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Report from the Light Water Reactor Sustainability Workshop on Advanced Instrumentation, Information, and Control Systems and Human-System Interface Technologies

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August 2009

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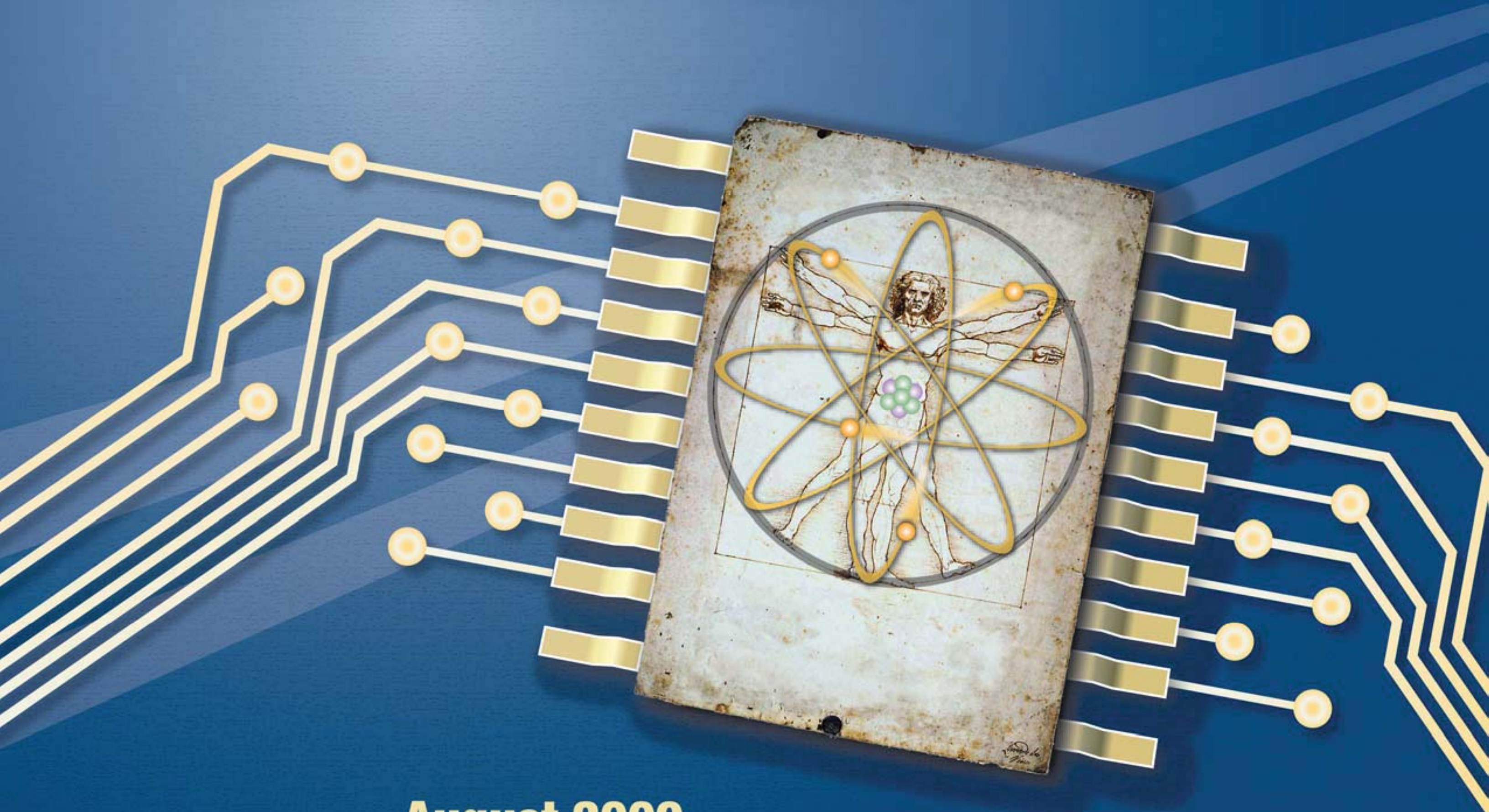
Held March 20–21, 2009, in Columbus, Ohio



August 2009

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ABSTRACT

The Light Water Reactor Sustainability (LWRS) Program is a research and development (R&D) program sponsored by the U.S. Department of Energy (DOE). The program is operated in close collaboration with industry R&D programs to provide the technical foundations for licensing and managing the long-term, safe, and economical operation of Nuclear Power Plants that are currently in operation. The LWRS Program focus is on longer-term and higher-risk/reward research that contributes to the national policy objectives of energy and environmental security.

Advanced instruments and control (I&C) technologies are needed to support the safe and reliable production of power from nuclear energy systems during sustained periods of operation up to and beyond their expected licensed lifetime. This requires that new capabilities to achieve process control be developed and eventually implemented in existing nuclear assets. It also requires that approaches be developed and proven to achieve sustainability of I&C systems throughout the period of extended operation. The strategic objective of the LWRS Program Advanced Instrumentation, Information, and Control Systems Technology R&D pathway is to establish a technical basis for new technologies needed to achieve safety and reliability of operating nuclear assets and to implement new technologies in nuclear energy systems. This will be achieved by carrying out a program of R&D to develop scientific knowledge in the areas of:

- Sensors, diagnostics, and prognostics to support characterization and prediction of the effects of aging and degradation phenomena effects on critical systems, structures, and components (SSCs)
- Online monitoring of SSCs and active components, generation of information, and methods to analyze and employ online monitoring information
- New methods for visualization, integration, and information use to enhance state awareness and leverage expertise to achieve safer, more readily available electricity generation.

As an initial step in accomplishing this effort, the Light Water Reactor Sustainability Workshop on Advanced Instrumentation, Information, and Control Systems and Human-System Interface Technologies was held March 20–21, 2009, in Columbus, Ohio, to enable industry stakeholders and researchers in identification of the nuclear industry's needs in the areas of future I&C technologies and corresponding technology gaps and research capabilities. Approaches for collaboration to bridge or fill the technology gaps were presented and R&D activities and priorities recommended.

This report documents the presentations and discussions of the workshop and is intended to serve as a basis for the plan under development to achieve the goals of the I&C research pathway.

CONTENTS

FIGURES

TABLES

ACRONYMS

BWR	boiling water reactor
COTS	commercial off-the-shelf
CPU	central processing unit
CSNI	Committee on the Safety of Nuclear Installations
DI&C	digital instrumentation and control
DOE	Department of Energy
EdF	Électricité de France
EPRI	Electric Power Research Institute
FPGA	field programmable gate arrays
HFE	Human Factors Engineering
HOF	human organizational factors
HRP	Halden Reactor Project
HSI	human-system interface
I&C	instrumentation and control
INL	Idaho National Laboratory
IO	integrated operations
IT	Information Technology
LTO	Long Term Operation (project)
LWR	light water reactor
LWRSP	Light Water Reactor Sustainability Program
MDEP	Multinational Design Evaluation Program
MPE	maintenance proficiency evaluation
NCS	Norwegian Continental Shelf
NEA	Nuclear Energy Agency
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
O&M	operations and maintenance
OECD	Organization for Economic Cooperation and Development
OEM	original equipment manufacturer
OLF	Norwegian Oil Industry Association
OSU	Ohio State University
PDA	personal digital assistant
PRA	probabilistic risk assessment

PSA	probabilistic safety assessment
R&D	research and development
SSC	systems, structures, and components
TOP	technical opinion paper
TPE	task proficiency evaluation
V&V	verification and validation
WGHOF	Working Group on Human and Organizational Factors

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1. BACKGROUND

The Light Water Reactor Sustainability Program (LWRS) is a research and development (R&D) program sponsored by the U.S. Department of Energy (DOE). The program is operated in close collaboration with industry R&D programs to provide the technical foundations for licensing and managing the long-term, safe, and economical operation of nuclear power plants that are currently in operation. The LWRS program focus is on longer-term and higher-risk/reward research that contributes to the national policy objectives of energy and environmental security.

DOE's LWRS Program Vision is captured in the following statements:

> *Existing operating nuclear power plants will continue to safely provide clean and economic electricity well beyond their first license extension period, significantly contributing to reduce U.S. and global carbon emissions and enhance national energy security while protecting the environment.*
>
> *There is a comprehensive technical basis for licensing and managing the long-term safe, economical operation of nuclear power plants. Sustaining the existing operating U.S. fleet will also improve its international engagement and leadership on nuclear safety and security issues.*

Two strategic program goals support the achievement of this vision:

1. Support the long-term licensing and operation of the existing operating nuclear power plants to successfully achieve planned lifetime extension up to 60 years and lifetime extension beyond 60 years.
2. Maintain and enhance the performance of the existing operating fleet of LWRs to ensure superior safety, high reliability, and economic performance throughout their lifetime.

Three strategic means support the achievement of the program goals:

1. Develop the fundamental scientific basis to understand, predict, and measure changes in materials, systems, structures, and components as they age in environments associated with continued long-term operation of existing LWRs.
2. Apply this fundamental knowledge in collaborative public-private and international partnerships, developing and demonstrating methods and technologies that support safe and economical long-term operation of existing LWRs.
3. Identify and verify the efficacy of new technology to address obsolescence while enhancing plant performance and safety.

Five principal R&D pathways addressing the strategic program goals have been identified to better understand the challenges posed by nuclear power plant aging. These R&D pathways focus on improving the fundamental aging and degradation knowledge basis in reactor material sciences; creating improved inspection and monitoring technologies; fostering development of advanced fuels; and incorporating risk-informed, performance-based techniques in safety margin characterization and life extension decision-making. Following is a list of these R&D pathways as well as a description of each area's specific R&D objective:

1. **Nuclear Materials Aging and Degradation**. Research to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants. Provide data and methods to assess performance of systems, structures, and components essential to safe and sustained nuclear power plant operation.
2. **Advanced LWR Nuclear Fuel Development.** Improve the scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding performance in nuclear power plants. Apply this information to develop high-performance, high burn-up fuels with improved safety, cladding, and integrity, in addition to improved nuclear fuel cycle economics.
3. **Advanced Instrumentation, Control, and Information Systems Technologies.** Through the use of scientific knowledge basis and advanced phenomenological modeling, establish advanced condition monitoring and prognostics technologies for use in understanding the aging of systems, structures, and components of nuclear power plants. Develop and demonstrate information system technology enhancements for knowledge migration and regulatory compliance.
4. **Risk-Informed Safety Margin Characterization.** Bring together risk-informed, performance-based methodologies with fundamental scientific understanding of critical phenomenological conditions and deterministic predictions of nuclear plant performance, leading to an integrated characterization of public safety margins in an optimization of nuclear safety, plant performance, and long-term asset management.
5. **Economics and Efficiency Improvement.** Improving the economic performance and efficiency is a vital part of extending the lifetime of existing operating LWRs. Power uprate has been adopted to produce more power outputs for the nuclear industry. This activity focuses on developing methodologies and scientific bases to enable more extended power uprates or ultra power uprates. Other aspects of the plant operations and applications, such as alternative cooling technologies and non-electric applications, will also be studied.

Advanced instruments and control (I&C) technologies are needed to support the safe and reliable production of power from nuclear energy systems during sustained periods of operation up to and beyond their expected licensed lifetime. This requires that new capabilities to achieve process control be developed and eventually implemented in existing nuclear assets. It also requires that approaches be developed and proven to achieve sustainability of I&C systems throughout the period of extended operation. The strategic objective of the DOE's Advanced Instrumentation, Information, and Control Systems Technology R&D pathway is to establish a technical basis for new technologies needed to achieve safety and reliability of operating nuclear assets and to implement new technologies in nuclear energy systems. This will be achieved by carrying out a program of R&D to develop scientific knowledge in the areas of:

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As an initial step in accomplishing this effort, the Light Water Reactor Sustainability Workshop on Advanced Instrumentation, Information, and Control Systems and Human-System Interface Technologies was held March 20–21, 2009, in Columbus, Ohio, to enable industry stakeholders and researchers in identification of the nuclear industry's needs in the areas of future I&C technologies and corresponding technology gaps and research capabilities. Approaches for collaboration to bridge or fill the technology gaps were presented and R&D activities and priorities recommended.

This report documents the presentations and discussions of the workshop and is intended to serve as a basis for the plan under development to achieve the goals of the I&C research pathway.

2. WORKSHOP

The Light Water Reactor Sustainability Workshop on Advanced Instrumentation, Information, and Control Systems and Human-System Interface Technologies, organized by Ohio State University (OSU) in conjunction with Idaho National Laboratory (INL) and the Electric Power Research Institute (EPRI), was held in Columbus, Ohio, March 20–21, 2009. Appendix A includes the workshop agenda and Appendix B includes a list of workshop participants.

The workshop format included a series of keynote presentations from nuclear power-producing asset owners and researchers. The presentations were accompanied by a series of break-out sessions, where working groups discussed the challenges facing utilities in managing current I&C technologies, desired states for I&C technologies that are or will be needed during long-term operation, and gaps that must be addressed through R&D to achieve an end state that supports long-term facility operation. Section 2.1 summarizes the keynote presentations, Section 2.2 summarizes the discussions of working groups, and Section 3 provides information about related efforts to develop or assess digital technologies for nuclear plant applications by other organizations.

2.1 Keynote Presentations

Several of the keynote presentations summarized the current situation of I&C technologies at existing fleets of nuclear power plants. A common theme in these presentations was the increased frequency of the effects of aging and obsolescence of analog I&C technology. For long-term operation, asset owners view digital technologies for I&C as essential. They also perceive a need to explicitly incorporate digital technology capabilities into their future business models for plant operation—something that has not occurred with analog I&C. Several presentations described the anticipated benefits of digital I&C systems, justification for adoption, and barriers to incorporation in the nuclear power industry.

Accompanying the asset owners' presentations, EPRI provided an overview of its Long-Term Operation (LTO) Project, defined in 2008 in partnership with member utilities to address modernization of nuclear plants. Électricité de France provided an overview of long-term goals for incorporating digital I&C in their fleet of operating plants. They also presented a technical perspective on incorporating digital system reliability into probabilistic risk assessment or probabilistic safety assessment, which may be needed for licensing digital technologies for use in commercial nuclear power plants. The Halden Reactor Project provided a summary of recent efforts related to enterprise-wide modernization of operations in North Sea oil-producing companies. The products of these modernizations are new concepts for operations that emphasize integration of onshore and offshore activities of the enterprise. Because many of the nuclear asset owners in the United States now operate fleets of generating assets, this presentation offered some insight into other sectors' efforts to address fleet-wide engineering and economy-of-scale solutions to modernization issues. The presentations are summarized below.

