5. GENERATION OPTIMIZATION

Every kilowatt-hour of electricity produced by a nuclear plant replaces a kilowatt-hour of electricity that would have to be produced using some other technology. At present, the only viable alternatives to nuclear for baseload power plants are coal, oil, and gas, all of which produce greenhouse gases, and varying amounts of chemical pollutants. Assuming no new nuclear plants will be built in the near term in the United States, then the strongest contribution that can be made by the nuclear energy sector to minimizing greenhouse gas accumulations is to ensure that currently operating plants produce the highest energy output consistent with safe operation. The maximization of output requires that the plants be kept operational through the end of their safe, reliable, and economic lifetimes, that their performance be optimized for maximum power output and availability, and that the operating licenses be renewed to extend the plants' operating lifetimes. The highest justifiable power levels and the greatest possible capacity factors are vital.

The goals of the generation optimization element of this Plan are to address key technological issues which impact the potential for license renewal and that support the desired improvement in operating effectiveness. This improvement is necessary not only for increased plant output, but also to ensure the economic competitiveness and viability of the nuclear option as the U.S. utility industry moves into a deregulated environment. As mentioned in Chapter 1 (future medium term goal on competitive nuclear energy generation options, objective related to ALWR advances), an additional goal within generation optimization is to transfer and apply technologies developed for advanced reactors to meeting current plant needs. Examples of this include improved source term methodologies, improved combustible gas control systems (passive autocatalytic converters), etc.

Research and development for generation optimization are needed in the following technology areas:

1. Installation of Digital Instrumentation and Control (I&C) systems

   R&D for this area needs to address the technological and institutional and regulatory issues which impact the feasibility and cost effectiveness of replacing deteriorating, obsolete, and inefficient analog I&C systems with digital systems, particularly for safety and important-to-safety systems.

2. Advanced Sensor Technologies

   R&D for this area is required to improve the accuracy, reliability, and comprehensiveness with which key process variables are measured and other plant information is obtained.

3. Advanced Monitoring, Diagnostics, and Control Systems

   R&D for this area needs to focus on the development of systems that will provide effective on-line and off-line support to plant operations, maintenance, and engineering staffs to optimize plant operation and maintenance functions.

4. Human Factors

   Research is required to fill the gaps in the knowledge and understanding of human performance issues as they relate to changes in plant equipment and procedures. Tools and methods need to be developed to enhance human performance and minimize human errors.

5. Advanced Safety Analyses

   R&D for this area needs to focus on determining the transients which limit the rated power of a plant in order to develop advanced safety analyses methods which can allow increases in rated power while maintaining adequate margins for safe operation.

6. Advanced Nuclear Fuel

   R&D for this area needs to focus in the short term on improved reliability and resolution of recent licensing issues related to high burnup fuel performance. Longer term R&D should focus on achieving even higher burnup fuel cycles, using higher enrichment fuels, in order to extend the time between refueling outages.

Each of these technology areas contributes to the goal of generation optimization through increases in one or more of the following subgoals:

a. To keep existing plants operating (as long as they are safe and commercially viable),

b. To get more hours of operation out of each plant per year, and

c. To get more power per hour of operation out of each plant.

The specific quantities that are most significantly improved by each technology area are indicated in Table 1.

Table 1. Technologies for Optimization of Nuclear Plant Power Generation

	Digital I&C Systems	Sensor Technologies	Monitoring, Diagnostics, and Control Systems	Human Factors	Safety Analyses	Nuclear Fuel
More Years of Operation/Plant	X		X			
More Hours of Operation/Year Per Plant	X		X	X		X
More Power/Hour of Operation	X	X	X		X	X

A description of each technology area is provided below, along with specific work to support the objectives in the area.

5.1 Installation of Digital Instrumentation and Control (I&C) Systems

Resolution of issues surrounding the use of digital instrumentation and control systems, especially in a licensing environment, is needed for wide-scale implementation of this technology. The management of the degradation of analog instrumentation and control components in many operating plants is reaching a critical point in many countries. Most plants have obsolete components that are no longer being produced commercially and that need frequent recalibration and maintenance. Their failure has led to about 38% of the Licensee Event Reports filed by utilities. Many plants in the United States and around the world are considering upgrades utilizing digital-based systems to take advantage of a commercial base of vendors; improved resistance to calibration drift; and increased capability for self-diagnosis, data handling, and easy maintenance. However, there are several outstanding issues concerning the use of digital technologies in nuclear plants. The U.S. utility industry must address these issues when they replace older safety systems with new digital safety systems. Furthermore, the Canadians, the French, and the British have also had to address issues involving the use of digital systems in new plant designs.

The issues concerning the use of digital I&C in nuclear power plants have been documented recently in a National Research Council report Digital Instrumentation and Control Systems in Nuclear Power Plants: Safety and Reliability Issues (National Academy Press, 1997). These issues are described briefly in the following text.

The use of digital I&C systems may introduce new types of failure modes that can affect operations and/or safety. Modern applications of digital I&C use multilayered architectures in which local controllers perform component-level control functions, higher-level controllers coordinate in a supervisory way the control of systems of components, and still higher-level stations perform plant-level supervisory functions and data analyses. There are performance aspects of systems which transcend the particular components that comprise the system or even the functions of the system itself. These "systems aspects" include the performance of the architecture of the I&C system, the communication between various levels of the architecture, the allocation of functions to various parts of the system, the distribution of computing resources throughout the system, the security of the system, and the ability to upgrade the system components easily while dealing with the concern that unconnected, uncoordinated systems could reduce operational efficiency and have the potential to overwhelm the operator. The issue concerning these systems aspects, particularly for backfits, is that the effects of operation of one component on another in a distributed multilayered system are sometimes overlooked. There have been instances of "data storms" in which so much data is requested by some subsystem that the communication networks bogged down.

