# Appendix 7.0
# Design and Evaluation Methods

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# Acronyms

| | |
|---|---|
| AFCI | Advanced Fuel Cycle Initiative |
| CFD | computational fluid dynamics |
| D&EM | Design and Evaluation Methods |
| DOE | Department of Energy |
| EMWG | Economics Modeling Working Group |
| FY | fiscal year |
| GIF | Generation IV International Forum |
| MWG | Methodology Working Group |
| NERI | Nuclear Energy Research Initiative |
| NGNP | Next Generation Nuclear Plant |
| NHI | Nuclear Hydrogen Initiative |
| NTD | National Technical Director |
| PIRT | phenomena identification and ranking tables |
| PR&PP | proliferation resistance and physical protection |
| R&D | research and development |
| RSWG | Reactor Safety Working Group |
| SFR | Sodium-Cooled Fast Reactor |
| SIM | System Integration Manager |

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# A7.1 INTRODUCTION AND BACKGROUND

The design of Generation IV systems will require simulation capabilities that provide accurate predictions of system performance. Viability of new technologies and design features will require confirmation by credible analyses verified with experimental data. Credible analyses will also be required as the basis for regulatory reviews and licensing of Generation IV designs of choice. The required simulation capabilities include computer codes and databases for simulating neutronic, thermal-hydraulic, and structural behavior in steady-state and transient conditions. For each system and type of analysis, the adequacy of existing analysis tools will need to be assessed and the required enhancements to their capabilities implemented and qualified.

Many of the required analytical capabilities are crosscutting because they are applicable to multiple Generation IV systems. Examples are Monte Carlo and deterministic transport methods for neutronics modeling, modern computational fluid dynamic (CFD) methods for heat transfer and fluid flow simulation, and modular code systems for fuel cycle evaluations and simulation of transients and postulated accidents. Advances in these capabilities will help reduce uncertainties in predicted system behavior, which can be exploited in system development by targeting the best performance achievable without exceeding the capabilities or limits of the technologies employed by the system.

A need has also been identified in *A Technology Roadmap for Generation IV Nuclear Energy Systems* (DOE 2002) to advance methodologies for evaluating overall system performance against the Generation IV goals of sustainability, economics, safety, reliability, and proliferation resistance and physical protection (PR&PP). Capabilities previously developed require revision and extension to make them more quantitative, to improve their process for employing expert judgment, to quantify uncertainty in evaluated performance, to represent better unique features of Generation IV systems, and to account more comprehensively for important factors influencing performance. Application of these methodologies will help guide the research and development (R&D) on the systems and provide a basis for judging the success of the R&D as it progresses.

## A7.1.1 Crosscut Description

The objectives of the Generation IV design and evaluation methods R&D activities are to:

- Enable cost-effective development of high-performance Generation IV systems by providing capabilities for system design development, safety enhancement, and performance optimization
- Provide methodologies for measuring the performance of Generation IV systems against Generation IV technology goals
- Support R&D prioritization based on results of system design analyses and performance evaluations
- Form the groundwork for safety review, licensing, and regulation of Generation IV systems.

Design and Evaluation Methods (D&EM) R&D addresses the need for validated analysis tools for design of Generation IV systems and confirmation of their safety. These analysis tools include (1) modeling approaches, (2) computer codes, and (3) databases used to represent neutronic, thermal, fluid-flow, and structural phenomena in steady-state and transient conditions. They also represent the mutual coupling among these phenomena and their coupling with additional phenomena (e.g., fuel behavior, fission gas release, materials damage, chemical reactions, etc.) developed within other elements of the Generation IV, Advanced Fuel Cycle Initiative (AFCI), and Nuclear Hydrogen Initiative (NHI) programs.

A second major area of R&D in D&EM is to advance methodologies for evaluating overall system performance against Generation IV technology goals. This is accomplished through participation in the Methodology Working Groups (MWGs) established by the Generation IV International Forum (GIF).

