplication between related ICHMI efforts
- Provide a programmatic path forward for the research and development of supporting ICHMI technologies needed for realization of Gen IV and NGNP.

Key elements of success. In order to meet the above programmatic goals and develop an effective Gen IV program, the ICHMI activities must accomplish the following tasks:

- Integrate and coordinate with program schedule and milestones for the other Gen IV-focused development areas
- Leverage international activities and existing infrastructure outside of the existing Generation IV International Forum (GIF) collaborations
- Coordinate performance of common research among all initiatives.

Selection and scheduling of focused ICHMI activities should be tied to critical stages for NGNP and provide programmatic support in one or more of the following ways:

- Address critical parameters and processes
- Provide simulation to support design decisions and the construction planning process
- Evaluate mature technologies within other application areas for use in nuclear power plants, including addressing issues relevant to U.S. NRC technology acceptance
- Explore emerging technologies for beneficial application in the plant and similar U.S. NRC acceptance
- Engage vendors and end users in design, development, and evaluation of ICHMI technologies

- Link to other DOE and/or related industry programs to leverage concurrent research, development, and evaluation activities.

The ICHMI RD&D roadmap provides a plan that, if implemented, reduces the possibility of future plants being limited to obsolete, low-functionality, labor-intensive ICHMI technology due to lack of technological maturity or licenseability. Further, ICHMI RD&D enables other advanced nuclear power plant technologies, including improved sensors and monitoring to achieve higher fuel burn up and stable operation at higher temperature, increased use of automation and modern control rooms to reduce staffing, and greater use of information to enable fleet-wide asset management programs.

The following is a summary of the proposed deliverables for this project, not necessarily for this initial effort but for the crosscut program:

- A prioritized plan for technical activities and programs to support conceptual design decisions associated with instrumentation, controls, and human-machine interaction
- Development of ICHMI design specifications
- Preparation of request for proposal for instrumentation systems, controls systems, and human interface systems in support of the nuclear system, hydrogen production facility, power conversion, energy transfer, operations, and licensing
- Completion of the conceptual design and trade-off analysis studies based on prototype requirements specifications
- Licensing strategy and technological review methodology
- Acquisitions strategy support for ICHMI.

ICHMI Roadmap Deliverables

- *Prioritized plan of ICHMI technical activities and programs*
- *Conceptual design and trade-off analysis studies*
- *ICHMI design specifications*
- *Preparation of request for proposal for instrumentation systems, controls systems, and human interface systems for advanced nuclear facilities*
- *Licensing strategy and technological review methodology*
- *Acquisitions strategy support for ICHMI systems*


ICHMI Funding Priorities

- *Crosscut ICHMI program Establishment*
- *Harsh Environment Tolerant Sensor Project*
- *Regulatory Basis Development for NGNP ICHMI Technologies Project*
- *NGNP Operational Concept Development Project (Demonstration and Deployment)*
- *NGNP ICHMI Architecture Development Project*
- *ICHMI Technology Assessment and Gap Analysis Project*

8. ACRONYMS

AMES-NDT	aging materials evaluation and studies by non-destructive techniques
ATR	Advanced Test Reactor
CBM	condition-based maintenance
CCPS	Center for Chemical Process Safety
COL	combined operating license
CROW	Control Room Operator Workstation
DAC	Design Acceptance Criteria
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
DOE	Department of Energy
DOE-NE	Department of Energy Office of Nuclear Energy, Science, and Technology
EDF	Électricité de France
EMI	electro-magnetic interference
EPAC	Energy Policy Advisory Committee
EPRI	Electric Power Research Institute
ESFAS	engineered safety feature actuation system
FY	fiscal year
Gen III+	Generation III+ (nuclear energy systems)
Gen IV	Generation IV (nuclear energy systems)
GIF	Generation IV International Forum
GNEP	Global Nuclear Energy Partnership
GT-MHR	Gas Turbine-Modular Helium Reactor
HFE	Human Factors Engineering
HMI	human-machine interface
HRA	human reliability analysis

HSI	human system interface
IAC	ICHMI Advisory Committee
IAEA	International Atomic Energy Agency
ICHMI	Instrumentation, Controls, and Human-Machine Interface
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
I-NERI	International Nuclear Energy Research Initiative
INL	Idaho National Laboratory
IRPM	ICHMI RD&D Program Manager
IT	information technology
ITAAC	Inspection Testing Analysis and Acceptance Criteria
JNT	Johnson noise thermometry
LER	Licensee Event Report
LWR	light water reactor
MHTGR	Modular High-Temperature Gas-Cooled Reactor
NEI	Nuclear Energy Institute
NERI	Nuclear Energy Research Initiative
NGNP	Next Generation Nuclear Plant
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NSF	National Science Foundation
NTD	National Technical Director
NUREG	Nuclear Regulatory Commission Report
O&M	operation and maintenance
OEM	original equipment manufacturer
PC	personal computer



PRA	probabilistic risk assessment
PBMR	Pebble Bed Modular Reactor
R&D	research and development
RD&D	research, development, and demonstration
RFI	radio frequency interference
RPS	reactor protection system
SPDS	Safety Parameter Display System
SRP	Standard Review Plan
U.S. NRC	United States Nuclear Regulatory Commission
V&V	verification and validation
VHTR	Very High Temperature Reactor
WG	working group



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Appendix A
ICHMI Functional Overview



Appendix A

ICHMI Functional Overview

A final Gen IV reactor design has not been selected for full development in the U.S., yet this report proposes the establishment of research in ICHMI technologies. To understand the urgency of the request for ICHMI research, it is important to understand what an ICHMI system consists of and what it contributes to the achievement of the goals for the Gen IV program.

The field of ICHMI technologies is broad and varied. To facilitate an understanding of the scope covered by this roadmap, Figure A-1 illustrates the relationship of ICHMI components addressed in this report. The left side of the sphere represents technologies that are *function focused* and address the capabilities that embody the sensing, communications, monitoring, control, and presentation and command systems between

the process (the reactor, heat transport, and energy conversion systems) and the plant personnel (operations and maintenance staff). The right side of the sphere represents instrumentation and is *equipment focused*. It is comprised of the measurement string from the sensors and signal processing elements to the diagnostic modules and controllers (computational platforms) and on to actuation devices.

The variety of technologies that constitute the ICHMI systems of a nuclear power plant can be difficult to address as a whole because of the depth and breadth of the discipline, or, more precisely, disciplines. Therefore, the tactic frequently taken in addressing ICHMI is to approach the technology in terms of more manageable and segmented focus areas. In



Figure A-1. The ICHMI scope addressed in this roadmap.

addition to the plant-focused technologies, ICHMI also includes technical fields, such as human factors, information management, simulation, software engineering, system integration, probabilistic risk assessment, prognostics, and cyber security.

The ICHMI system, together with plant personnel, is in effect the “central nervous system,” (see Figure A-2) the senses and brain for the plant. The ICHMI, through subsystems, senses basic parameters, monitors performance and system health, integrates information, and makes adjustments to plant operations as necessary. It also responds to failures and off-normal events, thus ensuring goals of efficient power production and safety.

A simplified, functional overview of an ICHMI system is provided below:

- Sensor subsystems: Nearly every aspect of plant processes use some form of physical measurement. These physical measurements take the form of sensors and instruments with signal conditioning that detect physical parameters in the plant, such as neutron flux,

temperatures, pressures, flow, valve positions, electrical current levels, and radiation levels. New nuclear energy production technologies will require new and different types of sensors and instruments to measure physical processes. This includes sensors that will be required to work in high-temperature environments and measure process parameters that are quite different from those measured in light water reactors (LWRs) in operation today.

