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A Strategy for Nuclear Energy Research and Development

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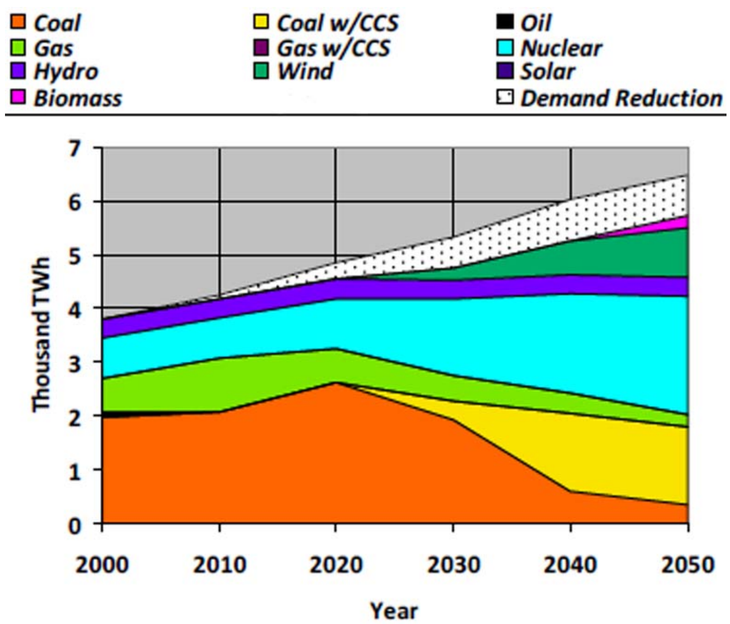
Overview

The United States is facing unprecedented challenges in climate change and energy security. President-elect Obama has called for a reduction of CO_2 emissions to 1990 levels by 2020, with a further 80% reduction by 2050. Meeting these aggressive goals while gradually increasing the overall energy supply requires that all non-emitting technologies must be advanced. A recent Electric Power Research Institute (EPRI) study called the PRISM analysis defines a possible technology mix[1] within the electricity sector that would help achieve a comparable goal (see figure below).[2] In it, nuclear generation rises 20% from current levels by 2020 and nearly 200% by 2050.



The development and deployment of nuclear energy can, in fact, help the United States meet several key challenges:

1) Increase the electricity generated by non-emitting sources to mitigate climate change
2) Foster the safe and proliferation-resistant use of nuclear energy throughout the world
3) Reduce the transportation sector's dependence on imported fossil fuels
4) Reduce the demand on natural gas for process heat and hydrogen production.

However, because of the scale, cost, and time horizons involved, increasing nuclear energy's share will require a coordinated research effort—combining the efforts of industry and government, supported by innovation from the research community.

THIS REPORT OUTLINES THE SIGNIFICANT NUCLEAR ENERGY RESEARCH AND DEVELOPMENT (R&D) NECESSARY TO CREATE OPTIONS THAT WILL ALLOW GOVERNMENT AND INDUSTRIAL DECISION-MAKERS TO SET POLICIES AND CREATE NUCLEAR ENERGY INITIATIVES THAT ARE DECISIVE AND SUSTAINABLE.

The nuclear energy R&D strategy described in this report adopts the following *vision*:

> **"Safe and economical nuclear energy in the United States will expand to reduce greenhouse gas emissions and enable economic growth, while providing leadership for responsible expansion of nuclear energy internationally."**

Six goals are defined to achieve this vision:

1) Maintain today's nuclear fleet of light water reactors
2) Significantly expand the fleet with advanced light water reactors
3) Develop non-electric applications for high-temperature reactors
4) Assure safe, long-term used fuel management
5) Assure long-term nuclear sustainability
6) Strengthen United States leadership internationally

Specific objectives are developed for each goal, and R&D to support them is summarized in three technology areas:

- Light water reactor (LWR) and advanced light water reactor (ALWR) R&D
- High-temperature reactor (HTR) R&D
- Fast reactor and advanced fuel cycle (including waste management) R&D

The purpose of this report is to align and strengthen the partnership between the federal and private sector nuclear R&D programs. The analysis underlying the proposed R&D includes the pacing of technology needed to enable greater reliance on nuclear energy throughout this century. The analysis is not presented here, but is based on the MERGE techno-economic model[3] that EPRI uses to evaluate least-cost technology combinations while meeting the economy's energy demands. Other efforts, such as the 2007 U.S. Climate Change Science Program *Scenarios of Greenhouse Gas Emissions and Concentrations*,[4] and the 2008 International Energy Agency report, *Energy Technology Perspectives: Strategies and Scenarios to 2050*,[5] have provided insights considered in this report.

