NUCLEAR ENERGY RESEARCH AND DEVELOPMENT ROADMAP

REPORT TO CONGRESS

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U.S. DEPARTMENT OF ENERGY

Nuclear Energy

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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
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

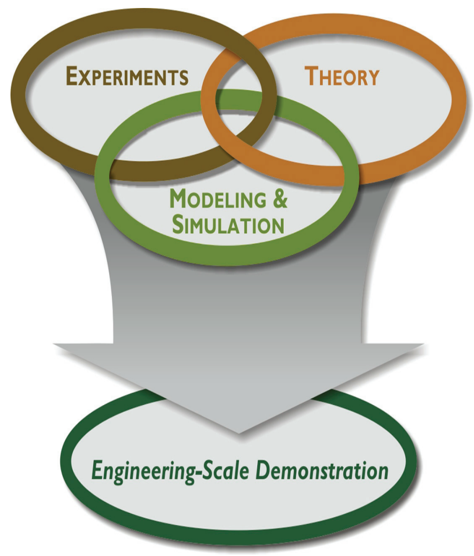
It is important to assure that the benefits of nuclear power can be obtained in a manner that limits nuclear proliferation and security risks. These risks include the related but distinctly separate possibilities that nations may attempt to use nuclear technologies in pursuit of a nuclear weapon and 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

Figure 1. Major Elements of a Science-Based Approach



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).

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

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.

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.

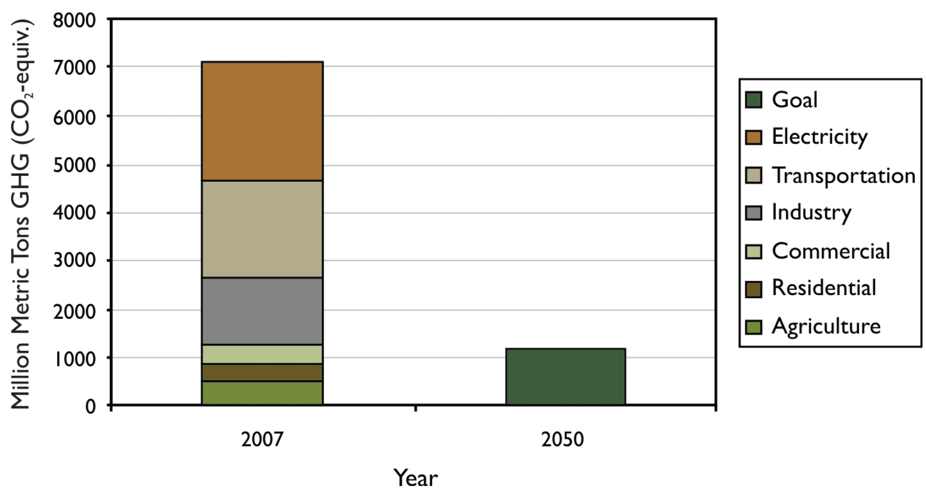
> To achieve its energy security and GHG reduction objectives, the U.S. must develop and deploy clean, affordable, domestic energy sources as quickly as possible.

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.

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).

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



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 required to achieve a high quality of life. Economic development, combined with efforts to limit carbon emissions, will likely lead to a

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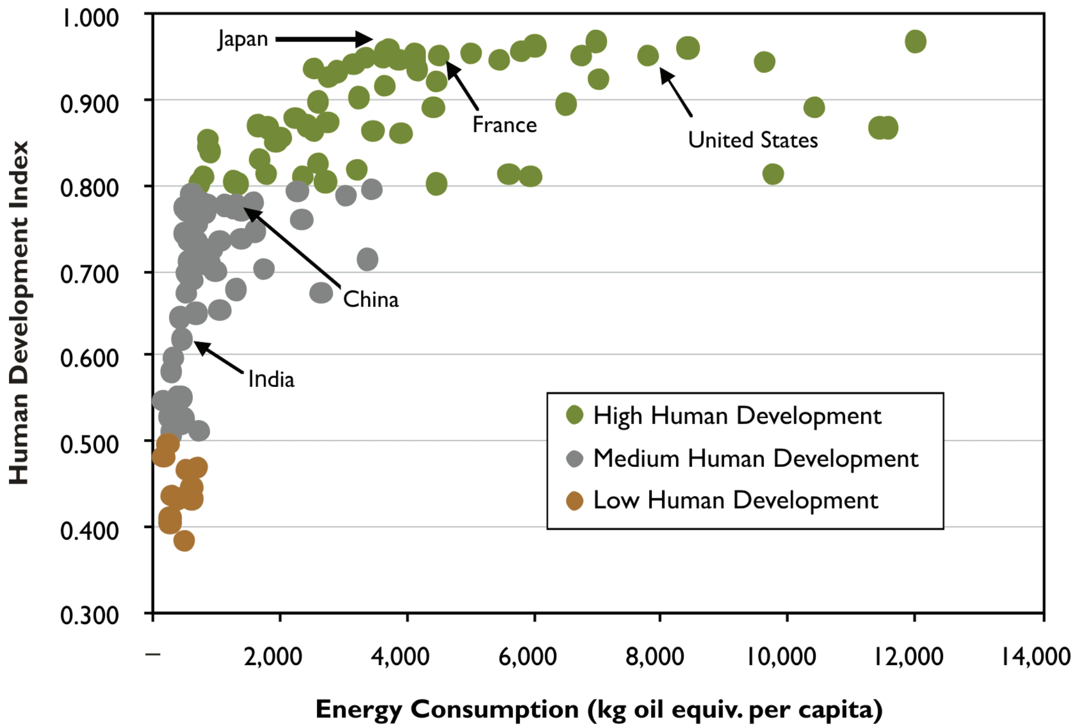
[1] 2007 GHG emissions reported in EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2007* EPA 430-R-09-004, April 15, 2009. Administration emission goals taken from the "Testimony of Peter R. Orszag, Director of the Office of Management and Budget, Before the Committee on the Budget, U.S. House of Representatives" on March 3, 2009.

[2] The index was developed by the United Nations to enable cross-national comparisons of development and is updated in an annual report. The derivation of the index was introduced in United Nations Development Programme, *Human Development Report 1990*, Oxford University Press, 1990.

significant expansion of nuclear power. The U.S., in concert with the international community, must develop the technologies and systems to accomplish such expansion while limiting proliferation risks.

Figure 3. 2005 Human Development Index vs. Energy Consumption (Per Capita Kilograms Oil Equivalent)

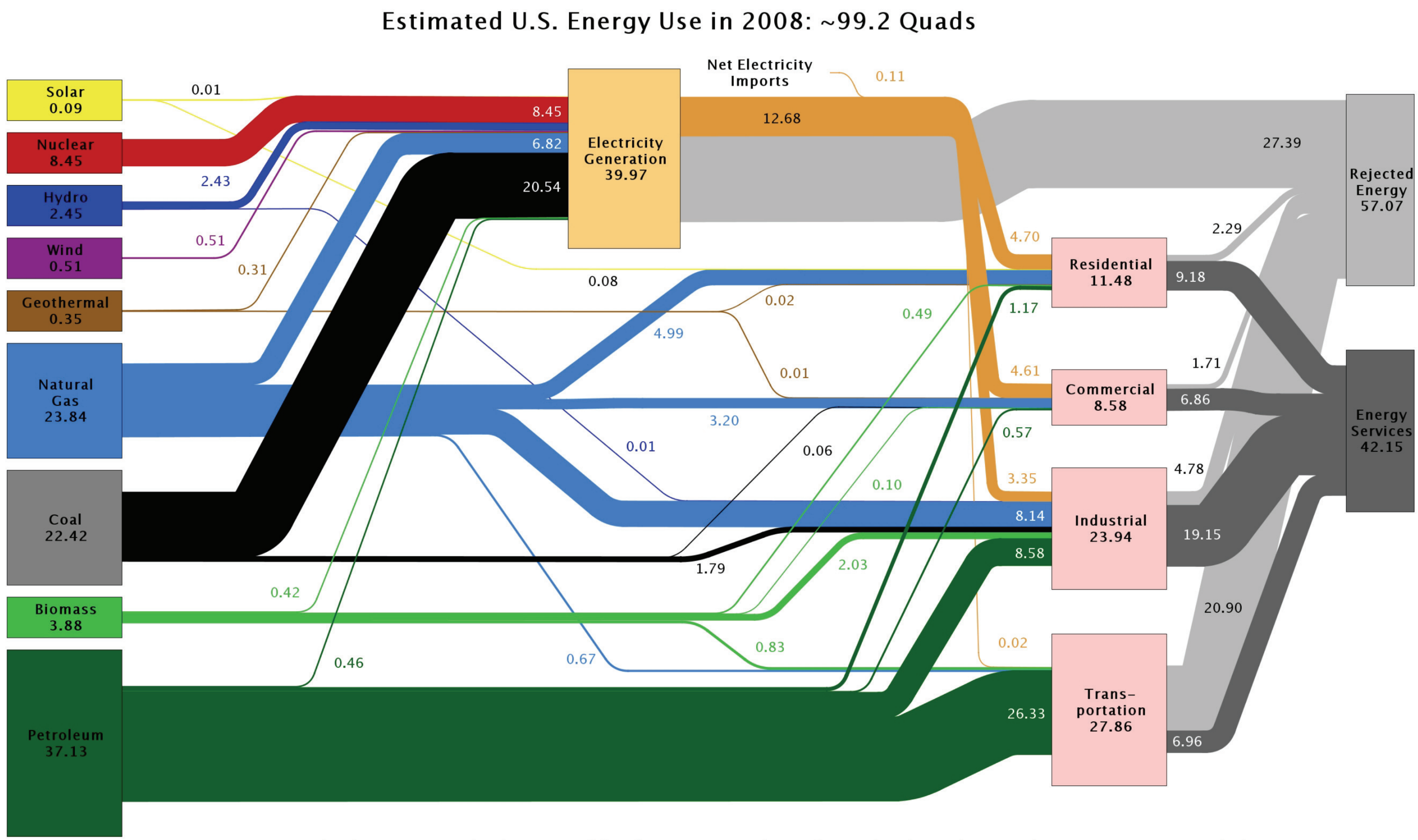


As we move forward, efficiency and conservation will become ever-increasing components of energy policy. However, conservation and energy efficiency alone will not be sufficient to maintain a desirable quality of life.

The United States currently consumes roughly 100 quadrillion British Thermal Units (BTU), or 100 quads, of primary energy.[3] This represents 25% of world's energy consumption in a country that produces 30% of the global gross domestic product (GDP). Figure 4 shows energy consumption in the United States as a function of sectors and energy sources. At present, 40% of the total energy consumed is in the form of electricity, of which about 20 percent is generated by nuclear power. With 6 billion metric tons (MT) of emitted carbon dioxide (CO_2) as a result of fossil fuel usage (see Figure 5), the United States contributes 25 percent of global GHGs emitted.

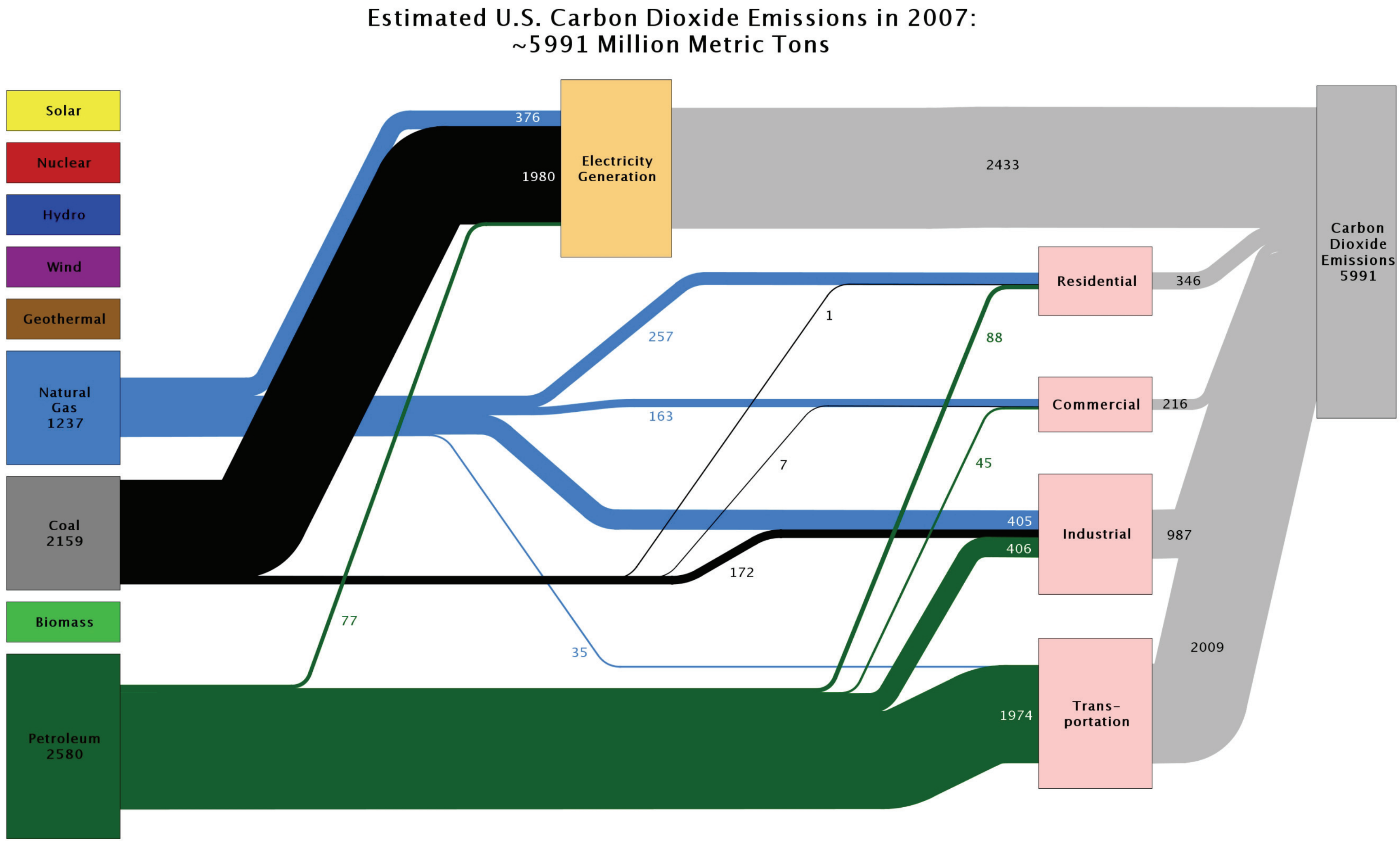
[3] The data in Figures 5 and 6 are reported by the U.S. DOE Energy Information Agency "An Updated Annual Energy Outlook 2009 Reference Case," 2009.

