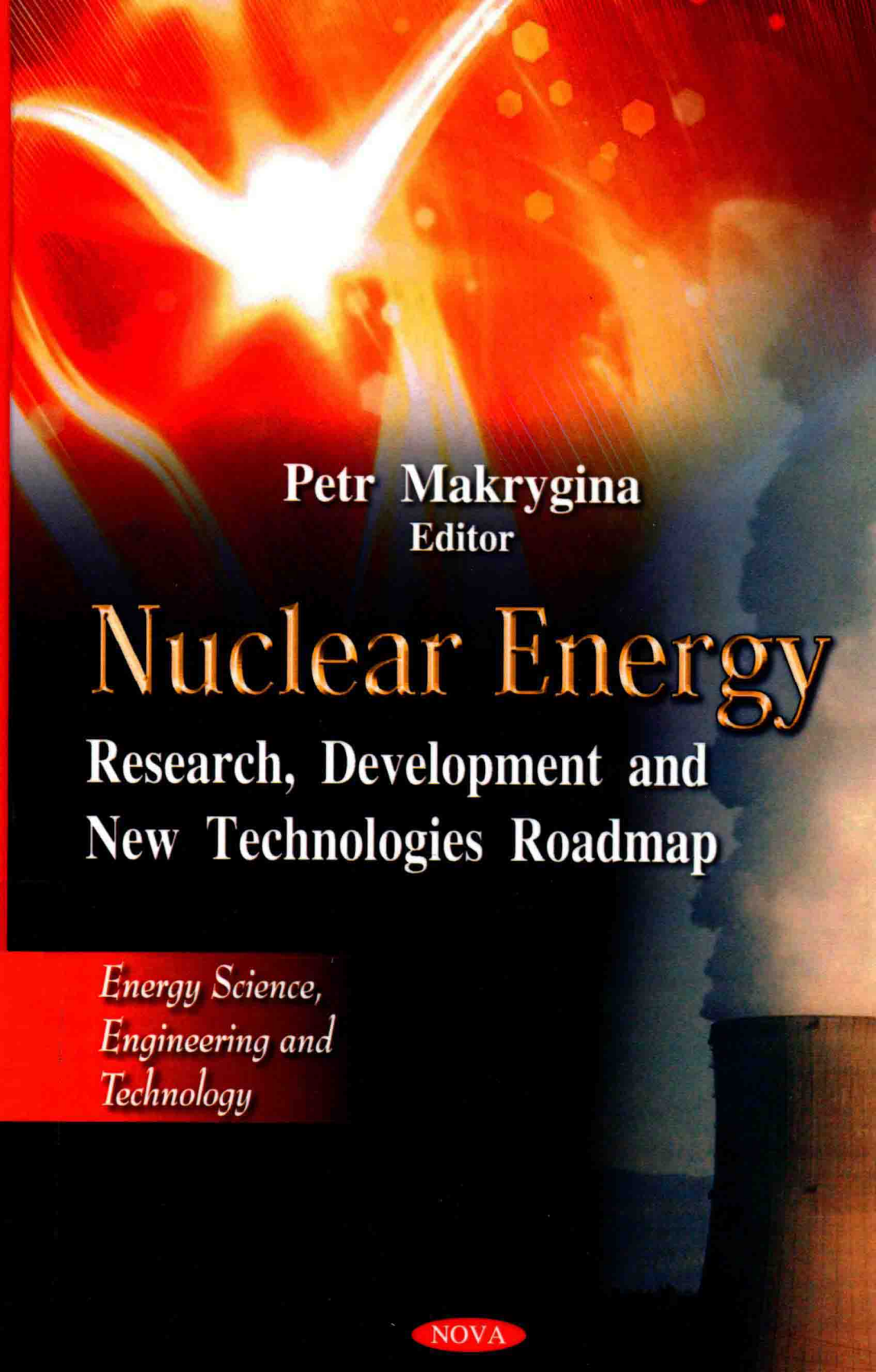
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Research, Development and New Technologies Roadmap
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ENERGY SCIENCE, ENGINEERING AND TECHNOLOGY

NUCLEAR ENERGY

RESEARCH, DEVELOPMENT AND NEW TECHNOLOGIES ROADMAP

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PREFACE

This book provides a roadmap for the Department of Energy's (DOE's) Office of Nuclear Energy (NE) research, development and demonstration activities that will ensure nuclear energy remains a viable energy option for the United States.