Total funding needs from government and industry for the proposed research agenda covering the initial 2010-2015 period are estimated at $3.5 billion. This includes R&D needed to support the successful deployment of light water reactors through mid-century as well as to create options for non-electric applications and the long-term sustainability of nuclear energy. The immediate priority is on ensuring the longevity of existing and new light water reactors, followed by the development of non-electric applications. While sustainability is a longer-term issue, funding must be provided in the near term due to the long lead time involved.

Goals and Supporting Objectives

High-level research and development objectives for each of the six goals are described below.

1) Maintain Today's Nuclear Fleet of Light Water Reactors

Increasing nuclear energy's share of U.S. electricity generation in the near term can be accomplished most effectively by striking a balance between sustaining the existing LWR fleet and building new ALWRs. A longer period of commercial operation of existing plants can lower the required new plant build rate and take advantage of amortized plant investments, thereby limiting energy cost increases. In both cases, high standards of safety and environmental protection will govern nuclear plant operations. This gives rise to two objectives for today's nuclear fleet:

1.1 Successfully achieve planned life extensions for existing LWRs to 60 years, and then further extend operating licenses beyond 60 years (nominally 80 years)

1.2 Maintain the superior safety, high reliability and economic performance of existing LWRs throughout their full lifetime.

These objectives are the primary focus of the *Strategic Plan for LWR Research and Development: An Industry-Government Partnership to Address Climate Change and Energy Security*.[6] The first objective was also the subject of a 2008 workshop co-sponsored by the U.S. Department of Energy (DOE) and Nuclear Regulatory Commission (NRC) on plant life extension R&D, entitled *Life Beyond Sixty*.[7] A survey of nuclear utility executives conducted in late 2007 showed strong support for pursuing plant relicensing beyond the current 60 years. As discussed in its *Long-Term Research Activities*,[8] NRC anticipates initial utility requests for life extension beyond 60 years to be submitted in the 2014 to 2019 timeframe, necessitating a concerted effort over the next 5-10 years to enable this option.

Relicensing alone does not assure high levels of nuclear generation. Nuclear plants must maintain their excellent safety records with high availability and low production costs. All of these attributes are reflected in the fleet's capacity factor. The existing fleet now operates above an average 90% capacity factor, far superior to its 56% capacity factor 25 years ago, primarily due to improvements in plant management and operations, operational training, equipment maintenance and reliability, and technological improvements. More broadly, these improvements reflect effective management practices, advances in technology, and the sharing of safety and operational experience. Successfully operating the fleet to 60, 80, or even more years will require research into additional technology and process improvements, both to meet the challenges of advancing nuclear plant age and to maintain performance.

2) Significantly Expand the Fleet with Advanced Light Water Reactors

For nuclear energy to significantly grow its share of U.S. electricity generation, many new ALWRs must be built and operated. The EPRI PRISM analysis suggests that 20 GWe of additional nuclear capacity could be installed by 2020, which would contribute 10% of the needed CO_2 reduction for the U.S. primary energy supply. This gives rise to four objectives for the new ALWRs to be built:

2.1 Successfully license, construct and operate new ALWR designs to firmly establish their viability and to provide assurance that additional plants will be built and operated at competitive capital and production costs

2.2 Address infrastructure shortfalls that could limit ALWR deployment in large numbers, enabling new plant build rates in the United States of five or more per year by 2020

2.3 Adapt lessons learned from the first ALWRs and innovate new technologies that will further improve safety, reliability, and economic performance over the life of the plants

2.4 Maintain safe and reliable used fuel management systems.

Following years of preparation by industry and government, new nuclear plant construction plans are moving forward in the United States. Currently, companies have submitted license applications for 26 new reactors to the NRC. Given past experience, it will be crucial to anticipate and effectively address unanticipated problems that may arise as the new ALWRs are added to the existing fleet.

