Light Water Reactor Sustainability Program Plan

Fiscal Year 2009

September 2008

DOE Office of Nuclear Energy

DISCLAIMER

The Light Water Reactor Sustainability Program Plan describes the research and development scheduled to start in fiscal year 2009. Even though this program plan is being released, the research and development plans are still under development, most in collaboration with international, university, and industry partners. The LWR Sustainability Program research and development plans continue to evolve, and this document will be updated annually or as needed. For current information regarding this document or the plans described herein, please contact:

Ronaldo H Szilard, Director
Technical Integration Office
Light Water Reactor Sustainability Program
Idaho National Laboratory
(208) 526-8376
ronaldo.szilard@inl.gov

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Idaho National Laboratory
Idaho Falls, Idaho 83415

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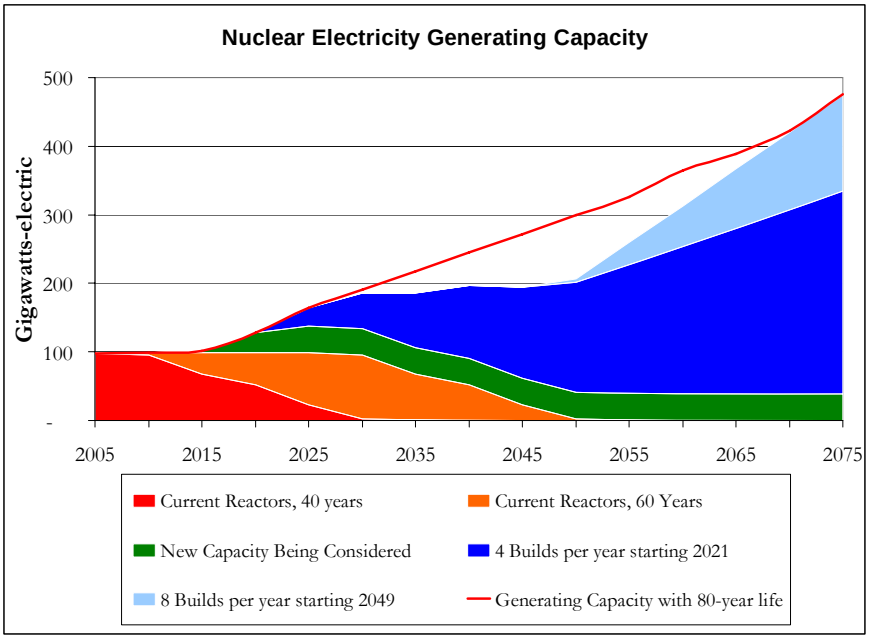
EXECUTIVE SUMMARY

The *Light Water Reactor Sustainability (LWRS) Program* is a research and development (R&D) program sponsored by the Department of Energy (DOE), performed 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 current nuclear power plants. DOE's program focus is on longer-term and higher-risk/reward research that contributes to the National Policy objectives of energy security and environmental security.

There is growing consensus that large carbon dioxide (CO_2) reductions and energy security with stable supply and prices for electricity cannot be achieved without a major contribution from nuclear energy. Nuclear power has reliably and economically contributed almost 20% of electrical generation in the U.S. over the past two decades. It remains the single largest contributor of non-CO_2-emitting electricity, ultimately providing more than 70% of the non-emitting energy generation capacity in the U.S.

By 2030, domestic demand for electrical energy is expected to grow to levels 30 to 40% higher than today's levels.[1] At the same time, most currently operating nuclear power plants will begin reaching the end of their 60-year operating licenses. Figure 1 shows projected nuclear energy contribution to the domestic generating capacity. If currently operating plants do not operate beyond 60 years, the total fraction of generated electrical energy from nuclear power will begin to decline—even with the addition of new nuclear generating capacity.



The red line represents the total generating capacity of current and planned nuclear power plants, assuming extended operation to 80 years. The unshaded area below the line represents lost capacity if the current nuclear power plant fleet is decommissioned after 60 years.

Figure 1. Projected nuclear power generation.

Replacement of this large 100 GWe generating capacity with other alternatives would likely have larger CO_2 emissions, cost more, or be less reliable.

The unique capabilities of nuclear power to meet national goals were recognized in the National Energy Policy[2] which called for expansion in nuclear energy in the U.S. Subsequently, the National

Energy Policy Act of 2005[3] authorized the Nuclear Energy Systems Support Program supporting R&D activities addressing reliability, availability, productivity, component aging, safety, and security of existing nuclear power plants. The purpose of the LWRS Program is to implement this Congressional directive with initial focus on providing the technical basis for sustaining the current nuclear generating capacity for the long-term. Using the public-private partnerships created while developing the *Strategic Plan for Light Water Reactor Research and Development*,[4] DOE uniquely possesses the tools and relationships to help integrate and coordinate critical research initiatives to help solve the Nation's energy and environmental challenges.

The LWRS Program Vision is captured in the following statements:

> ***Existing nuclear power plants will continue to safely provide clean and economic electricity well beyond their first license extension period, significantly contributing to national energy security and protecting the environment.***
>
> ***There is a comprehensive technical basis for licensing and managing the long-term safe, economical operation of nuclear power plants.***

Three Strategic Program Goals support the achievement of this vision:

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 supporting 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.

Four 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 development of high-performance, high burn-up fuels with improved safety, cladding, integrity and improved nuclear fuel cycle economics.
3. ***Advanced Instrumentation, Control, and Information Systems Technologies.*** Through 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.

Each of these R&D pathways supports the needs of both industry and government in sustaining the existing nuclear power plant fleet as a viable option. There is overlap among the four R&D pathways but the chosen pathways organize the LWRS Program on technical issues that will extend the life of the existing fleet of nuclear power plants beyond the first license extension period.

Section 1 of this program plan provides the purpose of the LWRS Program in supporting national energy policy objectives. Section 2 provides a description of the Program's objectives. Section 3 describes the four R&D pathways as well as the each area's specific research topics. Section 4 describes the organizational structure, management of the program, and outlines the program's multiple interfaces. Section 5 illustrates a three-year budget summary, starting in FY-09.

With the present 60-year licenses beginning to expire in 2029, utilities are likely to initiate planning baseload replacement power by 2014 or earlier. If the option to extend current plant lifetimes is not available, the strategic planning and investment required to maintain the current LWR fleet may not happen in a sustainable manner. Given this, the research window to address fundamental aging questions must start now and is likely to extend through the following 11-year period, 2009 to 2020. The LWRS Program represents the beginning of the timely collaborative research needed to retain the U.S.' existing nuclear power infrastructure.

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ACRONYMS

ALWR	advanced light water reactor
BDD	binary decision diagramming
BIM	Building Information Model
BOC	beginning of cycle
BWR	boiling water reactor
CC	coolant chemistry
CDF	core damage frequency
CO_2	carbon dioxide
CRM	configuration risk management
DBAs	design-basis accidents
DBA	design basis accident
DOE	U.S. Department of Energy
DOE-ID	U.S. Department of Energy-Idaho Office
DOE-NE	U.S. Department of Energy-Office of Nuclear Energy
DOE-HQ	U.S. Department of Energy-Headquarters
DPC	direct probability calculation
DSA	deterministic safety analysis
EPRI	Electric Power Research Institute
FGR	fission gas release
FP	fuel performance
FY	fiscal year
HSI	human system interface
I&C	Instrumentation and Control(s)
INL	Idaho National Laboratory
IAEA	International Atomic Energy Agency
IGSCC	intergranular stress corrosion cracking
IASCC	irradiation assisted stress corrosion cracking
ICHMI	instrumentation, control, and human machine interface
IWOs	interagency work orders
LERF	large early release frequency
LTO	long-term operation
LWR	light water reactor
LWRS	Light Water Reactor Sustainability

MOU	memorandum of understanding
MPOs	memorandum purchase orders
NDE	non-destructive evaluation
NERI	Nuclear Energy Research Initiative
NK	neutron kinetics
NRC	U.S. Nuclear Regulatory Commission
OECD	Organization for Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory
PCI	pellet clad interaction
PIRT	phenomena identification and ranking table
PRA	probabilistic risk analysis
PCMI	pellet cladding mechanical interaction
PWR	pressurized water reactor
R&D	research and development
RISMC	Risk-Informed Safety Margin Characterization
RPV	reactor pressure vessel
SCC	stress corrosion cracking
SCI	Sustainability Critical Information
SCT	sustainability critical analytical tools
SiC	silicon carbide
SM	structural mechanics
SMAP	safety margin action plan
SSC	systems, structures, and components
TH	thermal hydraulics
TIO	Technical Integration Office
UC	uncertainty qualification
UOX	uranium oxide
MOX	mixed oxide
V&V	verification & validation
WBS	Work Breakdown Structure

Light Water Reactor Sustainability Program Plan

1. PURPOSE OF THE PROGRAM

1.1 Challenges in the Electrical Energy Sector

The electric energy sector is entering a time of serious challenge and tremendous opportunity. Expanding energy demand and a growing awareness of the environmental impact caused by different forms of electricity generation have prompted debate on how best to achieve a sustainable, affordable, and environmentally sensitive energy solution. Nuclear power is integral to meeting that objective.

The Light Water Reactor Sustainability (LWRS) Program is a research and development (R&D) program sponsored by Department of Energy (DOE), performed in close collaboration with industry R&D programs, with the aim to provide the technical foundations for licensing and managing the long-term safe and economical operation of current nuclear power plants. DOE's program focus is on the longer term and higher risk/reward research that contributes to the national policy objectives of energy security and reduction of carbon dioxide (CO_2) emissions.

Electric power is a vital component of the nation's economy and way of life. As U.S.' energy needs grow over the coming decades, the national energy supply faces growing pressures on both a global and domestic scale. Greenhouse gas emission is a mounting problem that threatens the future production of electricity from both coal and natural gas. In 2006, 70% of domestic electricity generation relied upon fossil fuels. In addition, reliance on imported sources of energy exposes the U.S. to price and supply volatility. Compounding the supply side challenges presented by environmental and economic pressures, increasing energy demands will place additional strain on domestic and international infrastructure creating additional shortfalls. Projections by the Energy Information Agency[1] show U.S. demand for electricity increasing 30 to 40% by 2030.

Construction of new nuclear power plants is a clear option for new emission free electrical generating capacity. As of September, 2008, fourteen Combined Operating License applications have been submitted to construct 23 new nuclear power plants.[5] Over 30 proposed nuclear power plants are currently in the planning or licensing stage, making it clear that new plant construction is an option that is being seriously pursued. Construction of these plants is likely to commence in or about 2010. It is expected that the actual construction and startup testing for each plant will take approximately five to six years to complete. Each nuclear power plant currently under consideration is expected to be capable of producing between 1.1 and 1.7 GWe, depending upon design. Assuming that the infrastructure to build and operate new nuclear plants expands to support four new starts per year in the U. S., new nuclear capacity could support electrical growth projections and replacement of some older carbon emitting generating units in the 2020 to 2030 time frame. However, in about 2030, unless there is further licensing renewal the current fleet of nuclear power plants will start decommissioning. Over the next two decades, this would result in a loss of 100 GWe emission free generating capacity. This is comparable to the electrical generation of new nuclear power plants built over the same time period, leaving a gap in projections of required emission-free generating capacity. This gap might be filled with higher construction rates of new nuclear plants or with other technologies. However, continued safe and economical operation of current reactors supported by the LWRS Program is a low-risk, low-cost option to fill the gap.

Nuclear power is the largest contributor of non-greenhouse-gas-emitting electric power generation, comprising nearly three-quarters of the non-emitting sources as shown in Figure 2. Energy efficiency and carbon storage are all expected to play increasing roles in providing clean, reliable energy; however,

nuclear power will be depended upon well into the 21st century for large-scale supply of dependable clean electricity.

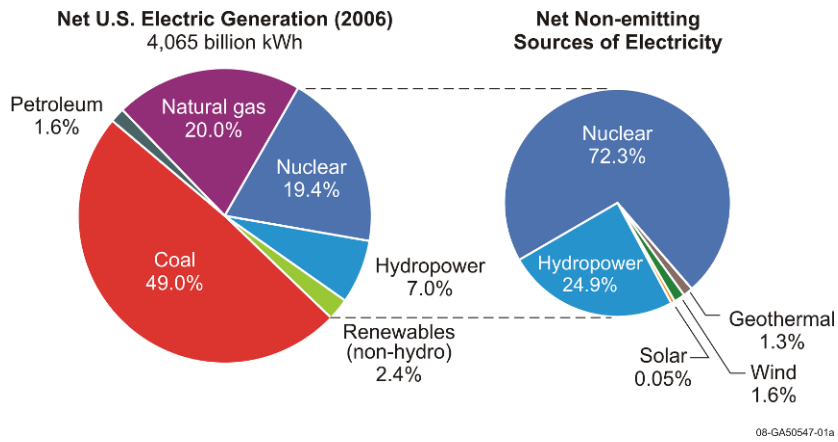

Figure 2. Current electric generating portfolio.

Other forms of low CO_2 emitting and renewable energy production also have the potential to produce environmentally friendly energy. Among the most promising are hydroelectric, wind, and solar power. In the U.S., hydroelectric power is the most widely used renewable energy and produced 7% of all electric power in 2006 but there is limited opportunity for expansion. Wind and solar power have demonstrated promise to produce environmentally friendly energy to meet the nation's growing demand. These sources of power are only recently deployed and currently contribute only a small fraction of the nation's rapidly growing energy demands. A graph of current capacity factors is shown in Figure 3. The very high capacity factor for nuclear power makes it the only reliable low CO_2 emitting source of baseload power available.

The national issues of energy security, environmental security, and the unique capabilities of nuclear power to provide solutions were recognized in the National Energy Policy.[5] The Policy called for expansion in nuclear energy in the U.S. Subsequently, the National Energy Policy Act of 2005 established and authorized the DOE's Nuclear Power 2010 Program to stimulate construction of new nuclear power plants with demonstration of streamlined but unproven licensing processes and facilitating "first mover" new nuclear power plants. The Policy also authorized R&D programs for advanced and existing nuclear power plants. For existing LWRs the Act called out "research and development activities addressing reliability, availability, productivity, component aging, safety and security." The LWRS Program addresses long-term issues in these areas with initial emphasis on component aging. The National Academies reviewed DOE's Nuclear Energy R&D Program in 2007 and recommended a program of R&D supporting current LWRs.[6]

In early 2007, planning leading to the LWRS Program was initiated by DOE, with the Idaho National Laboratory (INL) engaging the Electric Power Research Institute (EPRI), and other industry stakeholders. The aim was to develop an R&D strategy addressing nuclear energy issues within the framework of the National Energy Policy and the Policy Act of 2005. Based on considerable analysis and information gathering, the "*Strategic Plan for Light Water Reactor Research and Development*," was developed and reviewed by an independent committee of experts. The Plan recommending ten top-priority areas for a Government-Industry cost-shared R&D program was issued in November 2007.

Building on the Strategic Plan and the collaborative relationships that were developed while preparing it, DOE and INL immediately started developing the LWRS Program. In February of 2008, DOE and the U.S. Nuclear Regulatory Commission (NRC) sponsored a workshop which identified the necessary R&D for long-term operation and licensing of nuclear power plants.[7] The input from a large set of stakeholders provided important definition of needs and focused the program objectives on long-term operation of existing nuclear power plants.

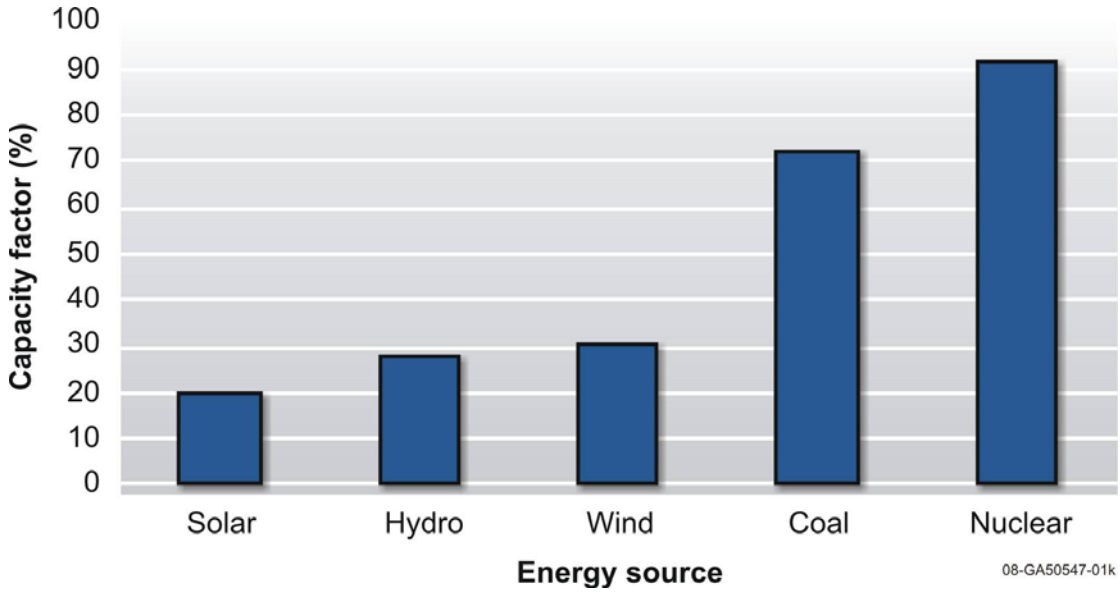

Figure 3. U.S. electrical generation capacity factors by energy source.

In developing the Strategic Plan and more specific program plans, it has become apparent that Government-Industry cost sharing arrangement for R&D is desirable to address the long-range, policy-driven goals of government and the acceptability and usefulness of derived solutions to industry. The LWRS Program requires the long-term vision and support of national laboratories to address strategic reliability and safety requirements of existing nuclear power plants that could not be addressed by more inherently tactical organizations. The long-term, higher-risk research required to construct a fundamental scientific basis to understand the complex effects of plant aging is not likely to be carried out by industry alone.

While industry is likely to invest in applied research programs that are directed towards enhancing operations or in developing incremental improvements, industry is also unlikely to invest significantly in the research programs that focus on longer-term or higher-risk gains. Additionally, since research necessary for nuclear power plant life extension is of a broad nature providing benefits to the entire industry, it is unlikely that a single company will make the necessary investment on its own. Given the present focus of the utility industry, government cost sharing and involvement will be required to promote the necessary programs that are of crucial long-term importance. The LWRS Program, by incorporating a long-term collaborative industry stakeholder inputs and shared costs, will support the strategic national interest of maintaining nuclear power as an available resource.

Over the past several decades, academia and national laboratories have made enormous advances in the area of general materials science and modeling of fundamental structures. Applications of these sciences, although not specifically nuclear in nature, have the potential to bring tremendous advances over the narrowly focused, step-wise improvements the nuclear industry has realized thus far. Additionally, because of their unique resources such as experimental irradiation and post-irradiation examination facilities, the national laboratory infrastructure is positioned to bridge the nuclear industry, R&D, and demonstration infrastructures. The LWRS Program serves to facilitate use of this knowledge with further R&D specific to the current fleet of nuclear power plants in understanding the ongoing and complex challenges to LTO.

In summary, the electrical energy sector is challenged to supply increasing amounts of electricity dependably, economically, and with reduced CO_2 emissions. Consistent with the National Energy Policy, nuclear power is an important part of the answering the challenge through long-term safe and economical operation of current nuclear power plants along with building new ones. The LWRS Program is designed

to provide, in collaboration with industry programs, the sound technical basis for licensing and managing the long-term safe operation of nuclear power plants.

1.2 Current Nuclear Power Plant Fleet and the Path to Long-Term Operation

The R&D necessary to support licensing and managing the long-term safe operation of the existing fleet of nuclear power plants is based on the status of the plants and the technical/scientific information that underpins their current and projected long-term operation. This section reviews the status and outlines the path forward.