Figure 4. U.S. Primary Energy Use in 2008



Source: LLNL 2009. Data is based on DOE/EIA-0384(2008), June 2009. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Figure 5. U.S. Carbon Dioxide Emissions in 2007



Source: LLNL 2009. Data is based on DOE/EIA-0384(2008), June 2009. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Carbon embodied in industrial and commercial products such as plastics is not shown. The flow of petroleum to electricity production includes both petroleum fuels and the plastics component of municipal solid waste. The combustion of biologically derived fuels is assumed to have zero net carbon emissions – lifecycle emissions associated with biofuels are accounted for in the Industrial and Commercial sectors. Totals may not equal sum of components due to independent rounding. LLNL-MI-411167

The Administration's clean energy and climate change objectives are ambitious and achievable. Successful achievement of these objectives will require solutions to technical challenges associated with various energy sectors, including:

- *Electricity Sector GHG Production* – As seen in Figures 4 and 5, the U.S. electricity production sector annually consumes 40 quadrillion BTU of primary energy, producing 4,150 million MWh of electricity, and emitting 2,400 million MT of CO_2. The average carbon intensity of the U.S. electric-generating sector is 0.58 MT–CO_2/MWh of electricity produced. While far from the world's highest carbon intensity (China produces 0.87 MT-CO_2/MWh of electricity), U.S. electric-generating-sector carbon intensity is far higher than some industrialized countries. For instance, France emits only 0.09 MT–CO_2/MWh of electricity produced. There is clearly both the need for, and the real potential for, significant improvement in U.S. electric-generating-sector carbon intensity and GHG emissions.
- *Transportation Sector Energy Use and GHG Emissions* – The transportation sector is currently responsible for 33% of GHG emissions (Figure 5). In addition to more energy-efficient internal combustion engines, electrification of the transportation sector using new low-carbon electricity-generation technologies will assist in reducing these emissions. Successful electrification of the transportation sector is also dependent on improvements in battery technology to enable high-density energy storage to meet vehicle service range requirements.
- *Industrial Sector Energy Use and GHG Emissions* – Industrial use of energy is responsible for 16 percent of the country's GHG emissions (Figure 5). About half of these emissions come from chemical facilities and oil refineries. The development of GHG-free technologies that can generate and deliver significant thermal and chemical energy to industry is needed.

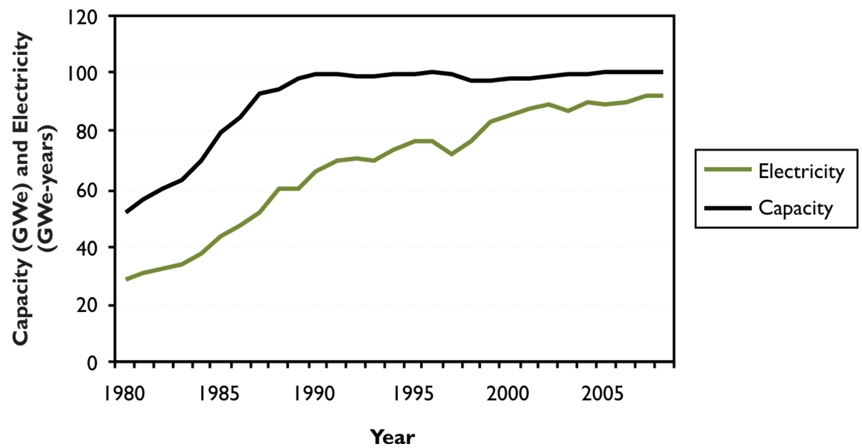
The driver for the new energy policy is to continue to generate energy, mostly from domestic sources, at an affordable price. The policy must meet increasing demand, with considerably reduced GHG emissions, and without stifling GDP growth.

2.2 The Value and Need for an "Energy Portfolio" Approach

Given the issues noted in Section 2.1, an effective energy policy will almost certainly rely on the development and use of a portfolio of domestic clean energy sources. This is true not only because of resource limits at various points in the energy supply chain but also because all energy sources face economic, technical, and societal risks to their successful deployment.[4] R. Socolow and S. Pacala, in "A Plan To Keep Carbon In Check,"[5] have demonstrated the potential for energy portfolio approaches to enhance U.S. energy security and reduce the threat of global warming. The following section discusses the role of nuclear energy as an element of the U.S. energy portfolio.

2.3 Nuclear Energy as an Element of the Future U.S. Energy Portfolio

Figure 6. U.S. Nuclear Energy History, 1980 – 2008



(EIA, *Annual Energy Review 2008*)

In 2007, the 104 light-water reactors (LWRs) currently operating in the United States generated 806 billion kilowatt-hours (kW-hrs), equivalent to 92 gigawatt-years (GWe-yrs). As shown in Figure 6, even though the generating capacity of the nuclear fleet has been essentially flat for almost twenty years, the production of nuclear electricity continued to grow largely as a result of increased capacity factors. The fleet's average capacity factor improved from 56.3% in 1980 to 91.9% in 2008.[6] This improvement was driven by reactor operators and the efforts of the Electric Power Research Institute (EPRI), spurred by NE-sponsored R&D into high-burnup fuels that allowed utilities to shift from 12-month operating cycles to 18- or 24-month operating cycles that reduced downtime. Additionally, some growth can be attributed to power uprates that increased capacity at existing plants.

While in operation, nuclear power plants do not emit GHGs. Every MWh of electricity produced with nuclear energy avoids the emission of approximately 1.0 MT of CO_2 if the same amount of energy had been generated with conventional coal-fired technologies or approximately 0.6 MT of CO_2 if the energy had been produced with natural gas. Since the per capita electricity consumption in the United States is approximately 14 MWh of electricity per year per person, nuclear energy offers the prospect of avoiding what could otherwise be an annual personal carbon footprint from electricity production of up to 14 MT of CO_2. In addition, nuclear power

[4] R. Socolow and S. Pacala, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies." *Science*, August 13, 2004: 968-972.

[5] *Scientific American*, September 2006

[6] EIA, *Annual Energy Review* 2008, Table 9.2.

is dependable. It is available day or night, when the wind is blowing and when it is not. After more than three decades of outstanding safety performance, the public acceptance of nuclear energy has turned in favor of its deployment.[7] However, continued and increased use of nuclear energy faces several key challenges:

- *Capital Cost* – The current fleet of nuclear power plants produces electricity at a very low cost (approximately 2–3 cents/kilowatt-hour) because these plants have already repaid the initial construction investments. However, the capital cost of a large new plant is high and can challenge the ability of electric utilities to deploy new nuclear reactors. Thus, it is important to reduce the capital cost by innovative designs. The introduction of smaller reactors might reduce capital costs by taking advantage of series fabrication in centralized plants and may reduce financial risk by requiring a smaller up-front investment.
- *Waste Management* – At present, no permanent solution to high-level nuclear waste management has been deployed in the United States. Innovative solutions will be required to assure that nuclear waste is properly managed. The Administration has initiated the Blue Ribbon Commission on America's Nuclear Future to conduct a review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense used nuclear fuel and nuclear waste. The results will inform the Government's process to establish a policy for used fuel and waste management. Ultimately, while the need for permanent waste disposal can never be eliminated, transition to nuclear energy technologies that significantly reduce the production of long-lived radioactive waste – rather than deal with it after it is produced – is a desirable goal.
- *Proliferation Risk* – There is considerable interest in the global expansion of nuclear energy. However, such expansion raises concerns about the proliferation of nuclear weapons, including nuclear explosive devices, stemming from access to enrichment and reprocessing activities that might produce weapons-usable materials. Development of innovative technologies and international policies are essential to prevent nuclear proliferation by nation-states as well as nuclear terrorism by rogue entities. Furthermore, a more robust capability to evaluate and compare proliferation and terrorism risks is needed. In addition, it is in the U.S. interest to engage nations contemplating civil nuclear power for the first time in order to help them develop an indigenous infrastructure designed to deploy the technology in a safe and secure manner.
- *Safety and Reliability* – As existing plants continue to operate and new plants and new types of plants are constructed, it is vital that the excellent safety and reliability record of nuclear energy in the United States be maintained. It is also important that the U.S. share its experience with other countries and work with them to ensure safe operation of their plants.

[7] Ref. http://www.gallup.com/poll/117025/Support-Nuclear-Energy-Inches-New-High.aspx.

3. MISSION AND GOALS OF THE OFFICE OF NUCLEAR ENERGY

The analysis presented in Section 2 supports the conclusion that increased greenhouse gas-free electricity production is necessary to achieve the transition to a clean-energy economy.

3.1 The Office of Nuclear Energy Mission

The primary mission of NE is to advance nuclear power as a resource capable of meeting the nation's energy, environmental, and national security needs by resolving technical, cost, safety, security, and proliferation resistance, through R&D and demonstrations, as appropriate. Progress in these areas should promote the deployment of fission power systems in a socially acceptable, environmentally sustainable, and economically attractive manner.

Four specific research and development objectives for nuclear energy development outline NE's approach to delivering progress in the areas noted above. The objectives are:

- *R&D Objective 1* – Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors.
- *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.
- *R&D Objective 3* – Develop sustainable nuclear fuel cycles.
- *R&D Objective 4* – Understand and minimize the risks of nuclear proliferation and terrorism.

The four objectives are discussed more fully in the following sections.

3.2 Nuclear Energy R&D Objectives and the Role of NE in Achieving Them

This section presents a description of the four R&D objectives and NE's role in making progress in these areas.

3.2.1 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 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 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. The DOE R&D role will focus on aging phenomena and issues that require long-term research and are generic to reactor type.

3.2.2 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 technology, include the substantial capital cost of new plants and the uncertainties in the time required to license and construct them. More advanced plant designs, such as small modular reactors (SMRs) and high-temperature reactors (HTRs), will have additional barriers for deployment. These reactors have characteristics that could make them more attractive than today's technology. SMRs, for example, have the potential to achieve lower proliferation risk 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's role in overcoming the barriers in this area is substantial. DOE supports 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.

3.2.3 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 complement institutional measures in limiting proliferation risk. The key challenge for the government in this R&D objective 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. DOE will conduct R&D in this area to investigate the 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 for direct disposal for each MWh of electricity produced. Additionally, evaluate the inclusion of non-uranium materials (*e.g.*, thorium) in 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 utilization of the fuel resource 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 be 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.

