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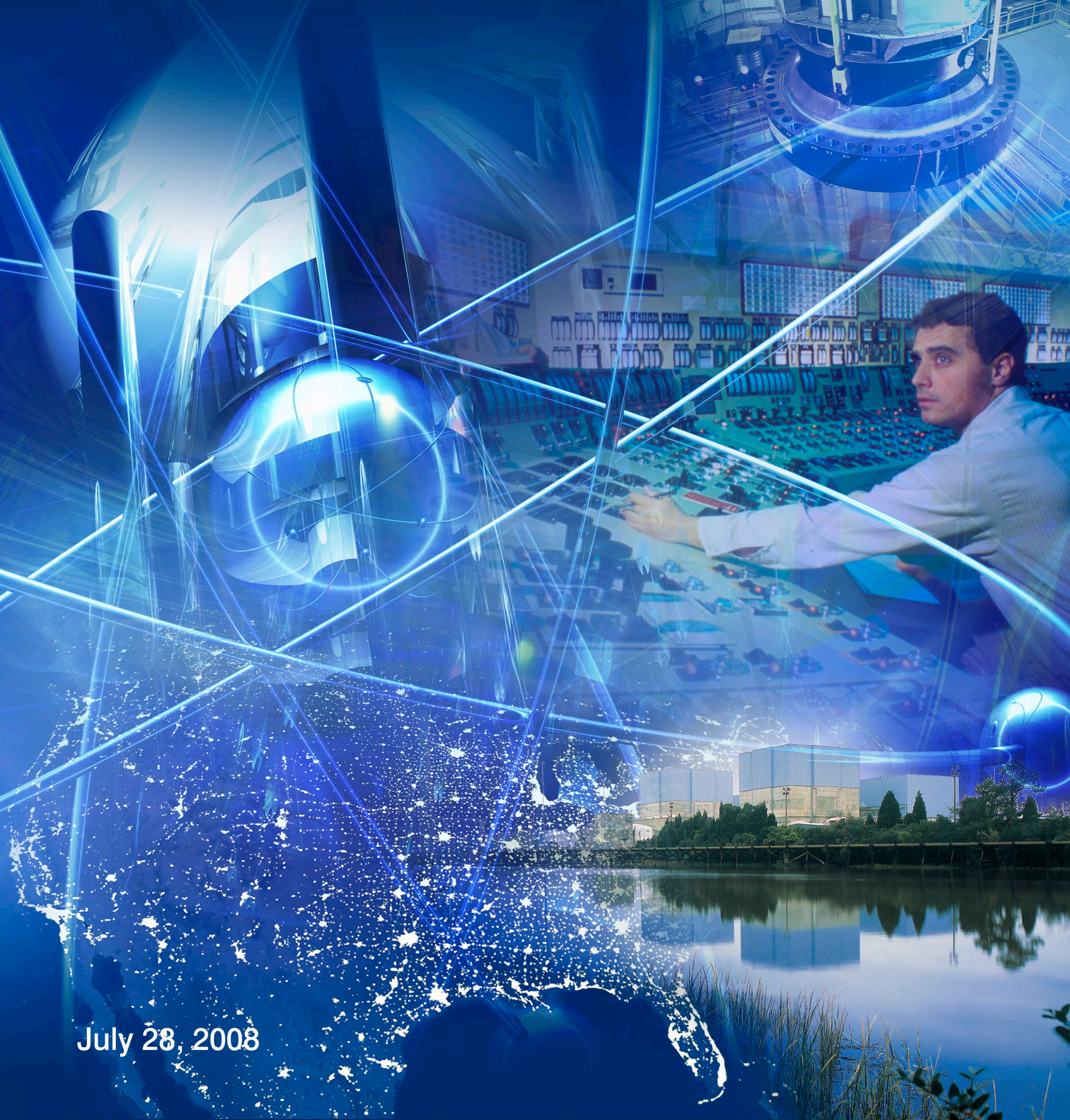
Nuclear Energy for the Future