2.1.1 Electric Power Research Institute (EPRI)

Many issues need to be examined to ensure that nuclear power plants continue to operate safely and productively during an extended lifetime. Some of these issues will create challenges for the implementation of I&C systems in the nuclear industry. Also, opportunities for new I&C technologies are plausible given longer lifetimes and allow for strategic planning to achieve and measure the benefits from plant I&C modifications. These increased benefits will be obtained by taking advantage of modern digital I&C, information, and communications technologies. The longer-term perspective affords an emphasis on plant and personnel reliability and productivity improvements. Another opportunity is the ability to design the system for replacement as needed. It is reasonable to expect that some digital systems will become obsolete and need to be replaced more than once during extended operations. Therefore, when the digital system is designed, it will be beneficial to include approaches to facilitate changes to minimize the time and cost required to implement modernization programs.

In addition to the economic advantages of extending the operational lifetime of nuclear power plants, there is a substantial environmental motivation to extend the lifetime of operating nuclear power plants as well as to build new nuclear power plants. Examples of digital I&C, human-system interfaces (HSIs), information, and communications that offer beneficial opportunities include:

- Smart sensors and transmitters that are harsh-environment tolerant
- Controls that are self-testing, self-diagnostic, error tolerant, and self-correcting
- Modular control and protection systems with improved algorithms that provide increased robustness and flexibility
- User-friendly HSIs to allow the user to successfully and efficiently accomplish tasks
- HSIs that improve access to data, enhance situation awareness, and support decision-making
- Online monitoring, diagnostics, and prognostics of equipment, even from remote locations, that can reduce the likelihood of equipment damage and forced outages
- Simulation and visualization with interactive interfaces that support planning and decision-making; improve designs and facilitate early input from users; support development, tuning, and testing; improve job performance; and reduce the likelihood or consequences of human errors
- Automation and intelligent agents that reduce repetitive, time-consuming, and error-prone activities
- Reduced time demands and stress for humans, allowing them to better focus on essential activities requiring human capabilities.

EPRI defined the LTO Project in 2008 with R&D work beginning in 2009. The objective of the LTO Project is to provide technology for continued operation of nuclear plants worldwide at high performance levels through 2030 and beyond. One of the four major technical areas in the LTO Project is I&C and Information Technology. In 2009, related R&D activities are being performed in the areas of:

- New I&C and HSI capabilities and architectures
- Online monitoring, diagnostics, and prognostics for critical SSCs

Additional areas of emphasis will be added based on future needs and opportunities.

Modern digital I&C, HSI, information, and communications technologies offer opportunities for successful long-term operation of existing nuclear power plants and construction of new plants by addressing strategic and tactical needs and opportunities. Effective use of these technologies can provide:

- Enhanced safety
- Increased functionality and productivity
- Reduced operations and maintenance costs
- Reduced time to locate and access needed information
- Reduced likelihood of human errors
- Increased availability and reliability
- Added flexibility and performance advantages
- Supportive cooperation among systems, among staff, and between systems and staff

- Remote expert support
- Increased planning efficiency
- Enhanced design capabilities
- Reduced radiation dosage
- Enhanced knowledge capture and presentation
- Improved training and pre-job briefing.

By providing the right people and systems with the right information at the right time, modern digital I&C, HSI, information, and communications technologies enable an infrastructure that allows plant and corporate staff to do their jobs better and faster with reduced human error. These technologies may encourage a younger work force to enter the nuclear power industry because the technologies are familiar.

The increased functionality and new capabilities that these technologies afford have the potential for significant benefits that need to be realized. Often when the requirements for a new digital system are written, the approach has been to require a like-for-like system to the existing analog system—or a system with some minor improvements. However, as I&C research pathways are explored to extend the service life of nuclear power plants, the added functionality benefits of modern digital I&C, HSI, information, and communications technologies should be important considerations. In some cases, benefits such as self-checking and improved information access will encourage incorporation of more modern technology features into plant operations. In other cases, this analysis may indicate that a like-for-like replacement is the best business strategy, but this will be an informed decision based on careful consideration of the benefits versus costs of the technology.

Modern digital technologies can provide the nuclear power industry with increased functionality and capabilities in a number of ways:

1. **Monitoring, diagnostics, and prognostics.** Modern digital I&C, HSI, information, and communications technologies can enable on-line monitoring of equipment and early detection of equipment degradation. Equipment problems can be diagnosed and time to failure projected. This ability supports improved equipment reliability and facilitates preventive maintenance to reduce the likelihood of equipment damage, unplanned outages, and safety challenges, while reducing maintenance costs and the likelihood of maintenance errors. Technologies such as wireless communication, fiber optics, smart transmitters, and wireless sensor networks enable real-time access to more plant data and allow early fault detection, diagnostics, and prognostics for equipment.

   Further, the ability to remotely monitor plant, system, and equipment conditions allows remotely located experts to evaluate the plant's operational state, diagnose problems, predict time to failure, and recommend appropriate responses. In addition to human expertise, large amounts of information exist that can support monitoring, diagnostics, and prognostics in distributed sources, including from other plants. The ability to remotely monitor equipment performance and to access appropriate information from distributed sources will allow the best expertise in the utility (or outside the utility) to evaluate equipment conditions and perform fault detection, diagnostics, and prognostics throughout the fleet.

2. **Human-System Interfaces (HSIs).** Human-system interfaces are the window into plant operation and the means for taking action. These interfaces are also essential for other non-operation activities such as training, analyses, design, and planning. The HSIs can have a major impact on situation awareness, decision-making, information sharing, and performing tasks. Modern digital, HSI, information, and communications technologies enable better and richer HSIs based on user-friendly design.

In general, a well-designed HSI exhibits the following characteristics:

- Represents the situation accurately
- Meets user expectations
- Supports situation awareness and crew task performance
- Minimizes secondary tasks and distractions
- Balances workload
- Is compatible with users' cognitive and physical characteristics
- Is error tolerant
- Is simple to use and understand
- Allows for standardization and consistency
- Provides timely information to support decision making
- Is open and gives feedback
- Is appropriately flexible.

These digital technologies provide capabilities that are impossible with technologies that are currently dominant in nuclear power plants. Information can be presented in a manner that is more easily and quickly understood. The capability to evaluate and present preconditioned decision-quality information, potentially from multiple sources, assures that reliable information will be available for critical decision-making and other uses.

3. **Simulation/Visualization and Automation.** Simulation and visualization are powerful capabilities to support nuclear power industry activities such as situation awareness, training, practice, planning, design, evaluation, education, decision-making, off-site support, information presentation, knowledge capture, testing, familiarization, and many other functions. They enable people and organizations to do their jobs better, faster, and easier with greater insight and less likelihood of error. Examples of innovative simulation/visualization applications to support decision-making are shown in Table 1.

   Among the benefits of modern digital, HSI, information, and communications technologies are the capabilities to potentially enhance plant process automation and to provide more reliable and precise control. Tasks that are difficult, error-prone, time-consuming, repetitive, or tedious can be automated, freeing personnel to perform more supervisory activities and reducing the likelihood of human error.

   Newer approaches to automation reflect greater cooperation between automatic systems and plant personnel. Opportunities exist to use differing levels of automation in an effort to combine the advantages of both human and system capabilities. In addition, automation can reduce time demands, workloads, and stress, allowing staff to better concentrate on essential activities best suited to human skills and capabilities.

Table 1. Examples of modern visualization technology application to improve human decision-making.

Operations Applications	Maintenance Applications	Training Applications	Engineering Applications	Other Applications
Support plant and control room upgrades	Real-time support using virtual presentation methods	Simulator training using virtual interfaces	Design using virtual prototyping, simulation and evaluation	Personnel radiation tracking and protection
Control room staffing needs	Train, practice, and rehearse maintenance tasks	Virtual maintenance and task proficiency evaluation (MPE/TPE) testing	Process, data, and other visualization	Advanced virtual NDE training and testing system
Critical safety function visualization	Virtual tours and route planning, e.g., first-time outage workers	First responder security and emergency response training and rehearsal		Remote expertise, collaboration, training, and work
Reactor core visualization				3-D computer game to support recruiting

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Automation can be applied to functions such as monitoring and detection, situation assessment, information access, and response planning. Automation can also enable plants to be run safely with smaller staffs, as will likely exist due to more plants and fewer people available to run them, as well as for purely economic reasons. The ability to develop intelligent agents to get the right information to the right person at the right time can make a significant contribution to workload reduction and more efficient use of staff time. Automated capabilities can include surveillance of activities of humans and systems, reducing the likelihood of errors. An example of this is the use of smart tags to reduce the need for peer checking.

2.1.2 Duke Energy Corporation

The presentation by the speaker from Duke Energy Corporation indicates a readiness to adopt digital technologies in the nuclear industry. Digital systems are desired for:

- Safety-critical protection systems
- Integrated and local control systems
- Monitoring systems
- Diagnostic systems
- Plant information systems
- Highly integrated control room
- Component-level applications.

The industry, though, is targeting application of new technologies to point solutions, driven by performance and obsolescence concerns. This results in a fragmented, non-optimized approach rather than a transformative approach. Also, planning horizons are short, primarily because the nuclear industry does not drive technology from a business-need standpoint; rather, it reacts to developments in other energy production sectors. This approach is the result of digital technology not impacting or being incorporated into an asset owner’s business model for the enterprise. As a result, new I&C technologies do not currently displace the old costs of analog I&C—they add to them. Many beneficial technologies are marginalized by this approach. Consequently, actual cost-benefits are not currently captured or fully accounted for because digital I&C technologies are applied within the existing business model (i.e., as a way to manage aging or obsolete analog I&C, with no defined end state in mind.

Overall, industry performance reflected by measures of electricity generation costs is flat. As Figure 1 shows, a practical performance limit indicated by the asymptotic level of performance is reached, even though constant efforts are applied to improve performance. Digital is not driving significant plant performance improvement. Industry is getting ever-diminishing returns on its continued efforts to improve performance, and it is approaching the limits of human performance by force-fitting digital into current operating business models rather than transforming those models by use of digital.

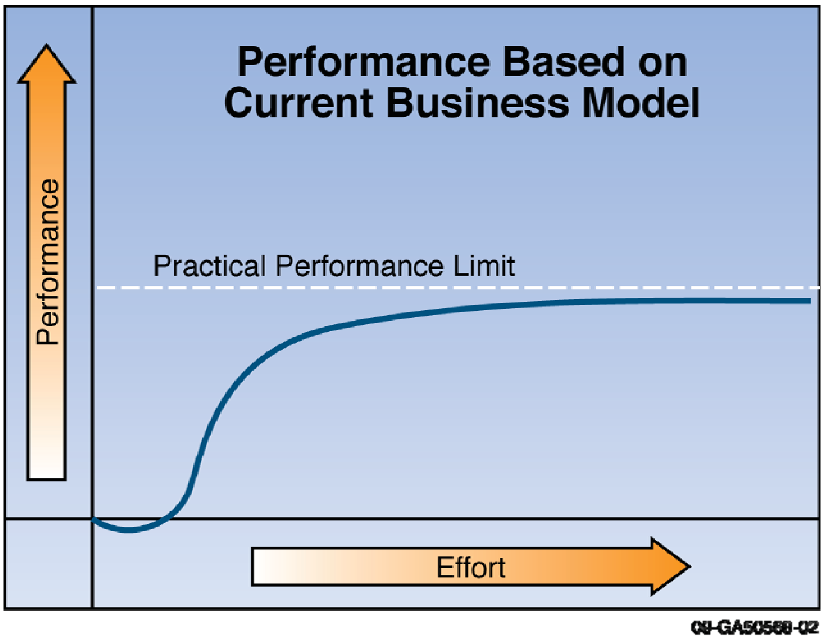

Figure 1. Achieving constant levels of performance through current technology and efforts.

The business model can be radically improved by a transformation from labor intensive to technology intensive, a change in which digital is the enabling technology. However, to be effective, the transformation must encompass the entire industry—plant owner/operators, suppliers, service providers, and regulators.

To accomplish this transition, the industry must work the problem backwards, defining new operating business models with bottom-line performance requirements. The following factors need to be targeted in developing these models:

- Plant staff and types of resources
- O&M cost
- Plant safety margin
- Targeted plant capacity factor.

Further, the industry must realize that business models drive technology, so the industry must:

- Define the enabling technologies to achieve the business model
- Specify the performance requirements based on displaced business functions rather than what is technically feasible

- Identify secondary technologies that are leveraged by the total model
- Work from both ends and meet somewhere in the middle using an iterative process.

A proposed new operating business model would have minimum permanent plant staff, with production focus rather than specialized skills. Also, digital systems would enact most plant functions and provide first-order advisory assistance; industry expertise would be automatically engaged when specialized skills are required, and plant data and analysis tools would be standardized across the industry.

The intent of this model would be to strive for plant optimization by (1) establishing a detailed dynamic plant model that continually compares actual to predicted performance; (2) diagnosing and compensating for deviations, if possible; (3) quantifying and using performance penalties (either cost or safety margin) to prioritize the response; and (4) pinpointing deficiencies and initiating corrective measures using both onsite and offsite resources.

The proposed next steps are to:

1. Conduct the research to develop the new operating business model for nuclear plants
2. Identify and develop the technologies needed to enable the model
3. Define an "open standard" to enable seamless interaction among owner/operators, suppliers, service providers, and regulators
4. Develop a migration path from the current state.

2.1.3 Exelon Corporation

The presentation by the speaker from the Exelon Corporation emphasized experiences and some of the barriers to component replacement. The primary barrier to success is that new solutions to most I&C problems use a different technology: digital. Digital technologies operate differently (i.e., in discrete steps vs. continuously) and may be more susceptible to interference and disruption from the nuclear plant operating environment, which includes electromagnetic interference, seismic conditions, and radiation. This new technology may also require a change in infrastructure, such as networking versus point-to-point wiring in use today. Further, there are concerns that some digital devices—especially those comprised of both hardware and software—may fail in new ways that are also unique and unfamiliar. The assessment of digital system and component reliability is also challenging because standard methods have not yet been adopted for use in the nuclear environment.