- Monitoring subsystems: These subsystems monitor the signals and other information produced by sensors and evaluate that information to determine whether and what type of response may be needed. They can contain sophisticated diagnostic and prognostic functions. Diagnostics refers to techniques for identifying and determining the causes of deviations or faults in the plant systems or processes. Prognostics refers to methods for using sensor data to estimate the rate of physical degradation and the remaining useful life of equipment, predicting time to failure, and applying this

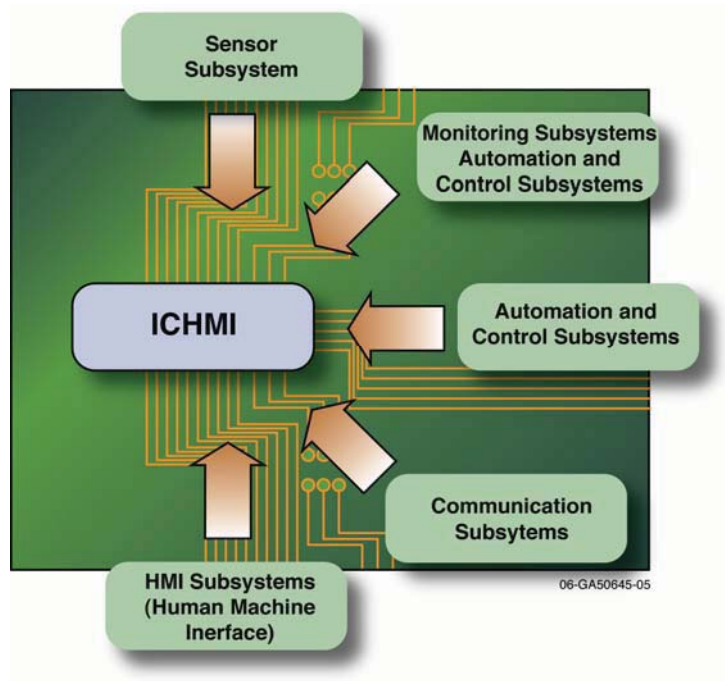


Figure A-2. ICHMI subsystems that, together with plant personnel, make up the “central nervous system” of the nuclear power plant.

information to more effectively manage a facility's assets and to schedule maintenance on an as-needed basis.

- Automation and Control subsystems: Digital control systems provide the capability to implement more advanced control algorithms than those that have been used in U.S. nuclear power plants to date. Current plants rely primarily on single-input, single-output, classical control schemes to automate individual control loops. Advanced control schemes include matrix techniques for optimal control, nonlinear control methods, fuzzy logic, neural networks, adaptive control (a control that modifies its behavior based on plant dynamics), expert systems, state-based control schemes, and schemes that combine multiple control methods in a multimode or hierarchical system to achieve optimum performance. Application of these advanced techniques will lead to more integrated control of plant systems and processes (versus separate, non-interacting control loops) and greater complexity. More modern control systems also provide the capability of more interaction and cooperation between automation and personnel, which essentially makes "man and machine" team players in the accomplishment of plant control functions.
- Communications subsystems: Information flow throughout the ICHMI system and to devices being monitored and controlled is provided through a variety of communication systems that may include wireless technology. A classical ICHMI architecture provides point-to-point wiring of measured variables to the monitoring and control systems. The communications subsystems for a modern ICHMI are configured in a flexible network architecture and have greatly expanded functionality, increasing the effectiveness of plant maintenance by providing field access to instruction manuals and diagnostics, enabling "smart" transducers to signal their service condition to the plant engineering staff.
- HMI subsystem: Plant personnel monitor and control the plant using resources such as

information displays, alarms, controls, and support systems (including diagnostic and prognostic information). These systems work with personnel to help them understand the plant's condition and diagnostic problems and to help them take necessary actions.

Figure A-3 illustrates how the ICHMI subsystems fit within the context of system operations. In the midst of information and digital technology growth, these systems represent some of the greatest potentials for advancement in functionality, reliability, and processes within plant operations.

Advanced ICHMI systems enable precise monitoring of plant performance, thus providing better data to plant control systems. The ICHMI system enables plant personnel to more effectively monitor the health of the plant, identify opportunities to improve the performance of equipment and systems, and anticipate, understand, and respond to potential issues and problems. Improved controls provide the basis for optimized performance, operating more closely to performance margins, and the improved integration of automatic and human response enables them to work cooperatively in the accomplishment of both production and safety goals. The ICHMI system also monitors the plant processes and various barriers that prevent potential release of radioactive material to the public. The use of advanced ICHMI systems directly impacts the performance of the entire plant and, consequently, the economics, safety, and security of future reactor designs as well.

Many new nuclear power plant designs have significant passive aspects, but even for these new plants, much of the overall ICHMI architecture can be designed to be applicable to a variety of reactor types. Thus, an opportunity exists to define ICHMI goals that will ensure the best "central nervous system" for Gen IV and NNGP programs, utilizing an integrated, adaptable operating system that takes advantages of the latest technology. This technology roadmap identifies goals and implementation issues for developing ICHMI systems that evolve alongside NPP operations.

