Reactor and Fuel Cycle Technology Subcommittee
Report to the Full Commission

DRAFT

Blue Ribbon Commission on America’s Nuclear Future (BRC)
Washington, DC
June, 2011

PREAMBLE

The Reactor and Fuel Cycle Technology Subcommittee of the Blue Ribbon Commission on America's Nuclear Future (BRC) was formed to examine issues related to the potential of existing and future reactor and fuel cycle technologies and related research and development (R&D) programs. The Subcommittee was co-chaired by the Honorable Pete Domenici and Dr. Per Peterson and included the following Commissioners: Dr. Albert Carnesale, Susan Eisenhower, Dr. Allison MacFarlane, Dr. Richard Meserve, Dr. Ernest Moniz, and the Honorable Phil Sharp. BRC co-chairs, Rep. Lee Hamilton and Gen. Brent Scowcroft, participated as members *ex officio*.

The scope of the Subcommittee's work is outlined in the BRC's charter, which states that the Commission will "provide advice, evaluate alternatives, and make recommendations for a new plan" to address a series of issues related to managing the back end of the nuclear fuel cycle, including specifically: "Evaluation of existing fuel cycle technologies and R&D programs. Criteria for evaluation should include cost, safety, resource utilization and sustainability, and the promotion of nuclear nonproliferation and counter-terrorism goals."

Subcommittee members met three times between July 2010 and October 2010 to hear testimony from experts and stakeholders and to discuss the issues before the Subcommittee. Subcommittee members also traveled to France, Japan, and Russia in early 2011 to visit advanced reactor and fuel cycle facilities in those countries and hear about their programs. Subcommittee members also visited Department of Energy facilities at the Idaho National Laboratory, at the Hanford, Washington site and at the Savannah River Site in Aiken, South Carolina. A wide variety of organizations, interest groups, and individuals provided input to the Subcommittee at meetings and through the submission of written materials (copies of all of these submissions, along with records and transcripts of past meetings, are available at the BRC website (www.brc.gov). The Subcommittee benefitted greatly from these inputs as well as from public feedback on the "What We've Heard" report prepared by the Commission staff. We are indebted to the many people who have offered their expertise, advice and guidance.

This report highlights the Subcommittee's conclusions and findings to date and articulates a set of consensus recommendations for further consideration by the full Commission. It also provides a summary of the background and context, technical considerations, and stakeholder input that have informed the Subcommittee's findings and recommendations.

The Subcommittee welcomes comment on this report from all interested parties. Comments can be submitted electronically at www.brc.gov or by mail at:

Blue Ribbon Commission on America's Nuclear Future
c/o U.S. Department of Energy
1000 Independence Avenue SW, Washington, DC 20585

A draft of the full Commission's main report will be released by July 29, 2011 in accordance with the schedule set out in our charter. To be considered as the Commission develops the first public draft of its main report, comments on this Subcommittee report must be received by July 15, 2011. All comments will be made publicly available on the Commission website. Any comments received after July 15th will be considered as the Commission prepares its final report, which is due to the Secretary of Energy by January 29, 2012.

EXECUTIVE SUMMARY

The Reactor and Fuel Cycle Technology Subcommittee was formed to respond to the charge—set forth in the charter of the Blue Ribbon Commission—to evaluate existing fuel cycle technologies and R&D programs in terms of multiple criteria. According to the charter: "Criteria for evaluation should include cost, safety, resource utilization and sustainability, and the promotion of nuclear nonproliferation and counter-terrorism goals." Given the Commission's specific focus on policies for managing of the back end of the nuclear fuel cycle, the Subcommittee also addressed the closely related question of whether any currently available reactor and fuel cycle technologies, or any not-yet commercial technologies that are now under development, have the potential to change either the fundamental nature of the nuclear waste management challenge the United States confronts over the next several decades or the approach the U.S. should take to implement a plan for the storage and ultimate disposition of spent nuclear fuel and high-level radioactive waste.

To answer these questions, the Subcommittee reviewed the most authoritative available information on advanced reactor and fuel cycle technologies, including the potential to improve existing light-water reactor technology and the once-through fuel cycle, as well as options for partially or fully closing the nuclear fuel cycle by reprocessing and recycling spent nuclear fuel. We also reviewed the current research plan and proposed budget of the Department of Energy's Office of Nuclear Energy and the adequacy of existing regulatory and legal frameworks to accommodate new reactor and fuel cycle technologies and facilities. It is important to emphasize at the outset that the Subcommittee did not undertake original research on the merits of different technologies and fuel cycle options; rather, we relied on several existing studies from a variety of reputable sources. To conduct a wholly new assessment at the level of detail and technical rigor needed to meaningfully augment the results of previous assessments was deemed unrealistic given the scope and resources of the BRC as constituted and is in any case not necessary to fulfill the charge to the Subcommittee as we understand it.

As this Subcommittee's work has proceeded, we have witnessed the unfolding of a severe nuclear accident at the Fukushima Daiichi nuclear power station in Japan. These events have underscored the importance of nuclear safety as a primary criterion in the development and application of nuclear technology. They have also underscored the importance of treating spent fuel management and storage as a central part of the safety regime. Technological advances hold promise for improving the safety of nuclear energy systems—ensuring that this promise is realized must be a priority of U.S. nuclear policy, with respect to both RD&D investments and deployment decisions.

The Subcommittee's central conclusion, detailed at greater length in the pages that follow, is two-fold:

(1) Advances in nuclear reactor and fuel cycle technologies may hold promise for achieving substantial benefits in terms of broadly held safety, economic, environmental, and energy security goals. To capture these benefits, the United States should continue to pursue a program of nuclear energy research, development, and deployment (RD&D) both to improve the safety and performance of existing technologies and to develop new technologies that could offer significant advantages in terms of the multiple evaluation criteria identified in our charter (i.e., safety, cost, resource utilization and sustainability, waste management, and non-proliferation and counter-terrorism).

(2) No currently available or reasonably foreseeable reactor and fuel cycle technologies—including current or potential reprocess and recycle technologies—have the potential to fundamentally alter the waste management challenge this nation confronts over at least the next several decades, if not longer. Put another way, we do not believe that new technology developments in the next three to four decades will change the underlying need for an integrated strategy that combines safe, interim storage of spent nuclear fuel with expeditious progress toward siting and licensing a permanent disposal facility or facilities. This is particularly true of defense high-level wastes and some forms of government-owned spent fuel that can and should be prioritized for direct disposal at an appropriate repository.

It is important to note that both of the above points stand independently of any conclusion one might reach about the desirability of closing the nuclear fuel cycle in the United States. The Subcommittee could not reach consensus on this issue. *As a group we concluded that it is premature at this point for the United States to commit irreversibly to any particular fuel cycle as a matter of government policy. Rather, there is a benefit to preserving and developing new options.* RD&D should continue on a range of reactor and fuel cycle technologies, described in this report, that have the potential to deliver societal benefits at different times in the future. If and when technology advances change the balance of market and policy considerations to favor a shift away from the once-through fuel cycle, that shift will be driven by a combination of factors, including—but hardly limited to—its waste management impacts. In fact, safety, economics, and energy security are likely to be more important drivers of future fuel cycle decisions than waste management concerns *per se*.

In light of these central conclusions our recommendations are summarized below.

<u>Recommendation #1</u>: ***The U.S. government should provide stable, long-term RD&D (research, development, and demonstration) support for advanced reactor and fuel cycle technologies that have the potential to offer substantial benefits relative to currently available technologies in terms of safety, cost, resource utilization and sustainability, the promotion of nuclear nonproliferation and counter-terrorism goals, and waste storage and disposal needs. A well-designed federal RD&D program is critical to enabling the U.S. to regain its role as the global leader of nuclear technology innovation and should be attentive to opportunities in two distinct realms:***

1) ***Near-term improvements in the safety and performance of existing light-water reactor technology as currently deployed in the United States and elsewhere as part of a once-through fuel cycle, and in the technologies available for storing and disposing of spent nuclear fuel and high-level waste.***

2) ***Longer-term efforts to advance potential "game-changing" nuclear technologies and systems that could achieve very large benefits across multiple evaluation criteria compared to current technologies and systems.*** *Examples might include fast-spectrum reactors demonstrating passive safety characteristics that are capable of continuous actinide recycling and that use uranium more efficiently, or reactors that—by using molten salt or gas coolants—achieve very high temperatures and can thereby supply process heat for hydrogen production or other purposes, or small modular reactors with novel designs for improved safety characteristics and the potential to change the capital cost and financing structure for new reactors.*

In making this recommendation and the one that follows, the Subcommittee is mindful that federal RD&D funding of all kinds will be under enormous budget pressure in the years ahead. It will therefore be especially important to focus scarce public resources on addressing key gaps or needs in the U.S. nuclear RD&D infrastructure and to leverage effectively the full range of resources that exist in industry, the national laboratories, and the academic community. Furthermore, while the charge of this Subcommittee is to make recommendations to the government, we also want to clearly emphasize the importance and value of continuing and stable industry RD&D investment in reactor and fuel cycle technologies.

In the effort to target scarce resources as effectively as possible, the Subcommittee recommends funding well-designed, multi-purpose national scientific user test facilities[1], following the model of the Advanced Test Reactor Scientific User Facility at Idaho National Laboratory, that can be used to advance knowledge in several areas of inquiry. Such national user facilities exemplify the kind of RD&D infrastructure that could yield particularly high returns on public investment.

Recommendation #2: ***The Subcommittee concurs with the recent findings of the President's Council of Advisors on Science and Technologies (PCAST) concerning the need for better coordination of energy policies and programs across the federal government; for a substantial increase in federal support of energy-related research, development, demonstration, and deployment; and for efforts to explore new revenue options to provide this support.***[2]

Specifically, the recent PCAST report endorsed an earlier proposal by the American Energy Innovation Council[3] to provide $16 billion in annual federal support for energy technology innovation—an increase of $10 billion per year over current funding levels, with all of that increase coming from new revenue sources. Of this $16 billion-per-year total, PCAST recommends that $12 billion be directed to basic R&D and $4 billion to large-scale demonstration projects. The U.S. Department of Energy's budget for nuclear energy R&D in recent years has totaled approximately $500 million per year. Additionally, the Subcommittee notes that the recent MIT study estimates that about $1 billion per year is appropriate for supporting the necessary nuclear R&D and infrastructure programs.[4] However, the Subcommittee does believe that judgments about the appropriate level of funding will ultimately depend on the overall resources available for energy innovation and must be made in the context of a broader assessment of energy policy goals and the potential of different energy technology options.

Recommendation #3: ***A portion of the federal nuclear energy RD&D resources should be directed* to *the U.S. Nuclear Regulatory Commission (NRC) to accelerate a regulatory framework and supporting anticipatory research for novel components of advanced nuclear energy systems. An increased degree of confidence that new systems can be successfully***

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[1] National scientific user facilities (NSUF) provide specialized instrumentation and expertise that enable scientists and other users to carry out experiments that could not be done in their own labs.

[2] President's Council of Advisors on Science and Technology (PCAST). *Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Federal Energy Policy*. November 2010. Available at: http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-energy-tech-report.pdf.

[3] American Energy Innovation Council (AEIC) – A Business Plan for American's Energy Future – http://www.americanenergyinnovation.org/full-report

[4] The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study, Massachusetts Institute of Technology, 2010

licensed is important for lowering barriers to commercial investment.

The Subcommittee believes that NRC efforts in this area—including new efforts in anticipatory research, some of which are already underway—should receive 5 to 10 percent of total federal funding for reactor and fuel cycle technology RD&D.[5] While 5 to 10 percent would represent a relatively small fraction of total federal investment in nuclear energy RD&D, it would amount to a large increase in the amount of funding devoted to developing an improved regulatory framework for new nuclear energy technologies and would further strengthen the NRC's scientific and technical capability to act as an independent regulator. Finally, we support the NRC's current risk-informed, performance-based approach to developing regulations for advanced nuclear energy systems.

Recommendation #4: ***The United States should continue to take a leadership role in international efforts to address global non-proliferation concerns and to improve the safety and security of nuclear facilities and materials worldwide. This could include: support for multi-national, industrial-scale fuel cycle facilities, joint efforts with other countries to improve security and accountability technologies and protocols for nuclear materials and capabilities, and improvements in existing multilateral agreement frameworks.***

The Subcommittee heard a range of views on whether and to what extent U.S. fuel cycle decisions and policies have influenced fuel cycle decisions made by other nations over the past several decades. Whatever view one has about the past, the Subcommittee believes that it is important for the United States to play a leadership role in technological and diplomatic efforts to reduce proliferation risks and improve the safety and security of nuclear materials and facilities worldwide. This should occur both via the U.S. nuclear community's involvement in international efforts to advance better nuclear energy technologies and management approaches and through U.S. participation in international nonproliferation and nuclear security regimes and initiatives. The Fukushima accident, in particular, should prompt concerted efforts by international organizations, nuclear industry regulators, technology vendors, nuclear system operators, and technical support organizations to promote the safe application of nuclear energy systems and the safe management of nuclear wastes in all countries that pursue this technology.

The Subcommittee recognizes the importance of continued development of modern safeguards and security technologies for application in existing facilities and in combination with

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[5] Almost 90% of the NRC's budget comes from fees charged to licensees with only 10% coming from federal appropriations. It is important to note we are emphasizing the increase in funds for the development of the necessary regulatory frameworks comes from the government and not from licensee fees.

safeguards-by-design approaches for new facilities. Maintaining accurate knowledge of the location and inventories of nuclear materials is a common requirement for International Atomic Energy Agency (IAEA) safeguards, physical security, and safety. Technical innovations to support nuclear safeguards and security, particularly those of verification and material accountancy, containment and surveillance, material control, and environmental monitoring are of high value for providing assurances of compliance with the IAEA safeguards regime and with emerging international norms for physical security, and should be maintained through existing efforts of the federal government, both domestically and in collaboration with international partners.

While the work of the Subcommittee focused on advanced reactor and fuel cycle and associated technologies, we also recognize that the goals of nonproliferation and nuclear security cannot be achieved by primarily technological means. Rather, success in this area depends on the effectiveness of diplomatic arrangements to strengthen the current nonproliferation regime, such as broader adoption of the IAEA's Additional Protocol, promoting policies, technologies, and fuel cycle choices that reduce proliferation risks while also taking steps to improve the security of nuclear materials and facilities, and continued use of bilateral nuclear cooperation agreements as effective policy tools.

With respect to U.S. policy for the nuclear fuel cycle, this Subcommittee believes that the establishment of multinational or regional fuel cycle facilities under comprehensive IAEA safeguards could be a very positive development, giving countries an option to enjoy more reliable access to the benefits of nuclear power while simultaneously reducing proliferation risks. Similarly, spent fuel take-away arrangements[6] would allow countries, particularly those with relatively small national programs, to avoid the very costly and politically difficult step of providing for waste disposal on their soil. Fuel take-away could also provide a strong incentive for emerging nuclear nations to take key actions, such as ratifying the IAEA Additional Protocol, that can strengthen non-proliferation and further isolate the current small number of problematic proliferant states.

The United States has implemented a relatively small but successful initiative to ship used foreign research reactor fuel to U.S. facilities for storage and disposal. This program has demonstrated meaningful nonproliferation and security benefits. *A similar capability to accept spent fuel from foreign commercial reactors in limited quantities, in cases where the President would choose to authorize the imports for reasons of U.S. national security, would be a*

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[6] Spent fuel take-away arrangements are broadly defined as negotiated agreements for governments with fuel cycle capabilities to assume liability for supplied or obligated fuel and develop permanent disposition solutions for managing used fuel in concert with countries seeking nuclear energy.

desirable component of a larger policy framework that creates a clear path for the safe and permanent disposition of U.S. spent fuel. The decision to authorize imports of foreign spent fuel would have to be clearly linked to progress in developing storage and permanent disposal capacity for U.S. wastes; thus, implementing effective domestic nuclear waste management strategies can serve U.S. nonproliferation objectives. Unfortunately, the failure to develop broadly-accepted domestic nuclear waste management strategies limits U.S. nonproliferation policy choices in the context of nuclear fuel cycles. Government support for limited fuel supply and take-away initiatives to advance U.S. national security interests could change the way disposal facilities are perceived by the public and by the national security community—not simply as final resting places for nuclear waste, but as essential elements of a comprehensive strategy for maintaining the nuclear energy option while simultaneously addressing proliferation and security concerns.

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Implicit in the charter of the Blue Ribbon Commission is the recognition that any discussion of new reactor and fuel cycle technologies must be framed in terms of widely held policy objectives—objectives that are relevant not only to the future of the U.S. civilian nuclear power industry, but to our nation's ability to advance a much broader set of social, economic, energy, environmental, and national security goals. We should be interested in new reactor and fuel cycle technologies to the extent that they offer tangible benefits compared to currently available technologies and to the extent they make it possible to maximize the energy contribution from nuclear power while also minimizing associated costs and risks. In other words, the Subcommittee takes the view that future decisions concerning the development and deployment of advanced reactor and fuel cycle technologies should be driven by broader energy policy objectives, rather than by any *a priori* commitment to a particular system or fuel cycle option.

Un-tethered from these underlying policy objectives, technology discussions too often devolve into debates between proponents of one system versus another or, in the nuclear context, between proponents of one fuel cycle or reactor design versus another. Whether the United States should adopt the long-term strategic goal of closing the nuclear fuel cycle, in particular, has been a contentious and much-debated question for decades. Members of the Subcommittee hold a range of views on the subject. Other countries (notably France, Russia and Japan) have determined that energy security or other policy goals take precedence over the often conflicting goal of minimizing energy costs. The apparently believe that the higher short-term costs of developing and deploying advanced nuclear systems are justified in order to achieve their long-term policy aims, or perhaps they assume higher future prices of uranium and enrichment and lower costs for reprocessing. However, particularly in the immediate aftermath of the Fukushima incident, which has caused some rethinking about reactor safety issues, it would be extremely difficult and probably premature for us to attempt to settle that question for the United States at this point in time. Though research efforts to date have yielded several potentially promising reactor designs and fuel cycle concepts, there are a number of remaining uncertainties—encompassing questions not only of technical performance, cost, commercial viability, and proliferation and security impacts, but also questions about how the specific attributes of different options will mesh with economic and social conditions that are continuously evolving as well and with the uncertain trajectory of nuclear power utilization in the future.

In contrast, there is much less uncertainty about the underlying energy and nuclear technology challenges we face in the decades ahead. There is also far more consensus about what would constitute desirable outcomes. Safety, cost, resource utilization and sustainability, security and non-proliferation, and waste management are sure to remain paramount concerns that—together with broader questions of public acceptance and overall competitiveness with other energy resources—will be key to the nuclear industry's long-term prospects, not only in the United States but worldwide. Looking beyond nuclear power to the larger set of energy issues, the challenges are well-identified and even more daunting: At a global level, the central question is how to reconcile overall energy demand, including rapidly rising consumption in the developing world, with emerging environmental and resource constraints and without impeding economic development, exacerbating geopolitical tensions, or increasing the potential for national and regional conflicts. At a national level, the challenge for the United States is to position itself to meet future energy needs in ways that are also congruent with sustaining a vigorous domestic economy, maintaining global technological and scientific leadership, protecting public health and the environment, mitigating the impacts of climate change, and reducing energy-related national security risks and terrorism threats.

The analysis is further complicated not only because of the need to chart a path that balances a diverse set of goals, but also the need to evaluate these goals across a diverse set of activities. The full fuel cycle involves at the least mining, milling, conversion, enrichment, fuel fabrication, reactors, storage, and disposal, with possible addition of reprocessing/recycling facilities. Fuel cycles should be analyzed as an interconnected system in which each element must be compatible with and support the other elements. Our national objectives are not served by the development of reactors that are very efficient, but that do not mesh, for example, with a reprocessing or disposal system. Thus, all the components in an advanced fuel cycle should be examined as part of a system in which all the components should work together.

In sum, the Subcommittee concludes it is both more important and more productive at this time to focus on designing and implementing a nuclear research, development, and demonstration strategy that makes effective use of scarce resources and is continuously responsive to the broader policy objectives about which we already have broad agreement (as opposed to seeking consensus on the merits of particular technology and fuel cycle pathways). Our full report elaborates further on these issues and outlines the Subcommittee's findings regarding the potential advantages and disadvantages of different reactor and fuel cycle options.

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FIGURES

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LIST OF ACRONYMS

ALWR	advanced light water reactor
BRC	Blue Ribbon Commission on America’s Nuclear Future
BWR	boiling water reactor
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
FR	fast reactor
HTR	high temperature reactor
INL	Idaho National Laboratory
INPO	Institute of Nuclear Power Operations
IT	information technology
LWR	light water reactor
MC&A	material control and accountability
MOC	modified open (fuel) cycle
MOX	mixed oxide (fuel)
MW	megawatt
MWe	megawatt (electric)
MTHM	metric tons of heavy metal
MTU	metric tons of uranium
NEI	Nuclear Energy Institute
NNSA	National Nuclear Security Administration
NRC	Nuclear Regulatory Commission
OT	once-through (fuel cycle)
PUREX	plutonium uranium extraction
PWR	pressurized water reactor
R&D	research and development
RD&D	research, development, and demonstration
SNF	spent nuclear fuel
TMI	Three Mile Island
TRU	transuranic
WIPP	Waste Isolation Pilot Plant

1. INTRODUCTION AND STRUCTURE OF REPORT

As directed by the BRC's charter, the R&FCT Subcommittee undertook to evaluate alternative nuclear energy systems according to specific criteria, all of which have direct relevance to the broader policy goals discussed in this and other BRC reports. Given the focus of the Commission's work as a whole, we paid particular attention to the implications of different reactor and fuel cycle alternatives for managing spent nuclear fuel, although (as we have already noted) we understand that waste considerations are only one of several drivers for future technology decisions.

Specifically, we looked at the following criteria:

- Safety of reactors and fuel cycle facilities
- Waste management
- Cost
- Sustainability
- Promoting nuclear non-proliferation goals
- Promoting counter-terrorism (physical security) goals

To organize our inquiry we began by identifying four broad strategies for alternative nuclear energy systems: the once-through cycle as currently practiced, an alternative once-through cycle, a modified open cycle, and a fully closed cycle.

Our findings concerning the potential advantages and disadvantages of specific technology options within each of these four broad categories are summarized in Chapter 3 of this report, which also provides a more detailed discussion of the evaluative criteria we applied in undertaking this (mostly) qualitative assessment. In many cases, more detailed and technically rigorous treatments are available in BRC commissioned papers (www.brc.gov) and other comparative analyses conducted in recent years by the National Research Council, DOE and others. Before turning to a discussion of different technology and fuel cycle options, however, we begin by providing some background and context. Chapter 2 of this report provides a very brief review of the history of nuclear technology development in the United States and worldwide together with an overview of the characteristics and features that distinguish different reactor technology and fuel cycle systems.

Later chapters of this report discuss the current federal nuclear RD&D program and identify potential RD&D needs and priorities going forward (Chapter 4) and then return (in Chapter 5) to the specific policy issues that have a large international dimension, specifically safety, and non-proliferation and counter-terrorism (including physical protection).

2. NUCLEAR FUEL CYCLE BACKGROUND

2.1 A Brief Review of Nuclear Power Development in the United States

The first demonstration of nuclear fission occurred in a rudimentary reactor built on the floor of a squash court at the University of Chicago in 1942. Fission technology was then used in the atomic weapons that ended World War II. After World War II, scientists who had accomplished these feats began work to develop peaceful uses for atomic energy, focusing primarily on electricity generation for industry, commerce, and household use. President Eisenhower's "Atoms for Peace" speech before the United Nations in 1953 heralded the promise of peaceful worldwide application of atomic power as well as means to limit its future use as a weapon.

During the early years of civilian nuclear power development a large number of test and demonstration programs examined most of the plausible pathways for harnessing nuclear power. Early progress was led by the Naval Nuclear Propulsion program, which built and launched the first nuclear powered submarine, the USS Nautilus, in 1955. Parallel efforts on experimental reactor designs in Idaho, and a land-based application of Nautilus reactor technology at Shippingport, PA, demonstrated the potential for practical, commercial-scale generation of nuclear electricity. During the early years, the U.S. government maintained leadership and ultimate control of these developments, but advocates for commercialization of nuclear technology for power generation, particularly in Congress, also began a process of transitioning the technology to the private sector.

Commercial nuclear power began to expand rapidly in the 1960s and 1970s, with 22 reactors operating in the United States in 1970, and over 50 more under construction. Although reactors fueled by low enriched uranium and cooled and moderated by light water were the norm, a few demonstrations were made of liquid-metal cooled reactors fueled by uranium and plutonium, as well as high temperature gas reactors cooled by helium and moderated by graphite, and a fluid-fueled molten salt reactor. (See Section 2.2 for reactor descriptions.)

From about the mid 1950s to the early 1970s it was assumed that uranium scarcity would require spent fuel from U.S. commercial power reactors to be reprocessed and the recovered materials used to fuel so-called "breeder" reactors. However, a series of events during the 1970s slowed and fundamentally changed the course of nuclear energy development:

- The 1973 Arab oil embargo that rapidly stunted the growth in the country's GNP and with it a rapid drop in the rate of growth of energy consumption in the U.S., from 7% per year to 2% to 3% per year.[7]

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[7] Congressional Budget Office, "Financial Condition of U.S. Electric Utility Industry", March, 1986.

- The testing of a nuclear explosive device in India in 1974, which changed perceptions of the proliferation risks associated with nuclear fuel cycles.
- The cessation of commercial fuel reprocessing ventures in the U.S. (West Valley, NY, Morris, IL, and Barnwell, SC) as a result of technological, economic and political pressures.
- The reactor accident at Three Mile Island (TMI) in Pennsylvania, which brought fundamental changes to nuclear regulation in the U.S., as well as a new system of self-monitoring established by the commercial nuclear industry.
- The decision by the Ford and Carter administrations not to provide Federal funds for reprocessing of commercial spent fuel, which was based primarily on proliferation concerns, along with other factors led to the adoption of a "once-through" fuel cycle and, subsequently, to the cancellation by Congress of the DOE-funded Clinch River Breeder Reactor project.

These events in the 1970s led to the cancellation of about 120 reactor orders. The slowdown developed into a full-blown hiatus in new nuclear plant orders that stretched from 1979 to today. This hiatus was the backdrop for new thinking about spent fuel management, as the Nuclear Waste Policy Act of 1982 and its amendment in 1987 both assumed very little nuclear energy development in the U.S. beyond the plants that existed at the time.

Following the TMI accident, the industry created the Institute of Nuclear Power Operations (INPO) to set uniform standards and to share best practices across the industry. Industry also undertook a number of other initiatives to cope with lost public confidence, rapid expansion of nuclear safety regulation, design and engineering problems being evidenced in plant operating experience, and poor nuclear plant economic performance in relation to competing fossil power generation.

A survey conducted by the Electric Power Research Institute (EPRI) in the early 1980s surprisingly found that nuclear utility executives were not ready to abandon nuclear energy as an option for the future.[8] However, these executives saw future growth in nuclear energy as contingent on major changes in the design, operation, and regulation of new reactors. They would demand safer and simpler designs that were easier to operate and maintain. They recognized that building in greater safety margins and maintainability features could increase the capital costs of nuclear power, but they appreciated that these investments could lead to higher plant availability and lower operating and maintenance costs over the life of the plant.

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[8] Jones, et al., "Technical and Institutional Preparedness for Introduction of Evolutionary Water Cooled Reactors." Presented at IAEA Symposium on "Evolutionary Water Cooled Reactors: Strategic Issues, Technologies, and Economic Viability", Seoul, Republic of Korea, 30 Nov. – 4 Dec., 1998

These executives also demanded a more stable and predictable licensing process for new plants.

Utility executives also rejected departures from proven fuels and materials. They strongly favored continued reliance on light water reactor technology, but also urged development of passive safety concepts to simplify LWR safety systems. Out of this survey grew the utility-led Advanced Light Water Reactor Program, which developed a Utility Requirements Document and funded, with matching support from DOE, the development of new advanced designs that are the basis for the new plants being licensed by the NRC for construction today.

Economic deregulation of electricity markets in the early 1990s, driven in part by the Energy Policy Act of 1992, put additional pressure on commercial nuclear power. Deregulation also created the possibility that nuclear plants with poor operating records, that otherwise might have been decommissioned, could instead be sold. Following the sales of the first few nuclear plants during the 1990's, it was found that their reliability and availability improved rapidly, often within 18 months, under new management practices. As shown in Figure 1, this coincided with a general trend of improving plant reliability and availability.