The NRC currently licenses 104 nuclear power plants operating in 31 states, as shown in Figure 4.

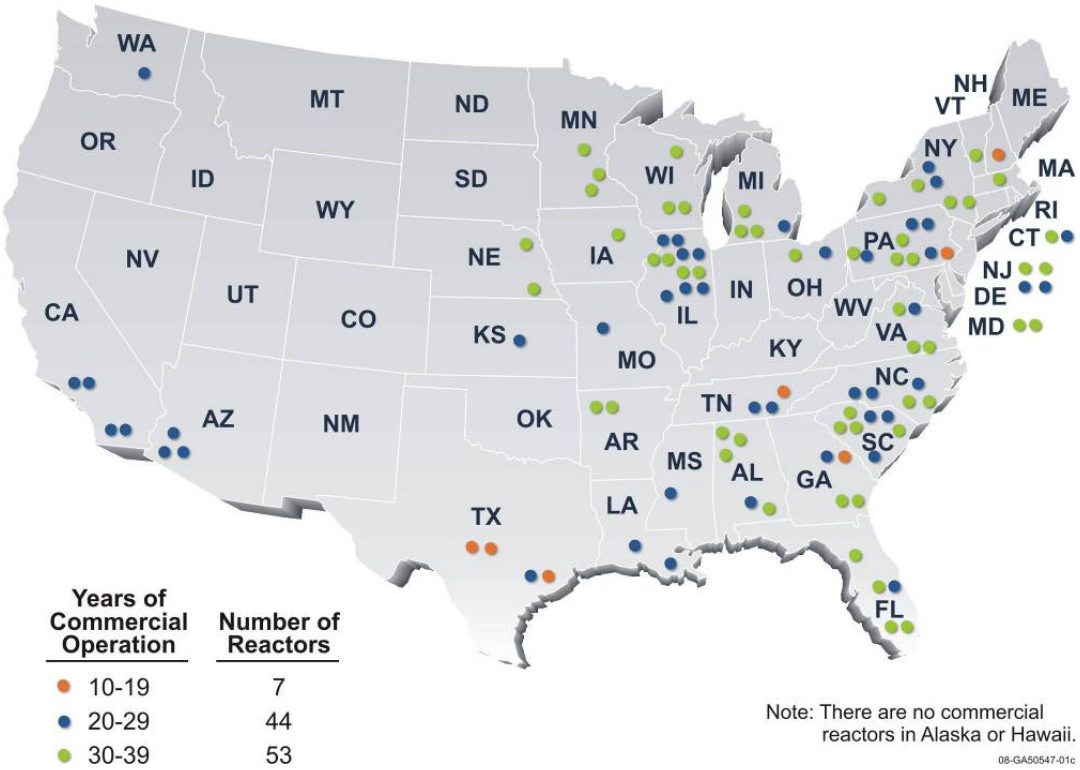

Figure 4. Operating nuclear power plants.

Figure 5 shows the following: (1) the oldest nuclear power plant started operation in 1969 and the newest plant started operation in 1997 and (2) more than 90% of operating nuclear power plants have been issued, are applying for, or plan to apply for a 20-year license extension currently available from the NRC (shown in pie chart). This license extension will result in a licensed operating life of 60 years.

The fleet has demonstrated a remarkable improvement in performance with capacity factors improving from 70% in 1997 to 90% in 2007 as described in Industry Journals.[8] This significant improvement in performance has made nuclear power plants considerably more economical to operate. As a sign of the increasing value of nuclear power, one reactor, Browns Ferry-1, was restored to operation in 2007 after being shutdown in 1985. A second Tennessee Valley Authority reactor, Watts Barr-2, will restart construction that was stopped due to construction difficulties in 1985 as well.

The numerous benefits of nuclear power have helped it become a vital and trusted source of power - currently supplying nearly one-fifth of the U.S. electricity demand. However, the nuclear industry will face a critical transition within the next 20 years. Beginning in 2029 and extending until 2055, the 104 existing U.S. plants could cease operations as they reach the end of their extended operating licenses.

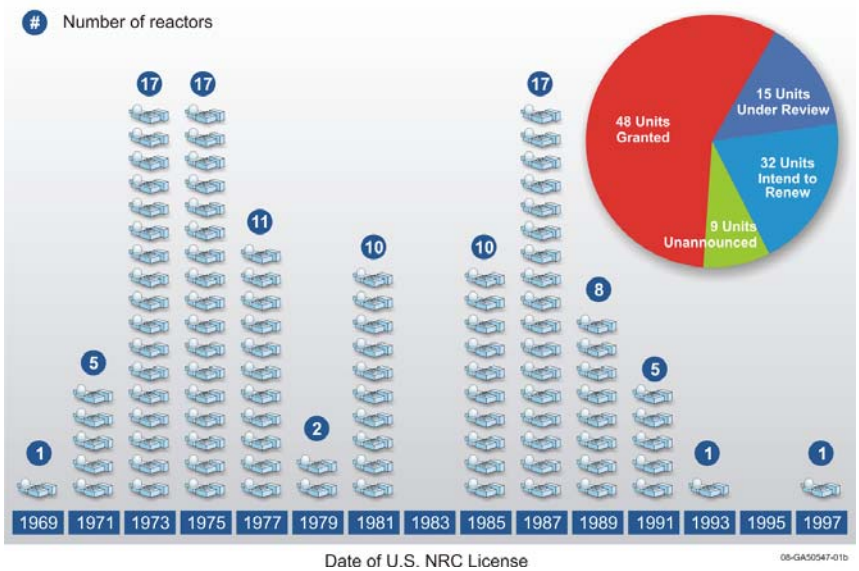

Figure 5. Nuclear power plant initial license date and license extension plans.

Absent additional research to address critical plant aging issues, it may be anticipated that these valuable generating stations will be retired after reaching 60 years of operation, resulting in the loss of over 100 gigawatts of clean electric generation capacity and potentially risking the stability of the U.S. electrical energy supply. Furthermore, with the state of present research, degradation and obsolescence threaten to decrease power production from these plants even before their scheduled end of licensed lifetimes.

In order to receive a 20-year license extension, a nuclear power plant operator must ensure that the plant will operate safely for the duration of the license extension. The 40-year operating license period established in the Atomic Energy Act was based on anti-trust considerations and not technical limitations. Additional 20-year license extension periods are presently authorized under the governing regulation of 10 CFR Part 54. This rule places no limit on the number of times a plant can be granted a 20-year license renewal as long as the licensing basis is maintained during the renewal term in the same manner and to the same extent as during the original licensing term.

This regulatory process ensures the continued safety of all currently operating plants during future renewal periods. The license extension process requires both a safety review and an environmental review, with multiple opportunities for public involvement. It is a robust process that prioritizes safety above all other considerations. The applicant must demonstrate safety issues through technical documentation and analysis, which the NRC then confirms before granting a license extension. A solid technical understanding of how systems structures and components (SSCs) age is necessary for nuclear power plants to demonstrate continued safety. There is a well-established knowledge base for the current period of licensed operation. However, additional research will be needed to obtain the same robust technical basis required for continued operational evaluations beyond 60 years.

1.3 Critical Path for Nuclear Power Plants

Ultimately, extending the life of an existing asset is an individual utility business and risk decision. A utility anticipates that, in most situations, extending the life of an existing nuclear power plant is likely to cost less than building a new plant, but operating costs must remain competitive. Individual owner-operators are likely to seriously consider extending the life of their existing nuclear power plants well in advance of committing to new construction, assuming existing assets can economically meet anticipated demand growth and assuming that the option to do so is still available. It is also likely that decisions extending nuclear power plant lifetimes will be accompanied by facility upgrading and uprate assessments, thus helping to manage operational risks of aging and taking advantage of technical enhancement opportunities. Such capital spending decisions will require a thorough business case and a technical understanding and predictability of aging and degradation risks.

Commercial utility and investment decisions required to develop, construct, and license baseload generation must be made far in advance of power demands outgrowing supply capacities. Actions to retain the U.S.' existing nuclear power infrastructure must begin in a timely manner so that these resources may be relied upon in future decades. Commercial utility and investment decisions required to develop, construct, and license baseload generation must be made far in advance of power demands outgrowing supply capacities. Given the risk-adverse influences of financial markets, state public utility/service commissions, and the NRC, power-generating utilities must prudently use all available information in carrying out these decisions. With extended operational lifetimes, aging-related technical or operational questions that did not exist previously have now become important decision factors. As 60-year licenses begin to expire starting in 2029, utilities will need to start planning at least 15 years in advance by 2014.

Extending nuclear power plant life beyond 60 years is expected to remain a technically viable option for filling the power-generation gap between older plants' license expiration and newer plants coming online. In addition to the environmental benefits, extending the life of highly efficient existing plants defers the up-front costs of building a new nuclear plant.

Applications for life extensions from 60 to 80 years are likely to be submitted starting between 2014 and 2020, as noted by the NRC's Long-Term Research Plan (2007). Given this timeframe, the corresponding research window to support the utility's decisions to invest in life-extension and to support NRC decisions to extend the license must start now and should focus on the eleven-year period from 2009 to 2020.

2. DESCRIPTION OF THE PROGRAM

2.1 Vision

Today's commercial nuclear power plant fleet has produced environmentally friendly power reliably in the U.S. for decades. As these plants reach the end of their original 40 year operating license and enter their first 20 year extended license, the sound engineering principles used in designing and building them are being applied to demonstrate their continued safety for a possible second license extension. In order to preserve the option of continued safe and economical operation of these plants, a technical basis is required for the utility to evaluate investments in life-extending improvements and for the regulator to accept license extension applications. This Program Plan identifies R&D activities to enhance the scientific understanding of aging mechanisms important to the SSCs in nuclear power plants and to develop methods and technologies to manage plant aging and evaluate safety of plants for longer term operation.

The LWRS Program Vision is captured in the following statements:

> ***Existing nuclear power plants will continue to safely provide clean and economic electricity well beyond their first license extension period, significantly contributing to national energy security and protecting the environment.***
>
> ***There is a comprehensive technical basis for licensing and managing the long-term safe, economical operation of nuclear power plants.***

Extending the life of nuclear power plants is a vital step in meeting U.S. electrical needs today and in decades to come. By keeping these plants safely in service, the nation will retain valuable infrastructure and allow additional time to construct new sources of clean, reliable, and secure energy. Until other reliable sources of power are built and placed on the electrical grid, the existing fleet of nuclear power plants is necessarily a vital component of the economy.

The LWRS Program is designed to help achieve this vision by addressing long-term operational challenges that face the U.S. nuclear utilities.

The following strategic goals support the vision:

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 operations of existing LWRs.
2. Apply this fundamental knowledge in collaborative public-private, and international partnerships, developing and demonstrating methods and technologies supporting 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.

Since safety is a fundamental requirement for reliable economic operation, most of the knowledge and methodologies developed in this program are expected to serve both the regulator and the utility. This commonality is a key consideration in defining the R&D pathways and individual R&D projects.

2.1.1 Fundamental Scientific Basis

Ensuring public safety is a prerequisite to all nuclear power plant operating decisions. For extended operating periods, it must be shown that adequate aging management programs are present or planned and that appropriate safety margins exist throughout the subsequent license renewal periods. Through research, this program will seek to contribute to the technical foundation on which licensees can base

their analyses to determine if these adequate safety margins can be maintained. In order to make the technically justified case when deciding to apply for a subsequent license extension, the nuclear industry will require definitive knowledge into the effects of aging.

2.1.2 Economic Viability

Once scientific research establishes how nuclear power plants will age and aging management programs are identified, operators must demonstrate the costs associated with continuing to maintain and operate their nuclear power plants are justified and remain in the best interest of their owners. It is likely that as nuclear power plants operate beyond their original license periods, significant component replacements will become necessary, increasing costs. Each utility will need to be able to accurately predict such costs in order to make sound business decisions regarding continued long-term plant operation.

Technology, in combination with effective plant management programs, is expected to support new opportunities for further cost savings in areas such as aging management, information technologies, operations and maintenance, training, fuel design, and management. Some of these cost improvements will be within the scope of a regulatory license renewal process (e.g., reactor pressure boundary materials issues), while others may be important to continued economic viability but not have regulatory significance. Safety and economic viability are considered complementary goals. Developed properly, programs that enhance economics are also likely to benefit plant safety.

2.2 Implementing Strategy

Achieving the strategic goals of the LWRS Program will require extensive collaboration with industry and utilization of extensive technical expertise in U.S. and international R&D institutions. Further, recognizing the need to support the education and training of next generation scientists and engineers, the following strategic guidelines were established to guide the organization and implementation of the program.

- Leverage institutional knowledge and collaborative opportunities between the nuclear industry, national laboratories, universities, and the Federal government in developing the basic scientific understanding in predicting key materials characterizations.
- Build relationships using the LWRS Program Vision and Goals across established relevant research interests in materials aging and degradation fields, both at the international and domestic levels
- Integrate university Nuclear Energy Research Initiative (NERI) projects with selected R&D pathways
- The LWRS Program will be accountable to sponsors, partners, and other stakeholders.

The LWRS Program is comprised of four principal R&D pathways, each of which focuses on a key technical element ensuring the safe, economic and reliable operation of the existing nuclear power plant fleet. Each area supports the needs of both industry and the regulator in sustaining the existing nuclear power plant fleet as a viable option. The four R&D pathways are:

1. Nuclear Materials Aging and Degradation
2. Advanced LWR Nuclear Fuel Development
3. Advanced Instrumentation, Controls, and Information Systems Technologies
4. Risk-Informed Safety Margin Characterization.

The objectives of these R&D pathways are to create a greater level of safety through application of increased knowledge and an enhanced economic understanding of plant operational risk beyond the first license extension period. These R&D pathways also provide possible solutions to future challenges and will ensure future safe and economic extended nuclear power plant operation.

3. PROGRAM R&D PATHWAYS

3.1 Nuclear Materials Aging and Degradation

3.1.1 Background and Introduction

Nuclear reactors present a very harsh environment for components service. Components within a reactor core must tolerate high temperature water, stress, vibration, and an intense neutron field. Degradation of materials in this environment can lead to reduced performance, and in some cases, unexpected failure. There are many different types of materials within the reactor itself: over 25 different metal alloys can be found within the primary and secondary systems, not to mention the materials that make up the concrete containment vessel, instrumentation and control, and other support facilities. A small sampling of these metals is shown in Figure 6 for a pressurized water reactor (PWR).

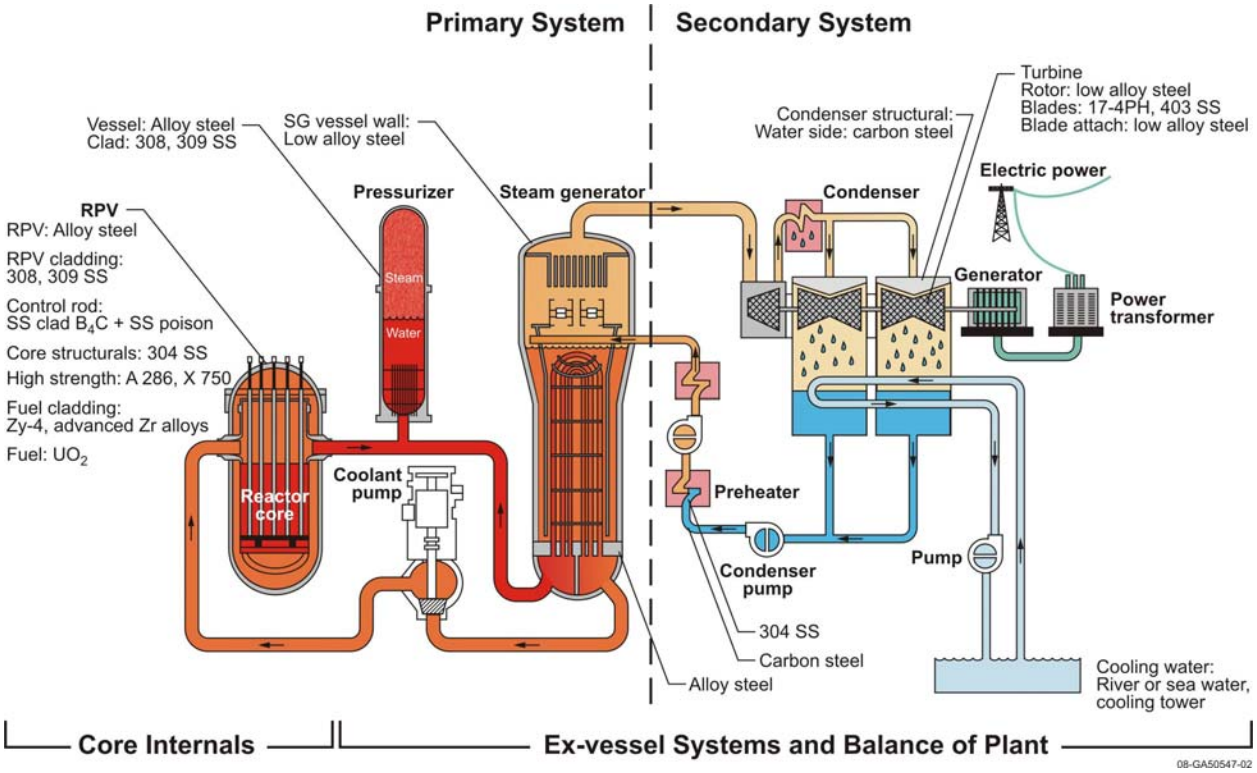

Figure 6. LWR metals.

The aging and degradation of materials exposed to this aggressive environment for an extended time is quite complex and could impact reactor reliability, availability, and, potentially, safe operation. Routine surveillance and component replacement can mitigate these factors, although failures still occur. With reactor life extensions beyond 60 years, many components must tolerate the reactor environment for a previously unanticipated service life. This may increase the vulnerability of components and introduce new degradation modes. Understanding, controlling, and mitigating materials degradation processes are priorities for safe and efficient long-term reactor operation. The LWRS Program research will provide the understanding to predict and manage materials degradation in a safe and economical way.

Concerns regarding the long-term degradation of reactor materials originate from a number of sources. When 47 nuclear utility executives were recently polled on the most challenging issues facing further life extension, two-thirds cited plant reliability as the key issue with materials aging and degradation of the reactor metals, concrete, cable and piping as the top concerns for plant reliability.[9]

3.1.2 R&D Pathway Strategy – Vision and Objectives

The Nuclear Materials Aging and Degradation R&D Pathway vision and objectives are captured in the following statements:

Vision for 2020: Material research provides an important foundation for licensing and managing the long-term, safe, and economical operation of nuclear power plants. Aging mechanisms and their influence on nuclear power plant SSCs are predictable with sufficient confidence to support planning, investment, and licensing for necessary component repair, replacement, and relicensing. Understanding, controlling, and mitigating materials degradation processes are key priorities. Advanced monitoring, advanced non-destructive examination (NDE), and results from ongoing materials R&D continue to reduce unpredicted failures from unpredicted aging mechanisms. Based on today's knowledge, there are no unpredicted events from long-term operation of nuclear power plants that would affect the public confidence in their safety and reliability.

Objectives: The strategic objectives of the Nuclear Materials Aging and Degradation R&D pathway are to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants and to provide data and methods to assess performance of SSCs essential to safe and sustained nuclear power plant operations.