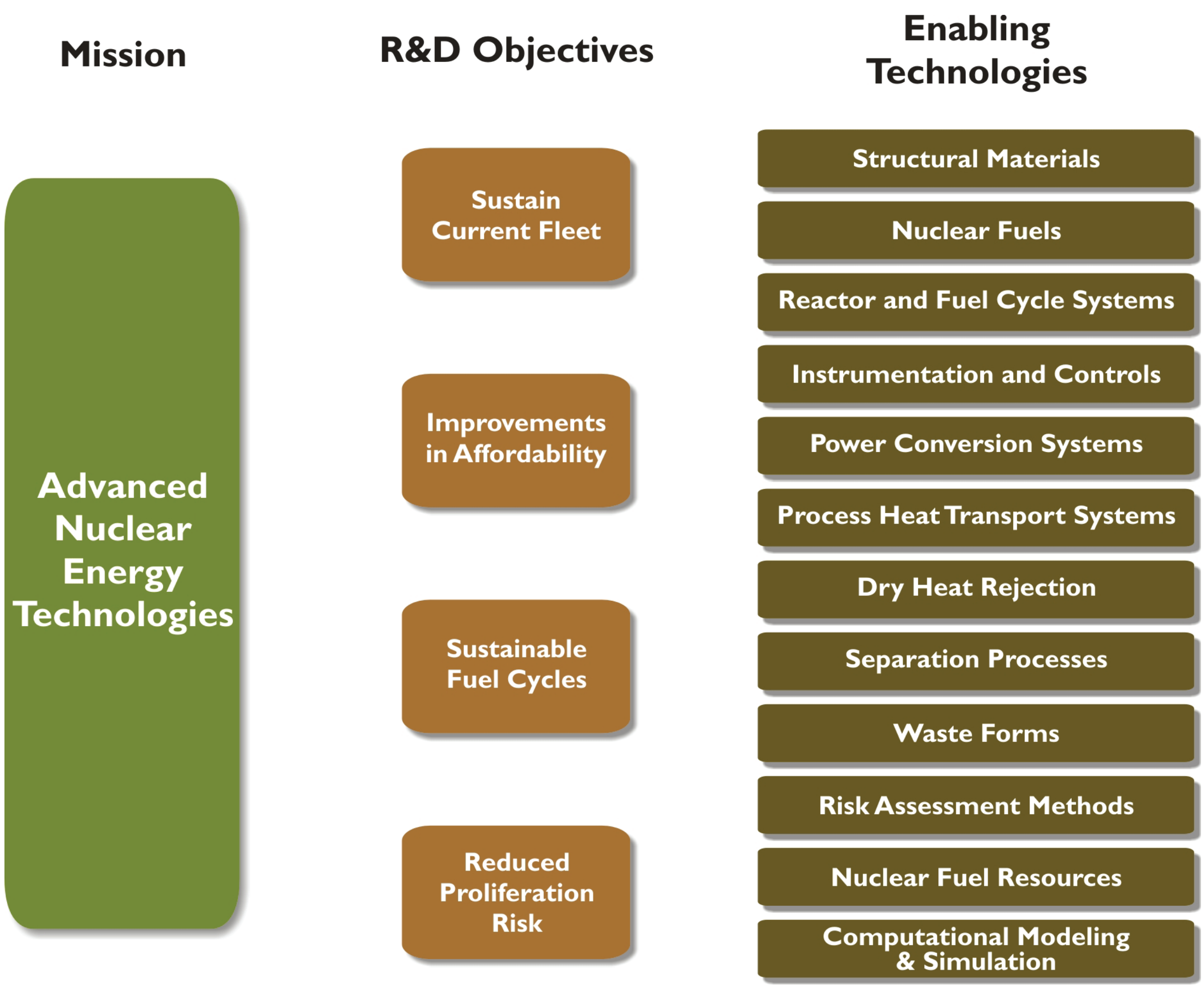
3.2.4 R&D Objective 4: Understand and Minimize the Risks of Nuclear Proliferation and Terrorism

It is important to assure that access to the benefits of nuclear power can be enabled while limiting nuclear proliferation and security risks. This goal requires an integrated approach that incorporates simultaneous development of nuclear fuel cycle technology, safeguards and security technologies and systems, new proliferation risk assessment tools, and non-proliferation frameworks and protocols. These activities must be informed by robust assessments that identify potential approaches for limiting risks of specific technologies and nuclear fuel cycle system options. NE will work with other organizations such as the National Nuclear Security Administration (NNSA), the Department of State, the NRC, and others in further defining, implementing and executing this integrated approach. Aspects of this research may help to inform the exploration of concepts such as international fuel service arrangements.

4. An Integrated Nuclear Energy Roadmap

This section presents an objective-focused roadmap to advance nuclear energy technologies. As depicted in Figure 7, the activities described here ultimately "unpack" to a suite of science and technology development activities, many of which will support more than one R&D objective.

Figure 7. NE Mission, R&D Objectives, and Technologies



The approach incorporates a portfolio of long-term R&D objectives and a balanced focus on evolutionary, innovative, and high-risk–high-payoff R&D in many diverse areas. The organization and coordination of the science and technology thrusts ("Enabling Technologies" in

Figure 7) will be a focus of program and strategic planning follow-on implementation plants, but is briefly addressed in Section 5.2 of this document.

In laying out the activities in each of the R&D objectives described below, we must remain goal-oriented to avoid falling into the trap of doing a great deal of work that, while interesting, fails to address the challenges to the deployment of nuclear energy. The following sections highlight areas in which NE may undertake future R&D. These R&D activities have been considered with the end in mind to ensure that the linkage between research and solution is clear. To that end, in depicting the timelines of activity for the R&D objectives below, the charts show a distinction between near-term milestones toward which the NE R&D plan is designed to progress, represented as triangles, and longer-term potential outcomes that provide a framework for the milestones, which are shown as ovals. The milestone charts attempt to depict the stages of development so as not to leave a sense that new technologies can be immediately deployed at a commercial level. Not every milestone or potential outcome outlined in these charts represent actions that are within DOE's roles and responsibilities, and research paths will include many decision points that require choosing the most promising options for continued R&D. Especially as technology matures, industry has a role and a responsibility to share the costs of making progress. It is ultimately industry's decision which commercial technologies will be deployed. The federal role falls more squarely in the realm of R&D.

These long-term milestones and potential outcomes are not set in stone, and in some cases the following sections outline multiple competing paths within an objective, knowing that ultimately only one direction will be chosen. In all cases, the activities, milestones, and plans outlined in this document will be reconsidered and revised periodically to ensure that NE R&D is consistent with priorities and reflects what we have learned from these efforts. Activities will be reviewed and modified as necessary through the established budgetary and decision-making processes.

Although some smaller component or process "demonstration" activities are mentioned, these are largely field tests and other actions to provide proof or validation of system elements. They are not large-scale demonstrations like the Next Generation Nuclear Plant (NGNP). Any decisions to embark on such large-scale demonstrations will be the result of decision-making processes that include the relevant stakeholders in the Executive Branch and Congress and will be made in accordance with NEPA and DOE Order 413 requirements. This R&D will enable these stakeholders to understand the potential tradeoffs embodied in these decisions.

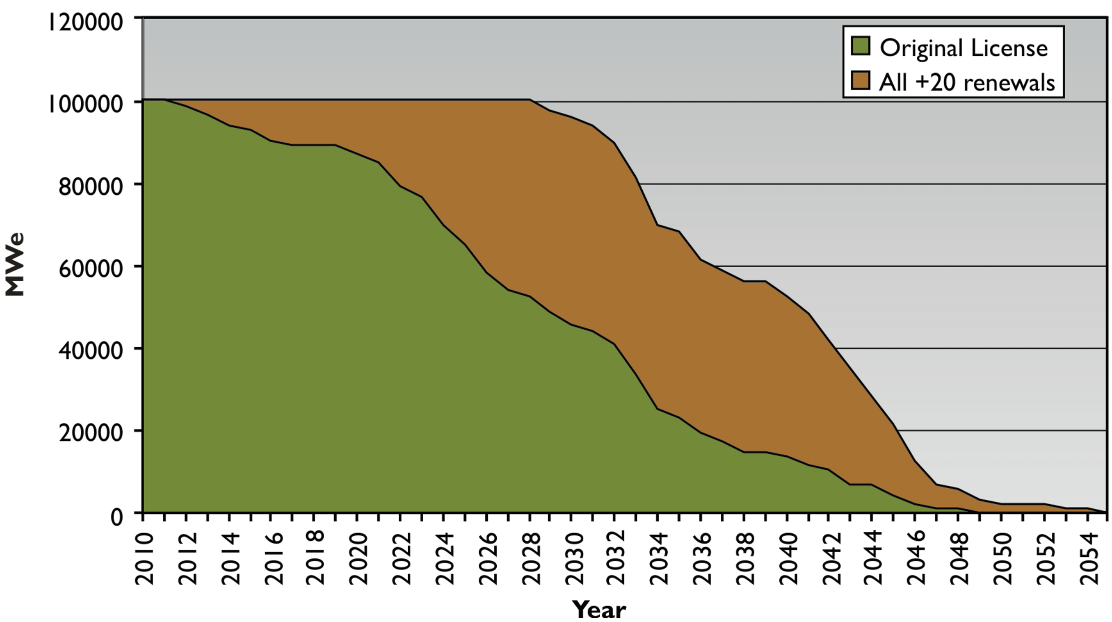
4.1 R&D Objective 1: Develop Technologies and Other Solutions that Can Improve the Reliability, Sustain the Safety, and Extend the Life of Current Reactors

The current fleet of 104 nuclear power plants has reliably and economically contributed almost 20 percent of electricity generated in the United States over the past two decades. However, by

2030, even those current nuclear power plants that have received 20-year extensions from the NRC authorizing 60 years of life will begin reaching the end of their licensed periods of operation. Figure 8 shows projected nuclear energy contribution to domestic generating capacity from those plants that have already received 20-year license extensions. If current plants do not operate beyond 60 years, the total fraction of generated electricity from nuclear power could begin to decline, even with the addition of new nuclear-generating capacity.

Replacing the current fleet would require hundreds of billions of dollars. Replacement of this 100 GWe-generating capacity with traditional fossil plants would lead to significant increases in CO_2 emissions. Extending operating licenses beyond 60 to perhaps 80 years would enable existing plants to continue providing safe, clean and economic electricity without significant GHG emissions. The objective of this R&D objective is to provide a comprehensive technical basis for extending the life of today's LWRs that could be used to inform licensing and managing the long-term safe and economical operation.

Figure 8. Nuclear Capacity With and Without License Extensions



4.1.1 Challenges Facing the Current Fleet

The following are the major challenges facing the current fleet:

- Aging and degradation of system structures and components, such as reactor core internals, reactor pressure vessels, concrete, buried pipes, and cables.
- Fuel reliability and performance issues.
- Obsolete analog instrumentation and control technologies.

- Design and safety analysis tools based on 1980s vintage knowledge bases and computational capabilities.

Industry's economic incentive to meet these challenges in order to continue the safe and reliable operation of existing plants is tremendous. As such, federal activities undertaken in this area will be cost-shared with industry. Industry, working through EPRI or through the various owners' groups, will engage some of these problems directly. 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 government holds a great deal of theoretical, computational, and experimental expertise in nuclear R&D that is not available in industry. The benefits of assisting industry with R&D on life-extension apply not only to current plants but also to the next generation of reactor technologies still in development.

4.1.2 R&D Topics for Life Extension and Performance Improvement

The overall focus of the R&D activities will be to improve a power plant operator's ability to manage the effects of the aging of passive components and increase operational efficiency and economics. In selecting projects for federal investment, it is vital that due consideration be given not only to how each of the R&D activities support achievement of safety and economic sustainability for existing LWRs, but also to how the R&D results will be more broadly applicable to the next generation of reactor technologies. These activities should also be integrated with outside sources of information and parallel R&D programs in industry, the NRC, universities, and other laboratories, both domestic and international. Close coordination with the NRC as appropriate is needed to assure that R&D programs focus on issues relevant to licensing.

The following are R&D topics where NE will focus its efforts to help provide solutions to the challenges listed above, thereby helping enable reactor life extension beyond 60 years with improved performance. Progress on this long-term and high-risk–high-reward R&D, which supports the current nuclear power plant fleet, will provide the scientific underpinnings for plant owners to make billion-dollar investment decisions to prolong the economic lifetime of these assets. R&D findings will also inform improvements in the lifetime of future-generation reactor designs.

- *Nuclear Materials Aging and Degradation* – Develop a 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.
- *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 the development of high-performance, high-burnup fuels with improved safety, cladding, integrity, and economics.

- *Advanced Instrumentation, Information, and Control (II&C) System Technologies* – Research to address long-term aging and obsolescence of existing instrumentation and control technologies and to develop and test new technologies. Establishing a strategy to implement long-term modernization of II&C systems will be the focus of federal R&D, while industry will focus on the more immediate benefits of adapting existing digital technologies to current plants. NE will work with industry to develop advanced condition-monitoring technologies for reliable plant operation, improved understanding of physical methods of degradation, and the means to detect and characterize these processes.
- *Risk-Informed Safety Margin Characterization (RISMC)* – Bring together risk-informed, performance-based methodologies with fundamental scientific understanding of critical phenomenological conditions and deterministic predictions of nuclear plant performance to provide an integrated characterization of public safety margins in aging nuclear power plants. Such an approach will better characterize safety margins and should improve the reliability and efficiency of plant operations. RISMC will also be applicable to future generations of nuclear power plants.
- *Efficiency Improvement* – Improve the efficiency of the current fleet while maintaining excellent safety performance is one of the primary objectives of life extension. Power uprates have contributed to improving the current fleet's economic performance. This activity focuses on developing methodologies and scientific bases to enable more extended power uprates.
- *Advanced Modeling and Simulation Tools* – Conduct R&D needed to create a new set of modeling and simulation capabilities that will be used to better understand the safety performance of the aging reactor fleet. These tools will be fully three-dimensional, high-resolution, modeling integrated systems based on first-principle physics. To accomplish this, the modeling and simulation capabilities will have to be run on modern, highly parallel processing computer architectures.