Even with a successful launch of the first ALWRs in the U.S., there will be barriers to large-scale deployment. The infrastructure to build and operate many new plants must be revitalized. For example, upgrades or new factories for forging and fabricating heavy section pressure vessels and components have been announced, but need to be brought online. A build rate of several units per year will strain the skilled craft workforce and the suppliers of nuclear-grade components and equipment, unless they can be expanded in time. Higher build rates will strain investment capital markets, the skilled and professional workforce, and even the NRC's ability to license and regulate the new plants. International suppliers can contribute to overcoming these barriers. However, expanding our domestic infrastructure in nuclear energy is in the national interest, since it bolsters our energy independence. Progress on these infrastructure issues is already evident, driven largely by supply and demand. It will be important to monitor this progress against anticipated needs, to ensure that market forces can continue to drive the rate of progress that is needed.

3) Develop Non-Electric Applications for High-Temperature Reactors

Using nuclear energy for applications beyond the generation of electricity would also help reduce greenhouse gas emissions from large process heat operations currently fired by liquid fuels and natural gas. Currently, 35% of U.S. natural gas consumption, or 8 quadrillion Btu/year, is devoted to industrial use. About 80% of this amount is used to supply process heat in oil refineries and petrochemical plants; the remaining 20% feeds and fuels the production of hydrogen through steam reforming of methane. Price increases over the past decade have pushed about one-half of domestic fertilizer and methanol production offshore, taking jobs out of the United States and impacting the cost and availability of these commodities. Process heat and hydrogen generated by nuclear energy has the potential to restore these domestic industries and reduce the heavy demand on natural gas for the production of transportation fuels.

The following objectives are envisioned:

3.1 Develop high-temperature gas-cooled reactor technology with successful demonstration of process heat delivery and prototypical hydrogen production

3.2 Commercialize HTRs to address a significant fraction of the consumption of natural gas from industrial process heat.

Achieving these objectives will require substantial research, development and demonstration spanning HTRs and process heat and hydrogen delivery systems. High-temperature reactors are a leading-edge Generation IV technology in the United States, with considerable support and interest internationally.

External forces could impact these two objectives. For example, large-scale deployment of plug-in hybrid electric vehicles (PHEVs) may drive expansion of baseload electricity needs. Desalination of seawater could present another important application: While reverse osmosis plants powered by nuclear electricity may be the more likely prospect, the use of process heat in distillation-based processes remains a possibility.

4) Assure Safe, Long-Term Used Fuel Management

Management of used fuel, and the portion that is ultimately disposed of as nuclear waste, is a key issue for public confidence in nuclear energy. Also, a global expansion of nuclear energy will ultimately challenge known and reasonably assured natural uranium resources using conventional fuel cycles. A flexible and integrated approach is needed that prepares the United States for a technically mature, proliferation-resistant and commercially-driven economic closed fuel cycle. The following objectives are envisioned:

4.1 Expand interim storage to safely store used fuel for long-term recycling and/or disposal

4.2 Develop mined geological repository capacity, with first priority given to the disposal of the fraction of used fuels that offer little or no economic potential for recycle

4.3 Advance a new generation of LWR fuel that would enable a reduction in the volume of LWR fuel requiring storage, transportation and disposal.

The first two objectives establish a flexible system for managing used fuel, with the capacity to safely and effectively store used fuel and to permanently dispose nuclear waste or used fuel. If a closed fuel cycle is not implemented, the interim storage inventories would be transferred to the repository. If a closed fuel cycle is implemented, the interim storage sites would have fuel reprocessing and refabrication facilities established on-site or nearby, and only residual wastes would transfer to the repository.

In the second objective, the fraction of used fuels that would be less likely to be recycled include light water fuels discharged during the 20^{th} century and packaged in transport, aging and disposal casks (TADs), the initially small amount of gas reactor used fuels, and other special cases. All of these would be sent to the repository without reprocessing. Also, options should be examined for developing repository capacity in crystalline rock, clay and salt formations.

The third objective would increase LWR fuel burnup capability, which could then reduce the volume of used fuel shipped and stored prior to implementing used fuel recycling – assuming needed licensing approvals. It would also enable longer operating cycles, potentially improving plant availability.