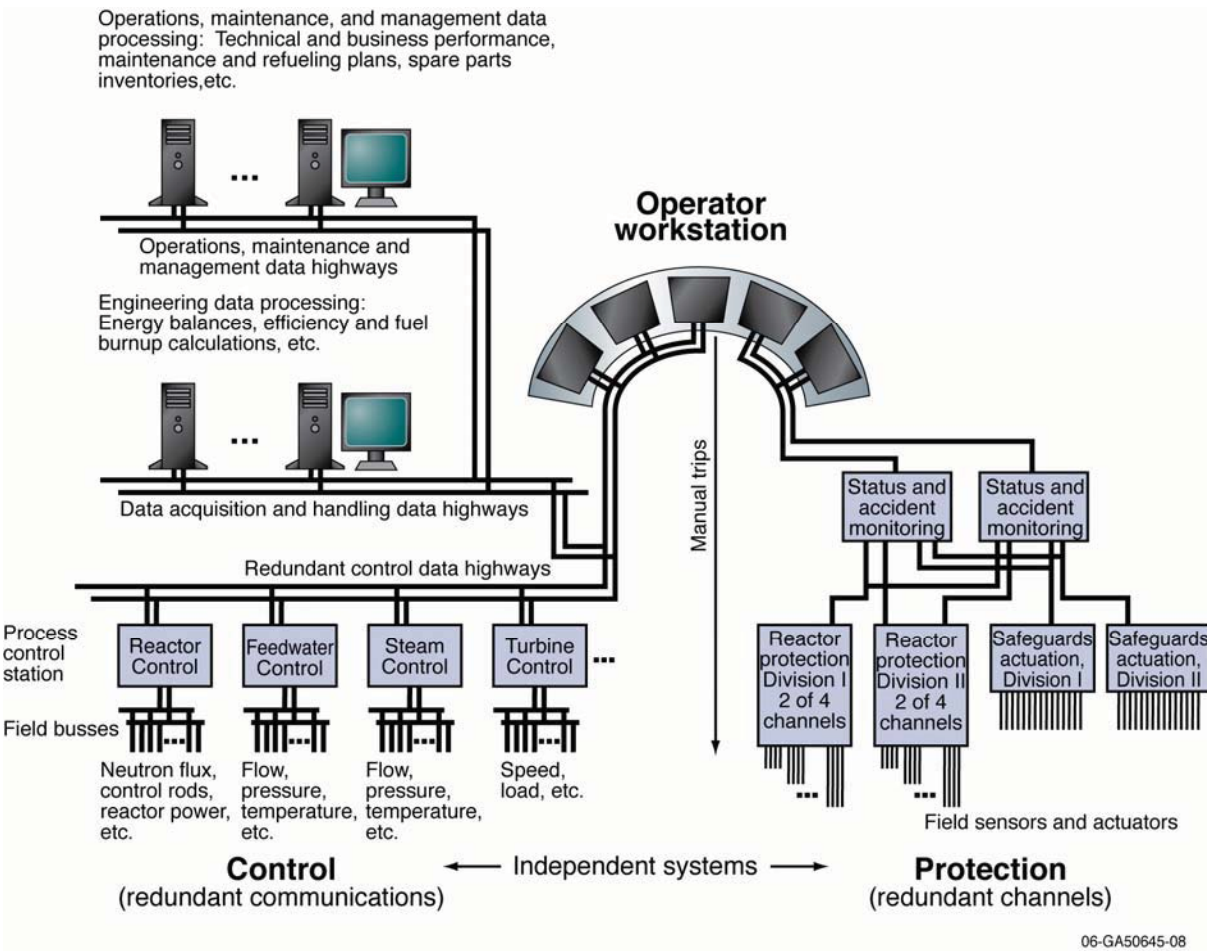


Figure A-3. Illustration of nuclear power plant ICHMI system (National Research Council 1997).



Appendix B

Operations



Appendix B

Operations

B-1. GOALS

The overall goal of the Operations framework is to maximize and ensure the economic competitiveness of Gen IV and NGNP nuclear plants. Operating nuclear power plants to economically and safely produce electricity throughout the plant's lifetime is the chief function of the nuclear power industry. The net cost of power from present generation nuclear power plants is already competitive with (or lower than) that from other generators. The largest component of the day-to-day cost of nuclear power generation in plants today and Gen IV plants is operations and maintenance (O&M), which is dominated by plant staffing costs. This contrasts dramatically with fossil fuel power plants where the quotidian costs are primarily from fuel. Therefore, operational efficiencies in areas such as maintenance and security are proportionally more important to the nuclear power industry.

B-2. CHALLENGES

Conditions that could challenge the achievement of optimal plant operation include an ICHMI design and operational approach that does not efficiently employ staff and also limits plant availability and the learning process involved with nontraditional modes and configurations of plant operation.

B-2.1 Optimized Staffing

The numerator of the net plant cost to watts generated ratio contains plant operational cost. Plant operational cost is traditionally subdivided into fuel, replacement equipment/materials, and personnel costs. While ICHMI has only a small impact on fuel costs, it can have a significant impact on equipment and materials costs through process monitoring and component health monitoring that extends equipment lifetimes by maintaining operations within design limits.

ICHMI's primary impact on operational cost, however, is by amplifying the capabilities of each member of the plant staff. Improved ICHMI has been progressively driving down plant staffing levels and costs from two persons per megawatt towards one-half person per megawatt. In Gen IV and multiunit NGNP deployments, this ratio is planned to be further reduced largely through more intelligent instrumentation supporting widespread plant prognostics and online component health monitoring, ubiquitous information networking, and optimized human-machine interaction design enabling maintenance staff to proactively address equipment maintenance issues before they impact plant operations.

B-2.2 Achieving High Plant Availability

Achieving high plant availability (>95%) is required to make the economic case for Gen IV plants. LWR plant availability has increased steadily for the past 25 years in the U.S., to the point where unplanned trips are rare events and the refueling outage length tends to be limited by fuel and major component manipulation. Even so, of the remaining unplanned trip events, roughly one-third of the remaining trips are related to ICHMI. Acquiring the experience necessary to achieve this level of availability has taken many years of concerted effort by financially motivated utilities. The NGNP will have a significantly different technology suite than existing LWRs. Avoiding the multiyear learning curve required to achieve and optimally operate the new technologies is a principal challenge for the NGNP. Achieving and maintaining the high level of availability will be further challenged as a significant number of new plants are built, spreading the available skill base across a significantly larger market. Optimally leveraging the existing staff skills will depend on the availability of process instrumentation

automation, enhanced online condition monitoring, and self-diagnostics.

B-2.3 Operation of New Plant Designs

Gen IV plants will employ nontraditional plant configurations with different ICHMI staff operating roles that support plant applications beyond base load electricity generation. The new technologies have not had the benefit of many years of operational experience and, therefore, have the potential to require significant learning periods to achieve efficient levels of operation. Smaller, non-LWR plants will require a different operational regime with smaller operational and overall staffing levels per reactor in order to be profitable, including the ability to run in a multi-reactor arrangement under a single control center. Operating several reactors as a single plant has been authorized under the Energy Policy Act of 2005 as part of the revised Price-Anderson Act, which defines a plant as a multi-unit configuration with up to ten individual elements. Multi-reactor control grouping has never been done before in a nuclear plant, in the terms of either licensing or operational space.

A revised control room configuration and operational control process is inherent in this type of multi-reactor control grouping to ensure that personnel remain aware of the overall status of the plant. This will require alarm and information presentation concepts that are different from modern plants. In addition, new control approaches and increases in automation and human-automation cooperation will require new HMI concepts.

Current licensing under 10 CFR 50 requires individual control of a single unit in a regime that is covered under NUREG 0737 and associated procedures for normal, abnormal, and emergency operations, with associated required instrumentation indications available for decision making in accordance with the procedures. Gen IV plant operation will require an operational regime that is different and will accordingly require an update to the NRC's regulations. Additionally, the new plant designs are intended

to be able to support additional products other than base-load electricity generation. Both different ICHMI technology and concepts of operation will be required to support the different balance-of-plant systems that may be employed.

B-2.4 Optimized Maintenance

Improved approaches to maintenance will be required for Gen IV plants in order to provide operational and economic efficiencies. ICHMI technologies will provide an important basis for realizing these efficiencies. Online condition-based monitoring, diagnostic, and prognostic systems can provide timely information to help identify the need for maintenance interventions at an appropriate time to enable the allocation of maintenance resources in an efficient manner. The analysis tools, including on-line condition monitoring, diagnostic, and prognostic functions, provided by these capabilities can reduce the time needed to troubleshoot problems, identify corrective actions and improve plant safety through reduced PRA. Integration of maintenance information provided by these systems into maintenance workstations will fundamentally change the way maintenance staff monitor the plant's systems and components and perform their tasks.

B-3. NEEDS

Achieving the high plant availability with minimized operational costs requires development and introduction of a significant amount of improved technology. This section adumbrates the general technology development needs, which are then fleshed out into a technology development plan in the roadmap chapter of that name.

The key to achieving efficient plant operation and effective maintenance is to provide accurate knowledge of the processes involved in plant operation and the current status of the plant. Gen IV plants feature higher temperature processes to achieve higher plant thermal efficiencies and allow for process heat delivery and possible co-located hydrogen production. Higher temperatures are a primary instrument stressor, which effectively obsolesces much of the

established LWR instrumentation base, from temperature, to neutron flux, to position measurement. In addition, the chemically aggressive environments envisioned for some versions of hydrogen production require durable, reliable process monitoring instrumentation, which remains undeveloped. Moreover, to reduce the maintenance labor requirements per reactor, lower drift instruments that use inherent or easier calibration will be required in NGNPs. Smart instrumentation, including calibration and instrumentation self-diagnostics, appears more likely to necessitate reliable electronics in higher radiation areas than current plants. An additional intent of the aggressive environment-tolerant, high-accuracy process monitoring coupled with component health monitoring is to enable plant operation nearer component margins, maximizing the plant output while minimizing plant downtime and component replacement costs..

Plant component health information needs to be ubiquitous in Gen IV designs to support optimized maintenance scheduling and minimize nonproductive, information-access work by plant staff. This ubiquitous information access needs to be intelligently structured to support appropriate personnel actions and minimize human error rates and impacts and to incorporate lessons learned during plant operation. In addition, plant health and performance information needs to be accessible by offsite experts, both to ensure optimal response to abnormal conditions and to transfer lessons learned by one plant throughout the industry.