3.1.3 R&D Pathway Scope

The Nuclear Materials Aging and Degradation R&D pathway activities have been organized into four areas: (1) reactor metals, (2) concrete, (3) cable aging, and (4) buried piping. Each of these research areas is described below. Unlike consumable materials such as fuel and other components that are periodically replaced during plant life, these SSCs were installed with the intention that they would operate for the safe life of the nuclear power plant. As the nuclear power plant licensees seek approval for extended operation, the way in which these materials age beyond 60 years will need to be evaluated and their capabilities reassessed in order to ensure that they can maintain the required design functions safely and economically. A detailed description of the primary forms of degradation in nuclear power plants is presented in *Materials Degradation in Light Water Reactors: Life After 60*.[7]

3.1.3.1 Reactor Metals

Material degradation within a nuclear reactor is highly complex. Numerous types of metal alloys can be found throughout the primary and secondary systems. Some of these materials, particularly the reactor internals, are exposed to high temperatures, high pressures, water and complex chemistry environments, and neutron irradiation. This creates degradation mechanisms that may be either unique or environmentally exacerbated. Three areas that offer distinct and differing challenges include the reactor pressure vessel (RPV), reactor internals, the primary system, and welds. Regulations require that each of these areas maintain conservative safety margins of fracture toughness to ensure plant safety and reliability. The reactor core internals, like the RPV, are subjected to a diverse set of stresses, corrosion, and irradiation. Service life beyond 60 years will generally increase the time at temperature and the neutron fluence a core component is exposed. This leads to an increased vulnerability and severity for known degradation mechanisms and the occurrence of new degradation mechanisms. Components outside the reactor pressure vessel are also subject to degradation without the added complications of an intense neutron irradiation field. The combined action of corrosion and stress can still create many different forms of failure in these components. Research programs in these areas will provide a foundation for licensing and safe operation for extended lifetimes beyond 60 years.

3.1.3.2 Concrete

Nuclear power plants include large concrete structures, with much of the foundation, containment, shielding, storage pools, and other buildings made of reinforced concrete. In other non-nuclear applications, concrete has withstood the aging process quite well. However, the environment at a nuclear

reactor is unique and the continued reliability of concrete must be assured for both normal operations and potential casualty situations. Overall, the performance of concrete at operating plants has been good, although there have been some instances of deterioration reported, mostly early in plant life, which have been attributed to construction or material deficiencies.

3.1.3.3 Cabling

Aging of the electrical insulation on cables is a concern that currently faces the operators of existing nuclear power plants. Utility companies can carry out cable inspections using NDE techniques to detect damage but these techniques typically require the cable to be unpowered to produce reliable results. Degradation of these cables is primarily caused by long-term exposure to high temperatures. Additionally, stretches of cables that have been buried underground are frequently exposed to groundwater. Research into the expected lifetimes and degradation modes of cables is needed. The degradation and aging mechanisms of cabling must also be evaluated. Continued research into the development of acceptance criteria for existing electrical tests is needed for existing and newer cable insulations. Finally, the development of one or more aging models for insulation would be useful in projecting remaining life.

3.1.3.4 Buried Piping

Maintaining the many miles of buried piping is an area of concern when evaluating the feasibility of continued nuclear power plant life. While much of the buried piping comprises either secondary plant or other non-safety-related cooling systems, other buried piping is vital for reliable operation and direct safety function. Maintaining the integrity and reliability of all of these systems is necessary for continued safe nuclear power plant operation. These systems must be maintained to ensure predictable plant operation and to maintain plant efficiency. Mitigation strategies for preventing degradation need to be developed along with improved inspection and monitoring techniques.

3.1.4 R&D Pathway Highlights

The main program elements for the Nuclear Materials Aging and Degradation R&D pathway are described below. They represent the major technical challenges as well as provide key opportunities for collaboration and integration with other research efforts. As a result, the scope and objectives of these four tasks are more mature than other potential research areas within this R&D pathway.

3.1.4.1 Reactor Metals

Single Variable Studies of Irradiation Assisted Stress Corrosion Cracking in Austenitic Stainless Steels

The neutron irradiation fluence on reactor components can produce large property and dimensional changes in materials. Extending the service life of a reactor will increase the total neutron fluence to each component. Fortunately, radiation effects on stainless steels, the most common core constituent, are also the most examined.

In addition to elevated temperatures, intense neutron fields, and stress, reactor components must also be able to withstand a corrosive environment. Corrosion is a complex form of degradation that is strongly dependent on temperature, material condition, material composition, water purity, water pH, water impurities, and gas concentrations. The operating corrosion mechanism will vary from location to location within the reactor core and a number of different mechanisms may be operating at the same time.

While all forms of corrosion are important in managing a nuclear reactor, irradiation assisted stress corrosion cracking (IASCC) has received considerable attention over the last four decades due both to its severity and unpredictability. An example of IASCC in a failed PWR baffle bolt is shown in Figure 7. Despite over thirty years of international study, the underlying mechanism of IASCC is still unknown. The lack of mechanistic understanding and a lack of existence of any alloy that is not susceptible to IASCC means that this is a degradation mode of prime importance for safe life beyond 60 years.

The objective of this program element is to evaluate the response and mechanisms of IASCC in austenitic stainless steels with single variable experiments. Crack growth rate tests and complementary microstructure analyses will provide a more complete understanding of IASCC by building on past EPRI-led work for the Cooperative IASCC Research group.

In addition, this program element will support the LWRS Program strategic goals by providing key data and mechanistic understanding of IASCC, which is expected to become more severe with extended service beyond 60 years. This data will also be used to support utility and regulator life extension decision processes.

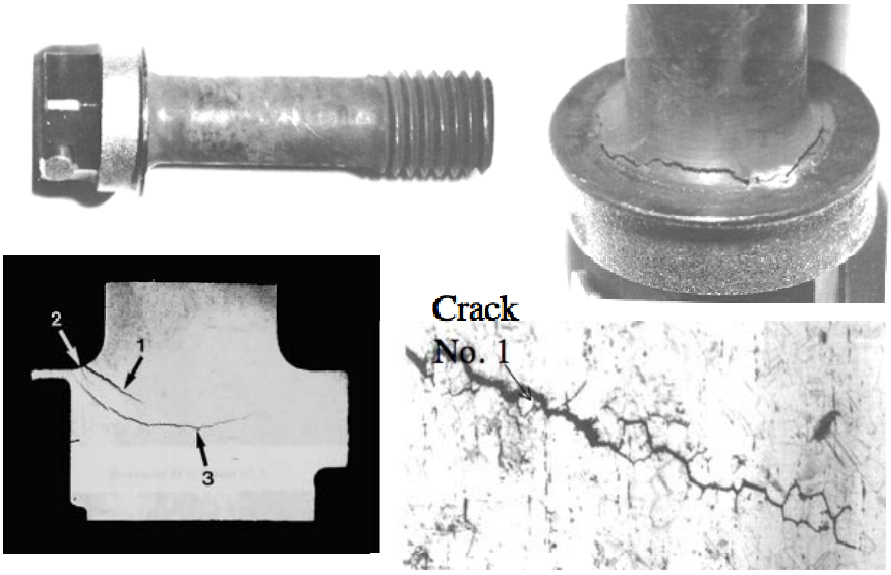

Figure 7. IASCC damage to baffle bolt taken from a reactor.

Evaluation of Flux Effects and High Fluence Degradation of RPV Steels

The RPV is the largest single component at a nuclear power plant site and forms the major pressure boundary for an LWR. The pressure vessel for a boiling water reactor (BWR) is shown in Figure 8. Current regulations require RPV steels to maintain conservative margins of fracture toughness so that postulated flaws do not threaten the integrity of the RPV during either normal operation and maintenance cycles or under accident transients, like pressurized thermal shock.

The last few decades have seen remarkable progress in developing a mechanistic understanding of irradiation embrittlement. However, there are still significant technical issues that need to be addressed to reduce the uncertainties in regulatory application. The present understanding of radiation damage is not fully quantitative and does not address all potentially significant variables and issues. The combination of irradiation experiments with modeling and microstructural studies will provide an essential understanding to aging evaluations of RPVs.

The issues regarding irradiation effects, briefly summarized in this section, are those identified by a cross-section of researchers in the international community. Of the many significant issues discussed, those having the most impact on the current regulatory process and life extension require both experimental and modeling research. Moreover, the combination of irradiation experiments with modeling and microstructural studies provides an essential element in aging evaluations of RPVs.

Figure 8. Boiling water reactor LWR RPV.

Evaluating high fluence effects (embrittlement and/or late blooming phases) is essential in ensuring RPV integrity for operation beyond 60 years. Both industrial capsules and single variable experiments may be required to evaluate the potential for embrittlement and to provide a better mechanistic understanding of this form of degradation. This effort also provides an opportunity for early programmatic success and can build upon past efforts. One example is a capsule of surveillance specimens irradiated to high fluence in the Palisades Nuclear Power plant. Testing will include impact and/or fracture toughness evaluations, hardness, and microstructural analysis.

This work will support the LWRS Program strategic goals by providing key data and mechanistic understanding of a material degradation phenomenon that is expected to occur based on current knowledge. A more complete mechanistic understanding of this degradation mode will be critical to reducing uncertainty and providing reliable long-term predictions for this critical reactor component.

This task is of high technical interest for EPRI's LTO Program effort. The laboratory testing time and cost equivalents for high-fluence specimens already existing in the Palisades Nuclear Power plant are at least 20 years and approximately $5M. Using existing irradiated specimens could potentially result in considerable time and cost savings for the LWRS Program.

The collaboration potential is high with existing programs at the NRC and other international efforts (the International Atomic Energy Agency [IAEA], for example). In addition, university researchers have played key roles in past RPV programs and can provide significant technical value to this effort.

Crack Nucleation and Initiation for Ni-based Alloys and Stainless Steels

Understanding and modeling the mechanisms of crack-initiation is a key step in predicting and mitigating SCC in the primary and secondary water circuits. An examination into the influence of surface conditions on precursor states and crack initiation is also needed for Ni-based alloys and austenitic stainless steels. This effort would include crack-growth rate testing of Ni-based alloys and stainless steels in simulated LWR water chemistries. Carefully controlled microstructure and surface states will be used to generate single variable experiments. The experimental effort in this task will be complementary to efforts being initiated at the Materials Aging Institute which are focused primarily on modeling of crack initiation.

This work will support the LWRS Program strategic goals by providing key data and mechanistic understanding of intergranular stress corrosion cracking (IGSCC) in Ni-based alloys and stainless steels,

which is expected to become more severe with extended service beyond 60 years of lifetime. This work also provides data and a mechanistic understanding to enhance the current state of knowledge of IGSCC and inform life extension decision processes for components that are the primary pressure boundary.

This task is of high interest for EPRI's LTO Program effort, both technically and financially, and additional cost-sharing opportunities are being explored. Collaboration with existing programs at the NRC and new efforts supported by the Materials Aging Institute are anticipated. University researchers may play an important role in providing mechanistic understanding and/or modeling of crack initiation processes and fracture mechanics.

3.1.4.2 Concrete

As concrete ages, changes in its physical properties will occur over time as a result of slow kinetic processes (e.g., slow hydration, crystallization of amorphous constituents, and reactions between cement paste and aggregates), as well as environmental influences, such as exposure to elevated temperatures and radiation. Changes to embedded steel reinforcement as well as its interaction with concrete can also be detrimental to concrete's service life. These changes do not have to be detrimental to the point that the concrete will not be able to meet its functional and performance requirements.

The properties of concrete and the associated steel rebar in sustained high temperature areas such as reactor vessel supports and moist environments will need to be revalidated to assure long-term operation. The long-term stability and performance of concrete structures within a nuclear power plant is a concern as there is little operational data or experience to inform relicensing decisions. Further, a number of concrete SSCs, such as the containment structures, cannot be replaced.

As relatively little attention has been paid to concrete aging in LWRs to date, a prioritization of structures and related degradation mechanisms should be assembled, based on operational experience. Subsequently, a number of issue-based R&D projects can be undertaken in an effort to further understand the issues and determine how they may impact LTO.

This work will support the LWRS Program strategic goals by using industry experience to tailor R&D efforts to emerging issues in the U.S. fleet of nuclear power plants (e.g., leaking spent fuel pools). These issues have the potential to impact license extension decisions if an effort is not undertaken to further understand them.

This task is of high interest for EPRI's LTO Program effort, both technically and financially, and additional cost-sharing opportunities are being explored. Collaboration with organizations such as with the domestic utilities or internationally through the IAEA, Nuclear Energy Agency, and Materials Aging Institute are also anticipated. Further, this work may build upon other non-nuclear concrete performance databases such as the Advanced Cement-Based Materials Program. University researchers may also play an important role in this research. Several leading universities currently participate in the Advanced Cement-Based Materials Program.

3.1.4.3 Cabling

The degradation of electrical and signal cabling within a nuclear power plant will be important for extended reactor service. Of particular concern is the long-term performance of both low, <1000V and medium voltage cabling, 4 kV to 35 kV. Most of the concern for low-voltage cabling is due to degradation resulting from localized adverse conditions. For medium voltage cable, the main concern is wet aging of underground cable. Extended service will broaden the number of cables, which may require replacement over an 80-year lifetime. Many practical issues related to access, testing, and replacement exist for any cable-related performance issue. Additionally, the degradation and aging mechanisms alternate forms of cabling, such as fiber optics, must also be evaluated if these materials are to be used as long-term replacement cables.

Unfortunately, monitoring and surveillance techniques for medium voltage cables are not as advanced as for low-voltage cabling. The replacement of medium-voltage cabling is perhaps more complicated than low-voltage cables due to the extra stiffness of the larger cables and confined ductwork and cable trays. These difficulties create several key research needs. These needs include localizing potential failures before they occur and testing and assessing the condition of cables without the use of high voltages and disconnection of load.

3.1.4.4 Buried Piping

Piping of support system water is a key component for a nuclear power plant. The degradation of raw water piping can have significant adverse affects on plant reliability and increase operating costs. Common degradation modes of these pipes may include microbiologically induced corrosion, tuberculation, weldment attack, or pitting. An example of tuberculation of a pipe is shown in Figure 9. As a result of this degradation, there is a need for improved understanding and prevention of piping degradation.

These issues are most severe for piping that is buried under reactor buildings or other equipment. In these locations the piping is inaccessible for direct inspection, diagnosis, repair, and/or replacement. This motivates several research needs related to the long-term use of the buried piping in the existing nuclear power plant fleet, including evaluation and repair activities. One important long-term research need is improved inspection tools and methodology. Improved techniques for determining the integrity of piping will help provide information on service life remaining and locations for repair.

Figure 9. Tuberculation of raw water pipe.

3.1.5 Milestones

- **FY-09:** Initiate the first set of high-priority research tasks. Initial activities may include further planning, prioritization of experiments within each task, and identifying and procurement of necessary samples.
- **FY-09:** Complete a mid-year progress report on the various research tasks. This report may include updates on the procurement of irradiated specimens, progress on testing plans, as well as any preliminary results on initial testing (e.g., crack growth rate tests, tensile tests, and analysis of these results).
- **FY-09:** Complete final status reports for each of the initial research tasks. These reports will be compiled into a year-end report.
- **FY-09:** Complete a year-end report that will include an updated strategic plan for this R&D pathway.
- **FY-10:** Complete planning for acquisition of in-service samples from existing LWRs. These samples will be critical in understanding in-plant degradation. Examples may include core internals from the Zion plant or concrete or internals from the Millstone plant (both of which have been shut down and are preparing for decommissioning).
- **FY-10:** Conduct a technical review meeting during the second half of the year. This meeting will provide an opportunity to review results from the on-going tasks and prioritize and plan FY-11 tasks.
- **FY-10:** Complete a year-end report that will include updates on testing in the initial research tasks and an updated strategic plan.

- **FY-11:** Conduct a technical review meeting during the second half of the year. This meeting will provide an opportunity to review results from the on-going tasks and prioritize and plan FY-12 R&D tasks.
- **FY-11:** Complete a year-end report and provide further updates on testing in the initial research tasks. This report will also include an updated strategic plan.

3.1.6 Schedule

The schedule for the Nuclear Materials Aging and Degradation R&D Pathway is shown below in Figure 10.

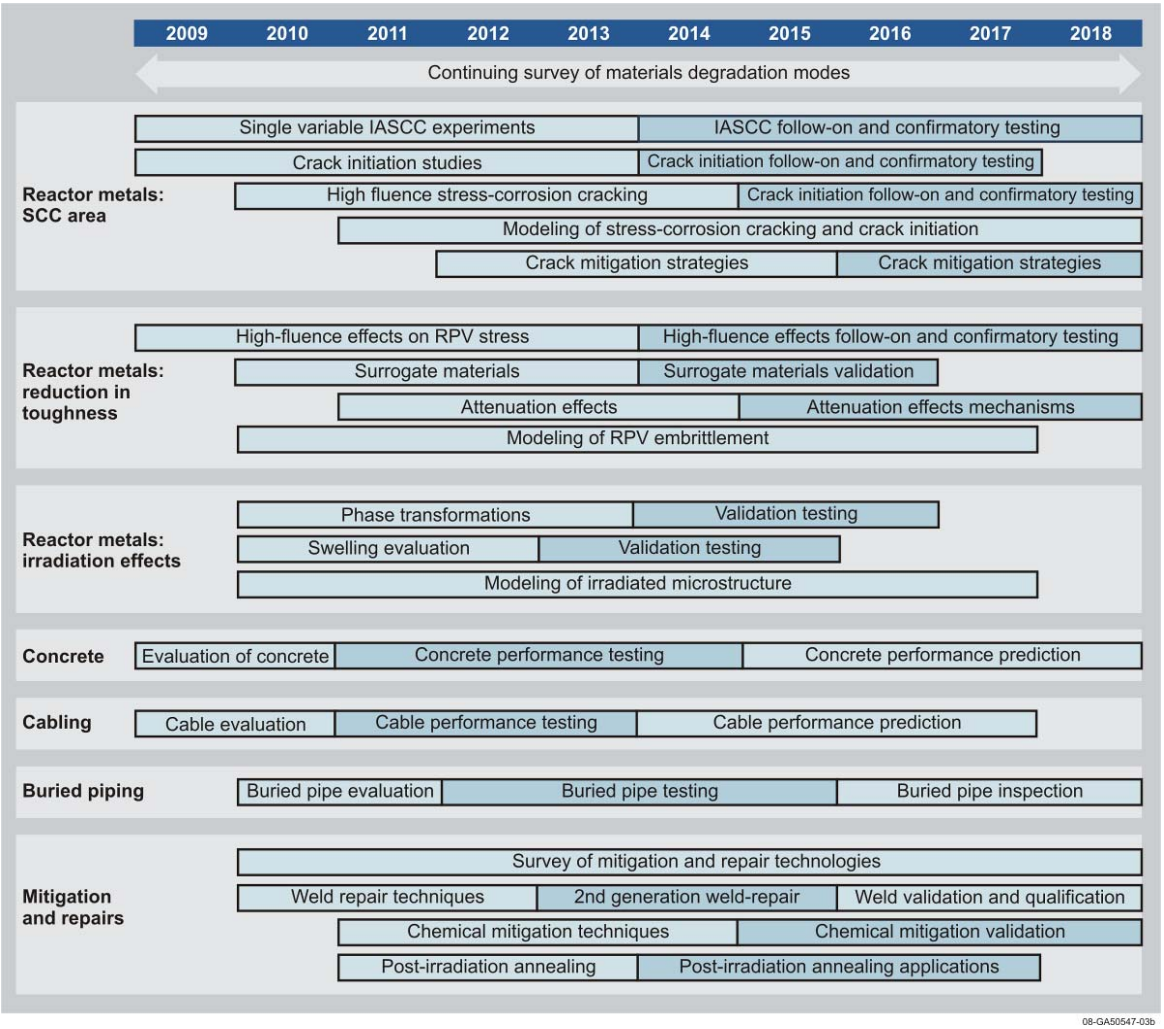

Figure 10. Nuclear Materials Aging and Degradation R&D pathway schedule.