5) Assure Long-Term Nuclear Sustainability

Fast reactor and nuclear fuel reprocessing technologies could enable uranium fuel resources to sustain world energy supplies from nuclear power for centuries. About 100 times more energy is available in the used fuel and enrichment tails than the amount extracted in the first cycle through a light water reactor. Extracting the additional energy involves recycling U-238 and long-lived transuranics in fast reactors. Recycling in fast reactors also has the ability to reduce the amount of waste sent to geologic disposal, although low-level and greater-than-class C waste volumes will increase if recycling is implemented.

Fast reactors produce electricity at roughly the same efficiency as LWRs and ALWRs. Their capital costs are projected to be higher than ALWRs, necessitating R&D to reduce these costs. Fast reactor designs may range from ‘breeders’ that can produce more usable nuclear fuel than they consume (i.e., with a high conversion ratio) to ‘burners’ (i.e., producing less new fuel but consuming more transuranic elements, with a low conversion ratio). This strategy is based upon fast reactors having a conversion ratio of about 1, which somewhat simplifies the recycling by avoiding the development of high proportion transuranic fuels for burners, as well as the management of plutonium fuel for other reactors in the case of breeders. A decision to evolve the fast reactors to breeding could come later and would be based on considerable experience with fast reactors to establish their safety, security, reliability, and commercial competitiveness.

The strategy envisions recycling most long-lived actinides in fast reactors (full actinide recycle). While other approaches to the fuel cycle have been implemented overseas, such as mixed oxide (MOX) recycle in thermal reactors, such intermediate steps are not likely in the United States, given the long-term potential for fast reactors and the modest benefits of MOX recycle in terms of used fuel management, economics, and nonproliferation. The fast reactors would first recycle used fuel from LWRs and ALWRs.

Fast reactor technology has had limited experience with recycling used LWR fuel. The nuclear industry has accumulated operating experience from about 20 sodium-cooled reactors world-wide, and other fast spectrum reactor technologies have been proposed. The economics, reliability, safety and associated recycling operations of fast reactors still need considerable development to attract commercial interest.

Before large-scale deployment of fast reactors can occur, a demonstration of the final system (reactor and associated recycling) is needed to establish the system's overall performance: Key issues are operational safety and reliability, life cycle costs, safeguards and security, and the ability to handle all waste streams. The demonstration would be preceded by extensive testing of the key components such as fuel, steam generators and sodium storage. The goal of this comprehensive demonstration should be to achieve on the order of 100 reactor-years of cumulative operation before commercial deployment. Fast reactors are another leading-edge Generation IV technology, with considerable support and interest internationally. International collaboration will reduce the time and cost of this R&D.

The decision to deploy will be driven partly by the price of natural and enriched uranium, when the ability to cost-effectively unlock the energy content of its U-238 could bring commercial interest. The ability of fast reactors to reduce the heat load of long-lived nuclear waste sent to the repository is also a benefit with potential to optimize the use of repository space. The relative costs of geologic and low level waste disposal versus fuel recycling will also be a factor in the economics.

Overall, a decision about mid-century regarding the closing of the fuel cycle with fast reactors would be informed through two objectives:

5.1 Advance fast reactor technology, including reprocessing and fast reactor fuel fabrication, to a level of confidence sufficient to show that if and when used LWR fuel is separated and reprocessed, reactors capable of consuming the actinides will be available and economically feasible

5.2 Demonstrate and gain operational experience with LWR and ALWR used fuel reprocessing and fast reactors, eventually to a level of full-scale operation on the order of 100 reactor-years.

These objectives address the R&D needed to guide decisions on the technical and economic viability of closing the fuel cycle. The time needed to develop full actinide recycle is lengthy, however, and the United States needs to proceed now in order to be prepared to respond with an assured solution as market conditions begin to favor closed fuel cycles. Recycle technology options for HTRs should be created if prospects develop for their large scale deployment.