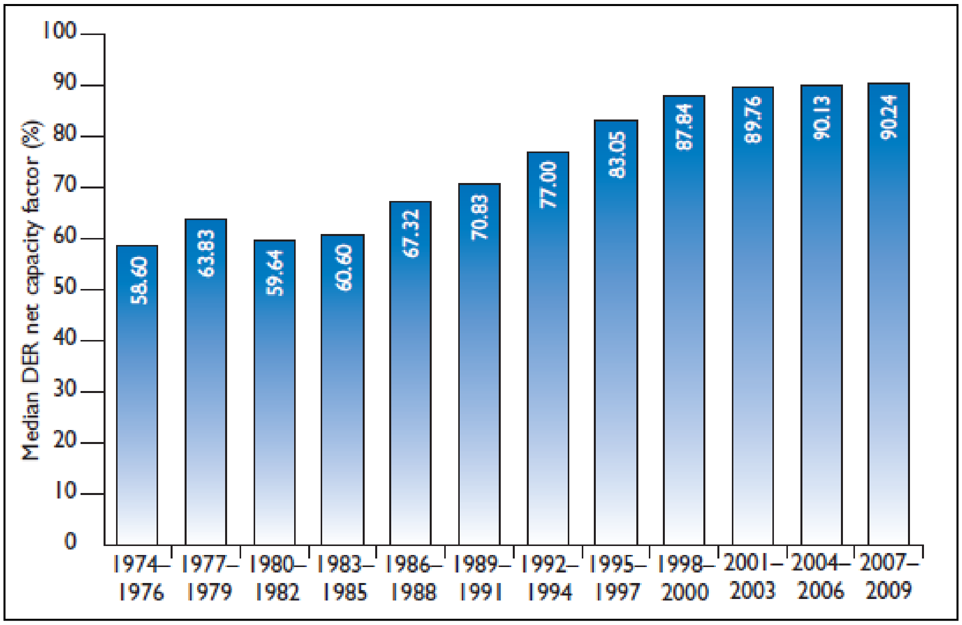

Figure 1. Median Design Electrical Rating (DER) capacity factor of the U.S. reactor fleet (1974-2009)[9]

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[9] Blake, E. Michael, "Capacity factor remains over 90%", Nuclear News, May 2010, pgs. 39-43.

Improving operating practices and plant reliability have contributed to a positive trend in workplace safety statistics (this is not surprising, as hazards to plant personnel tend to be lower during operating periods than during maintenance and refueling outages). While most safety related statistics show that the safety of U.S. reactors has improved significantly over the last two decades (for example, see Figure 2), significant safety problems have also occurred during this period. For example, inadequate in-service inspection and other flawed procedures and safety violations delayed the discovery of extensive corrosion of the reactor vessel head in the Davis Besse plant in 2002, caused by a persistent leak of borated water.

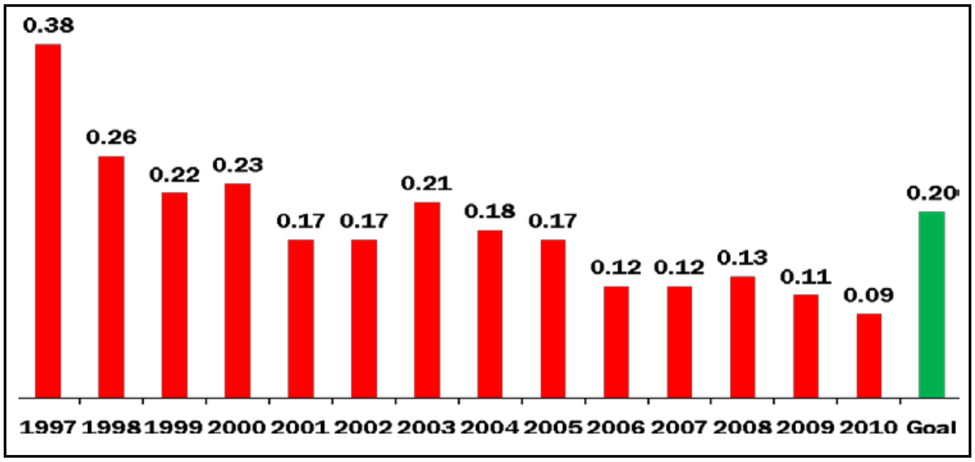

Figure 2. U.S. Nuclear Worker Lost-Time Injury Rate (1997-2010)[10]

The event at the Fukushima Daiichi reactors in Japan is the first major nuclear accident to be initiated by a severe natural disaster, rather than by a combination of equipment failures and human error. While natural disasters of this magnitude are fortunately rare, when they occur their effects on civil infrastructure must be studied closely, since it is impossible to study these effects fully in the laboratory. Clearly, as a first-of-a-kind and very severe event, the Subcommittee notes that the accident at Fukushima should be expected to provide a large number of lessons that will require changes to existing nuclear reactors, and will impact design and operation of new reactors as well.

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[10] Number of accidents resulting in lost work, restricted work, or fatalities per 200,000 worker hours. Nuclear Energy Institute (http://www.nei.org/resourcesandstats/documentlibrary/safetyandsecurity/graphicsandcharts/usnuclearindustrialsafetyaccidentrate/) and World Association of Nuclear Operators

2.2 A Primer on Reactor and Fuel Cycle Technology

This section provides an overview of the main characteristics and features that distinguish different types of reactors and fuel cycles. It is intended for the non-expert reader, as background for understanding the technology comparisons that are the subject of the next chapter (Chapter 3). We begin by describing four broad fuel cycle strategies or options: the once-through fuel cycle as currently practiced in the United States, an alternative once-through fuel cycle, the modified open fuel cycle, and the fully-closed fuel cycle. It is important to emphasize at the outset, however, that no rigorously specified definition exists for these options—indeed there is considerable variation in how technologies or combinations of technologies are identified or grouped in the literature and in discussions within the nuclear industry and scientific community.

A nuclear power reactor uses the energy released during nuclear fission (splitting the nucleus of atoms) to create heat, which is then available for generating electricity or other applications. Nuclear reactors are just one of a series of integrated components that are collectively referred to as the nuclear fuel cycle – see Figure 3. When discussing nuclear fuel cycles, the cycle is usually broken into the "front end" and the "back end". The front end consists of everything from the mining of the uranium ore to the use of the uranium fuel in the reactor. The back end of the fuel cycle typically consists of the stages that occur after irradiated nuclear fuel has been removed from the reactor core – which include storage, disposal and reprocessing.

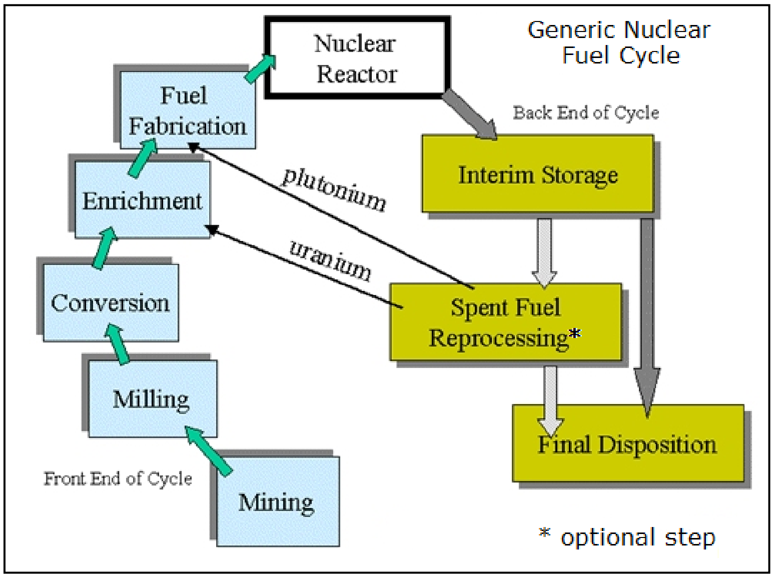

Figure 3. Generic Nuclear Fuel Cycle[11]

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[11] Adapted from EIA - http://www.eia.doe.gov/cneaf/nuclear/page/images/intro_fig1.jpg

The Once-Through Fuel Cycle - The nuclear fuel cycle as employed in the U.S. is called the "once-through" fuel cycle because it uses its nuclear fuel only once. The once-through fuel cycle begins with the mining and milling of uranium (natural uranium is mined from the ground, similar to many other resources) – as shown in Figure 4. Natural uranium consists mainly of two isotopes[12]: the easily fissioned (or "fissile") isotope uranium-235 (U-235) and uranium-238 (U-238). In a sample of natural uranium, U-235 only accounts for 0.7% of the total mass, while U-238 makes up most of the balance. For use in a standard light water reactor (LWR), the U-235 content must be increased (or "enriched") to 2-5 percent. The enriched uranium is then formed into fuel assemblies to operate the light-water reactors that comprise the entire U.S. reactor fleet.

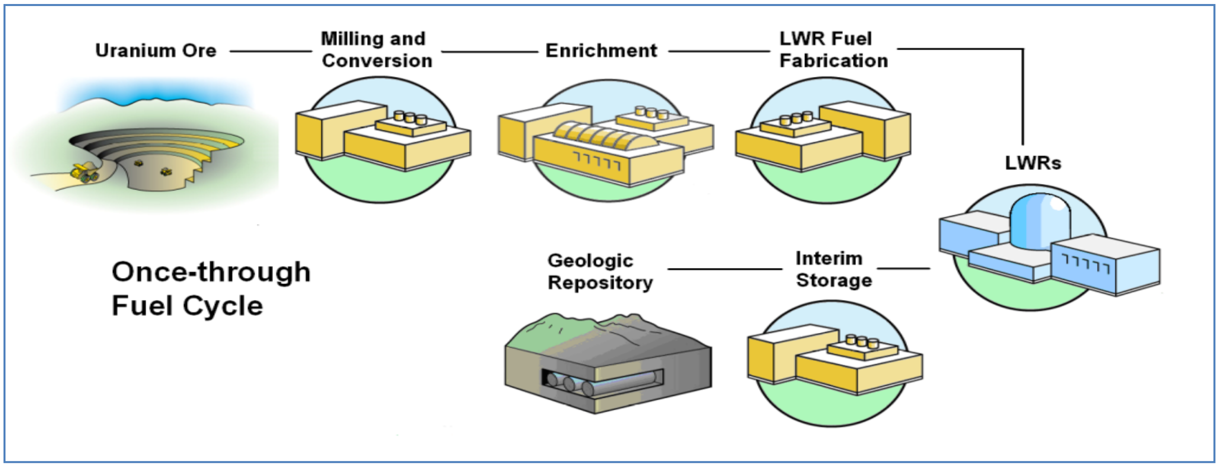

Figure 4. The Once-through Nuclear Fuel Cycle[13]

A typical light water reactor in the United States is loaded with anywhere from 200 to 800 fuel assemblies (totaling approximately 100 metric tons of uranium oxide) at a time and will need roughly 20 metric tons of fuel replaced each year. A commercial fuel assembly is a square bundle of long, hollow metal rods each of which holds a stack of uranium oxide pellets—a typical fuel assembly, depending on the type of reactor for which it is intended, contains between 0.2 and 0.5 metric tons of uranium, is about 14 feet long, and weighs between 700 and 1400 pounds. (See Figures 5 and 6)

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[12] Isotopes are different atoms of the same element, meaning they have the same number of protons, but a different number of neutrons. In the case of uranium, all isotopes have 92 protons, but U-235 has 143 neutrons while U-238 has 146 neutrons.

[13] Wigeland, et al., "Identification, Description, and Characterization of Existing and Alternative Nuclear Energy Systems", May 2011. Commissioned paper for the BRC. www.brc.gov

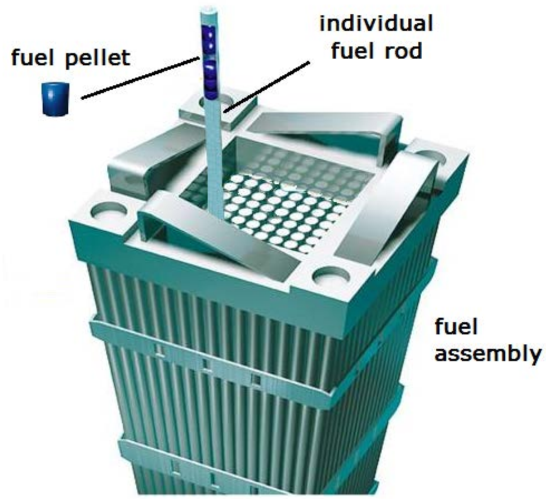

Figure 5. Example fuel assembly[14]

Figure 6. Workers handling fresh nuclear fuel assemblies[15]

After four to six years inside a reactor, a fuel assembly will no longer generate heat efficiently and must be replaced. At this point the fuel is considered used or spent.[16] When first removed from the reactor core, spent fuel assemblies are highly radioactive and extremely hot. They are transferred under water into a steel-lined, water-filled storage pool within the facility, which helps to shield the radiation and cool the fuel. After a period of time when then fuel has cooled sufficiently[17], there are two general options for handling the used fuel: (1) storage and eventual disposal to ensure long-term isolation from the biosphere and to protect against potential public health and environmental damage from long-lived radioactive materials, or (2) reprocessing to separate and remove still usable constituents (including U-235, U-238, and plutonium) from the spent fuel for re-use as reactor fuel, and processing of remaining materials into waste forms.

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[14] Adapted from AREVA NP, Inc. graphic from http://www.chemcases.com/nuclear/nc-06.html

[15] Graphic from U.S. Energy Information Administration - http://www.eia.doe.gov/cneaf/nuclear/page/intro.html

[16] Throughout this document we employ the term “spent” nuclear fuel. “Used fuel” is the term that appears in the Commission’s charter, but “spent fuel” (sometimes abbreviated “SNF”) is the term used in much of the literature on this topic and in many U.S. regulations and statutes concerning the back end of the nuclear fuel cycle. The different terminology reflects a profound policy debate as to whether the fuel is a waste (hence “spent”) or a resource to be recovered through recycling (hence “used”). We use the older terminology, albeit without prejudging the answer to the policy debate.

[17] Industry practice is to keep spent nuclear fuel in the spent fuel pools a minimum of five years before placing in dry cask storage.

When fresh uranium fuel is placed in a reactor, it typically contains about 3% U-235 and 97% U-238. When it is removed, it contains about 1% U-235, 93% U-238, 1% plutonium, 0.1% minor actinides[18], and 4-5% fission products[19] as shown in Figure 7.

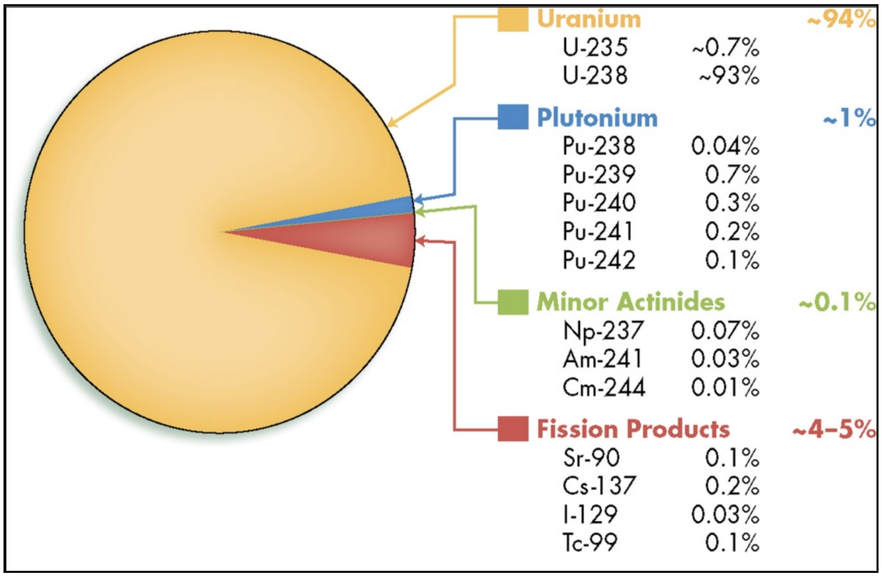

Figure 7. Elements of Spent Nuclear Fuel[20]

The reprocessing (sometimes referred to as just "processing") of spent fuel is made especially difficult by its high level of radioactivity. Process equipment must be heavily shielded and most operations and maintenance must be remotely accomplished in order to limit personnel exposure. Various reprocessing methods have been used to separate individual components of spent fuel, but the most widely adopted method to date is called the PUREX process (Plutonium URanium EXtraction). With the PUREX process, spent fuel is chopped up, dissolved in acid, and chemically separated into various liquid streams (particularly plutonium and uranium). The plutonium and uranium can then be utilized in various fuel cycles options – as discussed later in this section, and the status of reprocessing facilities worldwide is discussed further in Section 2.3.

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[18] Minor actinides are the elements in the actinide family not including uranium and plutonium (consider the major actinides). The most relevant minor actinides in relation to managing spent nuclear fuel are americium, neptunium, and curium.

[19] Fission products in spent fuel are typically created by the splitting (fissioning) of the uranium-235 isotope into smaller atoms. Although some fission products can serve a useful purpose, most are designated for disposal in the majority of fuel cycles.

[20] EPRI Spring Journal 2008, http://mydocs.epri.com/docs/CorporateDocuments/EPRI_Journal/2008-Spring/1016422_NuclearFuelCycle.pdf

Reactor Types – What Makes them Different?

A reactor can be characterized by the type of fuel, moderator, neutron spectrum, and coolant that it employs:

Nuclear fuel contains heavy atoms that can fission (or split into two slightly unequal halves) when hit with neutrons. The splitting of the atom produces energy (in the form of heat), plus excess neutrons that go on to create more fissions. Natural uranium consists of 99.3 percent of the isotope U-238 and 0.7 percent of the isotope U-235. The term “enrichment” describes that step of the fuel cycle where the concentration of U-235 in natural uranium is increased, typically to a level of 4–5 percent for most commercial reactors.

Moderators are substances that act to slow down (or “moderate”) high energy neutrons resulting from fission. Ordinary water (“light” water) is the most common moderator. Its primary advantages are that it is abundant and that it is efficient in slowing down neutrons. Its primary disadvantage is that it tends to absorb neutrons, preventing them from splitting other atoms and thus reducing the rate of fission reactions. Most fissionable isotopes (and especially U-235) fission much more easily when the neutron striking them has been slowed down or “thermalized” in the reactor core. Thermal-spectrum reactors can operate with fuel with low concentrations of fissile isotopes, while “fast-spectrum” reactors require higher concentrations.

Neutron spectrum refers to the speed of neutrons in the reactor core. In a fast reactor most neutrons are moving at speeds at nearly the speed they possess at the moment of fission. In a slow or “thermal” reactor, by contrast, the neutrons have been slowed down (hence the name “thermal” or “thermalized” reactor). Thermalized neutrons are moving thousands of times slower than fast neutrons. Fast reactors are said to have a “hard” spectrum (higher energy, faster neutrons), while thermal reactors with low energy neutrons have a “soft” spectrum. The vast majority of commercial-scale reactors operating in the world today are thermal reactors.

Coolants are fluids that transfer heat from the reactor core to another component (or region) of the reactor system where that heat can be used to generate steam to drive a steam turbine (or in the case of some gas-cooled reactors, drive a gas turbine directly). The most common liquid coolants are water, liquid metal such as sodium, lead, and bismuth, and fluoride salts; the most common gas coolants are helium and carbon dioxide.

For the first two decades of commercial nuclear power development the expectation in the United States was that nuclear fuel would be reprocessed and that the U.S. would proceed with the short-term use of a modified open fuel cycle (described below) on the way to deploying a fully closed fuel cycle (also described below). It was envisioned that spent fuel would be stored on site in storage pools only temporarily, which drove reactor designers to only include relatively small spent fuel storage pools at most reactor sites. By the 1970s, however, the United States abandoned commercial reprocessing—on the basis of a combination of policy concerns (largely having to do with nuclear weapons proliferation) and economics – and the government soon after assigned DOE the responsibility of developing a disposal facility for spent fuel.

As DOE fell further and further behind in its efforts to site and open a permanent geologic repository for high-level waste and spent nuclear fuel and as utilities began to run out of space in their water-filled storage pools, more of the spent fuel was moved to massive concrete or steel casks, or concrete-shielded horizontal storage cavities for dry storage in open-air, above-ground enclosures at the reactor site. Today, dry cask storage is considered the preferred option for extended periods of interim storage (i.e. multiple decades up to 100 years or possibly more).

The output of spent nuclear fuel from the nation's commercial nuclear power plants varies with the amount of electricity produced by these plants. In recent years, the annual figure has ranged from 2,000 to 2,400 metric tons. Currently, all but a very small fraction of the still-growing commercial spent fuel inventory—which currently stands at approximately 66,000 metric tons nationwide—is being stored at reactor sites. Until the United States develops a disposal and/or reprocessing solution the final disposition pathway and timeframe for moving these materials remains uncertain.

Alternate Once-Through Fuel Cycles are similar to the existing once-through fuel cycle in that their defining characteristic is the absence of any reprocessing of spent nuclear fuel. As a result, storage and eventual disposal is needed for all spent fuel. However, future approaches to the once-through fuel cycle could incorporate advances or improvements over current practice. For example, uranium may be enriched to a higher concentration of U-235 to achieve higher burn up.[21] Improved cladding materials such as silicon carbide may also enable higher burn up while offering improved safety margins, reduced maintenance, and improved waste-form performance. Higher burn ups also reduce the quantity of waste generated for each unit of energy produced.[22] There are limits to how much the burn up can be increased however, and to the benefits that can be achieved through this approach.[23] Systems that result in nearly complete consumption of natural uranium in a once-through cycle, while theoretically possible, are not considered realistic.

Other variations on the current once-through cycle could involve the use of thorium fuels, which might—in some once-through configurations—produce modest reductions in waste streams and plutonium production. Otherwise, however, waste disposal and non-proliferation metrics for once-through thorium fuels are essentially the same as for uranium fuels. Higher

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[21] The term "burn up" refers to the utilization of the uranium in the fuel. The higher the burn up, the more uranium has been used (by fission) to generate energy.

[22] Higher burn up will produce little change in the amount of natural uranium needed to fuel the overall system, since the uranium that is used to make higher burn up fuel needs to be enriched to a proportionately higher level.

[23] The tolerance of fuel and fuel cladding to withstand higher burn up will ultimately limit burn up increases. According to DOE's FY2006 Alternative Fuel Cycle Initiative (AFCI) Comparison Report, doubling the burn up in the once-through fuel cycle could yield a 38 percent reduction in long-term radiotoxicity and a 13 percent reduction in estimated peak repository dose.

uranium enrichments needed to drive these cycles might offset savings in enrichment capacity and natural uranium consumption.

Finally, different reactor and irradiation technologies could potentially be used in the context of future versions of the once-through fuel cycle, including the option for both fast reactors and externally driven sub-critical facilities. Both systems offer the potential to eliminate the need for enrichment and also achieve very efficient use of natural uranium.

Operating Commercial-Scale Reactor Types

Light Water Reactors (LWRs): In LWRs, the coolant and the moderator are one and the same: ordinary ("light") water. To fuel these reactors, uranium is enriched to 4–5 percent U-235 and most of the fissions that occur in the reactor core are caused by low-energy ("thermal") neutrons. Heat from fission is transferred in the cooling water to a steam generator, where steam is generated to drive a turbine. This type of reactor is called a pressurized water reactor (PWR). In a boiling water reactor (BWR), steam is created by allowing the cooling water to boil directly in the reactor core region, thus eliminating the need for steam generators. The current U.S. fleet of operating commercial reactors includes 69 PWRs and 35 BWRs. A less common type of light water reactor, the light water graphite reactor, uses enriched uranium fuel in vertical light-water-cooled pressure tubes, surrounded by graphite blocks as the moderator. A Russian version of this design, called the RBMK, was the design used at Chernobyl and is no longer used outside of Russia.

High Temperature Reactors (HTRs): Most HTRs use gases for their coolant, although some designs use liquid salts. Typical HTR designs use graphite as the moderator. Still deployed extensively in the UK (18 of their 19 operating reactors use carbon dioxide as a coolant), most high temperature reactor developers have shifted to helium-cooled, graphite moderated reactors for use in the future, while researchers are exploring the use of fluoride salts as low-pressure coolants. Some HTR concepts allow for direct drive or indirect drive of a gas turbine for power conversion, thus avoiding the steam cycle typical of other nuclear (and many fossil-fueled) thermoelectric plants, and achieving significantly higher plant efficiency. Although graphite moderated reactors can and did operate on natural uranium, future HTRs are being designed to operate on enriched uranium (often higher than LWR enrichment levels), while salts may also be used for fluid fuels that would enable thorium-based fuel cycles.

Pressurized Heavy Water Reactors (PHWRs): PHWRs typically operate on natural or slightly enriched uranium and use heavy water (D_2O) as both the moderator and coolant. Deployed primarily in Canada and India, PWHRs are also utilized in South Korea, Romania, and China. The most utilized version of the PHWR is the CANDU (Atomic Energy of Canada Limited's CANada Deuterium Uranium reactor). As in the PWR, the primary coolant generates steam in a secondary circuit to drive the turbines and generate electricity. By allowing individual pressure tubes to be isolated from the cooling circuit, PWHRs can be refueled without shutting down.

Liquid Metal Reactors (LMRs): LMRs typically use sodium (or other liquid metals) as the coolant and operate on mixed uranium and plutonium fuels that fission in a "fast" neutron spectrum. The design of the fuel and the shape of the reactor core can be adjusted to allow for increased, decreased, or self-sustaining production of fissile material (i.e., Pu-239) as the reactor operates. All U.S., British, and French LMRs are shut down and largely decommissioned. Japan completed construction of the Monju fast reactor in 1994, but it experienced a sodium leak in 1995 and was shut down. After returning to operation in May 2010, the Monju reactor was shut down again after experiencing an accident during a refueling operation. The Monju reactor is presently not expected to resume operation until 2014. Russia has had better success with fast reactors, with its BN-350 and BN-600 reactors starting up in 1972 and 1980, respectively. The BN-350 no longer operates. The BN-600 is still operating, and the BN-800 is under construction.

Breeders and Burners: A "breeder" reactor is one in which the conversion ratio (the amount of fissile material it produces compared to the amount of fissile material it uses) is greater than one – thereby "breeding" or creating more fissile material than it is using for fission. A "burner" reactor is one in which the conversion ratio is less than one, thereby "burning" or utilizing more fissile material than it is producing. Breeder reactors, operating in tandem with spent fuel reprocessing, allow for "closed" fuel cycles, in which most fuel constituents can be recycled.

Modified Open Fuel Cycle: We have defined this category to encompass a very wide range of possible fuel cycles with multiple possible combinations of different reactor, separations, and fuel fabrication technologies.[24] Our definition includes any fuel cycle in which some of the spent fuel is processed rather than being directly disposed of after a single pass through a reactor (see Figure 8). Spent fuel could be processed just to improve the characteristics of the resulting waste streams for disposal, but because LWR spent fuel is sufficiently robust to provide an effective waste form, it is unlikely (particularly from a cost perspective) that it would be reprocessed purely for separating its constituents and processing them into specialized waste forms.

Another approach could be the application of non-chemical methods to process spent fuel so that some of the resulting products can be reconstituted into new fuel for a different type of reactor, after which the residues would be sent for disposal. As an example, volatile and gaseous fission products may be removed during high-temperature processing, so there is no overall separation of non-volatile fission products, transuranics, and uranium.[25] The purpose of this approach is to increase the utilization of uranium fuel and reduce total waste generation.