3.2 Advanced LWR Nuclear Fuel Development

3.2.1 Background and Introduction

Nuclear fuel performance is a significant determinant in nuclear power plant operational performance, safety, and economics. In addition, fuel design economies impact costly long-term spent fuel storage options. Over the past two decades, the nuclear power industry has improved plant capacity factors by incremental improvements in fuel reliability and use, or “burnup.” However, these upgrades have effectively reached their maximum achievable impact within the constraints of existing fuel design,

materials, licensing, and enrichment limits. Although the development, testing, and licensing cycle for new fuel designs is typically long (about ten years from conception through utility acceptance), these improvements are often used with only an empirical understanding of the fundamental phenomena limiting their long-term performance.

Continued development of high-performance nuclear fuels through fundamental research focused on common aging issues can enable plant operators to extend plant operating cycles and enhance the safety margins, performance, and productivity of existing nuclear power plants. The Advanced LWR Nuclear Fuel Development R&D pathway is created to perform research improving reactor core power densities, increasing fuel burn ups, advanced cladding integrity, and developing enhanced computational models to predict fuel performance. This research is further designed to demonstrate each of these technology advancements while satisfying all safety and regulatory limits through rigorous testing and analysis.

To achieve optimal fuel costs and use while remaining within safety boundaries, significant steps beyond incremental improvements in the current generation of nuclear fuel are required. Fundamental improvements are required in the areas of nuclear fuel composition and performance, cladding integrity, and the fuel/cladding interaction are needed to reach the next levels of nuclear fuel development. These technological improvements are likely to take the form of revolutionary cladding materials, alternate isotope fuel compositions, and enhanced fuel mechanical designs. As such, these changes are expected to have substantial beneficial improvements in nuclear power plant economics, operation, and safety.

3.2.2 R&D Pathway Strategy - Vision and Objectives

The Advanced LWR Nuclear Fuel Development R&D Pathway vision and objectives are captured in the following statements:

Vision for 2020: Advanced high performance fuels are an essential part of the safe, economic operation of LWRs. The new fuels have improved safety margins and economics and are more reliable. The fuel provides head-room for additional power uprates and high burnup limits. The scientific basis for fuel performance is well understood and its response to changing operational conditions and transients is predictable. This supports continuous improvements to reliability and operational flexibility for the nuclear power plant fleet.

Objectives: The strategic objectives of the Advanced LWR Nuclear Fuel Development R&D pathway are to improve the scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding performance in nuclear power plants. Apply this information to development of high-performance, high burn-up fuels with improved safety, cladding, integrity and improved nuclear fuel cycle economics.

3.2.3 R&D Pathway Scope

The main activities for the Advanced LWR Nuclear Fuel Development R&D pathway are described below. These three R&D activities will be applied strategically to demonstrate feasibility of design, increase the understanding of fuel behavior, and develop enhanced modeling and simulation codes to support LWR sustainability. An LWR's fuel performance strongly impacts the reactor's direct costs, operating capacity factor, disposal costs, and safety margin. The application of sustainability concepts to LWRs will improve both the current fuel designs and the ability to predict the performance of those designs.

3.2.3.1 Advanced Designs and Concepts for Fuel and Cladding

The purpose of this program area is to increase the understanding of advanced fuel design concepts, including the use of new cladding materials, to increases to fuel lifetime, and expansions to the allowable fuel performance envelope. These improvements will then allow the fuel performance related plant operating limits to be relaxed in areas such as operating temperatures, power densities, power ramp rates,

and coolant chemistry (CC). Accomplishing these goals leads to economic benefits as well as improvement of operating safety margins.

3.2.3.2 Advanced Mechanistic Understanding of Fuel Behavior

This program area will involve the testing and modeling of specific aspects of LWR fuel, cladding and coolant behavior. Examples include pellet cladding interaction (PCI), fission gas release, CC effects on corrosion, and crud (oxide) formation. The improved understanding of fuel behavior can be used in fuel design, licensing and performance prediction.

An improved fundamental understanding of phenomena that impose limitations on fuel performance will allow fuel designers, fabricators, plant chemists, and code developers to optimize the performance of current fuels and the designs of advanced fuel concepts. A life-cycle concept will be applied so that optimization will be applied to fabrication, in-reactor use, and performance as spent fuel in storage. The fundamental mechanistic models will provide a foundation for supporting LWRS Program strategic objectives in developing advanced fuels.

3.2.3.3 Advanced Tools

This program area will use the increased understanding of specific fuel performance phenomena that will be integrated into encompassing fuel performance advanced tools. These advanced tools, including modeling and simulation codes, advanced experimental capabilities, and real-time performance monitoring, will be developed to enhance plant and repository efficiency. In addition, the advanced tools developed will be used to minimize the time required to realize the gains made through this R&D effort by decreasing the amount of time needed for materials development and fuel qualification.

3.2.4 R&D Pathway Highlights

The scope of the pathway includes all aspects important to fuel design and performance including assembly design, CC effects, and cladding material performance and development. Figure 11 shows a typical PWR fuel assembly. A BWR assembly is of different design but the fuel rods are quite similar.

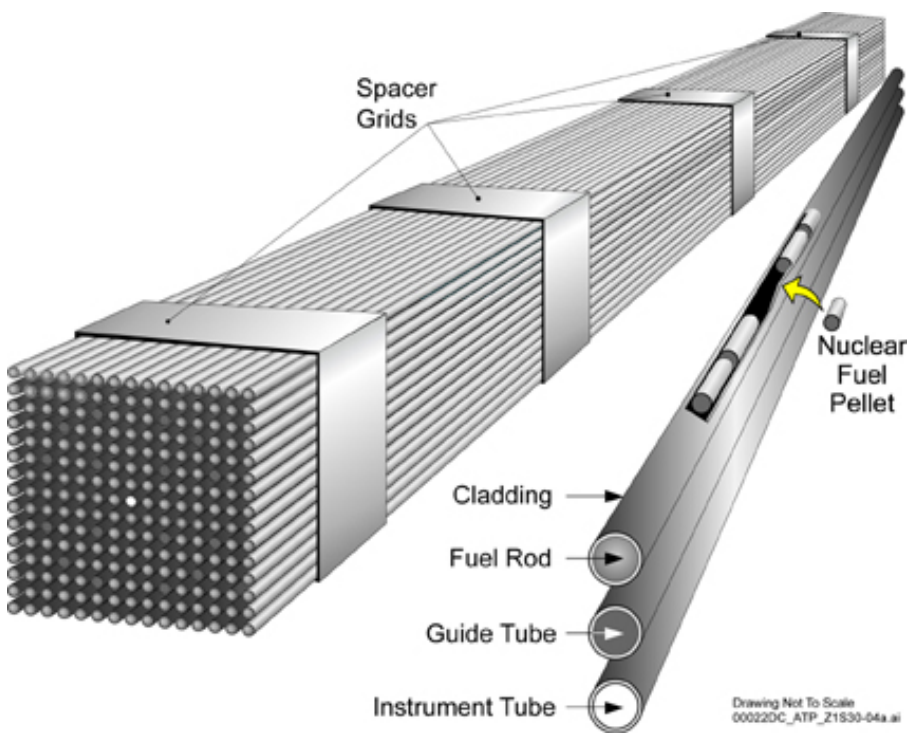

Figure 11. Nuclear fuel assembly.

Current planning efforts have identified a number of R&D program elements that support the advanced designs and concepts, advanced mechanistic understanding of fuel behavior, and advanced tools. These program elements are described below.

3.2.4.1 Advanced Designs and Concepts for Fuel and Cladding

Industry needs to evaluate new and alternative fuel compositions and content. Some of the benefits that may be gained by having options in fuel composition include: (1) more efficient fuel management, (2) fewer assemblies for storage if higher burnup, and (3) an optimized fuel cycle length (options of three- and four-year cycles leads to fewer outages or shorter maintenance-only outages).

Some of the technology options for the Advanced Designs and Concepts for Fuel and Cladding program element may include: (1) alternate fuels (UOX/MOX, uranium nitride [UN], uranium carbide [UC], hydride), (2) novel designs (annular fuel, innovative shapes, liquid metal bond), (3) dopants for PCI, thermal conductivity, and (4) advanced cladding (i.e., optimized next generation zirconium alloys and silicon carbide [SiC]).

However, there are many issues that must be addressed to make these new fuel types acceptable for nuclear power plant use. For example, for current fabrication, operation, and storage, the licensing basis requires uranium of less than 5% enrichment. In order to use enrichments greater than 5%, the full impact of changing this licensing basis must be evaluated. Other, more technical issues related to increased enrichment include: fabrication, reactor operation (excess reactivity at beginning of cycle [BOC]), transportation limits, criticality limits, spent fuel storage limits, and fuel cycle economics. While there may be other issues with other fuel types, the enrichment increase provides an example of a program element with industry-wide scope.

3.2.4.2 Advanced Mechanistic Understanding of Fuel Behavior

Coolant Chemistry (CC) Effects on Corrosion

Cladding corrosion and crud formation are central issues to nuclear fuel reliability. An experimental campaign will be integrated with a modeling effort to study the effects of CC on cladding corrosion. A coupled model and tool development effort will be initiated. This task will include the development of a multiphysics model including aspects of two-phase flow, heat transfer, neutronics, and crud deposition. These efforts will focus on 3-D and multiphysics simulation codes coupled to CC modeling capability to represent more realistic reactor and fuel environments including thermal hydraulics and computational fluid dynamics, species transport and chemistry in fuel-clad system, neutronics, reactor coolant water chemistry, and crud deposition. The initial goal of this task would be to have an impact on experimental design. Based on available funding, a validation effort with operating experiments would be conducted. Another subtask includes an extrapolation to true reactor conditions that will require self-consistent neutronics. This effort will also consider include the impact of localized boiling by use of improved two-phase flow and heat transfer models.

An experimental program would be designed to provide data to validate modeling efforts and understand corrosion and crud formation behavior. The experimental and modeling efforts would need to be closely coordinated and should represent conditions in both PWRs and BWRs. Model validation efforts could be enhanced by the inclusion of: (1) out-of-pile testing simple fuel rod geometry (i.e., crud deposition on heated rod), (2) out-of-pile testing of complex geometries (i.e., fuel bundles, electrically heated rod bundle), (3) in-pile testing of multiphysics predictions, and (4) enhancing the existing database with the knowledge gained through the collaboration of national laboratories, EPRI, universities, industry, and international partnerships.

Fission Gas Release and Swelling Behavior

The intent of this program element is to develop a multiscale modeling capability to describe fission gas release (FGR) using in traditional and advanced concepts. The model development effort that benefits

this R&D pathway is described in more detail in the Modeling Efforts Section. The benefits for producing this model include removing the current limiting parameter of uncertainty in analyzing and predicting FGR and developing the capability for predicting novel fuels including the swelling component of the model. This will provide a foundation for other fundamental mechanism-based modeling, such as pellet clad interaction (PCI).

The mesoscale, microstructural model development and refinement must include methods to introduce irradiation defects, temperature, and a power profile. Fundamental materials parameters and phenomena will be included to allow validation of fission gas transport, diffusion coefficients, grain restructuring, bubble size, and distribution. The FGR mechanism and a more accurate radial power profile will be part of the integrated model.

To accomplish the LWRS Program objectives, the multi-scale modeling capability, which leverages high-speed computers capable of simulating mesoscale-coupled microstructure mechanic models, will be translated into a simplified model for higher-length-scale engineering codes (e.g., FRAPCON, FALCON).

Pellet Cladding Interaction

PCI continues to be a significant cause of LWR fuel failures.[10] The pellet clad failure mechanism is complicated by long and short term time elements that are not clearly understood. The intent of this program element is to create a multiscale modeling capability to describe PCI as is proposed in FGR modeling. As in FGR modeling, the benefits of this model would include a better understanding of a limiting parameter of uncertainty in and better prediction of PCI behavior.

The PCI activity is to develop the project planning and project selection for FY-10 and beyond. PCI tasks will include an experimental campaign integrated with a modeling effort. The experimental campaign will consider conventional irradiation ramp testing, iodine stress corrosion cracking (SCC) compatible with a Cumulative Damage Index Model or testing of other fabrication approaches that mitigate PCI fundamental mechanisms.

Scope development in the area of PCI may be focused on:

- Developing an experiment program that may include:
  - Planning and initiating ramp testing to investigate PCI
  - Testing of Iodine SCC test matrix compatible with a Cumulative Damage Index Model or testing of cracked pellet, concentrated species, stress concentrators, or other needed samples.
- Developing and testing a novel fabrication technique for homogeneous fuels of innovative shape.
  - Developing commercially available techniques for nuclear fuel fabrication with homogeneous microstructure and densities to ameliorate end-capping
  - Developing innovative fuel pellet geometries.
- Developing high fidelity models
  - Creating models adaptable to complicated design geometry such as part-length rods, different rod lengths, and impact of increased power and flow uncertainties
  - Developing 3-D models with equivalent resolution and expandability of current 2-D models
  - Including material behavior (constitutive) models and numerics for multiple special geometries (2-D r-z + r-theta with materials modeling and axial splicing/interaction).

Hydrogen Behavior

Hydrogen affects many aspects of fuel performance, especially cladding mechanical integrity, swelling, etc. The purpose of this program element is to research specific hydrogen effects separate from

other CC effects. Scope development should include determination of the hydride-induced, ductile-to-brittle transition of cladding for storage and transportation applications. The program should:

- Investigate how hydride reorientation affects mechanical behavior of spent fuel cladding and the susceptibility to these effects during storage and transport and develop a damage-based model of fuel rod performance during storage
- Address thermomechanical conditions representative of drying operations, storage, and transportation, including hoop stress, temperature cooling rate, thermal cycling and ductility and fracture resistance
- Enhance existing mechanistic-based engineering codes to model fuel rod performance during cask accidents.

3.2.4.3 Advanced Tools

Non-destructive Examination

The NDE focus will be on providing techniques to examine, or monitor in real time, those effects being studied in the other areas of fuels R&D. This area will cross-cut heavily with the Advanced Instrumentation, Control, and Information Systems Technologies R&D pathway in an effort to develop advanced inspection capabilities for poolside examinations and in reactor monitoring. The ability to monitor aspects of ductility loss in spent fuel cladding while in storage, by a non-destructive hydrogen measurement technique is an example of this program element.

Advanced Experimental Capabilities

The development, reestablishment and improvement of advanced experimental capabilities is a critical need for accomplishing LWRS Program objectives. Advanced fuel designs and concepts require advanced experimental capabilities to verify and validate high fidelity multi-scale models. These experimental capabilities will also support validation efforts by the Risk-Informed Safety Margin Characterization Pathway. Examples of such advanced experimental capabilities include irradiation ramp testing for characterizing PCI behavior, and thermal hydraulic fluid dynamic test loop with control and monitoring capability for temperature, flow, linear power, and possibly coolant technologies.

A survey of existing U.S. and international organization's capabilities will be conducted. A plan that evaluates each required experimental capability will be developed. The steps needed to prepare and implement a testing program using the experimental capabilities will be presented. The implementation plan can include refurbishment of existing capability, establishing new, domestic capability, and leveraging international partnerships.

Modeling Efforts

Central to the Advanced LWR Nuclear Fuel Development R&D pathway is the development and use of fuel performance models, which is key to the success of other program elements such as fission gas release and swelling, CC accelerated corrosion and crud deposition, and PCI. This program element should lead to developing high fidelity models and interfaces between neutronics, thermal hydraulics, fluid dynamics and CC.

The models will be adaptable to complicated design geometry such as part-length rods, different rod lengths, and impact of increased power and flow uncertainties. The 3-D models will be developed with equivalent spatial and temporal resolution and expandability of current 2-D models. The high fidelity modeling will include material behavior (constitutive) models and numerics for multiple special geometries (2-D r-z + r-theta with materials modeling and axial splicing/interaction). To ensure modeling efforts benefit all users from industry, academia, national laboratories and the DOE, the LWRS Program will make data and code publicly available, provide code portability using simplified subroutines for higher-length scale codes, and define inputs and outputs of each length-scale modeling tool.

3.2.5 Milestones

3.2.5.1 Advanced Designs and Concepts for Fuel and Cladding

- **FY-09:** Conduct a workshop on advanced fuels and cladding for LWRs in the first quarter of FY-09.

3.2.5.2 Advanced Mechanistic Understanding of Fuel Behavior

Coolant Chemistry

- **FY-09:** Plan and conduct an advanced Fuel Design and Concepts Workshop in the second quarter
- **FY-09:** Develop a 3D mesoscale model framework for microstructural evolution that can couple to a fuel performance code
- **FY-09:** Generate a plan for an experimental campaign to investigate CC–crud–corrosion interaction with a validation experimental suite
- **FY-09:** Complete a year-end report that will include updates on modeling efforts and testing in the initial program elements. This report will reflect revised tasks and a prioritization plan for FY-10
- **FY-10:** Develop a simplified, phenomenological model that translates the 3D mesoscale microstructural model to be used with an engineering fuel performance code
- **FY-10:** Plan and conduct a technical review meeting during the second half of the year. This meeting will provide an opportunity to review results from the current program elements and plan FY-11 projects
- **FY-10:** Complete a year-end report that will include updates on modeling efforts and testing in the initial program elements. This report will reflect revised program elements and prioritization plan for FY-11
- **FY-11:** Plan and conduct a technical review meeting during the second half of the year. This meeting will provide an opportunity to review results from the current program elements and plan FY-12 projects
- **FY-11:** Complete a year-end report that will include updates on modeling efforts and testing in the initial program elements. This report will reflect revised program elements and a prioritization plan for FY-12.

3.2.6 Schedule

Figure 12 presents the schedule for the Advanced LWR Nuclear Fuel R&D pathway areas, including the modeling efforts that will be of benefit to the other R&D pathways. The diagram demonstrates the integration between modeling, design efforts, and fundamental understanding. It further shows the ties to the performance periods that were chosen so that the results of the R&D are responsive to decisions that need to be made concerning the potential for 60-year life extensions of existing nuclear power plants.

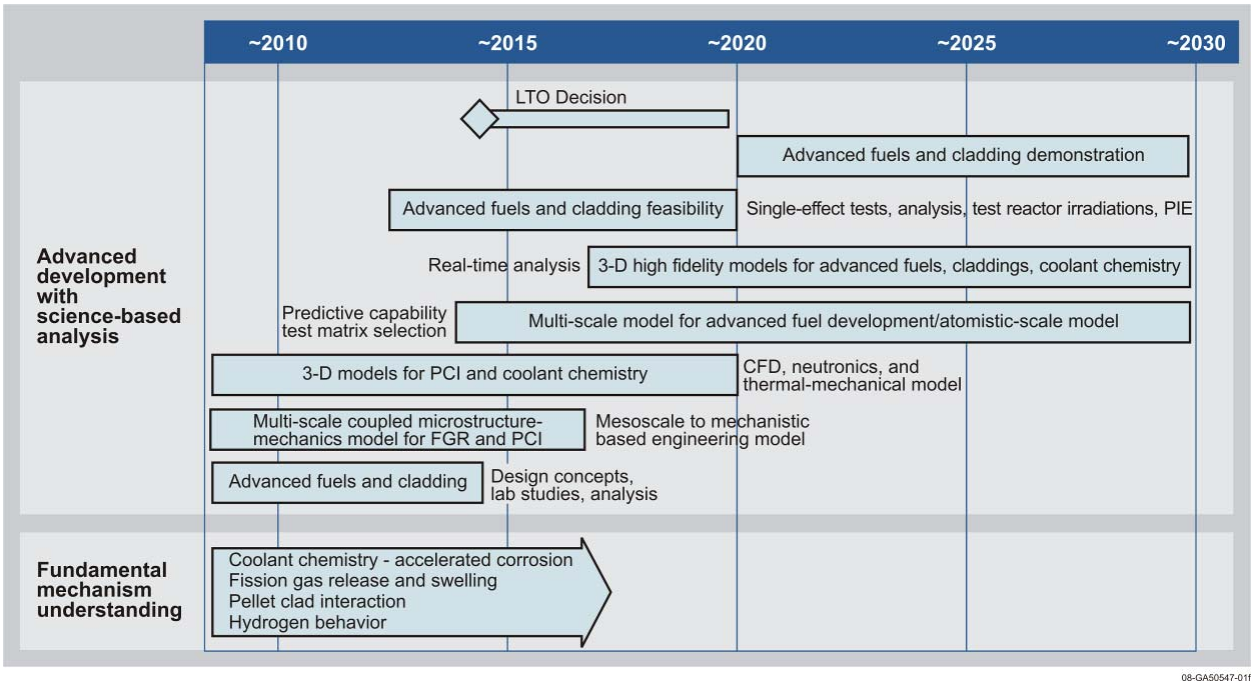

Figure 12. Advanced LWR Nuclear Fuel Development R&D pathway schedule.