Executive Recommendations for R&D Capabilities



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Executive Recommendations for Nuclear R&D Capabilities

Summary

The energy crisis looming before the United States can only be resolved by an approach that integrates a portfolio of options. Nuclear energy, already an important element in the portfolio, should play an even more significant role in the future as the U.S. strives to attain energy security and reduce carbon emissions. This report identifies the current and future nuclear research and development capabilities required to make this happen. The capabilities support: (1) continued, safe operation of the current fleet of nuclear plants; (2) the availability of a well qualified and trained workforce; (3) demonstration of the next generation nuclear plants; (4) development of a sustainable fuel cycle; (5) advanced technologies for maximizing resource utilization and minimization of waste and (6) advanced modeling and simulation for rapid and reliable development and deployment of new nuclear technologies. In order to assure these capabilities are made available, a Strategic Nuclear Energy Capability Initiative is proposed to provide the required resources during this critical period of time.

Scope

The scope of the recommendations encompasses the commercial use of nuclear energy and what the federal government should do to support its expanded use to increase energy security and reduce carbon emissions. Consequently, the report does not address the production of industrial and medical isotopes, or the use of nuclear energy for space exploration. Nor does the report address the capabilities provided by the commercial nuclear industry, such as low-level waste management. Within its scope, the report does not recommend a specific set of facilities, because this is the responsibility of the DOE through its National Environmental Policy Act and Project Management Order processes. In the context of this report, capabilities mean innovative, well-structured research and development programs, a viable work force, and well-equipped specialized facilities. These capabilities are targeted investments that that because of their complexity or cost can only be made efficiently and timely by the government and are critically important to our nation's energy policy. Understanding and agreeing upon these investment targets is the essential first step in developing a long-term investment strategy.

Background of Report

Energy security, energy prices, and the environmental impact of energy production have risen to the top of the national agenda. The United States must increase production capacity, reduce dependence on imported oil, and reduce CO_2 emissions. Recent studies project that U.S. energy demand will increase by at least 30% by the year 2030. Electricity production, which accounts for one-third of the current man-made CO_2 emissions globally, must grow even more rapidly to keep pace with demand even with substantial efficiency improvements.

Safe, reliable, affordable nuclear energy will play an ever increasing role in the generation of base load electricity. Nuclear power generates no CO_2 emissions; its life-cycle carbon footprint is negligible. The nuclear industry is working with the U.S. DOE to extend the service life of the currently operating reactors, deploy advanced light water reactors as quickly as possible, explore nuclear applications beyond electricity production, develop next generation reactors, and prepare for closing the nuclear fuel cycle.

Achieving these goals will require substantial capabilities that include innovative, well-structured, and adequately funded research and development programs, a viable work force, and well-equipped specialized facilities. Currently only a portion of the required capabilities exists. Developed by a team of senior executives from the nuclear energy industry, academia, and the national laboratories (identified in Appendix A), this Letter Report provides a set of recommendations to address gaps in required capabilities.

The Process

In early 2008, the U.S. DOE Office of Nuclear Energy requested Battelle work with the domestic nuclear energy industry, the academic community, and the national laboratories to conduct an independent analysis of the capabilities required to support the achievement of the industry's prioritized goals. A three-phase process identified the highest priority capabilities.

In the initial two phases, key studies were conducted to provide the basis for the development of recommendations. The first study, ***Nuclear Energy for the Future Required R&D Capabilities – An Industry Perspective*** was prepared with the participation of 34 organizations representing the nuclear energy industry, academia, and the national laboratories. It articulates the industry's goals for the 2010 to 2050 timeframe and identifies and prioritizes the required capabilities to accomplish these goals. The second report, ***Assets Required for a Nuclear Energy Applied R&D Program***, assesses the availability and state of existing facilities to provide the required capabilities identified in the first study. Some additional DOE NE R&D program capability requirements beyond those identified in the first study are also addressed in the second study.