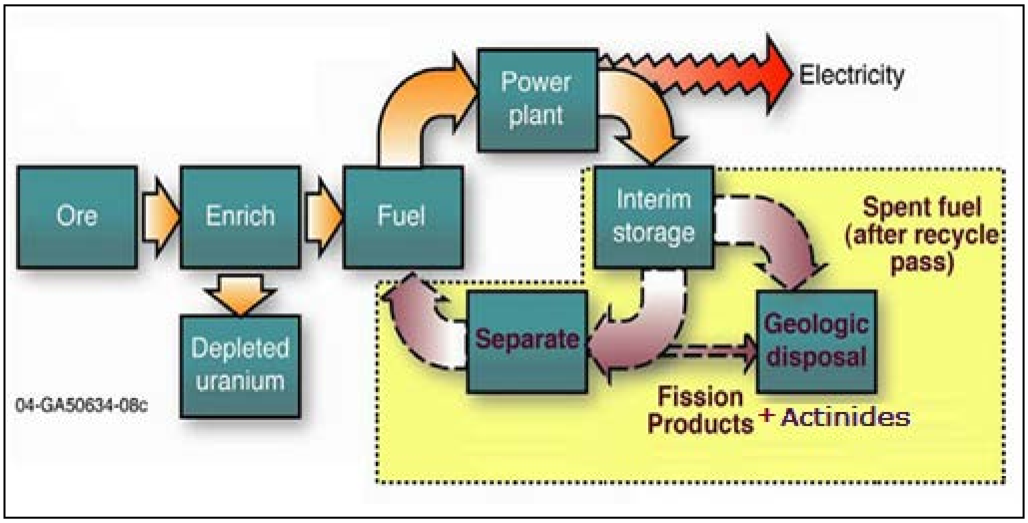

Figure 8. Modified Open Nuclear Fuel Cycle[26]

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[24] The subcommittee notes there is no consistent or generally accepted definition of what constitutes a modified open cycle

[25] A specific example of this is the DUPIC fuel cycle, where used light water reactor fuel is reconstituted for further irradiation in a heavy water reactor without separating the actinides from each other or the fission products.

[26] Idaho National Laboratory, BRC Commissioned White Paper, *Identification, Description, and Characterization of Existing and Alternative Nuclear Energy Systems*, May 2011

The more likely scenario for a modified open cycle in the U.S., if adopted, would involve the reprocessing and limited recycling of some constituents of spent light water reactor fuel. In this scenario, one or more elements from the spent fuel are separated and recovered to be used again,[27] but this is only done once or a few times before the spent fuel is disposed. As a result, the spent fuel, the high-level waste from spent fuel reprocessing, and transuranic-contaminated materials such as cladding hulls will require geologic disposal. The preparation and fabrication of the recycle fuel may also differ significantly from the fabrication of typical uranium fuel, because it will have to be performed in a sealed environment (either with glove boxes or in shielded hot cells).

From a waste management standpoint, the benefits of the modified open cycle compared to the once-through cycle depend on the composition and the physical and chemical compositions of the spent fuel and high-level waste that result from this approach. Recycle activities also produce quantities of low-level and TRU-contaminated wastes from recycle facility operations that are not produced in the once-through option, but also require disposal strategies.

As already noted, the modified open cycle in general could have many variations, especially where more than one reactor type is included in the fuel cycle. Both thermal and fast reactors can be used, as well as externally-driven systems[28]. There are also numerous potential separations technologies, depending on the elements to be recovered for recycle, which adds still more possible options. Including different fuel types, the possibility of using thorium, and different disposal paths results in a long list of specific fuel cycle combinations.

However, modified open cycle options all share four basic characteristics:

- The need for uranium fuel (natural or enriched, depending on the reactor)
- Reprocessing of spent fuel once or a few times
- Incorporating some processing products into new fuel
- Disposal of both high level, low level, and transuranic wastes from reprocessing, as well as spent fuel

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[27] Typically, for example, plutonium would be extracted for re-use in mixed oxide (MOX) fuel.

[28] Externally-driven systems are systems that generate a source of neutrons without fission, such as accelerators or cyclotrons.

<u>Fully-Closed Fuel Cycle with (Sustained) Recycle</u>: The defining feature of full recycle strategies is that spent fuel is reprocessed such that only high-level wastes from the separations process and transuranic contaminated wastes such as cladding hulls require geologic disposal (see Figure 9). The aim is to recycle elements that can be used for fission. While interim storage can provide substantial benefits in reducing the decay heat generated by fission products, recycle and transmutation[29] provides the only practical approach to reduce the longer-term decay heat generated by transuranic elements (TRU).

The reduction of long-term repository doses by the transmutation of very long-lived elements depends on the specific repository environment. Some of these elements, including many of the TRU elements, may have very low mobility following deep geologic disposal. However, for those elements that may be mobile, recycle can enable transmutation, or the incorporation of these elements into waste forms with greater chemical stability than is provided by spent fuel. Because no chemical separation processes can ever be perfect, the high-level wastes generated as part of a full recycle strategy, as well as fuel cladding and reprocessing equipment that contacts transuranic-bearing materials, will contain small amounts of transuranics and thus will also require deep geologic disposal.

Full recycle strategies can be further subdivided into “burner” vs. “breeder” fuel cycles. Burner full recycle options “burn up” the long-lived actinides; most burner concepts employ fast reactors and either uranium or uranium and thorium fuels. For burner cycles, material that fissions easily (such as uranium-235 or plutonium-239, referred to as “fissile” material) needs to be added with every recycle. Commonly, for burner cycles the fissile material used is expected to come from recycled LWR spent fuel (such as from reactors operating on a once-through fuel cycle or an existing inventory of spent fuel).

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[29] Transmutation is the transforming of elements into other elements. Transmutation of elements occurs in a reactor due to the heavy flux of neutrons generated by the fission process.

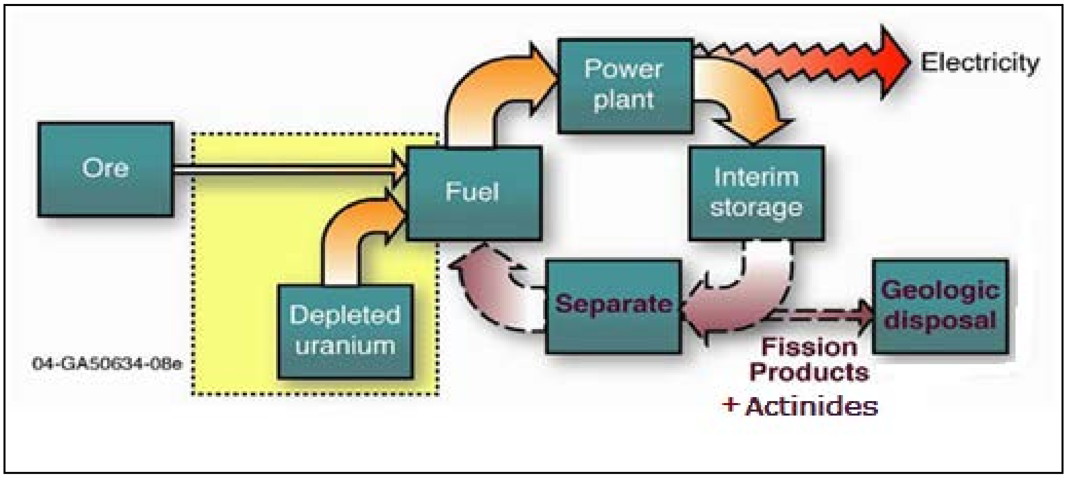

Figure 9. Fully-Closed Nuclear Fuel Cycle with (Sustained) Recycle[30]

Recycled transuranics can be used two ways in a burner reactor - either mixed with new uranium fuel to fabricate combined fuel elements consisting of fresh uranium and recycled transuranics (in which case all fuel fabrication must be done remotely in shielded hot cells) or they can be placed in the reactor as separate fuel elements (separate fresh fuel and recycled fuel elements). However, there are also examples where fuel fabrication may not be needed at all, such as in certain molten salt reactor designs with periodic or continuous fuel reprocessing.

A breeder fuel cycle with thermal reactors operating with uranium/thorium fuel was demonstrated at Shippingport in a specially designed light water reactor in the 1970's. Breeder cycles are also possible using molten salt reactors with thorium-bearing fluid fuel. However the more conventional solid fuel has made sodium-cooled fast reactors the primary choice to date among nations that have pursued the breeder fuel cycle. Once started, the "breeder" fuel cycle would displace the need for enriched uranium fuel even for starting new reactors; it would also continue to satisfy the waste management goal of greatly reducing transuranics in the waste streams. On the other hand, in the fast-spectrum uranium fuel cycle the quantity and mass flows of transuranics actively circulating through different fuel cycle facilities during recycle is greater compared to a once-through fuel cycle. Breeding cycles involving thorium generally have much smaller transuranic inventories, but are less effective in transmuting transuranics in existing uranium fuel inventories.

From a waste management standpoint, if operated for a century or more a continuous recycle can at least theoretically achieve a balance in which all spent fuel is reprocessed, with no spent fuel requiring disposal as the system continues to operate.

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[30] Idaho National Laboratory (2011)

Managing the nuclear fuel cycle in the U.S. entails considerations spelled out in the Commission's charter, including safety, cost, resource utilization and sustainability, and the promotion of nuclear nonproliferation and counter-terrorism goals. In considering the potential future use of nuclear power and the development and deployment of advanced reactor and fuel cycle technologies in particular, it is important to evaluate every component of the interconnected fuel cycle, and to consider all of these concerns and any associated impacts.

The work of the Blue Ribbon Commission is focused on approaches to managing the back end of the fuel cycle in the United States, though we recognize that any strategy must, of necessity, consider all aspects of the fuel cycle as an integrated whole.

2.3 Status of Nuclear Reactors and Nuclear Fuel Cycle Developments in the United States and Abroad

All of the nuclear technology assessments considered by this Subcommittee take the once-through fuel cycle—as currently practiced in the United States using light-water reactor technology—as the baseline or reference nuclear energy system for comparison to alternative systems. Light-water-cooled, thermal-neutron spectrum reactors generate all of the nuclear power produced in the U.S. and are the technology used at more than 80 percent of the nuclear power plants around the world today (see Table 1). Improved versions of this technology also account for nearly all new reactors under construction or planned now by utilities for future construction. Worldwide, 440 nuclear reactors provide approximately 14% of the world's electricity and 5.7% of total primary energy used.[31,32]

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[31] IAEA 2010 – International Status and Prospects of Nuclear Power - http://www.iaea.org/Publications/Booklets/NuclearPower/np10.pdf

[32] World Nuclear Association - http://www.world-nuclear.org/info/reactors.html, update for April 13, 2011

Table 1. Operating Nuclear Power Units by Reactor Type, Worldwide[33]

Reactor Type	# Units	Generating Capacity MWe
Pressurized light-water reactors	268	248,439
Boiling light-water reactors	88	82,019
Graphite-moderated light-water reactors	15	10,219
Heavy-water reactors, all types	50	25,408
High temperature reactors, all types	18	8,949
Liquid-metal-cooled fast-breeder reactors	1	560
Totals	***440***	***375,594***

The United States currently has 104 operating light water reactors - 69 pressurized water reactors and 35 boiling water reactors. These reactors are located at 65 different sites in 31 states across the U.S. (see Figure 10). In 2010, these reactors provided 19.6% of U.S. electrical generation - approximately 807 billion kilowatt-hours. Worldwide, nuclear reactors provided 14% of total electricity generation.[34]

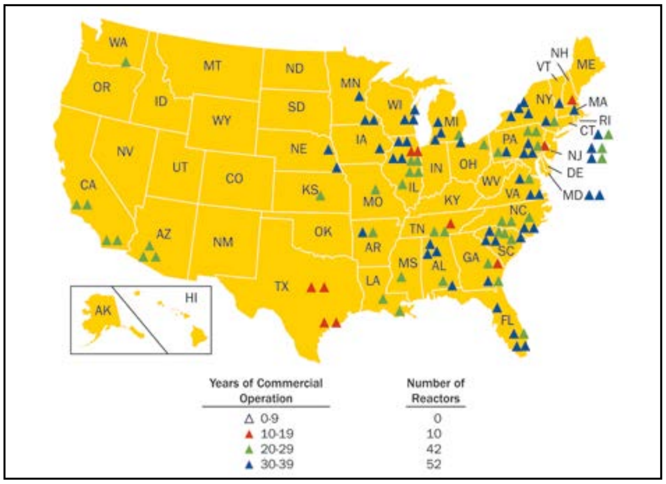

Figure 10. Location of U.S. Commercial Nuclear Power Reactors and Their Years of Operation[35]

There are currently 61 reactors under construction around the world and significant expansion of nuclear power is planned in some countries in the years ahead, particularly in China, Russia,

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[33] *Nuclear News – 13th Annual Reference Issue*, American Nuclear Society, March 2011 – BRC updated this data to include the loss of 2,719 MWe capacity from Fukushima Daiichi Reactors 1-4.

[34] Ibid.

[35] Source: NRC, http://www.nrc.gov/reactors/operating/power-reactors-map-sm.jpg

India, and South Korea.[36] Table 2 shows reactor data for 2010 including the regions where reactor construction is underway. Prior to the events at Fukushima, Japan had been planning the addition of over a dozen new nuclear power plants. However, the situation at the Fukushima Daiichi nuclear power plant is forcing the Japanese government to reconsider its long-term energy policy, which had assumed that nuclear power would continue to play a larger role in the power spread. Japan's Prime Minister Naoto Kan was reported as saying that Japan should "start from scratch" on its energy policy, reconsidering the earlier plan that called for increasing the role of nuclear power to 50 percent, up from the current 30 percent.[37]

Table 2. Nuclear Power Reactor Statistics Worldwide[38]

Region	Reactors in operation (2010)		Reactors under construction (2010)		Nuclear Power (2008)	
	Number	Net Capacity (MWe)	Number	Net Capacity (MWe)	Use (EJ)	% of country's electricity generation
North America	122	113,316	1	1,165	9.76	19.04
Latin America	6	4,119	2	1,937	0.32	2.38
Western Europe	129	122,956	2	3,200	8.97	26.68
Central and Eastern Europe	67	47,376	17	13,741	3.64	18.30
Africa	2	1,800	0	0	0.14	2.11
Middle East and South Asia	21	4,614	6	3,721	0.16	0.99
Far East	90	80,516	32	34,820	5.35	10.15
World	***441***	***374,697***	***60***	***58,584***	***28.34***	***14.03***

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[36] World Nuclear Association - http://www.world-nuclear.org/info/reactors.html, update for April 13, 2011

[37] Greenwire News, "Nuclear Crisis: Japan's energy plans in flux after accident", May 10, 2011. http://www.eenews.net/Greenwire/2011/05/10/archive/13?terms=Japan

[38] Adapted from Tables B-1 and B-2 from IAEA – International Status and Prospects of Nuclear Power

Countries with existing nuclear power plants are not the only countries considering nuclear power. A 2010 report by the International Atomic Energy Agency (IAEA) said that some 65 countries without nuclear power plants “are expressing interest in, considering, or actively planning for nuclear power” at present, after a “gap of nearly 15 years” in such interest worldwide.[39] Of these 65 un-named countries, 21 are in Asia/Pacific, 21 in Africa, 12 in Europe (mostly eastern Europe), and 11 in Latin America. However, of the 65 interested countries, 31 are not currently planning to build reactors, and 17 of those 31 have grids of less than 5 GW, “too small to accommodate most of the reactor designs on offer.” The report added that technology options may also be limited for countries whose grids are between 5 GW and 10 GW.

Additionally, the IAEA report states that of the countries planning reactors, 14 of them “indicate a strong intention to proceed” with introduction of nuclear power; seven are preparing but haven’t made a final decision, 10 have made a decision and are preparing infrastructure, two have ordered a new nuclear power plant and one has a plant under construction. The U.S. State Department notes that 12 of these countries have taken concrete steps towards such programs.[40] Several of these “new-entrants” have already committed to construction of new reactors based on the advanced light water reactor technology like that being used at new plants now entering construction in the United States, China, and elsewhere. It is likely that five major reactor designs certified by the U.S. NRC represent the future of standardized commercial reactors for 21st Century deployment: AP1000, ESBWR, ABWR, U.S. EPR (based on the French vendor AREVA design), and U.S. APWR (based on the Japanese vendor Mitsubishi design). The AP1000 is currently under construction in China and in early site preparation in the United States. Other designs may be submitted in the future to the U.S. NRC for design certification review (e.g., potentially the standard South Korean APR-1400 design).

In the U.S. today, light-water reactor technology is deployed as part of a once-through fuel cycle in which mined uranium is enriched, used once as a reactor fuel, and then stored pending ultimate disposition (see Nuclear Fuel Cycle Figure 3). Special facilities are necessary for each step of the fuel cycle; and the Nuclear Regulatory Commission directly regulates 14 of these facilities across the U.S. in addition to several uranium recovery facilities in New Mexico, Nebraska and Wyoming. Table 3 lists each of these facilities.

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[39] IAEA (2010) http://www.iaea.org/Publications/Booklets/NuclearPower/np10.pdf

[40] U.S. Department of State, United States Information Pertaining to the Treaty on the Nonproliferation of Nuclear Weapons, 2010, http://www.state.gov/documents/organization/141928.pdf

Table 3. Fuel Cycle Facilities Directly Regulated by the U.S. Nuclear Regulatory Commission[41]

Licensee/Facility	Location	Type
AREVA Enrichment Services (under review)	Idaho Falls, ID	Gas Centrifuge Uranium Enrichment
AREVA NP, Inc.	Lynchburg, VA	Uranium Fuel Fabrication
AREVA NP, Inc.	Richland, WA	Uranium Fuel Fabrication
B&W Nuclear Operations Group	Lynchburg, VA	Uranium Fuel Fabrication
GE-Hitachi (under review)	Wilmington, NC	Laser Separation Uranium Enrichment
Global Nuclear Fuel-Americas, LLC	Wilmington, NC	Uranium Fuel Fabrication
Honeywell International, Inc.	Metropolis, IL	Uranium Hexafluoride Production (Conversion)
Louisiana Energy Services (in construction)	Eunice, NM	Gas Centrifuge Uranium Enrichment
Nuclear Fuel Services (active facility with license renewal application submitted and undergoing partial decommissioning)	Erwin, TN	Uranium Fuel Fabrication
Shaw AREVA MOX Services , LLC (in construction/under licensing review)	Aiken, SC	Mixed-Oxide Fuel Fabrication
U.S. Enrichment Corporation	Paducah, KY	Gaseous Diffusion Uranium Enrichment
U.S. Enrichment Corporation (cold standby)	Piketon, OH	Gaseous Diffusion Uranium Enrichment
U.S. Enrichment Corporation (in construction)	Piketon, OH	Gas Centrifuge Uranium Enrichment
Westinghouse Electric Company, LLC (Columbia Fuel Fabrication Facility)	Columbia, SC	Uranium Fuel Fabrication
Crow Butte Resources, Inc.	Chadron, Nebraska	Uranium Recovery Facility – In Situ Recovery (ISR)
Hydro Resources, Inc.	Crown Point, New Mexico	Uranium Recovery Facility – In Situ Recovery (ISR)
Uranium One Americas, Inc.	Campbell County, Wyoming	Uranium Recovery Facility – In Situ Recovery (ISR)
Power Resources, Inc.	Douglas, Wyoming (Converse County)	Uranium Recovery Facility – In Situ Recovery (ISR)
Kennecott Uranium Co.	Sweetwater County, Wyoming	Uranium Recovery Facility – conventional uranium mill
Uranium One U.S.A.	Johnson & Campbell Counties, Wyoming	Uranium Recovery Facility – In Situ Recovery (ISR)

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[41] U.S. Nuclear Regulatory Commission - http://www.nrc.gov/info-finder/materials/uranium/ and http://www.nrc.gov/info-finder/materials/fuel-cycle/

Although the U.S. does rely on the once-through fuel cycle for its commercial electrical generation, it will soon be adopting the use of MOX fuel as a result of the 2000 Plutonium Management and Disposition Agreement (PMDA), which commits both the United States and Russia to dispose of no less than 34 metric tons (MT) of excess weapon-grade plutonium each. The combined amount, 68 metric tons, represents enough material for approximately 17,000 nuclear weapons.[42] The MOX facility will blend surplus weapon-grade plutonium with depleted uranium oxide to make mixed oxide fuel for use in existing nuclear power plants. It will take approximately 15 years for the MOX facility to process the 34 MT of plutonium. Although the U.S. had a small MOX fuel fabrication capability in the 1970s[43], the PMDA necessitated rebuilding a U.S. MOX fuel fabrication capability. The U.S. Department of Energy (DOE) signed a contract in 1999 with Duke COGEMA Stone & Webster (DCS), now Shaw AREVA MOX Services, to design, build, and operate a MOX Fuel Fabrication Facility on the DOE's Savannah River Site near Aiken, South Carolina. Construction is still in progress, with the facility scheduled to open in 2016.

Other countries, notably France, the United Kingdom, Japan, and Russia, are implementing alternatives to the once-through fuel cycle and are using fuel reprocessing as part of their fuel cycle choices (see Table 4).[44] But currently no nation has ever achieved a fully closed nuclear fuel cycle, including spent fuel reprocessing, breeder reactors, and the associated fuel fabrication, waste stream management systems, etc. The closest any country has come to this is France, which operates a large reprocessing plant at La Hague. That plant uses PUREX technology to separate Pu from spent fuel, which is then mixed with uranium and fabricated into MOX at another facility in Marcoule, France. MOX assemblies are burned once in LWRs and then placed in wet storage, with options for either further reprocessing and potential burning in fast reactors, should that technology be developed commercially, or for disposition in a future geologic repository. The reprocessing facility at La Hague has historically handled about 75% of the world demand for spent LWR fuel reprocessing services.[45] The UK and France have also reprocessed significant amounts of gas-cooled reactor fuel, and that Russia and France have reprocessed a much smaller amount of fast reactor fuel.

With the exception of the French facility at La Hague, which has operated at greater than 60% capacity when sufficient commercial demand existed, all the other facilities are typically

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[42] NNSA MOX factsheet - http://nnsa.energy.gov/mediaroom/factsheets/mox

[43] Kerr-McGee's Cimarron Fuel Fabrication Plant made MOX fuel pins for the DOE's Fast Flux Test Reactor

[44] IAEA, *Spent Fuel Reprocessing Options*, IAEA TECDOC-1587, Aug. 2008 - http://www-pub.iaea.org/MTCD/publications/PDF/te_1587_web.pdf

[45] *Abridged History of Reactor and Fuel Cycle Technologies Development: A White Paper for the Reactor and Fuel Cycle Technology Subcommittee of the Blue Ribbon Commission*, Gary Vine, Longenecker & Associates, March 15, 2011

operating at ~25% capacity or lower, mostly because of technical and environmental restrictions. [46] Although the majority of the facilities listed here had a role in supporting military missions many years ago, virtually all reprocessing capacity is dedicated to civilian applications today.

Table 4. International Current and Planned Reprocessing Capacity[47]

Country	**Site**	**Plant**	**Fuel Type**	**Operation**		**Capacity (MTHM)**	
				Start	Shut-down	Present	Future
China	Jiuquan	RPP	LWR	?			25
	Lanzhou		LWR	2020			800
France	La Hague	UP2	LWR	1967		1000	1000
	La Hague	UP3	LWR	1990		1000	1000
India	Trombay	PP	Research	1964		60	60
	Tarapur	PREFRE 1	PHWR	1974		100	100
	Kalpakkam	PREFRE 2	PHWR	1998		100	100
	Kalpakkam	PREFRE 3A	PHWR	2010			150
	Tarapur	PREFRE 3B	PHWR	2012			150
Japan	Tokai-mura	JAEA TRP	LWR	1977		90	90
	Rokkasho-mura	JNFL RRP	LWR	2007		800	800
Russian Federation	Chelyabinsk	RT1	VVER-440 BN-350 BN-600 RR	1977		400	400
	Krasnoyarsk	RT2	VVER-1000	2025			1500
		Demonstration facilties	VVER-1000 RBMK	2013			100
UK	Sellafield	B205	GCR	1967	2016	1500	
	Sellafield	Thorp	LWR/AGR	1994	2016	900	
Total Capacity						***5,950***	***5,475***

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[46] Vine (2011)

[47] IAEA TECDOC-1587, Aug. 2008

2.4 Key Findings

(1) Light water reactors (LWRs) dominate the world market for nuclear generation and remain the primary choice today for utilities planning to add new nuclear generation

(2) Today the United States, Canada and several other nations employ a once-through fuel cycle while nations such as France, Japan and Russia employ a modified open fuel cycle; while these latter nations have stated that their use of a modified open cycle has been adopted as a step toward employing a fully closed nuclear fuel cycle, no nation so far has actually achieved a closed fuel cycle.

3. EVALUTION OF FUEL CYCLE ALTERNATIVES

3.1 Context of Analysis

Numerous studies have been undertaken in the last decade to assess and compare various reactor and fuel cycle options.[48] Collectively they have analyzed numerous combinations of strategies and technologies but because the underlying parameters and assumptions are not consistent, the quantitative results of these studies are not comparable. Additionally, many of the potential technologies require considerable development before a defensible comparison could be made. As a consequence, it is not possible at this time to distill quantitative comparisons across alternative nuclear energy systems and then draw definitive conclusions based on those comparisons.

Recognizing that the BRC is charged with developing policy-level findings and recommendations and was not constituted to undertake detailed technical research or analysis, we opted to compare alternative nuclear energy systems in qualitative terms and with reference to broad strategic goals. Specifically, the Subcommittee considered a range of alternative nuclear energy systems over a long time horizon and identified three representative alternatives to the once-through light water reactor (LWR) strategy: one of which is already in use, and the other two that have substantive differences from the once-through cycle and have received extensive previous study. We then discuss the major qualitative differences between these alternatives and the existing once-through LWR fuel cycle, based on the findings contained in the literature available to the Subcommittee.

Relative to the once through fuel-cycle, different nuclear energy system strategies involve a wide range of trade-offs in terms of safety, cost, resource utilization and sustainability, waste management, and the promotion of nuclear nonproliferation and counter-terrorism goals. These trade-offs complicate any effort to compare the relative merits of different nuclear energy systems, particularly given uncertainty about technological developments and social conditions going forward. The conclusions reached by different technology assessments and comparative analyses are heavily influenced by input assumptions and by the relative weight given to different policy objectives (e.g., reducing waste vs. minimizing proliferation risk vs. maximizing resource utilization)—making it difficult to compare results across studies.

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[48] For example, see Bunn 2003; Dixon 2008; DOE 2003, 2004, 2006; EPRI 2009, 2010; MIT 2003, 2009, 2010, 2011; Shropshire 2009; Wigeland 2008, 2009; Wilson 2011; and NWTRB 2011

3.2 Criteria for Comparing Nuclear Energy Systems

Evaluating various nuclear fuel cycle technology options and nuclear energy system configurations against national policy goals requires the development and application of evaluation criteria. The criteria set forth in the BRC charter include safety, cost, resource utilization and sustainability, and the promotion of nuclear nonproliferation and counter-terrorism goals.

Safety – Recent events in Japan have reinforced the importance of a focus on nuclear safety. Although the impact of the radiological releases in Japan has been very small in the United States, the events there will and should affect public attitudes toward nuclear technology. Even if in the end the health consequences of the Fukushima accident prove to be substantially smaller than the direct loss of life from the earthquake and tsunami, the disruption caused by evacuations and relocation of local populations and the economic costs of this accident will be very high, and thus the potential danger of a nuclear disaster remains an abiding public concern. This concern must be directly and forthrightly addressed.

Compared to existing nuclear infrastructure, it is reasonable for society to expect that new nuclear infrastructure should be safer, from the perspectives of probabilistic risk assessment, defense in depth, and various quantitative measures that relate to safety such as forced outage rates and worker lost-time injuries. For example, new Generation III/III+ reactor designs typically have a greater degree of physical separation between redundant active safety equipment, or replace active safety systems with passive systems, when compared to existing Generation II plants. When considering the complete nuclear fuel cycle, risks related to the mining and milling of uranium and the transportation of radioactive materials may also contribute to a difference in safety. A variety of metrics can be used to quantify safety, including accident frequency (such as low probability/high consequence events like that at Fukushima), core damage frequency (the probability that an incident could lead to overheating and physical damage to the reactor core), occupational radiation dose (for workers at a facility), population radiation dose and maximally exposed individual dose (for the potentially affected public), etc.

Occupational safety and health (OSH) considerations must also be a part of any analysis of nuclear energy system safety; a commissioned paper prepared for the BRC[49] concluded that, “The nuclear industry’s level of OSH performance is significantly stronger than that of other U.S. energy sectors” and that OSH risks at the back-end [of the nuclear fuel cycle] should be

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[49] *From Three Mile Island to the Future - Improving Worker Safety and Health In the U.S. Nuclear Power Industry*: A White Paper Prepared for the Blue Ribbon Commission on America's Nuclear Future, Stoneturn Consultants, First Revision, March 30, 2011

manageable in diligent operations. The report also identifies certain areas for improvement, such as reducing radiation doses received during plant outage work, that provide opportunities for industry and regulators to take new actions to ensure that the nuclear workforce operates as safely as possible.

Cost is often among the primary criteria used to evaluate nuclear systems and fuel cycles. Costs can be estimated for specific aspects of the fuel cycle or on a lifecycle basis for the system as a whole. Often costs are expressed in terms of the productive output of the system—for example, as the total levelized cost of electricity generated on a per-kilowatt-hour or per megawatt-hour basis.