3.3 Advanced Instrumentation, Control and Information Systems Technologies

3.3.1 Background and Introduction

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

The industrial base has largely moved to digital-based systems, and vendors are gradually discontinuing support and stocking of needed analog spare parts. The reason for the transition to digital I&C systems lies in their important advantages over existing analog systems. Digital electronics are essentially free of the drift that afflicts analog electronics, so they maintain their calibration better. They have improved system performance in terms of accuracy and computational capabilities. They have higher data handling and storage capacities, so operating conditions can be more fully measured and displayed. Properly designed, they can be easier to use and more flexible in application. Indeed, digital systems have the potential for improved capabilities (e.g., fault tolerance, self-testing, signal validation, process system diagnostics) that could form the basis for entirely new approaches to achieve the required reliabilities. Because of such potential advantages, and because of the general shift to digital systems and waning vendor support for analog systems, the U.S. nuclear power industry expects substantial replacement of existing, aging analog systems with digital I&C technology. For the same reasons, designs for new, advanced nuclear power plants rely exclusively on digital I&C systems.[11]

Significant issues exist with regard to licensing of digital systems for nuclear applications, their suitability in some of the environmental conditions that are found in nuclear power systems, and criteria for decision related to automation and safety. Such technologies are, and will be, the norm in power generation industries worldwide, and the transition to digital I&C systems is necessary in order for

today's commercial energy systems to remain a safe and economically viable part of the nation's energy supply.

Inspection and monitoring are essential to allow plant operators to detect degraded performance and potential material issues before they cause significant impact on safety or reliability. Traditionally, inspections have usually occurred during planned power plant shutdowns for refueling, as driven by conservative assessments of failure rates and deterministic schedules.

The emerging field of prognostics may enable online monitoring and modeling of systems which could augment these traditional inspection programs. A graphic of prognostics is shown in Figure 13. Risk insights can be used to optimize inspection scheduling in order to minimize plant downtime.

The findings of the National Research Council emphasize that the U.S. nuclear power industry is not evolving to utilize the full capabilities and characteristics of the available instrumentation, control, and human machine interface (ICHMI) technologies.[11] As a result, the nuclear power industry has not realized the benefits that these technologies afford.

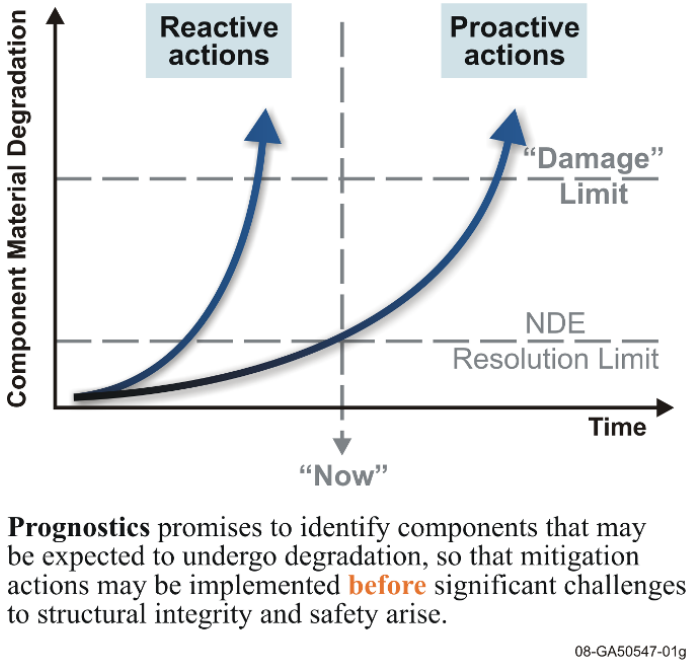

Figure 13. Graphic representation of Prognostics for Component Degradation.

Advanced digital technology consolidates monitoring functions, increases interconnections, and enhances functionality, thus substantially changing I&C system architecture at nuclear power plants. This integration improves nuclear plant safety by reducing human error, increasing plant physical security, and enabling critical failure precursor monitoring through prognostic applications. Additionally, this technology is anticipated to contribute to the long-term economic viability of the existing plants by reducing operating costs and outage times, unnecessary condition monitoring, and component maintenance or replacement.

Rapid advances in this area can make technology management difficult, as plant licensees must ensure the continued compatibility of their systems. This characteristic will require a focus on design modularization and the adoption of consensus standards or industry guidelines upon which regulatory approvals can be based.

Integrated and automatic digital control systems are the norm in most process industries and have been shown to lead to advances in reliability, performance, and safety. U.S. nuclear power plants presently have almost no primary circuit automatic controls and the use of digital monitoring and actuation of safety functions is limited by strict regulatory requirements. The use of modern digital I&C systems, and their more easily maintained subsystems, will eliminate a significant reliability risk to current nuclear power plants as less reliable analog systems are replaced. The improved functionality and control interface will provide the opportunity for greatly improved operations similar to other modern complex systems. The digital systems will also interface more easily with the infield systems required to monitor the plant to a higher resolution necessary for a longer operating life.

3.3.2 R&D Pathway Strategy - Vision and Objectives

The Advanced Instrumentation, Control and Information Systems Technologies R&D Pathway vision and objectives are captured in the following statements:

Vision for 2020: The safe, reliable, economical long-term operation of nuclear power plants is supported by modern instruments, control, and information systems. A technology upgrade process is established and in active use. The modern digital technology features centralized, automated, on line monitoring and information management of nuclear power plant SSCs and supports integrated operations, maintenance, and management decisions.

Objectives: The strategic objectives of the Advanced Instrumentation, Control, and Information Systems Technologies R&D pathway are to establish scientific knowledge basis and advanced phenomenological modeling, advanced condition monitoring and prognostics technologies for use in understanding the aging of SSCs of nuclear power plants. This integrated information base will then be used to develop and demonstrate information system technology enhancements for knowledge migration and regulatory compliance.

3.3.3 R&D Pathway Scope

The scope of the Advanced Instrumentation and Control and Information System Technologies R&D pathway will be carried out in four areas of synergistic research that will build capabilities and technologies that can be brought to bear on the problem of extending the functionality and expected service lifetimes of I&C systems in today's nuclear power plants. These are further described below.

3.3.3.1 Centralized Online Monitoring and Information Integration for Critical Structures, Systems, and Components

Considerable work in this R&D pathway area has been performed in various DOE-sponsored programs and in other commercial industries. However, little work has been done to demonstrate the feasibility and applicability of developing or applying methods from other demonstrations to nuclear power systems in current LWRs. As well, the suitability of such methods and their scalability must be assessed within the broader context and number of systems that must be monitored in LWRs. Because of these reasons and budget, FY-09 activities will emphasize program plan development via a technology roadmap that applies to this R&D area over the course of its execution. Because of the number of potential and available methods that can be applied in this pathway area, methods for benchmarking and validation should also be pursued. In FY-10 and beyond, the program should emphasize the selection of SSCs to serve as reference systems, the testbeds that will be employed to evaluate online monitoring technologies, criteria needed to demonstrate diagnostic and prognostic performance, the development of improved sensors and networks for monitoring, and eventually demonstration of scalable technologies and guidelines for their deployment and implementation.

3.3.3.2 New Instrumentation & Controls and Human System Interface Capabilities and Architectures

Considerable work and demonstration of capabilities in this research program area has been carried out in research centers worldwide and in a limited number of commercial projects internationally. Key constraints in the U.S. nuclear power market include commercial and regulatory decision-making. In FY-09, efforts will begin to develop approaches to modernization and life cycle management via consideration of strategic criteria, including the technical, organizational, and financial aspects of decision-making related to modernization of LWR control and human system interface (HSI) technologies. In FY-10 and out-years, a public-private consortium will develop new capabilities in automation, intelligent agents, simulation, and human-system interfaces in order to achieve long-term needed functionality and improved integration among systems. The work will be carried out using a combination of physical and virtual distributed testbeds, following a design process that includes reliability criteria and verification processes and demonstrations that will support regulatory decision-making.

3.3.3.3 Life Cycle Non Destructive Examination Information & Assessment

This program area provides cross-cutting support to the materials program in the form of implementing diagnostic and prognostic technologies via improved sensors and characterization techniques and information management of data for life-cycle asset management. In FY-09, work will be initiated to assess the current state-of-the-art, technology maturity, and potential for various NDE technologies to support assessment of primary systems to enhance current assessment capabilities and passive structures. In FY-10 and out-years, work will be coordinated with the Nuclear Materials Aging and Degradation R&D pathway to develop and deploy NDE technologies that meet criteria for sensitivity, accuracy, and reliability needed to improve measurement of aging- and degradation-related phenomena. In addition, techniques for analyzing the resulting assessment data will be developed emphasizing diagnostic and prognostic capabilities. Demonstrations of the resulting technologies and systems will be provided that include information systems for automated material condition assessments using NDE testing data, on-line monitoring data, and diagnostic and prognostic models.

3.3.3.4 Maintaining the Operating, Licensing and Design Information Basis

Owner-operators of all future plants anticipate receiving at plant turnover from their architect-engineer a fully integrated Building Information Model (BIM) representing the design basis and as-built status of the plant. This BIM will become the operating and licensing basis of plant operations. This model will then become a living life-cycle information model for supporting all plant O&M processes, capital improvements, and external commitments. The natural evolution to an extended BIM is not readily available for existing plants.

The R&D work scope for existing plants is to specify an effective extended plant information model appropriate for existing plants that can be achieved evolutionarily and sustained for the life of the plant. Technology gaps will be filled by adapting technology from other applications and by innovative new methods. Effectiveness will be demonstrated by limited applications and validations. Ultimately, a full plant implementation will be performed.

No work is planned in this pathway area pending the final determination of FY-09 and out-year budgets.

3.3.4 R&D Pathway Highlights

The Advanced Instrumentation and Control and Information System Technologies R&D pathway supports the overall goals of the LWRS Program and will be implemented through a coordinated set of R&D activities focused on technology development and deployment within I&C systems. The strategic selection was based on a 1997 study conducted by The National Research Council on the state of

instrumentation, control, and human machine interface (ICHMI) architectures, also referred to as digital I&C systems, in nuclear power plants and the challenges involved in modernization.[10]

The strategy for selection of R&D activities is based on the desired capability to deploy technologies that:

- Better characterize and manage plant aging and its effects by providing information from SSCs
- Mitigate aging of current I&C systems
- Manage functional obsolescence of existing I&C systems
- Facilitate maintenance of I&C systems by a future work force
- Are sustainable and can be maintained as operational within the needed safety and design basis envelope required over the lifetime of the facility.

The highlights of the R&D activities selected to best support the R&D pathway are described below.

3.3.4.1 Centralized online monitoring and information integration for critical structures, systems, and components

This program area includes R&D needed to provide information technology and models of system behavior emphasizing aging and degradation to enable real time automatic statistical analysis, pattern recognition, and criteria to diagnose degrading conditions and predict remaining useful life of SSCs. This research area emphasizes the development of models of critical systems and the ability to diagnostically monitor and predict performance in order to achieve high availability in critical systems, improve asset management of high-value resources, and to avoid safety challenges. It is also expected that improved automation and analysis of data about system performance collected online will reduce costs associated with system monitoring and provide more accurate and timely information about the function and condition of plant systems.

3.3.4.2 Advanced Instrumentation & Controls and Human System Interface Capabilities

This program area includes activities needed to develop the approach to achieve life cycle renewal of information and control capabilities needed to continue to operate nuclear power systems safely and efficiently. Figure 14 shows the historic evolution of control room automation and HSI capabilities in representative classes of control system architectures. On the left side are the aging analog-type, single-point control systems. Characterized by a single visual interface over a physically large area, these systems are representative of most LWR control room and control systems in nuclear power plants today. Functional and operationally oriented technologies offer improvements over the analog systems in use by integrating information into tailored displays that can be designed to support goal-oriented tasks and activities. While able to reduce the physical footprint of today's control room systems, advanced systems must be evaluated to minimize the introduction of secondary tasks, overload of limited cognitive and perceptual resources, and to achieve human-system performance gains. Some more advanced systems are purely digital and offer unprecedented integration of function, automation, and high reliability. Such ecologically oriented systems integrate considerations of functions, operations, tasks, and designs into compact control rooms capable of supporting the activities of the operational organization. However, testbeds are needed to facilitate deployments of each of the digital design paradigms and few facilities exist currently.

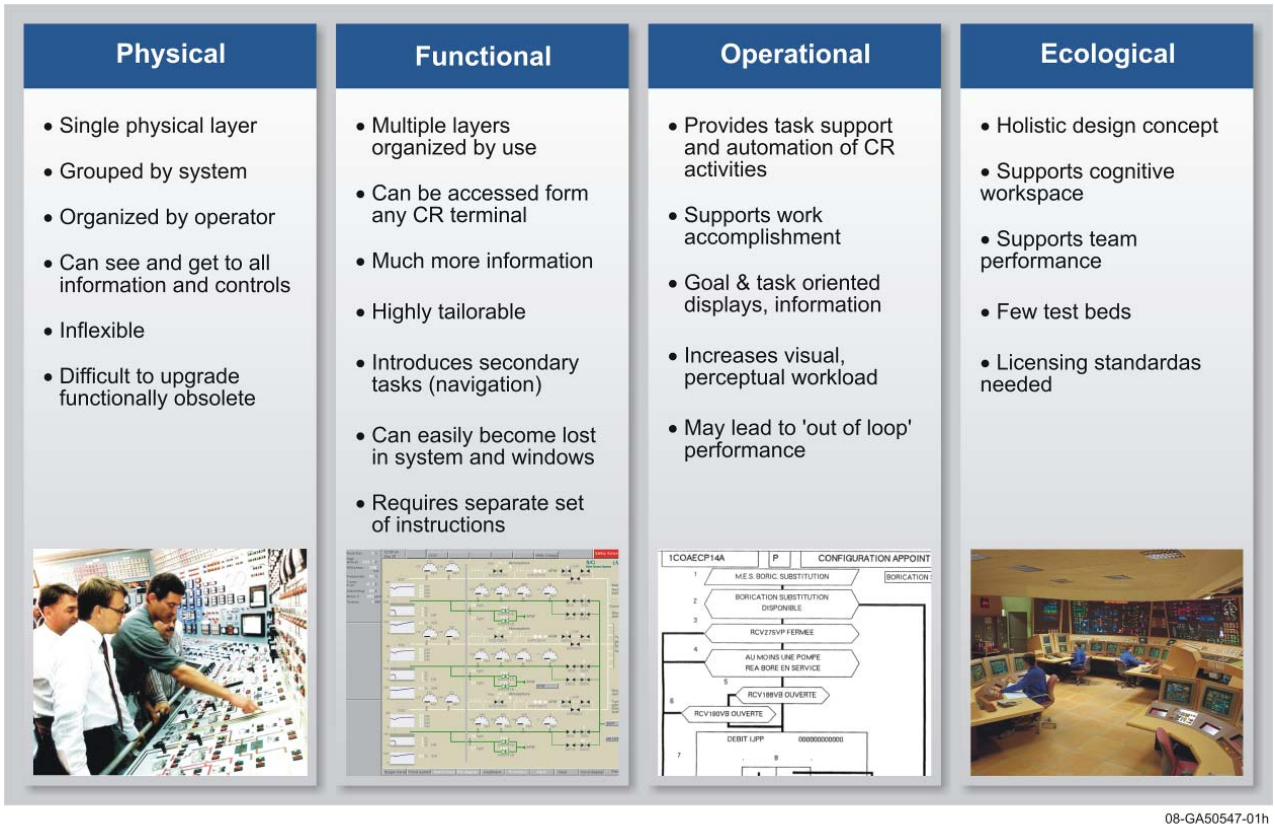

Figure 14. Historic evolution of control room automation in representative classes of control room architectures.

Using a combination of simulation-based design and human-in-the-loop testing, approaches to life cycle design of improved control room automation will be developed to support long-term operability from the perspectives of safety and asset management. This includes new approaches to design and evaluation of advanced human system interfaces and intelligent automation that enhance the reliability of human performance and minimize the opportunity and consequences of error.

3.3.4.3 Life Cycle Non-Destructive Examination Information and Assessment

This program area represents a cross-cutting element that ties to the Nuclear Materials Aging and Degradation R&D pathway. This program area supports development and deployment of sensors to measure characteristics of physical SSCs to assess the effects of aging and material degradation on nuclear systems. This also includes the technology for data capture and storage for nuclear power plant primary systems to support forthcoming diagnostic and prognostic models. In addition, this program element will support needed development, validation, and deployment of inspection and characterization technologies as needed for passive elements in nuclear power plants, such as concrete, cabling, underground storage systems, and buried piping. Finally, methods will be created to support integrated information management for simulation of degradation conditions, assessment of conditions, life utilization, and prediction of remaining safe life for critical nuclear plant materials.

3.3.4.4 Maintain Operating, Licensing and Design Information Basis

This program area supports development of technologies and their deployment to manage, store and use information about the configuration of systems, and their design basis over the course of workforce and system transition. This includes both the tacit knowledge of plant staff, including operational knowledge, as well as physical information. This program area will emphasize methods to extract data

and make it readily available to support design, maintenance, training, and asset management. The plant information model development will leverage the rapidly evolving technology available for major capital projects. It will also leverage the continuing advances in search engines and information integration technology. The project will balance the costs associated with greater capability and the benefits associated with fewer resources, averted risk of plant events or shutdown, and competitiveness with other generating options.

3.3.5 Milestones

3.3.5.1 Centralized Online monitoring and information integration for critical systems, structures, and components

- **FY-09:** Develop the R&D roadmap for centralized on-line monitoring of SSCs
- **FY-10:** Initiate pilot program for demonstrating centralized on-line monitoring
- **FY-10:** Benchmark diagnostic and prognostic technologies
- **FY-11:** Initiate demonstration program and continue benchmarking
- **FY-12 and Beyond:** Demonstrate and deploy prototype technology.

3.3.5.2 New Instrumentation & Controls and Human System Interface Capabilities and Architectures

- **FY-09:** Develop workshop report on simulation technologies for Advanced I&C
- **FY-10:** Develop test-bed and provide initial capability demonstrations
- **FY-11:** Develop distributed simulations and provide design demonstrations
- **FY-12:** Develop human-in-the-loop facilities and improved automation and integration capabilities
- **Out-Years:** Select technologies for licensing application demonstrations.

3.3.5.3 Life Cycle Non Destructive Examination Information & Assessment

- **FY-09:** Develop report on state of the art & technology maturity for advanced NDE techniques
- **FY-09:** Evaluate readiness of passive component NDE methods
- **FY-10:** Assess feasibility of on-line monitoring methods
- **FY-11:** Develop, select and deploy NDE technologies and test on representative systems
- **FY-12:** Deploy and refine NDE techniques and develop integrated information systems
- **Out-Years:** Integrate NDE and information capabilities with diagnostic and prognostics to support condition assessments.

3.3.5.4 Maintaining the Operating, Licensing and Design Information Basis

- **FY-10:** Assess life-cycle information modeling options for safety-related, regulated, complex facilities. Define the appropriate architecture for nuclear plants
- **FY-11:** Specify innovative information capture technologies and processes for populating the information model
- **FY-13:** Complete limited information model construction and testing
- **FY-14:** Demonstrate full deployment at an existing facility.