The sustainability of light water reactors will benefit enormously from advanced modeling and simulation capabilities. The NE Modeling and Simulation Hub will integrate existing nuclear energy modeling and simulation capabilities with relevant capabilities developed by the Office of Science, the NNSA, and others. The results will leapfrog current technology to provide a multi-physics, multi-scale predictive capability that is a revolutionary improvement over conventional codes. A key challenge will be to adapt advanced computer science tools to an applications environment. The hub is intended to create a new state-of-the-art in an engineering-oriented multi-physics computational environment that can be used by a wide range of practitioners to conduct ultra-high fidelity predictive calculations of reactor performance.

4.1.3 Key Activities

The following chart outlines potential milestones and future national industry aims for this objective. It presents a distinction between near-term milestones toward which the NE R&D plan is designed to progress, represented as triangles, and longer-term potential outcomes that provide a framework for the milestones, shown as ovals. The milestone charts attempt to depict the stages of development so as not to leave a sense that new technologies can be immediately deployed at a commercial level. Not every milestone or potential outcome outlined in these charts represents actions that are within DOE's roles and responsibilities, and research paths will include many decision points that require choosing the most promising options for continued R&D. All DOE R&D activities will be evaluated and revisited regularly and modified as necessary through the budget process to ensure the portfolio reflects past progress and current priorities.

Although some smaller component or process "demonstration" activities are mentioned, these are largely field tests and other actions to provide proof or validation of system elements. They are not costly, large-scale demonstrations like NGNP. Any consideration to embark on such large-scale demonstrations will be the result of decision-making and budget development processes.

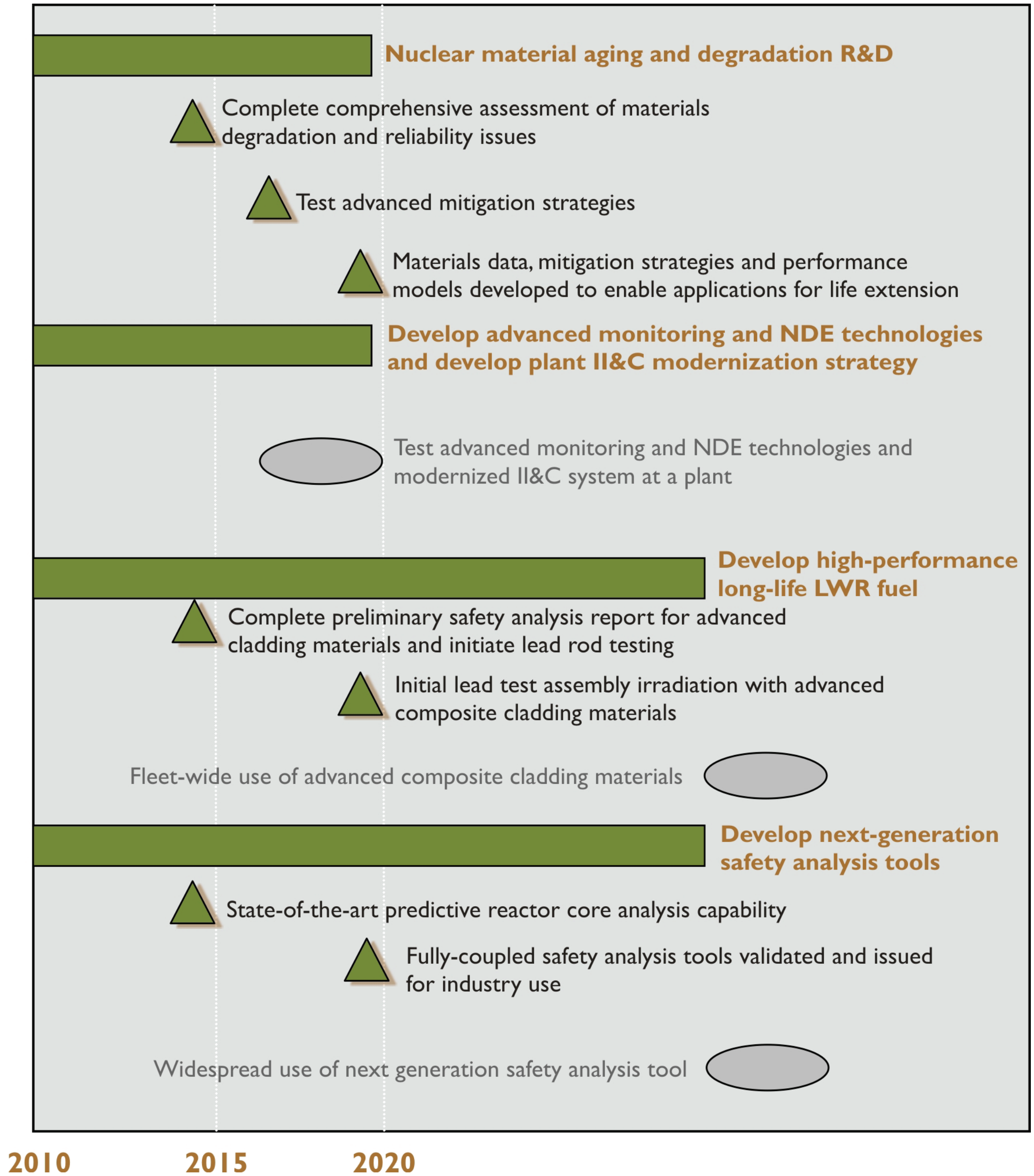
4.2 R&D Objective 2: Develop Improvements in the Affordability of New Reactors to Enable Nuclear Energy to Help Meet the Administration's Energy Security and Climate Change Goals

The previous 30-year U.S. hiatus in new nuclear plant orders presents a number of immediate hurdles for the construction of new plant designs. Utility investors are still wary of the new regulatory framework, which will not be fully exercised until the first new plant begins operation. There are also concerns regarding the large capital costs of plants and associated difficulties in financing their construction.

NE's objective is to assist in the revitalization of the U.S. industry through R&D. By advancing technologies through R&D, NE can help accelerate deployment of new plants in the short term, support development of advanced concepts for the medium term, and promote design of revolutionary systems for the long term. Work will be done in partnership with industry to the maximum extent possible. Elements of NE's strategy in this area include:

- Assist industry to improve light water reactors using existing technologies and designs.
- Explore advanced LWR designs with improved performance.
- Research and develop small modular reactors that have the potential to achieve lower proliferation risks and more simplified construction than other designs.

Figure 9. Key Activities for R&D Objective 1



- In the longer term, support R&D of advanced reactor technologies that offer lower costs and waste generation.
- Investigate revolutionary reactor concepts that promise to significantly reduce costs and improve performance of nuclear energy.
- Support R&D of nuclear energy's potential to displace fossil fuels in the production of process heat.

Implementing this strategy will require that DOE work in partnership with the nuclear industry and, to the degree appropriate, the NRC.

4.2.1 Challenges Facing New Reactor Deployments

There are several new plant designs, often referred to as Gen III+, that have been certified or are being reviewed by the NRC for immediate deployment in the United States. Potential owners of these Gen III+ plants must overcome serious financial hurdles. All near-term options for new plants are large LWR designs that are optimized for baseload electricity production. Smaller reactors that could be deployed in modules might help reduce the up-front capital costs associated with large plants by allowing utilities to incrementally "step up" to larger electrical capacities while generating revenue and repaying initial debts. New reactor designs beyond Gen III+ may also be deployed. In many cases, new technologies will be needed to enable these new designs, and innovative features will need to be fully demonstrated. Certain aspects of the regulatory framework need to accommodate these new technologies and design features, especially for designs that differ significantly from the large LWR plants in operation today. Economic competitiveness will remain the major hurdle for all novel concepts, including smaller reactors and reactors for non-electric applications.

During the 30-year hiatus from new plant orders in the United States, some nations have continued to grow their nuclear industries. As a result, some other countries have advanced the state-of-the art in manufacturing of nuclear plant components and have made progress in applying more efficient construction techniques. The domestic industry can learn from these international experiences.

4.2.2 R&D Topics for Enabling New Builds

In the United States, it is the responsibility of industry to design, construct, and operate commercial nuclear power plants. However, DOE has statutory authority under the Atomic Energy Act to promote and support nuclear energy technologies for commercial applications. In general, appropriate government roles include researching high-potential technologies beyond the investment horizon of industry and also reducing the technical risks of new technologies. In the case of new commercial reactor designs, potential areas of NE involvement could include:

- Enabling new technologies to be inserted into emerging and future designs by providing access to unique laboratory resources for new technology development and, where appropriate, demonstration.
- Working through the laboratories and universities to provide unique expertise and facilities to industry for R&D in the areas of:
  - Innovative concepts and advanced technologies.
  - Fundamental phenomena and performance data.
  - Advanced modeling and simulation capabilities.

- New technology testing and, if appropriate, demonstration.
- Advanced manufacturing methods.

Representative R&D activities that support each of the roles stated above are presented below. The level of DOE investment relative to industry investment will vary across the spectrum of these activities, with a generally increasing trend in DOE investment for longer-term activities. Finally, there is potential to leverage and amplify effective U.S. R&D through collaborations with other nations through multilateral and bilateral agreements including the Generation IV International Forum, which is investigating multiple advanced reactor concepts. DOE is also a participant in OECD/NEA and IAEA initiatives that bear directly on the development and deployment of new reactor systems.

4.2.2.1 Accelerate Advancements in LWR Designs

Given the maturity of the Gen III+ LWR designs, R&D needs are necessarily limited, as the design of these plants is well underway or already complete, some of them are being built overseas, and many have been ordered in the United States and elsewhere. Nevertheless the R&D topics identified jointly with industry for R&D Objective 1 are all applicable to this task.

R&D of more advanced LWR concepts, including novel materials, fuels, and innovative system architectures, is a legitimate role for DOE and its laboratories in partnership with industry. This R&D will help address long-term trends in the capital cost of large LWR plants. Much of this research is also expected to be applicable to non-LWR technologies.

4.2.2.2 Accelerate the Development of SMR Designs

Several U.S.-based companies are seeking to bring new SMR designs to market, including some with potential for deployment within the next decade. Many of these designs use well-established light-water coolant technology to the fullest extent possible to shorten the timeline for deployment. As such, R&D needs for these technologies are minimal. However, these designs may include new features, such as the use of an integral primary system reactor (IPSR) design and components that are not currently used in commercial plants, such as helical-coil steam generators. DOE will hold workshops with LWR SMR vendors and suppliers, potential utility customers, national laboratory and university researchers, DOE, NRC, and other stakeholders to identify potential priorities to enable their commercialization and development. The Administration will evaluate potential priorities in the context of the appropriate federal role to identify the most cost-effective, efficient, and appropriate mechanisms to support further development.

SMR designs that are not based on LWR technology have the potential to offer added functionality and affordability. In this area, NE will support a range of R&D activities, such as basic physics and materials research and testing, state-of-the-art computer modeling and simulation of reactor systems and components, probabilistic risk analyses of innovative safety designs and features, and other development activities that are necessary to establish the concept's feasibility for future deployment. For SMRs that are based on concepts with lower levels of technical maturity, the Department will first seek to establish the R&D activities necessary to prove and advance innovative reactor technologies and concepts. The Department will support R&D activities to develop and prove the proposed design concepts. Emphasis will be on advanced reactor technologies that offer simplified operation and maintenance for distributed power and load-following applications and increased proliferation resistance and security.

Activities will focus on showing that SMRs provide an innovative reactor technology that is capable of achieving electricity generation and performance objectives that meet market demands and are comparable, in both safety and economics, to the current large baseload nuclear power plants.

NE may also support the development of new/revised nuclear industry codes and standards necessary to support licensing and commercialization of innovative designs and, consistent with NRC guidance and regulations, identify activities for DOE funding to enable SMR licensing for deployment in the United States.

4.2.2.3 Develop Advanced Reactor Technologies

Future-generation reactor systems will employ advanced technologies and designs to improve performance beyond what is currently attainable. Moving beyond LWR technology, for example, may enable reactors to operate at higher temperatures and improved efficiencies resulting in improved economics. Advanced materials may make reactors easier to construct while also enabling better performance. Improved designs utilizing these advances could reduce the capital costs associated with the current set of reactors being considered. Two prominent examples of advanced reactor technologies worthy of further investigation include:

- The high temperature gas-cooled reactor (HTGR), a graphite moderated thermal-spectrum reactor operated at high temperature for efficient generation of electricity and heat delivery for non-electric applications.
- Fast-spectrum reactors that could provide options for future fuel cycle management and could also be used for electricity generation (see R&D Objective 3).