In the third phase of the process, the senior executive team reviewed the results of both studies; discussed industry goals, current DOE program activities, and capability gaps; and identified the priorities and recommendations that follow:

- Maximize the continued safe operation of the existing nuclear plants
- Support enhanced nuclear education and training capabilities that complement industry efforts to ensure the availability of a well-qualified and well-trained workforce
- Develop and demonstrate next generation reactor technologies that expand the applications of nuclear energy
- Develop affordable, proliferation-resistant recycle technologies needed to create a sustainable nuclear fuel cycle
- Improve the utilization of uranium resources and reduce waste disposal requirement through the continued development of fast reactor technology
- Utilize advanced modeling and simulation to accelerate the development and deployment of nuclear systems
- Create the Strategic Nuclear Energy Capability Initiative to provide the significantly increased investment in nuclear science and technology capabilities.

Excellence in science and engineering is **the essential foundation** for the continuing success of nuclear energy. Recent U.S. investments in nuclear science and engineering education reveal inconsistent implementation of policy and Congressional intent. As its R&D budget diminished to near zero in the late 1980's, the Office of Nuclear Energy reduced its university support. A new program that showed promising growth was inexplicably abandoned in 2006; since then DOE NE has repeatedly tried to restructure its university program. These attempts have led to confusion and uncertainty throughout the government, industry and academia, resulting in a lack of priority for developing required core competencies. The overall result has been a steady reduction of nuclear education laboratories including on-campus research reactors, and lagging development of teaching and research faculty. Concurrently, the growing demand for graduates in nuclear science and engineering and supporting engineering disciplines has been well documented by such industry and professional organizations as the American Nuclear Society, the American Physical Society, the Health Physics Society, the Electric Power Research Institute, and the Nuclear Energy Institute. Consequently, stronger and continuing investments in core competencies are required in the U.S. to realize the promise of nuclear energy, to increase our energy security and reduce our carbon emissions.

Several other federal agencies, including Department of Homeland Security, National Nuclear Security Administration, the U.S. Nuclear Regulatory Commission, and U.S. DOE's Office of Civilian Radioactive Waste Management and Office of Science, support nuclear research and development programs. Opportunities for synergy and cost effective collaboration to provide the needed capabilities for accomplishment of these recommendations are required.

The Recommended Actions

Maximize the continued safe operation of existing nuclear plants **–** We recommend DOE NE, in partnership with the nuclear energy industry, undertake a carefully defined and focused R&D program to help maintain the extended safe operation of the commercial light water reactor fleet while optimizing the power production from each plant for as long as practical.

In 2007, the 104 operating nuclear power plants in the United States produced 20 percent of the country's electricity at the lowest cost, other than hydroelectric. Plant safety, reliability, and economics have improved substantially over the past 29 years, since the Three Mile Island 2 accident. The existing reactor fleet is recognized as one of the pillars of the U.S. electrical energy production infrastructure. The age of the operating plants ranges from 13 to 39 years. Almost 90% of the operating reactors have secured, or plan to secure, license renewals by the U.S. Nuclear Regulatory Commission (NRC) for an additional 20 years of operation, representing a benefit of hundreds of $B to the U.S. economy. In addition, extension of life beyond 60 years is under evaluation by the nuclear energy industry and the NRC.

The extended operation of the existing reactors mandates the maintenance of the industry's excellent safety record and high (>90%) capacity factors. To achieve these goals continued improvements in plant operations, training, equipment and maintenance are required. Technologies and R&D investments necessary to extend reactor operation beyond 60 years include improved fuel performance, plant equipment with increased reliability, enhanced materials aging management programs, prognostic systems to optimize component life, and more efficient inspection and repair techniques. Additionally, enhanced systems analysis and integration capabilities are needed to support plant up-rates and optimization of plant systems. A successful outcome of these efforts would enable continued safe and cost efficient operations for many years to come. Advanced modeling and simulation of nuclear plant systems will become increasingly important in assessing materials aging, performance optimization, maintaining safety margins, and accelerating regulatory reviews.