Because existing reprocessing facilities have not been deployed in an open market setting, there is significant uncertainty in most cost projections for modified open and closed fuel cycles. Additional uncertainties are present in the forecasting of uranium prices and resource estimates, which have fluctuated markedly over the years. Another relevant metric is capital cost or capital at risk—that is, how large an initial investment is needed to build a facility or (in the case of capital at risk) how much capital must be sunk before the investment begins to generate a return. The metrics of capital cost and capital at risk are particularly important for the reactors required to implement advanced fuel cycles because over half of the cost of nuclear electricity production arises from these construction costs. The return on investment also depends upon the structure under which electricity prices and waste disposal fees are assessed. For example, under the existing Nuclear Waste Policy Act fee structure, the services of spent fuel transportation, consolidated interim storage, and disposal are provided as a bundled service for a fee assessed based upon total electricity generation. Absent a mechanism to rebate cost savings, the bundling of these services removes economic incentives to implement technologies that could reduce transportation, storage, and disposal costs.

While the foregoing constitute useful measures for a commercial enterprise to decide whether a particular nuclear energy system or technology can be competitive, testimony received by the Commission noted that such measures are incomplete because they do not fully account for societal benefits (such as job creation) and societal concerns (such as the socioeconomic impacts arising from the potential stigma of hosting a nuclear facility).

Sustainability is a very broad term and can be understood to include a wide array of environmental impacts related to the nuclear fuel cycle and related facilities. Resource utilization is an element of sustainability that, in the context of a nuclear fuel cycle, is generally measured in terms of consumption of uranium (or thorium) ore, since uranium is the natural resource at the center of fission energy systems. More broadly, the sustainability of energy technologies must consider all resources used during the life cycle of a facility, including materials such as steel, concrete, and copper, as well as the emissions of pollution into the environment and the energy resources consumed and emissions resulting from production of fuel. At various times, the long-term availability of uranium has been seen as a potential constraint on the continued use of nuclear energy, although more recent estimates of global uranium supply suggest that resources are more than adequate to support current and planned nuclear energy systems for at least the next several decades[50]. Because, on a per megawatt of generating capacity basis, nuclear plant construction uses small amounts of steel, concrete, copper, and other natural resources,[51] the only other significant natural resource issue that has been raised in connection with nuclear energy systems centers on the use of fresh water, which is used in large quantities as a coolant in various reactor designs. For light water reactors, water withdrawal and thermal pollution of aquatic ecosystems in the vicinity of power plants may be an issue in some locations, especially where water resources are constrained. Advanced reactor technologies, such as high temperature reactors, may have substantially lower or even zero water consumption, or possibly even increase water resources by providing desalination.

Another aspect of sustainability is energy security. In the context of nuclear energy this concerns the extent to which potential nuclear energy systems could decrease our consumption of energy from foreign sources.

Non-proliferation and Counter-terrorism concerns have long been intertwined with nuclear technology and policy debates—in fact these concerns were among the factors that motivated the U.S. government's earlier decision (in the 1970s) to forego reprocessing in favor of a once-through fuel cycle. The terrorist attacks of September 11, 2001 added a new dimension to this set of issues, raising concern about the potential for similar direct attacks or acts of sabotage against nuclear facilities in addition to more familiar concerns about the potential for theft or diversion of nuclear materials and capabilities toward weapons applications.

Enrichment, reprocessing, and recycled fuel fabrication are generally recognized as particularly sensitive elements of the fuel cycle from the standpoint of weapons proliferation concerns. These technologies can not only serve nuclear power needs, but can give countries the technical and physical capacity to obtain the direct-use nuclear materials required for a weapons program. These proliferation risks include the potential that countries might attempt to secretly divert materials from civilian nuclear facilities that they have declared to the IAEA

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[50] For example, see *The Future of the Nuclear Fuel Cycle*, Massachusetts Institute of Technology, 2011

[51] Quantities of steel and concrete used in construction of nuclear plants are approximately half those in for conventional coal plants and 1/10 those for wind. Per F. Peterson, Haihua Zhao, and Rober Petroski, "Metal and Concrete Inputs for Several Nuclear Power Plants," Report UCBTH-05-001, UC Berkeley, February (2005). S. Pacca and A. Horvath, Environ. Sci. Technol., 36, 3194-3200 (2002).R.H. Bryan and I.T. Dudley, "Estimated Quantities of Materials Contained in a 1000-MW(e) PWR Power Plant," Oak Ridge National Laboratory, TM-4515, June (1974)

under the NPT, that countries might use know-how and equipment from declared programs to aid the construction of clandestine production facilities, for example clandestine enrichment plants, and that under some circumstances countries might choose to withdraw from the NPT and then overtly misuse materials and facilities.

Measuring non-proliferation or counter-terrorism characteristics of various nuclear energy systems is far from straightforward; among the considerations that come into play is what quantities and forms of sensitive nuclear material (including separated plutonium) exist at various points in the fuel cycle; what level of uranium enrichment capacity is needed to support the fuel cycle; and whether the materials separated as part of a given fuel cycle would be particularly attractive and/or particularly susceptible to undetected diversion for malicious purposes.

Waste Management as it relates to nuclear energy systems focuses on the need to manage some nuclear wastes over very long timeframes, during which they can remain radiotoxic and hazardous to humans and the environment. In fact, benefits from a waste management standpoint—including possible reduction in the quantity of long-lived radionuclides, increase in the chemical stability of waste forms, or reduction in repository heat load—is often among the major rationales cited for pursuing alternatives to the once through fuel cycle. Given the existence of many possible waste streams and different ways of characterizing those streams, a variety of metrics can be used to quantify waste-related impacts, including waste volume or mass, radiotoxicity, short and long term heat generation, the repository capacity required to dispose of the waste, and estimated peak dose rate for the maximally exposed individual at the perimeter of a waste repository or facility (the latter metric depends not only on the character of the waste, but on specifics of the repository's design and geologic environment; in most cases long-term repository performance is dominated by a small number of long-lived radionuclides).

Efforts to evaluate the waste management implications of advanced fuel cycles are complicated by the system of nuclear waste classification currently in use in the United States.   This system is based on the source of origin and the concentration of certain listed radionuclides for many wastes and is not informed by a comprehensive assessment of the waste characteristics important to the performance of disposal systems. The Subcommittee notes that though many stakeholders believe the time has come for an overhaul of the U.S. waste classification system, there is also considerable concern that changes could foster the perception that wastes are being inappropriately reclassified into lower classes or have other unintended consequences—especially considering the complex web of laws and regulations that rely on the current system. Adding to this ambivalence about reform is a widespread perception that the current approach to classification—for nuclear waste generally, and for LLW in particular—is adequately protective of human health, despite its shortcomings and complexities. These considerations notwithstanding, the NRC staff has identified a number of options for revising the waste classification and other aspects of LLW disposal on which it will obtain stakeholder input during the next year. Additionally, the NRC staff is planning to identify a number of options for changing the definition of HLW as part of developing a framework for licensing fuel reprocessing plants and plans to send a paper on the framework to the Commissioners by the end of fiscal year 2011. ***The subcommittee endorses and encourages efforts underway at the NRC to the revise the waste classification system.***

3.3 Challenges in Comparing Nuclear Energy Systems

A central objective of this Subcommittee is to qualitatively evaluate nuclear energy systems and technologies to assess whether potentially significant improvements are possible compared to existing fuel cycle technology. Many challenges arise in attempting to compare different nuclear energy systems. First, such comparisons generally rely on analyses conducted by the designers or supporters of the fuel cycle(s) in question. As such, they often reflect different underlying assumptions and owner biases and make use of different metrics. All of these challenges are exacerbated by substantial uncertainties in our understanding of the characteristics and performance of systems that have never been deployed.

When comparing the potential benefits and liabilities of different nuclear energy systems (fuel cycles and deployment strategies), for example, numerous assumptions must be made—many of them involving information that is not available for advanced technologies that are still under development, including:

1. The growth rate of nuclear electricity production
2. Current and ultimate performance, cost, and reliability of competing nuclear energy system technologies
3. Waste generation rates, composition, and characteristics
4. Measures for non-proliferation, nuclear material and energy security, and safeguards in an uncertain future domestic and international environment
5. Price and availability of natural resources into the future
6. Constraints on the size/capacity of future waste disposal sites
7. The importance of various radionuclides (e.g., TRU vs. fission products) to the performance of unknown future repository sites

The problem of uncertainty applies not only to these input assumptions, but to assessments of the candidate technologies themselves. Most advanced fuel cycle technologies have never been constructed or operated at a commercial scale, and many exist only in paper studies or small scale laboratory and test reactor experiments. As a result, the behavior of these systems when deployed on a large scale is subject to significant uncertainty and requires extrapolation from existing technology. Furthermore, even existing reprocessing technologies deployed at commercial scales in France, the UK and Japan, have large uncertainties in their economic metrics. As a consequence, most fuel cycle systems analyses produce results with large uncertainty bands, whether explicitly indicated or not, and are best used for a qualitative, comparative analysis rather than for a predictive estimate of their absolute performance.

3.4 Comparing Fuel Cycle and Nuclear Energy System Options

The baseline for our qualitative comparison is a nuclear energy strategy based on once-through LWRs. This is the baseline because it is the current system in the U.S. and in the majority of the world's nuclear nations. It should be noted that as a baseline this system allows for continuing improvements such as higher fuel burn up resulting from improved cladding and improved safety features.

A system involving a modified open cycle was selected for comparison chiefly because it is the only other fuel cycle strategy that is currently being utilized, specifically through the use of mixed-oxide fuel (MOX).[52] Used in France since the 1970s, MOX fuel is also used in reactors in Germany, Switzerland, Belgium and Japan. The United States is currently building a MOX fuel fabrication facility in South Carolina to utilize excess defense plutonium, and the United Kingdom, China, and Russia are also in various stages of operation or planning for the use of MOX fuel.

A system using fast reactors and a closed fuel cycle was considered because its efficient use of uranium resources has the potential to be sustainable for centuries while reducing the amount of long-lived radionuclides in the resulting waste, increasing the waste loading in a repository, greatly reducing the amount of uranium mined, and eventually eliminating the need for uranium enrichment.

The defining feature of the fourth system is a high-temperature reactor that can achieve temperatures greater than 600°C (light water reactor outlet temperatures are about 300°C) operating on a once-through fuel cycle. This system was selected because it has the potential to displace the use of fossil fuel across all energy sectors, not just electricity production. Examples of energy-intensive industries where high-temperature nuclear process heat could be

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[52] Mixed Oxide Fuel (MOX) consists of a mix of recycled plutonium and uranium.

used are cement and steel manufacturing, and petroleum refining (see Figure 11). High-temperature nuclear process heat could also be used to produce hydrogen for transportation fuels by directly decomposing water instead of using electrolysis or decomposing natural gas, and the high power conversion efficiency can also make dry cooling and thermal desalination of seawater practical.

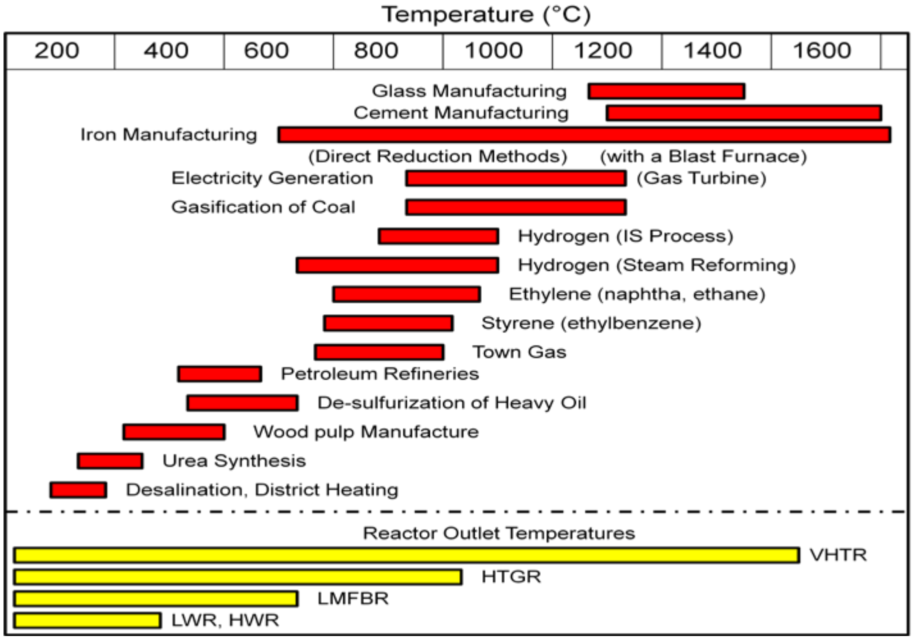

Figure 11. Temperatures required for various industrial applications and outlet temperatures of various reactor designs.[53]

The DOE is currently planning to build a demonstration plant of this type, called the Next Generation Nuclear Plant, at the Idaho National Laboratory. The reactor would be cooled with helium gas, moderated with graphite, and use low-enriched uranium fuel. It would be capable of generating electricity as well as supplying process heat.

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[53] Adapted from Idaho National Laboratory, Next Generation Nuclear Plant Research and Development Program Plan, INL/EXT/05-0281 (January 2005). VHTR = very high temperature reactor, HTGR = High temperature gas reactor, LMFBR = liquid metal fast breeder reactor, HWR = heavy water reactor.

Many additional system options exist that have received varying levels of study. For example, nuclear energy systems that involve a fast-spectrum reactor capable of achieving very high temperatures by using a molten salt or gas coolant, or a thermal-spectrum, high-temperature molten-salt reactor using thorium have also been proposed. Such systems could potentially offer many of the combined benefits of the alternatives listed. However, these systems have not received systematic study and the component technologies for these types of systems are less well developed.

The results of this comparison for the baseline strategy and the three nuclear energy systems selected for comparison are shown in Table 5 and are discussed in greater detail below.

Table 5. A comparison of the existing once-through, conventional light-water reactor fuel cycle with representative advanced nuclear energy systems in the long term

Criterion	**Once-Through LWR**	**Once-Through w/High-Temperature Reactor**	**LWR Modified Open Cycle**	**Fast-Spectrum Reactor with Closed Fuel Cycle**
Nuclear Energy Description	*Clad uranium oxide fuels irradiated in LWRs with evolutionary improvements*	*High-temperature reactors (such as those using graphite-based fuels) capable of temperatures over 600°C operating on a once-through fuel cycle. Being pursued in DOE's Next Generation Nuclear Plant project*	*Clad uranium- and mixed-oxide fuels irradiated in LWRs with evolutionary improvements. MOX fuel is irradiated once and then sent to repository.*	*Fast-spectrum liquid-metal-cooled reactors capable of continuous recycle of actinides*
SAFETY				
Reactor and fuel cycle safety[54]	Baseline, with potential for further improvement	Potential for improvement; all must meet similar regulatory requirements	Potential for improvement; all must meet similar regulatory requirements	Potential for improvement; all must meet similar regulatory requirements

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[54] Although the safety evaluation of the once-through fuel cycle is marked as the baseline – this does not suppose the safety is perfect. Even given consistent and approved safety design standards across fuel cycles, they still have room for improvement.

Criterion	Once-Through LWR	Once-Through w/High-Temperature Reactor	LWR Modified Open Cycle	Fast-Spectrum Reactor with Closed Fuel Cycle
COST				
Capital and operating costs	Baseline	Test reactors have operated well, but demo (Fort St. Vrain) was unreliable. Fuel costs are uncertain and may be high. RD&D is needed on to provide a basis for design, licensing, and evaluating long-term economic viability.	Capital cost increased because of need to build reprocessing and MOX fuel fabrication plants. Operating costs also increased due to the high cost of fabricating fuels containing Pu. Cost of electricity increased a few to several percent. Technology is relatively mature with evolutionary improvements largely in the hands of industry.	Previously built reactors (mostly prototype/demo) were often unreliable and not economic. Significant capital cost for recycle facilities. RD&D is needed to provide a basis for design, licensing, and evaluating long-term economic viability.[55] Operating costs relative to baseline largely depend on the future price of uranium, fuel fabrication cost, and operational reliability.
SUSTAINABILITY				
Uranium utilization[56]	Baseline	Similar uranium requirements, although can vary by design	~19% reduction in uranium requirements	~95% + reduction in uranium requirements
Global climate impacts	Baseline	Potential for major reduction in carbon dioxide by using nuclear process heat in fossil-energy-intensive industries and to produce hydrogen for non-carbon-based transportation fuels	About the same as the baseline	About the same as baseline
Energy security	Baseline	Potentially large benefit in reducing petroleum imports now used to fuel non-electricity sectors	About the same as the baseline	About the same as baseline
NONPROLIFERATION AND COUNTER-TERRORISM				
Non-proliferation	Baseline	Reference designs require similar enrichment capacity capable of producing 8-20% uranium enrichments. Fuel is more difficult to reprocess.	Involves use of reprocessing, enrichment, and MOX fuel fabrication technology, and deployment of facilities for same Increased proliferation risk. Creates highest inventories of separated Pu.	Involves use of reprocessing and plutonium-bearing fuel fabrication technology, and deployment of facilities for same. Enrichment technology needed during transition to fast reactors. Increased proliferation risk due to separated Pu or Pu + other actinides.

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[55] "No existing deterministic cost study of full recycling is credible, because there has been no engineering demonstration of full recycling." Testimony delivered by Geoff Rothwell on August 30, 2010

[56] The table compares nuclear energy systems in the long-term which means the R&D has been successfully completed, the fuel cycle in question has been adopted, and the transition phase is over so that the US is relying on just that system.

Criterion	**Once-Through LWR**	**Once-Through w/High-Temperature Reactor**	**LWR Modified Open Cycle**	**Fast-Spectrum Reactor with Closed Fuel Cycle**
Counter-terrorism	Baseline	Similar to baseline	Involves production and inventory of co-processed nuclear materials (U/Np/Pu) and 5-10% enriched uranium, and fuels containing same. Increased security risk due to separated materials and additional facilities.	Involves production and inventory of co-processed nuclear materials (U/Np/Pu) and fuels containing same. Increased security risk due to separated materials and additional facilities.
WASTE MANAGEMENT				
Disposal safety: toxicity and longevity of waste	Baseline (which will continue to evolve)	Repository: Similar to baseline Fuel Cycle: ~ Similar fuel cycle public and occupational risk from mining and milling	Repository: Slight reduction in the amount of TRU in wastes. Tailored waste form for ~90% of the HLW Fuel Cycle: ~17% reduction in fuel cycle public and occupational risk from reduced mining and milling, increase from emissions from reprocessing	Repository: Tailored waste form for fission products; potential for reduction in long-term repository dose from TRU elements if recycle is sustained for decades to centuries Fuel Cycle: ~85% reduction in fuel cycle public and occupational risk from reduced mining and milling, increase from emissions from reprocessing
Volume of waste[57]	Baseline	~10X increase in SNF volume going to repository. ~About the same non-mill tailings low level waste as the baseline.	~Similar repository waste volume: less SNF/HLW, more secondary waste. ~20% decrease in near-surface wastes, esp. mill tailings and DU. About the same non-mill tailings low level waste as the baseline.	~38% increase in repository waste volume: less HLW, more secondary waste. ~95% decrease in near-surface wastes, primarily due to mill tailings and DU. ~40% decrease in non-mill tailings low level waste due to greatly reduced throughput in the front end of the fuel cycle.
Repository space requirements	Baseline	~Similar to baseline	Similar to the baseline	~75% decrease in repository space required when TRU are recovered and recycle is sustained over many decades to a couple of centuries. If Cs and Sr are then removed from the waste, repository space requirements are reduced by 95-98% but alternative disposition of the Cs and Sr (e.g., 300-year surface decay storage) is required.

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[57] Assumption: Depleted uranium is deemed acceptable for near-surface disposal. If repository disposal is required the volume of repository waste increases ranging from 3 to 30 times for all but the closed fuel cycle, although decay heat and toxicity are not affected for 100,000 years.

Below we discuss in more detail the results of our qualitative comparison between the baseline once-through system and the alternative systems we considered with respect to each of the major evaluative criteria discussed in Section 3.2.

Safety –New reactors constructed in the future will continue to be governed by regulatory requirements for safety. We can expect that these requirements will be modified in light of the still-unfolding events in Japan, and we can expect new reactors to incorporate design improvements to address lessons learned from the Fukushima accident. These improvements may focus on areas such as assuring long-term effective cooling if back-up electrical power supplies are lost, having the capability to rely upon alternative heat sinks if the normal heat sink is disabled, having the capacity to prevent and mitigate the effects of explosive materials such as hydrogen, and assuring the capability to rapidly connect and activate portable electricity generation and coolant injection pumps.

It is reasonable for society to expect that new nuclear infrastructure will have higher safety levels than existing infrastructure, just as society requires for other civil infrastructure (i.e. - U.S. building code requirements are updated periodically). The NRC has established policy goals for advanced reactors that encourage similar improvement and will guide U.S. design efforts for new reactor technologies..[58] New reactor and fuel cycle facility technologies can be expected to rely increasingly upon passive safety systems and other design features that improve safety, economics, physical security and safeguards in a synergistic way. The licensing of these new safety systems will require the use of risk-informed performance criteria, and best-estimate simulation methods that include uncertainty quantification. These methods have been pioneered in the United States in the licensing of new advanced light-water reactor (ALWR) designs using passive safety systems. More recent experience with commercial development of small modular reactors has emphasized the importance of early interactions between reactor developers and the NRC, and having an established regulatory framework to guide early investment and design decisions.

Cost - Cost remains a key issue for nuclear energy and one that can be expected to strongly influence the industry's future prospects. Recent studies indicate that the current once-through nuclear energy systems can be competitive with coal and natural gas electricity

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[58] SECY-08-0130, "Updated Policy Statement on Regulation of Advanced Reactors," U.S. Nuclear Regulatory Commission, September 11, 2008. (ADAMS Accession No. ML082261489)

generation.[59] Because the capital cost of reactors contributes substantially more to the cost of nuclear electricity than fuel and waste disposal costs, reactor construction costs and reliability clearly play an important role. Capital costs depend on factors such as the total quantity of materials used in construction, the degree to which construction can be modularized and shifted into factories, and the overall construction schedule (which can in turn be influenced by factors such as public acceptance). These costs are difficult to estimate in the United States, given the length of time that has elapsed since the last U.S. reactors were constructed. Uncertainty over capital costs will continue to persist until construction of the first few new advanced LWRs occurs in this country.

In the modified open cycle (MOC) capital and backend operating costs are increased because of the need to build and operate facilities to reprocess uranium oxide fuel and to fabricate the recovered neptunium/plutonium and some of the uranium into fresh fuel. However, front-end operating costs are reduced because less natural uranium, conversion, and enrichment services are required. On balance, most estimates project that the levelized cost of nuclear electricity at the bus-bar from a modified open cycle would range from being essentially the same as the cost of the once-through fuel cycle[60,61] to an additional 15%[62]. In a 2007 report to Congress[63], the CBO stated that the costs of a modified open cycle would be approximately 25% more than the once-through cycle, although studies that the CBO researched for their report had a modified open cycle costing 6%[64] to 100%[65] more than the once-through cycle.

Experience from the construction and operation of a number of commercial prototype metal-cooled (mostly sodium) fast reactors and one high-temperature helium-cooled reactor can help shed some light on the cost issues likely to arise for fast reactor closed fuel cycle and high-temperature once-through fuel cycle systems. While some of these reactors produced electricity, all had the high capital costs and all were less reliable than what is required of a

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[59] MIT, 2011. Table 2.2 shows that levelized cost of new nuclear power is 6.6 cents per kwh, compared to coal at 6.2 and natural gas at 6.5. This assumes a natural gas price of $7/million BTU, a risk premium reduction through federal first-mover incentives, and no cost for carbon emissions.

[60] Overview of AREVA's Nuclear Fuel Recycling Activities - Presentation to The Blue Ribbon Commission on America's Nuclear Future from the La Hague Facility Visit on February 20-21, 2011. www.brc.gov

[61] MIT, 2011, pg. 103 notes the levelized cost of electricity for the modified cycle would cost less than 2% more than the once-through cycle

[62] EPRI, Nuclear Fuel Cycle Cost Comparison Between Once-Through and Plutonium Single-Recycling in Pressurized Water Reactors, EPRI Report 1018575, Feb 2009 Report

[63] Costs of Reprocessing Versus Directly Disposing of Spent Nuclear Fuel, Statement of Peter Orzag before the Committee of Energy and Natural Resources of the United States Senate. November 14, 2007.

[64] Boston Consulting Group, *Economic Assessment of Used Nuclear Fuel Management in the Unites States*, July 2006

[65] Bunn, et al., *Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, December 2003.

commercially viable nuclear reactor. These deficiencies must be successfully addressed if these reactors are to become economically viable. Doing so should be a primary target of future RD&D programs.

Sustainability –The sustainability criterion involves three considerations: resource consumption, the potential for global climate impacts, and energy security.

Resource consumption is concerned with how efficiently a nuclear energy system uses the natural resources underpinning it. For nuclear energy systems this includes fuels (uranium but also possibly thorium), as well as materials consumed in the construction of facilities. In general, the construction of nuclear power plants uses relatively small amounts of construction materials, so the focus of sustainability assessments is typically on fuel resources. The LWR-based MOC requires about 19% less uranium than the baseline with about half of this effect resulting from reprocessing and recycling plutonium as MOX fuel and the other half from re-enriching the recovered uranium to produce more enriched uranium and depleted uranium tails. This nuclear energy system also has commensurately lower conversion and enrichment requirements. Reprocessing spent MOX more than once (not considered in Table 5) offers some additional benefits but with diminishing returns because the fissile content of the plutonium is degraded in the LWR's thermal spectrum and eventually cannot be recycled because in-reactor safety requirements cannot be met. At most, three recycles may be possible but other countries using the MOC use only a single recycle.

In the case of the once-through high-temperature reactor (HTR), the amount of uranium resources required is roughly similar to the LWR, because while the HTR has a much higher thermal efficiency than a LWR, this is offset by lower efficiency in fuel utilization. However, the fact that both the baseline LWR and HTR systems are once-through imposes a fundamental limit on how efficiently uranium is utilized: 90% or more of the mined uranium constitutes the depleted uranium stream from the enrichment process.

The situation in the case of the fast reactor operating on a closed uranium-plutonium fuel cycle is different. Fast reactors can produce more fissile material than they consume (see earlier discussion of breeder reactors). This has two important implications for uranium utilization. First, the uranium used in this reactor is not enriched so there is no depleted uranium stream, and depleted uranium from once-through nuclear energy systems can be used as fuel. Because the fuel is reprocessed and recycled, the uranium can also be recycled.

Thus this system can, in principal, increase the energy recovered from mined uranium by a factor of 50 or more with the amount of energy recovered being limited only by the losses of uranium during recycle. Fast and thermal spectrum reactors could, in principal, recover similar amounts of energy from thorium.

A second consideration under the criterion of sustainability concerns the potential for advanced nuclear energy systems to help address global climate change. Many scientists and policymakers are concerned that carbon dioxide emissions from fossil fuel combustion are having adverse impacts on global climate[66]. As a consequence, to the extent that nuclear energy can reduce carbon dioxide emissions from fossil fuel combustion, nuclear energy can help address those climate concerns.

While displacing use of fossil fuels used to produce electricity would be helpful, the benefits are inherently limited because electricity production accounts for only 40% of U.S. energy consumption. The other energy-consuming sectors are transportation (29%) in which petroleum products are dominant, industry (21%) in which a mix of fossil fuels are used for process heat, and commercial/residential (10%) which is reliant on petroleum products and natural gas for space heating. Displacing the use of fossil fuels in these sectors requires that two issues be addressed.

First, a number of important industrial processes require process heat at temperatures well above what can be achieved by LWRs (perhaps 350°C) or liquid metal cooled fast reactors (perhaps 550°C). These industries include manufacturing of iron and steel, glass, and cement. Second, displacing use of petroleum products that supply most of rest of the energy for all three of these sectors requires a source of combustible fuel that is not based on carbon.