### A7.1.2 Overall Timeline

The overall timeline for D&EM research conforms to the timelines currently foreseen for developing the Generation IV systems. Accordingly, the first five years are devoted to providing the capabilities needed for (1) resolution of viability issues for Generation IV systems, (2) development of high-performance Next Generation Nuclear Plant (NGNP) and Sodium-Cooled Fast Reactor (SFR) designs, and (3) down-selection among reactor systems and options. Additionally, there is early emphasis on establishing the evaluation methodologies, so that they may be used in evaluating progress toward the Generation IV goals and in choosing among system design alternatives.

In the second five-year phase of the program, the analysis methods will be increasingly focused on the specific designs adopted for the NGNP and SFR systems and on the development of other Generation IV systems. These methods will be formally qualified for use in design development and licensing. Moreover, in this second phase, the evaluation methodology efforts will be directed to supporting the application of the methodologies for evaluating the performance of selected system designs.

## A7.2 RESEARCH AND DEVELOPMENT STRATEGY

### A7.2.1 Objectives

The objective for this program element is to provide the analytical tools and evaluation methodologies needed to develop high-performance Generation IV systems. This can be accomplished most efficiently by taking advantage of existing analysis capabilities and improving them as needed. Accordingly, the strategy is to:

1. Establish modeling requirements for each system, working with the System Integration Manager (SIM) and the GIF project management board responsible for system design development and safety confirmation
2. Assess the adequacy of existing tools and databases by examining their capabilities relative to the requirements, identifying gaps, and comparing predictions against results that are independently obtained through measurement or analysis
3. Implement required modifications to the analysis methods and define the needs for new measurements
4. Validate the models and analysis methods by confirming their ability to simulate the physical phenomena of interest with sufficient accuracy and precision.

Both initial assessment and validation of models are based substantially on comparisons with measurements. Identification of relevant measurements and the need for additional measurements is thus included as an integral part of the D&EM work.

### A7.2.2 Scope

Work scope for D&EM consists of the following three components:

- ***Modeling Improvement:*** Planning, implementation and qualification of analysis capabilities (computer codes and data) for designing Generation IV systems and confirming their safety.
- ***Evaluation Methodologies:*** Development of methodologies for evaluating overall system performance and measuring progress toward the Generation IV technology goals.
- ***D&EM Program Coordination:*** Work with Generation IV Program participants and international partners to advance design and evaluation methods in a coordinated and cost-effective manner.

Highlights of the R&D in each area are provided in Section A7.3.

### A7.2.3 Role in Viability Research and Development

Accurate and efficient design capabilities are needed not only for the development of high-performance Generation IV systems, but also for the coordination and cost-effective execution of the viability R&D for each system. An essential part of this viability R&D is to develop design concepts that provide a cohesive framework for technology development (e.g., for fuels and materials) and ensure the integration and compatibility of different technologies. In developing these conceptual designs, there is a strong incentive to reduce modeling uncertainties that necessitate conservatism in design (which limit performance gains) or potentially costly efforts to improve upon the capabilities of available technologies.

Improved evaluation methodologies also benefit the viability phase R&D because they enable better assessment of progress afforded by technology advances toward the Generation IV goals. In particular, they can provide an improved basis for determining the performance benefits of a technical option (e.g., a material having higher temperature capabilities) and for selecting among competing technical options.

### A7.2.4 Research Interfaces

The D&EM activities will be performed by a team of U.S. national laboratories, universities, and commercial organizations, in cooperation with participants from other GIF countries, and under the leadership of a National Technical Director (NTD). The NTD is responsible to the Department of Energy (DOE) for coordinating the overall D&EM program and providing the required interfaces with Generation IV SIMs and NTDs responsible for other technical areas in the Generation IV, AFCI, and NHI programs. An important goal is to coordinate the assessment, development, and qualification activities across Generation IV systems to avoid duplication of effort and to ensure that relevant developments in other national and international programs are effectively utilized in the development of Generation IV systems.

#### A7.2.4.1 Relationship to Generation IV International Forum Research and Development Projects

The D&EM research directed to improving analysis models and tools is coordinated within the broader scope of research defined for each Generation IV system by the responsible System Steering Committee. These modeling improvement efforts will be included in the U.S. contribution to the GIF project plans for computational methods improvement or system design and integration.