A second issue is the lack of a generally accepted solution to specifying, producing, and controlling the software needed in high-reliability nuclear systems. Most software QA processes involve controlling the software design process and/or testing the software produced for satisfaction of the requirements. Experience has shown that neither of these approaches has proven totally satisfactory.

A third issue is the possibility of common modes of failure in software-based systems. One way of achieving high reliability in systems is through the use of redundancy. The threat of a common mode of failure (or a common cause of failure) raises concerns about reliability claims if the redundant systems cannot be proven to be diverse. It is difficult to prove that software-based systems are diverse if they serve the same functional requirement. This is true because so many software systems use the same building blocks and basic algorithms, generally at a low level (such as square root calculations) unseen by the system designer.

A fourth issue is difficulty in assessing the safety and reliability of digital systems. The British, Canadian and French nuclear industries have struggled recently in attempts to prove reliability of 10^{-6} failures on demand for their new digital protection systems.

A fifth issue is the lack of an agreed-upon, effective methodology for designers and regulators to use in assessing the overall impact of computer-based, human-machine interfaces on human performance in nuclear plants. Digital technology offers a rich environment for advisory systems, display systems, and alarm filtering. However, it is difficult at best to show that reliance on these types of digital-based systems will reduce the number of cognitive and/or manual errors.

A sixth issue is the need for a mutually acceptable methodology for evaluation and acceptance of the use of commercial off-the-shelf (COTS) digital systems in nuclear plants. The National Research Council panel pointed out that the use of off-the-shelf technology for digital systems is a good idea if the application in the nuclear plant is very similar to that in the commercial experience base. If the application is very different, however, the fact that there have been many instances of successful usage in other applications is by no means adequate proof that the new application will be successful. EPRI, the utilities and the Nuclear Regulatory Commission (NRC) have recently agreed on a methodology for the use of COTS equipment in nuclear applications. This methodology needs to be tried in some demonstration applications.

A seventh issue examined by the NAS panel is "case-by-case licensing." The concern is that the regulatory bodies around the world will examine digital applications on a case-by-case basis, without a common set of reference points. NRC has recently issued a revised Standard Review Plan for licensing digital-based I&C which should provide stability to the process of licensing of new systems; however, there is still a concern about regulatory ratcheting, in which the number and scope of questions increases from one license application to the next.

An eighth issue is a concern about the adequacy of the technical infrastructure within the NRC and the nuclear power industry to support the use of digital I&C in safety and safety-related systems. The research program of the NRC and the industry seemed [to the NAS panel] to be disjointed, with no strategic thrusts. The panel recommended that a strategic plan be developed, drawing together the needs [and perspectives] of the major stakeholders. There is also a concern that the research supported by NRC, the industry, and DOE does not receive strong peer review by recognized experts in the human factors and the software engineering communities.

5.1.1 Current R&D

EPRI, several utilities, and the NRC have been involved in some aspects of digital systems for nuclear plants for the past few years. A guideline was developed to identify requirements for licensing digital systems that has been endorsed in a generic letter by the NRC. Another guideline was developed on electromagnetic compatibility and it received a safety evaluation report (SER) from the NRC. Good progress has been made in the generation of an approach for utilization of COTS equipment in nuclear plants that is acceptable to regulators and designers alike. The guideline on COTS has also received an SER. A guideline was also developed on the generic acceptance of commercially available programmable logic controllers (PLCs) for safety and safety-related systems. An SER is going through final approval on this. EPRI has developed strategic planning methodologies to support utilities in determining when and how to modernize I&C systems. These methodologies are used for developing Life Cycle Management Plans, Plant Communication and Computing Architecture Plans, Upgrade Evaluation Reports, and System Maintenance Plans. EPRI has also developed a number of digital system implementation guidance documents besides the ones mentioned above. These include guidelines on software verification and validation, abnormal conditions and events, and requirements definition.

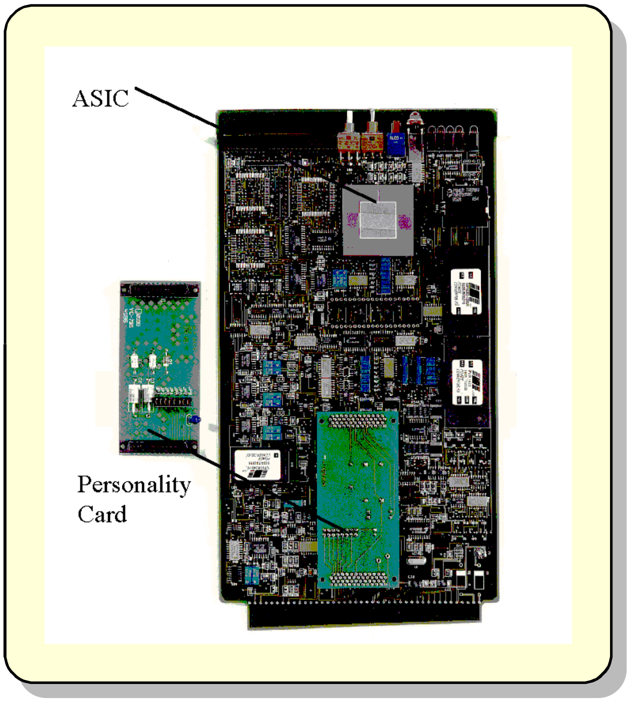

Figure 5-1 Universal ASIC Modules Directly Replace Analog Cards in Nuclear Plant Protection Systems

