

# Nuclear *Energy*

Power for the  
Twenty-First Century



Argonne  
National Laboratory



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# *Nuclear Energy: Power for the 21<sup>st</sup> Century*

## **1. Vision and Goals for the Future Use of Nuclear Energy**

Energy is vital to human civilization. It underpins national security, economic prosperity, and global stability. As the world's most powerful and prosperous nation, the U.S. must lead the way in developing a diverse energy system that can meet rapidly growing world energy demand in a way that promotes peace, prosperity, and environmental quality.

Over the last decade, extensive studies have made it clear that renewable energy sources, while very important, will never be sufficient alone. Technology advances leading to cleaner fossil fuel plants are also important, but are not enough to satisfy future energy demands. Hydrogen is being proposed as a transportation fuel, but hydrogen is an energy carrier, not a basic fuel or energy supply. At this time the best option for making up the shortfall between supply and demand is nuclear power. Therefore, the diverse energy system deployed in the U.S. must include a growing component of nuclear energy.

In July 2002, the Directors of six U.S. Department of Energy (DOE) National Laboratories wrote to the Secretary of Energy to urge DOE to “*implement a comprehensive and integrated plan to further the development of nuclear energy and the management of nuclear materials.*” Such a plan can help achieve the Laboratory Directors’ vision:

***Vision:**  
Sustainable peace, prosperity, and environmental quality, enabled through immediate U.S. leadership in the global expansion of nuclear energy systems.*

A key recommendation in the Laboratory Directors’ letter was for the Secretary to “*accelerate and enhance Departmental nuclear energy, reactor waste and nuclear materials management programs:*

- *To assist the deployment by U.S. industry of multiple new power plants by 2020;*
- *To reduce actinide waste and plutonium stockpiles by closing the fuel cycle;*
- *To restore the industrial and R&D infrastructures;*
- *To provide technologies and strengthen the regime for safeguards integrated within existing and advanced fuel cycles; and*
- *To provide sustainable energy sources that mitigate global climate change and water availability issues.”*

The Laboratory Directors have prepared an Action Plan that builds on the recommendations of the July 2002 letter and sets three challenging goals:

***Goal #1: Reduce air pollution and global climate risk and improve energy security by meeting an increasing fraction of future US and world energy needs through safe and economic nuclear energy solutions***

***Goal #2: Achieve a 90% reduction of reactor waste requiring repository disposal by 2050 by significantly reducing the amount of uranium, plutonium, and minor actinides in disposed waste***

***Goal #3: While expanding the use of nuclear technology world wide, reduce the threat of nuclear weapons proliferation***

This document was written by technical staff members at the six National Laboratories to support the Laboratory Directors' Action Plan. It describes the government's historical role in the development of commercial nuclear energy, the benefits of further reliance on nuclear energy, the challenges facing future nuclear deployments, the path forward for achieving the three goals, and the resource requirements needed to put the U.S. on a path to achieve the goals.

## 2. The Role of the U.S. Government in Nuclear Energy Development

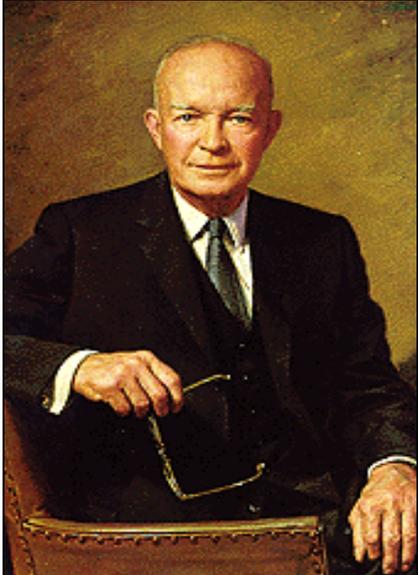
The phenomenon of nuclear fission was discovered in the early 1930s, initiating developments that resulted in an industrial capability to harness the atom within the following decade. The discovery and demonstration of nuclear fission generated a great deal of excitement in the scientific community, because it was quickly realized that the energy potential of the atom far exceeded the energy potential of any other known energy resource. The U.S. government initiated development of nuclear energy technology, constructed and operated prototype nuclear power plants, participated in materials production and the development of a supply infrastructure, shared the initial deployment risk with industry, and developed a policy framework that allowed industry to commercialize the technology.

Through the Atoms for Peace Program [Fig 2.1] [1], the U.S. shared the technology with other countries in exchange for commitments to not develop nuclear weapons. The International Atomic Energy Agency (IAEA) was established as an independent auditor to verify these commitments. The Atoms for Peace Program provided the basis for active international R&D collaboration in the peaceful use of nuclear energy for the next three decades and led to the implementation of the IAEA's concept of nuclear material safeguards.

The U.S. became the major nuclear power that other countries looked to for guidance in the development of nuclear technologies, and a vast scientific and technical base in the peaceful uses of nuclear energy was developed. The U.S. led the development of the first three generations of nuclear energy through a strong government-industry partnership. This partnership led to the demonstration of early prototype reactors in the 1950s and 60s, construction of commercial power reactors in the 1970s and 80s, and development and certification of advanced light water reactors in the 1990s.

The first three generations of nuclear energy have been very successful, due in large part to U.S. leadership. For example:

- Nuclear energy supplies more than 20 percent of U.S. and 16 percent of world electricity [2].
- U.S. nuclear plants are highly reliable, and in 2001 produced electricity for 1.68 cents per kilowatt-hour on average [3]. This low cost is second only to hydroelectric power among baseload generating options.

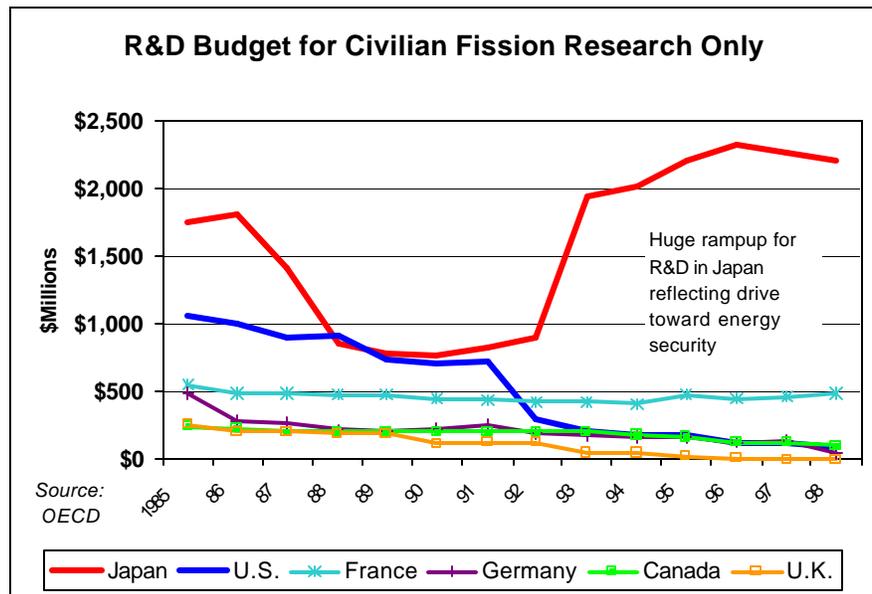
<p><b>When President Eisenhower announced that the United States would launch its Atoms for Peace initiative, few could have predicted the course events would take. As a policy designed to assure the technical and political leadership of the United States, this initiative was an unqualified success for at least the first few decades after the initiative was launched.</b></p>		<p><b>Eisenhower Started Atoms for Peace to:</b></p> <ul style="list-style-type: none"><li>◆ Exploit the vast potential of nuclear energy</li><li>◆ Prevent the spread of nuclear weapons</li><li>◆ Provide commercial opportunities for U.S. industry</li><li>◆ Ensure U.S. influence over nuclear programs world-wide</li></ul>
<p><i>"Peaceful power from atomic energy is no dream of the future. That capability, already proved, is here now - today." - President Eisenhower, "Atoms for Peace," December 8, 1953</i></p>		
<p><b>Fig. 2.1 Purposes of the Atoms for Peace Initiative</b></p>		

- Since 1970, through the use of nuclear energy, the U.S. has avoided the emission of more than nine billion tons of carbon dioxide, and one hundred million tons of the air pollutants nitrogen oxides and sulfur dioxide combined [4].
- Nuclear energy plays a large role in the U.S. economy. In 2001, the 103 U.S. nuclear power plants generated 769 billion kilowatt-hours of electricity [3], having a retail value of nearly \$50 billion.
- U.S. technology has formed the basis for most nuclear energy systems worldwide.
- In return for access to peaceful nuclear technology, more than 180 countries have signed the Non-Proliferation Treaty to help assure that peaceful nuclear activities will not be diverted to making nuclear weapons.