The use of digital systems may not fit with existing ways of doing business. In order to minimize the amount of effort spent on regulatory and other reviews, the use of pre-engineered solutions ought to be maximized. To do so, clear, well-bounded specifications and a true understanding of the regulatory and structural differences between sites and systems where new digital technologies will be implemented is required. Supply management would need to include equivalency screening, especially where new solutions combine functions that were previously separate. At issue is the potential that combining functions could compromise the need to maintain diversity in sensors and actuation systems or defense in-depth to prevent the existence of vulnerable, single failure points in the system. The need to maintain configuration management will create new questions when performing replacements of analog with digital technology. This includes some of the following:

- When is a sub-part replacement below the level of formal engineering and regulatory review?
- How and when is it necessary to control vendor configuration management?
- When is it appropriate to perform incremental maintenance upgrades to keep in step with the vendor?

The speaker also noted the importance and difficulty of creating a business case for replacements (e.g., piece-wise) as well as modernization efforts (e.g., system-wide upgrades) even though new technologies are proven to be more reliable. Difficulties arise due to limitations with how the present accounting structure quantifies, for example, the costs of supporting older I&C technologies as opposed to assessing concomitant improvements in reliability and risk metrics through more widespread use of newer, more efficient, and highly reliable digital technologies.

2.1.4 Entergy Corporation

The speaker from Entergy Corporation presented keys to successful innovation and O&M improvement on an enterprise scale and discussed how goals for improvement could include the introduction of digital I&C. These keys were separated into two categories: Operations and Organization.

Keys to successful innovation in Operations include:

- Safety
- Plant performance
- Avoidance of unplanned shutdowns
- Equipment reliability
- Business measurements.

Both industrial and nuclear safety issues were discussed, with a focus on measurement of all facets.

Keys to successful innovation in Organization include:

- Retaining a highly skilled workforce in current plants as well as recruiting and developing new staff
- Optimized structure
- Standardized processes
- Effective use of technology
- Selective outsourcing.

Entergy has initiated several strategic initiatives to transform current business approaches. This strategy includes a number of cost-effective alternatives that are instrumental to achieving transformation of these business approaches. Table 2 summarizes some of the desired outcomes and attributes of transformed business approaches.

Table 2. Summary of innovation goals and desired outcomes.

	Existing U.S. Plant	Modernized U.S. Plant	New U.S. Plant
O&M Cost ($/MwHr)	100%	80%	60%
Staffing (Hours) –Single Unit –Dual Unit	1.6M 2.4M	1.2M 1.7M	832K 1.1M
Instrument & Control	Analog	Hybrid	Digital
Plant Support	Decentralized	Centralize	Centralized/Outsource
Design	Individual	Common Concepts	Standardized
Maintenance	Time Based	Hybrid	Condition-Based
Processes/Procedure	Paper	Less Paper	Paperless
Training	Specialized	Specialized	Cross Trained
Asset Management	Tribal Tacit Knowledge	Hybrid	Centralized Monitoring

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Of particular interest to the workshop, Entergy's goals for strategic improvement include targeted reductions in O&M costs. The main areas for targeted improvement relate to staffing, where a 25% reduction in staffing is desired for a modernized U.S. plant. Also, I&C technologies are envisioned to be hybrid for some period of time, meaning they will incorporate a mixture of both analog I&C and digital I&C technologies. As operations now occur across a fleet of plants, there is a goal to achieve more centralized planning and expertise in managing equipment performance and reliability. This includes more online monitoring and trending with a goal to achieve more performance-based maintenance. Also, enterprise-wide processes and procedures are envisioned as moving from largely paper-based to a combination of electronic and some paper-based methods.

As can be seen in Table 2, targeted changes in processes and technologies are needed to realize the goals of these transformative activities. This includes digital technologies in many aspects of plant operations and management, from process and procedures to instrumentation and controls, and even concepts around organizing and utilizing expertise and the workforce. This strategy is expected to drive operational costs down over time while improving performance and maintaining a high level of operational safety.

2.1.5 Électricité de France (EdF)

The speaker from EdF stated that the issues affecting advanced I&C systems and advanced HSIs may be divided into two main categories: safety and licensing issues on the one hand, and long-term plant operation issues on the other.

2.1.5.1 Safety and Licensing

Different countries may have significantly different regulatory requirements and assessment practices regarding digital systems and equipment. This leads to differences in I&C architectures and increased costs and delays because the design solutions accepted, and the construction experience gained, in one country do not always benefit projects other countries. Also, the lack of standardization does not facilitate the operation and maintenance of a fleet, which limits the build up of useful operating experience. Research could be performed to provide inputs to the Multinational Design Evaluation Program (MDEP) and help it achieve its goal.

Research efforts could also focus on the developments necessary to increase confidence in digital systems and equipment. Several complementary approaches may be used: analysis of past operating experience to identify problematic issues, improved evaluation methods (e.g., use of formal verification methods, or assessment of defensive design measures), and simpler designs (e.g., using programmable electronics).

Last but not least, research could provide a more systemic approach in the assessment of the overall impact of digital systems and equipment on plant safety and performance. As noted by H. W. Lewis in *Technological Risk*, "A complicated system cannot be made safer by focusing attention on one isolated part of it, and then making that one part stronger or more reliable. It may do more harm than good." To this end, research on the appropriate representation of digital systems and equipment in probabilistic risk assessment (PRA) models could be very useful.

2.1.5.2 Long-Term Plant Operation

Long-term plant operation raises several issues as far as digital systems and equipment are concerned:

- **Sustainable I&C**. Research may help plant operators in determining the optimal lifetime of their existing I&C. Research may also help them choose the most appropriate replacement or upgrade strategy. Lastly, research is needed to help ensure that the systems and equipment we install today or tomorrow are indeed designed for a long lifetime and replaceable in the future.
- **Plant stress reduction**. Advanced digital I&C and HSI may be used to reduce the stresses in key, hard-to-replace plant components, e.g., through gentler reactor protection mechanisms, reduced plant equipment failures, and improved human factors.
- **Health monitoring of key plant components**. Advanced digital I&C and research may be used to monitor the health of plant components such as the reactor vessel and the containment building.
- **Improved performance**. Advanced digital I&C and research may lead to improved plant and human performance because of the inherent reliability and characteristics of digital systems and the improved information available to the operators.
- **Increased plant safety**. As new plants are designed and built to increased safety standards, it will be necessary for existing plants to follow suit, and advanced digital I&C and HSI can play a significant role.

EdF is investigating an approach to improve the representation of digital I&C in probabilistic safety assessment (PSA) models while keeping the models simple and usable. One objective of the approach is to include not only the negative effects (e.g., due to failures on demand or spurious actuations), but also the positive effects (e.g., due to improved online monitoring, controls, or human interfaces) of new digital systems. The approach considers the different failure and common-cause failure mechanisms (random mechanisms, systematic mechanisms, and human factors) and uses a combination of probabilistic and deterministic methods to identify and quantify the dominant failure and common-cause mechanisms in the PSA.

In new builds or through upgrades, digital equipment and systems play an important role in the operation and control of nuclear power plants and their main components. Digital equipment and systems offer advanced capabilities and improved hardware reliability. They may also be prone to specific failure mechanisms including common-cause failures. Many products are available and many digital architectures are possible for a given project, so it is important that designers are able to evaluate the real impacts of the proposed solutions on plant safety.

Typically, safety assessments are performed at two very different levels: (1) systems and individual components and (2) at the plant level. In general, assessments of digital equipment and systems are based on deterministic analyses, whereas plant-level assessments rely mainly on probabilistic techniques. Unfortunately, the experts in one type of assessment often have limited understanding of the other. Current safety goals, the omnipresence of digital equipment (including so-called “smart devices”), more complex digital architectures in new builds, and the need to represent the positive effects of digital I&C on system safety require an extension of our current representation of digital equipment and systems in plant PSA models.

The Compact Model was developed in the 1990s for the N4 series of NPPs in France. It has been accepted by the French Nuclear Safety Authority and is referenced in the international document IEC 61838. The Compact Model was derived from a detailed probabilistic model, based on Markovian techniques, that was extremely complex. Given the difficulty of integrating and maintaining a full digital system representation in the plant PSA, a simplified representation of the I&C top events was developed. The Compact Model is thus neither a structural nor a behavioral model of digital equipment and systems; rather, it is a functional representation that embodies the main outcomes of safety and dependability assessments made by digital I&C experts that can be shared with PSA experts and incorporated in a PSA model. The simplifications made are legitimate and acceptable for the N4 series.

Each I&C top event comprises three parts (see Figure 2):

- Acquisition, represents a group of redundant sensors and encompasses the measuring cell module, the analogical/digital conversion module, and the transmission of the data to the logic part
- Logic processing (programmed equipment) represents programmable logic controllers
- Actuation, or actuator control, commands the electrical and hydraulic systems.

An I&C top event is typically represented with four basic events (see Figure 2):

- One for sensor failures
- Two for logic processing failures (the first corresponding to specific logic, such as the loss of a single logic unit, and the second corresponding to common logic, such as the concurrent loss of multiple logic units of the same technology due to CCF)
- One for actuator control failures.

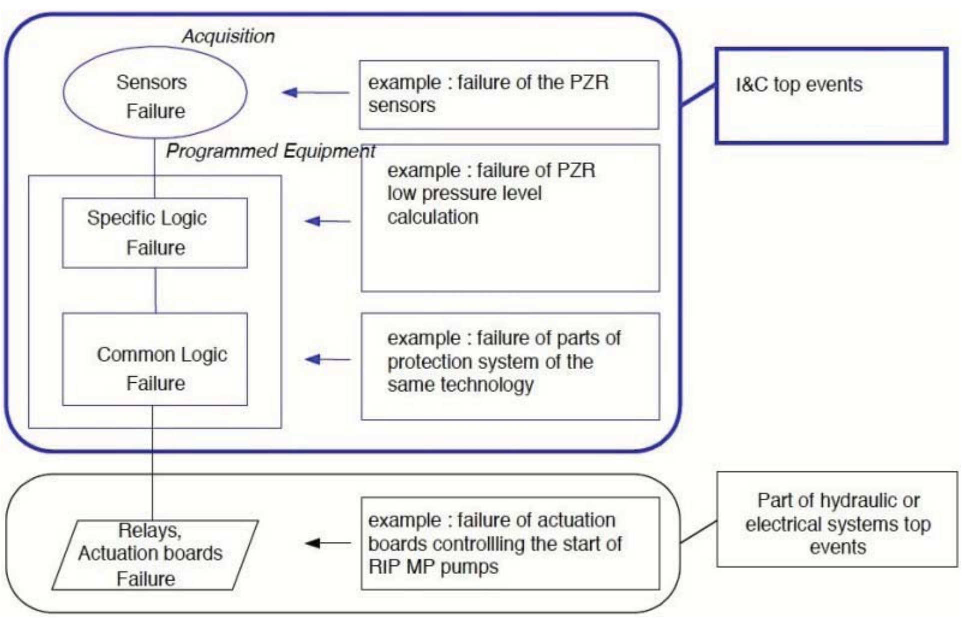

Figure 2. Representation of an I&C top event in the compact model.

Several factors have led to the consideration of an "Extended Compact Model" for future I&C systems:

- Digital equipment and systems are even more ubiquitous than in the N4 series
- Current digital I&C architectures tend to increase in complexity, in particular due to more ambitious functional capabilities, extensive use of data communication networks, and regulatory concerns regarding digital CCF
- A significant volume of operating experience with digital systems and equipment important for safety is now available

One of the major justifications of the use of digital equipment and systems is that advanced functional capabilities such as online equipment monitoring or improved human-system interactions may provide significant benefits to safety.

Figure 3 illustrates the concepts within the Extended Compact Model as envisioned in the SPINOSA project.

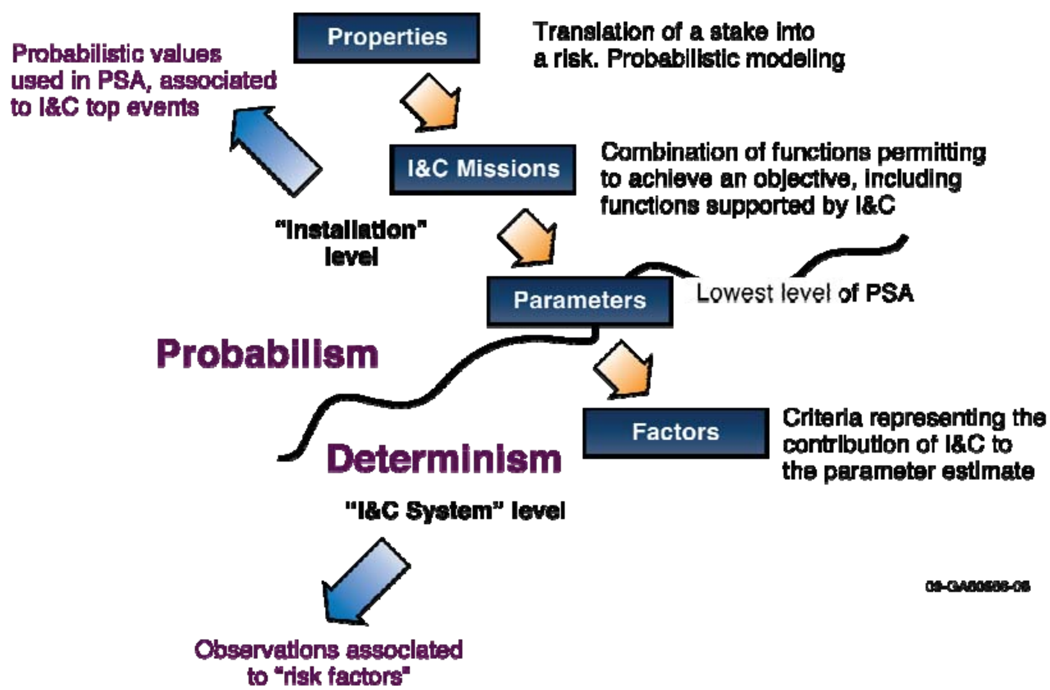

Figure 3. The key concepts of the SPINOSA approach from plant level to I&C level.

To establish the connection between the probabilistic assessment at plant level and the deterministic assessment at I&C level, the following step-by-step approach is proposed:

1. Identify plant safety properties that are dependent on I&C
2. Identify digital top events
3. Conduct sensitivity analyses to identify critical digital top events and spurious events
4. Identify parameters
5. Justify parameter values
6. Calculate the result of the PSA model.

The SPINOSA project is currently investigating an estimation method based on the identification of the elements (specification, hardware and software components, parts of design, manufacturing processes, operational procedures, etc.) that are the most likely to contain residual errors that could be activated during operation and cause systematic failures. This identification is based on a detailed knowledge of the design and of the development process of the digital equipment and systems in question. A taxonomy dedicated to systematic failures and supported by a field analysis will be developed.