The NRC is funding some work in the development of regulatory guidelines for digital-based systems as well as some work on the environmental effects caused by high temperature, smoke, and electromagnetic pulses on digital systems. Furthermore, the NRC has collaborated with the Halden Reactor Program to investigate automated tools for evaluation of software. The Department of Energy (DOE) and EPRI developed a requirements document which called for the use of digital-based systems in Advanced Light Water Reactors (ALWRs). This document was approved by the NRC. However, all of this work performed to date was at a conceptual level and did not include detailed I&C system design. There is no DOE program on digital I&C replacements for analog systems. There is an industry program between EPRI, the Westinghouse Owners Group, and Westinghouse on the use of Application Specific Integrated Circuits (ASICs) for replacement of reactor protection system modules and some control modules for Westinghouse nuclear power plants (see Figure 5-1). EPRI is working with a number of utilities and PLC suppliers to generically qualify commercially available PLCs for safety applications. An effort to use a prequalified commercially available PLC for an emergency diesel control system has been started. An initial evaluation of a dynamic safety system approach for reactor protection systems has been completed. EPRI is currently working with a utility to design and implement a distributed plant process computer system that will support integration with distributed control systems in the future.

5.1.2 R&D Needs

For most of the issues described above, there seems to be no clear-cut technical solution. Rather, the approach recommended by the National Research Council report is for the development of a consensus on best practices for handling the issues. To provide a focus for a dialogue among designers, owner-operators, regulators, analysts, and other stakeholders, demonstration projects at nuclear power plants are required. These projects will show best practices for addressing several issues in the design, evaluation, and licensing of digital safety and control systems. Applications using new digital-based technologies and guidelines need to be developed to prove the applicability of the new technologies and guidelines, to develop lessons-learned experience, and to demonstrate cost and benefits.

The goals of this technology area are to develop the most promising approaches for the most simple and controllable software and hardware designs for nuclear power plant safety and control systems that are also highly reliable and cost-effective. ASIC and programmable logic controllers (PLC) are proven technologies possessing the benefits of digital technology without many of the perceived disadvantages associated with software. This can substantially reduce the development and qualification costs of the system while reducing the licensing risk of implementing digital systems. By limiting the number of possible functions of the system, potential failure modes are limited; testing is also simplified and regulatory acceptance should be easier. Research in this area would develop at least enough applications and get them accepted by the NRC to build a consensus between the NRC and the designers/analysts on best practices. The application of the technology resulting from work would:

- Facilitate continued operation of nuclear power plants under deregulation of electric power industry
- Facilitate the overall improvement of nuclear power plant performance.

An additional goal will be to develop a standardized dynamic safety system (DSS) equipment platform for application to the nuclear power industry plant I&C system replacement process, use the DSS platform to implement a reactor safety system, and obtain acceptance by the NRC. For a limited number of key safety systems, the nuclear power industry requires systems with the highest level of integrity. Static safety systems (the conventional fail-safe systems used today), although highly reliable, require periodic manual testing to demonstrate that they are maintaining their fail-safe design and will function when required. Dynamic safety systems operate dynamically (on-line self-checking) with insertion and processing of test signals for continuous verification of functionality of both hardware and software components. The final checking of signal patterns is performed by a solid-state component; thus DSS offer the benefits of digital functionality and reliability while avoiding concerns about undetected software problems that could prevent system performance when demanded.

To enable the accomplishment of the above and other goals in this plan element, generation optimization testing facilities are needed where new I&C and human factors technologies can be evaluated prior to installation in operating plants. The National Academy of Sciences report on "Digital Instrumentation and Control Systems in Nuclear Plants, Safety and Reliability Issues" recommended that DOE and NRC consider coordinating a facility in which the U.S. nuclear industry can prototype and empirically evaluate digital-based I&C and proposed designs for human-machine interfaces. Such a joint facility could be used to evaluate the impact of new commercially available off-the-shelf digital-based technologies that may be proposed for plant protection, control and monitoring/diagnostics.

Specifically, the facilities would support: development testing methodology to assess and assure equipment and software quality; development and evaluation of industry standards; commercial off-the-shelf equipment evaluation; evaluation of cost effectiveness of proposed I&C replacements and upgrades; testing and evaluation of new developments such as sensors, ASICs, PLCs, and wireless technology; testing and evaluation of distributed control networks; evaluation of system diagnostic methodologies; evaluation of human performance in a complex process control environment; and evaluation of new control room designs and retrofits on operator performance.

The facilities will provide the needed testing resources for use by DOE, national laboratories, utilities, reactor owners groups, NRC, and international collaborators: D/A and A/D interface options for connecting hardware to plant simulations; virtual laboratory capability to provide remote utilization; communication architecture testbed to evaluate different protocols and to test "plug and play" I&C replacements such as ASICs, PLCs, etc.; sensor testbed; diagnostic methodologies testing capability; environmental testing; maintenance training and strategy testing; and modular generic simulations capable of rapid reconfiguration to represent the dynamics of commercial reactor types.

The high priority projects identified for commencement in FY 1999 are listed below, along with the principal objectives of each project. See Volume II for detailed descriptions of these and other high priority projects in this area. See Volume III for descriptions of all projects in this area.

Project ID:	5-1
Project Title:	Development of Application Specific Integrated Circuit Based Reactor Safety and Control Systems
Principal Objective:	Develop, demonstrate and obtain NRC acceptance of ASIC-based safety and control systems.

Project ID:	5-2
Project Title:	Programmable Logic Controller Platform Qualification Technology and Applications
Principal Objective:	Develop, demonstrate and obtain NRC approval for three safety-related applications of PLC-based systems.

Project ID:	5-3
Project Title:	Digital System Demonstration Plants
Principal Objective:	Modernize two nuclear power plants with digital equipment using life cycle management planning to identify systems to be modernized.