Nuclear energy in the U.S. experienced an economic and regulatory surge forward in the 1990s, with the operators of the majority of the U.S. light water reactors expected to file for license extensions and the Nuclear Regulatory Commission moving toward simplifying the licensing process and streamlining regulatory procedures. Electricity generating companies are also seriously studying new plant construction.

Even with this record of success, some difficulties still face nuclear energy in the U.S. High costs associated with construction delays and regulatory uncertainties have discouraged the building of large, capital-intensive plants. Public confidence in the safety of nuclear energy was threatened by the Three Mile Island and Chernobyl accidents, and while confidence has been restored in recent years, a serious nuclear accident or terrorist attack on a nuclear plant anywhere in the world could again undermine public confidence. Establishing a final repository for spent nuclear fuel has taken longer than expected. And finally, worldwide deployment of nuclear energy has contributed to concerns about accumulating plutonium inventories and the potential for the proliferation of nuclear weapons.

Even though the U.S. has a healthy and thriving domestic nuclear electricity generating infrastructure, the U.S. nuclear vendor enterprise has been dramatically reduced, and the nuclear industries in other nations have expanded to fill the leadership void once held by the U.S. By 1996, fifteen additional nations had developed some nuclear fuel cycle capabilities without any U.S. involvement. Many nations have established their own multi-lateral networks to ensure future cooperation on nuclear technology development, and some nations in these networks have not signed the Non-Proliferation Treaty. The result is that other nations have independently developed supplier capabilities to provide nuclear energy services throughout the world, and U.S. influence on the evolving global nuclear infrastructure has waned.



**Fig. 2.2 Nuclear Energy R&D Expenditures [5]**

Support for research and development has also waned. The U.S. government decreased its commitment to nuclear energy research over the past 10 years. By 1997, virtually all U.S. nuclear energy R&D programs had been terminated [Fig. 2.2]. While this trend has been reversed in recent years, U.S. nuclear energy R&D levels are still well below historical norms.

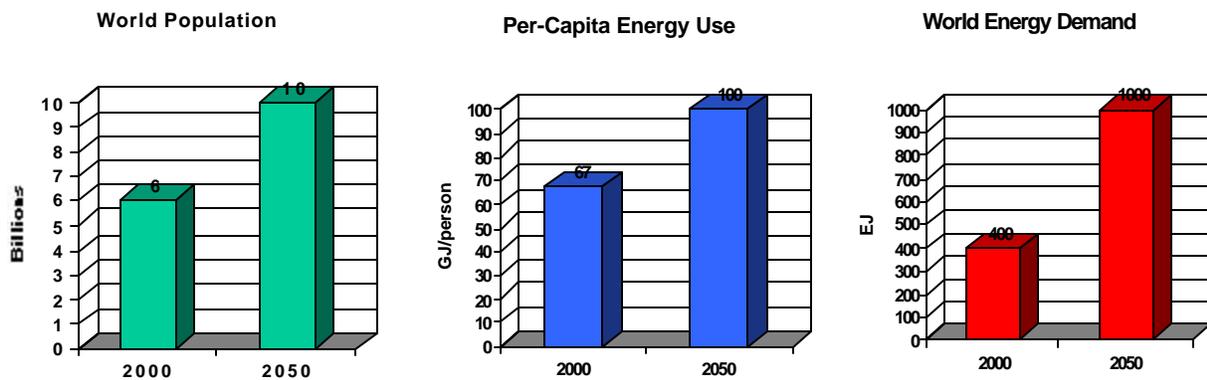
Recently, a recognition of the importance of nuclear energy has resurfaced in the government. A new National Energy Policy [6], which recognizes nuclear energy's potential contribution, and the announcement of nuclear power initiatives by the Bush administration indicate renewed interest in the peaceful possibilities of the next generation of nuclear energy systems. At U.S. research institutions, seminal concepts are being explored that could revolutionize nuclear energy technology, help regain U.S. influence, and revitalize the global nuclear industry based on modern value systems regarding nuclear safety and proliferation risk management.

### ***Nuclear Energy: Power for the 21<sup>st</sup> Century***

The growing need for abundant, secure, and affordable energy to power the world economy; the steady depletion of secure oil and natural gas reserves; the increasing awareness of the importance of environmentally responsible emissions-free energy sources; the excellent economic performance and safety record of nuclear power; and a renewed post-Cold War U.S. interest in secure nuclear materials management have combined to create a new but perishable opportunity for the U.S. to lead the next nuclear era. By asserting world leadership, the U.S. has a unique opportunity to promote the development and deployment of secure, safe, and clean nuclear power technology that can foster a more peaceful and prosperous future.

### 3. The Need for Energy and the Nuclear Power Option

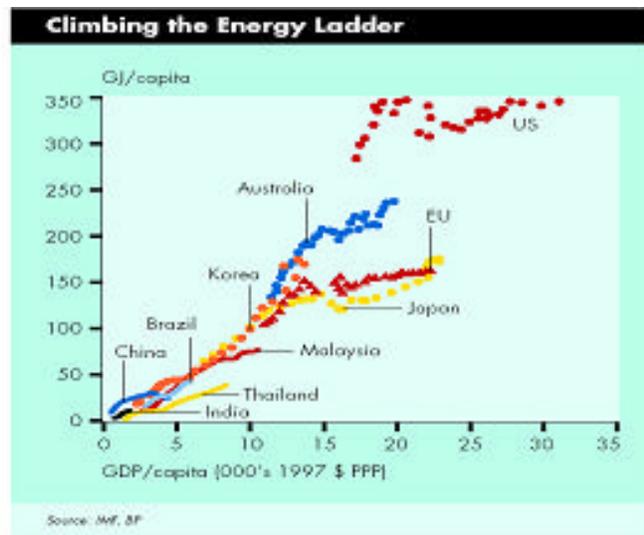
Energy security and national security are strongly linked. Energy supply impacts international relations, the environment, and global prosperity. Economic development and population growth drive the world's need for increased supplies of energy. The economic development of less-developed countries is necessary to avoid widespread suffering from poverty, disease and premature deaths, and to reduce the vast gulf in living standards between developed and developing nations—conditions that create instability and a potential for regional and global conflicts. Projections by the World Bank [7] and other organizations show world population increasing to 9-10 billion by 2050 [Fig. 3.1]. Worldwide, per-capita energy use is expected to rise by 50 percent over that same time [Fig. 3.2] (to 100 GJ/person per year, which amounts to about one-third of current U.S. per-capita consumption [Fig. 3.4]). As a result, world energy demand may more than double [Fig. 3.3] (for example, see [8]). Plentiful, affordable, and environmentally responsible forms of energy must be employed to meet that demand.