6) Strengthen U.S. Leadership Internationally

The worldwide nuclear renaissance includes the expansion of nuclear energy within the 30 countries that have already deployed it, as well as the adoption of nuclear energy by a dozen or more countries that are considering expansion and that will need the necessary knowledge, regulatory regime and supporting infrastructure. The United States has a strong interest in providing leadership that can assure that nuclear technology and deployment is advanced in a manner that meets accepted safety and nonproliferation criteria. Three objectives address the range of needed leadership:

6.1 Collaborate with leading worldwide developers and exporters of commercial nuclear technology and equipment to provide leadership for the development of current and next generation systems and to facilitate a substantial U.S. share of the new ALWR plant and fuel market

6.2 Assert U.S. leadership, in cooperation with the International Atomic Energy Agency (IAEA), in developing a proliferation-resistant assured nuclear fuel supply regime to manage global uranium enrichment and fuel cycles, and to demonstrate preferred technologies and safeguards in the U.S. fuel cycle for potential application globally

6.3 Collaborate with countries interested in deploying commercial nuclear technology for the first time, guiding the implementation of effective nuclear regulations, legal and policy frameworks, and supporting infrastructure.

The first objective is focused on the countries that have a significant role in commercial nuclear technology development and supply, such as those in the Generation IV International Forum and others such as India. The latter two objectives are focused on countries that have a significant interest in importing commercial nuclear technology, primarily reactors, fuel and services. Establishing interim storage would also allow the United States to engage in the near term in international fuel cycle initiatives to assure fuel supply and take-back for countries that forgo the development of enrichment and reprocessing. The United States should work closely with the IAEA on these two objectives.

Implications for Nuclear Nonproliferation and Closed Fuel Cycles

This nuclear energy strategy was developed in the context of U.S. nonproliferation policy, "to discourage the accumulation of separated plutonium, worldwide," as reiterated in the *National Energy Policy*.[9] This objective has been supported in studies by the National Academy of Sciences, National Commission on Energy Policy, and Massachusetts Institute of Technology. Despite concerns about the impact of used fuel reprocessing on nuclear proliferation, there appears to be recognition and bipartisan support for R&D in advanced fuel cycle technologies that are cleaner, more efficient and more proliferation resistant than existing reprocessing technologies. Most acknowledge that U.S. experience with older reprocessing technologies has been mixed and should not be the model for the future.

The primary motivation for closing the fuel cycle in this strategy is long-term global sustainability, reduction of greenhouse gases, and energy security—providing an energy supply option through the breeding of additional nuclear fuel in fast reactors that can power the world for centuries. Importantly, the full actinide recycle technology that permits this level of sustainability is also capable of providing adequate proliferation resistance for the expanded use of nuclear energy around the world.

The closed fuel cycle is not a substitute for a geologic repository, which is still needed under any scenario. Improved used fuel management is a potential inherent benefit of recycling, with the degree of improvement dependent upon technology advances. Based on its extensive work, EPRI believes that spent nuclear fuel and geologic disposal pose a small and acceptable risk to society, whether or not the long lived actinides in the used fuel are reduced further by recycling.

The open fuel cycle, comprised of interim storage (on-site or centralized) and a geologic repository for disposed fuel and waste, is the safest and most proliferation-resistant means of used fuel management available today. Viable and flexible storage and disposal paths will allow the United States to become a full partner in the international partnerships that manage global nuclear fuel cycles. Specifically, the nuclear fuel supply and used fuel take-back arrangements cannot proceed until supplier nations have a means to assure new fuel supply and used fuel take-back for those nations that desire to deploy nuclear energy plants for peaceful purposes and that agree to forego building their own uranium enrichment and reprocessing systems. In the longer term, recycling technologies that meet U.S. standards for proliferation resistance can begin accepting used fuel from user nations, per this arrangement, and begin to work off any backlog of foreign used fuel that is stored temporarily in the United States.

This strategy envisions the United States helping formulate and then joining an international fuel supply regime under strict standards established and monitored by the IAEA. This regime uses the existing commercial nuclear fuel supply chain, under which suppliers provide fresh fuel and take back used fuel under international non-proliferation standards. For the United States, interim storage is the quickest and least expensive means of establishing used fuel take-back capability. While siting such storage facilities will present challenges, addressing proliferation should transcend siting issues.

Summary of Required Research and Development

Total funding needs from government and industry for this research strategy covering the initial 2010-2015 period are estimated at $3.5 billion. Specific areas are discussed below.