Understanding and managing material aging and improving fuel performance are essential when considering extending reactor service life beyond 60 years and to maximize performance, while maintaining the requisite safety performance. Nuclear R&D facilities including fuel development laboratories, thermal irradiation capabilities, and hot cells for post irradiation examination are required to provide the needed understanding and improvements.

Conclusion – Invest in research and development to further improve and enhance the performance of the existing nuclear plants. Currently available nuclear facilities, with appropriate maintenance and improvements, provide the required facility resources in the near term.

Enhance nuclear education and training facilities to assure the availability of a well qualified and trained workforce – We recommend DOE reassert its legislated role as the steward of nuclear science and engineering education. In this role DOE should ensure that colleges and universities have adequate funding support for nuclear research and specialized nuclear education and R&D facilities including university research and training reactors. In addition, DOE should coordinate with other federal agencies to ensure the domestic needs for nuclear scientists and engineers are met in an integrated and cost effective manner. Strong academic programs are critical to achieving the excellence in science and engineering which is the essential foundation for the continuing success of nuclear energy in the U.S. Universities with successful programs can play key roles in preparing the next generation of nuclear scientists and engineers to meet the national energy needs.

Education is the foundation for building the core competencies that the U.S. needs if the energy security and environmental goals are to be achieved. The development of a robust nuclear energy workforce is upmost on industry's agenda, and is critically important for our national research infrastructure. Workforce development has to be a shared investment between industry and DOE, with each having responsibility for key areas. Industry has urgent concerns with the building, startup, and operation of advanced light water reactors, as well as the replacement of an aging workforce for the existing nuclear plants and programs. This requires skilled craftsmen, technicians and degreed engineers and improved training and development methods. DOE's focus is primarily on developing degreed personnel to ensure the development of needed core competencies in science and technology, which would enhance U.S. competiveness, and sustain a robust research capability.

In prior decades, nuclear engineering enrollments diminished and investment in nuclear education facilities commensurately waned. The latter was highlighted by closure of more than half of the university research reactors. In spite of this erosion of capability, nuclear engineering education is still an area of U.S. leadership, an asset that must be preserved, particularly now that undergraduate enrollments have increased to record levels.

An effective university nuclear science and education program would consist of the following elements:

1. Basic infrastructure and core competency development – to provide for the development and maintenance of the national educational infrastructure and core competencies through scholarships, fellowships and young faculty and researcher grants.
2. Long-term competitive peer-reviewed university R&D programs involving research projects that are mission and idea driven – to enable the development of basic technology needed for the next 20 years and beyond.
3. Laboratory and industry driven R&D programs – to provide significant opportunity for national laboratories, universities, and industry to work together on DOE NE program mission driven R&D.

Further, DOE is encouraged to join industry, professional organizations, state and local communities in supporting K-12 and trade school education with carefully selected, highly leveraged projects. Great effectiveness can be achieved by linking and leveraging these activities with university nuclear science and engineering programs.

Conclusion – New investment in education and training capabilities is required – further evaluation of specific facility requirements is necessary.

Develop and demonstrate next generation reactor technologies that expand the applications of nuclear energy – We recommend DOE continue developing productive partnerships with industry in order to expand the nuclear market into applications beyond generating electricity. In particular, the immediate opportunity is in supplying process heat for industrial applications. There is also a developing market for regional small to intermediate size reactors. Thanks to technology readiness resulting from previous investments, the U.S. can exercise international leadership in both of these areas if DOE makes them priority goals.