**Fig. 3.1-3 Forecasted Increases in Population and Energy Demand**

#### Requirements of 21st Century Energy Supplies

Economic well-being and stability require that both developed and developing countries have access to increased amounts of reliable and affordable energy. In addition, preservation of the environment and avoidance of adverse human health impacts will increasingly motivate the use of forms of clean energy – forms whose extraction, conversion, transmission and use have acceptably small impacts on the world's ecology. These requirements are frequently referred to as requirements for “sustainable energy.” Sustainable energy supplies are often defined as those that are stable, flexible (can help meet demands in more than one energy end-use sector), affordable, and have an acceptable impact on the public and the environment. As will be explained in the following sections, nuclear energy has the ability to meet all of these requirements. Recognizing these benefits, many countries have made it a goal to deploy



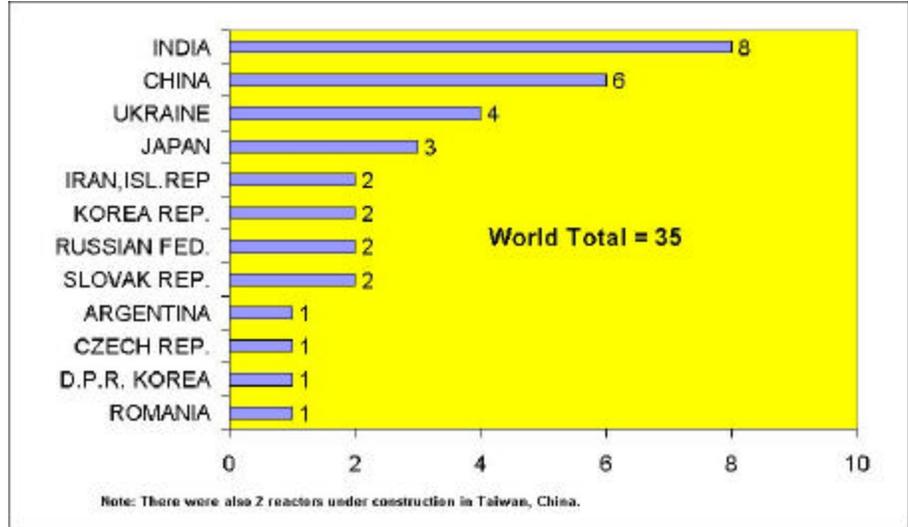
Source: Royal Dutch Shell, "Exploring the Future – Energy Needs, Choices and Possibilities"

**Fig. 3.4 Per Capita Energy Use of Select Countries**

nuclear systems, which has already led to significant construction, especially in Asia [Figure 3.5].

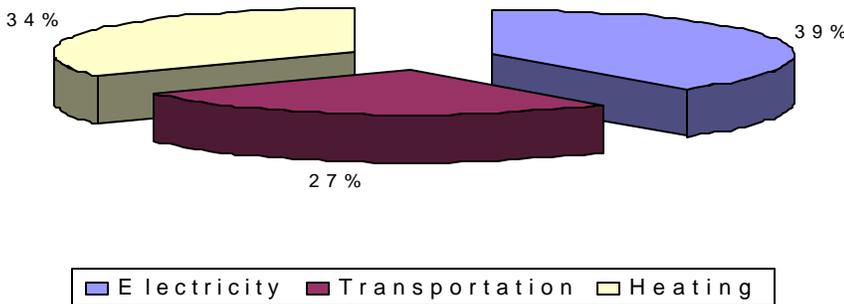
**Energy Stability**

Energy end-use occurs in three sectors – transportation, heating (non-electric, both home and industrial), and electricity [Fig. 3.6]. Electricity, at about 39 percent, is the largest sector in the U.S., followed by heating at 34 percent and transportation at about 27 percent of U.S. energy use. As illustrated in Figure 3.7, these three sectors differ greatly in the degree of energy supply diversity.



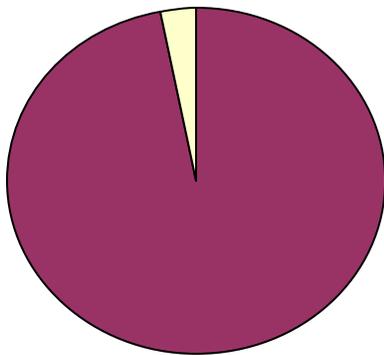
**Figure 3.5 Nuclear Power Plants Under Construction**  
Source: International Atomic Energy Agency 2000.

**Fig. 3.6 U.S. Energy Use by Sector [9]**

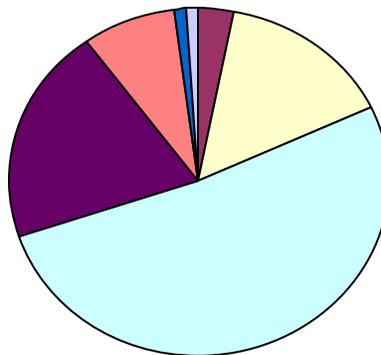


The benefits of diversity in electricity supply are well known. Electricity prices have fluctuated only by  $\pm 10$  percent over the past several years, and these fluctuations have been largely predictable, reflecting increased summertime demand. On the other hand, gasoline has essentially no competition as a transportation fuel, and prices have fluctuated  $\pm 30$  percent over the past few years [Fig. 3.8]. Oil price fluctuations have led to several

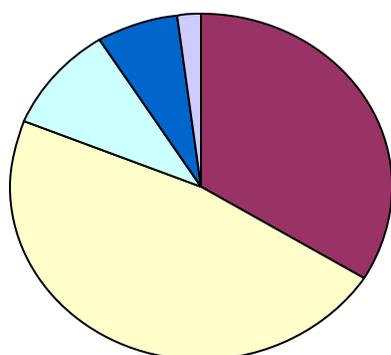
Source of U.S. Transportation Energy Supply (%)



Source of U.S. Electricity (%)



Source of U.S. Heating Energy Supply (%)



Oil Natural Gas Coal Nuclear Hydroelectric Biomass Other Renewables

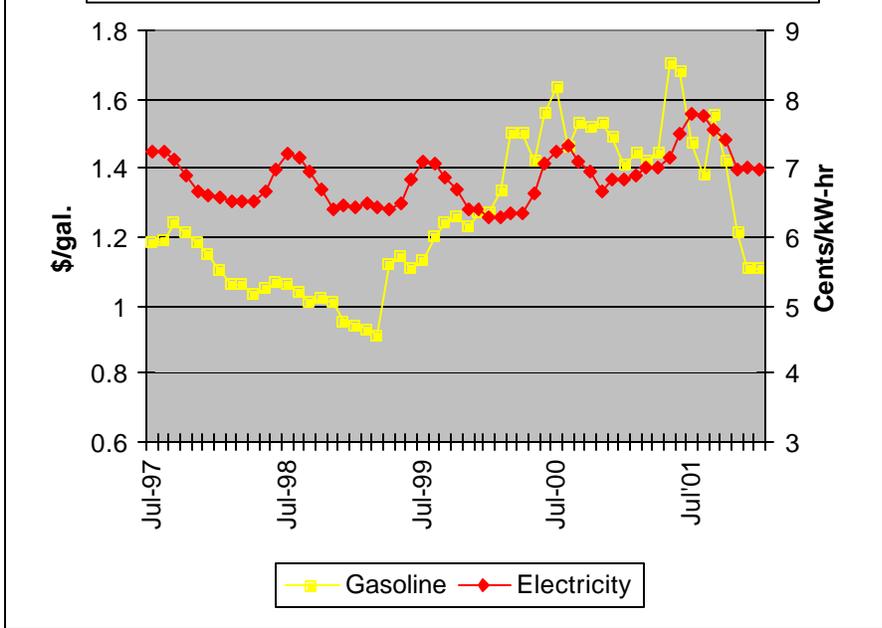
**Fig. 3.7 U.S. Energy Sources by Energy End-Use Sector [10, 11, 12]**

energy price shocks over the past three decades. The timing of these shocks correlates closely with the timing of most of the major economic downturns since the 1970s [Fig. 3.9].

More than half of U.S. oil supplies come from foreign sources, much of this from unstable regions of the world. U.S. dependence on foreign sources of natural gas is also growing, although currently most of the foreign supply of natural gas comes from Canada. To capture the benefits of supply diversity across all energy-use sectors, the U.S. must reduce its reliance on foreign supplies in the transportation sector, avoid becoming too reliant on foreign

supplies in the heating sector, and maintain diversity of supply in the electricity sector. The challenge, of course, involves developing domestically available energy sources that can satisfy these needs. Fortunately, nuclear energy can contribute to meeting all of these goals through the production of electricity, process heat, and hydrogen.