Nuclear energy could offset the use of fossil fuels for transportation in at least two ways. If plug-in hybrid or all-electric vehicles achieve significant market penetration, nuclear-generated electricity can be used to generate the electricity needed to power those vehicles. Another possible approach is the use of nuclear energy to produce hydrogen, which can be burned directly like natural gas, or made into liquid fuels that have a low fossil carbon content that can then be burned/combusted in engines or used in fuel cells. Most hydrogen[67] is currently produced using a process called steam reforming, which involves reacting water with natural

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[66] This view is expressed in several reports of the U.S. National Academies. See National Academy of Sciences. “America’s Climate Choices”, http://americasclimatechoices.org/ACC_Final_Report_Brief04.pdf

[67] A small fraction (~4%) of the hydrogen is produced by electrolysis of water, which could avoid carbon dioxide emissions if non-fossil electricity were used but the resulting hydrogen costs 3-10 times hydrogen produced by steam reforming and so it is only economic if very cheap electricity (e.g., hydropower) is available.

gas to yield the hydrogen and, unfortunately, carbon dioxide. Hydrogen can also be produced in chemical reactions that do not involve carbon-based fuels but such processes require temperatures well above what can be achieved by LWRs or fast reactors. High-temperature reactors may offer an alternative to both of these hydrogen production methods.. In particular, the high-temperature heat from the reactor coolant would be transferred to an intermediate fluid such as a molten salt and the heated salt would be piped to the process requiring the high temperatures either directly or indirectly – to produce hydrogen to be used to make other fuels.

A third consideration under the criterion of sustainability is energy security, which is usually understood to be a function of the nation's dependence on unreliable and/or expensive energy resources. While the U.S. economy is self-reliant and hence energy secure when it comes to coal and natural gas, it is clearly reliant on petroleum supplies that are both unreliable and expensive. Energy security concerns are an important reason why some countries, not endowed with energy resources as large as those in the U.S. (e.g., France, Japan) embarked on aggressive nuclear energy programs long ago. The potential for each of the four nuclear energy systems to substantially reduce U.S. dependence on foreign oil is given in the previous section and the results of comparing the four are the same: the high-temperature reactors have the potential to yield domestically produced liquid fuel supplies whereas the other three nuclear energy systems do not.

Nonproliferation. Considerations regarding nonproliferation and counter-terrorism are discussed in this and the following section in the narrow context of comparing alternative nuclear energy systems and are covered in broader perspective in Chapter 5.

The Subcommittee believes that nonproliferation and counter-terrorism are considerations of particular importance that have not always received the attention they deserve in evaluations of nuclear fuel cycles and nuclear energy system alternatives. The potential proliferation pathways created by the four fuel cycle options listed above depend in part upon the physical configuration of the system, and in particular on the physical location and ownership of the facilities used to perform enrichment, as well as reprocessing and recycled fuel fabrication. As described in Chapter 5, under the Nuclear Nonproliferation Treaty (NPT) and other international and bilateral agreements, there exist a number of institutional and technical approaches to reducing proliferation risks. While none of these approaches are perfect, taken together collectively they have helped reduce the number of proliferant states the international community, and can help to further isolate problematic countries so they do not become role models for other emerging nuclear energy nations.

Access to civil nuclear energy technology can provide a significant inducement for nations to take on key legal obligations related to nonproliferation, in particular to accept safeguards monitoring of their civil nuclear energy infrastructure by the International Atomic Energy Agency (IAEA) under a comprehensive safeguards agreement, and potentially, if expected or required as a condition of supply, to ratify an IAEA Additional Protocol to provide the IAEA broader rights to perform inspections to verify the absence of undeclared, clandestine nuclear material production activities.

But access to civil nuclear energy technology also provides capabilities that could potentially contribute to a weapons proliferation effort. The potential pathways include the clandestine diversion of materials from declared facilities, the use of technical know-how and equipment from declared facilities to aid the construction of separate, clandestine production facilities, and, under some circumstances, withdrawal from the NPT and then overt misuse of materials and facilities, commonly referred to as "breakout."[68]

The reactor technologies associated with the four fuel cycle options can be safeguarded effectively to provide timely detection of any attempt to divert fresh or irradiated fuel, because the fuel elements and assemblies can be accounted for as items. Thus power reactors are typically unattractive sources for the clandestine diversion of material. They likewise differ significantly in design from the types of small production reactors, similar to the production reactor constructed by the North Koreans, which might be attractive for a clandestine production facility. Likewise, while power reactors could provide a source of low-burn-up irradiated fuel if a nation were to choose to withdraw from the NPT, without infrastructure and experience with technologies like hot cells and reprocessing, the subsequent effort to process material and produce weapons would be technologically risky and time consuming. For these reasons, power reactors are generally viewed to create substantially lower proliferation risk than enrichment and reprocessing.

All four of the fuel cycle options described above require substantial and large-scale deployment of enrichment infrastructure. While the high temperature reactor and modified open fuel cycle options require more and less enrichment capacity than the baseline open cycle, respectively, the differences are modest and do not change qualitatively the proliferation risks posed by enrichment. Even for the fully closed cycle, substantial enrichment capacity remains necessary during the transition to a nuclear fleet based on fast reactors. The proliferation risks associated with enrichment depend very strongly on how it is deployed.

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[68] A systematic methodology to evaluate proliferation pathways is provided in "An Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Systems," GIF/PRPPWG/2006/005, 2006. http://www.gen-4.org/Technology/horizontal/PRPPEM.pdf.

National enrichment programs provide a pathway for breakout, and of equal concern, access to technical know-how and equipment that can be used to construct clandestine enrichment facilities that are difficult to detect. Chapter 5 discusses the importance of developing multi-national or regional fuel cycle centers, with a principal goal being that all nations procure enrichment services from these sources rather than developing dedicated national enrichment programs. Broad utilization of multi-national and regional enrichment services can be encouraged by providing other attractive services, in particular spent fuel take away.

The modified open cycle and closed cycle options use reprocessing of spent fuel. Reprocessing involves the separation of plutonium-bearing materials in bulk form. The application of IAEA safeguards to provide timely detection of diversion is substantially more difficult and challenging for bulk materials than for individual items (e.g., reactor fuel assemblies). While safeguards methods have been developed for conventional large reprocessing plants, further improvement remains possible to increase the robustness and reliability of detection, and to reduce the probability of false alarms or false positives due to plant events or safeguards systems failures. Further work is also required to develop more effective and better integrated safeguards methods for advanced reprocessing technologies. As with enrichment, national reprocessing programs can provide a pathway for breakout and can simplify the development of separate, clandestine reprocessing facilities.

The proliferation risks posed by reprocessing are broadly similar to those from enrichment. One approach to limiting proliferation risk from both technologies is the development of multi-national and regional fuel cycle facilities, as discussed further in Chapter 5.

Counter-Terrorism – Terrorism remains a global problem. Terrorism risk from civil nuclear energy systems arises from two primary sources: the potential for sabotage of nuclear facilities or transport to cause radiologic releases, and the potential for theft of nuclear materials for use in improvised nuclear explosives. Counterterrorism efforts to reduce these risks involve a combination of international cooperative activities and national activities. The protection of nuclear facilities and materials is a national responsibility, but there exist a variety of international efforts that the U.S. leads or participates in to assist countries in strengthening this protection; these efforts merit further and increased support.

Because nuclear reactors operate with substantial amounts of stored energy and inventories of short-lived fission products, their safety systems require effective physical protection from acts of radiological sabotage. The new Generation III and III+ reactor designs simplify this protection substantially, because they provide a greater degree of physical separation between redundant safety equipment, making it more difficult to disable, and implement passive safety systems to a greater degree. Because passive safety systems do not require routine operator access for inspection and maintenance, they are easier to harden to be resilient against sabotage attempts.

The irradiated fuel produced by reactors provides another potential target for radiological sabotage. While the physical protection of spent fuel is covered by the Storage and Transportation Subcommittee, it is important to note that spent fuel stored at operating reactors can be protected by the same physical protection forces protecting the reactors. Spent fuel is generally not an attractive target for theft, due to its bulky form, substantial radiation levels, and difficulty for terrorists to process it to recover material that could be used in nuclear explosives. Old spent fuel, where radiation levels have dropped substantially, may generate increased risks for theft in the future.

Enrichment and fuel fabrication facilities that produce low-enriched uranium (LEU) fuel pose very small risks for radiological sabotage and for theft of materials, because LEU has relatively low radiotoxicity and cannot be used directly to manufacture nuclear explosives. Therefore LEU enrichment and fuel fabrication facilities typically require only minimal physical protection.

All spent fuel reprocessing methods that chemically separate fission products produce a plutonium-bearing product stream with radiation levels that are too low to provide self-protection, particularly in light of the willingness demonstrated by many terrorists to self-sacrifice. The risk of theft of reprocessed plutonium must be taken very seriously, because even a low-yield event from a crude terrorist nuclear explosive design would have devastating consequences in a crowded urban area, as would the disruption caused by the fear of additional explosions in other cities.

Therefore all reprocessing and recycled fuel fabrication facilities and transportation require effective physical protection measures to counter external theft threats, as well as effective human reliability programs to reduce insider theft risks.[69] Full-recycle methods, where all recycled materials are handled in heavily shielded concrete hot cells to protect workers, can be designed to provide large, passive physical barriers to theft. The passive barriers provided by hot cells can be more effective than typical bank vaults because hot cells do not require doors for routine human access. Therefore full-recycle fuel cycles can be expected to require less intensive physical security measures than do conventional reprocessing technologies.

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[69] Examples of personnel reliability program measures include background checks, portal access controls, portal radiation monitors, tamper-evident seals and tags for cabinets and valve handles, two-man rules, and supervisor observations. Properly implemented, all of these measures also increase a facility's safety and reliability.

Under all of the potential fuel cycle options, risks for radiological sabotage will be larger for older reactors, under the expectation that designers of new reactor and fuel cycle facilities will continue to introduce improved design features such as passive safety systems that are intrinsically more robust against acts of sabotage. Thus the key issue for controlling the risk of radiological sabotage will be to assure continuing and adequate investments in physical security systems and in human reliability programs, particularly for older reactor and fuel cycle facilities.

For the baseline once-through LWR fuel cycle, as well as for high-temperature reactors, the most likely long-term scenarios for theft of plutonium involve old spent fuel dispersed at shutdown reactor sites in other areas of the world, stored without adequate physical security. This concern is addressed by the Storage and Transportation Subcommittee, but these potential long-term risks also strengthen the arguments and this Subcommittee's recommendations for the development of multi-national or regional fuel cycle facilities and for creating the capability to provide spent fuel take-away for countries with small nuclear energy programs.

The modified open and closed fuel cycle options, which use reprocessing, create more immediate risks for theft of plutonium-bearing materials. Therefore these options require substantially more intensive human reliability and physical security than do the open fuel cycle options. Risks can be expected to be larger for older fuel cycle facilities, because designers can be expected to introduce design features in new facilities such as materials handling in hot cells that are intrinsically more robust against acts of theft, but overall risks from all facilities may grow as terrorist threats evolve and capabilities increase. In all cases the transportation of fresh plutonium-bearing fuels must be provided with effective physical protection; the collocation of reactors with reprocessing facilities can reduce transportation theft risks.

Because the theft of nuclear material anywhere in the world, or radiological sabotage leading to a large release, could have serious domestic consequences in the U.S. as well, the U.S. has a major national security interest in assuring that all nuclear facilities and materials, worldwide, have effective physical security.

Waste Management - Waste disposal is a common requirement for all nuclear fuel cycle strategies. No strategy can avoid the need to dispose of some long-lived radioactive materials, whether these materials include fission products with residual transuranics or whether they also contain larger quantities of transuranic elements. All spent nuclear fuel and high-level waste disposal options face the same issue of demonstrating the required long-term isolation for these materials. It should also be recognized that interim storage may be effectively used to substantially reduce heat generation from shorter-lived fission products for all categories of fuel cycles.

Evaluating the waste management implications of different systems requires consideration of three issues or metrics: disposal safety/risk, amount of waste, and repository space requirements.

Disposal Safety/Risk. This consideration concerns the post-closure safety of waste disposal facilities associated with the nuclear energy systems, especially the over the long-term (centuries and beyond).The risk to the public is typically expressed in terms of the estimated dose to the public near the boundary of a disposal site, and the dominant component of dose usually results from radionuclides that are assumed to be dissolved from the waste and transported to the accessible environment by ground water (although other transport phenomena may occur). The rate at which various radionuclides are dissolved and transported can be very sensitive to both the geologic setting containing the wastes and along the radionuclide disposal path. This site-specificity of radionuclide transport and, thus, dose to the public, makes generalizations concerning the impact of various nuclear energy systems difficult. However, because radionuclides that are not in the repository cannot lead to a dose, energy systems that send smaller amounts of long-lived waste to the repository are preferable to those that send larger amount of such wastes. Additionally, nuclear energy systems that allow the waste form sent to the repository to be tailored for disposal are preferable to those that do not. Two measures of disposal safety and risk reflecting these preferences are commonly used, and are considered here in the comparison of fuel cycle options. One is the long-term toxicity of the waste as measured by the amount of long-lived radionuclides sent to a disposal site. The second is whether the waste form can be tailored to the disposal environment.

Regarding a deep geologic repository, the long-term toxicity measure can be further specified to be the amount of long-lived transuranic isotopes sent to the repository because the amount of fission products generated is essentially constant for a given amount of energy production. In the case of the once-through nuclear energy systems all of the TRU produced in the reactor are sent to the repository and become part of the inventory that can be released over time. There is no processing of the SNF in this case so the waste form is LWR or HTR spent fuel.

In the case of the LWR modified open cycle there is a reduction in the amount of TRU being sent to the repository because fissions in the MOX fuel lead to a net destruction of the TRU compared to the once-through cycle, although the amount of minor actinides (TRU less plutonium) would be increased. However, for the purposes of this comparison, the reduction is so small as to be unimportant. Because SNF is being reprocessed, about 90% of the repository waste from the LWR modified open cycle can be tailored specifically to the repository environment and about 10% is in the form of MOX SNF.

In the case of the closed-cycle with fast reactors, sustained recycle of the TRU elements to destroy them while producing power is possible. In this case, the repository waste from each recycle would contain a much smaller fraction than other nuclear energy systems: 1-2% of the TRU resulting from process losses during reprocessing and fuel fabrication in tailored waste forms for high level waste, fission product wastes, cladding hulls and technology wastes[70]. However, closed fuel cycles with fast reactors operate with large inventories of TRU in the reactor cores and in out-of-reactor fuel cycle facilities. The actual rates of consumption of TRU tend to be small compared to the total TRU inventories, so that decades to centuries can be required to significantly decrease the total TRU inventory. This implies a long-term commitment to the operation of fast reactors, or the willingness to place the fast reactor fuel into disposal if a more rapid transition to a different energy source is desired in the future. If this is done, closed cycles with fast reactors can operate sustainably with substantially lower long-lived TRU going to the repository than the once-through cycle, for very long periods of time.

A deep geologic repository containing SNF or HLW is not the only source of long-term risk from the nuclear fuel cycle. The front end of the fuel cycle leaves tailings from uranium (or thorium) mining and milling[71], and depleted uranium tails from enrichment operations that pose a long-term risk. The risks result from radium (half life of 1600y) and its decay products that are not recovered in the milling plus a fraction of the uranium that could not be recovered during milling. The tailings are typically mounded into large piles that are covered with a cap composed of impermeable barriers, soil, and rock to prevent radon release, and water ingress and radionuclide transport. Depleted uranium tails are being converted to uranium oxide which is proposed for near-surface disposal, but no facility is yet licensed to do so. Analyses indicate that about 85% of the public and occupational risk from the nuclear fuel results from uranium mining and milling (none of the analyses account for depleted uranium disposal).[72] As might be expected from the earlier discussion of resource utilization, the amount of uranium used by the alternatives varies significant. As a consequence, the amount of uranium mining and milling required, and the resulting long-term risk from the nuclear fuel cycle varies significantly. In particular, the long-term risk from the entire fuel cycle is reduced by 17% for

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[70] Technology waste is a term used in France that includes all of the additional wastes generated by a given process (not including HLW, fission products, or cladding hulls) - and can include contaminated equipment, protective gear, etc. Technology wastes have various contamination levels and therefore require a range of disposal options from repository disposal to near surface burial.

[71] Uranium recovery by in situ leaching leaves a similar amount of naturally occurring radionuclides in the subsurface. Fuel cycle risk analyses including this method have not been identified.

[72] G. E. Michaels, Impact of Actinide Recycle on Nuclear Fuel Cycle Heath Risks, ORNL/M-1947 (June 1992). OECD Nuclear Energy Agency, Radiological Impacts of Spent Nuclear Fuel Management Options: A Comparative Study, (2000)

the LWR MOC and 85% for the closed-cycle fast reactor nuclear energy systems while long-term risks for the HTR nuclear energy system are similar to those of LWRs. Alternatively, the recovery of uranium from seawater, does not produce mill tailings and thus provides a reduction of risk potentially comparable to the closed-cycle fast reactor system.

Volume of Waste. The second consideration related to this criterion is the volume of waste being produced. The cost and occupational risk of a number of fuel cycle and waste disposal operations depend on the waste volume or the number of waste packages, as well as the engineered barrier system required for a specific geologic repository. There are two components to the volume consideration: repository waste volume and waste being disposed of on or near the surface of the earth. Repository waste includes SNF, HLW from reprocessing, and GTCC wastes from reactors and from reprocessing and recycled fuel fabrication facilities. Wastes being disposed of in the near surface are produced by all fuel cycle operations and facilities with the largest contributor being uranium recovery (mill tailings). Depleted uranium from enriching natural and reprocessed uranium, and low-level wastes produced by reactors and all fuel cycle facilities amounts to less than 1% of the tailings volume and is dominated by the front end of the fuel cycle.).

Concerning repository wastes, the once-through HTR system generates a substantially greater volume of SNF than the OT LWR because, even though the HTR SNF contains less uranium, transuranics, and fission products, the fuel is bulkier because the graphite moderator is part of the fuel. The LWR MOC generates about the same waste volume as the OT LWR and the closed-cycle fast reactor system generates about 40% more waste than the OT LWR waste destined for a repository. These outcomes are the result of two competing effects: on one hand the volume of vitrified HLW is significantly less than the volume of SNF but on the other hand reprocessing and recycled fuel fabrication produce GTCC wastes (e.g., fuel assembly structural metal and cladding, TRU-contaminated equipment and trash) that yield a net increase in the total volume.

Concerning low-level wastes destined for near-surface disposal, the LWR MOC and closed-cycle fast reactor nuclear energy systems result in volume decreases of 20% and over 95%, respectively, relative to the LWR once-through systems. The decreases are driven by the reduced need for uranium, (primarily production of uranium mill tailings but also depleted uranium and LLW from processes in the front end of the fuel cycle) in the alternative systems that dwarfs the additional volume of LLW produced by reprocessing and recycled fuel fabrication facilities. The volume of near-surface waste from the HTR system is similar to LWRs. The LLW (near-surface wastes less mill tailings) produced by the OT LWR, LWR MOC, and HTR are about the same and are dominated by the front end of the fuel cycle. The LLW from the closed-cycle fast reactor is about 40% less than that from the OT LWR cycle because there is much less front-end activity.

One important uncertainty in the foregoing results concerns disposal of depleted uranium tails. There has been considerable discussion in the last few years about whether the large amounts of concentrated depleted uranium that constitute the tails are acceptable for near-surface disposal, and this issue is under evaluation by the NRC as this report is being written. If depleted uranium is acceptable for near-surface disposal then the foregoing analysis maintains. To the extent that depleted uranium is not acceptable for near-surface disposal, it would require a more isolating disposal technology such as a deep geologic repository. If depleted uranium were to be sent to the repository it would dominate the repository waste volume, although not the radioactivity, decay heat, or toxicity until times approaching a few thousand years.

Repository Space Requirements. In general, the amount of repository space required (i.e., the areal extent of the repository) is not driven by the volume of the repository waste. Instead, the amount of repository space required is driven by the decay heat from high-heat wastes such as SNF and vitrified HLW. For times less than about 70 years the decay heat is dominated by the fission products Sr-90 and Cs-137. After that time the decay heat is dominated by TRU elements, especially Am-241 and Pu-238. While interim storage for 30 to 90 years can greatly reduce the total heat released by the fission products, it is largely ineffective in reducing the total heat deposited by TRU. To accommodate the heat the wastes are spaced sufficiently far apart so as to prevent the waste from overheating and undesirable deleterious effects on the surrounding geology from occurring. Other repository wastes that generate relatively little heat (e.g., most GTCC wastes) can be packed tightly together and account for a small fraction of the required repository space.

If there are no physical limits on the volume of repository space available, the spacing required between packages of heat-generating waste can be increased with trivial cost and effort: a matter of a little extra mining to acquire the increased spacing. However, if there are physical limits on the volume of repository space available then increased spacing might require another repository that is costly and time-consuming. In this circumstance, increasing the amount of waste that could fit into the available space could be an important advantage.

The high-heat wastes from the LWR modified-open cycle system require about the same amount of space as the once-through LWR system because the preponderance of the plutonium and americium that dominate the long-term decay heat are reduced little by the single pass through the reactor and the amount of Cs-137 and Sr-90 are essentially the same.

The once-through HTR system has about 25% lower repository space requirement because the HTR has a higher thermal efficiency, which means fewer fissions are required to produce the same amount of electricity as the once-through LWRs. The closed cycle fast-reactor system requires about 75% less repository spacing if a major fraction of the TRU are destroyed by sustained recycle instead of being part of the HLW waste stream that is disposed of in the repository. If the TRU are destroyed by sustained recycle, and in addition cesium and strontium are separated during reprocessing so they are not sent to the repository, then the repository space requirement decreases by 95 to 98%. However, achieving this requires an alternative way of managing the recovered cesium and strontium such as decay in a storage facility for a few centuries, which raises an entirely new set of siting, cost, security, and institutional control issues.

3.5 Summary Comparison

Analysis and Recommendations. Compared to the once-through LWR system, the modified-open cycle LWR system offers modest advantages in terms of uranium resource utilization, yielding a tailored waste form for most repository wastes, a modest reduction in enrichment requirements, and reduction of the volume of wastes requiring near-surface disposal such as mill tailings and depleted uranium tails. These advantages come with disadvantages: increased fuel cycle costs, increased physical security costs and risks for the protection of separated plutonium and fresh MOX fuels, and increased proliferation risks depending upon how reprocessing infrastructure is deployed compared to enrichment infrastructure. On balance, the subcommittee sees no compelling reason to encourage industrial-scale deployment of this nuclear energy system in the U.S. at this time.

Compared with either of the LWR systems, the once-through HTR system has the potential to yield some compelling advantages: the potential for a major reduction in the use of fossil fuels, which should lead to commensurate global climate and energy security benefits, and a significant reduction in repository space requirements. Most disadvantages of this system are modest: absence of a waste form tailored to the disposal environment, and the use of uranium having enrichment levels about twice that of once-through LWR fuels. The one major disadvantage of the HTR system is that only one demonstration reactor resembling projected future HTR designs was built and operated, and that proved to be very unreliable and costly. As a consequence, the HTR system will require substantial RD&D to determine whether it can become sufficiently reliable and economic so that deployment can be justified, all things considered. ***The Subcommittee recommends that the RD&D program on high-temperature reactors be continued.***

As with the once-through HTR nuclear energy system, when compared with either of the LWR systems, the closed-cycle fast reactor system offers a number of different and significant potential advantages. The closed-cycle fast-reactor system has the potential to yield a large increase in uranium resource utilization and reduction of enrichment and repository space requirements as well as the TRU content of repository wastes. Disadvantages of the closed-cycle fast-reactor nuclear energy system include potentially substantially higher electricity generation costs, due to higher construction costs for fast reactors compared to LWRs, increased physical security costs and risks associated with the separation, fabrication, and transport of plutonium and plutonium-bearing fuels, and increased proliferation risks. Technology for pyroprocessing and metal fuels, developed in the U.S. for the Integral Fast Reactor project, allow recycle to occur in hot cells and may provide significant security advantages over conventional reprocessing methods and fast-spectrum MOX fuels. As with the HTR system, the closed-cycle fast reactor will require substantial RD&D to determine whether it can become sufficiently reliable and economic so that commercial deployment can be justified. ***The Subcommittee recommends that RD&D on the closed-cycle nuclear energy systems be continued.***

Examination of the attributes of HTR and closed-cycle, fast-spectrum systems in Table 5 leads to the possibility that hybrid alternatives might be attractive. For example, molten salt reactors do not use metal cladding or structures in their reactor cores, and thus can operate at the same temperatures as HTRs. Fluid fuels eliminate the requirements to fabricate fuel assemblies from recycled material, and thus can use relatively simple chemical separations that maintain high radiation levels and self protection. The radioactivity and inaccessibility of these streams should partly ameliorate proliferation and terrorism concerns, although methods for applying IAEA safeguards remain to be developed. A prototype molten salt nuclear reactor (the Molten Salt Reactor Experiment) operated in the U.S. from 1965 to 1969 and at one point the U.S. had a program to develop a full-scale reactor. Substantial interest in this technology, today commonly called the Liquid Fluoride Thorium Reactor, has reemerged due to its capacity to operate at high temperatures with thorium fuel. However, as might be evident, the system described here is not as well developed as the HTR and closed-cycle fast reactor nuclear energy systems discussed above, and a major RD&D program would be required to bring it to fruition. The Subcommittee recommends that DOE perform a detailed technology assessment to determine the status of this technology as a basis for deciding whether it should be pursued further.

Other Alternatives: As noted earlier, there are many other alternative nuclear energy systems that might be considered. Below we briefly characterize some of these alternatives and how they might fit in to the rubric of considerations shown in the table.

- Thorium-based fuels in once-through cycles
    - Offer additional resources but other benefits and issues are essentially the same as for the once-through alternative.
    - Reduced amount of transuranic (TRU) elements in the used/spent fuel does not mean that the radiotoxicity of the spent nuclear fuel is lower or that the long-term risk from a repository containing thorium-based fuels is significantly lower than the risk from a repository containing uranium-based fuels.

- Alternatives involving a symbiotic once-through cycle from which TRU elements are recovered and used in a closed fuel cycle based on uranium or thorium.
    - If a decision is ultimately made to deploy fast-spectrum uranium reactors or thermal-spectrum thorium reactors with a closed fuel cycle—presumably because they were determined to be preferable to a once-through fuel cycle—the optimal combination of reactor types will be determined by reference to multiple evaluation criteria such as those listed at the outset of this section.
    - If fast reactors operating on a closed fuel cycle prove preferable to a once-through fuel cycle, a symbiotic system composed of once-through reactors and fast reactors operating on a closed fuel cycle could be used to transition to reliance on fast reactors.

- Small modular reactors
    - A strategy to change the approach to manufacturing, financing, and deploying reactors, rather than a distinct nuclear energy system or technology. The question is whether modular designs can offer advantages in terms of cost and safety.
    - Reactor alternatives in Table 1 (including the baseline), variants of these alternatives, and light-water reactors could theoretically all be implemented using “small” designs.
    - Small designs do not fundamentally change the waste management issues associated with the reactor type in question.

The fact that there are no clear winners among the advanced fuel cycle concepts currently under consideration suggests a policy to keep multiple options open. That said, certain fuel cycle strategies and technologies are clearly better developed than others—research in some areas has been underway for decades and it is possible that more mature technologies could be implemented more quickly, perhaps within a few decades. Other concepts are barely at the proof-of-principle stage and would require substantial investments of time and funding (and in some cases a number of revolutionary technical developments) to bring them to a level of maturity sufficient to evaluate their suitability for further development and potential implementation. Consequently, the level and duration of R&D effort needed to advance these concepts varies widely. Ironically, funding needs for technologies that are relatively more developed can be greater than for technologies still in an earlier phase of the RD&D process—particularly in the case of technologies that are ready to be demonstrated. At that point, large investments may be needed to provide the demonstration facilities required to make further progress. In the next chapter we explore the U.S. nuclear energy R&D plans and programs and offer suggestions for addressing the challenges facing those programs.

3.6 Key Findings

(1) Advances in nuclear reactor and fuel cycle technologies may hold promise for achieving substantial benefits in terms of broadly held safety, economic, environmental, and energy security goals, but continued RD&D will be required. Subcommittee members hold different views about the commercial promise of technologies for closing the fuel cycle and about the strength of the rationales often cited in arguments for (or against) moving away from the once-through fuel cycle as currently employed in the United States.

(2) No currently available or reasonably foreseeable reactor and fuel cycle technologies—including current or potential reprocess and recycle technologies—have the potential to fundamentally alter the waste management challenge this nation confronts over at least the next several decades, if not longer.

(3) Alternatives to the once-through fuel cycle (as practiced in the U.S., Sweden, Canada and elsewhere) or to the modified open fuel cycle (as practiced in France, Japan, and Russia and planned in some other countries) will require decades of development before they are ready for widespread commercial application.