3.3.6 Schedule

Figure 15 presents a schedule for the Advanced Instrumentation, Control, and Information Systems Technologies R&D pathway.

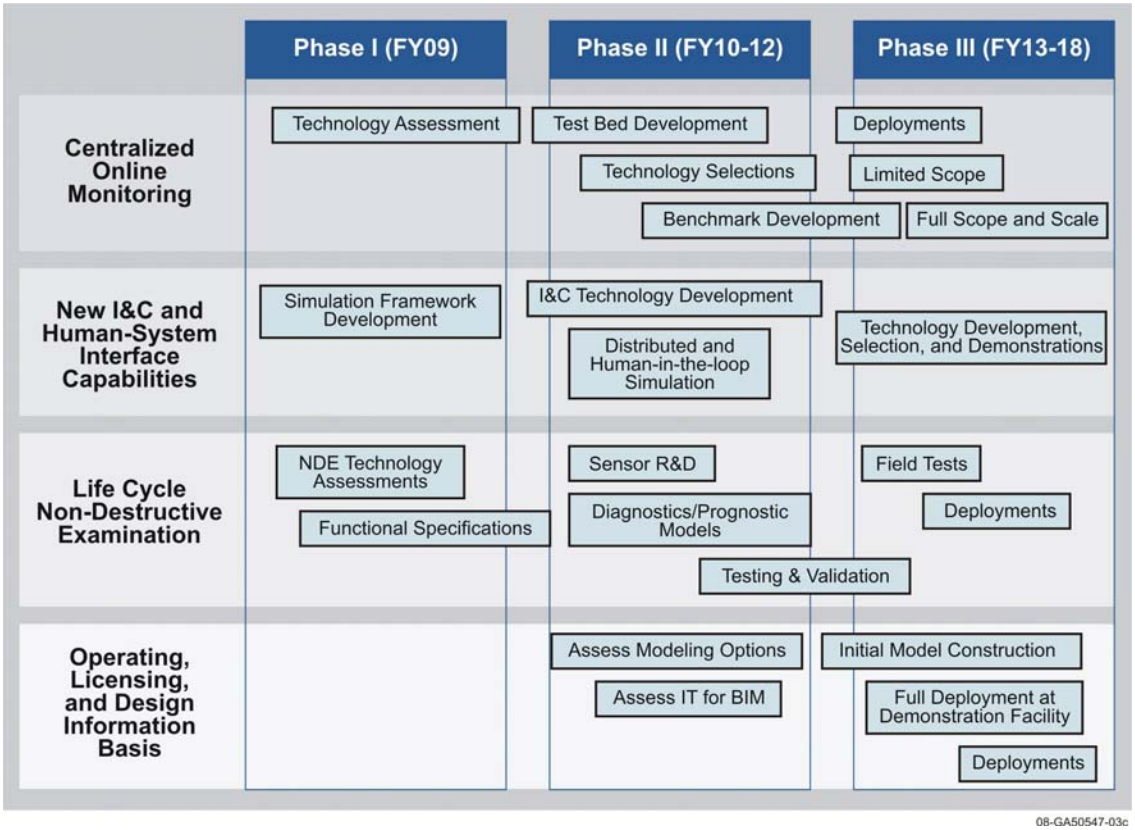

Figure 15. Advanced Instrumentation, Control, and Information Systems Technologies R&D pathway schedule.

3.4 Risk-Informed Safety Margin Characterization

3.4.1. Background and Introduction

The concept of safety margins as a cornerstone in nuclear reactor design emerged during the early days of nuclear power as a part of the defense-in-depth approach to ensuring nuclear safety. Defined as the minimum distance between the system's "loading" and "capacity," safety margin is expressed in terms of safety-significant parameters (e.g., fuel cladding temperature, containment pressure) and determined for a range of anticipated system operating conditions. Traditionally in nuclear power plant design and licensing, availability of safety margins must be demonstrated for a prescribed set of design-basis accidents (DBA). Due to limited knowledge, large (i.e., conservatively specified) safety margins are applied to compensate for approximations used in (the phenomenological, deterministic) models and associated computer codes which estimate the "loads" and the "capacity" in the reactor systems during the complex accident sequences.

Parallel with the deterministic safety analysis (DSA) approach, probabilistic risk assessment (PRA) methods have also been developed and applied to analyze the safety of nuclear power plants. Notably, safety margins calculated by the DSA methods (e.g., accident simulation codes, structural capacity codes) are used to support the specification of "success criteria" in the plant's PRA. Pioneered by the Reactor Safety Study/WASH-1400,[12] the PRA technology has matured and currently provides the nuclear power

industry and the regulator with a powerful tool to analyze plant safety, identify system vulnerabilities, provide a framework for effective resource allocation and focus research and plant operations on risk-significant safety threats. Dating back to the 1980s, migration toward risk-informed regulation has been supported by both the nuclear power industry and the U.S. NRC[13] with numerous applications that have resulted in both improved plant safety and performance.

The use of risk information in characterizing plant safety broadens the definition of "safety margin" relative to the one used in the traditional licensing (prescriptive) approach. As an example, under a risk-informed approach, the deterministic criteria specified for a number of enveloping DBAs could be replaced by risk-informed guidelines with the generalized performance-based safety margin considered in both event frequency and consequences.

The state of the art in R&D related to the risk-informed safety analysis topics can be viewed in three inter-related groups: (1) advanced PRA techniques, (2) advanced DSA techniques, and (3) methods and tools for analysis integration and visualization of results that support effective decision making. The overarching themes in all three groups are analysis completeness, uncertainty treatment, and computational efficiency so that more accurate and cost-effective techniques can be used in engineering applications. This provides a more realistic description of the nuclear power plant system and analysis of associated risks.

In the PRA area, development of advanced analysis techniques has been actively pursued. On the practical side, a substantial drive for risk-informed operation lies in broadening applications of configuration risk management (CRM). On the theoretical side, ongoing research on declarative modeling, direct probability calculation (DPC) and binary decision diagramming (BDD) aims to enhance the ability to model increasingly complex issues. While important advances are being made in improving the PRA techniques, their effective use in the decision process is limited by the current PRA technology, which uses current-generation DSA tools to determine success criteria, and does not have a framework to account for uncertainty in the deterministically estimated values of "load" and "capacity." For example, where margins are relatively small or where large uncertainties exist, it is possible for functional success to occur in the PRA event tree's failure branch, and inversely, functional failure can occur in the tree's success branch. This uncertainly in the accuracy of the PRA results can limit the usefulness of PRA in future decision-making. A particularly important example is the application of PRA to passive SSCs. Another example of a limitation of the current PRA methods is the assumption of independence of failure rates on the system's state and evolution. Techniques for dynamic PRA, which are intended to address this issue, are still in an early developmental phase.

In the DSA area, while incremental advances were made continuously over the past two decades to improve modeling of plant components and transient/accident phenomena, the system (plant) analysis tools used in industry's engineering applications remain based on the decades-old modeling framework and computational methodology that have not taken advantage of modern developments in computer/computational science and engineering. Fundamental limitations in the current generation of system analysis codes are well known to the community. Although the codes have served as an adequate basis to address safety margin analysis, significant enhancements will be necessary to support the challenges of extended and enhanced plant operations. Lack of confidence in the code's predictions is rooted in unquantifiable errors of numerical approximations and poorly combined but separate physical models. The separation of physics models in this approach (i.e., thermal hydraulics, neutron kinetics) are explicitly coupled in reactor transient simulations but fail to capture complex multi-dimensional behavior when such complexity may have a large influence on safety margins. Efforts to advance the DSA technology include R&D to bring advanced methods of Computational Fluid Dynamics (CFD) to support plant safety analysis. For example, the CFD methods have proven instrumental in the study of complex flow phenomena (mixing/stratification, asymmetric flow) that occur in reactor downcomers and lower plena during certain transients and accidents. Being a valuable tool to investigate detail fluid physics, high-resolution (fine-grain) CFD is computationally expensive and not practical for whole-system

simulations of plant transients/accidents in the production mode. Furthermore, due to heterogeneity and high priority for multi-physics treatment of nuclear power plant transients and accidents, the commercial CFD codes (with their frozen and fluid-centric structures) are not conducive for use as a multi-physics simulation framework required for the next generation of system analysis tools.

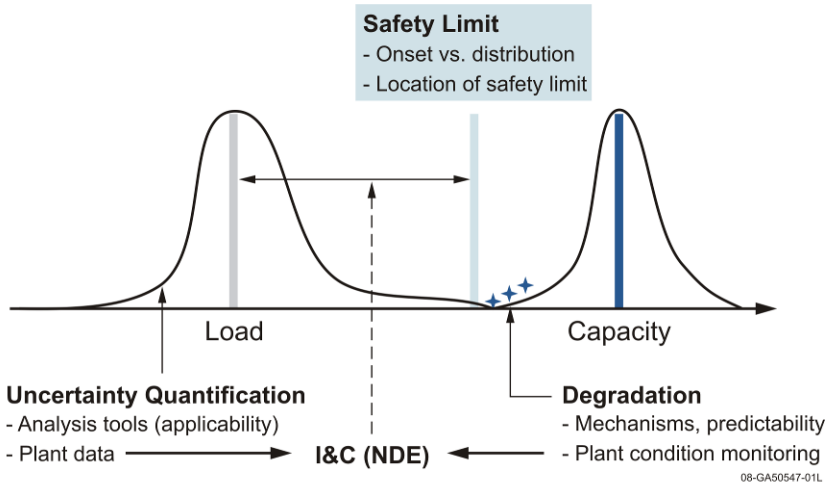

Figure 16. Elements of the RISMC model for LWRS Program.

With respect to methodology for integrated safety assessments, quantification and utilization of plant safety margins and their regulatory implications have received increased attention during recent years, paving way to the formulation of Risk-Informed Safety Margin Characterization (RISMC) as an R&D pathway. A comprehensive review of the state of the art and discussion of open issues related to RISMC can be found in the CSNI Safety Margin Action Plan (SMAP) group report NEA/CSNI/2007(9). Beyond the still-open formidable questions on a RISMC framework, it is widely recognized that the success of a risk-informed approach requires enhanced simulation tools (computer codes) to enable system analysis with high fidelity and treatment of uncertainties which can be significant, for example, in non-DBA and beyond-DBA situations. These challenges will increase as plant operational life is extended.

Figure 16 depicts elements of RISMC in the context of the LWRS Program. In the spirit of defense-in-depth, margin is considered to be significant to the degree that it exceeds uncertainties and variabilities associated with a given comparison between “load” and “capacity.” This idea applies to success of active functions as well as passive SSC integrity, which is instrumental to the characterization, mechanistic understanding, prediction, and monitoring of the plant aging and degradation behaviors and their impact on plant life extension decision making.

3.4.2. R&D Pathway Strategy - Vision and Objectives

The Risk-Informed Safety Margin Characterization R&D Pathway vision and objectives are captured in the following statements:

Vision for 2020: Advanced analysis methods and simulation tools for predicting and managing plant response and safety margins are an accepted and essential part of operating and licensing nuclear power plants. Using the science-based models and databases, the risk-informed safety margin characterization provides effective support and guidance to plant operations, maintenance, major components replacement, and plant licensing decisions.

Objectives: The strategic objectives of the RISMC R&D pathway are to 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.

3.4.3. R&D Pathway Scope

Given the above vision and goals, the RISMC research pathway aims to develop an integrated decision framework and advanced analysis and implementation tools to support safety margin assessment that enable more accurate characterization and visualization of the nuclear power plant's safety margins.

In the context of risk-informed regulation, safety-margin, while broad in concept, remains a fundamental tenant of both the regulatory and operational decision-making framework. The RISMC R&D pathway is driven by the recognition that risk-informing plant safety margins present an avenue to enhance the operational flexibility and safety benefits obtained from the transition towards risk-informed and performance-based regulation. Such a vision is actual and germane to the mission of the LWRS Program.

A major challenge to the life extension decision making lies in large uncertainties in predicting plant safety margins. Existing methods and tools used today in deterministic and probabilistic safety analysis, by themselves and within the current assessment framework, are not adequate to cost-effectively manage the long-term risk and operability significance associated with the aging of SSCs. There are both conceptual and technical capability gaps in frameworks, tools, and data which need to be filled to enable the integrated and defensible decision-making regarding the continued long-term operation of nuclear power plants.

The strategic objectives for the RISMC R&D pathway are split into two sections. First, the RISMC methodology would improve the completeness of PRAs applied to current LWR technology (for example, by including passive component reliability and safety margins into PRA to go beyond the use of safety margin as a simplistic static criteria [e.g., go/no go]). Thus, the RISMC methodology would facilitate further transition from regulation based on (and operation constrained by) safety margins computed for overly conservative (DBA) assumptions to risk-informed regulation with safety margins (aggregate probabilistic goals, e.g., core damage frequency [CDF] and large early release frequency [LERF]) determined comprehensively and consistently with the plant's actual risk profile.

Then, the RISMC implementation requires advanced (next generation) DSA tools for high-fidelity simulations of increasingly complex sets of plant transients in both DBA space and beyond. Sensitivity/uncertainty analysis machinery with built-in next-generation system codes would help reveal uncertainties that could significantly impact the evaluation of nuclear power plant safety margins. Such insights provide a basis for a quantitative "Phenomena Identification and Ranking Table" (PIRT) and would be very useful in guiding further efforts to improve models of most risk-significant phenomena, refine numerical approximations, and design new experiments to acquire the necessary data. The new generation production code would also facilitate the maturation and promulgation of a much-needed new culture in reactor safety analysis. The new culture's defining signature is the analyst's ability to place error bars on the computed results, i.e., to provide a statement of confidence in the predicted safety margin.

Notably, the RISMC developments must drive forward but be consistent with the engineering practice in the nuclear power industry so that the methods and tools developed would be used broadly by both utility analysts and regulators. Once matured and established, the RISMC developments will benefit the LWRS Program's objectives by (1) creating a strong technical basis for an enhanced risk-informed regulatory structure that enables the optimization of plant operation, inspection, maintenance, and replacement of the plant's SSCs, (2) enabling effective long-term management of the plant resources (for

which accurate characterization and prediction of safety margins are prerequisite), and (3) helping guide R&D planning toward maximum payoff from both resource utilization and risk perspectives.

The RISMC R&D pathway scope is shown in Figure 17. The grey areas, including part of the SCI and SCT boxes, depict the RISMC pathway R&D activity domain.

The guiding principle is to focus on developing knowledge/capability to facilitate enhanced decision-making and improved regulatory/public acceptance of long-term plant operation. Furthermore, the RISMC R&D pathway is envisioned as a mechanism to provide an integrating science-based framework to enable *effective visualization and efficient implementation* of advances achieved in the other LWRS Program pathways. The RISMC pathway provides, on the front end, a means to risk-inform the R&D efforts performed in the other LWRS Program pathways; and on the back end, a mechanism for the effective implementation of advances achieved in them.

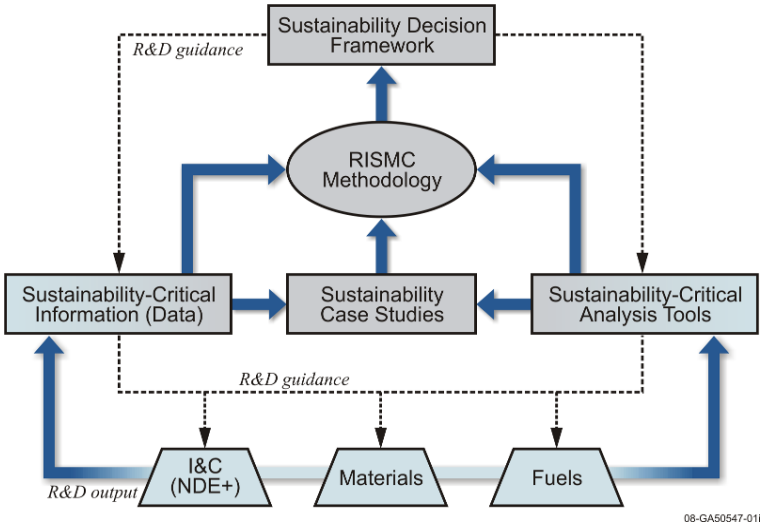

Figure 17. R&D strategy of RISMC for LWR sustainability.

The centerpiece of the strategy is the development of the "RISMC Methodology" to support the overall LWR "Sustainability Decision (Framework)." The approach taken to this development (at least in the initial stages of the LWRS Program) is through "(Sustainability) Case Studies," which will examine the potential benefits and issues of RISMC in situations where existing decision processes may not be sufficient to address long-term sustainability needs and objectives.

The success of a "Sustainability Decision" imposes requirements for "Sustainability-Critical Information (Data) (SCI)" and "Sustainability-Critical Analytical Tools (SCT)." A significant part of SCI and SCT is anticipated to be derived from advances made in the LWRS Program's other technological R&D pathways that are modeling physics-based behavior to predict degradation and failure modes in aging systems. Another important part of SCI/SCTs will also be created as part of RISMC R&D (longer-term) activity, and include activities such as advanced models and computer codes for high-fidelity simulation of plant transients and accidents and advanced PRA modeling and quantification techniques. An example of this modeling is how testing, inspection, and maintenance activities could impact SSC risk-performance over the long periods of plant operation that the LWRS Program effort is intended to facilitate.

3.4.4. R&D Pathway Highlights

The RISMC R&D pathway is built on the vision that the long-term operation of the existing fleet of nuclear power plants requires continued demonstration of high-level of performance in plant reliability, safety, and economy, and that such an objective requires advanced methods and tools to support the

analysis of plant safety margins and input into operational decision-making that could impact them. While the RISMC R&D pathway planning does not exclude theoretical considerations and generic developments in a broad context, the programmatic approach is driven by the need to ensure effective use of limited resources to meet the anticipated time window (2014–2019) for nuclear power plant operators' investment decision-making to support plant life extension beyond 60 years. This "narrowing-down" of focus is necessary to develop necessary methods and tools to address the highest priority issues in a topic as broad as RISMC (which involves the whole domain of PRA and DSA and their short- and long-term developmental needs).

Under the RISMC research pathway, three interrelated project areas are considered:

- Integrated Risk Modeling (IRM)
- Enhanced Technology Integration (ETI)
- RISMC-Enabling Methods and Tools (M&T)

3.4.1.1 Integrated Risk Modeling (IRM)

The IRM research effort is concerned with the "RISMC Methodology" and "Sustainability Decision" boxes in Figure 17, addressing the RISMC pathway vision and objectives. In addition, further understanding of the Sustainability Decision and RISMC Methodology can also be found in Figure 16, which highlights potential impacts of long-term operation of commercial nuclear power plants that RISMC must address. From the regulatory and public acceptance perspectives, it is critical that a comprehensive and transparent methodology to define and subsequently quantify safety margins in the risk-informed framework and determine how these could change over the long operating lifetimes of nuclear power plants is established; in other words, to quantify uncertainties in loads and capacities. This, in turn, determines the setting of thresholds for decision-making regarding sustainment. Nuclear power plant life extension renders the tendency of the "capacity" distribution to have both an increased spread (i.e., increased uncertainty) and a potential movement to the left (i.e., reduced margin) due to SSC aging/degradation. This tendency for reduced margin is exacerbated by the trend (due to economic initiatives such as power uprates, higher fuel burnups, etc.) that could shift the "load" distribution to the right.

To achieve successful long-term operational sustainability of the current fleet of operating nuclear power plants, the impact of these effects must be analyzed and effectively managed. For accidents evaluated in the plant FSAR, 10 CFR 50.59 identifies numerous ways in which "changes" could adversely affect the frequencies or consequences of accidents, ranging from increases in the frequencies of existing failure modes to consequences of accidents previously evaluated, to the introduction of entirely new classes of scenarios, enabled perhaps by new or enhanced mechanisms of common-cause failure. In evaluating changes to safety margins from a risk-informed perspective, these kinds of changes will need to be considered not only in the context of the safety analysis used for plant licensing, but also in the broader context of plant operational and investment decision-making. Such a multi-faceted influence on the plant risk model will necessitate advances in modeling, quantification, and integration and, more broadly, a holistic treatment of safety margins.