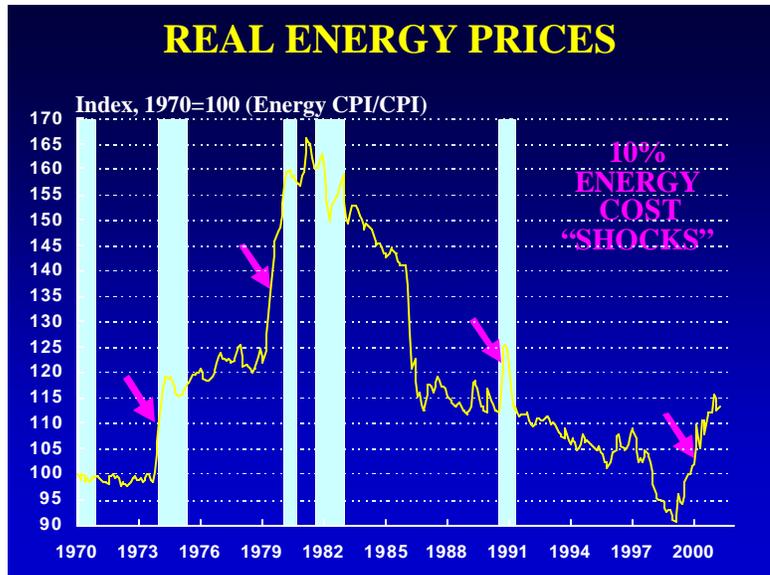
**Fig. 3.8 Monthly U.S. Gasoline and Electricity Prices [13,14]**



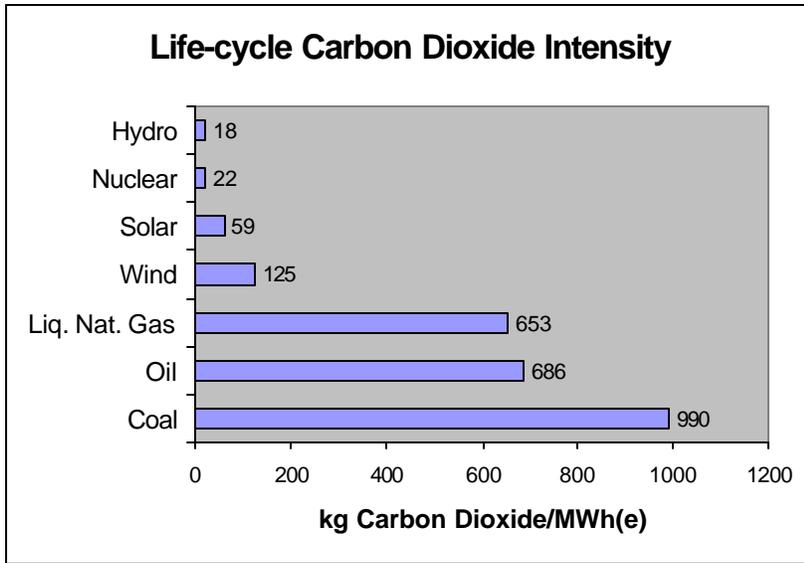
**Energy Flexibility**

The energy production systems in the 21<sup>st</sup> century will need to produce more than just electricity. Also expected are varied products such as hydrogen, fresh water, and process heat. All these products must be produced in quantities appropriate to meeting centralized or distributed demand and in a manner that minimizes adverse environmental effects.

With the dawn of a revolutionary transportation system envisioned, large quantities of hydrogen may be needed to supplement gasoline and diesel as transportation fuels. Currently, nuclear energy can generate hydrogen through the electrical process of electrolysis. In the future, nuclear-generated heat could be used to generate hydrogen more efficiently through high temperature thermochemical, thermoelectrical, and other high-temperature processes. The generation of hydrogen with nuclear energy can contribute enormously to energy independence and a cleaner planet through the elimination of locally polluting chemicals and greenhouse gases. Accordingly, the National Hydrogen Energy Roadmap recommends that



**Fig. 3.9 Timing of Economic Downturns [light blue bars] and 10% Energy Cost “Shocks”**



**Fig. 3.10 Life-Cycle Carbon Intensity of Various Energy Options [17]**

the DOE “develop advanced nuclear energy methods to produce hydrogen.” [15] For example, a 700 MWe nuclear plant can produce sufficient hydrogen from electrolysis to power about 650,000 cars [16]. Advanced reactors may be able to produce hydrogen twice as efficiently. Wind, solar, geothermal, and biomass can all be valuable sources of hydrogen production but their energy density

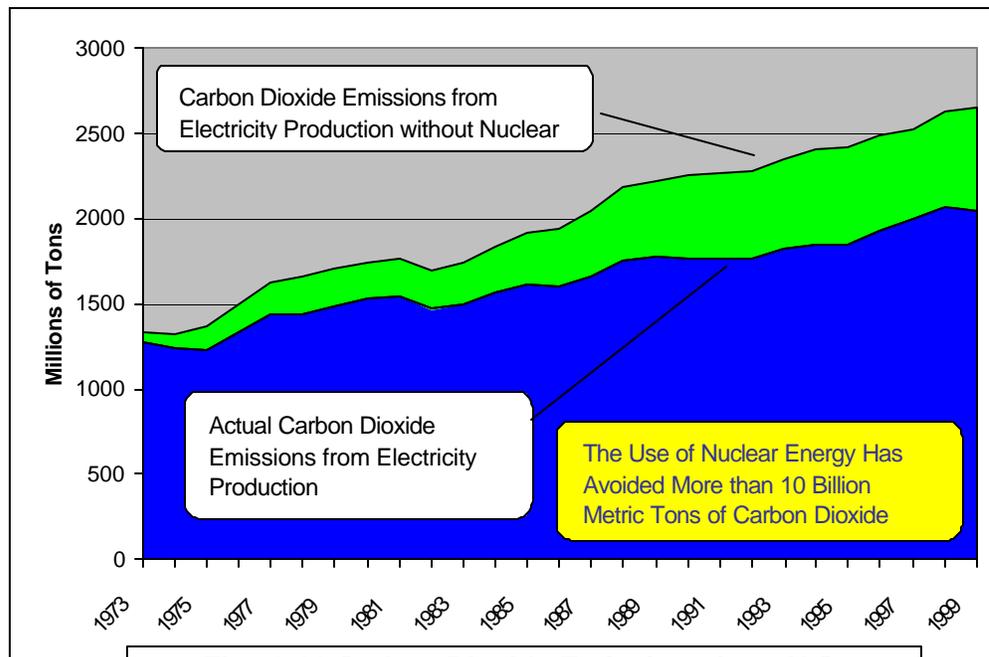
– a million times less than that of nuclear energy – may prevent these energy sources from generating the needed volumes of hydrogen.

Nuclear energy can also help meet heating energy demand by

generating high-temperature process heat. This heat, in turn, could be used for chemical production and other purposes. The energy could also be used for producing fresh water from seawater and contaminated surface and groundwater sources. Lack of fresh water is a looming crisis for the world community – even for major parts of the U.S. – and will put great pressure on energy supplies; nuclear power can make an important contribution.

**Energy Acceptability**

Nuclear energy can ensure a diverse energy supply in a manner that protects human health and the environment. Nuclear energy has an advantage over other carbon-free energy technologies in that it possesses a very high energy density, which is sufficient to produce very large amounts of electricity or hydrogen in a facility having a small footprint that produces small volumes of discharged waste. Nuclear also has a very low life-cycle carbon emission compared to other energy sources [Fig. 3.10].



**Fig. 3.11 Carbon Dioxide Emissions from U.S. Electricity Generation, 1973-2000 [18]**

The Secretary of Energy has recently reiterated the

President's "commitment to the United Nations Framework Convention and its central goal to stabilize atmospheric greenhouse gas concentrations at a level that will prevent dangerous human interference with the climate" and committed the U.S. to "an aggressive strategy to cut greenhouse gas intensity by 18 percent over the next decade [19]." Nuclear energy has already made a sizeable contribution to improving air quality, by enabling the U.S. to avoid more than ten billion tons of emissions of carbon dioxide over the past 30 years [Fig. 3.11], as well as one hundred million tons of the regulated air pollutants nitrogen oxides and sulfur dioxide combined. To stabilize carbon dioxide levels by mid-century with expected energy growth, requires the addition of 15-30 terrawatts of emission-free power, which is more than the total primary power produced worldwide today [20]. Because nuclear energy has an extremely low life-cycle carbon dioxide intensity, it can play a key role in the Administration's Clean Air/Clear Skies Initiative to improve air quality and reduce carbon and other emissions due to energy production.