Chapter 1- To achieve energy security and greenhouse gas (GHG) emission reduction objectives, the United States must develop and deploy clean, affordable, domestic energy sources as quickly as possible. Nuclear power will continue to be a key component of a portfolio of technologies that meets our energy goals. This document provides a roadmap for the Department of Energy's (DOE's) Office of Nuclear Energy (NE) research, development, and demonstration activities that will ensure nuclear energy remains viable energy option for the United States.

Chapter 2- The Nuclear Energy Enabling Technologies (NEET) Program proposed for fiscal year (FY) 2011 at the requested $99 million will develop crosscutting technologies that directly support and complement the Department of Energy, Office of Nuclear Energy's (DOE–NE's) advanced reactor and fuel cycle concepts, focusing on innovative research that offers the promise of dramatically improved performance. Pending FY 2011 Congressional Appropriation, the program will encourage the development of transformative, "out-of-the-box" solutions across the full range of nuclear energy technology, spurring revolutionary improvements in safety, performance, reliability, economics, and proliferation risk reduction.

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Chapter 1

NUCLEAR ENERGY RESEARCH AND DEVELOPMENT ROADMAP*

United States Department of Energy

LIST OF ACRONYMS

BTU	British Thermal Units
CO_2	Carbon dioxide
DOE	Department of Energy
EE	DOE–Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Agency
EPRI	Electric Power Research Institute
FE	DOE–Office of Fossil Energy
GDP	Gross domestic product
GHG	Greenhouse gas
GWe	Gigawatt (electric)
GWe-yr	Gigawatt-year (electric)
HTGR	High-temperature gas-cooled reactor
HTR	High-temperature reactor
IAEA	International Atomic Energy Agency
II&C	Instrumentation, information and control

* This is an edited, reformatted and augmented version of a United States Department of Energy publication, dated April 2010.

IPSR	Integral primary system reactor
ITAAC	Inspections, test, analyses and acceptance criteria
kW-hr	Kilowatt-hour
LWR	Light-water reactor
MPACT	Materials Protection, Accounting and Control for Transmutation
MT	Metric ton
MWe	Megawatt (electric)
MWh	Megawatt-hour
NDE	Nondestructive evaluation
NE	DOE–Office of Nuclear Energy
NEA	Nuclear Energy Agency
NGNP	Next Generation Nuclear Plant
NGSI	Next Generation Safeguards Initiative
NNSA	National Nuclear Security Administration
NRC	Nuclear Regulatory Commission
OECD	Organization for Economic Cooperation and Development
R&D	Research and development
RISMC	Risk-informed safety margin characterization
SC	DOE–Office of Science
SMR	Small, modular reactor
UNF	Used nuclear fuel

EXECUTIVE SUMMARY

To achieve energy security and greenhouse gas (GHG) emission reduction objectives, the United States must develop and deploy clean, affordable, domestic energy sources as quickly as possible. Nuclear power will continue to be a key component of a portfolio of technologies that meets our energy goals. This document provides a roadmap for the Department of Energy's (DOE's) Office of Nuclear Energy (NE) research, development, and demonstration activities that will ensure nuclear energy remains viable energy option for the United States.

Today, the key challenges to the increased use of nuclear energy, both domestically and internationally, include:

- The capital cost of new large plants is high and can challenge the ability of electric utilities to deploy new nuclear power plants.

- The exemplary safety performance of the U.S. nuclear industry over the past thirty years must be maintained by an expanding reactor fleet.
- There is currently no integrated and permanent solution to high-level nuclear waste management.
- International expansion of the use of nuclear energy raises concerns about the proliferation of nuclear weapons stemming from potential access to special nuclear materials and technologies.

In some cases, there is a necessary and appropriate federal role in overcoming these challenges, consistent with the primary mission of NE to advance nuclear power as a resource capable of making major contributions to meeting the nation's energy supply, environmental, and energy security needs. This is accomplished by resolving technical, cost, safety, security and proliferation resistance barriers, through research, development, and demonstration, as appropriate. NE's research and development (R&D) activities will help address challenges and thereby enable the deployment of new reactor technologies that will support the current fleet of reactors and facilitate the construction of new ones.

Research and Development Objectives

NE organizes its R&D activities along four main R&D objectives that address challenges to expanding the use of nuclear power: (1) develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors; (2) develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals; (3) develop sustainable nuclear fuel cycles; and (4) understanding and minimization of risks of nuclear proliferation and terrorism.