The translation of deterministic consideration in probabilistic parameters permits the so-called analytic-systemic approach, using the "Extended Compact Model" in the PSA to represent the various effects of digital I&C in the global safety of the plant. Figure 4 graphically depicts the six-step concept.

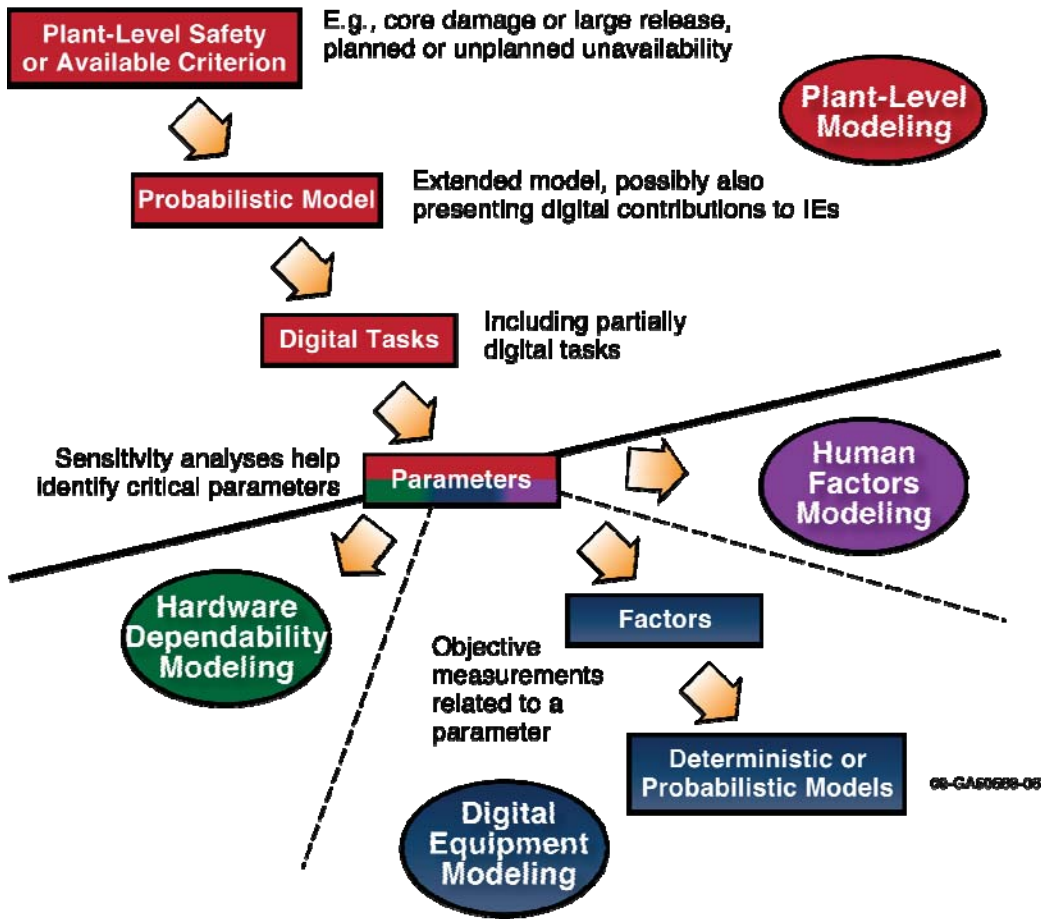

Figure 4. A proposal of general failure classification for I&C top events.

Several evolutions have led to the consideration of an "Extended Compact Model" for future I&C:

1. Digital equipment and more ubiquitous systems
2. Increased complexity in digital I&C architectures
3. Availability of a significant volume of operating experience with digital systems and equipment important for safety
4. Advanced functional capabilities, such as online equipment monitoring or improved human-system interactions that may provide significant benefits to safety.

The "Extended Compact Model" is currently being studied at EdF R&D in the ongoing research project SPINOSA. The research objective is to establish the connection between the probabilistic assessment at plant level and the deterministic assessment at I&C level, by a step-by-step approach, "descending" from PSA to critical parameters identification, and "ascending" from deterministic assessment of factors contributing to I&C safety to its representation in a PSA. The key points are the capability to perform sensitivity assessment at PSA level and a decomposition of the contributors to I&C random and systematic failures.

Future work will apply the approach on a full-scale safety case as part of the SPINOSA project, and lessons learned will be the subject of future publications.

2.1.6 Halden

The Norwegian Oil Industry Association (OLF) decided to implement an industry-wide integrated operations (IO) program as a new self-service concept for remote, real-time management of oil and gas fields on the Norwegian Continental Shelf (NCS). The decision was based on recommendations from a feasibility study indicating that IO can reduce operating costs by 20–30% and accelerate production by 5–10% through:

- Improvement of decision and work processes through implementation of IO and transfer of operations to virtual onshore operation centers
- Implementation of digital technology solutions that support remote, real-time management of drilling operations, reservoirs and production facilities, maintenance, and logistics.

The program's main goals were to establish a common digital infrastructure for offshore Norway, a set of industry-wide information security requirements for accessing this infrastructure; a set of common standards for the transfer of data from operations offshore to virtual operation centres onshore; best practices for remote, real-time management of oil and gas fields; and a knowledge industry that supports IO.

The purpose of the program was to develop an industry-wide platform for IO; define industry-wide practices for real-time management of oil and gas fields; communicate needs for R&D, competencies, digital products, and services associated with the implementation of digital services to universities and vendors; and revisit and further develop the business case for the implementation of integrated operations on the NCS.

The IO concept is based on the availability of new technology, particularly increased bandwidth, allowing for new work forms and sharing of data and information across distances. IO is a new approach to solving the challenges of having personnel, suppliers, and systems offshore, onshore, and in different countries. IO emphasizes removing the physical boundaries between people and making real-time cooperation across continents possible. IO involves using real-time data and new technology to remove the divides between disciplines, professional groups, and companies; information technology makes remote operation possible and forms the basis for new and more effective ways of working. Real-time transfer of data over long distances can be used to eliminate the physical distance between installations at sea and the support organization onshore, between professional groups, and internally between the oil companies and suppliers.

When working across professional boundaries and exploiting real-time data and technology that remove divisions such as time and place, the aim is to ensure better value creation for the future. Some of the benefits of IO are as follows:

- Improved HSI
- Increased efficiency

- Production optimization
- Improved recovery
- Better production control
- Better monitoring of equipment and more efficient maintenance
- Better resource exploitation
- Increased regularity (uptime).

A principal sketch of the collaboration between onshore and offshore personnel is shown in Figure 5.

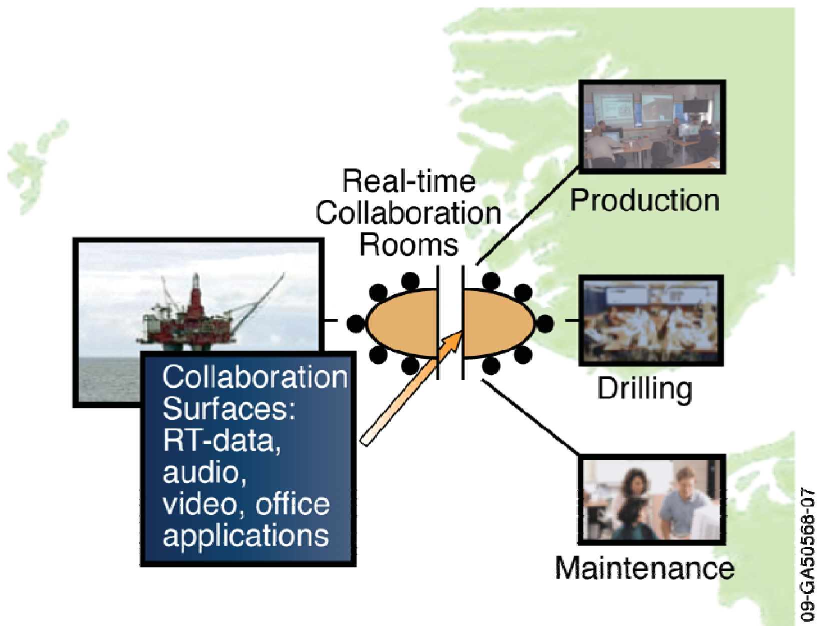

Figure 5. First generation IO as pictured by OLF.

The value potential of IO has been estimated in the form of increased recovery rates, increased and accelerated production, and reduced costs. Estimates are based on documented results from the implementation of IO measures in comparable fields, as well as conservative estimates of the effect of untried measures.

The effect of IO will create an added value in regard to the measures on which the fields have based their estimates for cost development and recoverable reserves. It is this added value that has been quantified.

The main benefits of implementing IO will be achieved through accelerated production from reserves and production optimization. This will require an aggressive implementation of IO on the NCS. Without aggressive implementation, the returns from IO may not be as great as anticipated.

To unlock the full potential, IO considerations must be a central component in early project phases and incorporated into the asset operational philosophy at the inception of the design. Figure 6 provides a conceptual framework for the implementation of IO approaches in NCS oil production. This figure shows the phased implementation of IO over time and the potential for improvements tied to its implementation. Fundamental to this is the transition of data to information to allow real-time decision making that is effective and grounded in knowledge, i.e., the appropriate people have the right information at the right time irrespective of their geographic location and organizational affiliation.

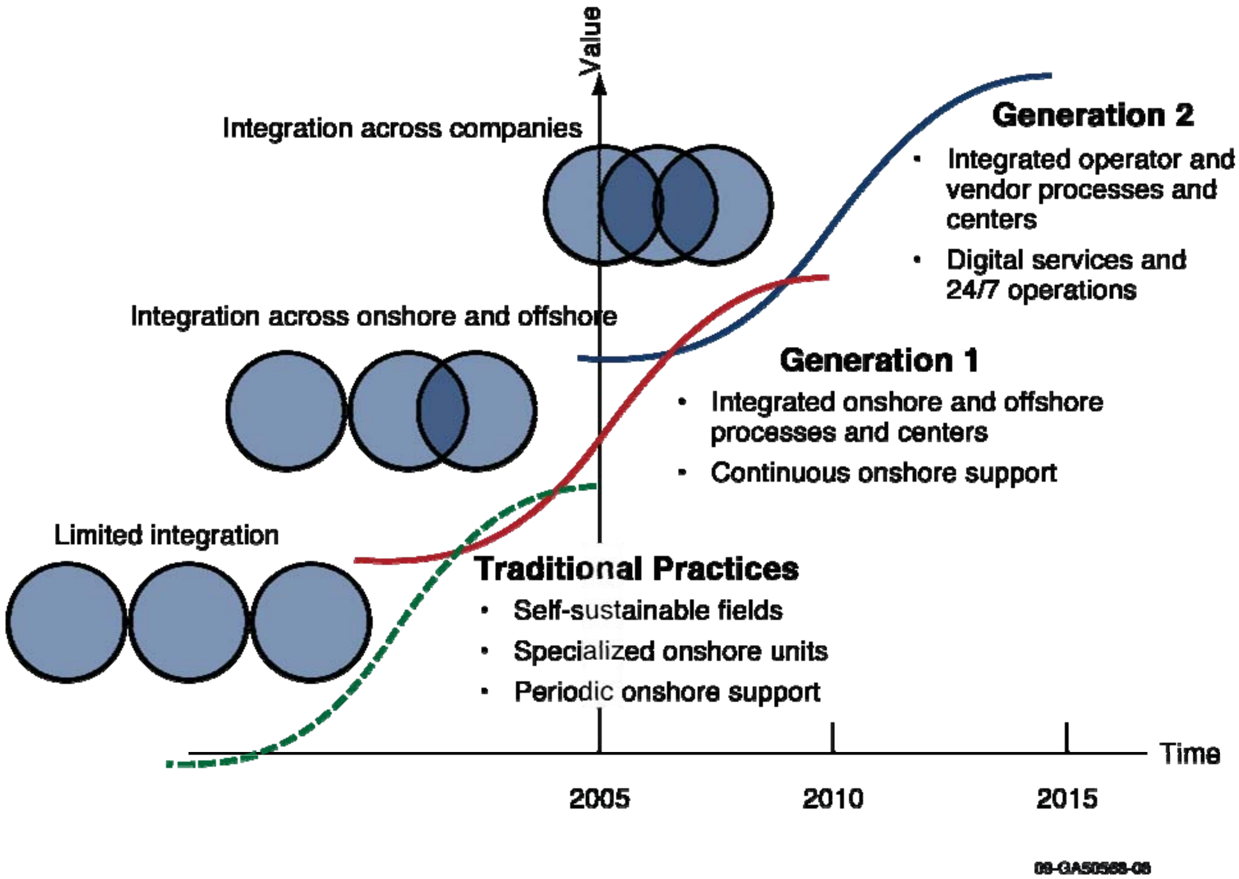

Figure 6. Integrated operations (IO) phased implementation plan.

Early project phases and the related documentation should have, as a core premise, an understanding of the decisions that need to be made to evolve a supporting organizational construct. In its simplest form, insights to a decision-making structure and consequently a potential organizational structure in outline may be revealed by the following questions:

- What decisions are to be made?
- What information is needed to be able to make those decisions?
- Which people are best qualified to make that decision?
- Where should those people be located?
- What work processes and technology are needed to present the decision makers with the right information at the right time irrespective of location and organizational affiliation?

The above questions should form the basis for the development of a subsequent information management strategy that addresses how to use, share, protect, and manage the information supporting the business objectives.

The operational philosophy defines how the asset is to be operated and thus drives the demand for technology and work processes, and not vice versa.

Furthermore, in achieving the twin goals of operational and project excellence, the roles and responsibilities of operators and vendors will be changed. Contracts and incentives will need to be adapted to accommodate the goal of IO and may result in new service offerings. More efficient ways of working will need to be developed if capital efficiency is to be preserved, and changes to organizational structure to support these new ways of working are to be expected. In support of these aspirations, the following emerge as key areas requiring specific consideration:

- Automation
- ICT infrastructure
- Information management
- An environment for collaboration.

The operational philosophy must be recognized as a tool that impacts the technology selection process during the project development phases and determines associated activities supporting the successful implementation of IO. The full implementation of IO will have significant economic value both for the commercial companies as well for Norway as an oil- and gas-producing country. Petro AS has estimated the added value on the NCS by employing IO extensively to be 150 billion Norwegian Kroner in net profit value term. OLF is about to release a similar scenario study about the economic impact of the next generation of IO on the NCS.

In its operational form, IO is about utilization of the new technology for working more efficiently and making better decisions. The areas of focus include both technology and the human organization. Work processes based on existing and new models for integrated work and cooperation are believed to be the main vehicle for changing the way of working according to the new IO philosophy.