### ***National and International Security***

In addition to the attributes of stability, flexibility, and acceptability, the expanded use of nuclear energy offers important benefits in the area of national and international security. The U.S. government has a primary responsibility to ensure national security and foster international stability, a critical dimension of which is protection against the proliferation of weapons of mass destruction. The potential for diversion and illicit use of nuclear materials is one of the important elements of this concern. It is essential that the implementation of nuclear reactor and fuel cycle technologies be carried out in ways that protect the nation and the international community against potential misuse.

Furthermore, it is clear that nuclear energy systems suitable for deployment anywhere on the globe – systems that are not only safe but also secure and proliferation resistant – can be developed if security is overtly designed into the nuclear cycle from the start. The diverse economic, infrastructure and defense conditions that exist in different parts of the world suggest the need to consider a variety of approaches to implementing nuclear energy in ways that address the needs of both advanced nations and less developed nations. In the less developed parts of the world, access to the benefits of nuclear energy may depend on the development of simplified energy production and fuel cycle systems, such as small self-contained nuclear energy sources. Such simplified systems imply a well-defined relationship between technology suppliers and technology users, and an appropriate international monitoring and regulatory framework for distributing and using nuclear energy sources. Both the technologies and the institutional frameworks will need significant development in order to achieve the long-term vision of widespread access to safe and proliferation-resistant nuclear energy.

A world unthreatened by nuclear proliferation through international cooperation and global nuclear materials management is a vision that the U.S. has strived to implement since the early years of the atomic age. The U.S. approach to controlling the spread of nuclear weapons has undergone three significant changes over the last fifty-plus years, with each change arising in response to significant events in the evolution of global nuclear power. These policy changes are expressed in the Atomic Energy Act, the Atoms for Peace Initiative, and the U.S. response to several events that occurred during the 1970's (including the detonation of a nuclear device by India and the resultant U.S. decision to forego nuclear fuel reprocessing). With the end of the 20<sup>th</sup> century, a new global nuclear infrastructure is evolving that presents a very different challenge, including as it does the vigorous pursuit of nuclear export markets by Russia and the development of an indigenous nuclear energy capability by India. Our vision for and approaches to assuring safe, secure, and legitimate nuclear operations must change to meet this challenge.

Given the ever-increasing stresses on individual nations' economic needs and access to the energy sources that fuel economic prosperity and national security, there is growing belief that a need exists to embark on a new nuclear era, with or without the leadership of the U.S. The fact that one cubic inch of uranium has the same energy content as 250,000 gallons of gasoline, 4-6 million pounds of coal, or 33 million cubic feet of natural gas makes nuclear energy an obvious candidate to fill the growing world energy gap. By recycling,

nuclear material resources could supply the projected electricity needs of the world for centuries. It is clear that nuclear energy will play a key role in meeting the future energy needs of the world.

In addition, there is enough known "surplus nuclear materials" throughout the world to supply one hundred 3000-MW(th) reactors for twenty years — an amount equal to the entire U.S. generating infrastructure. In advanced reactors, the use of this material would avoid generating billions of tons of air emissions that contribute to greenhouse gases. If used to support transportation energy needs, this material would also avoid the import of billions of barrels of oil. If these nuclear fuel materials were recycled, these numbers could be multiplied several times. On the other hand, this material could be used for thousands of nuclear weapons. Therein lies the paradox: the U.S. can either promote and enable the peaceful use of these nuclear assets to its advantage, or forever worry about their existence.

To move forward, it is important that our efforts to develop and introduce new technologies address these key issues and the development of supporting technologies related to national and international security. Some areas of emphasis include the development of remote and local sensing capabilities; monitoring, and communication systems that are resistant to interruption and highly reliable over long periods of time and development of advanced concepts; and approaches to achieve proliferation safety, including development of metrics of proliferation resistance, intrinsic measures for proliferation resistance, and extrinsic measures to provide for security through such means as advanced remote monitoring, sealed core transportable systems, etc. In addition, it should be noted that strong US technological leadership and a modern technology infrastructure not only promote world security but also provide economic benefits to the U.S.

In summary, nuclear energy has the ability to meet the key sustainability goals required of a 21<sup>st</sup> century energy source and offers important benefits to national and international security. However, there are challenges facing a large-scale deployment of new nuclear energy production. The next section discusses important challenges to an expanded deployment of nuclear energy.

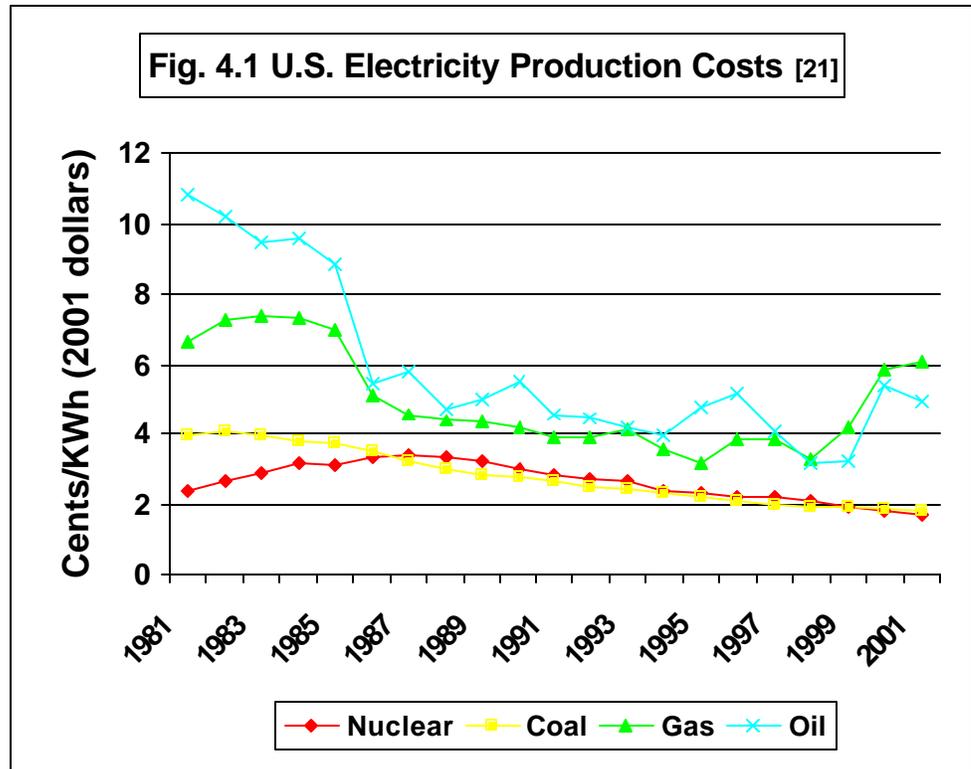
#### 4. Addressing the Challenges Faced by Nuclear Energy

As discussed in Section 3, there are many compelling reasons for nuclear energy to play a large role in the world energy mix. However, if nuclear power is to be deployed on a truly large scale, the systems that are deployed must be affordable, have an acceptable waste disposal solution, continue to be safe, and have acceptable resistance to proliferation of weapons-usable material.

In the U.S., the federal government has a role in promoting investments in energy diversity that result in profound improvements in national security, environmental health, and economic stability. The same rationale drives governmental investment in renewable energy, advanced energy exploration, and other energy initiatives. Because nuclear power plant investments are large and the plants have very long lifetimes, private sector investment decisions must seriously consider the risks associated with many factors over a very long planning horizon, including (i) electricity market structure and prices; (ii) the sometimes unpredictable regulatory climate; (iii) financial liability exposure in the event of accidents or terrorist acts; (iv) the stability of the fuel supply; (v) the reliability of the U.S. spent fuel disposition strategy, and (vi) governmental policies related to energy supplies and the environment. Given a decision that nuclear deployments are in the national interest, the private sector and government share the responsibility of undertaking the activities needed to ensure that the investment risk is reduced sufficiently to enable commercial deployment.