R&D Objective 1. Develop Technologies and Other Solutions that can Improve the Reliability, Sustain the Safety, and Extend the Life of Current Reactors

The existing U.S. nuclear fleet has a remarkable safety and performance record, and today these reactors account for 70 percent of the low greenhouse gas (GHG)-emitting domestic electricity production. Extending the operating

lifetimes of current plants beyond sixty years and, where possible, making further improvements in their productivity will generate near-term benefits. Industry has a significant financial incentive to extend the life of existing plants, and as such, activities will be cost shared. Federal R&D investments are appropriate to answer fundamental scientific questions and, where private investment is insufficient, to help make progress on broadly applicable technology issues that can generate public benefits. The DOE role in this R&D objective is to work in conjunction with industry and where appropriate the Nuclear Regulatory Commission (NRC) to support and conduct the long-term research needed to inform major component refurbishment and replacement strategies, performance enhancements, plant license extensions, and age-related regulatory oversight decisions. DOE will focus on aging phenomena and issues that require long-term research and are generic to reactor type.

R&D Objective 2. Develop Improvements in the Affordability of New Reactors to Enable Nuclear Energy to Help Meet the Administration's Energy Security and Climate Change Goals

If nuclear energy is to be a strong component of the nation's future energy portfolio, barriers to the deployment of new nuclear plants must be overcome. Impediments to new plant deployment, even for those designs based on familiar light-water reactor (LWR) technology, include the substantial capital cost of new plants and the uncertainties in the time required to license and construct those plants. Although subject to their own barriers for deployment, more advanced plant designs, such as small modular reactors (SMRs) and high-temperature reactors (HTRs), have characteristics that could make them more desirable than today's technology. SMRs, for example, have the potential to achieve lower proliferation risks and more simplified construction than other designs. The development of next-generation reactors could present lower capital costs and improved efficiencies. These reactors may be based upon new designs that take advantage of the advances in high performance computing while leveraging capabilities afforded by improved structural materials. Industry plays a substantial role in overcoming the barriers in this area. DOE provides support through R&D ranging from fundamental nuclear phenomena to the development of advanced fuels that could improve the economic and safety performance of these advanced reactors. Nuclear power can reduce GHG emissions from electricity production and possibly in co-generation by displacing fossil fuels in the generation of process heat for

applications including refining and the production of fertilizers and other chemical products.

R&D Objective 3. Develop Sustainable Nuclear Fuel Cycles

Sustainable fuel cycle options are those that improve uranium resource utilization, maximize energy generation, minimize waste generation, improve safety, and limit proliferation risk. The key challenge is to develop a suite of options that will enable future decision makers to make informed choices about how best to manage the used fuel from reactors. The Administration has established the Blue Ribbon Commission on America's Nuclear Future to inform this waste- management decision-making process. DOE will conduct R&D in this area to investigate technical challenges involved with three potential strategies for used fuel management:

- *Once-Through* – Develop fuels for use in reactors that would increase the efficient use of uranium resources and reduce the amount of used fuel requiring direct disposal for each megawatt-hour (MWh) of electricity produced. Additionally, evaluate the inclusion of non-uranium materials (*e.g.*, thorium) as reactor fuel options that may reduce the long-lived radiotoxic elements in the used fuel that would go into a repository.
- *Modified Open Cycle* – Investigate fuel forms and reactors that would increase fuel resource utilization and reduce the quantity of long-lived radiotoxic elements in the used fuel to be disposed (per MWh), with limited separations steps using technologies that substantially lower proliferation risk.
- *Full Recycling* – Develop techniques that will enable the long-lived actinide elements to be repeatedly recycled rather than disposed. The ultimate goal is to develop a cost-effective and low proliferation risk approach that would dramatically decrease the long-term danger posed by the waste, reducing uncertainties associated with its disposal.

DOE will work to develop the best approaches within each of these tracks to inform waste management strategies and decision making.