Project ID:	5-4
Project Title:	Software V&V Using Hardware Interlocks and Software Safety Architectures
Principle Objective:	The application of hardware interlocks and software safety architectures will reduce complexity of software construction and testing to achieve the required level of rigor in software quality assurance programs by providing either mechanical logic or fixed checkpoints in the software system to limit non-intended function of general-purpose software.

5.2 Advanced Sensor Technologies

Nuclear plants need improved sensors to enhance knowledge of the plant's state. Process sensors are the heart of nuclear plant operations providing information for plant protection, control, and maintenance.

Current plants are operated at less than their designed power because of uncertainties in process variable measurements. The existing sensors experience problems such as obsolescence, excessive surveillance and calibration requirements, inaccuracy and unreliability, and inability to directly measure parameters of interest. The goal of maximizing the power produced by nuclear plants thus creates a need to minimize measurement uncertainties through the development of new sensors to measure pressure, level, temperature, flow, radiation, neutron flux, coolant chemistry, hydrogen in containment, strain, displacement, velocity, and acceleration.

<u>Improved pressure measurement</u>
Pressure is a fundamental process variable that requires accurate and reliable measurement throughout nuclear power plants. Conventional pressure sensors have been studied extensively, yet significant areas remain for performance enhancement. Drift in pressure sensors is often 1–2% over a fuel cycle. Many conventional pressure sensors use oil to buffer the gauge mechanism from the process fluids and are subject to undetectable failures if the oil leaks. Moreover, verification and calibration of the performance of conventional pressure sensors requires significant periodic effort. The non-nuclear process control industry is undergoing a revolution in pressure measurement due to the advent of the single-chip pressure transducer. This is rapidly making the traditional pressure transmitter obsolete.

Fiber optic based pressure sensors offer a potential solution to the accuracy, calibration, reliability, and obsolescence difficulties of conventional pressure transmitters. They offer the advantages of reduced mass and size, resistance to vibration and shock, physical flexibility, high sensitivity, electrical isolation, immunity to electromagnetic interference (EMI), superior resistance to high temperature and radiation, reduced calibration requirements, and passive operation.

<u>Improved radiation measurements</u>. Reactor power is a key safety parameter at nuclear power plants and measurement of neutron flux is the accepted method for determining this power. Current flux measurement devices suffer from several limitations such as EMI sensitivity, single point of measurement, large size, cross sensitivity to gammas, and need for several separate systems to cover the entire flux range. Optical fiber-based radiation detectors have the potential

for solving many of these limitations. A distributive method for making direct measurement of reactor power would address many of the limitations exhibited by current methods and result in increased accuracy both in measured absolute power and in spatial power distribution, offering substantial potential for improved efficiency, increased capacity factors, and enhanced safety.

Improved primary flow loop measurement. Primary loop flow measurements are used to determine the core heat rate in PWRs and as such are a primary parameter in plant thermal efficiency. These measurements are conventionally made using flow meters based on differential pressure. A differential pressure flow meter consists of a flow-restricting orifice with pressure measurement devices located on either side. Such differential pressure flow meters have several fundamental performance limitations. Over time, contamination products can build up on the orifice, thereby changing its calibration. Also, some differential pressure transmitters have a failure mechanism (oil leak) that cannot be readily detected while they are in service. In addition, in differential pressure-based flow meters, the pressure change varies nonlinearly with flow rate, thereby limiting the range of the measurement and reducing its accuracy. Improved flow measurement could be attained through improved pressure measurement (see previous discussion) and use of "on-line" linearization.

Improved temperature measurements. Temperature is a primary parameter in power plant thermal efficiency. Conventional temperature sensors suffer from a variety of limitations such as drift, limited accuracy, EMI and radiation sensitivity, slow response time, and need for isolation from the process fluid. Fiber optic temperature sensors have the potential for overcoming all of these limitations. Plant thermal power directly corresponds to the temperature rise of the primary coolant. A differential temperature reading that is one percent too large reduces plant power production by one percent. (EPRI has reported that at one plant a one percent temperature measurement error leads to a 3.7% decrease in turbine efficiency if the sensor reads high and loss of component life if it reads low.) Resistance thermometer and thermocouple drift of a few percent is not uncommon in normal operation. Assuming a 2¢/kW-hr price for electricity, a one percent loss in generation for a 1000 Mwe plant corresponds to a loss of $1.7 million per year. In addition to immediate operational savings, improved temperature measurement has the potential for increasing the maximum allowed plant thermal power. By decreasing the uncertainty in the measurement of peak process temperature, the margin required between maximum allowed operational conditions and equipment failure can be reduced.

5.2.1 Current R&D

EPRI has several advanced sensor R&D projects under way now for:

a. Instrumentation maintenance and calibration reduction
b. Solid-state hydrogen sensor
c. Prototype ultrasonic Pressurized-Water Reactor (PWR) coolant flow/temperature measurement
d. Advanced in-core power sensor
e. Fiber optics in nuclear plants

5.2.2 R&D Needs

The purpose of this technology area is to develop and improve sensor capabilities for: (a) measuring important process parameters such as flow, fluid level, temperature, pressure, coolant chemistry, radiation, level, vibration and steam quality; (b) detecting and locating potential leaks in the steam generator as well as throughout the plant; and (c) on-line monitoring of components (valves, pumps, heat exchangers, cables, etc. It is also necessary to have the ability to measure these physical parameters in existing plants in locations where the original designs do not provide that capability. The use of small, lightweight, easy-to-install, inexpensive, reliable sensors with improved accuracy could improve many aspects of plant operation. Several technologies offer promise. These include:

a. Fiber optic sensors and data communication networks.
b. Surface acoustic wave sensors.
c. Ultrasonic sensors.
d. Micro- and millimeter-wave sensors.
e. Micro-cantilever-based sensors.
f. Wireless-based sensors for ad hoc monitoring.