##### *Economic Nuclear Energy Solutions*

Nuclear energy today is at or near the top of the list of the energy sources having the most favorable operating costs [Fig. 4.1]. Operating nuclear power facilities enjoy an outstanding competitive operations cost structure, so competitive in fact that most operating plants plan to renew their operating licenses for an additional 20 years. In addition, many plants have sought power up-rate approval, which is a means of extracting further energy from an existing plant. Over the past twenty years, improvements in plant operating reliability and increases in capacity have added the equivalent of 23 new nuclear plants worth of electricity generation, which is a major reason that new plant construction has not been necessary.



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Deregulation of electricity markets in several regions of the U.S. has brought market pricing to utilities doing business in those regions. This arrangement favors the construction of generating assets with low capital costs and short construction periods. In contrast, existing nuclear power assets were built as regulated assets

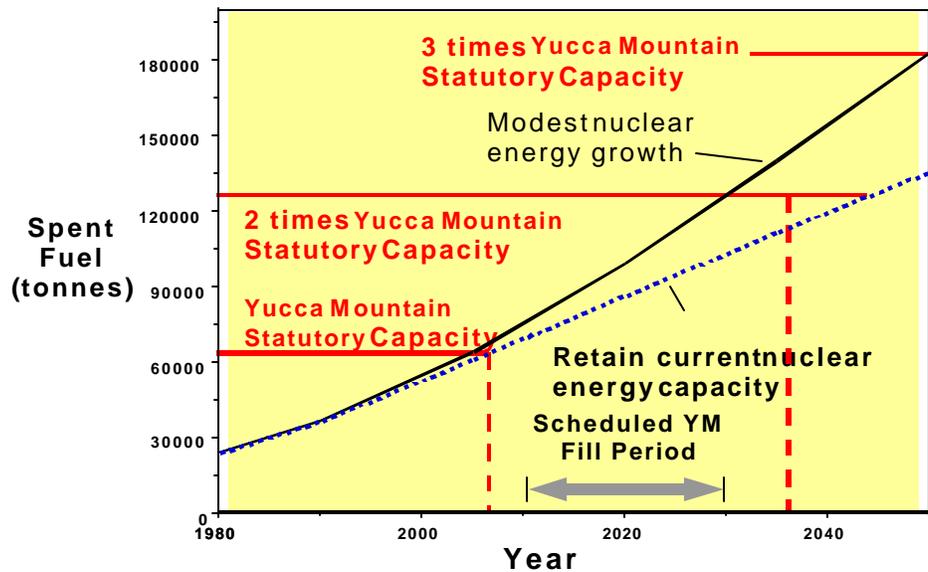
that were allowed capital cost recovery, plus a reasonable rate of return. The new arrangement accentuates the risks associated with a large capital investment. The private sector remains uncertain about whether it is willing to make the initial capital investment necessary to construct a new nuclear power plant. Reduction of the financial risk associated with the construction of the first few nuclear plants will be a key element in assuring a viable future for nuclear energy in the U.S.

In the United States, market decisions on where to invest limited capital for power plant and other energy market construction must consider capital/operating cost ratios, the timing of return on investment, and many other factors for which the construction of nuclear generating assets may not yield an immediate advantage. If the private sector is to invest capital in new nuclear plant construction, it will demand a return on that investment that is commensurate with the higher financial risk. In turn, government fiscal, tax, regulatory and security policy decisions directly influence risk, and a fundamental responsibility of the federal government is to promote private sector decisions that are in the long-term best interest of the nation as a whole.

For near-term deployments, the joint industry/government Nuclear Power 2010 initiative is addressing the demonstration of the Nuclear Regulatory Commission's early site permitting and combined construction/operation licensing processes. In addition, the Administration is working with Congress to ensure renewal of the Price-Anderson Act to limit exposure to financial liability in the event of accidents or terrorist acts. With respect to electricity market structure and prices, it has been recommended that the government consider aiding the private sector by mitigating the risks inherent in the construction of the first several new nuclear power plants in the U.S. A thorough analysis of the economic risks of new plant construction by Scully Capital Services [5] has shown that nuclear power can be fully competitive in the market place once the first several plants have been built and operated.

**Nuclear Waste Reduction**

In 2002, after almost 20 years of site characterization studies, the President and the Congress officially approved development of the Yucca Mountain site as the national geologic repository for spent nuclear fuel and high-level waste. While there are still a number of technical, regulatory, and legal hurdles to be overcome prior to placing the first spent fuel rod in the mountain, this long-delayed action effectively removed the largest



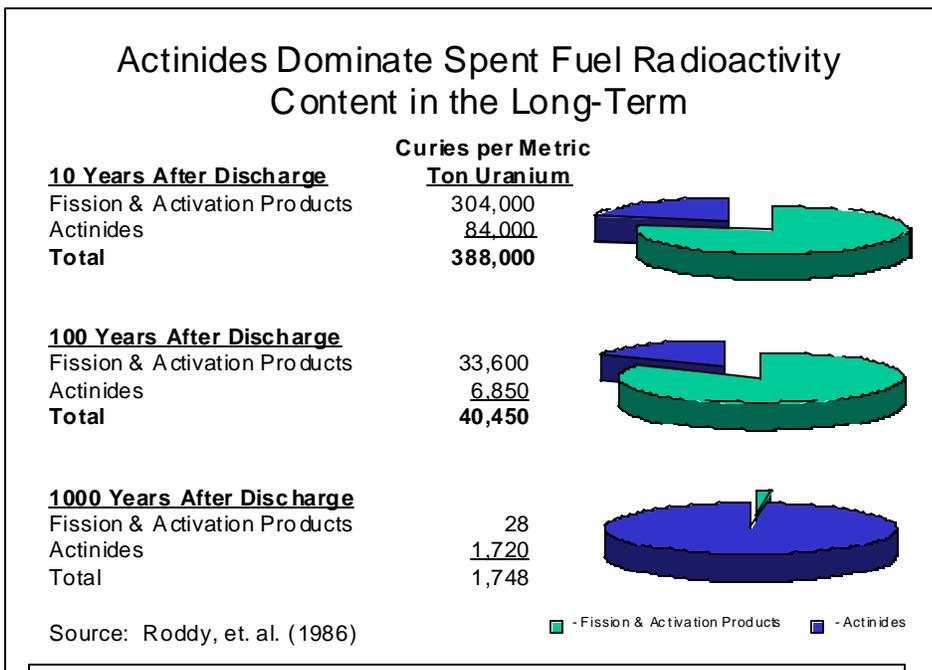
**Fig. 4.2 Spent Fuel Accumulations for Domestic Energy Scenarios**

impediment to the continued use of nuclear energy in the U.S. The cost of the Yucca Mountain Project — including the \$4 billion in costs for characterization and evaluation — is paid from a combination of federal funds for disposal of defense high-level waste and a one mil per kWh tax imposed on the sale of nuclear-generated electricity for the disposal of commercial spent nuclear fuel.

The initial statutory capacity of Yucca Mountain is 70,000 tonnes until a second repository is in operation. The tonnage is measured by the initial mass of heavy metal (mostly uranium) in the fuel. Of the total, 63,000 tonnes of capacity are reserved for commercial spent fuel, with 7,000 tonnes (equivalent) reserved for DOE spent fuel and high-level nuclear waste. Today there are approximately 44,000 tonnes of spent commercial fuel in storage, with another 2,000 tonnes generated each year. With the expected life extension of most of the currently operating reactors, the legislated capacity of Yucca Mountain is insufficient to accommodate all of the spent fuel that could be generated by the established fleet of reactors. However, the technical capacity of the characterized area of Yucca Mountain — estimated to be on the order of 120,000 tonnes — would be adequate if existing reactors were not replaced with new nuclear capacity. If it can be demonstrated that advanced fuel recycle technology can significantly delay the need for a second repository, Congress may have a substantial technical basis for deciding to allow the Yucca Mountain repository to expand to its technical capacity.

If nuclear energy is to be a part of the U.S. energy picture beyond the current fleet of power plants, government action is needed soon to provide assurance that new power plant deployments will not face an uncertain waste management mortgage. Fig. 4.2 indicates that even if the statutory capacity limit of the Yucca Mountain repository were lifted, a second repository would still be needed before 2050 if nuclear energy maintains its current electrical generating capacity. Through governmental action to enhance the nuclear fuel cycle to produce much less waste requiring isolation, the need for a second repository can be substantially delayed, perhaps into the next century.