The U.S. is also a member of the Generation IV International Forum, which is investigating additional advanced reactor systems that employ comparatively less mature technologies while offering significant potential for performance, safety, and economic advances.

Key areas of R&D for future systems could include:

- High-performance materials compatible with the proposed coolant types and capable of extended service at elevated temperatures.

- New fuels and cladding capable of irradiation to high burnup.
- Advanced heat delivery and energy conversion systems for increased efficiency of electricity production.
- Advanced modeling and simulation tools that can reduce uncertainties in predicted performance, improve characterization of uncertainties, and streamline the design of new reactor technologies.
- Systems design for revolutionary new reactor concepts.

4.2.2.4 Develop Technologies Consistent with Both Electric and Non-Electric Applications

An additional potential benefit from nuclear power could be realized through new plant designs that would be used to displace GHG-emitting fuels in the industrial sector while also generating electricity. Some industrial process heat applications require temperatures substantially above the 300–325°C outlet temperature of today's LWRs. Petroleum refining, for example, requires temperatures in the range of 250-500°C while steam reforming of natural gas requires process heat in the 500-900°C range. Achieving higher output temperatures requires switching to a new coolant technology such as gas, liquid metal, or molten salt. With these coolants, it may be possible to achieve outlet temperatures ranging from over 500°C for liquid metal coolants to over 900°C for helium or molten salt coolants. Achieving these temperatures, however, will require the development and qualification of fuels, materials and instrumentation, particularly at the higher end of the temperature range. Also, the use of coolants other than water will require the development of a variety of plant components and systems such as electromagnetic pumps for liquid metal coolants, compact heat exchangers for gas coolants, and chemical purification systems for molten salt coolants. These coolants will also require the development of new licensing requirements and codes and standards. While the economic market for dedicated process heat from nuclear power may be limited, reactors that could produce electricity as well as industrial process heat may have broader applications.

Key areas of R&D for future systems could include:

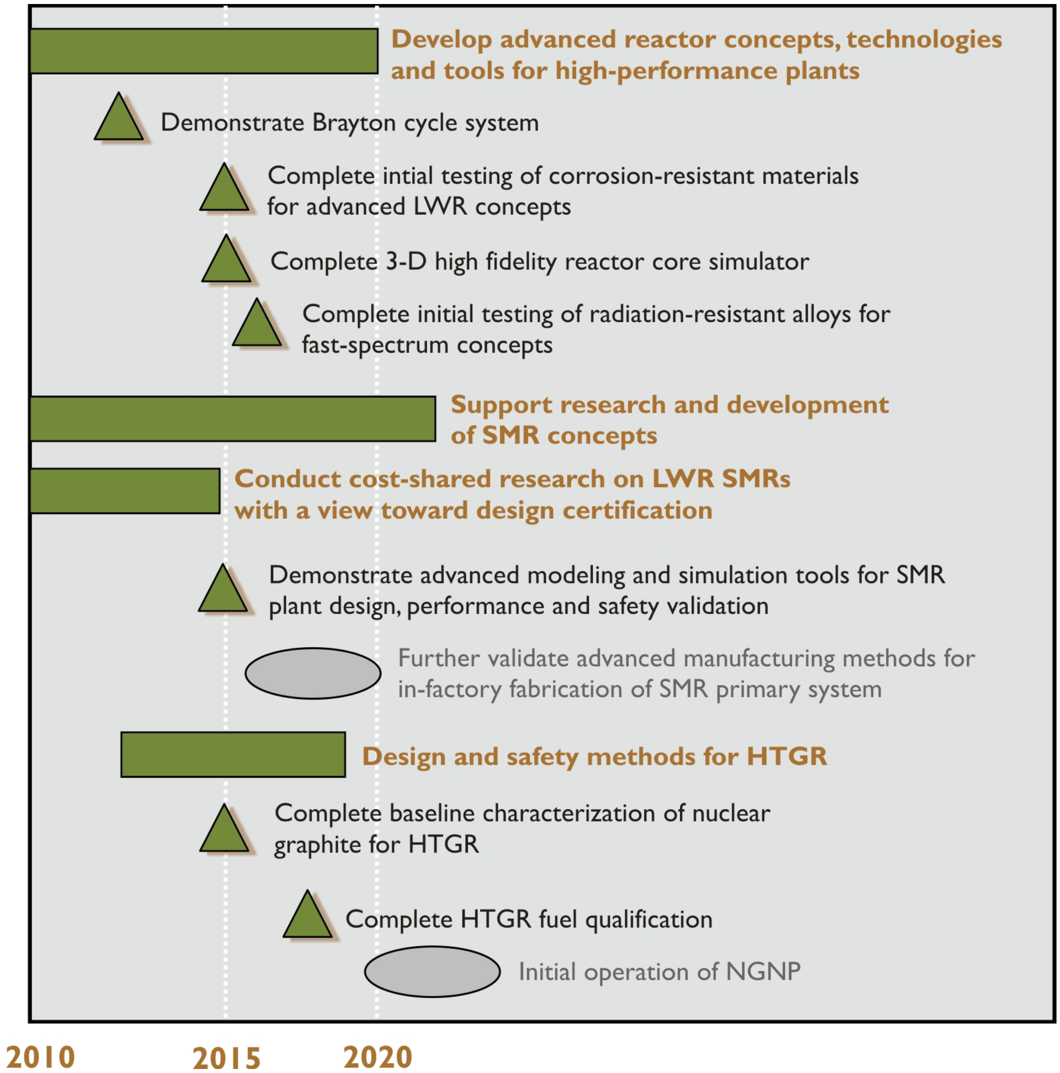
- *Develop interfacing heat transport systems* – Supply process heat with minimal losses to industrial users within several kilometers of the reactor.
- *Develop modeling and simulation capabilities* – These tools would improve understanding of interactions between the kinetics of the various reactor types and the kinetics of the chemical plants or refineries, which they would serve. Modeling may also be used to understand the long-term performance of catalysts and solid-oxide cells at an atomistic level.

4.2.3 Key Activities

The following chart outlines potential milestones and future national industry aims for this objective. It presents a distinction between near-term milestones toward which the NE R&D plan is designed to progress, represented as triangles, and longer-term potential outcomes that provide a framework for the milestones, shown as ovals. The milestone charts attempt to depict the stages of development so as not to leave a sense that new technologies can be immediately deployed at a commercial level. Not every milestone or potential outcome outlined in these charts represents actions that are within DOE's roles and responsibilities, and research paths will include many decision points that require choosing the most promising options for continued R&D. All DOE R&D activities will be evaluated and revisited regularly and modified as necessary through the budget process to ensure the portfolio reflects past progress and current priorities.

Although some smaller component or process "demonstration" activities are mentioned, these are largely field tests and other actions to provide proof or validation of system elements. They are not costly, large-scale demonstrations like NGNP. Any consideration to embark on such large-scale demonstrations will be the result of decision-making and budget development processes.

Figure 10. Key Activities for R&D Objective 2

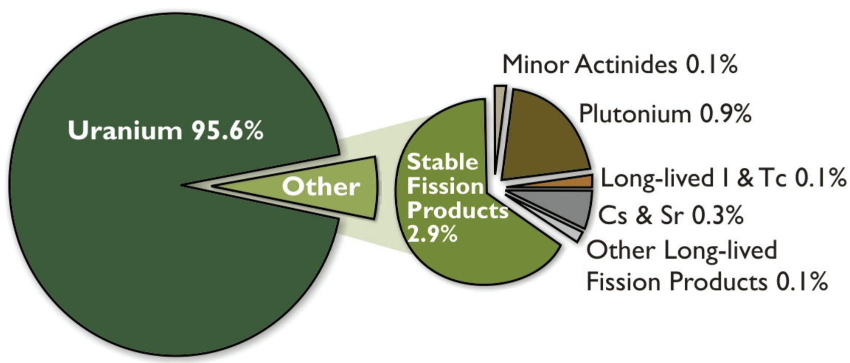


4.3 R&D Objective 3: Develop Sustainable Nuclear Fuel Cycles

Sustainable fuel cycle options are those that improve uranium resource utilization, maximize energy generation, minimize waste generation, improve safety, and limit proliferation risk. The principal challenge for the government in this objective 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. The Commission will review policies for managing the back end of the fuel cycle including alternatives for the storage, processing, and disposal of civilian and defense used nuclear fuel and nuclear waste. All research and development activities and plans outlined here will be revisited and revised as needed to reflect the Commission's findings and associated Administration decisions.

An expansion of nuclear power in the United States will result in a growth of the used nuclear fuel inventories. The Nuclear Waste Policy Act of 1982 gave the U.S. government the mission to safely manage the used fuel from these nuclear power plants. Research and development of sustainable nuclear fuel cycles and waste management activities is important to support the expansion of nuclear energy. Some of the attributes of the sustainable fuel cycle, including waste management and disposal technologies, include the responsible use of natural resources, preservation of the environment for future generations, safety, security, public acceptance, and cost effectiveness.

Figure 11. Constituents of Used LWR Fuel



The constituents of current used nuclear fuel (UNF) after discharge from LWRs are shown in Figure 11. As this figure shows, the vast majority of the material in the used fuel is uranium that is generally unchanged from the fuel that went into the reactor to produce energy. Uranium is considered an element in the category called "actinides," along with the "transuranic" elements of plutonium and the "minor" actinides: neptunium, americium, and curium, principally. These elements generally are long-lived and must be isolated from the environment for tens or hundreds of thousands of years. Actinides are also of interest because uranium and plutonium could be recycled to produce more energy in reactors, as could the minor actinides in fast-spectrum reactors. The remaining class of elements in the used fuel is fission products, many of which are stable and pose little concern. The short-lived fission products – primarily cesium and strontium – generate most of the hazard for the first hundreds of years of disposal. There are also fission products, notably iodine and technetium, that last for hundreds of thousands of years and must be isolated from the environment.

NE will research and develop nuclear fuel and waste management technologies that will enable a safe, secure, and economic fuel cycle. The NE R&D strategy will be to investigate the technical challenges that would be encountered in each of three potential methods and perform R&D within each of these tracks:

- *Once-Through* – Nuclear fuel makes a single pass through a reactor after which the used fuel is removed, stored for some period of time, and then directly disposed in a geologic repository for long-term isolation from the environment. The used fuel will not undergo any sort of treatment to alter the waste form prior to disposal in this approach, eliminating the need for separations technologies that may pose proliferation concerns. Less than one percent of the mined uranium is utilized in the present once-through fuel cycle.

- *Modified Open Cycle* – The goal of this approach is to develop fuel for use in reactors that can increase utilization of the fuel resource and reduce the quantity of actinides that would be disposed in used fuel. This strategy is "modified" in that some limited separations and fuel processing technologies are applied to the used LWR fuel to create fuels that enable the extraction of much more energy from the same mass of material and accomplish waste management goals.
- *Full Recycle* – In a full recycle strategy, all of the actinides important for waste management are recycled in thermal- or fast-spectrum systems to reduce the radiotoxicity of the waste placed in a geologic repository while more fully utilizing uranium resources. In a full recycle system, only those elements that are considered to be waste (primarily the fission products) are intended for disposal, not used fuel. Implementing this system will require extensive use of separation technologies and the likely deployment of new reactors or other systems capable of transmuting actinides.

The R&D approach will be to understand what can be accomplished in each of these strategies and then to develop the promising technologies to maximize their potential. One element that crosscuts all potential approaches is disposal and R&D activities will include a focus on those technologies. Additionally, storage will be an important part of any strategy, and R&D will be needed to assess the performance of storage technologies with higher-burnup used LWR fuels, as well as any potential new fuels that may be deployed in the future.

The discussion above is primarily focused on the uranium fuel cycle that is the norm throughout the world. An alternative that could be considered would be the use of thorium to replace at least part of the uranium in the system. Thorium could be used as part of a once-through, modified open, or full recycle fuel cycle. The appeal of thorium is two-fold. First, thorium is more abundant in nature than uranium and can be used to extend or replace uranium in the fuel cycle. Second, the use of thorium enables reduced production of transuranic elements that end up in used fuel. However, there are still technical and economic challenges facing thorium-based fuels. Thus some R&D to address related challenges may be considered. Significant R&D in the use of thorium has been performed previously in the United States and is currently being considered in other parts of the world (particularly in India).

Unlike R&D Objectives 1 and 2, management of UNF and development of fuel cycle technologies are primarily the government's responsibilities because the government is legally responsible for UNF. Thus, the necessary research, development, and demonstration, if appropriate, will be led primarily by the government. However, early and continuous industrial involvement is important because any technologies that are developed will ultimately be implemented by the commercial entities.

4.3.1 Major Challenges Associated with Fuel Cycle Options

Each of the potential fuel cycle strategies faces challenges, some of which may be shared with other approaches. Similarly, the R&D needed to overcome these challenges may support more than one strategy.