ICHMI technologies, particularly digital systems, have significantly shorter life cycles than the overall plant. Functional obsolescence is a continuing burden on the maintenance of current generation LWR plants. Hence, Gen IV ICHMI systems need to be considered in terms of functional modules and designed for easy replacement and upgrading (likely more than once) during the plant's lifetime. As ICHMI deployment costs dominate their capital costs, ease of installation with minimal cable pulling (e.g., through wireless connectivity) needs to be a prominent system feature. Part of the requirements for ease of upgrade and replacement design includes system design requirements and

intents into the plant information system. Maintaining compliance with the original plant design requirements reduces the regulatory oversight burden imposed by subsequent modifications and preserves all aspects of the original system functionality.

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Appendix C
Operating Environment



Appendix C

Operating Environment

C-1. GOALS

Generation IV reactor configurations that are being considered present different and more challenging environmental conditions than encountered in the current U.S. fleet of 104 Light Water Reactors (LWRs). These operating environmental challenges are a consequence of proposed operation at much higher temperatures than found in the plants in the current operating fleet. For example, the Gas Turbine-Modular Helium Reactor (GT-MHR) will have an operational temperature of approximately 1000°C as compared to 300°C in LWRs in currently operating plants. Temperatures of this magnitude pose significant challenges to components and personnel, especially radiation protection. The GT-MHR also uses helium gas coolant and graphite moderation rather than water, which provides both cooling and moderation. Other Gen IV systems use sodium coolant (fast reactor) or high-temperature light water (light water super critical reactor). These two reactor types present different, but no less challenging, environmental problems. Both present challenges in maintaining thermal margins and extreme environmental conditions.

To address new ICHMI challenges prompted by these new environmental conditions, RD&D efforts should be immediately initiated as several years will be required to design, test, and qualify components for operation in harsh environments, such as those present in many Gen IV reactor concepts. Simultaneously, standards comparable to IEEE 323, IEEE 344, and NRC guidance, such as the Standard Review Plan (Chapter 7 of NUREG 0800), must be modified to meet the Gen IV and NGNP operational and environmental parameters. All these activities require time to complete and should begin in the near future to prevent ICHMI issues from becoming critical path items. Currently, the investment required by industry to determine the needed changes in the qualification envelope, as required by NRC

guidelines, is too high to justify the investment and up-front capital necessary to complete the analyses. In addition, the initial application will be for a single demonstration unit. The business case for changes to the design, production line, and commercial service offerings for a new product like this is not currently justified. This rationale presents a strong basis for increased DOE sponsored research and development at this stage, early in the demonstration development, so that industry may participate in a prudent manner, paving the way for future deployment of full-scope commercial systems and components that meet the modified qualification envelope.

Specific goals for developing the operating environment include the following:

- Ensuring investment protection by maintaining plant thermal margins and optimizing capital equipment utilization (capital cost recovery)
- Supporting reactor concepts characterized by more extreme environmental conditions
- Reducing personnel radiation exposure.

C-1.1 Challenges

There are several challenges in developing the operating environment, such as supporting increased component lifetimes and extended ICHMI system service intervals and establishing compatibility with extreme environments. To complete commercialization of new technologies for application in the new operating and design-basis envelope for the Gen IV designs, multiple steps are required for analysis and testing, which are necessary to both approve the limits and establish commercial viability of acceptable product standards and specifications.

The first step is analysis of the required design-basis envelope for the expected worst-case

installation at a range of locations in the Gen IV plant. This is consistent with how the current fleet of plants completed the Environmental Qualification process. The establishment of these “harsh environmental limits” and “mild environmental limits” per 10 CFR 50.49 provides the basis for new equipment to be designed and tested. Close coordination between the research and development agency and the NRC research personnel will allow the industry standards to be developed in close coordination with the NRC regulation or regulation changes, necessary to provide a clear roadmap and guideline for applicants to follow in future commercial docketed applications for Gen IV reactor deployments.

After the required harsh and mild environments have been established for the Gen IV design, the required sensors and associated instrument and computer components can be evaluated and tested in accordance with the testing requirements of IEEE 323 and IEEE 344 for environmental and seismic acceptability. A similar process was performed under the leadership of EPRI for the currently deployed fleet of reactors, in applying EPRI TR-107330, Qualification of Commercial Grade Instrumentation and Control Equipment for Nuclear Safety-Related Applications. This process was tested on three sets of commercially available vendor equipment (i.e., Westinghouse, Framatome, and Triconex) with an application to the NRC for a generic Safety Evaluation Report covering the approval of the equipment for installation in safety-related systems within specific limitations. The difference between the EPRI TR-107330 demonstrations and the Gen IV RD&D required goals is that the commercial benefit of qualifying under the EPRI TR-107330 could be immediately demonstrated and applied to a number of potential customers. This is not the case for the Gen IV design, where the ultimate commercial sales will not occur for 10 to 15 years for multiple orders. Additional information on this subject is included in Section 4.4, Minimize Financial Risk, in the body of this report.

Gen IV goals require operational parameters significantly different than current LWRs, in that the environmental qualification and operational

processes have different moderator and control schemes. In addition, system safety-related and non-safety-related classifications differ from those currently covered in NUREG 0800, Standard Review Plan, which has a much smaller number of systems and subsystems that need to be classified as safety-related to support Gen IV plant operations. Also, IEEE 323 (IEC 60780) and IEEE 344 (IEC 60980) qualification envelope requires modifications for the Gen IV operational parameters and timeframes.

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Appendix D
Regulatory and Licensing Process



Appendix D

Regulatory and Licensing Process

D-1. GOALS

The regulatory and licensing process is a significant consideration in bringing new plants online. For the U.S. nuclear power industry to be successful, a strong, knowledgeable, and effective regulator is essential. The current regulatory framework for licensing nuclear power plants, including licensing of instrumentation, control and protection systems, and human factors engineering in nuclear power plants, has evolved significantly since the first nuclear power plants were licensed. The most recent updates to the regulatory framework are the 1997 revision of Chapter 7, Instrumentation and Control, of the Standard Review Plan (SRP) (NUREG-0800) and the 2004 revision of Chapter 18 “Human Factors Engineering” of the SRP. Although these updates incorporated the most up-to-date technical information available at the time, they did not include new methods or strategies needed to support Gen IV control, instrumentation, and protections systems or optimize the licensing on innovated digital systems that will be found in future nuclear power plants.

The Nuclear Regulatory Commission (NRC) is currently working to update the SRP and a significant number of Regulatory Guides in all areas, to support the first round of licensing of new nuclear power plants. To meet the deadlines associated with being prepared to complete the licensing review for these plants, this effort will only update most critical regulatory issues and will not optimize the current regulatory framework or look to include any Gen IV issues. The goals of the forward-looking research program are to provide the technical bases for the NRC to update its regulatory framework for instrumentation, control and protection systems, and human factors engineering to support an effective and predictable licensing that accomplishes the following:

- Ensures safety and regulatory compliance

- Permits licensing of optimized ICHMI and HFE solutions
- Ensures the ICHMI and HFR licensing does not become an impediment to meeting Gen IV goals.

D-2. CHALLENGES

There are several aspects of the regulatory framework that will be especially important to address when looking forward to a new generation of reactors. New plants will be licensed under a new regulatory process (10 CFR Part 52) that has not been fully implemented yet. ICHMI aspects of the design certification reviews were based largely on process rather than design; thus, Design Acceptance Criteria (DAC) were used. DAC are a form of ITAAC that address the design process rather than the specific aspects of the design itself. This means that a considerable amount of effort remains after certification. ICHMI aspects of the plant present unique challenges to safety reviews, meaning the rapid development of computer-based and software systems makes them a moving target that has to be accommodated during the process of review.