Advanced Light Water Reactors (ALWRs) are excellent for generating electricity. However, if we are to use nuclear energy to help provide other forms of energy, we have to develop and deploy higher temperature reactor systems. The use of water as a coolant restricts ALWRs to about 300C. Process heat applications for refiners and chemical plants require 250 to 550C, oil shale and tar sands processing requires 300 to 600C, electricity and steam cogeneration requires 350 to 800C, reforming of natural gas into hydrogen requires 500 to 900C while thermo-chemical processes or high temperature electrolysis of water into hydrogen and oxygen requires 550 to 1000C.

Demonstrating the use of nuclear energy for the production of process heat is an excellent opportunity for U.S. leadership in a developing market that could rival the electricity sector. High-temperature gas (helium) cooled reactors (HTR) have been under development for more than 40 years. Japan, France, China and India all have HTR development programs. The only large scale prototype currently under development is the Pebble Bed Modular Reactor (PBMR) in South Africa, which is designed to use the Brayton cycle to generate electricity. However, to be deployable in the U.S., the HTR technology must be demonstrated in a NRC licensed plant of sufficient size to convince the end users of its viability and potential competitiveness with other forms of energy, particularly natural gas.

The Next Generation Nuclear Plant (NGNP) is a publicly/privately funded partnership to design, license, build and operate a high temperature nuclear demonstration plant that will generate both electricity and hydrogen using process heat to drive a thermo-chemical or high-temperature electrolysis water splitting process. The NGNP would be the only large (300 to 400 MWth) demonstration of a combined electricity/process heat plant. The current DOE program addresses major technical issues such as fuel reliability and structural graphite and regulatory issues such as plant licensing. Engineering development and component test facilities are also needed to support demonstration of the NGNP.

In the past two years, the potential demand for small to intermediate size reactors in the 10 to 600 MWe size seems to be growing in areas that do not have the infrastructure for large ALWRs. While these reactors are thought to be primarily for developing countries, there may be a strong market for intermediate and small reactors in the less populated parts of the U.S. DOE should explore this need through a program like NP-2010 letting the industry take the lead on development, licensing, and deployment.

Conclusion – Provide continuing and sufficient federal resources to the NGNP and its supporting technologies to meet the public obligations of the partnership and assist with the licensing of first of a kind small to intermediate size reactors.

Develop the affordable, proliferation-resistant recycle technologies needed to create a sustainable fuel cycle – We recommend DOE: (1) maintain a substantial R&D program to develop the technologies required to implement a sustainable nuclear fuel cycle in the U.S., (2) increase university support to build a viable workforce, particularly in the field of radiochemistry, (3) implement a short-term strategy to increase the extent of collaborative R&D programs with those countries currently recycling nuclear fuel, including Japan, France and the UK, and (4) work with industry to develop improved, commercially viable technologies. In support of these recommendations, DOE should maximize the use of available domestic facilities for the development of a sustainable closed nuclear fuel cycle.

The current open nuclear fuel cycle discards the majority of the potential energy of the uranium as radioactive waste, a practice that may not be sustainable in light of the anticipated large global expansion of nuclear energy in the 21st century. The Yucca Mountain geologic repository for used nuclear fuel is at an early stage of license review and will not be available for many years. Used nuclear fuel is currently stored at the various utility reactor sites. The utilities expect to move used nuclear fuel offsite based on their existing agreement with the U.S. government. The used fuel can be safely stored for decades, so there is no immediate urgency to reprocess the fuel or put it in a deep geological repository. Nevertheless, there is **an urgency to proceed with an interim storage plan** that assures the public and the utilities that there is a national solution for the management of used nuclear fuel.

While there is no immediate uranium resource limitation, foreign experience has shown that development of affordable recycling technologies with robust, designed-in anti-proliferation features will likely take decades to develop and implement. It is in the security interest of the U.S. to remain highly engaged with the international community on the development and implementation of the sensitive technologies of the nuclear fuel cycle. Recycling nuclear fuel is practiced by several foreign countries, but the facilities require a significant (billions of dollars) upfront capital investment. Research is needed on methods to: make used fuel recycle more economical; develop advanced nuclear fuels; provide better methods of waste management; and develop and demonstrate new technologies for non-proliferation. These efforts require special facilities that can be operated safely while allowing research staff to work with highly radioactive materials

Over the last 30 years, many of the fuel cycle research and development facilities have been shut down due to lack of funds for sustained research and increased costs for maintenance and regulatory compliance. A few facilities are still operating in the national laboratory system which should continue to be used for R&D efforts supporting a sustainable nuclear fuel cycle, although significant investments will be required to meet 21st century research, safety standards and safeguards requirements.