- *Once-Through* – Improving the sustainability of a once-through approach to used fuel management begins with increasing the burnup of the fuel – the amount of energy that can be extracted from fuel in the reactor – which may also have the effect of consuming more actinides in the fuel, leaving less to be disposed. Increasing the burnup of a fuel will require ensuring that both the fuel itself and the structural material designed to keep it in place in the reactor will be able to withstand extended irradiation in the reactor and maintain its integrity when being stored after removal. Deploying advanced fuels will require that they first undergo a qualification process that can take a great deal of time, as researchers must irradiate and conduct examinations on test samples to assure their performance. Also, fuels that are notably different from those currently used in LWRs may drive changes in the fuel processing infrastructure that has evolved to meet current needs. To the extent that the deployed once-through fuel cycle is built upon enriched uranium fuels, the proliferation concerns associated with enrichment technologies will need to be addressed.
- *Modified Open Cycle* – A modified open cycle faces some of the same challenges as the once-through, along with some encountered in a full recycle approach. The modified open cycle introduces the possibility of a used fuel separations step to enable more options for producing fuels. This flexibility enables the inclusion of transuranic elements – notably plutonium – at concentrations capable of supporting ultra-high burnup, along with the attendant difficulties of developing these fuels. The challenges of developing high-burnup fuels discussed in the previous paragraph are applicable to this strategy. The use of separations technology to prepare the ultra-high-burnup fuel introduces difficulties in separations as well as managing proliferation concerns. A key element of this fuel cycle is the likely need to introduce advanced reactors that can utilize these new fuels. The overarching challenge in making a modified open cycle worthwhile is to determine if the improvement in fuel resource utilization and in the waste to be disposed is sufficient to justify the additional complication, potential proliferation concerns, and expense this approach would entail.
- *Full Recycle* – In a full recycle approach, used fuel is not directly disposed in a repository; rather, those elements of the used fuel that are deemed appropriate for recycling are reintroduced into reactors or other systems while the remaining elements are stabilized in a waste form and disposed. This strategy offers the potential of waste forms that pose far less long-term concern, although the approach would require overcoming not only technical challenges but also economic, proliferation, and public perception concerns. This system would rely on multiple separations processes that must minimize process losses and

waste generation while addressing proliferation concerns. Furthermore, fuels must be developed that will allow for the inclusion of all of those elements that are to be recycled in concentrations that vary over time. This is a central tradeoff in the full recycle approach: the more elements that are recycled, the better the waste form will be; however, more separation of elements in the fuel increases the technical and other challenges. Elements that are recycled must be capable of transmutation in a system – likely, but not necessarily, a fast reactor – to eventually eliminate them. In order for a full recycle strategy to be considered, the waste benefits and improved resource utilization produced by such a system must outweigh the complication, expense and potential proliferation concerns associated with it.

4.3.2 R&D for Sustainable Fuel Cycle Options

There are major R&D needs to understand how best to overcome the challenges posed by each of the fuel cycle approaches being considered. The potential R&D efforts that DOE would undertake would have a long-term view and would be science-based. It would take considerable time before the issues in the modified open and the full recycle alternatives would be overcome. Many R&D areas will be applicable to multiple strategies. Prior to beginning major R&D work in these areas, analyses will be performed to gauge the likely value of the efforts.

- *Fuel Resource Exploration and Mining* – The availability of fuel resources for each potential fuel cycle and reactor deployment scenario must be understood. Extended use of nuclear power may drive improvements in defining resource availability and on fuel resource exploration and mining. Primarily, this is work that the private sector would undertake, and how and when this would occur would depend on price and other market conditions. This is most relevant for a once-through approach, but even modified open cycles and full recycle systems may require comparable levels of natural sources of fuel for the foreseeable future. Most appropriate for federal involvement in this area would be R&D to support investigation of long-term, "game-changing" approaches such as recovering uranium from seawater.
- *Used Fuel Disposition* – All radioactive wastes generated by existing and future fuel cycles will need to be safely stored, transported, and disposed. This R&D will identify options for performing these functions, including research into disposal in a variety of geologic environments. This R&D will consider used fuel and high-level waste inventories arising from the current reactor fleet and any additional new builds, including the potential for changing used fuel characteristics from enhanced operations (*e.g.*, increased fuel burnup) and the projected inventories from advanced reactor and fuel cycle systems (*e.g.*, HTRs and SMRs). This research is important to all of the potential fuel cycle approaches.
- *Reduce Transuranic Production In Reactors* – One thrust in developing sustainable fuel cycles will be the exploration of nuclear fuels and reactors that significantly reduce the long-lived actinide content of the used fuel per MWh of energy produced. Exploration of

avenues both to reduce actinide production in present and near-term LWRs and to develop future non-LWR systems that produce lower actinide inventories in their used fuel is important. This research area is central to developing the high burnup fuels that will improve the attractiveness of a once-through or modified open fuel cycle.

- *Separation and Partitioning* – The development of processes to recycle used fuel is needed, as well as an evaluation of the feasibility and risks associated with recycling. The objective is to use a predictive approach to evaluate separation chemistry and processes to achieve the desired performance in terms of product purity, environmental impact, and losses. Though not applicable in a once-through system, this topic would be germane to a modified open cycle approach and central to a full recycle strategy.
- *Waste Forms* – It is necessary to develop understanding of waste form behavior over time to help inform decisions on recycle and disposal options. This understanding must extend over a broad range of potential waste chemistry and disposal environments so waste forms can be adapted and implemented when specific repository conditions are known. This R&D area may be somewhat relevant to strategies that rely on the direct disposal of certain used fuels (such as disposal of high-temperature gas reactor fuels) but the development of improved waste forms is a key component in enabling a full recycle strategy to achieve its promise.
- *Fuel Forms* – The science-based approach will combine theory, experiments, and multi-scale modeling and simulation aimed at a fundamental understanding of the fuel fabrication processes and fuel and clad performance under irradiation. The objective is to use a predictive approach to design future fuels and cladding to enable the development of ultra-high-burnup fuels in a modified open cycle and to demonstrate the inclusion of recovered actinides in transmutation fuels under a full recycle approach. In the early phases of the program, the major fuel fabrication activities include development of innovative processes to enhance the process efficiency and to improve the control of fuel microstructure for enhanced performance, including tailored fuel forms designed to limit excess actinides across the complex.
- *Material Reuse* – The research will focus primarily on recovered uranium for reuse in reactors to obviate the need to dispose of this material once separated from the rest of the used fuel. The critical areas that require process or equipment modifications will be identified, and technologies will be developed to enable the reuse (and in some cases the re-enrichment) of recycled uranium. Efforts will also investigate the potential recycling and reuse of other constituents of used fuel, such as the zirconium cladding, that are potentially useful but not currently being considered by industry because of uncertainties about material characteristics.
- *Transmutation Systems* – Transmutation is a process to change the characteristics of waste by turning recycled elements into elements with more desirable disposal characteristics. While the focus of most recent work has been on fast-spectrum transmutation reactors, thermal-spectrum transmutation can offer some waste management benefits. R&D would

focus on broadly applicable issues including areas such as materials and energy conversion. In addition, studies may be conducted to review the technical and economic aspects of external neutron source-driven transmutation systems to inform whether future investigation in this approach is warranted.

4.3.3 Key Activities

NE's science-based R&D program will provide a more complete understanding of the underlying science supporting the development of advanced fuel cycle and waste management technologies and, therefore, help provide a sound basis for future decision making. The program will also conduct scientific research and technology development to enable storage, transportation, and disposal of used nuclear fuel and all radioactive wastes generated by existing and future nuclear fuel cycles. Over the next decade, the R&D program will mainly be geared to ensuring that the needed breakthroughs and advancements are available and ready when needed. Examples of such technologies would include ultra-deep-burn LWR, HTR, or fast reactor fuel; reactor technologies to support optimized once-through fuel cycles; and advanced fast reactor concepts to support closed fuel cycles. These technologies would encompass all of the known and anticipated advances that could be expected to be available in areas including materials, design methods, components, and energy conversion.

In keeping with Secretary Chu's vision of using science to provide technological breakthroughs to solve America's grand challenges, the program will include long-term, high-risk–high-payoff R&D. This part of the program will seek revolutionary and transformational breakthroughs in systems, materials and components of the fuel cycle that can better meet the program's objectives. Examples of this could include novel reactor concepts such as molten-salt fuel reactors or thorium fuel cycles. Thus while evolutionary advancements are being made, revolutionary advancements will also be pursued such that, if successful, they could replace all or part of existing or near-term technologies. The roadmap includes milestones for selection of technologies as the program matures. Each approach has a set of reference technologies associated with these milestones:

- *Once-Through* – Develop higher-burnup fuel for LWRs.
- *Modified Open Cycle* – Develop ultra-high-burnup fuel for high-temperature gas-cooled reactors using transuranic elements from used LWR fuel. It is assumed that the NGNP or a comparable reactor will be available for fuel testing. Alternative approaches may require access to a fast-spectrum test reactor and nuclear fuel research capabilities.
- *Full Recycle* – Develop technologies to allow repeated recycling of transuranic elements in fast-spectrum reactors. The initial fuel for the fast reactors will come from separated used LWR fuel with successive reloads made from used fast reactor fuel. Access to a fast-spectrum test reactor will be essential for this research, as will nuclear fuel research capabilities.

The following chart outlines potential milestones and future national industry aims for this objective. It presents a distinction between near-term milestones toward which the NE R&D plan is designed to progress, represented as triangles, and longer-term potential outcomes that provide a framework for the milestones, shown as ovals. The milestone charts attempt to depict the stages of development so as not to leave a sense that new technologies can be immediately deployed at a commercial level. Not every milestone or potential outcome outlined in these charts represents actions that are within DOE's roles and responsibilities, and research paths will include many decision points that require choosing the most promising options for continued R&D. All DOE R&D activities will be evaluated and revisited regularly and modified as necessary through the budget process to ensure the portfolio reflects past progress and current priorities.

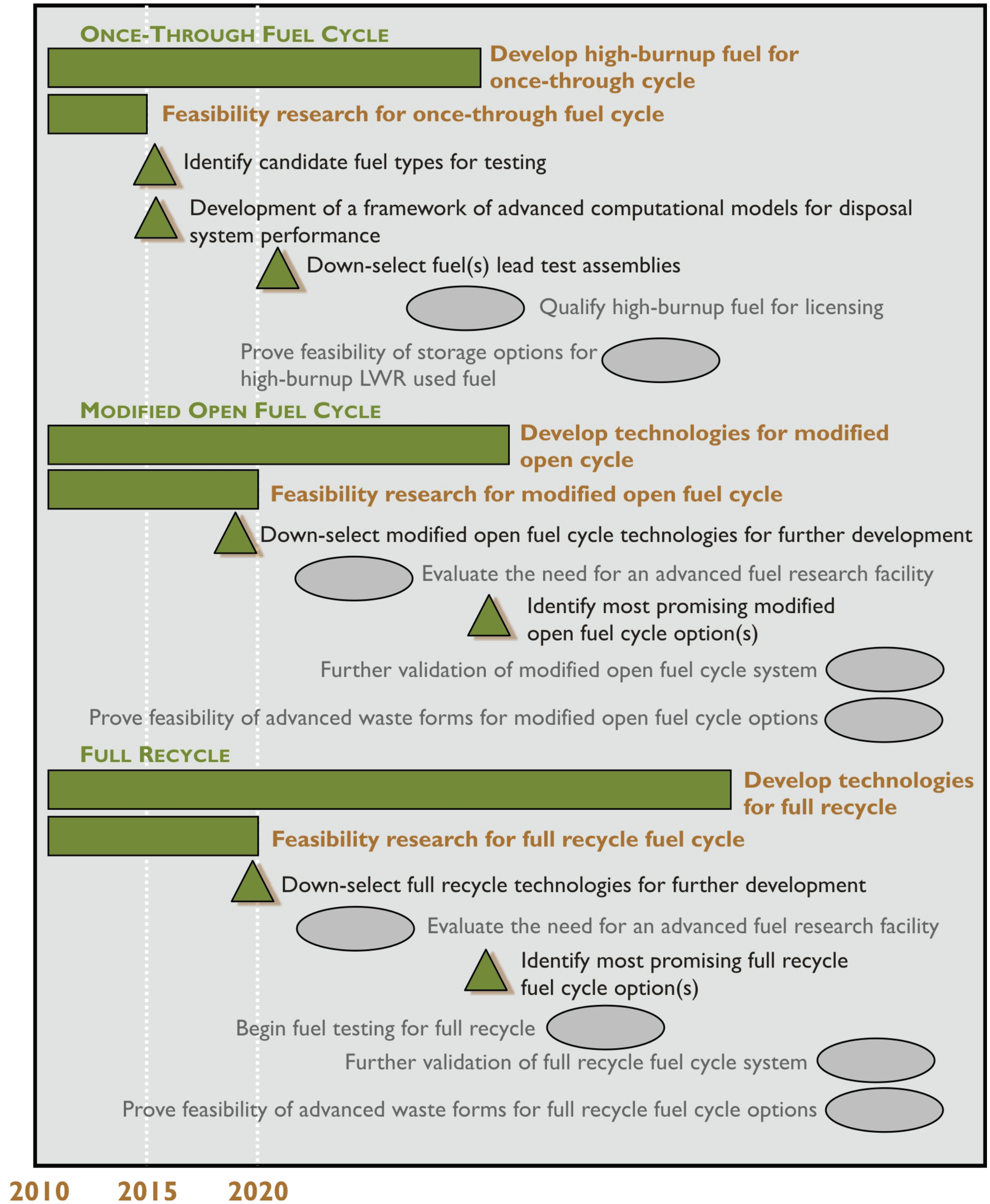
Although some smaller component or process "demonstration" activities are mentioned, these are largely field tests and other actions to provide proof or validation of system elements. They are not costly, large-scale demonstrations like NGNP. Any consideration to embark on such large-scale demonstrations will be the result of decision-making and budget development processes.