2.2 Working Groups Reports

Three working groups met separately in parallel to discuss current limitations, potential issues that could affect long-term plant operation, and needed research in the following areas:

1. Information technology and I&C system modernization
2. I&C system acquisition and use
3. Modernization strategies.

These areas were previously discussed with asset owner representatives and were agreed upon as topics to serve as an initial point for an R&D focus for long-term collaboration and planning for implementation of digital I&C and HIS innovations. Each group was assigned leaders and facilitators to motivate discussion and exploration of the issues. Each of the groups was asked to report back to the larger workshop participant group on the following:

- **Outcome Statement.** The vision for the desired situation needed to achieve safe and efficient operation of nuclear energy systems using digital I&C systems. When considering a scenario of long-term operation (i.e., beyond a period of 60 years of operation), what is this vision as it relates to the particular technical area?
- **Capabilities.** A description of what is needed to achieve the outcomes. This includes technical advances that enable the vision, or it may address limitations or perceived shortcomings with the status quo regarding the technical area (e.g., fix, replace, reduce, etc.).
- **Critical Needs and Priorities.** Activities and outcomes that must be completed or achieved. This could include removing barriers and current limitations, demonstrating a new technology or approach, and implementing the time frames and sequencing of activities to establish priorities for research.
- **Suggested Activities and Pathways.** Potential means to achieve the outcomes or objectives. Participants were encouraged to recommend some of the potential means to achieve the outcomes or

objectives that they identified. These were intended to illustrate and shape expectations for what asset owners considered successful outcomes of research and development projects.

- **Assumptions.** Suppositions or conditions that are needed in order for a proposed technical solution to achieve its desired effect. For example, one assumption that was discussed was whether current Advanced Light Water Reactor digital I&C licensing efforts may facilitate future introduction of digital I&C technologies into currently operating plants.
- **Technology Gaps.** Gaps in current technology capabilities that are, or could become, barriers to success in digital I&C technology integration. On the basis of discussions regarding capabilities and priorities, working groups were asked to identify these gaps, including the availability of needed technologies in the time frames desired, market factors (e.g., the ability to qualify a potential type of technology for nuclear applications), decision-making factors (e.g., the knowledge and confidence to make decisions regarding new technology introduction), and others that could be addressed through a program of collaborative R&D.

Each of the working groups addressed some aspects of these ambitious goals, and those discussions are summarized in the following section.

2.2.1 Information Technology (IT) and I&C System Modernization

2.2.1.1 Capabilities

The IT and Modernization group identified visualization technology, new automation technologies, sensors and other technologies for improving data quality and availability, and cost justification methods as high priority capabilities requiring improvement to support long-term operations.

Enhanced visualization capabilities are needed principally to support decision making and usability—especially for key control actions and decisions that affect plant availability and have the potential to impact safety. This includes suitable application of advanced user interfaces and assistive information technologies (e.g. computerized operator support systems) that afford enhancements over stove-piped analog information technologies. Much of the integration that must occur with information in nuclear plants today is performed by operators and other experts using their own mental and perceptual resources. Newer digital technologies provide improved means of integrating information from diverse sources and can display the results more clearly and concisely for direct use.

Improvements in sensor data are needed to achieve distributed awareness of process conditions. They offer the ability to supply data to distal groups, thereby creating virtual presence among operational groups. One aim of such technology is to create a shared workspace and common operational frame of reference between remote individuals and groups working with the same information. Such advances will support one of the strategic aims expressed by asset owners, which is to increase centralization and use of expertise. Improved visualization technologies will also facilitate situational awareness and decision-making capabilities.

The working group also stressed the need for automation to support workload reduction and to reduce the likelihood of human errors. Automation is needed to achieve the economic gains desired from IT modernization efforts and to support centralized functions. Automation is envisioned as taking advantage of the increased accuracy in measurement and control capabilities afforded by digital technologies, additional functionality not currently available with analog controls, and as a means to implement new functional paradigms of system control. The group recognized some of the challenges that may accompany future trends in increasing automation, such as increased cyber security issues. Although not discussed in detail, the group recognized that these and other challenges need to be accounted for (e.g., as a part of the cost analysis of technology introduction) and addressed as an explicit aspect of strategies for implementation.

Ensuring sensor and other data quality and the redundancy and independence of the data from these sensors was identified as another high-priority capability. While there is a need to make sure that the right information gets to the right places, it is also necessary to be confident of sensor information. It cannot be taken for granted that information is always reliable and accurate. The reliability must also be verifiable in a time-efficient manner. Two aspects of data reliability were considered—first that data, as they are collected, must be reliable, and the second, that IT systems must preserve the accuracy of the data. Adequate levels of redundancy and independence within the data streams are required, especially if they will be used to make decisions about the plant. Having only one pathway to transfer the information allows the possibility for introducing bias or other data communication errors. The IT systems that may be introduced for nuclear plant monitoring and control will be expected to meet the same requirements that exist for today's data or signal delivery systems. This is a point that will drive qualification issues of IT systems for nuclear plant applications, and it will need to include methods for assessing diversity, redundancy, and defense in depth of the digital system that are likely to be much different from those currently applied to analog systems.

2.2.1.2 Suggested Activities and Pathways

The activities and pathways discussed by the IT and Modernization group focused on the support of some of the key capabilities discussed above. In addition to these high-priority items, other suggestions were made regarding the workforce and leveraging existing technology from outside of the nuclear industry.

The first pathway the group suggested focused on the need to better articulate opportunities for high-value capability insertion. An activity for this topic would be to provide a formal way of assembling the constraints, criteria, and opportunities for the nuclear industry's digital systems needs (current and future) as they relate to plant operation and system control. In particular, it could be valuable to prioritize/articulate the high-return technology insertions, which, if fulfilled, could provide the most benefit. Highlighted in this discussion were the institution of communication techniques with the plant and utility management and development of educational materials for workforce training.

The next activity was related to leveraging experience from other industries (e.g., create a living database of experience in nuclear and other areas). The team's opinion was that digital technology is starting to show distinct operational costs savings throughout several industries—that is, it is becoming a much more mature science. Now is the time to take advantage of this maturity by the nuclear industry; it could be financially advantageous.

As part of this effort, one pathway should be to gather information from other industries that would leverage the lessons learned, best practices, and experiences from other fields that use similar technologies. A living record, like a dynamic database, would be the preferred method of collecting and storing, and using this information.

An important support pathway suggested by the team was to identify needs for research, demonstration, testing, and evaluation for each capability. In particular, an industry need and numerous stakeholders would benefit from a project that demonstrates the benefits of modern digital systems to the nuclear industry.

Finally, several points were made with respect to the activities surrounding the preparation for impacts of technology modernization on the workforce. Workforce development and training elements need to be present in every aspect of research, demonstration, and evaluation of new technologies. A gap between two segments of the current nuclear field workforce seems to exist: there is a generation of very knowledgeable people regarding the plants and nuclear technology, but they are less familiar with modern digital technologies. On the other hand, there is a new generation of workforce is very familiar with digital technologies but not with the existing plant technology. This is true for the R&D community as well as for industry. Human resources necessary to implement the new digital systems need to be identified.

From the workforce training and impacts perspective, it is also necessary to consider the change in culture surrounding the introduction of digital technologies. Software engineering in modern process control systems is very different than analog technology. Moving to new software-based process control technologies will require a change in the way people think about codes. The engineering approach to software is useful, but the software engineering designs are integrated and much more reliable because they are approached from a systems point of view.

A few additional activities were also mentioned by the group. One is to address the integration of new technology with existing technology. There are aspects of the current operations that the next generation of plants should adopt, and there are aspects that will be demonstrated in the new plants that should be retrofitted in the currently operating fleet. The working group questioned how this can be organized and combined in an effective and useful way. Essential to this discussion is the support of standards for plant data reporting and storage and the continued partnership with original equipment manufacturers (OEMs).

2.2.1.3 Technology Gaps

The group identified a number of gaps in capabilities and technologies that will need to be addressed to support the implementation of new technology in nuclear power plants, including:

1. Tools and technologies to support introduction and training on the new technologies within the existing workforce.
2. Projective mechanisms for assessing the reliability of new technologies. A consistent scheme to model and quantify the reliability of digital systems has not been established, although methods do exist and can be made available for research and trade studies.
3. Methods for estimating the costs and impacts of I&C obsolescence and induced mechanisms for failures of *in situ* plant digital I&C. This includes the ability to estimate maintenance costs associated with operating equipment and systems beyond their intended service lifetimes.
4. Design of I&C and software for maintainability (both locally and remotely). If a code is written properly it can be designed *for ea*se of maintenance and troubleshooting—just as other components are designed. Different approaches to maintainability both locally and remotely need to be considered for components (especially software components).
5. Methods and tools (diagnostic aids) to categorize failures for power plant systems. Another related need is the function and task analysis to justify the application of advanced control algorithms to plant evolutions and also to find plant and personnel productivity improvements. An important issue is to design the transition between human tasks and computer control.
6. Technology and demonstrations to support connectivity among work groups, make expert knowledge available, and improve integration and connectivity among systems, data, and personnel. This includes issues such as sensor data reporting, storage, and network integrity. A need exists for database organization and data collection automation.
7. As part of a larger program on plant modernization, additional research is needed on how to identify the most appropriate functions to automate, methods for performing trade studies about human-system function allocation, issues of teamwork and automation, situation awareness in highly automated and digital systems, adjustable control, verifying the performance of automation, and

issues associated with robustness and resilience (e.g., management of degraded automation and information, minimum inventory, and associated issues). Associated with this are issues of workforce specialization, targeted size, and location.

8. Under the topic of visualization, a number of gaps were discussed. In order to exploit the capabilities of modern visualization technologies, cost-effective methods for creating 3D models of existing facilities and for effective demonstration are needed.
9. Many of the R&D activities will require simulation or bench-scale research facilities. Plant simulators are primarily used for training and are mostly not physics-based. A gap exists with respect to the need for multi-platform, modular simulation technology to support technology R&D, as well as for conducting scale-up studies and tests and evaluations.
10. Regarding data collection, access, and integrity, there is a need to confirm that smart sensors can perform in radiation environments (and other harsh environments of a nuclear power plant). There is a need for data regarding low radiation dose survivability in detectors for boiling water reactors (BWRs) in particular. There is also a gap in knowing how to exploit smart sensor technology. A large number of electromechanical devices exist in the field. For which of those would it be beneficial to switch to electronic sensors without incurring huge expenses?

2.2.2 Data Acquisition and Use

2.2.2.1 Capabilities

The Data Acquisition and Use breakout group discussed several desirable capabilities of digital I&C systems as they apply to operations of plant systems and components; the improvement of condition monitoring, diagnostics and prognostics; and characteristics of plant management needed to implement a strategic approach to adoption of digital I&C.

A smoother operation of plant systems and components is an important capability of new I&C. “Smoothness” was defined in terms of the startup and shutdown of the plant equipment. The group agreed that a large number of equipment operations are operated on discrete on or off states, which adds to the wear and tear on the equipment. If changes in component states were to be more gradual, the equipment would last significantly longer. To better understand the impact of state change and usage patterns on the SSCs, the group suggested keeping track of usage (i.e. pump cycles) in the same way that a printer stores information on number of pages printed.

Condition monitoring, diagnostics, and prognostics are integral to system sustainability. Condition monitoring includes monitoring plant SSCs that are subject to aging effects that are not typically monitored in current plants. Improved diagnostics and, potentially, prognostics are necessary for understanding plant conditions, predicting future status of the plant, and preventing the need for safety system actuations. The development of an operating experience database system that can be integrated into an expert system is important to prognostics and would allow for improved knowledge management and its application to plant engineering. Condition monitoring includes not only collecting and documenting knowledge and expertise, but also establishing a structure and system for knowledge management that can be sustained and supplemented over time.

The three capabilities of plant management needed to effectively implement advanced I&C are:

1. **Safety system actuation.** This includes systems that monitor safety systems to determine that their functions are working properly and to manage safety margins in real time.

2. **Responsiveness of the plant to the electrical grid.** A plant that is responsive to a smart grid is important to the future electricity generation industry. To achieve this capability, plants are needed that are adaptable through improved transient response and power-following technologies.

3. **Enabling advances in automation and communication.** Automation of a knowledge management database among plants can replace substantial amounts of analysis by humans that is needed to search for and match current operating conditions in real time to assist in operational response decision making. The development of an automated system that compares transient signatures to occurrences at other plants by automatically searching and analyzing a database of events and responses could improve plant operations. A diagnostic and prognostic system that is based on stored operator knowledge and experience can reduce the dramatic loss of information that accompanies a loss of personnel when knowledge transfer is incomplete.

2.2.2.2 Critical Needs and Priorities

Instrumentation, standardization, and visualization were the critical needs and priorities identified by the Data Acquisition and Use group. The group agreed that new instrumentation technologies are needed that are much less cumbersome (e.g., portable and wireless) and are durable, affordable, stable, upgradeable, and less expensive than current technology, while providing the same or better safety margins. Therefore, R&D to support these goals is needed. The research should also focus on how to better plan for the integration of new technology for replacement and integration of emerging technology into systems as they mature and before they become obsolete. R&D activities need to generate technologies that meet specific client needs for I&C technology so that the R&D work will not sit on a shelf and be forgotten. To prevent this from happening, direct involvement in R&D planning and implementation by all stakeholders is needed.

To take advantage of many of the aspects of new I&C, a standardized format is needed for data sharing among plants and a formalized mechanism to share information between operating companies. An assessment of several possibilities to achieve sharing include standard models and databases, an open standard to allow consulting, “plug-and-play” models, standards for instrumentation and data collection that allow easy discussion and transfer of information, and centralization of operations. With standardization comes the ability to communicate among various stakeholders. One way to achieve communication is through data visualization, but there is also a need for standardization of visualization technology throughout the industry. More specifically, the concept of “Status at a Glance,” which is a visualization method of analyzing data graphically, was proposed as a potential development need.

2.2.2.3 Suggested Activities and Pathways

Critical needs and priorities can be met through activities that focus on plant organization, classifying new technologies, and monitoring plant systems.

Research on top-down functional analysis of plant systems and work groups, with a focus on human resource allocation, was the first suggested activity. Research efforts should look at all major plant functions, identify all basic and essential tasks, and determine what can be automated and what should remain as human tasks. Case history studies of how business models have been changed from human-based to collaborative technology-based approaches, such as IO, can serve as successful case studies. Efforts are needed to produce a standardized approach to detailed information and function analysis. Research should include studies to establish sensor requirements so that the best role for automation can be determined.