For the longer-term, the concept of an Advanced Fuel Cycle Facility that incorporates all the necessary capabilities should continue to be evaluated. A decision is needed as to whether these capabilities should be distributed, or consolidated into a single new facility or some combination of upgraded facilities and new construction. A careful analysis is recommended to determine a cost-effective strategy that minimizes the number of high security facilities and optimizes the use of existing capabilities.

Conclusion – Additional investment in domestic facilities and collaborative use of foreign facilities is necessary to provide the capabilities to develop technologies for closure of the fuel cycle. Near-term fuel cycle R&D activities should maximize the use of currently available facilities.

Improve the utilization of uranium resources and reduce waste disposal requirements through the continued development of fast reactor technology – We recommend developing fast reactor technology by building on our fast reactor core competencies and industrial development experience, enhancing cost-shared international collaboration, and ultimately a licensed prototype.

The U.S. is losing its expertise in fast reactor technology developed in the 1970s and 1980s. With the expected global surge of new nuclear installations, fast reactors are likely to emerge as a major sector of the nuclear mix because of their unique potential for resource utilization and waste management. Having closed major elements of its fast reactor development infrastructure such as the Experimental Breeder Reactor-II and the Fast Flux Test Facility, DOE should consider an interim strategy of rebuilding core competency using existing capabilities and relying on participation in fuel irradiation and other testing in international facilities.

Fast reactors are likely to have a central role in sustaining the nuclear fuel cycle later in the 21st century. They will convert troublesome actinides into high-quality energy sources and readily managed short-lived fission products. The technology supporting design of sodium-cooled fast reactors (SFR) is extensive, the result of over 50 years of R&D in the U.S. and other countries. Active SFR development programs are under way in China, France, India, Japan, South Korea and Russia. The U.S., France and Japan have recently signed a trilateral agreement for sharing the development of SFR technology. The global interest in SFR provides an excellent opportunity for the U.S. to leverage its significant investment in fast reactor technology development through strengthened international collaborations. It is further recommended that the U.S. provide technical leadership for SFR development by establishing a recognized core competency in several critical technology areas such as advanced fuels, safety, and power conversion.

Conclusion – Combining recognized core competencies in critical areas with a robust program of international collaboration will position the U.S. to move forward with its own licensed prototype demonstration when appropriate.

Utilize advanced modeling and simulation to accelerate the development and deployment of nuclear systems **–** We recommend DOE NE develop a robust nuclear modeling and simulation capability to accelerate the development and deployment of nuclear energy systems. Capabilities required include strengthened core competencies, modern software, high-performance computing, preservation of unique integral test data, and specialized capabilities for single effects testing.

Nuclear science and technology has not taken advantage of advances in modeling and simulation capabilities that have benefitted other technologies and scientific disciplines. While modeling and simulation does not replace the need for experiments, it can be used to inform the design of experiments, make better use of experimental data, greatly reduce development cycle length, and quantify safety and performance margins. Advanced modeling and simulation is an essential crosscutting tool for improving the performance of current reactors, and for the development and licensing of next generation nuclear reactors and improved fuel recycle technologies. We recommend that DOE NE at a minimum take the following four steps in the near term to accelerate the application of advanced modeling and simulations to nuclear energy systems:

1. Improve access to existing advanced modeling and simulation capabilities. DOE through the NNSA and Office of Science has extensive capabilities in advanced modeling and simulation. An initiative should be undertaken to provide quick access to the existing capabilities for application to nuclear energy systems.
2. Define the architecture needed for the advanced modeling and simulation of nuclear energy systems. Understanding the needed architecture (hardware, software, core competencies) over the development life cycle of advanced nuclear systems will provide an understanding of the investment required. The nuclear energy industry should participate as a user of such capabilities in the definition of the required architecture.
3. Establish a pilot program to demonstrate the value added by advanced modeling and simulation for improving the performance and operation, in particular materials aging management, of the current nuclear plants, for the design of new nuclear systems, safety analysis and licensing.
4. Quickly establish a low-cost, high-value program to document, validate and archive data from prior large scale experiments that would be impossible to repeat today. At minimum, an archive should be developed and maintained for physics, thermal-hydraulic, safety, fuels, and materials data. The archive should include any available test samples.

Conclusion – Develop a robust nuclear modeling and simulation capability to accelerate the development and deployment of nuclear energy systems.

Establish a new initiative for investing in required nuclear energy capabilities **–** We strongly recommend a Strategic Nuclear Energy Capability Initiative be established to provide the significantly increased investment needed to reestablish an internationally viable U.S. nuclear science and technology infrastructure.

Funds provided through the Initiative would be used to build core competencies, foster collaborations between industry, academia, and the national laboratories, enhance capabilities, maintain and modify currently available facilities and provide new R&D facilities and associated equipment. This Initiative would also provide the financial foundation for DOE NE participation in public-private partnerships and international collaborations to leverage U.S. taxpayer investment in required capabilities and facilities. To be successful, the **Strategic Nuclear Energy Capability Initiative** must have the following attributes:

1. Utilize an integrated, time-phased, and user-driven approach. The initial focus would be on building core competency in nuclear science and engineering, procurement of needed research equipment, improvement in current R&D facilities, and development of user-driven concepts for needed new R&D facilities.
2. Provide multi-year investments in a manner that enables efficient development of capabilities, commissioning of the needed facilities, and decommissioning of obsolete facilities.
3. Engage the nuclear energy industry, universities, and the national laboratories in the development and evaluation of user-driven concepts to provide the rationale for the investment to build over time to enable the construction of the new R&D facilities. Integrated periodic reviews of the Initiative with the user of the capabilities and facilities should be conducted to help ensure the investment is yielding the desired results.

Conclusion – Establish the Strategic Nuclear Energy Capability Initiative to provide the required resources during this critical period of time to assure the proper utilization of nuclear energy.

Recommendations

Based upon this independent analysis of the required R&D capabilities in the 2010 to 2050 timeframe the following recommendations are made.

1. Invest in research and development to further improve and enhance the performance of the existing nuclear plants. Currently available nuclear facilities – with appropriate maintenance and improvements – provide the required research capabilities for extending the safe and useful life of the existing nuclear fleet.
2. New investment in education and training capabilities is required to assure the availability of a well-qualified and trained workforce. Further evaluation of specific facility requirements is necessary.
3. Provide continuing and sufficient federal resources to the NGNP and it supporting technologies to meet the public obligations of the partnership and assist with the licensing of first-of-a-kind small to intermediate size reactors to develop and demonstrate next generation reactor technologies that expand the applications of nuclear energy.
4. Additional investment in domestic facilities and the collaborative use of international facilities will be necessary to address all of the activities necessary to create a sustainable fuel cycle. Near-term fuel cycle R&D activities should optimize the use of currently available facilities.
5. Combine recognized fast reactor core competencies in critical areas with a robust program of international collaboration to position the U.S. to move forward with its own licensed prototype demonstration when appropriate in order to improve the utilization of uranium resources and reduce waste disposal requirements.
6. Develop a robust nuclear modeling and simulation capability to accelerate the development and deployment of nuclear energy systems.
7. Establish the Strategic Nuclear Energy Capability Initiative to provide the required resources during this critical period of time to assure the proper utilization of nuclear energy.

Appendix A

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