Work needs to be done to gain regulatory acceptance of the reduction in instrument calibration proposed by the nuclear industry. The existing work on instrument monitoring and calibration has consisted of using multiple similar instruments. Work is needed to extend this through the development of techniques for the use of dissimilar instruments and to obtain regulatory acceptance of the use of these techniques. Demonstrations of the advanced instruments and of the calibration reduction techniques are needed to prove their reliability and benefits.

A four-phase task will result in the commercialization of advanced sensors for the nuclear power industry. The primary objective will be to develop sensors that are more accurate and that make a more direct measurement of physical variables. An additional objective will be to develop sensors that support diagnostics and engineering analyses to increase capacity factor. Small wireless microsensors (see Fig 5-2) that can be placed where the plant personnel need them at the moment, will be developed and demonstrated. These new sensors will have embedded intelligence and communication capability for remote monitoring.

The first two phases, "identification of measurement needs" and "advanced technologies that will meet those needs," will be completed during the first year. The third phase of the project, "development and demonstration of prototype sensors of highly promising technologies identified in phase two," will take place during the second and third years. The last phase of the project, "commercialization of

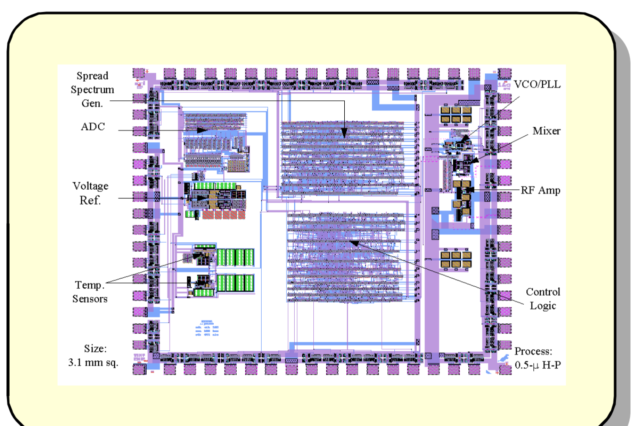

Figure 5-2. Wireless Telesensor Chip
Intelligent Wireless Sensors & Systems

selected sensors proven viable through the prototyping process," will be completed during the last two years.

The high priority projects identified for commencement in FY 1999 are listed below, along with the principal objectives of each project. See Volume II for detailed descriptions of these and other high priority projects in this area. See Volume III for descriptions of all projects in this area.

Project ID:	5-5
Project Title:	Instrument Surveillance and Calibration Verification (ISCV) - Phase II
Principle Objective:	Intelligent systems will be applied to the monitoring of critical plant instrumentation to detect failure and calibration drift and reduce the need of periodic removal for calibration.

Project ID:	5-7
Project Title:	Advanced In-Core Power Sensor
Principal Objective:	Develop and demonstrate an advanced self-calibrating in-core power sensor capable of direct measurement of local power deposition.

5.3 Advanced Monitoring, Diagnostics, and Control Systems

As nuclear plants age, their operations may have to be modified somewhat to account for degradation or suspected degradation of plant components such as steam generators, reactor pressure vessels (RPVs), pumps, and valves. In a complicated system like a nuclear power plant, it is impossible for humans to account in real time for the changing operational status of the thousands of components. Computerized monitoring, diagnostic, and advisory systems can offer valuable support. Operators have made limited use of such systems for many years. As computer technologies advance, the potential for improved simulation, diagnostics, and systems management increases. Furthermore, the goal of maximizing plant energy output motivates the development of vastly improved, computer-based tools for assisting operators to meet this goal.

5.3.1 Current R&D

EPRI has supported work in this area over the past several years. This includes the development of digital feedwater control systems for BWRs and PWRs, advisory systems for the movement of fuel assemblies during a refueling outage, and 10CFR50.59 safety reviews. A large number of monitoring and diagnostic systems and guidelines have been developed for equipment such as piping, motors, valves, and pumps. Substantial work has been done on erosion corrosion and microbiologically induced corrosion in nuclear power plant components. Knowledge-based systems and neural network systems have been used for small prototype diagnostic systems. Improved data-handling systems have been developed to support monitoring and diagnostic systems. The Halden Reactor Project also has an active program in early fault detection, computerized operating procedures, alarm filtering, and general surveillance systems. Both EPRI and the NRC are participants in the Halden work, primarily in an advisory capacity. Several smaller projects are under way in the United States. These are mostly funded by utilities, or to some degree by the National Science Foundation.

Despite the substantial improvements in plant operation potentially achievable with advanced monitoring and diagnostics technologies and control, there is no coordinated research program in this area in the United States. Several issues still need research and development. Among them are:

a. How can new diagnostic and advisory support systems be best exploited? This will vary from plant type to plant type, from utility to utility, and perhaps from year to year.
b. How can potential new failure modes (particularly human error) be avoided?
c. How can system reliability be demonstrated?
d. How can optimum use be made of the increased possibility for automation?
e. How effective and beneficial are the technologies in actual plant application?

5.3.2 R&D Needs

The previous efforts in this area have demonstrated the promise and basic feasibility of a variety of computerized operations assistance technologies. A significant R&D effort is now needed to identify and integrate the most promising of these technologies, to demonstrate their reliability through test implementations in actual plants, to quantify their benefits relative to enhancement of plant energy output and operational effectiveness, and to secure the required regulatory approvals.