Other activities that need to be pursued to address data acquisition and use include studies of plant aging as related to selecting instrumentation, selecting a minimum set of measurements needed for monitoring and assessment, creating a graded approach to data quality, and a convention to support the facilitation of real-time plant monitoring and data sharing.

Research is needed to determine what current technologies could be used to improve plant performance and measurement capabilities. Metrics and criteria by which to rate these technologies need to be defined so that the technologies can be categorized by need or potential use.

A specific research activity is the creation of high-fidelity models to gauge plant performance and that can serve as a platform to support research such as condition monitoring or prognostics and diagnosis. Such models should have enough detail and refinement to make operational decisions and to be used as diagnostic tools. A "virtual plant" could provide information about all plant parameters, provide troubleshooting assistance for daily operations, and act as an advisory system to the control room. If there is a difference between model parameters and plant parameters, the system should help determine the cause of deviation.

Support for a high-fidelity model would be based on:

- Creation of plant-wide analytical capabilities with integrated models of full plant systems and structures
- Automation of plant diagnostics.

The model would need to have the capability to analyze parameter departures from the predicted values to inform the operator when there is a problem, but it should be robust enough to be able to differentiate actual problems from false alarms. The model should differentiate between required safety systems and non-safety systems. The real-time verification and validation of data would be needed to support the high-fidelity model goals.

2.2.2.4 Assumptions

The Data Acquisition and Use breakout group made three important assumptions. The first was that cyber security concerns will soon be resolved on an industry-wide basis. This assumption is necessary to implement many of the data-sharing activities envisioned. The second assumption was that all future instrumentation would be "plug-and-play" and "off-the-shelf" and comply with industry standards. This dramatically simplifies upgrading to modern technology (from a forward-looking standpoint) and allows for much greater flexibility of the monitoring systems. The plug-and-play instrumentation is also assumed to comply with industry standards and thus streamline qualifications efforts. The third assumption focused on improving knowledge management at all levels of the industry. An information management structure will maintain engineering and operator knowledge and experience.

Further, the commitment to cooperation among operators, utilities, vendors, universities, research facilities, and national laboratories throughout the country and internationally is a necessary condition for a strong research program to succeed. This includes the organization of the way data are shared among companies, laboratories, and universities with a focus on maintaining security (cyber security in particular).

2.2.2.5 Technology Gaps

Technology gaps discussed included high-speed field buses and wireless technology. Under the wireless technology gap there was also a discussion of the radio frequency interference in the plants as being an issue that currently has no technological resolution.

Further, the group suggested that research be conducted regarding the calculation and use of synthetic plant variables (derived values). And, finally, the presentation and visualization of information to improve communication and data sharing (within the plant and throughout the industry) is a suggested research activity.

2.2.3 Modernization Strategies

2.2.3.1 Modernization of Information Technology

Modernization was described as a move towards maintaining an *integrated* I&C system that makes it simpler to sustain a standard for modernization, rather than to enhance individual systems on a piecemeal basis. Given this premise, a research challenge is to identify cost or performance drivers and quantify the benefits of modernization for stakeholders. Investment protection and impending obsolescence of currently used technology were identified as drivers to modernize I&C. For example, condition-based or reliability-centered maintenance can reduce maintenance costs but may require additional I&C and staffing which would increase costs. A benefit could be the avoidance of a premature shutdown of the plant.

2.2.3.2 Assumptions

The working group established four major assumptions and some supporting assumptions:

1. Modernization of the I&C systems over a nuclear power plant's lifetime is necessary due to I&C obsolescence.
2. Data will be collected in some way for use in evaluating the costs and benefits of modernization. Sources of this data will include research findings, nuclear usage history, past plant performance, non-nuclear industry data, and data from research collaboration with laboratories and universities. Since data in an easily accessible and usable form does not exist at the present time, an effort will need to be instituted to assemble it. As part of the effort, NRC would be expected to collaborate with industry to gather the data, and would then independently interpret it.
3. Uncertainties about digital I&C characteristics, including quality, reliability, life cycle, and cyber-security issues, can be resolved. Therefore, resolution of issues related to the reliability, quality, and life cycle of the digital I&C and cyber-security are subjects for a research program. Within this context, it was also assumed that while the nuclear industry does not drive development of new digital technology, the nuclear industry is a significant player in the implementation of new technology.
4. Most nuclear plants will be run as a fleet in the future, instead of as individual plants. This mode of operation is assumed to be more economical because decision makers can be in a centralized, smaller, and more easily informed group, as in an IO organization described earlier. Modernization on a fleet-wide basis improves the economy of scale and yields a better return on investments made on demonstrations and testing.

2.2.3.3 Capabilities

Capabilities to Support Decision Making

Information sharing mechanisms and methods and metrics to extract the economic costs and benefits that include means to evaluate the uncertainty of these estimates are necessary to support decision making and should be developed as part of the research agenda. Existing information sources include both nuclear (e.g., INPO, LERs, Compsys lessons learned reports, utility records, technology or vendor databases) and non-nuclear sources (e.g., telecommunication, aerospace and military sectors). A key research effort is to assess risks and costs associated with modernization and to compare these to risks and costs associated with the current analog systems using common metrics. Such an analysis must consider:

- Running the plant as is.

- Modernizing older plants.
- Decommissioning and rebuilding new plants.

While there are decision-making techniques that can be applied depending on the different philosophies adopted (e.g. operate the plant as is to minimize financial risk from I&C modernization, invest and risk a large amount of capital into new plants and new technology, etc.), a research program is needed to develop and support an industry-based approach to make decisions on adopting and implementing new technology.

The development of a demonstration facility where benefits of modern technology can be shown is a capability that should be developed. The facility must include more than just I&C—it must include IT, HSI, and business process capabilities. A demonstration facility needs to be able to articulate the concept that the true value of base infrastructure investments can be spread among multiple business centers to realize total value (e.g., in a smart grid, automated meters help the billing process, but it can also be used as grid sensors). Ideally, there would be a sharing of costs and risks across projects, units, and utilities through standardization and information sharing. The demonstration facility needs to be a flexible, living system. It must be designed in a modern, service-oriented architecture manner. It is necessary to incorporate modeling and simulation in the demonstration to be able to estimate the benefits of changes and to evaluate historical data as to how it could have been improved.

The ability to capture, analyze, and implement technologies and practices from other power generation sectors is a necessary capability because they have already implemented modernized I&C, and nuclear should not have to start anew. Although the nuclear field has some unique requirements that pertain to qualification or licensing, this research should focus on how to capture and credit the experience, understand the differences, and credit the similarities between nuclear and other power generation sectors.

Capabilities to Support Modernization Implementation

The methods for implementation will be driven by the goals of modernization (e.g. is the plant I&C being improved because of the need to improve some aspect of operation or is obsolete technology being replaced). Strategic planning for implementation is a necessary capability for going forward. Such planning includes (1) choice of vendors, platforms, and designers; (2) decisions relating to the use of commercial off-the shelf (COTS) I&C equipment from other industries; (3) alliances and cooperation between implementation stakeholders; (4) planning of target architecture and infrastructure; and (5) the planning of engineering and deployment organizations. Capabilities also have to include the support disciplines in engineering, PRA, and software engineering. It will be necessary to include provisions for a learning curve for vendors, designers, utilities, regulators. It will also be necessary to identify and characterize benefits of the implementation plan in terms of cost, human resources, safety, environmental issues, adaptability, scalability, replace-ability, long lifetime, and public perception.

In the implementation process, it is first necessary to recapture the design basis. I&C has been used to monitor active components. However, for life extension of the existing fleet, there is a need to monitor passive components. This offers a new challenge, and research is needed to determine how best to make the transition.

The capability to design future I&C systems that are simple and offer ease of use for operators may be achieved through standardization that can be licensed. Designing for sustainability, upgradeability, and replace-ability are also key considerations. The goal should be to design an I&C system that is meant to be upgraded every 5 or 7 years, because technology changes occur rapidly and I&C systems should keep up with advances. The new plants must take into account this variability over the entire life of the plant. It will be also necessary to interface with existing systems and equipment. Guidelines for deployment on sites will be needed. Such guidelines should cover topics such as installation and commissioning, recruitment, training, transition periods, and the identification of impacts on procedures, work organization, equipment, and need for new competencies.

2.2.3.4 Activities/Pathways

Three categories of decision-making activities were identified for future work: systems (databases), programs, and methods. While the capabilities outlined above are mostly directed towards extraction of information from data resources, asset owners also need a capability to analyze the operational experience databases that can be accommodated by plant management for decision making. The analysis would aim to capture experience and lessons learned from plant-provided data. The utilities also need methods and metrics that can be used to extract the economic costs and benefits and the uncertainty of these estimates. The activities should consider sustainability, i.e. building in the capability for longevity rather than building for a pre-specified lifetime. A significant amount of information can be gained from surveying other similar process industries to advance the state-of-the-art in the nuclear industry with transferable business cases.

Under the Modernization Implementation category, activities that would lead to improved reliability, availability, maintainability, and sustainability of I&C systems were suggested. One activity would be to develop methods and guidance that add I&C capabilities for monitoring passive SSCs and phenomena (underground piping, cabling, reactor containment, concrete, etc.) to improve surveillance for 60+ life extension. A second activity was to provide concepts and methods to design for replacement cycles.

2.2.3.5 Technology Gaps

The group listed *in situ* condition monitoring and cabling replacement as two important technology gaps. Alternates to cable replacement are wireless technology, which must be secure and fiber optics. Another technology gap focused on the need for advanced diagnostics or prognostics. There will be a need for new fully digital systems, including platforms based on emerging technologies such as field programmable gate arrays (FPGAs) and central processing unit (CPU)-based systems. There is a need for mobile technology such as electronic notebooks, personal digital assistants (PDAs), etc. Finally, there are technology gaps regarding data models and I&C standards, including combined I&C standards and digital technology standards, and a common data model.

3. WHAT ARE OTHERS DOING?

3.1 U.S. Nuclear Regulatory Commission (USNRC)

The U.S. Nuclear Regulatory Commission (NRC) is an important stakeholder in the I&C arena for the long-term sustainability of nuclear power plants since they are responsible for making safety decisions regarding life extension of the plants. For the plants to operate beyond their current lifetime, the NRC must license them. The NRC currently is focusing most of its I&C research on new and advanced reactors. However, for the I&C arena, most of the work performed for these new and advanced reactors is directly applicable to the LWRS Program arena. The results of research in digital I&C and human factors areas for new reactors can be applied to existing power plants as they prepare for life extension.

The NRC Office of Nuclear Regulatory Research is responsible for I&C research. The I&C branch and the Human Factors and Reliability Branch, are developing plans that will address questions similar to those posed in this report. Preliminary versions of these plans are described below.

3.1.1 Human Factors Research

NRC sponsored research to identify potential impacts of emerging technologies on human performance in advanced reactors and the technical bases needed to address them. The results of this research are summarized in the draft Nuclear Regulatory Commission/Contractor Report (NUREG/CR) titled "Human Factors Considerations with Respect to Emerging Technology in Nuclear Power Plants" (NUREG/CR-6947). This project identified topical areas where additional knowledge is needed to update NRC review guidance and regulations to support the staff in its safety reviews of the human performance aspects of new generations of NPPs.

The objective of NRC's human factors research is to develop the regulatory infrastructure (review methods and tools) to support the review of new and advanced reactor applications. These methods and tools will allow NRC staff to perform independent licensing reviews of the new human factors issues that will be related to existing and advanced reactors (e.g., better review methods and criteria for advanced, fully integrated, cockpit-style control rooms and unreviewed technology).

NRC has identified nine human performance issue areas for advanced reactors. Eight of these areas would be directly applicable to the LWRS Program and include:

- **Impacts of new operational designs on operator functions and tasks.** Human performance principles should be developed for job and task design to accommodate operational changes. Moreover, research would be valuable to aid in evaluating an applicant's specification of the new knowledge, skills, and abilities that may be required of operators resulting from the operational changes of new control room using I&C.
- **Allocation of functions for automation and staff.** Digital I&C facilitates the rapid, repetitive acquisition and analysis of data from a variety of plant systems and processes, the fusion of that information into higher-level representations (e.g., trend graphs), and the prospect of passively implementing certain actions (e.g., passive safety systems). These factors will affect operator functions and tasks at both the individual and team levels. It is desirable to specify more fully the impacts on human performance of automation based on the functions it will perform (sensing, analysis, decision-making, action) and the physical processes upon which the functions are performed. Research is needed to enhance the knowledge of the human performance principles that should be applied to allocate functions and tasks between personnel and automation to support human performance, particularly the potential impacts of degraded I&C when automated functions may fail.

- **Process complexity, opacity, and advanced HSI technology.** Digital I&C and human interface technology have the potential to greatly increase the complexity of the operators' tasks and their understanding of the underlying physical plant model and its current operational state (i.e., situational awareness). Data, methods, and tools would be valuable in assuring that key aspects of plant processes are represented in the HSI in a way that supports accurate situational awareness within and between operational personnel and that the HSI designs, as implemented, focus the operator's attention on the functions that support the safety of the plant.
- **Workload variations, transitions, and reduced staffing models.** New digital-based control rooms are likely to incorporate advanced HSI technologies such as high-resolution digital displays, multi-windowing capability, and a variety of split-screen effects to visualize related or independent aspects of processes. In addition, advances in software visualization techniques may be incorporated to form higher-level representations (data fusion) of lower-level process elements. These types of designs lack "persistence" (i.e., it is not always available), and the change from a display panel to even multiple display screens tends to reduce the availability of information (known as the "keyhole effect"). Task analytic data would be valuable to determine the characteristics of advanced HSI technologies that will adequately support human performance for the functions allocated to the operators. This information can also be used to assess workload, workload transitions and staffing needs, and tools and methods that can improve staff efficiency.
- **Teamwork and communication.** This research can develop quantitative and qualitative parameters for how remote communication and collaboration can be facilitated while maintaining safe operations. Advances in team training and assessment methods could be adapted to evaluate local and remote communications methods in advanced power plant designs.
- **Computer-based procedures and intelligent automation reliance and compliance.** Computer-based procedures are increasingly used in plants that are modernizing and can be expected to be a principal design feature of newly built systems. Available research indicates that computer-based procedures fundamentally alter how personnel process and share information and develop and maintain situational awareness. Additional research is needed to establish standard practices for computer-based procedures, including approaches to information display and sequencing, backtracking capability, checks that critical steps have been performed, and means to communicate procedure sequence to other personnel who are not actively observing displays. The human performance implications of using paper-based procedures as a back-up to system failure, as currently permitted, also should be assessed.