The wording of the current regulations and safety review guidance often reflects LWR technology. Thus, changes will be needed to address non-LWR designs. In addition, the regulations and safety review guidance reflect current concepts of operations used in today's plants. For example, the current definition of crewmember roles and responsibilities reflect the staffing approaches used in older, less automated plants. Another example is that safety monitoring reflects current approaches and LWR technology, such as in the requirements for the SPDS. New plants are likely to employ new concepts of operation and new technology implementations (as is discussed elsewhere in this document) that may not fit the current review criteria.

The ICHMI review process and its guidance may have to be modified to accommodate new design and evaluation approaches, such as the use of human performance modeling for HSI evaluation in place of data collected from actual operations crews. The current review guidance is based on a systems engineering process that itself is changing as new design and evaluation methods and tools become available.

Traditional controls and monitoring approaches provide an adequate basis for preliminary investigations into multi-modular architectural requirements. However, when one considers required unit-level, safety-related, and control instrumentation, the potential for innumerable combinations of equipment and related operational requirements quickly becomes apparent. In concept, although this problem can be mitigated by the clever use of automated digital systems, use of computers in safety-related systems introduces a new set of challenges that must be considered, such as common mode failure. As a consequence, a high-priority instrumentation issue is the need for a grass-roots, synergistic approach to the design of an ICHMI system for a multiunit nuclear power plant, which involves consideration of control, instrumentation, and the regulations that apply to safety-related instrumentation systems. To best address this challenge, consider the following Gen IV plant configuration:

- The nuclear plant is comprised of 8 units at 150 MWe each, equaling 1200 MWe
- Each unit is independently controlled and operated
- Each unit has 10 reactor protection system (RPS) variables and 10 emergency safety features actuation system (ESFAS) variables
- The plant has a common plant control room
- The plant has a limited sharing of plant turbine generators or gas turbines and feedwater systems.

If we assume that each physical variable requires quadruple redundancy (some may require

triple redundancy) then the entire plant could require as many as 640 safety-related channels. Each channel would have to meet 10 CFR 50, Appendix B, requirements, in terms of qualification of equipment and operational maintenance, such as setpoint analysis.

In the current regulations, significant challenges exist that allow a reduction in the number of safety-related channels in this configuration. GDC5 is the top-tier criterion for shared systems between units but does not give any details other than a scram from one unit (shared system initiator) cannot prevent an orderly shutdown of the other units. IEEE 603, paragraph 5.13 gives a few details on shared systems and points out that the ability to simultaneously perform the required safety functions in all units must not be impaired. It also references IEEE 308 for the shared power systems criteria and also IEEE 379 for the active single-failure criteria. The goal should be to take advantage of the shared systems by reducing the number of components and ICHMI systems as much as possible without reducing operational safety and reliability. Certain shared sensors may be able to be deleted if spatial considerations are still met along with divisional and train independence and separation (IEEE 384).

The safety classification of systems for current LWR designs is not appropriate for the Gen IV designs with revised safety and accident analysis. Currently NUREG 0800 Chapter 7 defines criteria for safety-related systems that apply to LWR but should not be applicable for a reactor design that cannot melt. The most recent experience in licensing the Gen IV design occurred in the 1980's and ended in the early 1990's for the Modular Helium Temperature Gas Reactor MHTGR, which was reviewed by NRC who completed the Safety Evaluation Report. This report included recommendations to the NRC Commission from staff on acceptability of the design and open items and issues that would require NRC Commission review and approval. One of the main open issues in the ICHMI design related to the classification of systems and components and the need for the Control Room Operator Workstation (CROW) is to have a safety-related function and scram switch in the

event of required operator action. The designation of additional safety-related systems requires the backup power and all associated environmental and safety criteria to be met. The challenge is to designate safety-related systems and components only where the safety-criteria of 10 CFR 50 or 52 applies.

D-3. NEEDS

The regulatory challenges noted above give rise to needed RD&D, such as the following:

- Establish common, accepted approaches to completing DAC so that each proposed design is not addressed with a unique licensing approach
- Support the development of a review process that accommodates the unique characteristics of ICHMI systems
- Establish methods for demonstrating necessary and sufficient conditions for obtaining license and demonstrating compliance
- Support the development of safety review guidance that supports a diverse concept of operations and technology more amenable of Generation IV plants
- Support the development of safety review approaches that accommodate and are based on new design and evaluation approaches
- Support the development of a technology neutral risk informed framework and formal acceptance criteria for risk contributions of ICHMI systems.

Addressing these needs will provide the technical basis from which the regulatory review guidance can be developed to meet them. The availability of this review guidance will help set clear expectations for how the NRC staff will evaluate new designs, reduce regulatory uncertainty, and provide a well-defined path to new reactor licensing.

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Appendix E
Investment and Economics



Appendix E

Investment and Economics

E-1. GOALS

The primary challenge facing new nuclear generation of any kind is related to capital investment versus other types of power generation. Nuclear and coal have similar profiles for the high level of investment required for construction. Natural gas, for example, has a lower level of required investment at the beginning of plant development but a much higher relative fuel cost over the lifetime of the plant. In order to enhance the competitiveness of the nuclear option, particularly for the Gen IV or NNGP, it will be necessary to achieve a number of key goals:

- Reduce construction costs (decrease cable runs and speed up acceptance of construction)
- Decrease lifecycle costs (allow for upgrading and standardization)
- Enable optimized operations by bringing improved technologies to commercial maturity
- Provide investment protection.

E-2. CHALLENGES

Conditions that could challenge the achievement of competitive investment for the Gen IV nuclear option are the costs of cable installation, higher lifecycle costs for nuclear ICHMI components, high threshold for market entry of new and improved components, and systems and investment protection for ICHMI systems and components.

E-2.1 High Initial Cost for Cable Installations and ICHMI Components

Current cable runs cost approximately \$1000 to \$2000 per foot for safety-related cable installations at current plants. Though new plants are expected to be less expensive, costs will still be high because of the cost of configuration management. In addition, new cabling for power and control will be required to meet IEEE 384 electrical separation requirements associated with IEEE 603. As a result, the challenge is to reduce the cost of cable runs by optimizing the design and installation process as well as consider using wireless in cases where it is acceptable for use.

E-2.2 Higher Lifecycle Costs for Nuclear Components and Systems

As noted in EPRI 102348 Rev. 1, digital systems are subject to a more accelerated rate of functional obsolescence due to the rapid change in IT and ICHMI hardware in the entertainment and world communications and control markets. Current and future plant requirements are based on updating control system configuration every 5 to 10 years, and maximum flexibility in licensing safety and non-safety systems is required to meet operational requirements and to allow quick implementation of the latest industry advancements.

E-2.3 Prohibitively High Upfront Costs for Commercializing Technologies

A small number of digital orders to date have not presented the manufacturers (OEM's) with a sufficient amount of orders to allow RD&D budgets to be increased to meet future nuclear orders of a different type. In fact, actual nuclear

orders are less than 5% of OEM sales orders and are at risk for reduction based on lack of future market.

The primary issue in the Gen IV program, as relates to commercial deployment, is that potential customers will not invest in purchase of a complete operating plant of the Gen IV design, until a demonstration unit has been built and operated successfully, to justify or prove the business case for customer use and reliable production of the plant output products. This provides the strong justification for DOE sponsored RD&D that leads to ultimate deployment of the commercial reactor version of the Gen IV design after completion of the demonstration unit.