This technology area provides for the development and demonstration of advanced information processing technologies that allow reactor plants to be operated more efficiently and reliably, consistent with the highest standards of safety. These advanced technologies will be designed to generate and substantiate information about the condition of plant components and equipment, to use this information to justify continued or extended operation, to maximize plant energy output, and to reduce plant operating costs, particularly operation and maintenance costs. Advances in computational technologies, numerical methods, and artificial intelligence techniques will be exploited in the development of these technologies and will result in a significant enhancement of the tools available to plant operations, maintenance, and engineering staff for the performance of the following functions:

a. Processing and validation of plant signals for reliable monitoring of the plant state.
b. Analysis of process information (direct sensor readings and computed information) for accurate, dynamic determination of required and actual safety margins, with the objective of eliminating excessive conservatism that unduly constrains output with no compensating safety benefit.
c. Diagnosis of plant systems, using validated sensor readings and diagnostic test signals, for reliable characterization of component conditions as needed to optimize plant operations and maintenance and to facilitate recovery from plant upsets.
d. Management and coordination of plant operation and maintenance activities using modern information processing technologies, knowledge-based advisory systems, computerized operation and maintenance procedures, and state-of-the-art human factors expertise.
e. Advanced control and management of plant systems for optimal plant output and reliability consistent with safety criteria.

Advanced process monitoring and signal validation capabilities will be developed based on new analytical techniques for plant state identification and early fault detection. These techniques provide early warning of process anomalies and/or instrument failure and in principle allow the replacement of a faulty sensor with a “virtual sensor” based on a highly reliable analytical estimate. This capability should mitigate the economic and safety penalties that can arise from sensor degradation or failure by providing the operator with timely information about the health of sensors, making it possible to terminate or avoid events that might otherwise challenge plant availability or safety goals. The process monitoring and signal validation techniques are also expected to provide a technical basis for reducing burdensome instrument calibration requirements and for scheduling corrective actions (sensor replacement or recalibration, component adjustment, etc.) at the optimum times.

New signal validation techniques are also expected to contribute to the goal of maximizing plant output. For example, it appears possible to use these techniques to justify the operation of PWRs at higher power levels than is currently possible based on power determination using feedwater flow rate measurements. These are performed using Venturi flow meters which are prone to fouling early during an operating cycle. This fouling causes the flow rate and thus the power to be overestimated and forces a derating of the plant. This derating can be avoided by use of the proposed sensor validation capability, which yields a reliable estimate of the actual flow rate, even after the flow meter calibration starts to deteriorate.

Improved sensor technologies and signal validation techniques will be used in conjunction with recently developed strategies for dynamic adjustment of trip setpoints to maximize power output within the safety limits. In these dynamic strategies, the setpoints are tailored more closely to the actual reactor state than is conventionally the case (conventionally, limiting safety system settings are derived by requiring that margins to safety limits be satisfied, even when unrealistic combinations of pessimistic assumptions are employed in the safety analysis). To capitalize fully on the potential of these advanced monitoring and margin optimization technologies, software modules for optimizing estimates of the reactor state (using validated measurements and analytic models, along with their respective uncertainties) will be developed and used in conjunction with modules that dynamically adjust limiting safety system settings so that unnecessary conservatism is eliminated in demonstrating compliance with safety limits.

With respect to plant diagnostics management of transient processes, there is a significant incentive to improve upon the diagnostic capabilities currently available to operations personnel for identifying the condition of plant systems and components. Enhancement of the reliability and timeliness of such diagnostic information also enhances the operators' ability to justify continued or extended operation of key components, to optimize maintenance and calibration schedules, and to take appropriate and timely actions in response to potential malfunctions. However, in spite of the interest in such advanced diagnostic techniques, their use has been limited by fundamental questions regarding the reliability of the digital software or algorithms and their underlying knowledge bases, and by the lack of portability of this software among different plant systems. To address these challenges in a fundamental manner, it is proposed to use innovative approaches in which the software’s knowledge is based on fundamental physical principles and not on empirical rules regarding specific events. This allows for generic and relatively small knowledge bases, as well as for the important attribute of system and plant independence.

Finally, there is a strong and widely recognized incentive to develop and deploy digital simulation and control systems as a replacement for the obsolete analog controllers currently in use. Advanced digital control systems (based, for example, on optimal algorithms, neural networks, and fuzzy logic), offer the potential of economically optimum and suitably constrained control actions in response to normal or off-normal variations in the plant state (see Fig 5-3). Verification and validation of these advanced I&C systems, particularly for safety system applications, is recognized to be a key challenge.

The high priority projects identified for commencement in FY 1999 are listed below, along with the principal objectives of each project. See Volume II for detailed descriptions of these and other high priority projects in this area. See Volume III for descriptions of all projects in this area.

Project ID:	5-8
Project Title:	Anticipatory Surveillance, Diagnostic, and Advisory System
Principal Objective:	The major objective of this task is to develop and demonstrate capabilities for signal validation and reliable monitoring of the plant state, for diagnosis of plant systems using validated sensor readings, and for providing advice to operations personnel to assist them in optimizing plant output consistent with safety objectives. A related objective will be to develop a software architecture that can accommodate existing and future surveillance, diagnostic and advisory functions using data from plant information systems.