R&D Objective 4. Understand and Minimize the Risks of Nuclear Proliferation and Terrorism

It is important to assure that the benefits of nuclear power can be obtained in a manner that limits nuclear proliferation and security risks. These risks include the related but distinctly separate possibilities that nations may attempt to use nuclear technologies in pursuit of a nuclear weapon and that terrorists might seek to steal material that could be used in a nuclear explosive device. Addressing these concerns requires an integrated approach that incorporates the simultaneous development of nuclear technologies, including safeguards and security technologies and systems, and the maintenance and strengthening of non-proliferation frameworks and protocols. Technological advances can only provide part of an effective response to proliferation risks, as institutional measures such as export controls and safeguards are also essential to addressing proliferation concerns. These activities must be informed by robust assessments developed for understanding, limiting, and managing the risks of nation-state proliferation and physical security for nuclear technologies. NE will focus on assessments required to inform domestic fuel cycle technology and system option development. These analyses would complement those assessments performed by the National Nuclear Security Administration (NNSA) to evaluate nation state proliferation and the international nonproliferation regime. NE will work with other organizations including the NNSA, the Department of State, the NRC, and others in further defining, implementing and executing this integrated approach.

R&D Areas

The Department expects to undertake R&D in a variety of areas to support its role in the objectives outlined above. Examples include:

- Structural materials
- Nuclear fuels
- Reactor systems
- Instrumentation and controls
- Power conversion systems
- Process heat transport systems
- Dry heat rejection
- Separations processes

- Waste forms
- Risk assessment methods
- Computational modeling and simulation

R&D Approach

A goal-driven, science-based approach is essential to achieving the stated objectives while exploring new technologies and seeking transformational advances. This science-based approach, depicted in Figure 1, combines theory, experimentation, and high-performance modeling and simulation to develop the fundamental understanding that will lead to new technologies. Advanced modeling and simulation tools will be used in conjunction with smaller-scale, phenomenon-specific experiments informed by theory to reduce the need for large, expensive integrated experiments. Insights gained by advanced modeling and simulation can lead to new theoretical understanding and, in turn, can improve models and experimental design. This R&D must be informed by the basic research capabilities in the DOE Office of Science (SC).

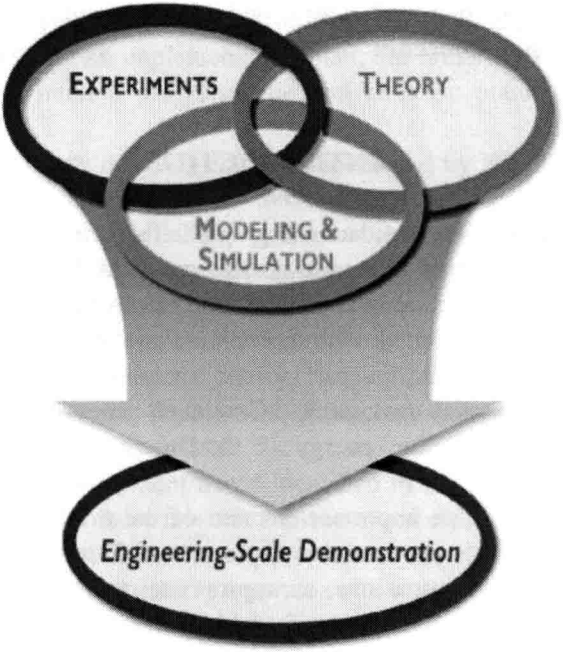

Figure 1. Major Elements of a Science-Based Approach.

NE maintains access to a broad range of facilities to support its research activities. Hot cells and test reactors are at the top of the hierarchy, followed by smaller-scale radiological facilities, specialty engineering facilities, and small non-radiological laboratories. NE employs a multi- pronged approach to having these capabilities available when needed. The core capabilities rely on DOE-owned irradiation, examination, chemical processing and waste form development facilities. These are supplemented by university capabilities ranging from research reactors to materials science laboratories. In the course of conducting this science-based R&D, infrastructure needs will be evaluated and considered through the established planning and budget development processes.

There is potential to leverage and amplify effective U.S. R&D through collaboration with other nations via multilateral and bilateral agreements, including the Generation IV International Forum. DOE is also a participant in Organization of Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) and International Atomic Energy Agency (IAEA) initiatives that bear directly on the development and deployment of new reactor systems. In addition to these R&D activities, international interaction supported by NE and other government agencies will be essential in establishment of international norms and control regimes to address and mitigate proliferation concerns.

1. INTRODUCTION

Access to affordable, abundant energy – chiefly from fossil fuel sources – has been a key enabler of economic growth since the Industrial Revolution. However, as the first decade of the 21st century draws to a close, the United States finds itself confronted with economic, environmental, and national security challenges related in part to the manner in which our society produces, distributes, and uses energy. Continued access to plentiful, secure, and environmentally benign energy is fundamental to overcoming these challenges.