3.4.1.2 Enhanced Technology Integration (ETI)

The ETI portion of the RISMC pathway focuses on the "Sustainability Case Studies" box in Figure 17, using real plant analysis, issues, and examples to scrutinize methodological and framework aspects developed in the IRM research. Given the feedback from the IRM research, the ETI project work scope also includes tasks on prioritization of R&D activities in LWRS Program and on visualization of R&D outcomes.

Extension of nuclear power plant operational lifetime has the potential to introduce large aleatory and epistemic uncertainties in predictions of both the plant's "load" and "capacity." An additional issue

associated with the RISMC framework is the potential impact of how the nature and magnitude of uncertainties on the selection of appropriate "safety limits" (Figure 16) and how the safety margins can be managed over time. Over the next decade, it is expected that advanced research in materials aging will provide an improved understanding of degradation mechanisms and support the early prediction of degradation ("onset"). However, it is likely that the material testing data and prediction methods will not be sufficient to generate a complete understanding characterizing the "distribution" of capacity (Figure 16). This will create extra uncertainties associated with currently unidentified aging mechanism or stressor. The effectiveness of LWRS Program materials research in generating relevant models and data (e.g., degradation onset and progression estimates) depends upon which data ("onset vs. distribution") will be employed in defining the safety limit, and how the level of uncertainty (including consideration of uncharacterizable uncertainties) impacts the choice for "location of the safety limit" (safety margins) in a decision framework. Within this integrated framework, RISMC would be used to inform the Materials Aging and Degradation R&D pathway of issues in which the current (or anticipated future) safety margin is identified to be a significant potential limitation to long-term nuclear power plant operation. Using this information, the Materials Aging and Degradation R&D pathway should then be structured to ensure appropriate actions (e.g., enhanced data acquisition, targeted material improvements) are taken to ensure adequate safety margins are maintained.

3.4.1.3 RISMC-Enabling Methods and Tools (M&T)

The M&T project addresses the Sustainability-Critical Tools (Figure 17), i.e., the capability gaps in PRA and DSA discussed in subsection 3.4.1. On the PRA side, effective techniques for dynamic PRA and inclusion of passive SSC reliability would constitute a high priority. On the DSA side, the present "capability" gap must be filled by a next generation of the system analysis codes, which would be (1) effective "decision-support" tools and (2) computationally affordable for use in individual plant safety analysis (i.e., support production runs).

Because of the significant investment in and acceptance of decades-old and tested legacy codes, such as RELAP5, RETRAN, and MAAP, the new generation production codes will be build on their existing capabilities while capitalizing on the extraordinary advances in computing power and computational science (including computational fluid dynamics, neutron diffusion/transport, and fluid-structure interactions) that have been achieved over of the past decades. Examples of advanced features anticipated in the next-generation system analysis code include:

- Consistent treatment of participating multiple physics, including core neutron kinetics (NK), core system thermal hydraulics (TH), structural mechanics (SM), CC and fuel performance (FP)
- CFD-based Coarse-Grain Modeling for turbulent and two-phase flow
- Fully implicit, nonlinearly (tightly) coupled multi-physics, using Jacobian-Free Newton-Krylov method
- High order, accurate, computationally effective and robust numerical solutions
- Parallel, high-performance computing
- Optimized operation for multi-processors (100-1000 CPU cluster)
- Adaptive model refinement
- Built-in sensitivity analysis and uncertainty quantification machinery, to provide guidance for model refinement and further research ("quantitative PIRT process").

The high-order accurate schemes, modern software architecture and rigorous procedures for verification and validation are critical in implementing algorithms for sensitivity analysis and performing uncertainty quantification—essential components to improve understanding and utilization of safety margins (see Figure 18).

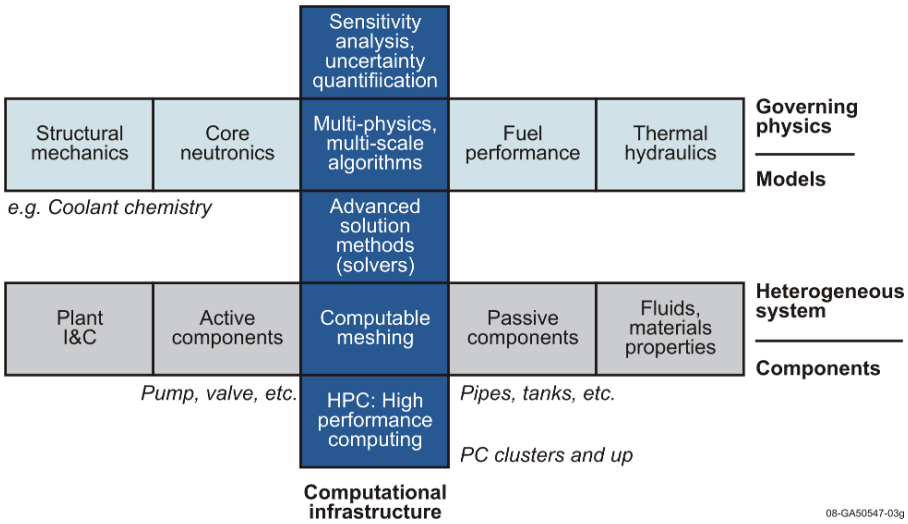

Figure 18. Composition of a next-generation production code for nuclear system analysis and safety margin quantification.

It should be noted that verification and validation (V&V) of the new system code presents a major challenge in both the task's technical complexity and resource requirements (Figure 19). It is crucial for the success of the code development that selection and implementation of models and numerical methods are consistent with the projected V&V capability.

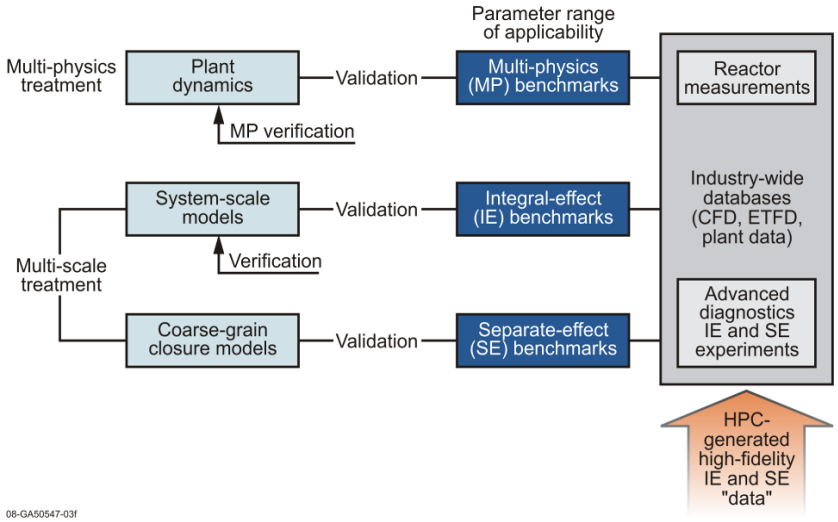

Figure 19. Multi-tier diagnostics and computer aided V&V strategy for the next generation system code.

The new DSA capability would help address, in a risk-informed manner, a number of safety and licensing issues facing the nuclear power industry. Multi-physics coupled treatment (e.g., NK-TH-FP, NK-TH-SM, NK-TH-CC) offer the potential to qualify and improve fidelity of the prediction of safety margins in design-limiting scenarios. These same advances and their promulgation in engineering applications would allow the identification and quantification of risk-significant transients (both for normal operating and accident sequences), on a scale never before achieved in probabilistic risk analyses.

Together, advanced deterministic and probabilistic modeling capabilities would greatly enable RISMC, to the benefit of both the regulator and the nuclear power plant operator.

In addition to tools necessary to perform the physics based safety margins evaluations, similar advanced tools will be necessary for integrating these results and performing the PRAs that assess the overall impact on plant nuclear safety risk. Risk-informed regulations and operations of nuclear power plants have become part of regulatory policy of the NRC and of the operational culture at U.S. nuclear power plants. With more than 3,000 operating years of experience in the U.S. alone, the next generation risk analysis tools will serve as a mechanism to optimize these requirements and processes. This optimization improves safety, plant performance, and cost to both the plant operators and to electricity consumers, and thus support long-term nuclear power plant sustainability.

Similar to the case for the physics-based safety margin codes, the new generation risk assessment tools will build on the existing capabilities of current technology. A conceptual vision of this integration tool, called Phoenix, has been developed by EPRI. As a platform for safety margin measurement and trending, Phoenix interfaces with the materials degradation matrix, real time I&C and equipment monitoring to update the input information, and produce recommendations for acceptance limits, risk trends, and priorities.

3.4.2 Milestones

3.4.2.1 Integrated Risk Modeling (IRM)

- **FY-09:** Identify the RISMC working group and organize the RISMC pathway workshop
- **FY-09:** Perform a scoping study of the RISMC methodology, framework and requirements
- **FY-09:** Update the long-term research plan for the RISMC pathway
- **FY-10:** Develop RISMC methodology – basic framework for IRM
- **FY-10:** Identify characteristics of the RISMC calculation engines
- **FY-10:** Identify long-term configuration control needs for information management
- **FY-11:** Develop the preliminary sustainability decision model
- **FY-12:** Develop the RISMC methodology – Advances
- **Out-years:** Complete Sustainability Decision Model
- **Out-years:** Complete the RISMC methodology – Complete.

3.4.2.2 Enhance Technology Integration (ETI)

- **FY-09:** Identify and initiate and plan LWR sustainability case studies
- **FY-10:** Identify preliminary the RISMC-based prioritization of R&D activities in LWRS Program
- **FY-10:** Complete investigation of Case Study #1
- **FY-11:** Develop basic method for visualization of R&D outcomes for LWRS Program
- **FY-11:** Complete investigation of Case Study #2
- **FY-12:** Complete the RISMC-based prioritization of long-term R&D activities in LWRS Program
- **Out-years**: Demonstration of the methods for visualization of R&D outcomes for LWRS Program
- **Out-years:** Conduct the new LWR sustainability case studies (new cases).

3.4.2.3 RISMC-Enabling Methods and Tools (M&T)

Sub-project on "Advanced PRA (quantification techniques)"

- **FY-10:** Evaluate the dynamic PRA techniques for aging risk analysis and management
- **FY-11:** Develop advanced PRA techniques (declarative modeling, hazard aggregation)
- **FY-12:** Create aging models in PRA
- **Out-years:** Plan data connectivity analysis
- **Out-years:** Create real-time analysis method for operational risk management

Sub-project on "Advanced DSA (next generation production code for system analysis with UQ)"

- **FY-10:** Develop architecture and infrastructure for the computational engine
- **FY-10:** Develop V&V methodology – preliminary
- **FY-11:** Implementation of basic solution methods, closure models, and components
- **FY-11:** Develop basic V&V of the new code
- **FY-11:** Implement algorithm for SA, UQ, CGM, and AMR
- **FY-12:** Implement advanced solution methods and closure models and components
- **FY-12:** Release testing version of codes
- **FY-12:** Demonstration of the code's intended capabilities
- **FY-13:** Develop comprehensive V&V methodology
- **FY-14:** Complete developmental assessment.

3.4.3 Schedule

RISMC R&D in the LWRS Program is planned in three phases:

In the first phase (FY-09), under "seed" funding, RISMC will focus on establishing the connection between the "Sustainability Decision Framework" and "RISMC Methodology," and selecting and planning an appropriate "Case Study."

In the second phase (subsequent two-three years, i.e., FY-10–FY-12), the activity is focused on conducting the selected "Case Studies" that demonstrate the RISMC methodology, provide insights and input to refine it, and identify gaps in SCI and SCT. As resources permit, activity could be initiated on developing RISMC-specific SCI and SCT (e.g., advanced PRA/DSA techniques) that complements SCI and SCT to be developed in other pathways.

The third phase (FY-13–FY-18) is anticipated to extend the developments planned and started in the second phase with respect to RISMC-specific SCI and SCT. In addition, once demonstration of the RISMC methodology is accomplished, it will be used to integrate advances obtained in the other LWRS Program R&D pathways.

Figure 20 shows the schedule of the three projects in the RISMC program pathway.

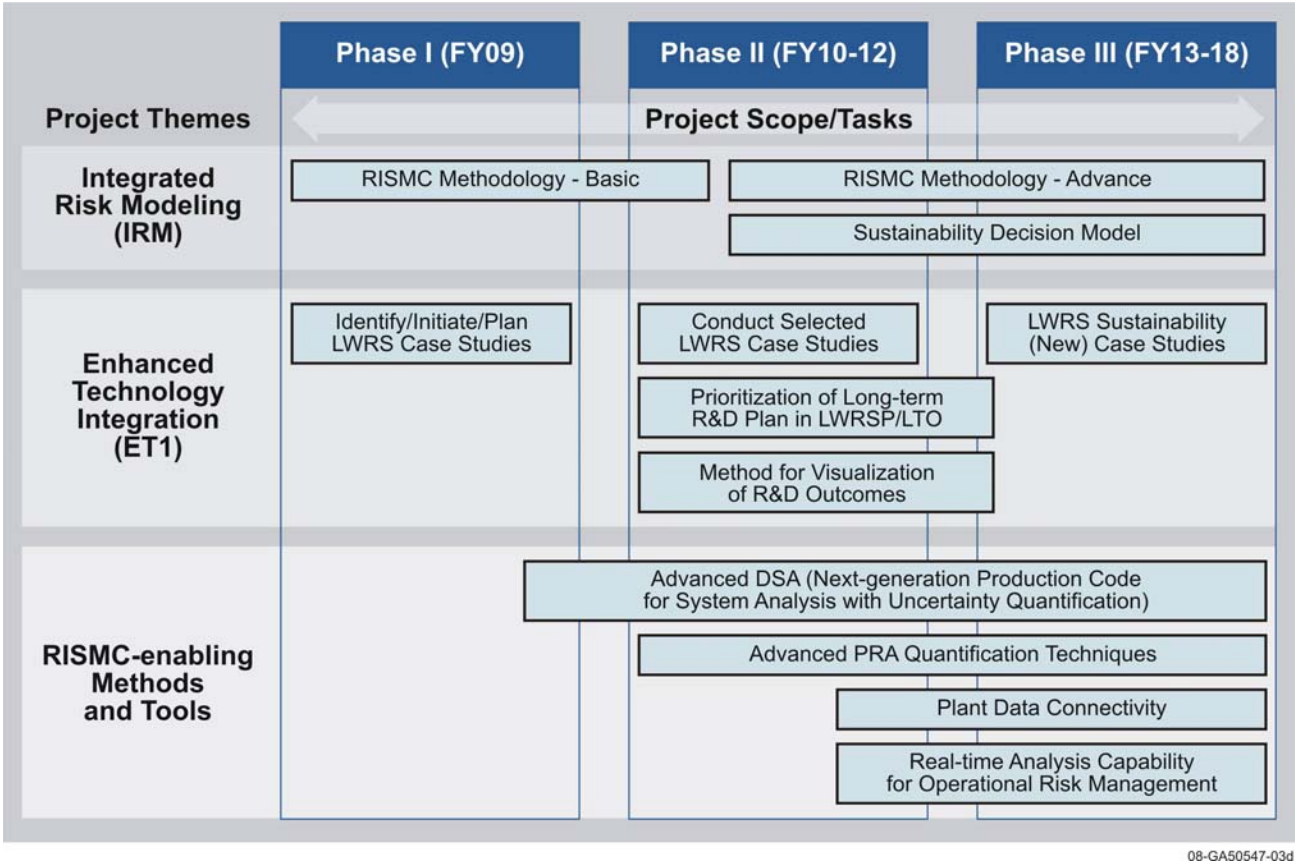

Figure 20. RISMC R&D pathway schedule

3.5 Pathway Crosscutting and Integration

Technical integration is an important and significant part of the LWRS Program. The R&D within the program is integrated across scientific and technical disciplines in the four R&D pathways. The LWRS Program is integrated with outside sources of information and parallel R&D programs in industry, universities, and other laboratories, both domestic and international. Different methods of integration are used depending on the situation and goals, as explained below.

3.5.1 Technical Integration within the LWRS Program

The interfaces between R&D pathways and the required integration across them are naturally defined by the common objectives for materials and fuel performance and the system monitoring of their performance. Similarly, the interface and integration of the pathways with RISMC R&D pathway is defined by data and models which affect performance, monitoring and control. This is illustrated in Figure 21.

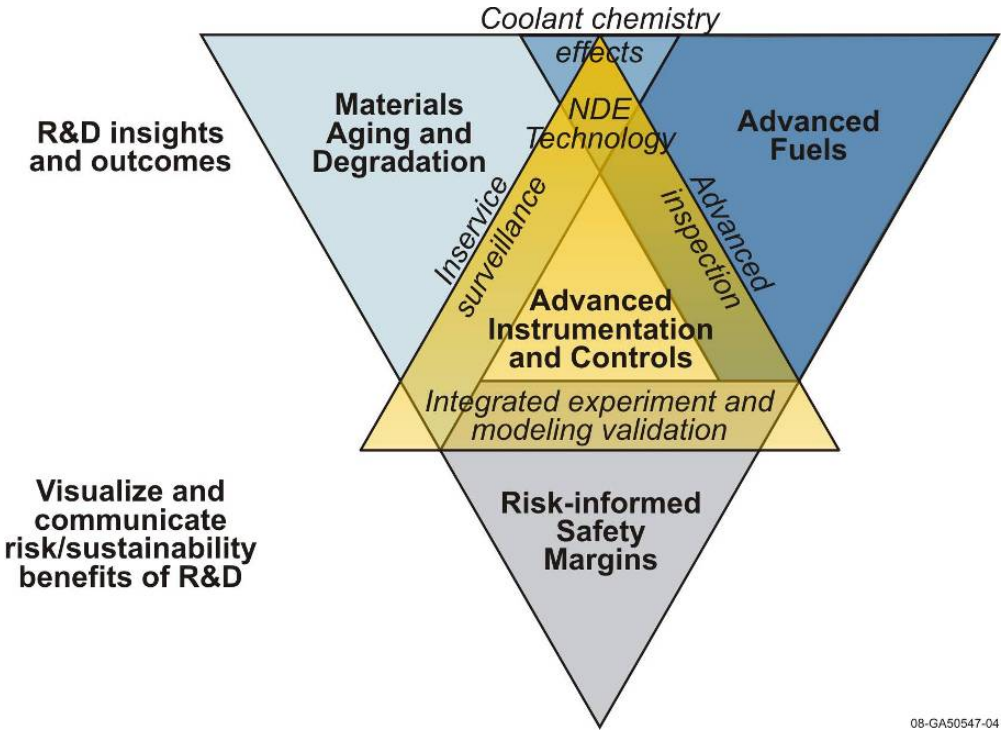

Figure 21. Integration of four LWRS Program R&D pathways.

Advanced understanding and modeling of materials and fuels and their degradation mechanisms are necessary to identify methods and requirements for advanced instrumentation and software for material surveillance, NDE technology and online monitoring systems. Some degradation mechanisms are common for fuel cladding materials and the materials in other reactor system components. This allows some common testing and analysis of results. Coolant chemistry changes can have positive or negative effects on different reactor structures and on the reactor fuel. In some cases, chemistry changes can reduce degradation of reactor structures, but at the same time increase degradation of the fuel performance through crud formation. Improved understanding and modeling of coolant transport mechanisms and crud formation requires strong materials, fuel, and RISMC R&D integration. Data and information from the Nuclear Materials Aging and Degradation and Advanced LWR Nuclear Fuel R&D pathways will be fed into the RISMC models. The results of RISMC analysis will guide the development of advanced fuels and I&C systems. Table 1 includes examples of some crosscutting areas in the LWRS Program.