The evaluation methodology activities are conducted by GIF MWGs reporting to the GIF Expert Group. Each MWG consists of GIF-designated experts from national laboratories, universities, and industry. Two MWGs were formed in fiscal year (FY) 2003 to advance the methodologies for evaluation of economics and of PR&PP. A MWG for risk and safety evaluations was chartered by GIF in FY 2005, and additional working groups may be formed in the future.

Although the GIF MWGs will focus primarily on developing and testing the required methodologies, they are also expected to support the application of the methodologies for Generation IV system evaluations. These evaluations will require significant effort and expertise beyond that of working group members (e.g., detailed familiarity with system design). Results of the evaluations will be used for periodic re-assessment of system performance and for guiding R&D priorities.

#### A7.2.4.2 University Collaborations

University researchers participate in the development of evaluation methodologies through their membership on the GIF MWGs. Professors from the Massachusetts Institute of Technology and the University of California at Berkeley are currently members of the PR&PP Expert Group, the latter as co-chair. The GIF Economics Modeling Working Group (EMWG), which is developing the economic evaluation methodology, currently has an economics professor from Stanford University as one of its members.

University professors and graduate students also participate in D&EM research through the university Nuclear Energy Research Initiative (NERI). Several proposals targeting improvements in Generation IV analysis and evaluation methods have been contributed in response to the NERI solicitation.

#### A7.2.4.3 Industry Interactions

As part of this Generation IV program element, modeling capabilities available from commercial or industrial organizations are evaluated for their applicability to the analysis of Generation IV systems. Notable examples are the “lattice physics” tools developed for light water reactor analysis and commercial CFD software for thermal-fluidic analysis. Industrial organizations are also expected to take part in GIF projects and the relevant Project Management Boards will provide a forum for coordination of contributions and efforts.

Representatives of foreign and domestic industry organizations, as well as retired experts with industry work experience, participate in the MWGs. In addition, industry representatives are invited to participate in seminars, workshops, and other forums organized as part of the Generation IV D&EM program activities.

#### A7.2.4.4 International Nuclear Energy Research Initiative

Many of the activities directed to improving Generation IV analysis capabilities are conducted as International Nuclear Energy Research Initiative (I-NERI) collaborations and are expected to be included within the scope of the Design and Safety Project defined for each Generation IV system by its GIF steering committee. Moreover, the U.S. investigators pursuing the modeling improvement tasks participate in international working groups organized by the Organization for Economic Cooperation and Development/Nuclear Energy Agency and the International Atomic Energy Agency, workshops focused on specialized topics (e.g., nuclear data, neutron transport methods, system dynamics modeling, and CFD applications), and other international forums.

# A7.3 HIGHLIGHTS OF RESEARCH AND DEVELOPMENT

Highlights of the R&D directed to improving modeling capabilities and evaluation methodologies are summarized below.

## A7.3.1 Modeling Improvement

### A7.3.1.1 Computational Fluid Dynamics Simulations

Although CFD has so far proven to be a useful design tool for light water reactor systems under normal operating conditions, its applicability for different types of coolants or for simulation of accident conditions remains to be established. To accomplish the Generation IV safety assurance objectives, creation of programs that increase the accuracy of CFD, extend its range of applicability, and experimentally validate its predictions as an engineering simulation tool will be important. The initial focus will be on verifying the applicability of commonly-used CFD software for different types of coolants, distinct heat transfer regimes, and a wide range of flow phenomena.

### A7.3.1.2 System Dynamic Simulation Tools

A crosscutting system dynamics tool for consistent assessment of concepts is needed. Planned activities include the evaluation, enhancement, and integration of modules from various system dynamics code versions that were previously developed for diverse reactor plant types. The proposed activity will advance such codes by integrating and validating existing capabilities, and extending them for analysis of Generation IV systems.

### A7.3.1.3 Nuclear Data

The uncertainties in nuclear data for higher actinides are significant and affect predictions of isotopic inventories, decay heat, and radiation emission characteristics. Data requiring additional assessments include energy release per fission, spontaneous fission model parameters, fission product yields, half-lives, decay energies, decay branching ratios, and radiotoxicity factors. Improved data needs to be incorporated into inventory tracking tools to ensure that they give accurate results.