4.4 R&D Objective 4: Understanding and Minimizing the Risks of Nuclear Proliferation and Terrorism

The final R&D objective for nuclear energy is to enable secure nuclear energy expansion by developing and demonstrating options that limit proliferation and physical security risks associated with nuclear power while also achieving economic, public health and safety, and environmental goals. These risks include not only the possibility that nations may attempt to use nuclear technologies in pursuit of a nuclear weapon, but also the concern that terrorists might seek to steal material that could be used in a nuclear explosive device. This requires NE advocacy for, and participation in, an integrated program to develop technologies, frameworks, and policy options for the future nuclear enterprise, cutting across all aspects of the fuel cycle.

The United States has extensive experience protecting nuclear materials, from the weapons program that has produced significant quantities of plutonium-239 and highly enriched uranium, to 104 commercial reactors in the U.S. today that handle, use, and store nuclear materials. Internationally, the U.S. has also contributed extensively to the development of technologies now used in the application of international safeguards to monitor used fuel recycling activities in England, France, and Japan. Going forward, safeguards and physical security will become even more integral components in the domestic and global expansion of nuclear power, including the development of future fuel cycle and reactor technologies that further increase the barriers against proliferation and nuclear terrorism.

Figure 12. Key Activities for R&D Objective 3



An integrated U.S. safeguards program provides an opportunity to design improved safeguards and physical security directly into the planning and deployment of new energy systems and fuel cycle facilities. Incorporating safeguards and physical security into the early design phase for new facilities will allow the international community to monitor and verify nuclear material more effectively and efficiently.

DOE has three programs that are collaborating to address safeguards and nonproliferation challenges. The NE Fuel Cycle R&D Materials Protection, Accounting, and Control for Transmutation (MPACT) campaign develops advanced nuclear material management technologies and methods in support of the future domestic U.S. nuclear fuel cycle. The Next Generation Safeguards Initiative (NGSI) within the NNSA Office of Nonproliferation and International Security is designed to leverage U.S personnel, technology, and R&D to add new capacity and significantly strengthen international nuclear safeguards. The third program, the NNSA Office of Nonproliferation Research and Development's Global Nuclear Safeguards R&D Program, whose mission is to support long-term nonproliferation R&D, rounds out the U.S. safeguards R&D efforts for nuclear energy. The work described in this section reflects NE's aspect of the integrated safeguards and nonproliferation work being performed within DOE. This work will be performed in direct collaboration or close coordination with NNSA activities.

In addition to addressing technical safeguards R&D needs, successful integration of these programs would develop revolutionary new tools for proliferation risk assessments and subsequent optimization of advanced nuclear energy systems from nonproliferation and physical security perspectives. The ultimate goal of this crosscutting effort would be to develop and use new analytical tools that could revolutionize our ability to compare proliferation and physical security risk of nuclear energy system options, including aspects of policy and human behavior as well as technical attributes.

As civilian nuclear power expands across the globe, it becomes more important that high standards of safety and security be implemented around the world. Looking only at how the R&D can improve nuclear technologies without considering who is to use these technologies, and the national and international frameworks under which they are operating, will provide an overly narrow perspective of proliferation risks. NE, in cooperation with other DOE offices and national agencies and in partnership and collaboration with other nations, must implement collaborative programs with civilian nuclear power programs in both experienced and inexperienced states in order to minimize proliferation and physical security risks, enhance reactor safety, maximize resource utilization through cooperative R&D, and encourage methods to minimize the dispersion of enrichment and reprocessing facilities worldwide.

4.4.1 Challenges

A key challenge facing the expanded use of nuclear energy and associated fuel cycles is minimizing the potential for the misuse of the technology and materials for weapons purposes. International treaties such as the Nuclear Nonproliferation Treaty, combined with transparency in the use of technology and materials, provide the basic building blocks to assure the peaceful use of nuclear energy. Fuel cycle infrastructure built upon these tenets while enabling the economic provision of fuel cycle services can help prevent the spread of sensitive nuclear technology and materials.

Today's key challenges are to take the wealth of knowledge and experience that exists within the international safeguards and physical security communities and to deploy advanced, affordable techniques to immediately detect the diversion of nuclear materials or the modification of systems. The key technical challenges that must be addressed include:

- Incorporation of nuclear safeguards and physical security technology into designs for fuel cycle facilities, advanced fast reactors, and associated nuclear materials storage and transportation systems.
- Development of proliferation risk assessment methodologies and tools that allow for an integrated view of fuel cycle options to be studied, optimized, and compared.
- Development of advanced containment and surveillance, smart safeguards information management systems, nuclear facility use-control systems, and next-generation nondestructive analysis and process-monitoring systems.
- R&D of advanced material tracking methodologies, process-control technologies, and plant engineering.
- Remote sensing, environmental sampling, and forensic verification methods.

Addressing these challenges will enable the use and expansion of nuclear energy for peaceful purposes to proceed in a safe and secure manner.

4.4.2 R&D for Understanding and Minimizing the Risks of Nuclear Proliferation and Terrorism

Some potential R&D areas for Objective 4 are:

- *Proliferation Risk Assessments* – Any fuel cycle technologies deployed in the U.S. must be considered in light of how other nations might choose to incorporate them into their own nuclear enterprises. Towards this end, it is important for NE to develop a means of understanding how these new technologies would be viewed by other countries in the context of their national goals. This research effort would develop the tools and approaches for understanding, limiting, and managing the risks of nation-state proliferation and physical security for fuel cycle options. NE will focus on assessments required to inform domestic fuel cycle technology and system option development. These analyses would complement those assessments performed by NNSA to evaluate nation-state proliferation and the international nonproliferation regime. Taken in conjunction, these comprehensive proliferation risk assessments will provide important information for discussions and decisions regarding fuel cycle options. These assessments will:
  - Exploit science-based approaches, to the extent possible, for analyzing difficult-to-quantify proliferation risk factors or indicators (e.g., capabilities, motivations, and intentions); address issues identified in several National Academy of Sciences studies

related to risk assessment; and leverage current state-of-the-art academic social science research in this field.

- Integrate the diverse decision factors (including economics, public health and safety, environmental benefits, and proliferation and terrorism risk reduction) for different fuel cycle options to understand the tradeoffs and potential synergies between these decision criteria.
- Apply these tools to study nuclear energy system options, and display the results in a useful format for decision makers.

- *Safeguards and Physical Security Technologies and Systems* – The NE focus is on the development of safeguards technologies and integrated systems for current and potential future domestic fuel cycle options. These technologies and systems contribute significantly to limiting proliferation and physical security risks while also achieving economic, public health and safety, and environmental goals. This requires that these activities be performed in an integrated program with the fuel cycle technology development activities. Opportunities exist to collaborate with other organizations (e.g. NNSA, the Department of Homeland Security, the Department of Defense) and will be utilized. NNSA will be responsible for evaluating the nation-state proliferation risks of deploying new fuel cycle technologies – particularly recycling technologies – outside of the United States.
    - <u>Advanced Instrumentation</u> – Many advanced fuel cycle processes, such as advanced aqueous reprocessing, electrochemical separations, and recycle fuel fabrication pose new challenges for safeguards and nuclear material management. The safeguards state-of-the-art will be advanced through a developmental program to improve the precision, speed, sampling methods, and scope of nuclear process monitoring and accountancy measurements, and innovative approaches for containment and surveillance. This effort supports the development of advanced safeguards instrumentation such as active interrogation methods based on neutron and photon drivers and advanced passive detectors, such as ultra-high resolution spectrometer and neutron multiplicity counting. Additionally, existing nuclear data is evaluated for the identification of gaps or needed improvements.
    - <u>Advanced Concepts and Integration</u> – Early integration of safeguards concepts into nuclear facility design is optimal to meet U.S. and international standards with minimum impact on operations. This requires development of a framework to codify the safeguards-by-design concept, applicable for both international safeguards and physical security for U.S. fuel cycle facilities. It also includes the evaluation of material attractiveness of relevant fuel cycle materials. A monitoring and control system must be developed that is secure and can rapidly authenticate and investigate summary and raw data to unequivocally distinguish process deviations, maintenance problems, and calibration and component failures from actual diversion events.
    - <u>Modeling and Simulation</u> – Development of modeling and simulation tools to enable new technology development, elucidation of high-impact R&D priorities, and approaches that optimize effectiveness and efficiency of the overall system will be

essential for the integration of new safeguards technologies and techniques into nuclear energy systems.

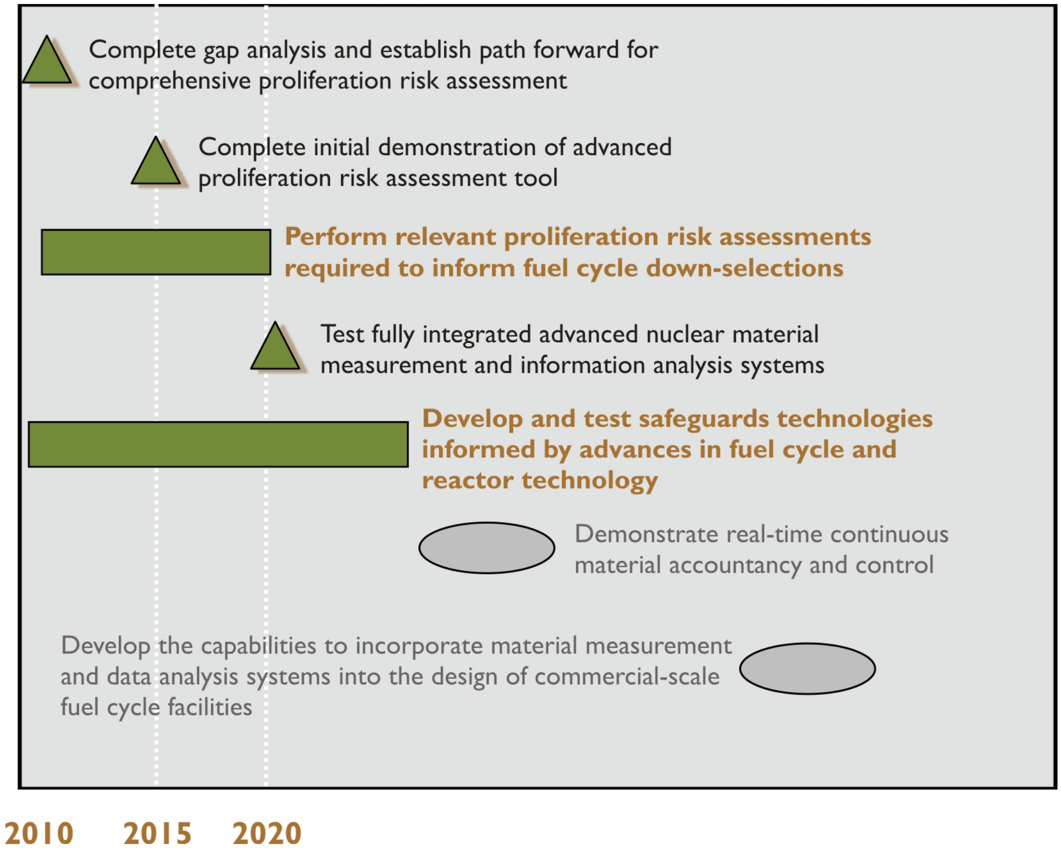
- *Nuclear Energy Technologies and Systems* – This element includes developing and assessing a sufficiently wide and innovative range of options (in concert with R&D Objectives 1–3) to achieve Objective 4. This includes, for example, options that enable decreasing the attractiveness and accessibility of used fuel and intermediate materials, transmuting materials of potential concern, optimizing safeguards and physical security systems approaches, and minimizing the number of needed enrichment and recycle facilities. In conjunction with NNSA, NE will lead the development of these options and implement mechanisms that tightly link and inform both this R&D and other elements of R&D Objective 4.