As a subset of the overall design, a significant number of instrumentation and control vendors are required to provide commercially available products that meet both the regulatory requirements and operator or user reliability requirements for safe and reliable operation and production of the plant's output products (e.g., electricity and hydrogen). These vendors are currently providing commercial equipment to the current fleet of 104 reactors in the U.S. and more than 330 reactors worldwide that are currently in operation. The Gen IV design in ICHMI for safety-system applications will require additional changes to the current product offerings in order to meet these goals and associated requirements. Because the estimate of operation of the demonstration unit is in the 2015 to 2020 timeframe, an insufficient amount justification is available for these vendors to upgrade the product line for Gen IV applications, when the orders will not occur for more than 10 years. This provides a strong rationale for DOE sponsored RD&D to support the demonstration unit with required qualified ICHMI equipment and the resultant standards and lessons learned for the vendors to be utilized in the commercial upgrades.

E-2.4 Investment Protection for ICHMI Systems and Components

Investment protection is a critical area in addressing asset management of both ICHMI

systems and those systems for which the ICHMI components monitor health and operability. Due to the high cost of replacement power, the initial investment in redundancy and relative reliability of ICHMI components and systems is justified by the business case. To optimize the life cycle costs, particularly in the reduction of unscheduled outages due to equipment failure, methods of investment protection in the form of control and protection features are critical to add during the design phase or as "lessons learned" become available after early operational experience has occurred.

With the technology improvements that have been made in ICHMI areas, significant enhancements in investment protection can be implemented to improve plant operational efficiency and reduce the potential for extended plant outages in order to recover from damaged equipment. Were this available in current designs, examples of the main turbine failures that occurred at the Salem and San Onofre plants in the 1990s and early 2000s would have been prevented, along with the expenditures of many tens of millions of dollars in both repair and replacement power costs.

E-3. NEEDS

In order to accomplish investment goals, the following needs should be met:

- Reduce relative construction costs for ICHMI system connections by configuration management optimization and using wireless connections where it is authorized for monitoring and control
- Decreased life cycle costs with implementation of life cycle management of installed components and systems
- Selection of highly reliable and industry supported equipment and platforms that are quickly and easily qualified for upgraded features and available for plant use in order to maintain the system at the latest technology levels where appropriate

- Protection regimes that address component, system, and plant availability optimization for the ICHMI systems
- Adopt functional modular design approaches.

Electric Power Research Institute, *Guideline on Licensing Digital Upgrades*, EPRI TR-102348, Revision 1, Electrical Power Research Institute, Washington, D.C., November 2002.

E-4. REFERENCES

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Appendix F
Technology Integration



Appendix F

Technology Integration

F-1. GOALS

As an important organization addressing technology integration issues, the IAEA International Working Group on Nuclear Power Plant ICHMI has prepared guidebooks to advise those preparing nuclear power projects and summarize the field of nuclear power plant ICHMI, including operating experience and new technologies. In the latest edition of these guidebooks the report concluded that the nuclear industry was woefully behind as compared with other industrial areas in the integration of new ICHMI technologies.

The state of the nuclear industry as reported by the 1999 IAEA report has changed little in the years since this document was written. While some advances have been made in the integration of new ICHMI systems, technological gaps, performance uncertainty, and regulatory acceptance have limited the full realization of the benefits of migrating to these new systems. Where modernization efforts have been achieved, the predominant reason has been the necessity to replace obsolete equipment rather than the enhancement of existing ICHMI functions (IAEA, 1999).

The Department of Energy needs to be concerned with this technological evolution for several reasons including the fact that the rapid development of digital technology is not being driven by the nuclear power industry. Other industries, through efforts to increase production, reduce manpower, and increase efficiency, are pushing new digital ICHMI development. Thus, the production of spare parts and the supporting infrastructure for older systems is rapidly vanishing, as a function of supply and demand. The result is that any new NPP construction will not be able to rely on past ICHMI technologies, simply because the vendor and production base likely will no longer be available.

State of the Nuclear Industry

The majority of the ICHMI systems which monitor and control today's NPPs are largely based on process technology from the 1950s and 1960s. Since that period, dramatic advances in electronics and computer technology have occurred and have resulted in multifold increases in functionality and performance. The reduction in cost has been equally spectacular. This combined effect of increased performance and reduced cost has made it possible for the ICHMI industry to quickly assimilate the rapid technological change. As a result, ICHMI technology has advanced more rapidly and more radically than any other discipline important to NPPs.

Unfortunately, while most industries have been able to apply the new technology in order to improve the reliability and efficiency of production, the nuclear industry has been relatively slow to do so. This is changing, however, and more NPPs are beginning to apply advanced ICHMI technology in all aspects of operation and maintenance.

IAEA Tech Report 387, Modern Instrumentation and Control for Nuclear Power Plants: A Guidebook, 1999, p 37

Taking the personal computer (PC) as an example, the lifespan of a household computer is estimated to be between 2 to 6 years. The lifespan consists of two specific elements: the functional lifespan and the useful lifespan. The functional lifespan describes how long the computer system will actually operate as designed, which is a function of system reliability. The useful life describes the capability of the computer to perform desired functionality including interfacing with other systems, which refers to its capability to adapt to

changing functional requirements, such as the capability to upgrade software. While not precisely reflecting nuclear plant ICHMI equipment, there are definite parallels between both types of equipment. ICHMI equipment integrated today will have a relatively short, useful time period, in terms of maintainability and adaptability. Systems must support the ability to implement incremental upgrades (software and hardware) with as little as a 5 to 6 year periodicity. With a dedicated, well-planned maintenance/refurbishment program and a sufficient spare parts inventory, platform lifetime can probably extend 10 to 15 years; however, migration to subsequent generation platforms needs to be addressed up front, rather than after the fact, as with analog systems. Also, considering that new nuclear plants will have a 60 to 80 year functional lifespan, three to four full system replacements can be expected for the ICHMI systems of new NPPs.

The rest of this section will address specific technologies and the surrounding issues associated with new technology integration. This discussion is by no means complete but serves as a template for future integration. The goals for technology integration are explained in the following sections.

F-1.1 Identify the Best Available Technology for Addressing Gen IV and NGNP Programmatic Needs

Industries outside of the nuclear power industry have already built tremendous experience and operational expertise in integrating new digital ICHMI technologies. The objective is to make use of best available technologies while broadening the market by adopting safety and non-safety grade instrumentation and control platforms from other industries. However, the adaptation of these technologies will require investigation into required adaptations and performance verifications in order to address safety and non-safety grade nuclear requirements.

This is not merely limited to the upgrading and integration of individual pieces of equipment. The desire is to make use of tools, support

systems, and other capabilities in order to improve productivity (plant and personnel) from other industries. To fully take advantage of information technology-based solutions to enhance plant capabilities and efficiency, a system of systems approach is required.

F-1.2 Identify Emerging Technologies to Fill Needs Not Currently Addressed with Current ICHMI Technology Proven for Nuclear Power Applications

NGNP and Gen IV reactors present unique challenges over the current fleet of reactors in terms of design, process, and O&M. These unique issues include high operating temperatures (900 to 950°C), new fuel and material designs, combined hydrogen and electricity production, new flow and heat transfer profiles, and reduced operations staffing levels.

F-1.3 Provide Methods for Informing ICHMI Systems Design and Implementation Decisions Based on Performance Measures and Risk Determination

This goal facilitates new designs for NGNP and Gen IV reactors. It is essential to develop accepted processes and methodologies that apply risk-informed approaches to making technology selection through informed technological decisions. Obsolescence will not be eliminated with the adoption of digital systems. The PC recently turned 25 years old and represents the rapid technological genesis to be expected from the computational machines that facilitate modern ICHMI systems. ICHMI solutions for implementation in NPPs should be sought that will have longer sustainable lifetimes, or will support easy and cost-effective replacement in the future as necessary. This requires flexible ICHMI architectures and function-based modularization with simplified structures suitable for adaptability and upgrading.