### A7.3.1.4 Monte Carlo Analysis Capabilities

The recent and continuing growth in computer power motivates the assessment and further development of Monte Carlo-based analysis capabilities applicable to multiple reactor types. Enhancement of these codes will also be investigated, including the propagation of errors as a function of depletion, provision of temperature interpolation capability, and modeling of thermal-hydraulic feedback.

### A7.3.1.5 Reactor Neutronic Design Codes

An integrated neutronic and depletion capability is needed for modeling non-equilibrium and equilibrium cycle operations of Generation IV systems, with representation of both their in-core and ex-core fuel cycle segments. Accurate modeling of systems with significant spectral gradients and changes of spectrum with depletion is a key requirement. The tool would employ advanced modules suitable for analysis of different Generation IV systems.

#### A7.3.1.6 Sensitivity Analysis Capabilities

Uncertainties in reactor physics data lead to uncertainties in predictions of depletion-dependent system characteristics. By using sensitivity analysis methods, it is possible to avoid explicit recalculation of the effects for each data variation and at the same time to obtain information on additional data needs. This activity will develop an analytical tool for burnup-dependent sensitivity evaluation and models for evaluating the uncertainties in predicted performance characteristics for different Generation IV designs.

### A7.3.2 Evaluation Methodologies

#### A7.3.2.1 Economics Evaluation Methodology

An integrated nuclear energy economics model is central to standard and credible economic evaluation of Generation IV nuclear energy systems. The innovative nuclear systems considered within Generation IV require new tools for their economic assessment, since their characteristics differ significantly from those of current Generation II and III nuclear power plants. In addition, the existing economic models were not designed to compare nuclear energy systems featuring innovative fuel cycles and capability for generation of electricity, hydrogen, and other energy products as well as energy conversion technologies, or to evaluate economics of deployment in different countries or world regions. The GIF EMWG is charged with developing an integrated economics model applicable to the comprehensive evaluation of the economic performance of Generation IV nuclear energy systems.

#### A7.3.2.2 Proliferation Resistance and Physical Protection Evaluation Methodology

Methodologies currently available for evaluating PR&PP of nuclear energy systems are limited by the lack of accepted figures of merit that provide a sufficient representation of system performance in these areas. A PR&PP MWG has been formed to develop an improved methodology for assessing Generation IV systems. This group is charged with developing a systematic method for evaluating and comparing the PR&PP of these systems, including their fuel cycle facilities and operations. To the maximum extent possible, a quantitative and standardized methodology is targeted, as is the ability to identify system features that contribute to the overall resulting assessment of the comparative PR&PP of the system.

#### A7.3.2.3 Risk and Safety Evaluation Methodology

The approach for evaluating risk and safety of Generation IV systems and the technical basis for their future regulation need to be established. There is considerable incentive to define an evaluation methodology that is independent of system/technology and that can support safety and licensing reviews of Generation IV systems deployed in different countries or world regions. The GIF Risk and Safety Working Group was formed to support this aim and, in particular, to (1) specify safety and quality goals and methodology for evaluating system performance relative to these goals, (2) facilitate integrated consideration of safety PR&PP goals, (3) provide recommendations to GIF on interactions with the nuclear safety regulatory community and other issues relevant to safety and regulation, and 4) interact with the Generation IV system steering committees and project management boards to provide insights for the definition of the R&D that advances safety, reliability, and quality goals.

### A7.3.3 Design and Evaluation Methods Program Coordination

This D&EM program component provides for coordination and oversight of R&D activities directed to improving modeling capabilities and evaluation methodologies. It also provides for maintaining cognizance of related R&D activities conducted in other national and international programs so that the benefits of those activities may be realized to the greatest extent possible by the Generation IV program. Finally, it provides for periodic reporting of results to DOE and GIF and their advisory review committees, as well as for participation in conferences, workshops, and educational forums.

## A7.4 PROJECT COST AND SCHEDULE

### A7.4.1 Fiscal Year 2006 Project Budget

Major D&EM program components are supported by FY 2006 funding as shown in Table A7.1.

Table A7.1. FY 2006 budget profile for D&EM Activities ($K).

| Task | FY-06[a] |
|---|---|
| Coordination of Design and Evaluation R&D | 160 |
| Improvement of Design and Safety Analysis Capabilities | 1,090 |
| Development and Application of Evaluation Methodologies | 1,107 |
| Total | 2,357 |

a. FY 2006 funding includes FY 2005 carryover funds.