Nuclear energy is an important element of the diverse energy portfolio required to accomplish our national objectives. NE conducts research and development, and demonstrations, as appropriate, that will help enable the benefits of clean, safe, secure and affordable nuclear energy to continue and expand.

Nuclear power is a proven clean, affordable, domestic energy source that is part of the current U.S. energy portfolio.

This document identifies opportunities and challenges associated with continued and increased use of fission energy to enhance our nation's prosperity, security, and environmental quality; outlines the NE role and mission in enabling the benefits of nuclear energy for our nation; and presents a strategy and roadmap to guide the NE scientific and technical agenda. The report presents a high-level vision and framework for R&D activities needed to keep the nuclear energy option viable in the near term and to expand its use in the decades ahead.

Section 2 describes the current energy production and utilization landscape in the United States. Section 3 articulates NE's fundamental mission and role in enabling nuclear energy solutions and presents the four R&D objectives for nuclear energy development that are the focus of NE activities. The details of the roadmap are presented in Section 4. The R&D approach presented in Section 5 embodies a goal-oriented, science-based R&D portfolio that includes both evolutionary and transformational, high-risk–high-payoff R&D, including those research areas that encompass multiple objectives. Finally, Section 6 provides a summary of the objects presented in this report.

This report is not an implementation plan, but rather provides a basis that will guide NE's internal programmatic and strategic planning for research going forward.

The report focuses on R&D activities sponsored by NE. The U.S. nuclear industry plays a central role in overcoming barriers and is ultimately responsible for the commercial deployment of the resulting technologies. NE intends to proceed in a manner that supports a strong and viable nuclear industry in the United States and preserves the ability of that industry to participate in nuclear projects here and abroad.

Finally, it should be noted that in some limited cases, NE's mission extends beyond terrestrial deployment of nuclear energy into other arenas, such as space applications of both fission and radioisotope power systems. Some technology development needs identified in this document also benefit space applications, but these mission arenas are not addressed in this roadmap. Educational programs, while vital, are interwoven through the technical programs and are not discussed as separate entities.

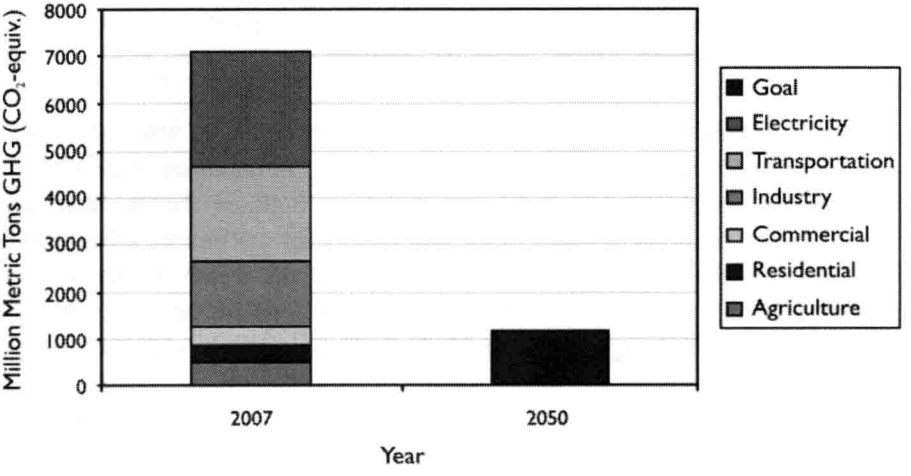

Figure 2. U.S. Greenhouse Gas Emissions.[1]

To achieve its energy security and GHG reduction objectives, the U.S. must develop and deploy clean, affordable, domestic energy sources as quickly as possible.

2. BACKGROUND

All governments of the world share a common challenge to ensure their people have access to affordable, abundant, and environmentally friendly energy. Secretary of Energy Steven Chu has reiterated the Administration's position that nuclear is an important part of the energy mix. He has recognized the importance of nuclear energy in meeting this challenge and supports R&D that can help increase the benefits of nuclear energy. A key objective that will shape the energy landscape of the United States is the transition to clean energy sources with reductions in GHG emissions (with a quantitative goal of 83% reduction below 2005 emissions levels by 2050, shown in Figure 2).

2.1. The Energy Landscape

The Human Development Index[2] is a commonly used measure of quality of life. Figure 3 illustrates that a nation's standard of living depends in part on energy consumption. Access to adequate energy is now and will continue to be