F-2. CHALLENGES

The integration of new technologies into nuclear safety and non-safety systems comes with challenges. Lessons can be learned and drawn from past operating experience. Brill (2000) conducted an analysis of the impact of instrumentation and control system failure on nuclear plant operations from 1994 to 1999 based on Nuclear Regulatory Commission (NRC) Licensing Event Reports (LERs). The goal of the study was to provide insight into the potential vulnerabilities of digital ICHMI systems and a basis for research as the new digital technologies are proposed for introduction into nuclear power plants. The study identified the following for the 6,681 LERs submitted during 1994 to 1998: 385 LERs involved digital anomalies and digital anomalies contributed to 60 of the 484 total reactor trips (~12%).

Brill further categorized the digital anomalies in terms of hardware 34%, software 32%, and human/systems interface 34%. What is remarkable about these statistics is that digital anomalies constituted to only a small percentage of the total of installed ICHMI systems.

While next generation designs may vary greatly from current implementation, and most certainly will involve new hardware and software, the Brill study shows the multidimensional challenges between hardware, software, and human performance that must be considered for new technology insertion.

F-2.1 System Challenges

Digital system reliability. The reliability of a computer-based control system is one of the most important user concerns, since the failure of a single component, such as a processor or a network, could disable major functions of a control system (IAEA, 1999). Although digital technology is very reliable, there is no accepted means of characterizing or quantifying the reliability of the software element of digital system implementations. Functional density is a critical issue when one considers the potential impact of a software error that could compromise

functionality and possibly inhibit defensive measures due to common-cause failure.

System situation awareness due to digital system complexity and interconnectivity. New technology has created tremendous functionality, but this functionality has come with the price of increased system complexity. While analog systems are nontrivial, they are often accessible in terms of operation and current state. Current digital systems are composed of intricate information networks with multiple layers of inter-process communication between equipment components. Additionally, individual elements may possess different levels of sophistication in terms of onboard processing. Coupled with the millions of lines of computer code, the level complexity can rapidly exceed the operator's ability to assess system performance and conduct troubleshooting outside of black box component replacement.

Quantified assessment of safety. Computerized system safety is dependent on software quality and safe software, which is software that contains no defects or only safe defects. Unlike hardware, for which the number of defects per unit time caused by wear and deterioration may be estimated with probabilistic methods, software faults take on a completely different form, because they result from a latent error that was not discovered during the checking stages. The approaches used to assess error risks are still the subject of much research (IAEA, 1999).

Physical and cyber vulnerabilities of new technologies. New technologies are not only required to address the technological challenges of physical nuclear plant operation, but design and implementation considerations must also include the current global conditions. The terrorist attacks of September 11, 2001, the foiled coordinated terrorist attack on multiple London-based airplanes, and the Blaster Worm infections of a nuclear power plant system have created an environment where new designs cannot be designed without considering security implications. Proliferation resistance and physical protection are corner stones for Gen IV designs. New ICHMI technologies must be developed and

implemented that support secure operations. New technologies must be developed that counter current and developing physical security and cyber security threats by minimizing the likelihood of attack and mitigating the consequences of successful attack. System survivability and system integrity are key to achieving fault tolerance and fault recovery. Along with the development systems supporting security elements, new systems must also be evaluated as to their effect on the current security posture, ensuring that the implementation of a new technology does not have unintentional consequences in terms of system vulnerability.

Acceptance by safety standards bodies. National safety committees are often reticent about accepting that a computerized system can guarantee reactor safety. The main reasons given are the innovative character of such technology and the difficulty of actually demonstrating the safety of a computerized system. The systems currently in use are too few and too recent to enable a consensus on acceptance criteria and methods to be formed by safety committees (IAEA, 1999).

Obsolescence. The rapid development of needed components could lead to the unavailability of spare parts in the short term. One currently accepted idea is that the more sophisticated components run the greatest risk of becoming obsolete. For example, a family of microprocessors could last only ten years. Experience has shown that the situation is in fact more subtle than this and that mechanical components, such as connectors and switches, are of more critical importance. Obsolescence is not specific to the computerized nature of the hardware (IAEA, 1999).

Maintenance costs. In the case of a computerized system, software maintenance relates solely to required modifications. Hardware maintenance covers periodic checks and the repair of any detected defects. The software may have to be modified, either because of a change in specifications in order to incorporate new processing capabilities or due to incorrectly performed. In a standard computerized system, if development has not been carried out carefully

and if the program is important, the cost of upgrading software could be considerable. In the case of a safety system, the situation is more favorable because the development methodology must have been codified. Nevertheless, revalidation and documentation accounts for most of the high costs of safety software (IAEA, 1999).

F-2.2 Software Challenges

Qualification of software. Qualifying software for NPP control applications is difficult because internationally acceptable standards, procedures, and methods are generally not available (IAEA, 1999). This is an especially important issue in terms of establishing a baseline for informing the U.S. NRC licensing group of risks.

Maintainability of software. In the past, when software was delivered it was considered that there should be little need to make revisions and that the cost of making such revisions would be small compared with the initial design cost. However, experience has shown that over the lifetime of software a need for change is inevitable and that the cost of such change is high. Revised software requires extensive testing to ensure that changes do not affect the functionality of the rest of the program. Because software maintenance can result in downloading different versions of the same software, version control and configuration management have to be provided in order to ensure that only the correct versions are used. Control system software should have maintainability built in on the basis of clearly stated maintainability requirements. This will minimize revisions, which are expensive, time consuming, and prone to error (IAEA, 1999).

Software common cause failure risk. In a redundant computerized protection system, the software is generally identical along the various channels and therefore constitutes a common cause failure risk. This risk forms a major current field of discussion between experts. There are still disagreements precluding consensus and, in the case of software that has been specifically safety engineered, experience and experimentation do not definitively confirm that the risk actually exists. Nevertheless, precautions are put in place

to mitigate potential vulnerabilities, with one of the consequences being provisions covering functional diversity (IAEA, 1999).

F-2.3 Hardware and Material Challenges

The identification of material and equipment performance characteristics in extreme environments, such as temperature, radiation, and corrosion, includes the challenges in monitoring the material performance of new technologies and the performance of sensors and supporting equipment.

F-2.4 Human Performance Challenges

Retraining of operating staff. During renovation work, the retention of operating staff and their adaptation to a new system that uses fundamentally different technology, is a major cause of concern. Personnel who are used to working with a system based on old technology could find that taking over a new system is difficult. Again, this difficulty seems more apparent than real (IAEA, 1999).

New system designs and technology insertion that increase overall system efficiency while targeting the elimination of certain routine human actions. Likewise, the elimination of specific human error modes may be targeted by the new technology. However, care must be taken because the new technology or design may very well alter the human behavior associated with using the system and working with fellow staff, thus changing system dynamics. This may create new human error modes that were not previously accounted for in human reliability analysis (HRA) or plant reliability analysis (PRA).

F-3. NEEDS

ICHMI technology RD&D is needed to address the technology challenges that have been described. The RD&D needs can be characterized in terms of effort to:

- Address technology gaps by advancing the state-of-the-art for nuclear power technologies
- Promote technology maturity through development and commercialization of nuclear power qualified ICHMI technologies
- Transfer advanced technologies to the nuclear power application domain through demonstration of nuclear power specific applications
- Establish methodologies and techniques (design and analysis approaches, assessment measures, and design and implementation toolsets) to enable implementation and licensing of emerging ICHMI capabilities in NPP applications.