Table 1. LWRS Program crosscutting areas.

Crosscutting Area	Materials Aging & Degradation	Advanced Fuels	Advanced I&C	RISMC
Coolant chemistry effects	x	x	x	x
Crack growth mitigation effects	x	x		x
Irradiation testing	x	x		
Irradiation source term changes		x		x
Improved on-line monitoring of reactor chemistry	x	x	x	x
Advanced instrumentation for the study of system degradation	x		x	x
Fuel failure mechanisms		x		x
Creation of SSC aging database	x		x	x
Advanced measurement techniques	x	x	x	x
Field testing and data collection/capture	x	x	x	x
Non-destructive evaluation/assay tools	x	x	x	x
Advanced inspection techniques	x	x	x	x

3.5.2 Enhanced Modeling as a Crosscutting Activity

The most common theme from all four R&D pathways is the use of computer modeling of physical processes or the development of a larger system computer model. The extensive use of computer modeling by all four R&D pathways is intended to distill the derived information so that it can be used for further research in other pathways and as the basis for decision making.

The computer modeling occurs in three forms with many overlapping aspects within the LWRS Program. Modeling a physical behavior, like crack initiation in steel, is an example of direct computer modeling. The resulting model is used to store information for use in other pathways and to use in its own right for further research.

A second computer modeling activity is the development of more detailed computer modeling tools capable of encoding more complex behaviors. One of the intended outcomes from Advanced LWR Nuclear Fuels Development research is new modeling tools that can describe behavior of such complexity that current computer models are incapable of producing adequate results for the LWRS Program. The increased accuracy will allow improved results to be incorporated into the other pathways.

The final computer modeling improvement is the creation of larger integrated databases that roll up results and allow decision making. The results from the RIMSC and Advanced Instrumentation, Control, and Information System Technologies R&D pathways produce computer models of this type. The large system wide integrated models allow complex behavior to be understood in new ways and new conclusions to be drawn. These integrated databases can then be used to further guide physical and modeling research improving the entire program.

Because of their overlapping nature and personal interfaces, these modeling activities tend to be natural crosscutting activities between R&D pathways. Computer modeling will remain an integrating and crosscutting element of the LWRS Program.

3.5.3 Coordination with other Research Efforts

In order to encourage communication and coordination with outside experts and parallel programs, the LWRS Program will: (1) be aware of issues and changes of technical needs affecting the long-term, safe, economical operation of LWRs, and (2) share information and resources with other professionals and programs that can assist the LWRS Program to provide timelier, less expensive, better solutions to the needs and issues.

Primarily, coordination will be with the EPRI LTO Program. At the program level, formal interface documents will be used to coordinate planning and management of the work. This will provide a ready source of information from EPRI's Nuclear Power Council and through their contact with utilities. At the R&D project level, frequent communication and collaboration are encouraged by both programs. Consistent with the vision of the LWRS Program, working relationships will be established with international organizations in FY-09. The goal is to facilitate communication and cooperative R&D with international R&D organizations.

3.5.4 Performance of Technical Integration and Coordination

The LWRS Program will lead and encourage technical integration and coordination of issues affecting the LWR LTO Program using methods that best match the issue. For known gaps in data, understanding, or technology, the LWRS Program will plan and manage integrated R&D projects through the LWRS Program TIO and its multiple interfaces.

To accommodate currently unknown issues or gaps in technology that may arise as result of ongoing R&D or nuclear power plant operations, a broader approach is necessary. This approach should include active internal and external communication with professional organizations, industry groups and interdisciplinary teams for project and program reviews. The Steering Committee is an essential part of this process. The LWRS Program encourages participation in professional technical societies, and national standards committees.

4. PROGRAM MANAGEMENT

4.1 Organization Structure

The entire LWRS Program falls within the DOE Office of Nuclear Energy (DOE-NE). Program management and oversight, including programmatic direction, project execution controls, budgetary controls, and TIO performance oversight is provided by the DOE Office of LWR Deployment (DOE-HQ) in conjunction with the DOE Idaho Operations Office (DOE-ID) (Figure 22).

DOE-ID will provide technical and administrative support to the LWRS Program. This support includes such activities as assisting in the development of the administrative requirements in support of contracting actions, conducting merit reviews and evaluations of applications received in response to program solicitations, performing all contracting administration functions, and providing technical project management and monitoring of assigned projects.

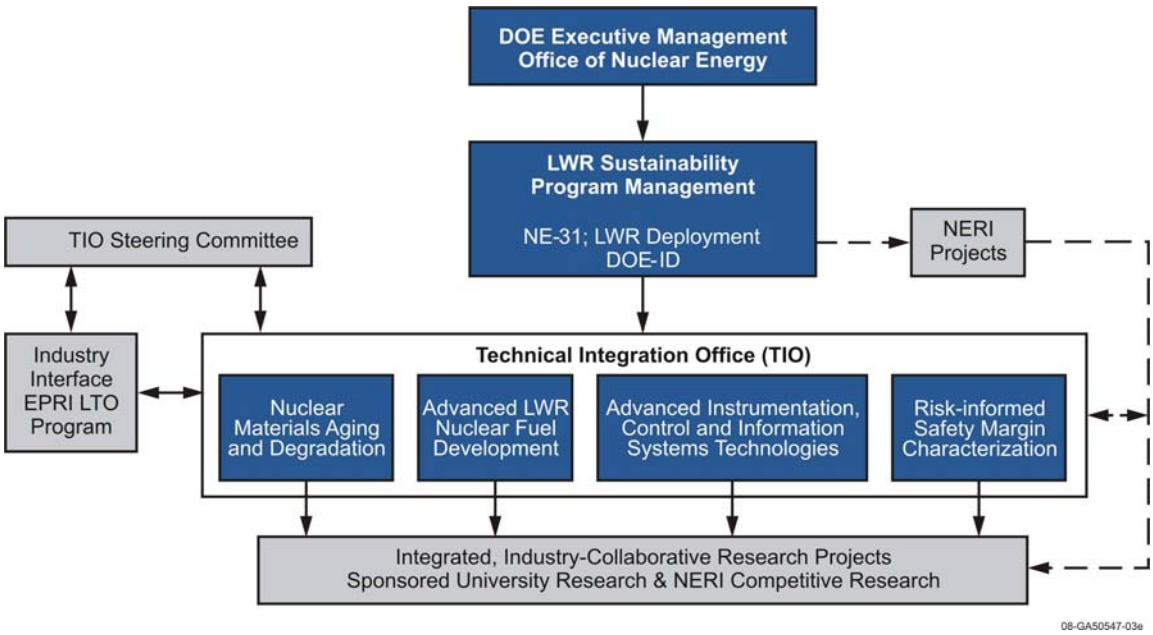

Figure 22. LWRS Program organization.

The TIO basic organizational structure is used to accommodate the crosscutting nature of the proposed research pathways. This organization is responsible for developing and implementing integrated research projects consistent within the LWRS Program vision and objectives. Additionally, the TIO is responsible for developing suitable industry and international collaborations appropriate to individual research projects and acknowledging industry stakeholder inputs to the program.

Within the TIO structure is the TIO Director, each of the four R&D Pathway Leads, and an external Steering Committee. Nuclear industry interfaces and stakeholders' contributions are accommodated in program development and project implementation actions through the TIO management structure. Recognition of continuing industry collaborations reflecting issues and concerns necessary to extend plant licenses are incorporated through the same program development and implementation actions.

The functional organization, reporting relationships, roles and responsibilities for the TIO are explained in the following sections and are shown in Figure 23.

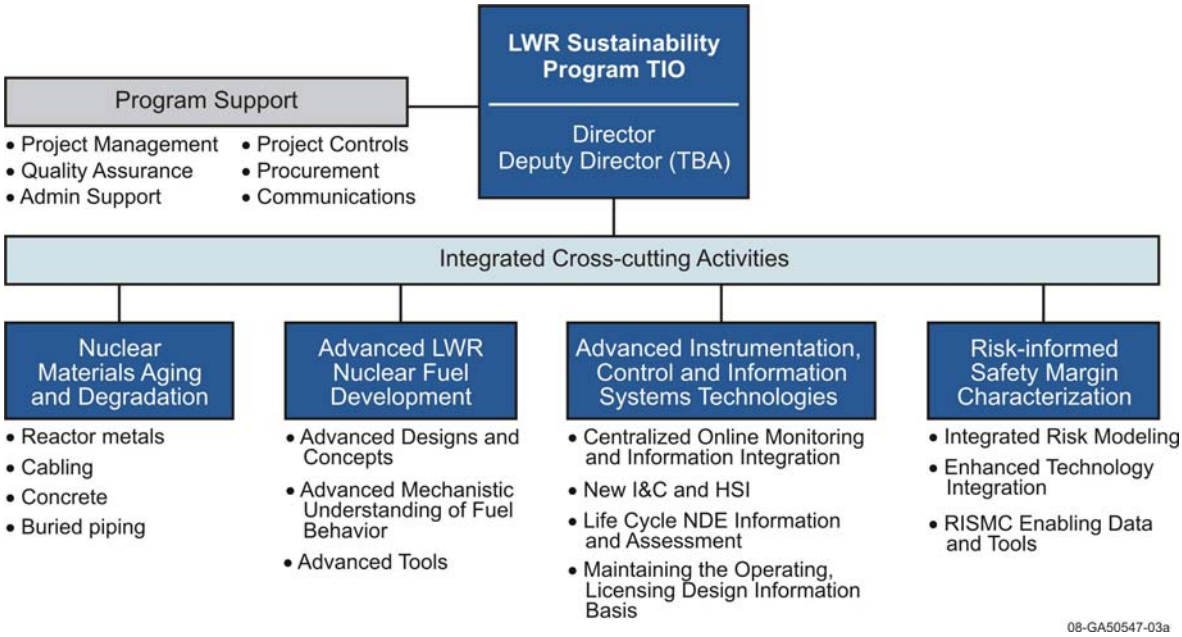

Figure 23. LWRS Program Technical Integration Office organization.

4.2 Roles, Responsibilities, Accountabilities, and Authorities

4.2.1 DOE Program Office

DOE is responsible for the Federal government's investments in nuclear power research, development, demonstration, and incentive programs, all furthering the nation's supply of clean, dependable nuclear-generated electricity. The LWRS Program conducts research enabling the licensing and continued reliable, safe, long-term operation of current nuclear plants beyond their initial license renewal period. The DOE Office of LWR Deployment directs the program, establishes policy, and approves scope, budget and schedule for the program through the LWRS Program Manager. The DOE LWRS Program Manager is assisted with the program management and oversight by DOE-ID.

The essential programmatic DOE functions include, but are not limited to, the following:

- Establish program policy and issue program guidance
- Establish requirements, standards, and procedures
- In cooperation with the TIO, establish requirements and develop strategic and project plans
- Establish performance measures and evaluate progress
- Represent the DOE program to other government agencies.

4.2.2 Technical Integration Office

The Technical Integration Office (TIO) supports the DOE Program Manager. The program is a cost-shared, collaborative program aimed to meet the needs of a diverse set of stakeholders. In addition to supporting the national policy (energy and environmental security needs), the Program supports the agreed upon technical needs of the NRC in assessing safety and relicensing requests for nuclear power plant extended life operation. It also supports industry needs for data and planning tools for long-term safe economical operation of their plants. The TIO is staffed with a Director, R&D Pathway Leads, and program management staff. The Director and Leads are all well-known technical and management experts from the DOE Laboratories. The TIO is structured and staffed to provide the Program Director with strong interfaces and communications with stakeholders, R&D plans based on stake holder needs,

proposals for R&D-specific projects and budgets, management of the projects including funding, and communication of the results.

The LWRS Program TIO is a national organization and is expected to have international participants as the LWRS Program evolves. The intent of the organization is to staff the program with the right people to accomplish the work, regardless of location or affiliation. As appropriate, the technology integration and execution activities will use facilities and staff from multiple national laboratories, universities, industrial alliance partners, consulting organizations, and research groups from cooperating foreign countries.

The TIO functions include:

- Maintaining the long-range technical strategy plan for the LWRS Program R&D
- Maintaining the LWRS Program Plan
- Developing annual project scope statements
- Developing and implement project execution plan
- Monitoring authorized project work
- Coordinating weekly/monthly status meetings
- Coordinating periodic technical review meetings
- Providing formal status reporting
- Maintaining baseline change control
- Performing project closeout planning and completion.

TIO Director. The TIO Director provides general program management for the LWRS Program. This position leads the planning, performance, and communication of results from the R&D pathways. The TIO Director works with the Program support team and R&D Pathway Leads to integrate and ensure all requirements are well defined, understood, and documented through long-range planning. The TIO Director works with the Project Support staff to ensure proper annual financial planning, scoping, oversight and scheduling of the project work. The TIO Director and the Steering Committee oversee the assignment of appropriate resources and evaluate and resolve the R&D needs of the LWRS Program. The TIO Director reports to DOE Program Manager.

TIO Deputy Director (TBD). A TIO Deputy Director will be assigned at a later date to assist the director, as needed.

R&D Pathway Leads. The TIO currently includes four R&D Pathway Leads for the major R&D areas currently developed. The leads are the technical managers for their pathways and are responsible to ensure that technical planning, project management, and leadership is provided for each pathway. R&D Pathway Leads are the primary interface between technically diverse organizations that form the structure of the LWRS Program. They are responsible for integration and translation of project requirements into an overall program plan tailored to accomplish their assigned R&D mission. They are responsible for establishing scope, cost, and schedule of the R&D activities. They interface with other R&D Pathway Leads to ensure effectiveness of crosscutting activities.

Program Support Team. The program support staff is responsible for the contractual operations of the TIO and assists other parts of the TIO to execute work. The team provides personnel with expertise in project management, QA, procurement, project controls, and communications. They provide the tools, structure, oversight, and rigor to maintain R&D schedules and interfaces to the LWRS Program, provide financial information to management (through the TIO Director's office), monitor technical progress, earned value (EV), and track milestones.

Steering Committee. A standing TIO Steering Committee will advise the TIO on the content, priorities, and conduct of the program. The Committee will be comprised of technical experts selected and agreed upon by the TIO Director and the DOE Program Manager. The committee as a group is knowledgeable of the various R&D needs of DOE, industry, and NRC, are broadly knowledgeable of ongoing and planned research as related to nuclear power technology, and are knowledgeable of policies and practices in the public and private sectors which are important for the collaborative R&D program. The TIO Director in consultation with the Steering Committee may form ad hoc subcommittees to review specific technical issues.

4.2.3 Program External Interfaces

The LWRS Program TIO is intended as a national organization and is expected to have multiple national laboratory, governmental, industrial, international, and university partnerships. As appropriate, the LWRS Program technology development and execution activities will use facilities and staff from:

- National Laboratories
- Universities
- Industrial alliance partners
- Consulting organizations
- Research groups from cooperating foreign countries.

The TIO is responsible to ensure the necessary memorandum purchase orders (MPOs), interagency work orders (IWOs), or contracts are in place to document work requirements, document concurrence with work schedules and deliverables, and transfer funds to the performing organizations for R&D activities.

- ***Industry Partnerships***

  EPRI has established their LTO Program to run in parallel with DOE's LWRS Program. The LTO Program like the LWRS Program is based on the LWR R&D Strategic Plan and also is focused on LTO of the current fleet of LWRs. Therefore, the government-private sectors' interests are similar and there is strong support for technical collaboration and cost sharing. Formal interface agreements between EPRI and the TIO will be used to coordinate collaborations. Contracts with EPRI or other businesses may be used for some work.

- ***Nuclear Regulatory Commission Partnership***

  DOE and NRC are preparing guidance for planning and conducting cooperative research projects. The guidance provided by this document will be used by all program participants.

- ***University Partnerships***

  Universities will participate in the program in at least two ways, (1) through the NERI Program and (2) with direct contracts to do work. In addition to contributing funds to NERI, the LWRS Program will provide to NERI descriptions of research from universities that would be helpful to LWRS Program. In some cases, R&D contracts will be let to key university researchers.

- ***International Partnerships***

  The TIO will seek to establish lines of communication and collaborative arrangements with international research institutions.

5. PROGRAM BUDGET SUMMARY

Table 2. Three-year budget profile for LWRS Program activities ($K).

	Work Breakdown Structure (WBS) Element	FY-09	FY-10	FY-11
1.1	Program Management & Controls	2,620	6,550	12,900
	Management Reserve			
	NERI			
	Small Business Innovation Research (SBIR)			
	Recission			
1.2	Technical Integration Office	780	2,000	4,000
	TIO Program Management and Controls			
1.3	Nuclear Materials Aging & Degradation	2,450	4,500	7,800
	Reactor Metals			
	Concrete			
	Cabling[a]			
	Buried Piping[a]			
1.4	Advanced LWR Nuclear Fuel Development	2,000	4,450	7,700
	Advanced Designs and Concepts			
	Advanced Mechanistic Understanding of Fuel Behavior			
	Advanced Tools[a]			
1.5	Advanced Instrumentation and Controls	1,000	3,000	6,800
	Centralized On-line Monitoring and Information Integration			
	New I&C and Human System Interfaces and Capabilities			
	Life Cycle NDE Information and Assessment[a]			
	Maintaining the Operating, Licensing and Design Information Basis[a]			
1.6	Risk-Informed Safety Margin Characterization	900	3,000	6,800
	Integrated Risk Modeling			
	Enhanced Technology Integration			
	RISMC Enabling Data and Tools[a]			
1.7	Research Pathway #5[b]		1,500	2,500
1.8	Research Pathway #6[b]			1,500
Total		9,750	25,000	50,000

a. Activities will not be scheduled to be performed in FY-09.

b. Program expansion pathways commensurate with recommendations by industry in the Strategic Plan overall objectives.

6. REFERENCES

(1) U.S. Energy Information Administration, "International Energy Outlook 2007," Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. Department of Energy Washington, D.C., May 2007.

(2) Office of the President, "Report of the National Energy Policy Development Group," Washington, D.C., May 2001.

(3) 42 USC 14801, 2005, "Energy Policy Act of 2005, (EPACT2005)," Federal Energy Regulatory Commission, August 8, 2005.

(4) INL/EXT-07-13543, "Strategic Plan for Light Water Reactor Research and Development," Idaho National Laboratory, November 2007.

(5) U.S. Department of Energy Nuclear Power 2010, *Nuclear Power Deployment Scorecard*, http://nuclear.energy.gov/np2010/neScorecard/neScorecard.html, Web page updated September 19, 2008, Web page visited September 24 2008.

(6) National Research Council of the National Academies, "Review of DOE's Nuclear Energy R&D Program," Oct. 2007.

(7) "Life Beyond 60 Workshop Summary Report, NRC/DOE Workshop U.S. Nuclear Power Plant Life Extension Research and Development," U.S. Nuclear Regulatory Commission and U.S. Department of Energy, Prepared by Energetics Inc., Feb. 19-21, 2008.

(8) Blake, Michael E., "U.S. capacity factors: Another small gain, another new peak," Nuclear News, May 2008, pp. 28-34.

(9) J.T. Busby, R.K. Nanstad, R. E. Stoller, Z. Feng, and D.J Naus, "Materials Degradation in Light Water Reactors: Life After 60," ORNL Report, ORNL/TM-2008/170.

(10) Electric Power Research Institute, 2008, The Path to Zero Defects: EPRI Fuel Reliability Guidelines, 2008.

(11) National Research Council (NRC), Digital Instrumentation and Control Systems in Nuclear Power Plants (Safety and Reliability Issues), 1997.

(12) WASH-1400 (NUREG-75/014), "Reactor Safety Study, An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," U.S. Atomic Energy Commission, October 1975.

(13) R.G. 1.174 Rev. 0, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions o Plant-Specific Changes to the Licensing Basis," U.S. Nuclear Regulatory Commission, January, 1998.

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