(4) It would be premature at this point for the United States to commit irreversibly to any particular fuel cycle as a matter of government policy. If and when future technology advances change the balance of market and policy considerations to favor a shift away from the once-through fuel cycle, that shift will be driven by a combination of factors, including waste management impacts, safety, economics, energy security, and other considerations.

(5) In sum, the Subcommittee finds it is both more important and more productive at this time to focus on designing and implementing a nuclear research, development, and demonstration (RD&D) strategy for the next several decades that makes effective use of scarce resources and is continuously responsive to the broader policy objectives about which we already have broad agreement (as opposed to seeking consensus on the merits of particular technology and fuel cycle pathways).

4. RESEARCH AND DEVELOPMENT

4.1 Background

Today, nuclear technologies worldwide can most certainly trace their roots back to innovative work done by the United States and the polices that have promoted their development. Since the earliest days of the civilian nuclear power industry in the United States, the federal government has played a large role. It undertook or sponsored the early research, development, and demonstration of nuclear technologies in the 1950s and early 1960s—initially for defense purposes, primarily in support of nuclear weapons and naval nuclear reactor development, but soon for civilian power applications. Early demonstrations of the commercial potential of nuclear energy generation through the Power Reactor Demonstration Program, such as the Shippingport reactor project, were conducted as public-private partnerships. Government involvement continued after the technology for civilian nuclear power production was transferred to the private sector. Throughout subsequent decades the federal government has funded nuclear energy RD&D and adopted policies, such as the accident liability and insurance framework established under the Price-Anderson Act and the Advanced Light Water Reactor Program (ALWR Program) and DOE 2010 Program, to support the demonstration and deployment of new generations of reactor designs. A short history of reactor and fuel cycle technology development, including a discussion of the federal role, may be found in the commissioned paper *Abridged History of Reactor and Fuel Cycle Technologies Development* on the Commission web site (www.brc.gov).[73]

Many U.S. government policies supporting commercial demonstration of new reactor technologies have aimed to reduce first-mover costs and risk, for example through loan guarantees and federal cost sharing for reactor design and licensing. Federal cost sharing with U.S. reactor vendors under the ALWR Program for NRC Design Certification of new passively-safe light water reactors (such as the AP-600 and ABWR), and cost sharing the development of three NRC Early Site Licenses by utilities under the DOE 2010 Program, arguably has played a central role in enabling current commercial activity to build new advanced light water reactors in the United States. Following the events in Fukushima, it is likely that these passive safety technologies pioneered in the U.S. will become the leading technologies for decades to come.

The opportunity to secure federal loan guarantees for new reactor construction has further advanced the prospect for new modular construction methods to be tested and new reactor

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[73] *Abridged History of Reactor and Fuel Cycle Technologies Development: A White Paper for the Reactor and Fuel Cycle Technology Subcommittee of the Blue Ribbon Commission*, Gary Vine, Longenecker & Associates, March 15, 2011

designs built (although only one nuclear loan guarantee has been achieved in the six years since the program was passed by Congress). Funding for many of these supportive government policies has been provided through DOE's nuclear energy program budget.

New nuclear energy technologies that could have significant performance improvement over existing technologies must emerge from R&D. This chapter begins by summarizing DOE's longer-term, high-level objectives for commercial nuclear energy research and development (R&D) based on a roadmap submitted to Congress in 2010. We then turn to a description of DOE's nuclear energy R&D program plans for FY 2011 and FY 2012, to R&D infrastructure issues and needs, and to efforts within the NRC to perform anticipatory research and to develop new regulatory frameworks for commercial development, licensing, and deployment of advanced nuclear energy systems. We then conclude with a discussion of challenges facing the U.S. nuclear energy R&D program and recommendations for addressing those challenges. ***The Subcommittee believes that a well-focused R&D program is critical to enabling the U.S. to regain its role as the global leader of nuclear technology innovation.***

4.2 The DOE Nuclear R&D Roadmap, Nuclear Programs, and R&D Budget

In April 2010, DOE submitted a report to Congress titled *Nuclear Energy Research and Development Roadmap*. The roadmap lays out, in mostly high-level and qualitative terms, plans and objectives for the Department's R&D activities related to civilian nuclear energy strategies, technologies, and systems.

The roadmap articulates four overarching R&D objectives for DOE's Office of Nuclear Energy over the next four decades, as summarized below.

R&D OBJECTIVE 1: Improve safety and reliability and extend lives of current reactors: DOE aims to work with industry and the NRC to safely extend the operating lifetimes of current plants beyond sixty years and, where possible, make further improvements in their productivity. The DOE role in this R&D objective is to 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 are generic to reactor type and develop advanced monitoring technologies and safety assessment techniques, among other activities.

<u>R&D OBJECTIVE 2: Improve the affordability of new reactors</u>: New reactor designs, such as small modular reactors (SMRs) and high-temperature reactors (HTRs) may offer improved safety and economics and other desirable characteristics. To pursue these opportunities, DOE intends to develop advanced reactor concepts, technologies and tools for high-performance plants; support R&D on small modular reactor concepts, including sponsoring cost-shared research related to design certification; and design and develop safety methods for high-temperature reactors using graphite-based fuels.

<u>R&D OBJECTIVE 3: Develop sustainable nuclear fuel cycles</u>: Specifically, DOE will investigate technical challenges associated with three potential fuel cycle strategies, including a “once through” fuel cycle, a “modified open” cycle, and “full recycling” (as defined in previous sections).

For the once-through fuel cycle, DOE plans to develop fuels that would increase the efficient use of uranium resources and reduce the amount of spent fuel generated for each megawatt-hour (MWh) of electricity produced—essentially by increasing the burn up of once-through fuels. This would include evaluating the use of non-uranium materials (*e.g.*, thorium) as reactor fuel options.

In the category of modified open fuel cycles, DOE aims to investigate fuel forms and reactor designs that would improve resource utilization and reduce the quantity of long-lived radiotoxic elements left in the spent fuel to be disposed of. This would be accomplished using simplified separation techniques that are claimed to have proliferation risks lower than full spent fuel recycle.

For full recycling, the goal is to claim a higher fraction of the energy potential of the original uranium while recycling or destroying most of the long-lived actinide elements such that the long-term toxicity of, and heat released by, the resulting waste streams is dramatically reduced. The challenge is to develop techniques that can achieve this objective in an operationally and environmentally safe, cost-effective and proliferation-resistant manner.

Prior to beginning major R&D work on these three fuel-cycle options, DOE intends to analyze a number of related issues, including the availability of fuel resources for different fuel cycle and reactor deployment scenarios; options for the disposition of waste streams from existing and future fuel cycles; options for reducing the presence of long-lived actinides in spent fuel; the feasibility and risks of alternative recycling processes; the behavior of different waste forms over time in different storage and disposal environments; fuel fabrication processes and fuel performance; options for the re-use of recovered uranium and other fuel constituents (such as metal cladding); and transmutation systems that can alter spent fuel elements such that they have more desirable disposal characteristics (e.g., shorter half-lives).

R&D OBJECTIVE 4: Understand and minimize the risks of nuclear proliferation and terrorism: DOE plans to pursue an approach that integrates technology development (including safeguards and security technologies and systems) with the maintenance and strengthening of non-proliferation frameworks and protocols. This approach recognizes that technological advances can only provide part of an effective response to proliferation risks: institutional measures—such as export controls, management systems and safeguards—are also essential. More specifically, DOE plans to (1) assess proliferation risks to inform future fuel cycle and technology decisions and (2) develop and test technologies designed to reduce proliferation risks.

Cross-Cutting R&D: DOE's 2010 roadmap also calls for ongoing R&D in a number of enabling, cross-cutting technology areas:

- 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

As this summary reveals, DOE's current nuclear energy R&D roadmap provides for both relatively short-term activities to support the safety and reliability of operating reactors and renewed construction of light-water reactors, and typically longer-term activities to develop advanced reactors and fuel cycle technologies. And as noted at the outset, the roadmap is generally qualitative and written at a high level, without much program or quantitative budget detail. Approximate milestones for the R&D objectives are shown for only the minority of activities expected to be completed before 2020. The roadmap does not contain timelines for activities expected to be completed beyond 2020.

As R&D activities continue, DOE anticipates reaching decision points at which fuel cycle strategies (e.g., once-through, full recycle, etc.) and technologies (e.g., oxide fuel vs. metal fuel, water vs. sodium-cooled reactor designs) will be evaluated and subsequently selected. Properly-conducted evaluations – which account for the interconnections among the various elements of the nuclear fuel cycle – will allow resources to be focused on the most promising systems, especially when it comes to more costly, large-scale development and demonstration projects. A major question for new nuclear energy technologies is when to take the step from R&D to commercial-scale demonstration. As discussed further below, the Subcommittee notes that at the stage of commercial-scale demonstration, federal cost sharing of development costs with industry can assure that the technology has actual commercial potential—as evidenced by private-sector willingness to invest—while still addressing the issues associated with first-mover risk that can otherwise prevent sufficient investment in new technologies. For example, current industry willingness to invest substantial financial resources into the development of small, modular reactors based on light water reactor technology provides evidence for the commercial potential of this technology. As R&D advances additional new nuclear energy technologies to the stage where commercial-scale demonstration may be warranted, federal cost sharing of development costs will remain the most appropriate approach to incentivize their commercial-scale demonstration.

DOE's nuclear energy R&D roadmap is intended to serve as a guide for the development of annual R&D program and budget proposals to Congress. As discussed below, nuclear energy R&D supported by DOE ranges from basic research on "enabling technologies" to applied research directed at existing reactors and potential new construction.

In examining DOE's nuclear energy R&D plans and programs, the Subcommittee remained mindful of the broader context for our nation's energy research, development and demonstration efforts. A number of studies have concluded that the United States suffers from a pervasive deficit of public and private investment in energy technology innovation given the importance of energy technologies to the economy, to our industrial competitiveness and energy security, and to the protection of human welfare and the environment.[74] For example, PCAST[75] points out that public investment in energy R&D in the United States, at around 0.03 percent of GDP, lags behind that of Japan, Korea, France and China when adjusted for the size of the U.S. economy.

The case for direct public investment in basic science R&D is well documented in the mainstream economics literature, which points to the inability of the funder to capture the commercial benefits of an investment in basic science as the primary reason why private

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[74] Battelle (2010), GAO (2008, 2006), Margolis (1999), Nemet (2006), PCAST (1997, 2010)

[75] Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Federal Energy Policy, President's Council of Advisors on Science and Technology, November 2010

investments in R&D would be expected to systematically fall short of socially optimal levels.[76] Influential reports such as the National Academies' *Rising Above the Gathering Storm*[77] have made the case for increased federal investment in basic science and have prompted actions such as the formation of the Advanced Research Projects Agency-Energy (ARPA-E) program within DOE to provide increased support for longer-range basic energy research investments.

The theoretical case for a direct government role (and arguably the effectiveness of many government interventions) diminishes as technologies move from basic research through the intermediary stages of development and demonstration to full-scale commercial deployment. Indeed, efforts to place government in a supportive role in these latter stages of technology development are regularly cast by critics as "corporate welfare." Even in these later stages of the innovation process, however, supportive policies and first-mover financial incentives are often required to overcome remaining deployment barriers.[78] For example, the annual rate of installation of new wind power in the U.S. fluctuated wildly over the past decade depending on the status of federal tax credits for renewable energy generation.[79] Looking specifically at incentives for nuclear technology, U.S. technical leadership in nuclear energy – while not as strong as it once was – has been bolstered by federal support that helped lead to the state-of-the-art AP-1000 and ESBWR reactor designs, and plans to construct new reactors in the U.S. arguably would not have advanced to their current stage without the prospect of federal loan guarantees (although, as noted earlier, agreement on only one guarantee has been achieved in the six years since the program was passed by Congress).

While government support for energy technologies can take many forms, this section focuses specifically on support provided via DOE's nuclear energy R&D programs. Support for nuclear energy RD&D has grown considerably over the past decade and, as shown in Figure 12, seems to have reached a relatively steady (if not optimal) level in recent years.

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[76] The basic argument is that private investors face a free-rider problem: they cannot appropriate or capture the full value of all the knowledge "spillovers" created by their investments in R&D. So their incentives to make these investments are diminished relative to the full social benefits they generate. This gap provides the justification for direct public investment in basic science R&D.

[77] *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, National Academies Press, 2007

[78] Under Section 218 of the Nuclear Waste Policy Act, for example, the federal government successfully provided cost-sharing for the demonstration and first licensed deployment of at-reactor modular dry storage technologies.

[79] Ragheb, M., USA Wind Energy Resources, 1/27/2010, https://netfiles.uiuc.edu/mragheb/www/NPRE%20475%20Wind%20Power%20Systems/USA%20Wind%20Energy%20Resources.pdf

The information presented below is based on budget documents prepared by DOE. These documents are generally longer and more detailed than the high-level roadmap discussed in the previous section. However, they provide only a one- or two-year snapshot of DOE's plans and activities. Table 6 provides a breakdown of FY2011 funding for DOE's major nuclear RD&D programs compared to the Department's FY2012 budget request. More details on the Department's nuclear energy R&D programs may be found at www.ne.doe.gov.

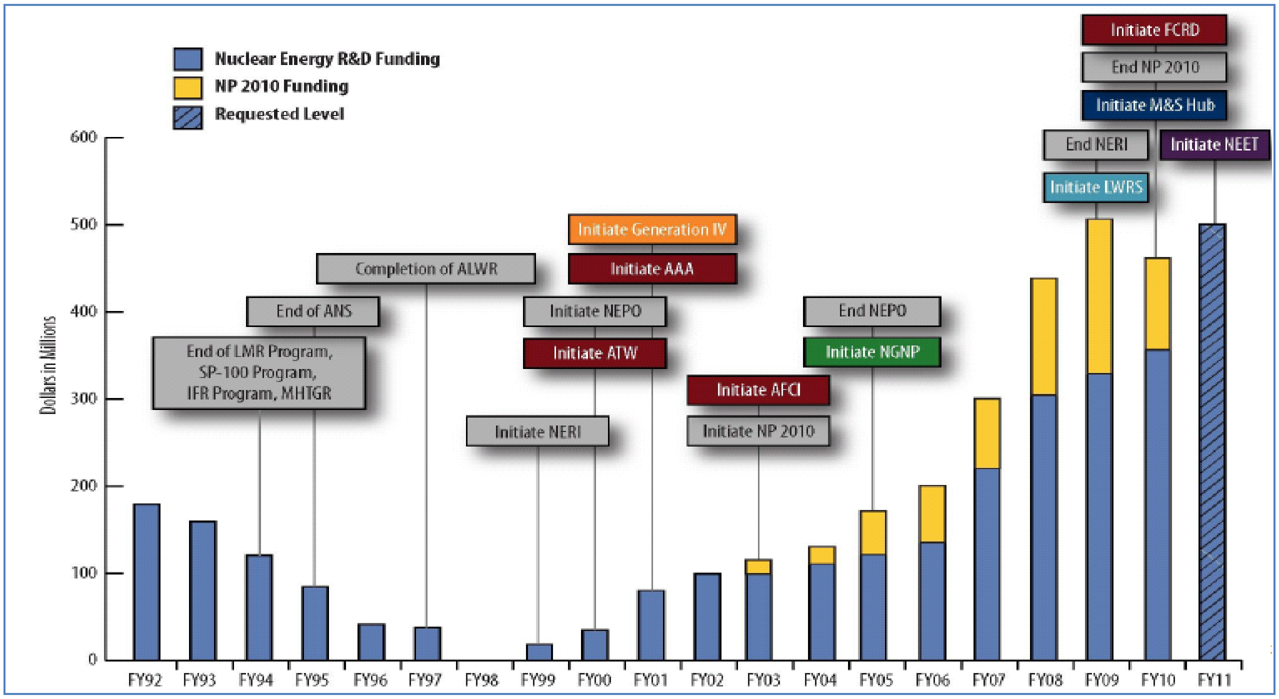

Figure 12. DOE R&D Funding Levels Fiscal Year 1992 - 2011[80]

Table 6. FY2011 budget and FY2012 budget request for the DOE nuclear RD&D program

Technical Areas		FY 2011 Current (in $1000s)	FY 2012 Request (in $1000s)
LWR SMR Licensing Technical Support		TBD	67,000
Reactor Concepts RD&D		TBD	125,000
Fuel Cycle Research and Development		TBD	155,010
Nuclear Energy Enabling Technologies		TBD	97,364
Integrated University Program		TBD	0
International Nuclear Energy Cooperation		TBD	3,000
	TOTAL	TBD[81]	447,374

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[80] Testimony of DOE Asst. Secretary Pete Miller to the BRC. July 2010, Idaho Falls, ID.

The remainder of this section discusses current and planned activities under each of the programs funded in FY 2011 and proposed to be funded in the FY 2012 budget request.

LWR SMR Licensing Technical Support: This new program is proposed to be split out of the Reactor Concepts R&D effort and to stand alone starting in FY 2012. The purpose is to support first-of-a-kind engineering and design certification activities for small modular water-cooled reactor designs through cost-shared arrangements with industry partners in order to accelerate deployment.

Reactor Concepts RD&D: This program aims to develop new and advanced reactor designs and technologies. Specific areas of R&D (there are no demonstration activities planned in the immediate future) are designed to address technical, cost, safety, and security issues associated with new reactor concepts. Individual projects within this program include small modular (non-light water-cooled) reactors advanced concepts R&D, the Next Generation Nuclear Plant demonstration project (NGNP), and other advanced reactor concepts. In addition, in cooperation with EPRI the program will develop advanced technologies for extending the life of existing light water reactors under the Light Water Reactor Sustainability program.

The largest share of the FY2011 budget request for reactor concepts (about 40 percent) is for the Next Generation Nuclear Plant Demonstration Project (NGNP), which aims to demonstrate electricity and/or hydrogen production with a high-temperature nuclear energy source.

Fuel Cycle R&D: The mission of this program is to develop nuclear fuel and waste management technologies. Beginning in FY2010, the focus of the program shifted from near-term technology development and deployment to long-term, science-based RD&D with the aim of improving current fuel cycle technologies and management strategies. Current plans call for the examination of three fuel cycle approaches: the current once-through fuel cycle, modified open fuel cycles, and full fuel recycle.

The current Fuel Cycle R&D program has dropped its earlier emphasis under the Global Nuclear Energy Partnership (GNEP) on constructing commercial-scale facilities and instead is now focused on RD&D with a new goal of deploying alternate fuel cycles in 2050. Several considerations have driven this change. One is the assumption that spent fuel from nuclear power reactors can be safely stored on an interim basis for at least 60 years. A second is that the expanded time allocated for RD&D will lead to new “science-based” and “transformational”

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[81] As of this writing DOE has not determined program funding allocations for FY 2011

fuel cycle technologies that will be superior to the more evolutionary technologies that would have been introduced earlier in the GNEP program.

The search for a more proliferation-resistant reprocessing technology than the PUREX process is being operated under this program. Criteria for success include: high throughputs, high product purity with minimal waste streams, very high decontamination of the transuranic product from lanthanide fission products, acceptable economics, and non-proliferation assurance (should not produce a separated stream of pure plutonium). Two forms of advanced separations processes for LWR and fast reactor fuels are being pursued:

- Advanced Aqueous processing: These are a suite of aqueous solvent extraction processes for LWR spent fuel. Advanced aqueous processes that meet the above criteria all involve an initial extraction segment named "UREX," (for Uranium EXtraction)that separates uranium and technetium from the spent fuel dissolver solution. Other extraction segments have been added to meet various requirements for an advanced process, all called UREX+ (UREX+1, UREX+1a, UREX+1b, UREX+2, etc. – about ten variations are being investigated).
- Pyro-chemical Processing (or "Pyroprocessing"): This process is applicable to metallic fast reactor fuels. It is based on molten salt electro-refining, a technique that has been used since 1996 for conditioning metallic spent fuel from the EBR-II reactor.

Both technologies face major challenges in meeting the stated goals. Scale-up to commercial throughputs, economics, and waste stream management are all particularly challenging.

Nuclear Energy Enabling Technologies: The Nuclear Energy Enabling Technologies Program collects activities that had been scattered under other programs in previous fiscal years. The focus is on innovative research in areas that are relevant to multiple reactor and fuel cycle concepts and that offer the promise of dramatically improved performance.

Together, these activities are intended to address crosscutting technology needs (such as advanced fuels and reactor materials, innovative manufacturing methods, sensor technologies, etc.), while also encouraging transformative, "outside the box" technological advances. To foster the latter, DOE is proposing to provide funding for investigator-initiated projects—to be selected via an open competitive solicitation—and for continued support of a modeling and simulation hub established in FY2010.

Integrated University Program: The aim of this program was to train thousands of young energy scientists and engineers across the United States by providing support to nuclear engineering and science programs at U.S. universities. DOE has requested zero funding for this program in FY 2012, but will continue to provide up to 20 percent of appropriated nuclear energy R&D funds to competitively-awarded university-based research.

International Nuclear Energy Cooperation: This program is intended to support the implementation of international cooperative RD&D activities that further the Office of Nuclear Energy's mission. Like the Nuclear Energy Enabling Technologies program, this program collects activities that had been scattered under other program headings in previous fiscal years.

4.3 Industry-funded Nuclear Energy R&D

Nuclear reactor vendors, nuclear power plant operators and others finance the conduct of research focused primarily on constructing new nuclear power plants (including SMRs) or on maximizing the output or improving the safety and reliability of existing nuclear power plants.

Work on specific new reactor designs is supported by nuclear power plant vendors, often in cooperation with the federal government (such as through the now-defunct Advanced Light Water Reactor and Nuclear Power 2010 programs). These cooperative efforts have led to the commercial availability of currently state-of-the-art reactor designs like the AP-1000 and the ESBWR. Public-private partnerships have also been used to develop alternatives to light water reactor technology, including the sodium-cooled PRISM reactor and the gas-cooled reactor concepts studied as part of the Next Generation Nuclear Plant project.

Industry and the federal government have also jointly-funded research or otherwise worked cooperatively to maximize the output or improve the safety and reliability of today's nuclear power plants. Much of the industry-sponsored effort is conducted through the Electric Power Research Institute (EPRI), a research and development organization funded primarily by electric generating companies. For example, production of nuclear electricity from existing plants grew substantially in the 1990s and 2000s as a result of increased capacity factors[82]. This improvement was driven by reactor operators and the efforts of EPRI, spurred by DOE-sponsored R&D into high-burn up fuels that allowed utilities to shift from 12-month operating cycles to 18- or 24-month operating cycles that reduced downtime.[83] EPRI and DOE are currently working together through DOE's Light Water Reactor Sustainability program on advanced technologies for extending the life of existing light water reactors. In addition, nuclear plant operators provide financial support for so-called "owners groups" which, among other things, support R&D into issues common to particular reactor designs. EPRI's 2011 budget for nuclear energy R&D is approximately $125 million.

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[82] The fleet's average capacity factor improved from 58.6% in 1974-76 to 90.24% in the 2007-09 period. Blake, E. Michael, "Capacity factor remains over 90%", Nuclear News, May 2010, pgs. 39-43.

[83] Nuclear Energy R&D Roadmap, Report to Congress, April 2010, p. 8

4.4 NRC R&D and Advanced Technology Licensing Efforts

The NRC is engaged in research efforts to ensure the safety of nuclear facilities during construction, operations and maintenance, and also conducts research to support regulatory functions. These research activities build the NRC's capability to perform independent confirmatory scientific and technical analysis for new license applications and amendments, and thus remain vital to strengthening the NRC's role as an independent regulatory authority for the safety and security of U.S. nuclear energy infrastructure. Earlier NRC research, for example to develop the Code Scaling, Applicability, and Uncertainty Analysis methodology, played a fundamental role in creating the regulatory framework that enabled U.S. reactor vendors to develop and license designs for new passive safety systems for ALWRs. NRC Design Certification remains the international "gold standard" for reactor safety, and continuing investment in NRC research to maintain this leadership provides one of the best opportunities for U.S. standards for safety and security to be adopted widely within the international community.

The NRC Office of Nuclear Regulatory Research is a major NRC program office with an annual budget of approximately $65M.[84] Principal areas of research include nuclear materials, new and advanced reactors infrastructure development, safety and severe accident analyses, risk analysis, human factors and reliability, and environmental and health effects. The large majority of this research is funded from fees charged to U.S. utilities and is focused on assuring the safety of NRC-licensed facilities, but the NRC is also engaged in research to prepare for the possible commercial use of new nuclear reactor and fuel cycle systems.

While DOE and the nuclear industry will need to conduct the majority of research in support of new nuclear technology, the NRC has an important function to play in working with DOE and the industry to identify the most probable future technologies and to develop appropriate regulatory frameworks. To help prepare for the regulation of future nuclear energy technologies, in December 2007 the NRC issued NUREG-1860, the Feasibility Study for a Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing. NUREG-1860 uses a probabilistic (risk-informed) approach in the identification and selection of licensing basis events. The NRC Commissioners have directed the NRC staff to pilot the technology neutral framework from NUREG-1860 in parallel with the licensing strategy for the NGNP. Support for the NRC's efforts to pilot the NUREG-1860 framework on the NGNP program has been provided under a reimbursable work contract with the DOE.

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[84] Brian Sheron, Director NRC Office of Regulatory Research - testimony to the BRC, August 31, 2010

The NRC is also examining its current regulatory framework to determine if changes are required to prepare for the potential use of reprocessing or recycling technologies. Given the relative lack of interest over the past few decades in the commercial deployment of reprocessing technologies in the U.S., the current NRC licensing requirements have evolved to focus mainly on reactors. The NRC is now planning to revise the regulatory framework for licensing potential new commercial reprocessing facilities. The NRC's current schedule calls for completing the regulatory basis and initial environmental activities in 2011 and 2012, to culminate in a request to the NRC Commissioners to proceed with rulemaking. If that request is approved, the NRC plans to issue a draft rule in 2014 and a final rule in 2015.

Earlier NRC anticipatory research has been highly productive in developing new approaches to validating safety models and played a key role in creating the licensing framework that enabled the development and licensing of passive safety systems for ALWRs. This research also built a strong base of scientific and technical capability that has greatly strengthened the NRC's ability to act as an independent regulatory authority. These facts provide the basis for the Subcommittee's recommendation that 5 to 10 percent of federal nuclear energy R&D funding be provided directly to the NRC to fund an independent program of anticipatory research and efforts to develop licensing frameworks for advanced reactor and fuel cycle technologies.

4.5 R&D Infrastructure in the United States—Existing Capacity and Future Needs

The U.S. government currently maintains a wide range of facilities to support its nuclear energy RD&D activities. These facilities include test reactors, large-scale hot cells, smaller-scale radiological facilities, specialty engineering facilities, and small non-radiological laboratories. Available capabilities include core competencies in reactor technologies, fuel cycle development, and systems engineering as well as the safeguards, security, and safety infrastructure to manage radiological and nuclear materials and testing under normal and abnormal conditions. Specific facilities include those for neutron irradiation, post-irradiation examination (PIE) and characterization, fuel development, separations and waste form development, and other specialized testing capabilities.

Most of this infrastructure is DOE-owned and much of it resides in the national laboratory system, though it is supplemented by university and some industry capabilities ranging from research reactors to materials science and testing laboratories. In addition, important sources of R&D support and expertise are housed in the nuclear engineering and radiation science programs of colleges and universities, and in corporations that are involved in developing, designing, manufacturing, and building nuclear power plants and other nuclear facilities. Additional capabilities specific to the U.S. Naval Nuclear Propulsion Program reside within the Department of Defense.

The remainder of this section focuses on the infrastructure, equipment, capabilities and assets needed to advance state-of-the-art nuclear energy technology RD&D, and it draws heavily on a summary of several recent studies of this issue[85], including studies commissioned by DOE's Office of Nuclear Energy and undertaken by Battelle Memorial Institute and Idaho National Laboratory. We do not include the manufacturing, waste management, cleanup or other facilities and capabilities that must be in place to support the RD&D enterprise. Nor do we cover the nation's nuclear weapons-related RD&D infrastructure, though it should be noted that some of this infrastructure—which is based almost entirely at the national laboratories—could be useful for some research activities related to advanced fuel cycle security and non-proliferation.

Maintaining the physical infrastructure needed to conduct nuclear energy RD&D tends to be significantly more costly than maintaining other types of RD&D infrastructure—in part because of the safety and security precautions involved in handling nuclear materials, and in part due to the age of the infrastructure, most of which dates from the 1960's and 1970's. While retrofitting these older facilities for new R&D activities has been the primary approach used to conduct new R&D activities in the last decade, investment to construct new facilities could likely result in increased research productivity and reduced research costs. As one way to help manage costs and promote research integration, DOE's current approach is to focus its nuclear facility investments at the Idaho National Laboratory (INL) while maintaining various unique capabilities at other sites and by coordinating with university-based research facilities. In addition, DOE makes its facilities available to industry and university researchers, often through joint research projects.