LWR and ALWR R&D

The continued safe and cost-effective operation of existing LWRs is essential in allowing the build rate of new ALWRs to rise sufficiently to offset the retirement of LWRs around mid-century. The LWR and ALWR technology advances needed to achieve the nuclear development agenda are developed in the *Strategic Plan for Light Water Reactor R&D*.[10] In brief, technologies are needed to sustain the high performance of reactor plant materials, instrumentation and controls, and fuel. Reactor plant material lifetimes must be sustained through improved lifetime performance, prediction, maintenance, and repair techniques. The plants must transition to the use of state-of-the-art digital instrumentation and control. Nuclear fuel should achieve burnup performance levels of about 80,000 MW-day/metric ton for the current fleet and for new plants in order to add additional operational flexibility.

The challenge for new ALWRs is to build them economically and on schedule, to operate them reliably, and to continuously improve their lifetime performance. The technology advances needed to achieve the deployment agenda are also developed in the *Strategic Plan*. Advanced fabrication, construction and inspection methods must be developed to deploy new reactors. The U.S. nuclear infrastructure and workforce must be revitalized, including an expansion and modernization of the electric grid to accommodate 21st century needs.

A number of technologies and initiatives are needed to afford continuous improvement of the operational performance of both LWRs and ALWRs, including:

- Sustain high performance of reactor plant materials
- Extend component life and improve lifetime prediction
- Improve inspection, diagnostics, maintenance and repair techniques
- Transition to state-of-the-art instrumentation and controls
- Enhance fuel reliability and performance; develop high-burnup fuel
- Develop alternate cooling technologies to reduce the demand for water
- Develop advanced fabrication, construction and inspection methods
- Extend application of risk management technologies and understanding of safety margins
- Improve equipment reliability and operational performance
- Design plant power uprates integrated with their impacts on plant life extension
- Develop technologies for plant security, with a focus on reducing manpower needs
- Develop technologies to minimize low-level waste

New missions and markets for light water reactors should be explored in the areas of desalination and low-temperature process heat. Additionally, infrastructure issues need to be addressed, such as increasing the number of nuclear safety-grade component manufacturers, building the skilled construction workforce, and expanding the high-voltage transmission network.

Funding needs for this R&D are estimated at $600 million in the 2010-2015 period. The cost share is estimated at 50% industry and 50% government.

High-Temperature Reactor R&D

High-temperature reactors could service a variety of process heat applications, including (1) upstream petroleum operations such as tertiary oil recovery, oil sands, oil shale, and coal to liquids and gas; (2) downstream petroleum operations such as hydrogen for sweetening crude oil; and (3) chemical industry applications of hydrogen in fertilizers, ammonia, methanol, and ethylene. In addition, HTRs could be used in remote locations to produce electricity, and potentially in the transportation sector to supply hydrogen for fuel cell vehicles.

These diverse missions require capable and flexible HTR designs that build on prior HTR experience but advance the technology for greater reliability and high operating temperatures. The DOE is sponsoring this work in partnership with an industry team and a number of international partners under Generation IV. Key R&D areas include:

- Fuels Technology **-** DOE has re-established the capability to manufacture and test coated particle fuel. Work must continue to demonstrate repeatable fabrication of highly reliable coatings and kernels on a commercial scale and to prepare for qualification testing in accordance with nuclear standards.
- Materials Technology **-** DOE has developed a conceptual design of a graphite creep capsule and has conducted preliminary creep, creep-fatigue, and environmental effects testing of high-temperature materials for intermediate heat exchanger applications. Much work remains to assess and qualify materials options for the reactor pressure vessel, hot ducting, hydrogen process heat exchangers and control rod guide tubes, and to qualify ceramic and metallic components. Licensing guidance is required for all these materials issues.
- System Design **-** Designing the integrated nuclear heat supply system, power conversion system, and hydrogen production facility requires finalizing key design parameters, such as reactor power, outlet temperature, plant configuration, etc. Improved computer methods are required to existing neutronic, thermal hydraulic, and safety codes applicable to HTR technology. Improved methods and associated experiments are needed to validate the computational tools.
- Test Facilities **-** Designing, constructing and operating the necessary test facilities (or modifying existing facilities) such as a high-temperature fluid flow test facility will advance the development and demonstration of HTR systems, key process equipment, and hydrogen production concepts.
- Hydrogen Process Development **-** Water-splitting process development must be advanced through demonstration of the integrated nuclear heat supply system, power conversion, and hydrogen production facility.