### A7.4.2 Ten-Year Project Schedule

A high-level schedule for D&EM R&D is shown in Figure A7.1. This schedule reflects the basic strategy adopted for improving computer code modeling capabilities in the areas of neutronics, thermal-hydraulics, and safety. Improvement of modeling capabilities for the NGNP and for fast reactors (particularly the SFR) is emphasized during the first few years. For each type of analysis capability, the early focus is on compilation of benchmark data (particularly measurements) for code qualification, assessment of existing capabilities, and determination of the needs for new measurements. Subsequent efforts are devoted to implementing and testing improvements of existing capabilities, and on software verification and validation.

Evaluation methodology efforts for economics and PR&PP are structured such that early efforts (through FY 2006) are mainly directed to development and documentation of the overall methodology framework. In a subsequent phase, the elements of the methodology are further detailed and incorporated in software intended to facilitate and standardize the system evaluations. Finally, the evaluation methodology activities are directed increasingly to supporting application to Generation IV systems and implementing modifications indicated by user experience and feedback.

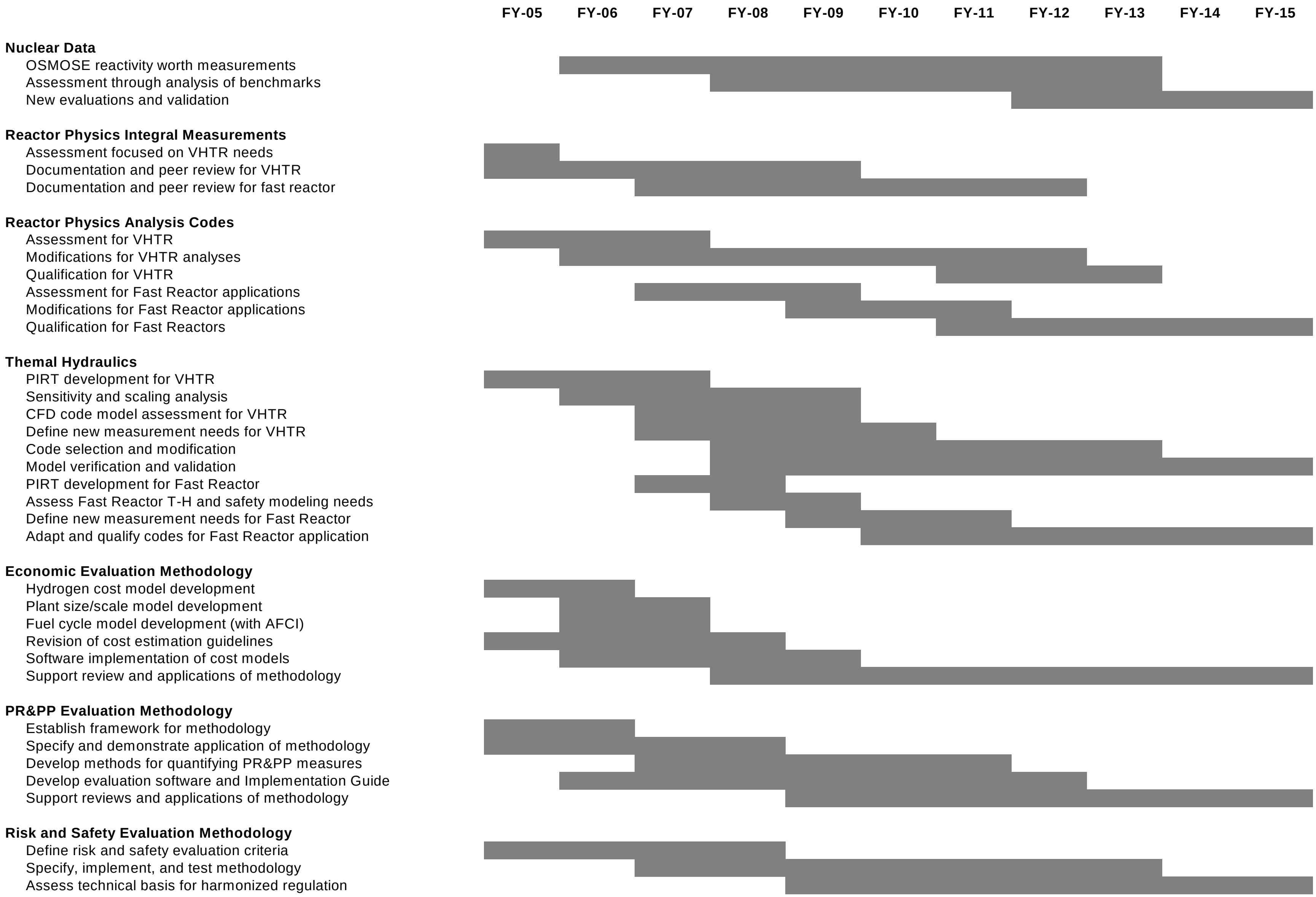


Figure A7.1. Ten-year project schedule.

### A7.4.3 Ten-Year Project Milestones

The major D&EM milestones are as follows:

FY 2006

- Report on enhancement of the DIF3D/REBUS-3 code system for NGNP analysis
- Report on integral reactor physics benchmark evaluations
- Report on contribution to OSMOSE program of actinide sample reactivity measurements
- Document coupled Reactor Excursion and Leak Analysis Program (RELAP5)-CFD calculation
- Document Graphite Reactor Severe Accident Code (GRSAC) sensitivity studies and contribution to NGNP phenomena identification and ranking table (PIRT) development
- Issue Reactor Safety Working Group program of work for review by DOE and GIF
- Document Markov model parameter estimation using the Sodium-Cooled Fast Reactor design example system characteristics
- Issue revision of PR&PP Implementation Guide
- Issue revision of EMWG Guidelines incorporating new models
- Issue summary report documenting EMWG test calculations.

FY 2007

- Report on PIRT development for NGNP
- Report on reactor physics model improvements for NGNP analysis
- Provide assessment report and best-practice guidelines for CFD code application to Generation IV systems