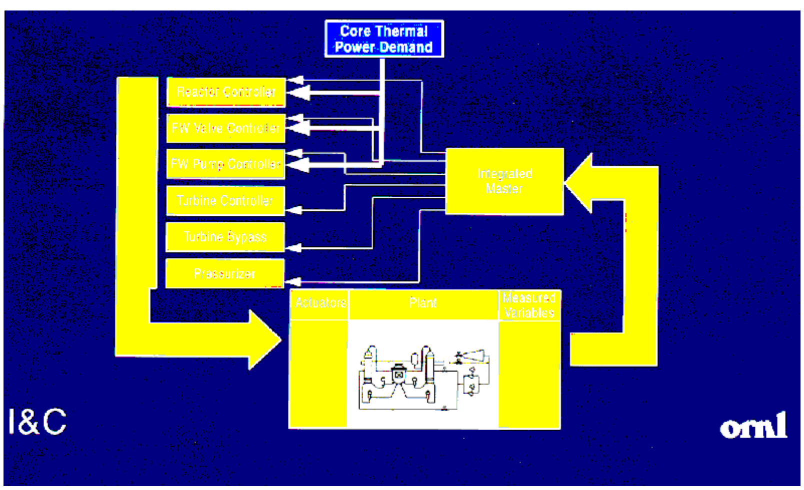

Figure 5-3 Advanced control concepts were applied to develop improved digital controllers for major systems in B&W nuclear plants

5.4 Human Factors

As previously discussed in this chapter, there are many improvements possible with advanced instrumentation and control systems, including advanced monitoring, diagnostics, and digital systems. However, each of these systems directly impacts on human performance and it is well documented, in a variety of sources, that 50 to 70% of the risk at nuclear power plants is associated with human error. These errors arise in a variety of areas, including design, operations, and maintenance, and can strongly influence plant capacity as well as plant safety. Human performance issues must not be considered as adjunct to system performance issues, rather the human issues are essential components of system performance. First and foremost, gaps in the knowledge and understanding of human performance issues as they relate to changes in plant equipment and procedures (which will change with control system changes, and maintenance) must be filled. Although work has been performed in these areas, a comprehensive look at the human's role is conspicuously missing. Secondly, tools and methods needed to enhance human performance and minimize human error must be identified and or developed.

5.4.1 Current Research

The amount of research in the human factors area related to nuclear power has significantly dropped since the original impetus post TMI. However, there are a few programs specifically investigating issues such as alarm handling systems, staffing, operator aids (including a variety of advanced control systems), guidelines development for controls and displays, and automated procedures. Much of this work is being conducted in Europe, in multinational agreements among the OECD Halden Reactor Programme, the Nuclear Regulatory Commission (representing the United States as a member nation), and EPRI. One of the problems with this arrangement for the United States is that all the Halden member nations (over 15) must agree to the research program so that exactly what is needed by the US may not be accomplished.

More recently this research has included data development for human reliability analysis, development of automated procedure systems and alarm filtering, and methods for staffing of hybrid control stations. Work needs to continue in each of these areas. Data collection regarding human failure events needs to be continued to ensure a valid, reliable source of human factor data (better data will lead to more certain estimates regarding the relative risk of systems, and better decision making). Standard approaches to automated procedure systems and alarm filtering should also continue to be a priority such that a best industry practice evolves that will be recognized as such. Research to date concerning the allocation of tasks and staffing for hybrid control stations needs to be completed to ensure proper integration of advanced technologies into existing nuclear power plants. A major failing of all this near term work is the development of an overarching plan of how these various improvements will impact the human's performance. And as has been seen in other high risk industries, it is catastrophic to suggest that one automate the human out of the loop.

5.4.2 Human Factors R&D Needs

The introduction of advanced instrumentation and control systems including automated and passive systems introduce new concerns in human performance. It is well documented, in other industries, that the introduction of automated systems can have a deleterious impact on operator performance. This can arise through degraded operator skills, or through the simple fact that automated systems may not perform as well as humans. Clumsy automation can lead to poor levels of system integration and in turn impact the operator's cognition of plant states. Clearly new I&C will not necessarily improve performance if the human is not central in the design. More advanced I&C systems that utilize digital interfaces can increase the occurrence of latent errors due to software problems or potential operator circumventions of poorly integrated systems. At times, these systems have been seen to increase workload during demanding times, and decrease the workload during undemanding times; the opposite of what is desired. Concerns exist in terms of how I&C failures may affect the operators' ability to perform, especially concerning the operator's vigilance, workload, and situational awareness of the plant state. These concerns extend to passive systems as well. In addition, these systems have the potential to impact the operator's ability to diagnose transients, and may provide new means of circumventions of procedures.

At the root of these concerns is the overall approach being used to design new systems and retrofits of old systems. Little attention has been given to human centered advanced design concepts. These concepts, start with the human at the center of the design process, designing the system based upon the human capabilities. This approach has seen success particularly in the aviation industry. Four key research objectives are discussed below.

<u>Impact of new technology</u>. Determine how technology changes will affect plant availability and safety, including tradeoffs between human and hardware performance. Specific attention should be paid to the types of errors, error rates and associated uncertainty, and the quantification of their impact.

<u>Human performance with digital control systems.</u> Study the effects automation has on human understanding and situational awareness in regards to plant transients. Develop standards that will lead to the minimization of operational errors, recovery, operator awareness, and problem solving ability.

<u>Development of operational philosophy consistent with life extension and advanced designs</u>. This would include the development of a human-centered next generation control room that considers how safe is safe enough, maximizing electric power production. And, that will consider more operator monitoring, less action, changes in the timing of accidents, and new levels of staffing and organization.

<u>Development of advanced operator interfaces</u>. Investigate and develop advanced interfaces (virtual systems) that will improve operator awareness and understanding of plant state. These systems will eliminate concerns regarding changes in operator workload as well as situational awareness.

See Volume III for descriptions of projects in this area.

5.5 Advanced Safety Analyses

The rated power for an operating plant is generally limited by one of the transients, usually a loss-of-coolant accident (LOCA), analyzed in Chapter 15 of the Safety Analysis Report. The LOCA analyses were usually performed with conservative evaluation computer models as specified in Appendix K of the Code of Federal Regulations (10CFR Part 50). The conservatism of the evaluation models can lead to an unnecessarily low value for rated plant power. The Nuclear Regulatory Commission (NRC) also allows the safety analyses to be performed with best-estimate computer models as long as uncertainties in the calculations are appropriately accounted for. The use of the more advanced (best estimate plus uncertainty) safety analyses has the potential to increase the rated power while maintaining adequate margins for safe operation.