  The design of intelligent aids to assist in various aspects of power plant operation should be guided by principles that will allow operators to rely on the systems to reduce workload and help solve problems, but not allow over-reliance by simply complying with automated system recommendations. This requires a balance between system reliability, providing redundant information about system state to operators, and methods for operators to verify the functioning of automated systems. Human performance research has identified particular types of systems, such as automated flight management, which have a level of opacity and complexity of operation that may lead to operator distrust or over-reliance, which may have been the case in the recent accident on the Washington, D.C. Metro. Research would be valuable to define appropriate levels of operator aiding that will balance reliance and compliance to provide the technical bases for staff reviews.
- **Alarm management.** Alarm management is an area of continuing concern in complex system design. Prior NPP events associated with "alarm avalanches" have led to preprocessing and prioritization schemes to reduce the number of noncritical alarms. It also has been found that operators can sometimes use noncritical alarms as a means of ensuring that a particular aspect of the process is functioning as expected. Digital I&C will greatly increase the ability to measure parameters against expected or critical values and to fuse disparate data into aggregate parameters. Research is required

to evaluate applications of digital I&C for alarm management and display, including incorporation of likelihood processing so that rare-event probabilities are considered in the overall approach to discrete alarm annunciation. Research also would be valuable on multimodality (visual, voice, tactile) alerting systems embedded in advanced HSIs and the impact of their characteristics on operator attention.

- **Human Factors Engineering (HFE) methods and tools.** Traditional human performance methods such as function allocation, task, and human error analysis are manually intensive and time consuming and do not scale well to the complexity of a NPP because the methods were originally developed to focus on self-contained human-system interactions. It is common in the human performance community to call for more and better methods to perform these kinds of analyses—usually by advocating an automated approach. These methods need to be assessed and validated for use in the nuclear community.

3.1.2 Digital I&C Research

The objective of NRC's digital I&C (DI&C) research is to develop the regulatory infrastructure (review methods and tools) to support the review of new and advanced reactor applications. These methods and tools will allow NRC staff to perform independent licensing reviews of the new I&C technologies that will be an integral part of existing and advanced reactors (e.g., better review methods and criteria for advanced, fully integrated, cockpit-style control rooms and unreviewed technology.

Specific research that would be applicable to the LWRS Program is expected in the following areas.

- **Develop analytical models for autonomous control of advanced reactors.** This research area entails the development of information and models needed to review and examine the advanced autonomous control methods that will be used in advanced reactors.
- **Develop regulatory criteria for control systems used to review advanced control algorithms that may be used in safety systems in advanced reactors.** This area of research will investigate the points at which control and safety systems are integrated and the extent of automated actions. In addition, this effort will develop information on the current methods likely to be used in advanced reactors and investigate the potential issues of using these algorithms in a reactor setting.
- **Analyze advanced diagnostic and prognostic methods needed to support licensing of advanced reactors.** Research in this area will entail the review of both current and developmental methods and systems proposed for these reactors and their integration into safety systems and systems important to safety.

3.2 Electric Power Research Institute (EPRI)

The keynote presentation from EPRI identified several critical issues that need to be addressed to allow operating plants to have long-term operation of up to 80 years or even more. Such issues include:

- Aging and obsolescence
- Need for new staff and bringing up their level of expertise quickly
- Maintaining high levels of safety and meeting new regulatory and environmental requirements
- Reducing the likelihood of human error, equipment damage, forced outages, exposure to radiation and other harsh environmental conditions (e.g., heat, cold, chemical) and challenges to safety
- Maintaining economic viability (improve efficiency and reliability and reduce time to perform jobs, time on critical path during outages, need for rework)
- Leveraging scarce resources

- Training supplemental workers who need to be brought to acceptable performance levels as quickly as possible
- Making technologies expected by younger generation available
- Addressing the issues to enable extended plant operation with new tools and capabilities.

For existing nuclear power plants to operate beyond 60 years, I&C systems will have to be modernized, with additional upgrades planned to gain substantial benefits from digital I&C and HSI. Areas that require further research include:

- **Sensors and data collection and transmission equipment** that works in harsh environments, can be wireless, self-testing and diagnostic, with I&C and HSI information and communications architectures
- **Monitoring, diagnostics, and prognostics** that support equipment reliability and predictive maintenance to reduce likelihood of equipment damage, unplanned outages and safety challenges as well as maintenance costs and likelihood of human maintenance errors
- **Simulation and visualization** that can:
    - Revolutionize training
    - Improve planning and decision-making
    - Support knowledge management
    - Improve design, reduce errors, and facilitate early input from users
    - Link design, procurement, planning, installation, and plant acceptance into a seamless information process
    - Support development, tuning, dynamic performance testing, man-in-the-loop operability testing, and human factors evaluation
    - Support rapid evaluation of proposed changes
    - Provide visualization of key documents showing interrelationships and linking references
- **Automation and intelligent agents** that can aid in reducing workload and the likelihood of human errors by automating procedures and repetitive and error-prone activities, use intelligent agents for information access, incorporate automatic checks for human and system activities, reduce time demands and stress levels allowing humans to better focus on essential activities, and enable humans to do what they do best and systems to do what they do best
- **Human-system interfaces** that facilitate well-informed situation awareness and decision-making with an emphasis on user-friendly design for the user to accomplishment of jobs through the application of human factors engineering principles with information presented in a manner that it is quickly and easily understood

Finally, there is an underlying emphasis on technology transfer and training that includes knowledge capture and presentation and the use of lessons learned and best practices to avoid learning curve mishaps by integrating knowledge captured into the design information, training content, and procedure content structure for lifetime retention and use.

3.3 International Activities

3.3.1 Committee on the Safety of Nuclear Installations

The Working Group on Human and Organizational Factors (WGHOF) of the Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency (NEA) , Committee on the Safety of Nuclear Installations (CSNI), developed a technical opinion paper (TOP) to identify a set of research topics that will enhance the state of knowledge related to the human and organizational factors (HOF) aspects of new and advanced NPPs and control station modernizations in existing plants. The results of this research will help assure reliable human performance when using new technologies. To develop this TOP, the WGHOF reviewed several reports that identified research questions in HOF areas and combined the recommendations from those reports with the findings from a 2006 workshop organized by the WGHOF and the Halden Reactor Project (HRP). This TOP is intended to promote the coordination of international research activities in HOF and to serve as an aid in identifying research programs that can be supported by international agreements on topics of common interest.

The research issues identified in these documents were integrated to form broader research program topics. The eight research areas are discussed in next section, "Research Program Topic Areas."

3.3.1.1 Research Program Topic Areas

1. **Human Factors Engineering (HFE) Methods and Tools**

   The research question in this topic area is: What are the strengths and limitations of new HFE methods and tools and what criteria should be applied in evaluating their acceptability for use in advanced reactor and control station designs?

   The objective of the HFE methods and tools program is twofold:

   a. Develop review guidance and acceptance criteria to ensure that new HFE methods and tools are being appropriately applied to NPP design
   b. Identify and/or develop tools for use by regulatory authorities to support reviews of the HFE aspects of NPP design, operations, and maintenance (examples include tools to assess plant staffing profiles and tools to examine changes to risk-important human actions).

2. **Operating Experience from New and Modernized Plants**

   The research question in this topic area is: What can be learned to improve HOF from collecting and analyzing detailed operating experience from current Generation III and III+ plants, as well as plants that have undergone extensive modernizations?

   The objective of this program area will be to collect the operating experience of current Generation III and III+ plants in areas pertaining to HFE.

3. **Evolving Concepts for the Operation of Nuclear Power Plants**

   The research question in this topic area is: What are the most safety-significant human performance implications of new concepts of operation in advanced NPPs and modernized control stations?

   The objective of this research program area is to prepare regulators and the industry for evolving concepts of operation and how these concepts of operation can impact human performance and ultimately plant performance.

4. **The Role of Automation and Personnel: New Concepts of Teamwork in Advanced Systems**

   The research question in this topic area is: What are the safety-significant HFE implications of automation and new concepts of teamwork in advanced systems?

The objective of this research program area is to better understand and define this new concept of team and to develop guidance for the review of function allocation and human-automation interaction in human-system teams.

5. **Management of Unplanned, Unanticipated Events**

   The research question in this topic area is: What are the characteristics of HSIs in new NPP and control station designs that are necessary to ensure personnel are able to manage unplanned and unanticipated events?

   The objective of this research is to improve the understanding of how operating crews assess situations, make decisions, and take actions so that HSI designs, training, and procedures can support the crews in the face of unplanned, unanticipated events. Understanding and responding to such events involves many aspects of plant design, including alarms systems, information systems, computer-based procedures, and new decision aids that are intended to support crews. The goal of this research is to develop a better understanding of how these systems can be brought together to ensure that operators are able to manage novel events.

6. **HSI Design Principles for Supporting Operator Cognitive Functions**

   The research question in this topic area is: What are good practices for implementing and using computer-based procedures (including backup), and ensuring reliance on and compliance with automated decision aids?

   The objective of this research program topic is to develop guidance for designing and evaluating new HSI technologies, including (1) their features and functions, and (2) the implications for human performance of and response to HSI failures. The main focus in this program will be the role of the principal HSI resources: alarms, displays, controls, procedures, decision support aids, and interface management features.

7. **Complexity Issues in Advanced Systems**

   The research questions in this topic area are: (1) What attributes of a new design contribute to its complexity from the operator's perspective? (2) What is the impact of increased complexity on human performance? and (3) How can complexity be measured?

   The objective of this research program will be to identify the underlying factors that make a plant, system(s), the HSIs, scenarios, tasks, or operations complex to plant personnel.

8. **Organizational Factors—Safety Culture/Safety Management**

   The research questions in this topic area are: (1) What are good practices for assuring a shared, strong nuclear safety culture and effective safety management practices across organizational and national boundaries and among new organizations and personnel entering the nuclear industry? (2) Where problems exist, what are the most effective means to assess corrective actions?

   The objective of this research is to identify effective methods for transmitting and maintaining a shared, strong nuclear safety culture and assuring the implementation of rigorous safety management practices among organizations and individuals who are new to the nuclear industry and will be designing, constructing, and operating new and advanced nuclear facilities. In addition, the research will prepare regulators to encourage and assess these new methods and practices.

4. SUMMARY AND CONCLUSIONS

4.1 Summary

4.1.1 Direction Setting Presentations

Digital I&C systems and components are deployed in a number of power generation settings worldwide. The U.S. nuclear power sector differs from these other settings in several key respects: analog systems that have been operated beyond their intended service lifetimes dominate I&C systems in place today; regulatory uncertainty and associated business risk concerns are dominant contributors to the status quo; and current utility business models have not evolved to take full advantage of digital technologies to achieve performance gains. As a consequence, digital technologies are implemented as point solutions to performance and obsolescence concerns with individual I&C components. This reactive approach is characterized by planning horizons that are, by nature, short—and typically allow for only “like-for-like” replacements to be made. This results in a fragmented, non-optimized approach driven by immediate needs. As a long-term strategy, this is not sustainable in light of the evolution of I&C technology, the availability of skills needed to maintain this antiquated technology, and the high costs and uncertainties associated with doing so.

In addition, the nuclear power industry does not drive the development of technology or availability. Rather, it reacts to developments implemented in other sectors of power generation. Thus, the potential benefits from additional from additional digital functionality are rarely realized. Digital replacements of this kind do not displace any of the old costs, but rather add to them. Hence, digital technologies do not impact the current business models of asset owners or become viewed from the perspective of long-term nuclear asset management. This tends to marginalize the potential benefits that can be achieved through technology development and deployment.

However, the nuclear industry as a whole recognizes that it is achieving ever-diminishing returns on continuing efforts to improve performance. In part, many of the early potential gains from human performance improvement programs have been achieved and utilities are beginning to recognize that they are approaching the limits of returns on human performance initiatives—if only as an optimization strategy. Compounding this is the fact that the quotidian costs of energy production in the nuclear power industry continue to be driven by operation and management (i.e., personnel) costs, in contrast to the fossil power generation sector whose daily generation costs are driven by the price of fuel. Taken together with such business factors, the individual force-fitting approaches to digital technology deployment, ever-increasing obsolescence, and long-term safety and reliability of analog devices necessitate a reconsideration of potential solutions involving digital technologies for nuclear energy systems. This reconsideration must include the long-term issues associated with monitoring and managing aging and degradation of plant systems as well as initiatives that must be undertaken to ensure the long-term sustainability of I&C systems in a way that achieves availability of a cost-competitive, reliable nuclear energy supply.

A technology-driven approach in this R&D area alone will be insufficient to yield the type of transformation that is needed to secure a long-term source of nuclear energy base load; a new approach is needed. An effective R&D initiative must engage the perspectives of stakeholders—asset owners, regulators, vendors, and R&D organizations—in order to articulate and initiate relevant R&D activities.

A theme that echoed in the direction-setting remarks of nuclear asset owners is that digital technologies are required—not just desired—to meet the operational demands of a 60-year or longer asset lifetime.

To displace the piecemeal approach to digital technology deployment, a new vision for efficiency, safety, and reliability is needed that leverages the potential of a range of digital options. This includes (1) consideration of goals for nuclear power plant staff numbers and types of specialized resources, (2) targeting O&M costs and the plant capacity factor to ensure the commercial viability of proposed long-term operations, (3) improved methods for achieving plant safety margins and reductions in unnecessary conservativisms, and (4) leveraging expertise from across the nuclear enterprise.

The majority of nuclear asset owners in the United States and Europe were represented at this workshop, which included just four utilities: Exelon Corporation, Entergy Corporation, Duke Energy, and Électricité de France (EdF). These companies own and operate 94 commercial nuclear units, not including other currently proposed mergers and acquisitions by EdF in the United Kingdom and the United States.

A program of R&D activities is needed to develop critical capabilities of digital technologies to support long-term nuclear asset operation and management. This includes comprehensive programs intended to (1) develop national capabilities at the university and laboratory levels; (2) create or renew infrastructure needed for long-term research, education, and testing; (3) support creation of new technologies and intellectual property; (4) facilitate understanding of, confidence in, and transition of these new technologies to the private sector; and (5) to achieve successful licensing and deployment in the commercial nuclear energy industry. Needed activities include:

- Sensor development and testing as well as characterization methods and technologies for a range of non-destructive evaluation (NDE) applications. This includes sensors for measuring material properties to derive parameter estimates of specific aging and performance features and analytic capabilities and methods for characterizing the state and condition of material properties in order to obtain “diagnostic” accuracy about material aging and degradation.
- Activities to build upon sensors, characterization, and more refined diagnostics to enable prognostic assessments of materials and performance to be made. This requires incorporation of information from material science studies.
- Improvement of nuclear power plant monitoring systems. The move from periodic, manual assessments and surveillances of physical systems to online condition monitoring represents an important transition.
- Modernization of information and control technologies used in nuclear energy production. Asset owners and regulators alike view these as key enablers in the dialogue of long-term asset and safety management. Advances in other industries (especially in North Sea oil production) that have led development in advanced IO using visualization to support real-time operations provide compelling evidence and case studies for the nuclear power industry.