- Complete economic evaluation methodology development
- Specify initial set of risk and safety evaluation criteria
- Update PR&PP Implementation Guide.

FY 2008

- Issue report on OSMOSE reactivity-worth measurements and confirm utility of measurements for reducing nuclear data uncertainties
- Complete NGNP sensitivity and scaling analyses for thermal-fluidic and safety-related phenomena
- Complete specification of PR&PP evaluation methodology
- Complete PIRT development for Fast Reactor
- Complete EMWG cost estimation guidelines
- Report on technology independent risk and safety evaluation criteria.

FY 2009

- Report on nuclear data assessments and status of validation tests using integral experiments
- Specify fast reactor modeling improvement needs
- Complete documentation of NGNP integral physics benchmarks
- Define needs for new measurements of NGNP thermal-fluid parameters
- Release economic evaluation software and user manual
- Report on risk and safety evaluation methodology and results of initial applications.

FY 2010-2011

- Complete modifications of Fast Reactor physics analysis software
- Perform verification and validation tests for neutronic design and fuel cycle modeling tools
- Perform verification and validation tests for system dynamics modeling tools
- Implement software configuration control for analysis capabilities
- Complete and document risk and safety evaluation methodology
- Document progress toward a unified technical basis for safety regulation in different countries/regions
- Apply economics methodology to evaluations of Generation IV systems (joint responsibility with system development teams)
- Complete methodology for evaluation of PR&PP measures.

FY 2012 and beyond

- Complete documentation of Fast Reactor integral physics benchmarks
- Complete OSMOSE reactivity worth measurements
- Implement and qualify Fast Reactor system dynamics modeling improvements
- Update design analysis software to accommodate system design changes and address findings of verification and validation tests
- Report on software verification and validation tests
- Complete and document risk and safety evaluation methodology; demonstrate application of methodology
- Apply PR&PP methodology to evaluations of Generation IV systems and fuel cycles (joint responsibility with system development teams).

## A7.5 REFERENCES

DOE, 2002, *A Technology Roadmap for Generation-IV Nuclear Energy Systems*, GIF-002-00, U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, December 2002.