The expanded use of nuclear energy will require either the construction of additional repository capacity, a different approach to the management of used nuclear fuel, or both. Nuclear fuel is quite compact, so physical volume is not the limiting factor in terms of efficient repository utilization. Rather, various



temperature limits in the waste packages and the mountain determine the maximum loading in the design of a Yucca Mountain-type repository. Minimizing radiological risk to future generations can be achieved through an appropriate combination of careful site selection, engineered barriers, production of robust waste forms, and a well-planned closure strategy.

A typical 500-kg light water reactor (LWR) spent fuel assembly contains about 95 percent unused uranium, less than 4 percent fission products, and slightly more than 1

percent transuranic elements (mainly plutonium). In a closed cycle, the uranium would be separated and stored at relatively low cost, leaving only about 27 kg of troublesome waste to be managed (5.4 percent of the total). There are a number of options for managing the radioactive materials (fission products and

**Fig. 4.3 Actinides Dominate Long-Term Radioactivity Content of Spent Fuel**

transuranics), all involving stabilization and disposal of fission products and at least some recycling of transuranics. The DOE's Advanced Fuel Cycle Initiative (AFCI) is beginning to evaluate these options.

From several earlier studies, it is known that transuranics in the repository would dominate both long-term heat generation and radiotoxicity [Fig. 4.3]. Greatly improving the utilization of a repository will require minimization of disposed transuranics [22], and maximum destruction (fission) of transuranics in nuclear reactors. Ultimately, fast-spectrum reactors, capable of fissioning all the transuranics, will be required. A well-designed recycle system can improve repository utilization by at least a factor of five over direct spent fuel disposal, while also while also reducing the long term radiological source term.

The advantages of recycle will come at a price. There will be R&D investment costs for improved separations and fuel fabrication technologies, capital costs for reprocessing and recycled fuel manufacturing facilities, additional (but manageable) risks to plant workers and the public from operation of these facilities, and a different set of proliferation risks to manage. However, the benefits of cleaner air and water, ample energy for all humankind, reduced repository cost and elimination of the need for a second repository in this century, and reduced inventories of weapons-usable materials will more than offset the cost. The key in the short term is to make the R&D investments that will allow the appropriate technology decisions to be made in time to affect the management of spent fuel generated from new nuclear power plants.

In the absence of a fast reactor infrastructure in the United States to close the fuel cycle, there are basically two options. The first is to recycle mixed-oxide fuel to existing reactors while storing the minor actinides for eventual destruction in a fast reactor. The second is to store spent fuel in Yucca Mountain with the knowledge that it is retrievable for recycle during the first 50 years of storage. Although it is possible to retrieve spent fuel for reprocessing prior to the repository's permanent closure, it is probably more cost-efficient and socially acceptable to begin to intercept, and thus greatly reduce, the waste stream to Yucca Mountain before the repository nears its technical capacity. In the interim, it is important to proceed with comparative R&D into advanced separations technologies (both aqueous and non-aqueous) and advanced fast spectrum reactors (both gas and metal-cooled) so that an informed decision can be made regarding which system to prototype.

### ***Maintaining Safety Excellence and Physical Protection***

Safety and reliability are essential priorities in the development and operation of nuclear energy systems. Nuclear energy systems must be designed so that, during normal operation or anticipated transients, safety margins are adequate, accidents are prevented, and off-normal situations do not deteriorate into severe accidents. As the events of September 11, 2001, made clear, nuclear energy systems must also be designed, constructed, and operated in ways that minimize their susceptibility to terrorist attack. This is true throughout the world, as an accident or an attack anywhere has negative consequences for all nuclear systems worldwide. At the same time, economic competitiveness demands a very high level of reliability and performance. Not surprisingly, the imperatives of safety and economic performance are linked; operating experience over the past decades has shown that the plants that are run the most safely are almost invariably the plants with the best economic performance.

As a result of this experience, there has been an emphasis over the years on improving the safety and reliability of nuclear power plants, reducing the frequency and degree of on- and off-site radioactive releases, and reducing the possibility of significant plant damage [for example, see the World Association of Nuclear Operators 2001 Performance Indicators for the U.S. Nuclear Industry]. As for physical protection, U.S. nuclear power plants rank very high among our best-protected infrastructure assets [23]. However, while the safety performance and physical protection of our existing nuclear plants are quite good, further improvements may be possible in next-generation nuclear power plants. For example, the simplification of plant control and protection by increased reliance on inherent methods of protection driven by the laws of

nature can substantially improve the public's understanding of safety and, ultimately, the acceptance of nuclear energy as a secure, safe, and sustainable energy source.

To support a major expansion of nuclear energy, the safety and reliability of future nuclear plants may rely on simplified designs that further reduce the already very small potential for severe accidents and their consequences. The achievement of these ambitious goals cannot rely only on technical improvements, but will also require systematic consideration of human performance as a major contributor to a plant's availability, reliability, inspectability, and maintainability. Strong U.S. leadership is critical to influencing the worldwide operational safety culture. R&D into new nuclear systems should increase public confidence with transparent safety approaches.

### ***Ensuring Proliferation Resistance***

Diverting materials from civilian nuclear fuel cycles has proven to be a highly unattractive route for nuclear-proliferant states to follow. Despite this fact, the specter of nuclear weapons proliferation has influenced nuclear policy, technology development and international relations since the dawn of the nuclear age. Because information on the design of a crude nuclear weapon is widely available, denial of access to nuclear material has been the principal barrier to nations and renegade organizations having illicit proliferation aspirations. Since September 11, 2001, there has been a new terrorism concern — dispersal of highly radioactive material by a conventional explosion. To deal with these issues, the National Laboratories have called for a new nuclear materials management regime that involves tracking and controlling not just uranium and plutonium, but all materials in the nuclear fuel cycle.

Since the late 1970s, U.S. policy has discouraged nuclear fuel recycling abroad, and has discouraged or prohibited recycle at home. Because recovering plutonium from spent nuclear fuel poses a formidable challenge to many countries and most sub-national groups, the once-through fuel cycle became not only policy, but also the unofficial benchmark of proliferation resistance. Closing the fuel cycle will require processing the fuel to at least some degree, potentially making the weapons-usable material in the spent fuel more susceptible to diversion or theft, at least in the short term. Whatever recycle technology choices the U.S. eventually makes, the overall proliferation resistance of the closed system must be no less robust than the current regime. Achieving this goal within an expanding nuclear energy framework will require implementation of a global strategy for nuclear materials management that ensures transparency in all aspects of the civilian fuel cycle, from enrichment through waste disposal.

An effective management strategy must integrate several complementary approaches to controlling nuclear materials. Institutional measures, such as international treaties and independent oversight, will continue to provide the backbone of the nonproliferation framework. The balance of the system — intrinsic proliferation resistant characteristics of fuel cycle technology and facilities, materials accountancy, and physical protection — must be designed to ensure that global nonproliferation objectives are achieved.