An effective response to the ICHMI technology challenges depends on the establishment of a focused crosscut program. A key factor that can enable success in such an effort is provision of an ICHMI technology test bed to facilitate the necessary RD&D. Specific RD&D needs that can be addressed through a program employing test bed facilities include the following:

- Quantitative reliability and safety metrics
- Validation techniques for software in safety critical systems
- Technical baseline assessments of human performance in the presence of new technologies
- Flexible hardware and software architectures that readily permit system upgrades and modification
- Accepted methodology and tools for conducting rapid assessment of technologies for their applicability for nuclear power plants
- In situ assessments of technology in the plant (the ability to assess technology performance in terms of equipment and people)

- Approaches for in-depth defense of new technologies
- Methods to monitor and increase situation awareness of system performance, thus reducing the complexity of understanding for operation and troubleshooting.

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Appendix G
Nuclear Infrastructure



Appendix G

Nuclear Infrastructure

G-1. GOALS

The infrastructure framework includes the personnel, engineering tools, and facilities that are necessary for supporting the development, implementation, and operation of advanced nuclear systems for new nuclear power plants. As a result of the relatively dormant state of the nuclear industry in the U.S., over the past several decades, aspects of that infrastructure have weakened considerably. To move forward with Gen IV plant designs, the infrastructure supporting technology development need to be strengthened, updated, and sustained. With respect to the development of ICHMI systems to support Gen IV plant design, three infrastructure goals must be addressed. The first goal is to provide an adequate number of trained and qualified personnel to support all aspects of Gen IV ICHMI systems, including design, testing, licensing, operation, and maintenance. The second goal is to ensure state-of-the-art methods and tools are available in order to provide the technical foundation to support the development and validation of Gen IV ICHMI applications. The third goal is to ensure adequate facilities exist for the testing, validation, and proof of advanced ICHMIT concepts.

G-2. CHALLENGES

Conditions that could challenge the achievement of an appropriate infrastructure for the development of Gen IV ICHMI systems are described in the following sections.

G-2.1 Insufficient Number of Available Personnel with Relevant Technical Expertise

There is a growing workforce challenge in the nuclear industry (Wogman et al, 2005). The U.S. nuclear industry has had difficulty attracting talented professionals into the industry, in part

because of these reasons: new plants have not been built; the ICHMI technology in most of the plants is predominantly older; and analog technology is not taught in schools, is not used in other industries, and is not viewed as a viable career path. An insufficient number of qualified personnel knowledgeable in modern and advanced ICHMI technology can limit the realization of state-of-the-art systems for Gen IV applications.

G-2.2 State-of-the-Art ICHMI Methods and Tools Are Not Adapted to Support Nuclear Plant ICHMI Development

State-of-the-art methods and tools are emerging in the digital ICHMI communities that provide new means to analyze, design, and test advanced systems. State-of-the-art computer-based engineering tools enable designers to rapidly develop and test technological solutions in a way that is traceable for both engineering change purposes as well as regulatory reviews. There are two issues the nuclear industry must address. The first is the adaptation of state-of-the-art, computer-based engineering tools to use in the nuclear environment, and the second is the establishment of an industry consensus on appropriate methods and tools that are acceptable to both developers and regulatory authorities.

As the nuclear industry has not generally embraced digital ICHMI technology in the U.S., such methods and tools have largely been developed for non-nuclear applications. To meet Gen IV objectives, design and analysis tools are needed that can support the efficient development of Gen IV systems. It will be necessary for the best and most promising methods and tools to be adapted to nuclear applications. For example, virtual reality has been used to design equipment layout, develop maintenance approaches, and design the layout of panels and workstations in control rooms. Such tools are often based on

models and data that need to be validated for use in the nuclear industry to be acceptable to designers, utilities, and regulatory organizations. The development and validation of such tools can provide the industry with efficient and acceptable approaches to engineering new, advanced systems.

There are no well-established standards that can be relied upon to assure safety. Software verification and validation techniques are evolving and need to mature further before they are sufficiently robust to establish firm, objective criteria. It is essential to establish industry-wide acceptance criteria for ICHMI methods and tools that are acceptable to both developers and regulators.

Ensuring that the best methods and tools are available and achieving consensus on their acceptability and appropriateness for nuclear applications will provide a foundation to advance Gen IV ICHMI systems with low risk of technology failure and licensing delays.

G-2.3 Lack of National Simulation Facilities to Support Advanced ICHMI Development, Testing, and Proof of Concept

In many industries involving complex human-machine interface systems, such as aviation, maritime, and rail, facilities exist that provide national testbeds focused specifically for those industries' research and development needs. A limiting factor in the development of advanced ICHMI technologies for Gen IV plant applications is the lack of a national facility to provide such a test bed for the nuclear industry. A national test bed is needed for a wide range of applications, including the following:

- Developing, integrating, and testing new concepts that can be implemented in many specific designs
- Demonstrating key enabling technologies for the application of advanced instrumentation and controls, HMI, and interface systems

- Developing training approaches for new operational concepts and new reactor designs.

G-3. NEEDS

The challenges above can be addressed through systematic RD&D programs to provide the infrastructure necessary for successful development and implementation and support of advanced ICHMIT systems for Gen IV reactors. A summary of these needed is provided in the following paragraphs.

A workforce planning activity is required that will address the needs of the ICHMI community. It should be similar to the activity recently completed for the fusion sciences community at the request of DOE (Thomas et al. 2003).

Educational programs in technical schools, colleges, and universities that focus on state-of-the-art ICHMI technologies and their nuclear applications will be needed. In addition to formal education and training, a key to developing the appropriate expertise will be providing personnel with practical experience, including internships and work experience in a supervised setting, such as currently operational NPPs.

Another consideration is that of attracting talented professionals into the nuclear industry. One aspect of securing talented professionals for Gen IV programs is to attract them from other industries that have been utilizing advanced ICHMI technology systems, such as the petrochemical and fossil energy industries. To ensure the availability of state-of-the-art methods and tools for ICHMI technology Gen IV applications, RD&D programs are needed to assess new and emerging technologies and assess them for suitability for nuclear applications and the adaptations or further developments that will be required to make them acceptable with the nuclear industry and regulatory frameworks.

Simulator facilities are needed to provide the platform for development, testing, validation, and demonstration of the advanced ICHMI enabling

technologies, and these facilities should perform the following functions:

- Test and qualify within a selected environment of advanced sensors for critical measured variables important to the safe and reliable operation of the respective selected design
- Demonstrate integration of multiple networked elements with control and display features
- Develop testing protocols for quantification of uncertainty in diagnostic and prognostic modules applied to the selected test bed sensors and control system
- Develop and demonstrate a hybrid diagnostician for forward and back propagation with prognostic correlation of selected faults and/or anomalies associated with the selected control system
- Demonstrate intelligent hierarchical control that integrates diagnostic and prognostic information with control decisions for the selected control system
- Demonstrate varying levels of autonomy of the overall plant control system
- Demonstrate the generation of software specification from system requirements using rigorous methods, such as sequence-based and formal language specification techniques
- Apply the model-based statistical testing for the quality certification of the selected software
- Development of in-parallel regulatory review and acceptance guidelines for selected system diagnostics, including integration with risk-informed, performance-based regulatory initiatives
- Develop improvements to the regulatory structure accounting for new operational modes of the plant
- Develop and investigate strategies for functional allocation in highly autonomous, adaptive control systems
- Develop and evaluate intelligent HMI technology to support event detection and situation assessment for operational and maintenance applications
- Develop and evaluate training approaches for new reactor designs and the new concept of operations that will emerge in order to meet Gen IV design goals.

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