Funding needs for this R&D are estimated at $1.9 billion in the 2010-2015 period, possibly leading to construction of a demonstration HTR in the United States after 2020. The cost share is estimated at 20% industry and 80% government.

Fast Reactor and Fuel Cycle R&D

Fast reactor and fuel cycle development is necessary to support nuclear fuel recycling efforts. R&D is needed in three broad areas: (1) LWR used fuel separation and refabrication into fast reactor fuel, (2) fast reactor core and systems design and technology, and (3) fast reactor used fuel separation and refabrication into fast reactor fuel. Each is presented below assuming aqueous reprocessing for LWR fuels and sodium-cooled fast reactors with electrochemical processing. While other technologies may ultimately be selected to perform these functions, these technologies are representative of the R&D needed. All areas will need safeguards and security technology development, as well as technology advances to establish commercial competitiveness.

Light water reactor used fuel separation will need to be scaled up gradually to assure its performance. Prototypic unit operation demonstrations will be performed using depleted uranium and surrogate materials to provide critical design information for used fuel recycling by the start of preliminary design activities. Following this, demonstration would include integrated operation of most of the separation steps, along with key solidification process steps that are not easily decoupled from the separation process. This phase will also provide sufficient separated materials to support both fuels and waste forms development. Later demonstration testing would include integrated operation of all of the separation steps and waste treatment processes.

Fuels containing the entire mix of transuranics must be qualified. Fuel testing and qualification will require a fast test reactor, whether built in the United States or arranged with international partners. As transuranic fuels are proven, the test reactor core would be converted to run 100% on these fuels, confirming design parameters for a full-sized demonstration reactor. Fuel fabrication will require a dedicated new facility, whether based on metal or oxide fuel. Licensing of the initial facilities is assumed to be by DOE, but later phases should demonstrate licensing by NRC, which will require a licensing strategy for commercial reprocessing and regulations to complement it.

Fast reactor designs must address issues related to economics, safety, system performance and reliability, and safeguards and security. Beyond the fuel, technology development is needed in coolant control (chemical, thermal and hydraulic), core structural materials, instrumentation and control, seismic isolation, fuel handling, reactor vessel and structures, maintenance and inspection technology, and balance of plant. A number of fast reactor component testing facilities will be required to support the development. An NRC licensing strategy for the fast reactor and associated recycling operations, and regulations to complement them, will be needed to support the first full-sized demonstration.

Fast reactor fuel separation will be based on different technology than the light water reactor separations. Facilities for testing the fast reactor fuel separation exist in the United States, so the development of separation and refabrication can proceed using both surrogate materials and test reactor used fuel. Key technology issues will be fuel performance with the added transuranics, losses during processing, and robust waste forms and packaging for various environments.

Funding needs for this R&D are estimated at $2.5 billion in the 2010-2020 period, with $1 billion in the first five years, using 100% federal funding. International cooperation on R&D can offset this amount significantly. This level of funding will provide the progress that is necessary for decisions to be made on whether to demonstrate or implement the options.

Conclusions

Nuclear energy development and deployment can help the United States meet critical environmental and energy challenges, yet it requires a coordinated R&D effort of industry and government.

The overall nuclear energy R&D strategy should be driven by a combination of long-term national goals for climate change mitigation, nonproliferation, and energy security in concert with market developments. The strategy should include the rebuilding of the nuclear industrial and R&D infrastructures.

The priorities in this nuclear energy strategy should address near-term, medium-term, and long-term priorities. R&D must proceed on all fronts to create technology options and inform decision-making:

- Near term:
  - Develop the technical and licensing basis for license renewal to 80 years
  - License and deploy new, standardized ALWRs starting in 2016
- Medium-term:
  - Develop geological repository capacity and interim storage for used fuel
  - Develop the technical confidence to introduce high-temperature reactor technology capable of generating process heat, hydrogen and electricity at competitive costs, for initial use by the petroleum and chemical industries
  - Develop the technical confidence to introduce new fuel cycle technologies for integrated, cost-effective used fuel management
- Long-term:
  - Deploy a highly sustainable closed fuel cycle

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