Early in 2008, DOE's Office of Nuclear Energy commissioned Battelle Memorial Institute to engage the domestic nuclear energy industry, academic community, and national laboratories to analyze the capabilities required to support the successful deployment of nuclear energy opportunities by 2050. [86] This series of reports was intended as a response to a 2008 review of

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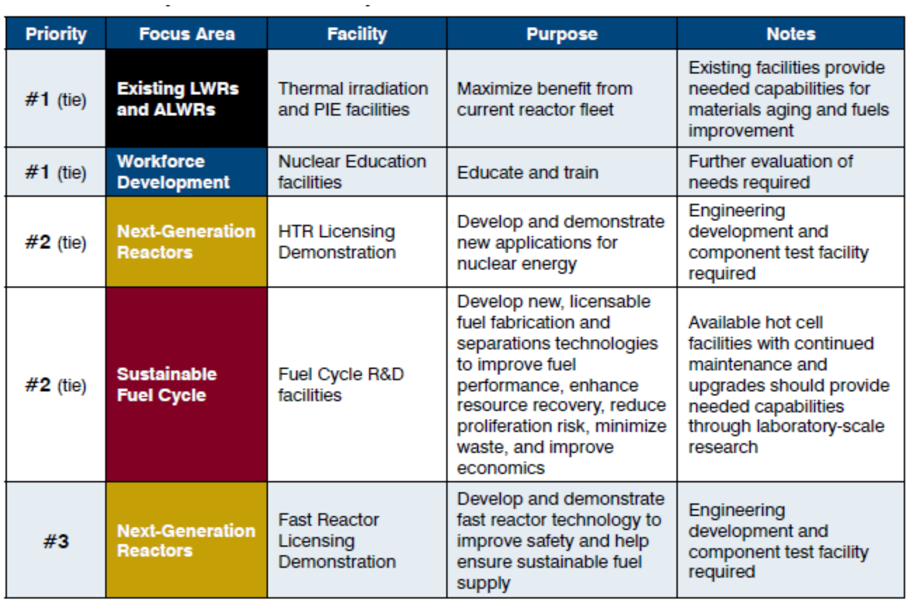
[85] Klein, Andrew C., "Nuclear Energy R&D Infrastructure Report for The Blue Ribbon Commission on America's Nuclear Future", 2011.

[86] "Nuclear Energy for the Future: Required Research and Development Capabilities – An Industry Perspective", Battelle Memorial Institute, Columbus, OH, 2008.

DOE's nuclear R&D programs by the National Academy of Sciences.[87] Ultimately, DOE, Idaho National Laboratory and Battelle conducted a three-phase process to identify the highest priority needs in terms of R&D capabilities and facilities.

In the first phase of its study, Battelle sought input from 34 organizations (representing the nuclear energy industry, academia, and the national laboratories) to articulate R&D goals for the 2010–2050 timeframe and identify and prioritize the required capabilities to accomplish these goals. In the second phase, Idaho National Laboratory assessed the availability and state of existing infrastructure in the U.S. in terms of providing these capabilities. In the third phase, a senior executive team—led by Battelle, but including members from industry, academia and the national laboratories—reviewed the results of both studies, along with industry goals, current DOE program activities, and capability gaps. Based on this review, the executive team identified a set of key priorities (shown in Table 7 below) in R&D focus areas that would require "unique-to-nuclear" facilities and capabilities for the nation's nuclear energy RD&D program.



Priority	Focus Area	Facility	Purpose	Notes
#1 (tie)	**Existing LWRs and ALWRs**	Thermal irradiation and PIE facilities	Maximize benefit from current reactor fleet	Existing facilities provide needed capabilities for materials aging and fuels improvement
#1 (tie)	**Workforce Development**	Nuclear Education facilities	Educate and train	Further evaluation of needs required
#2 (tie)	**Next-Generation Reactors**	HTR Licensing Demonstration	Develop and demonstrate new applications for nuclear energy	Engineering development and component test facility required
#2 (tie)	**Sustainable Fuel Cycle**	Fuel Cycle R&D facilities	Develop new, licensable fuel fabrication and separations technologies to improve fuel performance, enhance resource recovery, reduce proliferation risk, minimize waste, and improve economics	Available hot cell facilities with continued maintenance and upgrades should provide needed capabilities through laboratory-scale research
#3	**Next-Generation Reactors**	Fast Reactor Licensing Demonstration	Develop and demonstrate fast reactor technology to improve safety and help ensure sustainable fuel supply	Engineering development and component test facility required

Table 7. Summary of Nuclear R&D Facility Priorities[88]

In addition to those priority areas, the Batelle study also identified nine general and unique essential RD&D capabilities and/or facilities that it judged essential to conducting a successful nuclear energy RD&D program for the next 20 to 50 years. Because these capabilities/facilities were considered essential, we reviewed their status.

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[87] National Academy of Sciences, "Review of DOE's Nuclear Energy Research and Development Program", 2008

[88] Battelle (2008)

1. **Nuclear Education Facilities -** There remain approximately 27 research and training reactors on university campuses and most nuclear engineering programs have, at minimum, fundamental radiation detection and measurement laboratories. The recent introduction of the NEUP has enabled stronger and continuing investments in core competencies and infrastructure. During fiscal years 2009 and 2010 the NEUP provided more than $18M for infrastructure, instrumentation and facilities improvements on university campuses.

2. **Thermal Neutron Irradiation Capability -** Several thermal test reactor(s) of sufficient size and availability to irradiate new fuel design pins and material test specimens to provide prototypical results currently operate in the DOE complex. These include the Advanced Test Reactor (ATR) at INL and the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL). The ATR has recently been designated by DOE as a National Scientific User Facility.

3. **Fast Neutron Irradiation Capability -** There are currently no high volume fast neutron irradiation testing facilities operating in the U.S. Limited, small-volume R&D capabilities have been developed and exist at a few thermal research reactors. Currently, the U.S. uses irradiation capabilities in foreign countries to conduct limited tests on materials and fuel. Since the US has not operated any significant fast neutron irradiation capabilities for nearly two decades while other countries have continued to operate and provide such resources, the US could gain significant access to fast neutron irradiation capabilities at a fraction of the cost if it were to initiate and sustain international discussions on the development of these types of vital facilities.

4. **Radiochemistry Laboratories -** Over the last 30 years, many fuel cycle research and development facilities have been shut down or re-directed for other uses 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 (mostly at INL and ORNL, but also at the Savannah River Site near Aiken, SC, Pacific Northwest National Laboratory in Richland, WA, Los Alamos National Laboratory in Los Alamos, NM and Lawrence Livermore National Laboratory in Livermore, CA) which can continue to be used for RD&D efforts supporting a sustainable nuclear fuel cycle. As with the fast neutron irradiation capabilities discussed above, the US could gain access to significant sources of data and information if it took a lead role in the development of international collaborations resulting in sizable radiochemical RD&D laboratories.

5. **Hot Cells for Separations and Post-Irradiation Examination -** A number of DOE national laboratories maintain hot cell facilities that are currently used for separations research work, or could be configured to do so. These facilities span a wide range of size and activity type to support fuel recycle. Specifically, facilities[89] located at ORNL, INL, and the Savannah River Site (SRS) might possibly be considered use for in testing advanced separations technology; however the particular use must be fit into their original design and application envelope. Additionally, several large hot cell facilities in the DOE complex can be used to examine and test irradiated fuels and material.[90]

6. **Facilities for Thermal Transport and Safety Analysis -** Currently, there are no thermal loops operating in the DOE complex capable testing at the extreme temperatures required by the high-temperature gas-cooled reactor (HTGR) concepts being currently researched and developed. A small-scale HTGR testing facility is currently under development at Oregon State University and will be completed in the summer of 2011. Limited thermal transport and safety analysis facilities currently exist for licensing and computer code verification and validation for the current generation of light water reactors (LWR) and for some advanced LWR concepts.[91] There are limited to no thermal transport and safety analysis flow loops available in the US today for liquid metal or molten salt reactor simulation and testing, or for computer model validation and verification for these systems, or for safety analysis for use in licensing proceedings for these reactor technology types.

7. **Fuel Development Laboratories -** Fuel development typically proceeds through a number of phases prior to development of full-scale assemblies. Unfortunately, the full range of facilities does not currently exist although some of the national laboratory hot cells could be utilized, depending upon the size of the fuel components. International laboratories and fuel vendors, notably in France, Japan and Russia, might be utilized for a small number of fuel test development activities. Some of the required capabilities for the next-generation reactor fuels are currently available at national laboratories and in

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[89] ORNL's Radiochemical Development Center, the Fuel Conditioning Facility at INL, and the H Canyon facility at SRS

[90] They include the Hot Fuel Examination Facility (HFEF) at INL, the Irradiated Fuels Examination Laboratory (IFEL), the Irradiated Materials Examination and Testing Laboratory (IMET) at ORNL and the Chemistry and Metallurgical Research Facility Wing 9 hot cells at LANL. The HFEF has recently been designated by DOE as part of the ATR National Scientific User Facility for use by industry and academia, as well as by the traditional Naval Reactors and DOE users.

[91] These take the form of both integral systems test facilities, as exemplified by the APEX (advanced, large-scale pressurized water reactors) and MASLWR (small, modular pressurized water reactors) facilities at Oregon State University and the PUMA facility (advanced, large-scale boiling water reactors) at Purdue University, and separate effects testing facilities at INL and at Pennsylvania State University, University Wisconsin, University of California - Berkeley, Texas A&M University, North Carolina State University, Oregon State University, Purdue University and others.

industrial facilities that currently are used to develop the evolving fuel designs of the fuel vendors. Unlike new LWR fuel, however, recycled reactor fuel (MOX, for example) must be assembled remotely and will require heavily shielded and safeguarded facilities.

8. **Prototype High-Temperature Reactor for Licensing and Demonstration -** Across the globe, there are only a few small gas-cooled test reactors, including the High-Temperature Test Reactor (HTTR) in Japan and the 100-MWth reactor in China. The only large-scale Pebble Bed Modular Reactor (PBMR) prototype, previously under construction in South Africa, is no longer under consideration. The Next Generation Nuclear Plant (NGNP) would be the only large (300 to 400 MWth) demonstration of a combined electricity/process heat plant, if its design is ever completed.

9. **Prototype Fast Reactor for Licensing and Demonstration -** Most of the large-scale (greater the 200 MWth) fast reactors built globally have been shut down. The last large fast reactor shut down in the United States was the Fast Flux Test Facility (FFTF), which was built to test fast reactor fuel designs and primary circuit components. There are no current plans in the US for a prototype fast reactor demonstration at the present time. Internationally, a few fast reactors still exist where limited US licensing and demonstration activities could be arranged. These include operating reactors in Japan, Russia, India, and China. Furthermore, there are fast spectrum reactors currently under design and construction in Russia and India where US researchers and regulators could obtain valuable experience through extensive collaboration in licensing and regulatory research and development, if enabled by the host countries.

4.6 Addressing the Challenges Facing the U.S. Nuclear Energy RD&D Program

With federal discretionary budgets under increasing pressure, the ability to articulate a clear direction or agenda for the U.S. nuclear energy R&D program, to prioritize elements of that agenda, and to set performance objectives and evaluate the effectiveness of related activities on an ongoing basis will obviously be critical.

In the interest of maximizing the effectiveness of DOE's R&D program going forward, the Subcommittee is pleased to see that DOE is taking steps to launch a comprehensive Quadrennial Technology Review (QTR), consistent with a recommendation from a recent PCAST report.[92] According to DOE's QTR framing document, "the DOE-QTR is concerned primarily with

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[92] DOE's Quadrennial Technology Review framing document is available at http://energy.gov/QTR

activities to develop and demonstrate new energy technologies in support of national energy goals. These are multi-year efforts in which science, technology, economics, and energy policy intertwine. In view of the multitude of technologies that *could* be developed and demonstrated, analytically-based priorities and coordination of RD&D efforts with policy are essential to facilitate deployment by the for-profit sector."[93] The QTR will thus provide a useful opportunity to periodically revisit and refine DOE's existing nuclear R&D Roadmap and to situate nuclear programs in the broader federal energy R&D agenda. As part of the QTR, DOE should consider opportunities for improvement to its management program, both in terms of process and management and in terms of technology focus.

The Subcommittee believes that DOE's nuclear energy R&D Roadmap is a good science-based step toward the development of an effective, long-term R&D program. The Roadmap should be periodically updated (we recommend approximately every four years – consistent with the QER/QTR process – or when circumstances indicate). In addition, the Roadmap should be supported by more detailed, frequently updated, and transparent research and implementation plans.

As DOE develops RD&D program plans based on the QTR and on present and future versions of the Nuclear Energy R&D Roadmap it should explicitly apply the evaluation criteria noted in the BRC's charter and it should build in the flexibility needed to respond to unexpected technology developments and changing societal concerns and preferences. The recent and still-unfolding events at the Fukushima Daiichi nuclear power plant are just one example of the type of development that should be reflected in future updates of the R&D roadmap.

The Subcommittee urges that system assessments and evaluations account for the interconnections among the various elements of the nuclear fuel cycle (including transportation, interim storage, and disposal) and for broader safety, security, and non-proliferation concerns. For example, adding facilities to one phase or section of the nuclear fuel cycle could change overall system costs or otherwise affect the performance of the system as a whole. As concluded by a recent MIT report[94], the choices of nuclear fuel cycle (once through, modified open or fully closed) will depend upon both the technologies we develop and on a societal weighting of goals including safety, economics, waste management, and nonproliferation. As with reactors, once fuel cycle facilities are built they can be expected to operate for many decades. Thus decisions by industry to construct commercial-scale infrastructure will have major and very long term impacts on nuclear power development.

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[93] DOE Quadrennial Technology Review framing document, p. 5

[94] *The Future of the Nuclear Fuel Cycle*, Massachusetts Institute of Technology, 2010

Such choices can be made most effectively only if the interconnections between and among the elements of the fuel cycle system are well understood.

Implementation of the Roadmap and of supporting R&D programs will involve a broad range of participants including universities, industry, and national laboratories in cooperation with international research partners. Integrating the efforts of these disparate participants will require a concerted effort and is essential if DOE is to maximize the value of the RD&D it supports. DOE should undertake efforts to strengthen coordination and organizational and mission alignment across laboratories, energy hubs, innovation centers, and other entities.

Safety concerns, along with nuclear weapons proliferation and nuclear material safeguards and security (discussed in the following chapter), deserve special attention in the RD&D roadmap. Societal acceptance and commercial viability of present and future nuclear technologies will depend in large part on the perceptions of the public, regulators, policymakers and others regarding the safety and security of nuclear energy systems and their ability to restrain the proliferation of nuclear weapons. Integrating safety, security and safeguards considerations in future evaluations of advanced nuclear energy systems and technologies will allow the United States to maintain consistency between its technology development agenda, its commercial interests, and its international policy agenda.

As a result of the focus on repository design issues specific to the Yucca Mountain site, R&D on deep geologic disposal for the last few decades has been assigned a lesser priority within DOE's R&D portfolio. The move by DOE to absorb the R&D responsibilities of the Office of Civilian Radioactive Waste Management into the Office of Nuclear Energy presents an opportunity for better integration of waste management considerations into the DOE nuclear energy research agenda.

Going forward, the nuclear energy R&D program should include an emphasis on the development of disposal and waste form alternatives that are optimized to work with potential natural and engineered barriers in the disposal system. If alternative nuclear energy systems are deployed in the future, however, they will likely generate a greater variety of waste streams. Efforts to manage these wastes will benefit from an improved understanding of different combinations of geologic disposal environments, engineered barriers and waste forms. The R&D program on waste form and disposal alternatives should be coordinated between the DOE and the new nuclear waste management organization, with the understanding that generic research in this area would remain the responsibility of DOE (and would be paid for from general appropriations) and research specific to particular disposal sites would be undertaken by the new organization.

The federal nuclear energy research portfolio should include a research component that investigates the structure of public attitudes toward and concerns about nuclear power – why the public holds certain preferences and what those preferences are at any given point. As stated above, these public preferences will be critical to the successful deployment of advanced nuclear energy facilities – on either the front end or the back end of the fuel cycle[95]. Current understanding of public attitudes and preferences is inadequate, and in any event these attitudes and preferences will undoubtedly change with time and with changing views on safety, energy security, environmental protection and other issued. Targeted social science research can help improve understanding of the public's concerns and provide the foundation for a technically informed consideration of societal issues in the research agenda and in technology deployment decisions. Public acceptance and policy preferences are and will remain important – if not decisive – conditions shaping nuclear materials management policies.[96] The new organization charged with managing the nation's nuclear waste program could take the lead role in defining and providing funding for this type of research.

As noted earlier, annual budgets for the Office of Nuclear Energy's R&D programs in recent years (FY 2008-2011) have been approximately $500 million. Looking ahead, we see potential for increasing federal RD&D investment in nuclear energy technology to advance the core policy goals, as an element of general expansion of energy-related R&D. The Subcommittee notes that the recent PCAST report endorsed an earlier proposal by the American Energy Innovation Council[97] to provide $16 billion in annual federal support for energy technology innovation across all energy technologies—an increase of about $10 billion per year over current funding levels, with all of that increase coming from new revenue sources. Of this $16 billion-per-year total, PCAST recommends that $12 billion be directed to basic R&D and $4 billion to large-scale demonstration projects. While the PCAST report does not recommend a specific level of support for nuclear energy technologies, the Subcommittee also notes that a recent MIT study recommended roughly double the current funding level —approximately $1 billion per year—to support nuclear energy RD&D and related infrastructure needs. This is roughly double the U.S. Department of Energy's budget for nuclear energy R&D in recent years. The MIT study also concluded that additional funding would be needed to support large-scale

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[95] Michael O'Hare, "Nuclear Waste Facility Siting and Local Opposition", BRC Commissioned White Paper, http://brc.gov

[96] Hank Jenkins-Smith, "Public Beliefs, Concerns and Preferences Regarding the Management of Used Nuclear Fuel and High Level Radioactive Waste", BRC Commissioned White Paper, http:brc.gov

[97] American Energy Innovation Council (AEIC) – A Business Plan for American's Energy Future – http://www.americanenergyinnovation.org/full-report

government-industry demonstration projects at the appropriate time.[98]

In considering how such funding could be best applied, the Subcommittee believes that opportunities exist, both for incremental improvement in the technologies that currently dominate the U.S. and global reactor fleet and to achieve more profound nuclear technology breakthroughs in the longer term. To address the former, the United States should devote some share of RD&D resources to sustaining and improving light-water reactor technology, particularly in light of the increased attention to safety and waste management issues triggered by recent events in Japan. Technological advances in areas such as cooling system design, higher-burn up fuels, reactor power uprates, digital controls, material properties, and manufacturing techniques can reduce the amount of radioactive waste produced per unit of energy generated, reduce accident probability, and lower construction costs for new reactors. At the same time it will also be important to look beyond incremental improvements and continue to invest in more advanced and potentially game-changing technologies that are farther from being commercially competitive but that have the potential to change the waste situation and other system attributes in a fundamental way.

Turning to the infrastructure issues discussed previously, it is clear that while existing facilities are adequate to support continued R&D progress, particularly in the area of light water reactor technology, this infrastructure is quite old and substantially enhanced and larger-scale capabilities will be necessary to support a longer-term effort to develop advanced fuel cycles that include reprocessing or separations. In particular, and as noted in the Battelle study described earlier, existing U.S. capacity to conduct fast neutron irradiation is significantly deficient, especially if there is a desire to utilize this technology to recycle fissile material or destroy fission products in the future. A fast spectrum test reactor would best meet the range of R&D needs in this area. Likewise, radiochemistry laboratories, hot cells, and fuel development laboratories with the additional capacity and sophistication needed to investigate advanced fuel cycles would be needed, as would large-scale thermal loops and flow facilities to test thermal transport capabilities. Finally, pre-commercial prototypes are an important missing piece in the infrastructure available to support the continued development of high-temperature reactors and fast spectrum reactors. Both of these reactor concepts represent a significant departure from the current and next generation of light water reactor designs.

Meanwhile, much of the existing nuclear infrastructure in the national laboratories, industry and universities is more than 30 years old (and in some cases more than 50 years old). This does not mean it can no longer serve many of its intended purposes, but it does mean that

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[98] Related to the need for additional funding, a recent PCAST study suggested that a tax on energy be used to raise revenues for expanded federal investment in nuclear and other areas of energy technology R&D.

resources are needed to support modifications, upgrades, equipment additions, and sustained regular maintenance.[99] Maintaining and expanding the use of particular aspects of the current infrastructure, and developing additional facilities to meet new and/or expanded opportunities as resources allow – both domestically and internationally—appears to be the approach both DOE and the nuclear energy RD&D community have chosen for the time being.

A last issue concerns the need for early work to develop regulations for advanced nuclear energy systems such as reactors cooled by fluids other than water, aqueous and non-aqueous recycle facilities, and small modular reactors. The early development of regulatory frameworks would be extremely helpful both in terms of guiding the design of new systems and in terms of removing an impediment to commercial investment by providing an increased degree of confidence that new designs and systems can be successfully licensed. The efforts underway at the NRC (through the development of NUREG-1860) and elsewhere are needed to develop the regulatory framework to support continued development and eventual deployment of next-generation technologies. The Subcommittee believes that the NRC's efforts in this area, including new efforts in anticipatory research, should receive 5 to 10 percent of total federal funding for reactor and fuel cycle technology R&D. Recognizing that the vast majority of the NRC's funding is provided by NRC licensees and that the work on advanced nuclear energy system regulation is not being conducted in support of regulating those licensees, funding for the development of the advanced nuclear energy system regulatory framework should continue to be provided from government appropriations. Finally, the Subcommittee supports the NRC's current performance-based approach to developing regulations for advanced nuclear energy systems.

4.7 Key Findings

(1) Recent findings of the President's Council of Advisors on Science and Technologies (PCAST) highlight the need for better coordination of energy policies and programs across the federal government; for a substantial increase in federal support of energy-related research, development, demonstration, and deployment; and for efforts to explore new revenue options to provide this support.[100]

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[99] The task of retrofitting and/or upgrading older facilities has also become more challenging as environmental and other regulations have become more demanding. For example, tightened seismic requirements may necessitate extensive physical upgrades including enhanced bracing, new ventilation systems, new fire protection, and more. Efforts to expand existing facilities or site new facilities, meanwhile, may be complicated by the physical encroachment of other site activities and the surrounding community; by the availability of vital site infrastructure (including power, water, sewer, and office facilities); and by the need to comply with National Environmental Policy Act requirements, as well as new security requirements for the protection of nuclear materials.

[100] President's Council of Advisors on Science and Technology (PCAST). *Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Federal Energy Policy*. November 2010. Available at: http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-energy-tech-report.pdf.

(2) Federal R&D funding of all kinds will be under enormous budget pressure in the years ahead, so it will be especially important to focus scarce public resources on addressing key gaps or needs in the U.S. nuclear RD&D infrastructure and to leverage effectively the full range of resources that exist in the academic community and industry.

(3) Substantially enhanced and larger-scale facilities will be necessary to support a longer-term effort to develop advanced fuel cycles that include reprocessing or separations. Well-designed, multi-purpose national-user test facilities that can be used to advance knowledge of advanced fuel cycle options and other areas of inquiry are an example of the kind of RD&D infrastructure that could yield high returns on public investment.

(4) A well-conceived federal R&D program should be attentive to opportunities in both near-term improvements in the safety and performance of existing light-water reactor technology and in longer-term efforts to advance potential "game-changing" nuclear technologies and systems that could achieve very large benefits across multiple evaluation criteria compared to current technologies and systems.

(5) The DOE's nonproliferation work within the fuel cycle R&D program should ensure that new technologies are reducing the generation and/or availability of all proliferant materials of concern and not strictly plutonium.

(6) Public understanding and acceptance will be critical to the successful deployment of advanced nuclear energy facilities – on either the front end or the back end of the fuel cycle.

(7) The move by DOE to absorb the R&D responsibilities of the Office of Civilian Radioactive Waste Management into the Office of Nuclear Energy presents an opportunity for better integration of waste management considerations into the DOE nuclear energy research agenda.

(8) Ongoing efforts at the NRC to develop a regulatory framework for novel components of advanced nuclear energy systems, and to perform supporting anticipatory research, are essential to help guide the design of new systems and to remove a key impediment to commercial investment by providing an increased degree of confidence that new reactor and fuel cycle technologies can be successfully licensed.

5. INTERNATIONAL CONSIDERATIONS

5.1 International Reactor Safety

Recent events in Japan have reinforced the importance of a focus on nuclear safety. Although the United States will not suffer any significant material consequences from the radiological releases in Japan, the events there will and should affect public attitudes toward nuclear technology. Even if the health consequences of the Fukushima accident prove to be small compared to the direct impacts of the earthquake and tsunami, the potential danger of a nuclear disaster remains an abiding public concern. This concern must be directly and forthrightly addressed.

This means a careful scrutiny of what can be learned from the events in Japan and the introduction of any necessary changes in our regulatory system. It also requires the careful examination of these lessons in the context of the research, development, design, construction, and operation of the advanced technologies that are the subject of this Subcommittee's study.

The events in Japan also reinforce the need for expanded international efforts in safety that parallel the Subcommittee's suggestions (discussed in the next two sections of this Summary) for enhancing the international non-proliferation and security regimes. There are 60 reactors under construction around the world and significant expansion of nuclear power is planned in the years ahead, particularly in China, Russia, India, Korea, and Japan. Over 60 countries that do not currently have nuclear power plants have approached the International Atomic Energy Agency to explore the possibility of acquiring one and the IAEA anticipates that about 15 of these emerging nuclear nations will proceed over the next decade or two. Several of these "new-entrants" have already committed to construction. And in all nations that have or plan to construct nuclear reactor facilities, there is a paramount need to ensure the safety of spent fuel storage and disposal.

The capacity to pursue nuclear technology in the United States will depend to a large extent on other countries' success in achieving a high level of safety performance. Many of these countries have not yet demonstrated that they have the infrastructure or the commitment to a safety culture that provides confidence that they can succeed. ***A major international effort, encompassing international organizations, regulators, vendors, operators, and technical support organizations, should be launched so as to enable the safe application of nuclear energy systems and the safe management of nuclear wastes in all countries that pursue this technology.***

5.2 Nonproliferation Considerations

Because enrichment, reprocessing and recycled fuel fabrication facilities typically produce or utilize large amounts of separated materials as a result of their operations, particularly enriched uranium and plutonium, they are generally recognized as proliferation risks and are therefore considered particularly sensitive elements of the fuel cycle. These technologies can not only serve nuclear power needs, but can give countries the technical and physical capacity to obtain the direct-use nuclear materials required for a weapons program. These proliferation risks include the potential that countries might attempt to secretly divert materials from civilian nuclear facilities that they have declared to the International Atomic Energy Agency (IAEA) under the Nuclear Nonproliferation Treaty (NPT), that countries might use know-how and equipment from declared programs to aid the construction of clandestine production facilities, for example clandestine enrichment plants, and that under some circumstances countries might withdraw from the NPT and then overtly misuse materials and facilities.

Under the NPT and other international and bilateral agreements, there exist a number of institutional and technical approaches to countering these risks. These include measures such as:

- application of IAEA safeguards to provide timely detection of diversion of nuclear materials and to verify peaceful use of declared civil nuclear energy infrastructure,
- ratification of the IAEA Additional Protocol to allow IAEA access to verify the absence of clandestine production facilities,
- international agreements by nuclear supplier nations to apply export controls to detect and prevent transfers of dual-use equipment to clandestine production facilities,
- use of national technical means and human intelligence to detect clandestine production efforts,
- internationalizing the most sensitive parts of the fuel cycle to provide emerging nuclear energy nations with reliable and affordable access to these services, and
- the international system of bilateral and multilateral security and mutual defense agreements that reduce regional security concerns that could otherwise lead to decisions to proliferate.

None of these and other available approaches are perfect, but taken together these approaches can help reduce the number of proliferant states that the international community must manage, and can further isolate these problematic countries so they do not become viewed as being role models for the emerging nuclear energy nations in the developing world. Therefore all of these approaches merit continuing and substantial investment of U.S. resources and policy effort. The following sections take a more detailed look at some of these approaches – in particular to those pertinent to the charter of the BRC and to the charge of this Subcommittee.