Research in visualization, process control, and automation is envisioned through leveraging long-term collaborations with leading international research institutes and capitalizing on new national capabilities for simulation-based technology development and testing. The long-term objectives of these research activities are to demonstrate new concepts of operations for nuclear power generation assets that address the need for technology modernization, improved state awareness, improved safety, and optimized asset management.

There is a recognized need to conduct research to improve our knowledge and understanding of new technologies in order to ascertain how to best implement them in a highly risk-averse industry. Confidence has to be developed through demonstrations, pilot studies, and progressively more realistic application settings to vet and refine technologies.

4.1.2 Workgroups

The three breakout session groups developed highly consistent lists of priority research needs. These needs were focused on (1) visualization technology; (2) automation; (3) collection of information from the plant, from other plants, from research facilities and from international nuclear and other industry experience; (4) simulation; (5) decision-making support; (6) support to the implementation of modern I&C, improved condition monitoring, diagnostics, and prognostics; as well as (7) issues of design for maintenance and ease of replacement for the software components of the IT. In general, there was an emphasis on a need for improvement in the presentation and visualization of information that can be used to improve communication and data sharing (within the plant and throughout the industry) as a suggested research pathway. All the groups supported the idea that an automated knowledge database system that can help manage information exchange among plants would be desirable. Such a system would include operator tacit knowledge and experience that could be potentially automated for designers and operations.

All three work groups emphasized the importance of verification, validation, and reliability of data streams, as well as their use and transmission among experts, decision makers, and systems. Cyber security concerns with regard to data sharing were discussed by two of the groups. The resolution of cyber security issues may be needed before some aspects of modernization can be implemented. Problems or threats that accompany trends of increased automation and expertise centralization, which require a great deal of information and data exchange, may limit implementation of I&C. Therefore, cyber security is a technology challenge that must be addressed before successful implementation of some modernization strategies.

Not capturing the true cost of operating the plant (e.g., personnel and excess parts) remains a problem. There needs to be a way of capturing and analyzing costs and benefits to accurately assess the benefits of modernized I&C. A technology gap in mechanisms for capturing the costs of I&C obsolescence and in the existence of mechanisms for projecting failures of *in situ* plant electronic I&C exists. Thus, new methods to capture and identify maintenance costs are needed to quantify the cost of obsolescence. As part of this effort, capabilities need to be developed that specifically relate to an agreed-upon economic model. Two methods are suggested to answer the cost/benefit question: value proposition and risk-informed methods. There is a need to better articulate opportunities for high value capability insertion to better articulate the benefits of modern technology, and digital I&C in particular to management and the key stakeholders.

To accomplish much of the work suggested a demonstration facility and capability is needed where benefits of modern technology can be shown. The facility and capability must include more than just I&C; it must also include IT, HSI, and business process capabilities. To implement such a facility and capability there is a need for a commitment to cooperation among operators, utilities, vendors, universities, and national laboratories throughout the country and internationally. Such a facility and capability should be capable of performing research or integrating the results of research from others on topics such as automation, visualization, condition monitoring, diagnostics and prognostics, sensors and other technologies for improving data quality and availability, integrated operations, and human-system interface, as each of these were listed as important technology gaps.

There was recognition that other fields (e.g., petrochemical, defense, aerospace) have implemented modern I&C and that the nuclear industry must capture, analyze, and implement technologies and practices from these other fields so that lessons learned from other arenas can be assimilated. Although the nuclear industry has some particular constraints, there is a research need to determine how to capture and credit the experience, understand the differences, and credit the similarities between nuclear and other fields.

Finally, knowledge management was a focus topic for all three breakout sessions. To make use of past experience and expertise, a structured, industry-wide knowledge management system is needed. Engineering, operations, and maintenance knowledge from across the industry needs to be captured and validated in a system that can be accessed by designers and operators in a form that is easy to use and can be integrated into expert advisory or automated systems. This technology gap should be addressed in a structured R&D effort.

4.2 Conclusions

A program of R&D activities is needed to develop and enhance critical capabilities of instrumentation, information, and control technologies for long-term nuclear asset operation and management. This includes comprehensive programs intended to (1) develop national capabilities at the university and laboratory level; (2) create or renew infrastructure needed for long-term research, education, and testing; (3) support development and testing of needed I&C technologies; (4) improve understanding of, confidence in, and decisions to employ these new technologies in the nuclear power sector; and achieve successful licensing and deployment.

This workshop hosted by the Ohio State University Academic Center of Excellence in Instrumentation and Controls brought together a number of stakeholders from the research, vendor, services, and asset owner communities. A series of presentations and discussions focused on I&C technologies and related issues as they have the potential to influence the sustainability of nuclear energy systems in the operating fleet. Keynote presentations provided examples of the effects of aging and obsolescence of current I&C technologies at plants. As summarized earlier, a number of conditions characterize the current situation with existing I&C systems and motivate the need for transformation, including the following:

- **Many I&C systems in use today have been operated beyond their intended service lifetimes.** Although they remain safe due to the inherent design characteristics of the systems they control, they are evidencing the effects of aging and functional obsolescence.
- **The workforce entering the industry today is no longer being trained to maintain these older systems, a trend that will continue.** With the progression of time, these systems will become more unfamiliar to the workforce and become costlier and more difficult to maintain. In addition, it may become more difficult to attract a future workforce to work with what many may come to perceive as antiquated technology.
- **The nuclear power industry as a market segment does not drive developments of new digital I&C technologies.** It adopts what other market segments and process control markets already employ. Solutions are rarely tailored specifically for a nuclear market and may not be qualified for some nuclear power applications.
- **The current approach to deploying digital I&C is largely as piecemeal replacements for failing analog devices.** This marginalizes the many potential benefits of newer digital I&C
- **Rather than reducing costs of operation and maintenance,** this way of introducing digital I&C simply adds to the costs of maintaining the resulting collection of systems.
- **Uncertainty, characterized as a lack of familiarity and the desire to avoid risk,** currently inhibits licensees from attempting to implement the scale of modernization they believe necessary to achieve a long-term sustainable collection of modern I&C technologies. Modernization efforts underway or attempted are not perceived as successful and this reinforces the perception of these projects as being risky.

As a result of these conditions, inertia prevails although asset owners unanimously agree that transformational change is needed.

The OECD Halden Reactor Project provided a briefing on their ongoing efforts to support one kind of transformational change in the North Sea petroleum producing industry. A paradigm shift continues to occur regarding how best to manage production assets that are allocated among onshore and offshore locations. The approach to reengineering, termed 'Integrated Operations' employs advances in I&C technologies together with work process analysis to centralize expertise, reduce costs, and focus activities on supporting production. As a result, some of the approaches to production that are historically based have been redesigned and employ new technology to accomplish their purpose. The sector as a whole is experiencing reduced costs and new efficiencies in production, and a longer term strategy has been articulated for continued integration and improvement.

The nuclear asset owners at the workshop share a number of features and interests with the case study provided by Halden. Their companies respectively operate the majority of commercial nuclear energy systems in the United States and Europe. For them, solutions that can be achieved employing economy of scale are desirable and may provide a substantial portion of the justification for change. They also are experiencing declining gains or asymptotic returns on their constant productivity reinvestments and perceive that a combination of newer technology and process reengineering may provide them with the kind of gains in productivity that may keep nuclear power plant operation and profitability in line with other power generation assets.

Following the direction setting presentations and discussion, workshop participants met in parallel groups to discuss with asset owners and vendors the future of I&C technologies used by the nuclear power industry. A premise of the discussions was that transformational change is needed. Discussions were directed toward defining the changes needed, assumptions and conditions that may be needed to achieve change, and the capabilities and to some extent technologies that are desired. To the extent that they were able, working groups were also asked to recommend activities or a path forward to initiate the change and transformation needed. The following summarizes recommendations and discussions of the working groups.

- The costs of I&C obsolescence at existing plants bear on the issue of long-term operation. These costs are not currently captured and methods are needed to establish the financial justification for modernization. Participants agreed that a pilot modernization strategy of a candidate facility should be developed that would address these issues. As well, the strategy should target specific O&M costs, safety, and reliability issues that may be impacted through I&C replacement and modernization. Solutions that can be implemented to achieve economy-of-scale benefits should be identified, as well as candidate high value capability insertions that could serve as a reference for successful modernization.
- There is a perception and awareness that modernization of I&C technologies has occurred and continues in other sectors of power generation. Lessons learned from these industries should be developed to improve our understanding of the benefits and constraints of modernization efforts. Knowing that qualification of technologies for application in nuclear systems often requires additional effort, activities should be planned to collect data and experience that can be supportive of qualification. This will also provide some of the requisite information required by the NRC.
- A number of key assumptions were made or otherwise mentioned that bear further investigation as they relate to I&C modernization and sustainability issues. This includes the extent to which future modernization of I&C may benefit from reviews of modern I&C contained in ALWR submittals and whether cyber security issues can be effectively managed in data rich I&C architectures without cancelling many of the gains expected from the new technology.

A number of desired capabilities and outcomes were identified within the working groups. This serves as a useful starting point for planning; additional efforts are needed to develop greater specificity for R&D efforts. Advanced capabilities are needed in the following areas:

- **Improvements in data generation from plant processes and systems and tools to support their use across the nuclear enterprise.** As a part of targeting O&M costs and seeking improvements in power production, asset owners plan to establish centralized groups of experts to monitor, troubleshoot, and otherwise support plant operations. Specialized data and tools are needed to support the activities of these groups. This includes tools for analyzing plant equipment data, tools to facilitate the use of data, collaborative work systems to support distributed work, and the needed technologies to ensure the security of plant information.
  - Methods to verify and ensure data quality are needed, from the point of generation to the application data base, commensurate with the sensitivity of the intended use and because of the potential for greater reliance on their use.
  - Visualization to support real-time operations. This includes improvements in the types of data and their presentation available to operational staff for decision making and control. Visualization capabilities are also desired to support geographically distributed work groups conducting collaborative work. This was cited as an economy-of-scale-type solution by asset owners.
- **Improved capabilities for monitoring of nuclear power plant systems.** The move from periodic, manual assessments and surveillances of physical systems to online condition monitoring represents an important transition. In this regard, both the workshop attendees and the NRC have identified common needs to better understand the technologies that may be considered, and to conduct research to approach its integration and licensing.
- **Activities to build upon sensors and characterization data, to develop more refined diagnostics capabilities.** Advances in these areas are needed as are improved methods and algorithms to perform assessments of systems and materials. Tied with advances in online monitoring, these advances are needed to achieve condition monitoring and characterization for active systems and passive structures, systems, and components.
- **Facilities in which to carry out higher risk, longer term research, needed because of the risk most asset owners judge as being inherent in digital I&C modernization.** As discussed at the meeting, the vision for integrated I&C technologies to support long-term operations are beyond the scope of R&D of vendors and asset owners alike. Hence, facilities are needed to support a broad base of collaborations among researchers and other stakeholders to investigate future I&C concepts.

Several agencies and organizations have identified needs and established research programs to address some of the issues as well as some of the specific technologies discussed in this workshop. The U.S. NRC, for example, has identified a number of programs that are needed to support the development of a regulatory technical basis for some of the topics that may also be addressed through research in the LWRS Program. The OECD Nuclear Energy Agency (NEA) Working Group on Human and Organizational Factors (WGHOF) and the Electric Power Research Institute (EPRI) also have research initiatives that are being carried out with asset owners and in a number of countries that may provide the opportunity for collaboration and more effective research. Discussions have also taken place with the OECD Halden Reactor Project concerning joint research and participation in their collaborative research. There may also be other opportunities for collaboration that can be identified during out-year R&D activities. Collectively, some coordination and collaboration should be pursued, both to maximize the value of the planned research as well as to avoid unnecessary research and duplication.

Through long-term collaborations with leading international research institutes and capitalizing on new national capabilities for simulation-based technology development and testing, research in visualization, process control, and automation is planned. The long-term objectives of these research activities are to demonstrate new concepts of operations for nuclear power generation assets that address the need for technology modernization, improved state awareness, improved safety and optimized asset management.

There is a recognized need to conduct research to improve our knowledge and understanding of new technologies in order to ascertain how to best implement them in a highly risk averse industry. Confidence has to be developed through demonstrations, pilot studies, and progressively more realistic application settings to vet and refine technologies.

Appendix A

Workshop Schedule of Events

Appendix A

Workshop Schedule of Events

Thursday March 19th 2009

7:00-8:00am	Breakfast / Registration
8:00-8:30am	Welcome / ACE Perspective (Carol Smidts, Tunc Aldemir)
8:30-9:00 am	DOE Perspective (Rich Reister, Bruce Hallbert)
9:00-10:00am	Utility Panel -Digital I&C Needs (Ken Thomas – Duke; Ray DiSandro – Exelon; John Mahoney – Entergy; Thuy Nguyen - Electricite de France; Joe Naser – EPRI)
10:00-10:15am	Break
10:15-11:15am	Utility Panel Continued- Digital I&C Needs
11:15-11:45am	Experience with Digital Upgrades in the Oil Industry in the North Sea- Halden Project (Jan Porsmyr)
11:45-12:00pm	Breakout - Composition and Setting of Expectations
12:00-1:00pm	Lunch
1:00-3:00pm	Breakout- Discussion Sessions
3:00-3:15pm	Break
3:15-5:30pm	Breakout - Discussion Sessions
6:00-9:00pm	Franklin Park Conservatory Banquet

Friday March 20th 2009

7:00-8:00am	Breakfast
8:00-10:00am	Breakout - Discussion Sessions
10:00-10:15am	Break
10:30-12:00pm	Breakout - Discussion Sessions
12:00-1:00pm	Lunch
1:00-3:00pm	Breakout - Discussion Sessions
3:00-3:15pm	Break
3:15-4:45pm	Reports from Breakout Sessions
4:45-5:00pm	Closing Remarks

Appendix B

Workshop Attendees

Appendix B

Workshop Attendees

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