4.4.3 Key Activities and Milestones

The following chart outlines potential milestones and future national industry aims for this objective. It presents a distinction between near-term milestones toward which the NE R&D plan is designed to progress, represented as triangles, and longer-term potential outcomes that provide a framework for the milestones, shown as ovals. The milestone charts attempt to depict the stages of development so as not to leave a sense that new technologies can be immediately deployed at a commercial level. Not every milestone or potential outcome outlined in these charts represents actions that are within DOE's roles and responsibilities, and research paths will include many decision points that require choosing the most promising options for continued R&D. All DOE R&D activities will be evaluated and revisited regularly and modified as necessary through the budget process to ensure the portfolio reflects past progress and current priorities.

Although some smaller component or process "demonstration" activities are mentioned, these are largely field tests and other actions to provide proof or validation of system elements. They are not costly, large-scale demonstrations like NGNP. Any consideration to embark on such large-scale demonstrations will be the result of decision-making and budget development processes.

Figure 13. Key Activities for R&D Objective 4



5. R&D APPROACH

Section 4 of this roadmap presents NE's four R&D objectives. These objectives show the connection between how nuclear energy will contribute to meeting the nation's energy goals and the R&D that needs to be performed to enable that contribution. This section describes the approach that will be taken to perform this R&D, provides brief descriptions of the key areas of technological development that will be undertaken, presents a brief description of the facilities needed to perform this research, and describes the interfaces with stakeholders that will be required for success.

5.1 Solution-Driven, Goal-Oriented, Science-Based Approach to Nuclear Energy Development

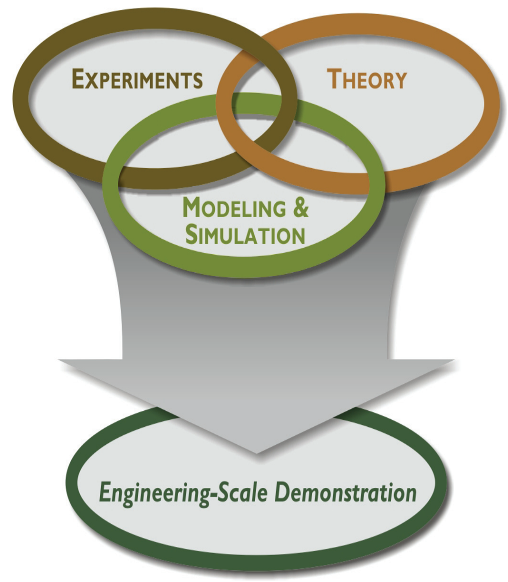
Nuclear power systems were initially developed during the latter half of the 20^{th} century. Their development was greatly facilitated by the nation's ability and willingness to conduct large-scale experiments. The federal government constructed 52 reactors at what is now Idaho National Laboratory, another 14 at Oak Ridge National Laboratory, and a few more at other national laboratory sites. By today's standards, even large experiments and technology demonstrations were relatively affordable. While relying heavily on the Edisonian approach in the 1950s and 1960s, the nuclear energy community was a rapid adopter of high-end computational modeling and simulation during the 1970s and 1980s. During this period, nuclear power plant designers and regulators developed and deployed many of the most demanding simulation models and tools on the most advanced computational platforms then available. Still, the United States embraced a regulatory process that relied, and still relies, heavily on the use of experiments to confirm the ultimate safety of nuclear power systems. Building upon the scientific advances of the last two decades, our understanding of fundamental nuclear science, improvements in computational platforms, and other tools can now enable a new generation of nuclear power plant designers, fabricators, regulators, and operators to develop technological advancements with less of a reliance on large-scale experimentation. The developmental approach employed in this roadmap embodies four elements, as depicted in Figure 14:

Experiments – These are generally small-scale experiments aimed at observation of isolated phenomena or measurements of fundamental properties. However, targeted integral experiments also will be needed in some cases.

Theory – Based either on first principles or observations made during phenomenological testing, theories are developed to explain fundamental physical phenomena.

Modeling and Simulation – A range of mathematical models for diverse phenomena at much different time and spatial scales are developed and then integrated to predict the overall behavior of the system. Key objectives of the modeling and simulation effort are to reduce the number of prototypes and large-scale experiments needed before demonstration and deployment and to quantify uncertainties and design and operational parameters.

Figure 14. Major Elements of Science-Based Research, Development & Demonstration



Demonstrations – While the state of knowledge can be significantly advanced through the combination of experiments, theory, and modeling and simulation, there may be instances where it is appropriate to work with the private sector to further develop and validate laboratory findings. Demonstrations can be a useful element in proving viability of new technologies, but their high cost must be considered in the context of a variety of other factors. There must be sufficient industry commitment for deployment of commercial technologies before such demonstrations would be considered. Any potential future demonstration activities will be evaluated on a case-by-case basis through the established decision-making procedures of the Department and budget formulation.

5.2 Enabling Technologies

A set of enabling technologies has been identified that support progress on multiple objectives. Where NE has an R&D role in these technology areas, coordination of NE's activities across these technologies must be implemented. For example, the NE "owner" of the fuel cycle objective in such a case will be responsible for coordination of all nuclear fuel work across objectives.

- *Structural Materials* – Advanced radiation and corrosion-resistant materials with extension to high-temperature applications benefit many of the R&D objectives, especially when conducted using a science-based development approach without relying heavily on empirical experiments. Thus, a synergistic R&D program can be developed to support all the objectives.
- *Nuclear Fuels* – The development of improved and advanced nuclear fuels is clearly a major objective for both existing LWRs and the entire spectrum of advanced nuclear energy systems discussed throughout this document. The short list of potentially needed

fuels include high-burnup LWR, fast reactor, and gas-reactor fuels; coated-particle fuels; fast-spectrum and thermal-spectrum transmutation fuels and targets; thorium fuels; and molten-salt fuels. A tightly coordinated and well integrated nuclear fuels R&D program must be developed to support all of the R&D objectives.

- *Reactor Systems* – The development of advanced reactor concepts and supporting technologies is a core function of NE. Advanced technologies and reactor concepts are needed to improve the economics of electricity production. Multiple advanced reactor concepts (LWR, small modular, gas-cooled, liquid metal-cooled, molten salt-cooled, etc.) may play a role in our nuclear future. The development of a robust advanced reactor system concept definition capability will be an important element of NE strategy development.
- *Instrumentation and Control* – The development and implementation of digital instrumentation and control systems will benefit current reactors as well as future reactors. Advanced instrumentation and control systems will also benefit future fuel cycle facilities. Safeguards technology development also relies on advanced instrumentation and plant control systems through safeguards-by-design.
- *Power Conversion Systems* – Advanced power conversion systems will lead to increased efficiency for the future reactors and facilitate the use of nuclear power in markets requiring process heat.
- *Process Heat Transport Systems* – The development of process heat transport systems that can be combined with multiple reactor technologies will enable the use of nuclear power to deliver needed process heat to the industrial sector.
- *Dry-Heat-Rejection Systems* – Advanced dry-heat-rejection systems will improve the environmental friendliness of the nuclear power plants and enable the deployment of nuclear energy in areas where water constraints might otherwise preclude its use.
- *Separations Processes* – This report has noted the wide variety of fuel cycle options that may be needed in the future to address U.S. energy security, economic, and sustainability goals. Our future ability to sustainably and economically recycle LWR fuels, fast reactor fuels, gas-cooled reactor fuels, molten salt fuels, *etc.* will depend, in part, on our ability to separate key elements from the waste that will not be disposed in a repository.
- *Waste Forms* – The ability to engineer, produce, and manage fuel cycle waste forms that are chemically and structurally stable over relevant periods of time from decades to hundreds of thousands of years (depending on the radioisotope) is critical to achieving a sustainable fuel cycle and must be closely integrated with both radiochemical research and repository systems research.
- *Risk Assessment Methods* – Advanced methods for risk assessment based on mechanistic modeling of system behavior will benefit the safety assessments of the new nuclear energy systems and fuel cycle technologies. State-of-the-art computational and experimental

techniques will benefit not only novel reactor concepts but other nuclear facilities needed for the fuel cycle.

- *Advanced Modeling and Simulation* – The science-based approach relies heavily on fundamental experiments combined with associated theories for predictive capabilities. However, a comprehensive use of the science-based approach for predictive tools with multiple interrelated phenomenologies requires advances in computational sciences where phenomena at different time and length scales can be bridged into an engineering code using modern computational platforms.

5.3 R&D Facilities and Infrastructure

Ultimately all design and safety tools for nuclear systems must be validated with underpinning experimental data. Without such a foundation in reality, licensing these systems would be virtually impossible. Experiments also provide essential waypoints for guiding the development of technology. Having such an experimental capability requires that nuclear energy R&D maintain access to a broad range of facilities from small-scale laboratories potentially up to full prototype demonstrations. Hot cells and test reactors are at the top end of the hierarchy, followed by smaller-scale radiological facilities, specialty engineering facilities, and non-radiological small laboratories.

Nuclear energy R&D 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. Future infrastructure requirements will be considered through the established budget development processes as needs arise.

The high cost of creating and maintaining physical infrastructure for nuclear R&D, including the necessary safety and security infrastructure, requires creativity and periodic realignment of infrastructure planning with programmatic direction. NE successfully employs a solid approach to maintaining infrastructure. The approach concentrates the high-risk nuclear facilities at the remote Idaho site, maintains unique capabilities at other sites if required, supports vital university infrastructure, negotiates equitable capability exchanges with trusted international partners, refurbishes and reequips essential facilities if required, addresses maintenance backlogs to ensure safe operation, and makes efficient use of modeling, simulation, and single-effect experiments.

5.4 Interfaces and Coordination

In order to achieve the objectives under each R&D objective, NE must closely coordinate its activities with other agencies, the nuclear industry, and international partners.

Other Department of Energy Offices –The use of a "science-based" approach to develop innovative nuclear energy systems and components requires a strong collaboration between NE and the Office of Science (SC) to employ the tools developed for science in engineering applications. Such tools include advanced experimental techniques, a fundamental understanding of materials behavior, and advanced computational sciences. R&D on storage and disposal of nuclear waste will be performed in coordination with the Office of Environmental Management (EM) and the Office of Naval Reactors (NR), as there are salient similarities in the disposition challenges facing each.

NNSA – Technology development for safeguards is a crosscutting tool that is applicable for both domestic and international uses. NNSA and NE are implementing a coordinated effort to address the safeguards R&D needs for domestic and international applications. These collaborative efforts address the assessment of proliferation risks, accountancy, and control (domestic) and verification (international) by contributing new safeguards technologies; recruiting a new generation of safeguards specialists into the U.S. national laboratories, universities, and industry; and informing the development of safe and secure nuclear facilities. NNSA will be responsible for evaluating the international nation state proliferation risks of deploying new fuel cycle technologies, particularly recycling technologies, outside of the United States.

NRC – Appropriate collaboration between DOE and the NRC will help assure that nuclear energy remains a viable option for the United States. The development of science-based tools to inform licensing paradigms is one key goal of this collaboration.

Nuclear Industry – The decision to deploy nuclear energy systems is made by industry and the private sector in market-based economies. However, it is important that industry is engaged during the definition and execution of the R&D phase and that industry participate in joint demonstration activities if such demonstration is deemed necessary and appropriate to facilitate commercialization and deployment of the resulting technologies and systems. As technologies are developed, cost-sharing with industry is an integral part of NE's agenda. DOE will proceed in a manner that recognizes the importance of maintaining a strong and viable nuclear industry.

International Community –Strong participation and leadership by the United States in international nuclear R&D, safety and nonproliferation programs is essential. Nuclear energy worldwide must be deployed with safety and security of paramount importance. In addition, several countries have established strong nuclear R&D programs and specialized expertise from which the United States can benefit, such as the leadership position of Russia, France, and Japan in fast reactor technology. Collaborations in nuclear technology R&D will be implemented through bilateral and multilateral agreements and through international organizations such as the Generation IV International Forum.

In order for nuclear power to continue to be a viable energy option in any country, including the United States, nuclear safety, security, and safeguards must be maintained at the highest levels on a global scale. DOE will help to achieve consensus criteria for safe reactor operation through international organizations, such as the World Association of Nuclear Operators, and seek to enhance safety standards for nuclear power, promote appropriate infrastructure at the national and international levels, and minimize proliferation risks from the expansion of nuclear power through its participation with the IAEA and related organizations.

6. SUMMARY AND CONCLUSIONS

This document presents an integrated strategy and R&D framework for the DOE Office of Nuclear Energy. In order to meet the Administration's goals of energy security and greenhouse gas reductions, nuclear energy must play an important role in the national energy portfolio. NE's derived missions in support of these national goals are to enable the development and deployment of fission power systems for the production of electricity and process heat. Four research and development objectives have been identified, which will guide NE's program and strategic planning. Progress in these areas will help ensure that nuclear energy continues to be among the suite of available U.S. energy options throughout the 21st century. These objectives are:

- *R&D Objective 1* – Develop technology and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors.
- *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.
- *R&D Objective 3* – Develop sustainable nuclear fuel cycles.
- *R&D Objective 4* – Understand and minimize the risks of nuclear proliferation and terrorism.