The Treaty on the Nonproliferation of Nuclear Weapons (NPT)

The Treaty on the Nonproliferation of Nuclear Weapons, commonly referred to as "The NPT", provides the foundation of the international nuclear nonproliferation regime. Opened for signature in 1968, the Treaty entered into force in 1970. The treaty currently has 189 signatories[101], divided between Nuclear Weapons States (NWS) and Non-Nuclear Weapons States (NNWS). Virtually all states in the international system have signed and ratified the treaty: only Israel, India, and Pakistan have declined to sign, and North Korea is the only state that has joined the treaty, but later exercised its right to withdraw.

The NPT is designed to promote three main objectives: to limit the spread of nuclear weapons, to encourage eventual nuclear disarmament, and to provide a framework and enable widespread access to peaceful uses of nuclear energy. The key provisions of the NPT therefore outline rights and responsibilities for state parties in the area of nuclear nonproliferation, nuclear energy, and disarmament.[102] Article I states that no NWS may "transfer," "assist, encourage or induce" any NNWS to "manufacture or otherwise acquire nuclear weapons." Article II requires NNWS parties not to "receive," "manufacture or otherwise acquire" nuclear weapons and "not to seek or receive any assistance in the manufacture of nuclear weapons." Article IV protects the right of all states to peaceful nuclear energy, conditional on their being in compliance with their Article II commitment: "Nothing in this Treaty shall be interpreted as affecting the inalienable right of all the Parties to the Treaty to develop research, production and use of nuclear energy for peaceful purposes without discrimination and in conformity with Articles I and II of this Treaty." Article VI of the NPT calls for all parties to work towards nuclear disarmament: "Each of the Parties to the Treaty undertakes to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament." As noted above, Article VI is often treated as exclusively applicable to

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[101] Sagan, Scott D. *The International Security Implications of U.S. Domestic Nuclear Power Decisions,* 2011. Commissioned paper for the BRC, www.brc.gov

[102] "The Treaty on the Nonproliferation of Nuclear Weapons," *United Nations*, available at http://www.un.org/disarmament/WMD/Nuclear/pdf/NPTEnglish_Text.pdf.

NWS, though it clearly states that *each of the parties* to the treaty must pursue "negotiations in good faith"[103] in pursuit of nuclear disarmament.

Although the NPT has certainly maintained the fabric of the global nonproliferation regime, the workhorse of the regimes has been the International Atomic Energy Agency (IAEA) safeguards system. Under cognizance of the IAEA, the safeguards systems serves as the verification mechanism for the NPT ensuring that all states are complying with their nonproliferation obligations to not use civil nuclear energy programs for nuclear-weapons purposes.

All signatories to the NPT are required to have a comprehensive safeguards agreement (CSA) in place. These CSAs cover "all source or special fissionable material in all peaceful nuclear activities within the territory of a State, under its jurisdiction, or carried out under its control anywhere."[104] Because IAEA safeguards are based on assessments of the correctness and completeness of a State's declared nuclear material and nuclear-related activities, these CSAs are utilized for verifying State reports of declared nuclear material and activities and are largely based on nuclear material accountancy, complemented by containment and surveillance techniques, such as tamper-proof seals and cameras that the IAEA installs at facilities. Verification measures include on-site inspections, visits, and ongoing monitoring.

Unfortunately, some events have challenged the efficacy and credibility of CSAs. In particular, in the mid-80's to early 90's, Iraq was engaged in a clandestine nuclear weapons program - violating its safeguards obligations under the NPT. As a result, the IAEA broadened the scope of the materials and facilities that safeguards cover and strengthened safeguards techniques.[105] In 1992, the IAEA Board of Governors reaffirmed the agency's authority to conduct "special inspections" of suspected undeclared sites in NPT non-nuclear weapon states, and in 1997, the IAEA Board of Governors adopted a new safeguards model. Known as the "Additional Protocol" or "AP", the protocol gave IAEA inspectors increased access to all aspects of a non-nuclear weapon state's nuclear program, even where nuclear material is not involved; required more detailed information on that program; allowed for use of improved verification technologies (such as environmental sampling); and required more extensive inspections at declared nuclear sites.[106] There are currently 104 countries with Additional Protocol agreements in force.[107]

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[103] Scott D. Sagan, "Shared Responsibilities for Nuclear Disarmament," *Daedalus* 138:4 (Fall 2009):157-68.

[104] IAEA, "The Safeguards System of the International Atomic Energy Agency," http://www.iaea.org/OurWork/SV/Safeguards/

[105] NTI, NPT Tutorial, http://www.nti.org/h_learnmore/npttutorial/chapter02_02.html

[106] IAEA, Model Protocol Additional to the Agreements Between States and the IAEA for the Application of Safeguards, (INFCIRC/540) - http://www.iaea.org/Publications/Documents/Infcircs/1997/infcirc540c.pdf

[107] http://www.iaea.org/OurWork/SV/Safeguards/sg_protocol.html - accessed May 5, 2011

Even with the Additional Protocol in place, growing nuclear energy demand and concerns over the spread of sensitive nuclear technologies place increasing strain on international safeguards. With the development of more reprocessing and enrichment facilities (see Chapter 2, Table 4), one of the most vexing problems facing safeguards activities will be the verification of physical materials at those fuel cycle facilities. In large bulk-handling facilities with high volume throughputs (hundreds to thousands of MTs) and complicated equipment schematics, material unaccounted for or "MUF" can represent a substantial proliferation challenge. Even as a small percentage of facility throughput, MUF can result in significant quantities of material being lost. Over the last 15 years, numerous examples of failures of material accountancy to achieve time detection and resolution of anomalies have come to light, involving large amounts of MUF that remained unresolved for months, years, or decades. [108]

The Subcommittee endorses R&D efforts on modern safeguards technologies and supports the work of the US Government in supporting the IAEA in this area. The NNSA is the principal federal sponsor of nuclear nonproliferation-related research and development and is currently (in conjunction with the national laboratories) working on the R&D of safeguards technologies focusing on: safeguards systems analysis and enhancements, safeguards-by-design, material control and accountability (MC&A) modernization, modern inventory controls, software & hardware development, collaborative IT tools, and real time process monitoring and data integration systems. ***Support for the development of novel safeguards technologies is not only imperative because of the fundamentally important nature of the threat, but because of compounding issues related to their development.*** The IAEA finds itself constrained financially, lacking the resources to perform research and development on the necessary technologies, while tasked with ever increasing responsibilities.[109] Additionally, the size of the "safeguards market" just doesn't allow for cost effective production of units and the investment of R&D money from commercial players, thereby limiting the IAEA to be reliant on R&D efforts of national governments.

Multilateral/Multinational Fuel Cycle Services Options

"Internationalized" approaches to providing access to sensitive parts of the nuclear fuel cycle are nothing new and have been discussed in multiple forms since the 1946 Acheson-Lilienthal

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[108] Testimony to the BRC delivered by Edwin Lyman on October 12, 2010

[109] The IAEA currently has 151 member states and their budget is $447 million in 2011. The United States provides about 25% of that figure.

report and Eisenhower's 1953 Atoms for Peace speech.[110] Trying to strike the balance between assuring supply of fuel services and guaranteeing adherence to nonproliferation norms is difficult at best. Several countries, including the United States, in concert with the International Atomic Energy Agency, have proposed an array of options that would provide countries with credible, cost-efficient options for assurance of supply, including the development of a backup supply or "fuel banks" of enriched uranium, international fuel cycle centers, and government-to-government agreements.

Today, as shown in Figure 13, the majority of nuclear energy programs worldwide are small, with less than 10 GWe of capacity (fewer than 10 reactors). Furthermore, while some uncertainty exists due to the nuclear accident that has occurred in Japan, the number of countries with small nuclear energy programs can still be expected to grow further. In 2011 Iran's first power reactor reached criticality at Bushehr, adding another country to the list shown in Figure 13. In addition, today 65 additional countries participate in IAEA technical cooperation projects related to the introduction of nuclear power. While worldwide the majority of national nuclear energy programs are small, the total installed nuclear capacity in these nations accounts for less than 15% of the total nuclear generation capacity. Given this structure for the global nuclear energy market, there exists a compelling practical and economic logic for nations to choose to use regional or international fuel cycle facilities and services, rather than developing nationally owned enrichment and reprocessing.

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[110] Regional Nuclear Fuel Cycle Centers study (1975-1977), International Nuclear Fuel Cycle Evaluation study (1977-1980), Expert Group on International Plutonium Storage (1978-1982), IAEA Committee on Assurances of Supply (1980-1987), United Nations Conference for the Promotion of International Cooperation in The Peaceful Uses of Nuclear energy (1987)

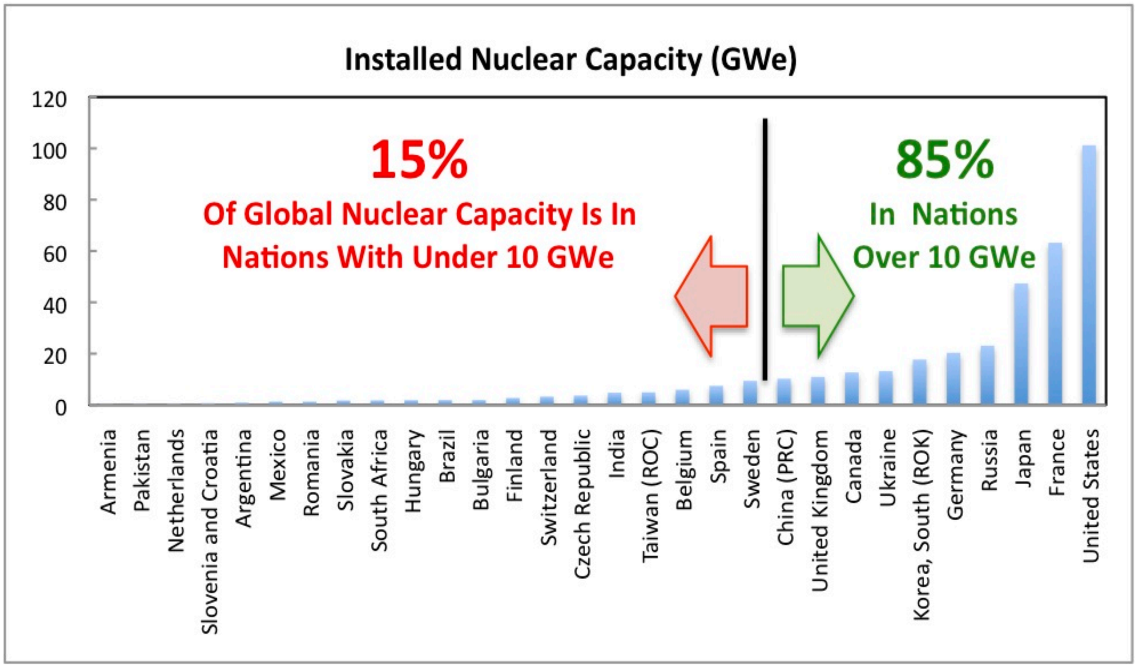

Figure 13. Worldwide distribution of civil nuclear energy generation capacity in 2010.[111]

In 2004, the Director General of the IAEA appointed an international expert group to consider options for possible multilateral approaches to the front and back ends of the nuclear fuel cycle. Their report, *Multilateral Approaches to the Nuclear Fuel Cycle – INFCIRC/640* [112], released in February of 2005, and categorized the options for assured fuel supply into three major and distinct categories: assurances of services not involving the ownership of fuel cycle facilities, conversion of existing facilities to multinational facilities, and the construction of new jointly-owned facilities.

Within the first option, it is assumed that a functional market operates for whichever fuel service is required, either through state-owned enterprises or commercial enterprises. Of course, market options currently vary across the fuel cycle (i.e. more commercial options exist for enrichment than they do for reprocessing, and none exist for spent fuel and high level waste disposal). While the diversity of supply options alone does not necessary reflect the health of a market and its ability to answer demand, it can affect the level of confidence a “supplied” country has in how “assured” their supplies are. In some cases the promise of supply via

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[111] http://en.wikipedia.org/wiki/Nuclear_power_by_country

[112] IAEA, *Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report submitted to the Director General of the International Atomic Energy Agency, INFCIRC/640*, 22 February, 2005. http://www.iaea.org/Publications/Documents/Infcircs/2005/infcirc640.pdf

existing and perfectly healthy markets is not good enough for a country to forgo their own indigenous fuel cycle development, ostensibly the case in Iran. This guarantee can be strengthened via increased levels of agreements beyond that of the normal market supply, either first through consortia of suppliers providing assurances, then through consortia of governments providing assurances, and lastly through agreements with the IAEA.

As the 2005 IAEA report noted, the advantages and disadvantages of either converting a national facility to an international facility or to building a new internationally managed facility varies based on the type of facility being discussed (enrichment, reprocessing, etc.). The advantages of converting a facility to international ownership include: lower capital investment required, no further dissemination of facility construction know-how, strengthened proliferation resistance due to international management and operating teams, and pooled expertise and resources. The disadvantages include: the potential need for additional facilities in politically diverse countries to provide necessary assurances that fuel supplies will not be withheld due to ideological reasons, existing property rights need to be balanced, potential proliferation risks due to increased international partners, difficulty of international management, and back-fitting of safeguards depending on the host nation's prior approach.

The advantages to building a new fuel cycle facility under international controls include: safeguards can be included in construction instead of backfit, pooled expertise and resources, facility can be sized economically, and strengthening of proliferation resistance through international management and operation. The disadvantages of building new facilities include: potentially higher proliferation risks due to broader access to know-how depending on the management model, uncertain commercial competitiveness, and breakout potential and retention of fissile materials.

Regardless of the advantages and disadvantages of each of the options, it is clear that cross-cutting technical, legal, cultural, political and financial factors related to the implementation of those options will affect the perceptions of the feasibility and desirability of those options and may be decisive in any future efforts to develop such approaches on the national and international level.

With respect to U.S. policy for the nuclear fuel cycle, this Subcommittee believes that the establishment of multinational or regional fuel cycle facilities under comprehensive IAEA safeguards could be a very positive development, giving countries an option to enjoy more reliable access to the benefits of nuclear power while simultaneously reducing proliferation risks.

Recent examples of these multinational "assurance" approaches include: the IAEA's $150 million fund for uranium purchases[113], Russia's creation of the International Uranium Enrichment Center[114] and the 120 MT LEU Fuel Bank[115] in Angarsk, and the establishment of the UK Nuclear Fuel Assurance Plan[116]. The UK plan is basically a bilateral agreement that is supposed to serve as a model for government-to-government arrangements between supplier and recipient states, where the supply of low enriched uranium is not disrupted for non-commercial (political) reasons.

Although the discussion of multinational facilities and fuel services typically focuses on securing enrichment and reprocessing facilities, the same concepts can be applied to the disposal of spent fuel and high level waste. All countries with nuclear power will have to store spent nuclear fuel and high level waste for some period of time and ultimately provide for disposal (internally or internationally) of the spent fuel or of the high-level radioactive waste components that remain if the spent fuel is reprocessed. Spent fuel contains approximately 1 percent plutonium and the self-protecting nature of the radioactivity will diminish over time, making the plutonium more accessible. Thus it is in the best interests of the United States and the international community to have spent fuel under effective and transparent control and to assure that in the coming century no spent fuel becomes "orphaned" anywhere in the world with inadequate safeguards and security.

Fuel take-away arrangements would allow countries, particularly those with relatively small national programs, to avoid the very costly and politically difficult step of providing for waste disposal on their soil. Fuel take-away could also provide a strong incentive for emerging nuclear nations to take key actions, such as ratifying the IAEA Additional Protocol, that can strengthen non-proliferation and further isolate the current small number of problematic proliferant states. The United States has implemented a relatively small but successful initiative to ship used foreign research reactor fuel to U.S. facilities for storage and disposal. This program has demonstrated meaningful nonproliferation and security benefits. ***A similar capability to accept spent fuel from foreign commercial reactors, in cases where the President would choose to authorize the imports for reasons of U.S. national security, would be a***

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[113] Fund was seeded by NTI and supplement by voluntary donation from the European Union, Kuwait, Norway, the United Arab Emirates, and the U.S. December 2, 2010 statement made to IAEA Board of Governors by Glyn Davies, U.S. Ambassador to the IAEA - http://vienna.usmission.gov/101203nfs.html

[114] Incorporated as a joint venture between Russia's Tekhsnabeksport and Kazakhstan's Kazatomprom

[115] The fuel bank consists of two 1,000 megawatt-reactor loads of LEU.

[116] Seen as a "virtual assurance mechanism that would facilitate access to nuclear energy to avoid the huge cost and technical challenge involved in establishing a nuclear fuel cycle." Statement made at the 2010 IAEA General Conference by Charles Hendy, Minister of State for Energy and Climate Change of the United Kingdom, http://www.iaea.org/About/Policy/GC/GC54/Statements/uk.pdf

desirable component of a larger policy framework that creates a clear path for the safe and permanent disposition of U.S. spent fuel. The decision to authorize imports of foreign spent fuel would have to be clearly linked to progress in developing storage and permanent disposal capacity for U.S. wastes.

The Subcommittee believes the availability of used fuel take-away would increase substantially the incentives for some emerging nuclear nations to forgo the indigenous development of sensitive fuel-cycle facilities in return for access to regional or international facilities. In that context, government support for limited fuel supply and take-away initiatives to advance U.S. national security interests can help change the way disposal facilities are perceived by the public and by the national security community—not simply as final resting places for nuclear waste, but as essential elements of a comprehensive strategy for maintaining the nuclear energy option while simultaneously addressing proliferation and security concerns.

5.3 Security and Counter-terrorism

A stated in the communiqué of the Washington Nuclear Security Summit, April 13, 2010, "Nuclear terrorism is one of the most challenging threats to international security, and strong nuclear security measures are the most effective means to prevent terrorists, criminals, or other unauthorized actors from acquiring nuclear materials. Success will require responsible national actions and effective international cooperation."[117] To date, the United States has worked to enhance global capacity to prevent, detect, and respond to nuclear terrorism by conducting multilateral activities aimed at strengthening the operations, plans, policies, procedures, and interoperability of partner nations, through a variety of activities, most recently including: the 2010 Nuclear Security Summit, Nunn-Lugar Cooperative Threat Reduction Programs (CTR), Global Threat Reduction Initiative Programs (GTRI), and the Global Initiative to Combat Nuclear Terrorism (GINCT).

Held in April 2010 and attended by 47 nations, the U.S.-hosted 2010 Nuclear Security Summit was launched with the goal of securing all vulnerable nuclear material worldwide within four years. Indicating a strong commitment on the part of the U.S. government, other achievements since that time have included: signing a plutonium disposition protocol with Russia[118], returning

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[117] U.S. Department of State – website, principles of the Global Initiative to Combat Nuclear Terrorism, http://www.state.gov/t/isn/c37071.htm

[118] Official U.S. Department of State blog - Secretary Clinton, Foreign Minister Lavrov Sign Plutonium Disposition Protocol, posted April 13, 2010 http://blogs.state.gov/index.php/site/entry/clinton_lavrov_plutonium_disposition_protocol

Russian origin HEU back to Russia[119], converting the Kyoto University research reactor in Japan from HEU to LEU[120], and pursuing ratification to an amendment of the Convention on Physical Protection of Nuclear Materials that would extend and strengthen the Convention's coverage of peaceful nuclear material in storage or use at domestic nuclear facilities, rather than merely in international transit. In preparation for the next summit, some U.S. experts are proposing the development of an international "nuclear material security framework agreement [that] would identify the threats to humankind from vulnerable fissile and radiological materials…and list actions and commitments required to mitigate them."[121]

Domestically, the NRC has chief responsibility for regulating nuclear security at commercially licensed sites, and the Department of Energy - through its National Nuclear Security Administration (NNSA) - focuses on the protection of the DOE facilities and materials. In response to the terrorist attacks of September 11, 2001, the NRC and the nuclear utility industry reevaluated physical security at the nation's nuclear power plants and required all plant operators to perform specific plant design studies, add further security personnel, enhance physical protection features, improve emergency preparedness, and provide additional personnel training. Nuclear industry groups and federal, state, and local government agencies assisted in the implementation of these measures and participated in drills and exercises to test new planning elements.

These new security measures include NRC requirements that licensees identify "mitigative strategies" to respond to any event that might cause the loss of large areas of a nuclear plant due to explosions or fire, including developing procedures and providing equipment to connect portable coolant pumps and power supplies to restore cooling and control functions to reactors and spent fuel pools. The value of this type of preparation, and the importance of assuring that the procedures can be implemented promptly, has been demonstrated following the natural disaster that severely damaged the Fukushima nuclear plant in Japan, where ultimately the connection of portable equipment to inject seawater into the reactors stopped the progression of fuel damage.

The NNSA also took several steps after 9/11 to protect its critical facilities, including strengthening its facilities against attacks through consolidating materials, implementing highly effective low and high-tech technologies, hiring additional security officers and improving their

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[119] In 2010, The U.S. returned Russian-origin HEU from Poland, Czech Republic, Serbia, and the Ukraine. GTRI Fact Sheet, http://nnsa.energy.gov/mediaroom/factsheets/reducingthreats

[120] GTRI Fact Sheet

[121] "The Urgent Need for a Seoul Declaration: A Roadmap for the 2012 Nuclear Security Summit and Beyond," by Kenneth N. Luongo, *Arms Control Today,* Washington, D.C., April 2012.

training and equipment, and improving cybersecurity by establishing new, more secure networks.

As we continue to strengthen our ability to secure nuclear facilities and materials, and in light of events unfolding in Japan, the Subcommittee believes the United States can and should provide leadership on improving both nuclear security and nuclear safety standards. Reviews conducted post-Fukushima will undoubtedly examine the safety and security benefits that could be achieved by improving instrumentation to measure key plant safety parameters including pool water inventories under conditions of station blackout and severe plant damage, reviewing and strengthening procedures for connecting portable pumps and power supplies, and reviewing potential benefits of by accelerating the transfer of spent nuclear fuel out of pools and into dry casks. The Subcommittee urges that such reviews be completed expeditiously and that unclassified results be shared with regulators and other appropriate entities around the world.

Finally, the Subcommittee finds that is important for the U.S. government to continue to support the IAEA's physical protection programs as well as efforts by the World Institute for Nuclear Security (WINS) to promote global best practices regarding nuclear security.

The physical protection of nuclear material and facilities to deter terrorist activity is paramount in today's security environment as the potential theft and sabotage of nuclear materials and facilities remains a real threat.[122] Furthermore, the theft of weapons usable material, sabotage or terrorist attack resulting in a large radioactive release anywhere in the world could create real domestic consequences here in the U.S., so our nation has a direct interest in incentivizing and enabling all nations to take seriously their national obligations to secure nuclear materials and facilities.

5.4 Key Findings

(1) A major international effort, encompassing international organizations, regulators, vendors, operators, and technical support organizations, should be launched so as to enable the safe application of nuclear energy systems and the safe management of nuclear wastes in all countries that pursue this technology.

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[122] According to the International Atomic Energy Agency (IAEA), 1,773 confirmed incidents of illegal possession, movement or attempts to illegally trade in or use nuclear material or radioactive sources occurred between January 1993 and December 2009. Information taken from the International Atomic Energy Agency's Illicit Trafficking Database - http://www-ns.iaea.org/security/itdb.asp

(2) The establishment of multinational or regional fuel cycle facilities under comprehensive IAEA safeguards could be a very positive development, giving countries an option to enjoy more reliable access to the benefits of nuclear power while simultaneously reducing proliferation risks. Similarly, the availability of used fuel take-away would increase substantially the incentives for some emerging nuclear nations to forgo the indigenous development of enrichment and reprocessing facilities in return for access to regional or international facilities.

(3) The successful theft of nuclear material anywhere in the world, or sabotage of a nuclear facility resulting in a large radiological release, could have substantial domestic impacts in the United States. The U.S. has worked to enhance the global capacity to prevent, detect, and respond to nuclear terrorism. This work merits continuing effort and investment.

6. CONCLUSION

Fifty years after it was launched using technologies originally developed for weapons applications, the civilian nuclear power industry has grown to play a substantial role in the nation's and the world's energy supply mix: Nuclear power plants today account for roughly 20 percent of U.S. electricity production and 14 percent of global electricity production. The United States has long been at the forefront of nuclear energy technology development and of international efforts to address nuclear-related safety, security, and weapons proliferation concerns.

The Subcommittee believes it is in our nation's interest to retain this leadership role. Regardless of one's view of the nuclear industry's near- and longer-term prospects more generally, several observations argue for making the financial, institutional, and diplomatic commitments needed to remain proactively engaged with this technology. One is that there are countries are planning to increase their nuclear energy investments—in some cases substantially—while other countries that currently lack nuclear energy infrastructure are interested in developing it. A second is that compelling arguments can be made for preserving the nuclear technology option in light of the energy security and environmental challenges humanity confronts over the next century, especially if intensifying climate concerns emerge as major driver of international and domestic energy policy. Finally, given the extensive body of nuclear expertise, facilities, and materials that already exists around the world, ensuring that these assets and materials, along with the safety, security and proliferation risks they present, are being managed responsibly will remain a national and international imperative for the foreseeable future.

Having reviewed different reactor and fuel cycle technologies and DOE's current R&D program, the Subcommittee concluded that advanced nuclear technologies hold sufficient promise for helping to address broadly held safety, security, and sustainability objectives and that continued federal investment to research, develop, and demonstrate these technologies is warranted. "Game-changing" technology advances that could advance multiple objectives simultaneously, in particular, have the potential to deliver substantial long-term returns on public investment and should be the focus of sustained, strategically targeted, and well-coordinated federal RD&D efforts. Given that many of these advanced technologies will take years to develop, however, we believe it is also appropriate to focus attention on nearer-term improvements that could enhance the performance and safety of currently available technologies, specifically the light-water reactor and once-through fuel systems that dominate the current fleet as well as the capacity expansions planned over the next two decades in different parts of the world. In the aftermath of Fukushima, in particular, renewed attention to safety issues is appropriate and to be expected.

We are aware that past assessments tend to find that the federal government is under-investing—both in energy RD&D generally and in nuclear energy RD&D specifically—relative to the magnitude and importance of the societal benefits that could be obtained by improving our technology options in these areas. While we are aware that calls for increased funding cannot be made lightly in the current, highly constrained political and fiscal environment, the majority of the Subcommittee supports the recent MIT recommendation that federal spending on nuclear energy RD&D be roughly doubled, to $1 billion per year (compared to budgets on the order of $500 million in recent years). In light of any funding decisions, the Subcommittee believes it is also useful to focus on improving the effectiveness of the federal RD&D program and on leveraging additional private and other non-federal resources.

Another important question for the Subcommittee, and one that is directly relevant to the main charge before the BRC as a whole, was whether any known or anticipated advances in nuclear technologies could fundamentally alter the waste management challenge the United States confronts over the next few decades. We concluded that the answer to this question was no. In other words, we see no technological development or change that would weaken the case for moving forward as expeditiously as possible to establish permanent disposal capacity for spent nuclear fuel and high-level waste. We believe this conclusion follows from any realistic assessment of the nature and quantity of high-level waste and fuel that must be managed and of the time required to successfully develop, commercialize, and deploy new nuclear energy systems. Nor does it depend how one views the desirability or feasibility of ultimately closing the fuel cycle. Different countries have approached the decision about whether to pursue a closed vs. open fuel cycle with different sets of priorities; the Subcommittee, for its part, did not reach consensus on this point. In our view it would be premature for the United States to commit to any particular fuel cycle option as a matter of government policy at this time, especially in light of the large uncertainties that surround many of the component technologies. Rather, we believe the appropriate emphasis for the U.S. program should be on preserving options that have high potential to deliver benefits across multiple evaluative criteria (safety, cost, resource utilization, non-proliferation, etc.).

The final set of issues we considered encompassed safety, security, and non-proliferation—all issues with important international and institutional as well as technological dimensions. U.S. leadership to address these concerns is needed, not only because the viability of nuclear technology as a future energy supply option depends on it, but because the public's health and safety and the nation's vital security interests are at stake. No simple prescription exists for tackling these inherently complex and interconnected issues, nor is it likely that any system can be made 100 percent safe, secure, and proliferation-resistant. Nonetheless, Subcommittee members are confident that substantial progress can be made by leveraging existing institutional assets; strengthening multi-lateral agreements; pursuing the development of secure multi-national fuel cycle facilities and spent fuel take-away arrangements, where appropriate and in our national security interests; and working proactively with all parties, including the public, the nuclear industry and the vast majority of other countries who share our strong interest in the safe, secure, and peaceful application of nuclear technology.