5.5.1 Current R&D

Westinghouse, together with EPRI and Consolidated Edison Co., has developed, and the NRC has approved, a methodology based on best-estimate-plus-uncertainty for analysis of large-break LOCAs. Siemens has also submitted a best-estimate-plus-uncertainty methodology for analysis of large-break LOCAs, but the methodology has not yet been approved by the NRC. Application of these methods could be used to raise the rated power of a plant that is limited by a large-break LOCA. However, a best-estimate-plus-uncertainty methodology has not been demonstrated for other transients, such as LOCAs initiated by small breaks. Westinghouse, Consolidated Edison, and EPRI are currently developing the methodology.

5.5.2 R&D Needs

The transients which limit the rated power for each operating plant need to be determined. The methodology to perform advanced safety analyses involving best-estimate and uncertainty calculations needs to be developed and demonstrated for each of the limiting transients.

See Volume III for descriptions of projects in this area.

5.6 Advanced Nuclear Fuel

Developing advanced nuclear fuel designs with higher power outputs, potentially higher enrichments, and longer life help achieve the objectives of optimized nuclear generation through less frequent refueling outages, higher capacity factors, improved economics, and ultimately greater contribution to reduced consumption of fossil fuels. High performance nuclear fuel also contributes to national objectives for reduced volumes of spent fuel.

5.6.1 Current R&D

In recent years, utilities have adopted more aggressive core designs and operating strategies to improve fuel cycle economics. These practices have resulted in new operating environments and reduced operating margins. Despite the best efforts of the fuel vendors to improve their products and the plant operators to protect the fuel by improved operation, fuel-related problems (such as incomplete control rod insertion, axial offset anomalies, and failed fuel degradation) continue. Some of these fuel-related problems have appeared as surprises, i.e., new and unanticipated problems associated with new designs which are intended to offer economic benefits and better performance.

In addition to the fuel-related problems and reduced margins, new regulatory issues have been raised about fuel of current design, *i.e.*, the behavior of high burnup fuel under reactivity-initiated accident (RIA) and loss-of-coolant accident (LOCA) situations. Although EPRI has been effective in providing analyses for use by the industry before the NRC on these issues, some operational restrictions are very likely in the near future. The industry needs a sound technology base to prevent undue and needlessly costly regulations and operational restrictions, while assuring safe operations. DOE has a direct interest in supporting the resolution of these issues.

EPRI has been asked by the utilities to work in concert with them and with the fuel vendors to formulate a comprehensive and proactive program leading to more reliable, robust fuel. The Robust Fuel Program has been formulated for this purpose. It provides a means to avoid or mitigate any adverse impact on plant operations from fuel-related problems or from NRC restrictions due to fuel issues.

This Program is addressing both current and anticipated future fuel-related issues. The issues to be addressed are:

(1) lack of consistent and comparable data for fuel performance and materials behavior,
(2) corrosion/hydriding of fuel cladding and assembly hardware,
(3) crud deposition and water chemistry issues
(4) licensing concerns and uncertainties,
(5) lack of high burnup materials and fuel performance data supporting current fuel designs
(6) incomplete control rod insertion [PWR],
(7) failed fuel degradation [mainly BWR],
(8) PCI failures in Zr-liner fuel [BWR],
(9) fuel rod failure-root cause investigations
(10) new fuel designs and materials,
(11) fuel reliability versus economic benefit, and
(12) high energy cores of mixed fuel designs

EPRI is arranging for a direct comparison of new materials from various vendors in a single lead test assembly with post-irradiation evaluations (PIE) using uniform test methods and reporting. Thus the resulting data will be directly comparable and unencumbered by commercial bias. All aspects of fuel issues will be addressed. This includes materials technology, water chemistry, thermal hydraulics and neutronics. A matrix consisting of experts in these fields has been established to accomplish this.

This Program is guided by the utilities, involves active participation of fuel vendors, and is managed by EPRI. Both INPO and NEI have liaison roles. This Program is being coordinated with other key fuel technology work world-wide, and specifically has been developed and coordinated with DOE, as they have been developing plans for complementary work. Also of interest is the program being planned by NRC. EPRI has served in an advisory role for NRC and

DOE programs and will strive for complementary work to minimize duplication The same is true for work in Europe (EdF, Halden, *etc*.) and Asia; EPRI is either a participant or has exchange agreements.

5.6.2 R&D Needs

The DOE participation in this program is particularly important because of the additional resources and unique facilities they can bring to bear from the national laboratories. DOE's role will complement EPRI's role, with more of the longer term and higher risk R&D being funded by the Federal Government. DOE proposed a High Efficiency Nuclear Fuel Program in FY97, with its primary goal being the development of ultrahigh burnup (>100GWd/MTU) commercial LWR fuel. DOE anticipates coping with all of the difficulties of increasing the allowed enrichment levels throughout the industry. This implicitly includes changing the license limits for fuel fabrication, storage, transportation, and individual reactors. Besides the enrichment infrastructure issue, an important part of this DOE Program is the development of suitable test facilities at the Advanced Test Reactor (ATR) and the Transient Reactor Test Facility (TREAT), hotcells at ANL and INEL and, of course, their use in LWR fuel tests. The upgrade of test reactors and hot cells form a major part of the first few years′ proposed effort and funding. The DOE program will complement industry efforts focused on increased fuel reliability at current burnup limits and current fuel designs and operating modes (*e.g*., cycle lengths). DOE's focus will be on high burnup materials properties and related response to power transients.