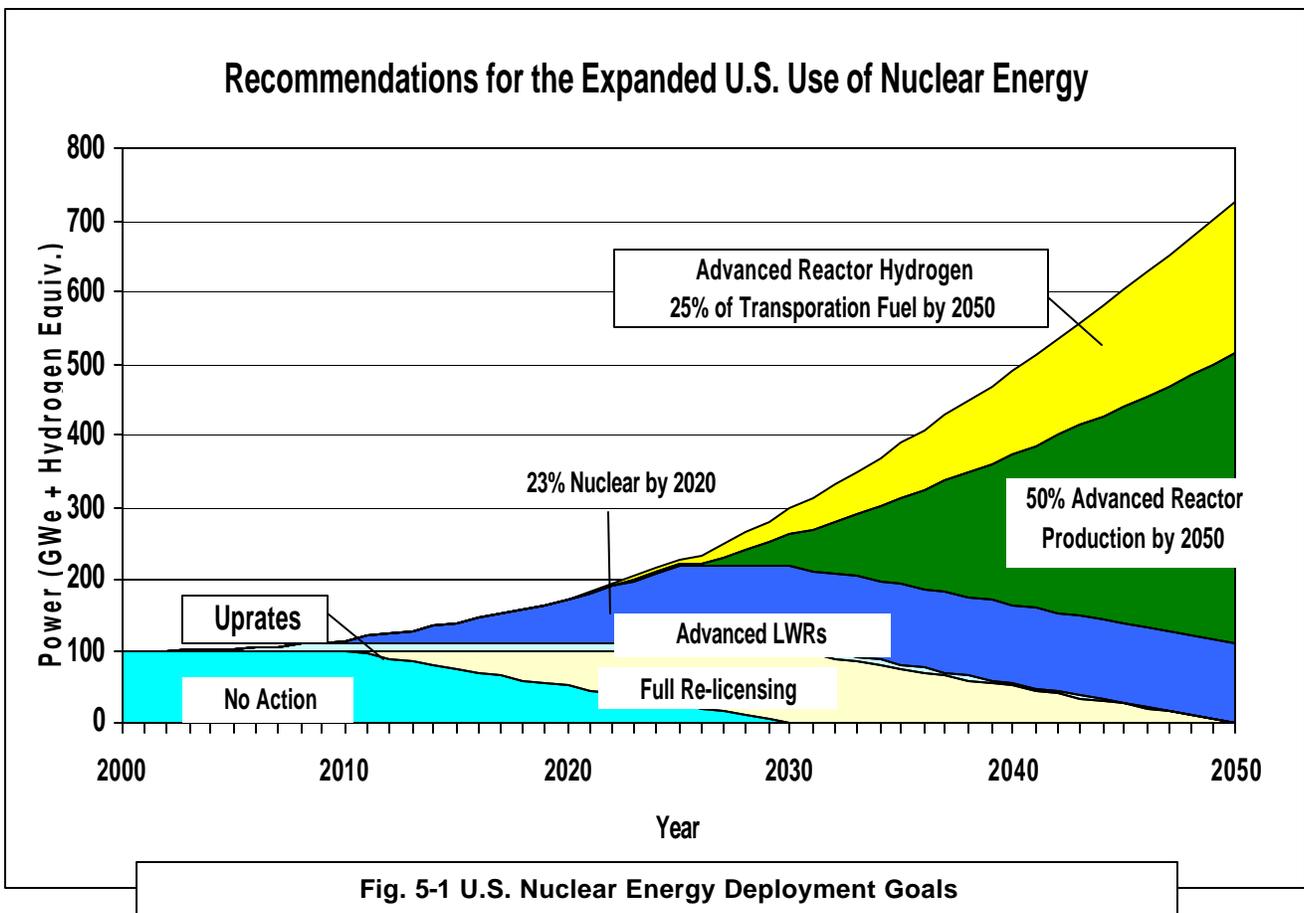
Preparation for a new nuclear nonproliferation regime should be included at the earliest stage of planning for a closed fuel cycle. A good starting point would be to develop a consensus proliferation risk assessment methodology to help evaluate technology tradeoffs and identify steps in the fuel cycle that require stronger extrinsic proliferation barriers. It will be important in developing this consensus to explore establishing quantitative measures where possible so that approaches can be compared and the most cost-effective methods identified. Capitalizing on the substantial progress that has been made in sensor technology in the past decade, modern monitoring systems should be integrated into new fuel cycle facilities and transportation systems starting with the earliest conceptual design. The new regime should also control radioactive materials that are not nuclear weapons-usable, but that could be dangerous in the hands of terrorists. Finally, tough decisions must be made about acceptable, reliable export and recycle technologies employed within the major supplier nations.

Although challenges to nuclear technology implementation exist and these barriers must be surmounted in the proper context of national security, a path forward for significant nuclear energy generation in the 21<sup>st</sup> century is clearly possible. The next section describes the initiatives that are underway and the additional steps that need to be taken to ensure that the U.S. can realize the full promise of nuclear energy.

## 5. The Path Forward

The benefits of a strong nuclear energy component to the future energy mix are clear, as detailed in Section 3. Accordingly, the U.S. National Energy Policy calls for "...the expansion of nuclear energy in the United States as a major component of our national energy policy." To meet the three goals for the expanded use of nuclear energy set by the Laboratory Directors, a comprehensive approach is required to address the challenges discussed in Section 4. Near- and long-term actions to address these challenges should:

- Provide significant incentives for near-term deployment of new nuclear power plants in the U.S.;
- Develop advanced Generation IV reactor systems that can support a major expansion of nuclear energy in the first half of the 21<sup>st</sup> century;
- Develop closed fuel cycle technology to produce the economically, socially, and politically sustainable fuel cycle of the future; and
- Establish new technologies and strengthen the regime for safeguards integrated within existing and advanced fuel cycles



The DOE has established small programs in each of these areas, as discussed below. However, to realize aggressive goals for the expansion of nuclear energy in the U.S. [see Fig. 5.1] and around the world will require action on new policies and legislation, as well as a significantly increased level of investment in the development of new nuclear technology. This section describes the efforts the DOE has underway and the next steps that will have to be taken by the Administration and Congress to meet these goals.

***Provide significant incentives for-near-term deployment of new nuclear power plants in the U.S.***

The removal of regulatory and financial uncertainties is critical to the near-term deployment of new nuclear power plants in the United States [24]. In February 2002, Secretary of Energy Spencer Abraham unveiled [25] the Nuclear Power 2010 initiative aimed at building new nuclear power plants in the U.S. before the end of the decade. Exploration and preparation of sites for new nuclear power plants is a critical step to ensuring that nuclear energy can grow in the U.S. market. The DOE is cooperating with industry through Nuclear Power 2010 in exploring a range of potential existing commercial, governmental, and new sites prior to a decision being made to undertake construction of a new plant. Through a competitive process, DOE has developed cooperative projects to seek Early Site Permit approval from the NRC under the new Part 52 licensing process. In addition to helping find acceptable sites for new nuclear plants, the DOE will offer to share the cost of demonstrating the new regulatory process that enables utilities to obtain a “one-step” combined construction and operating license for a new plant.

In 2002, the DOE commissioned a report by Scully Capital Services to examine additional steps that could be taken to reduce barriers and uncertainties and thereby facilitate the near-term deployment of new commercial nuclear power plants. The Scully Report recommends that the Administration and Congress consider a number of steps to help manage the financial risk of the first several plants, including:

- A federal credit program to support new plant financing in the event of delays outside the control of the industry, such as from judicial intervention;
- Financial support in the event of construction cost overruns;
- Support for one-time costs, such as first-of-a-kind engineering for new reactor designs;
- A direct loan program to help reduce capital costs; and
- Additional insurance capacity with broader coverage.

The Laboratory Directors recommend that the Administration and Congress further study these and other recommendations to determine if any or all of them should form the basis for new legislation. The ongoing efforts under the Nuclear Power 2010 program, along with new legislation possibly based on the recommendations of the Scully Report, should enable industry to place an order for at least one new nuclear plant by 2008 and meet the industry’s goal of providing 23 percent of U.S. electricity by 2020 [26]. While the actions needed to support the deployment of new plants in the near-term largely do not involve the National Laboratories, the Laboratories stand ready to assist the DOE and industry, as appropriate.

***Develop and demonstrate advanced Generation IV reactor systems that can support a major expansion of nuclear energy – for both electricity production and generation of hydrogen for transportation – in the first half of the 21<sup>st</sup> century***

It is the objective of the Generation IV program to design advanced nuclear energy systems that optimally respond to the challenges set forth in Section 4. The Generation IV International Forum (GIF) was founded in 2000 for the purpose of facilitating international cooperation in designing, developing, and deploying next-generation advanced nuclear energy and fuel cycle systems that can be licensed, constructed and operated in world markets. The ten countries of the Forum (Argentina, Brazil, Canada, France, Japan, the Republic of South Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States) have undertaken the two-year development of a comprehensive Generation IV Technology Roadmap [27]. The Roadmap describes the needs for cooperative R&D to produce one or more demonstrated Generation IV advanced reactor and fuel cycle systems, and sets forth development plans that would allow each of the systems to be ready for



deployment by 2020-2030 in the world market. Six Generation IV system concepts have been selected for initial research and development [Table 5.1] [28].

The Laboratory Directors recommend that the DOE and the other countries participating in Generation IV accelerate their research programs over the next several years to determine which combination of these six reactor systems best meets the goals of Generation IV [Fig. 5.2] as well as the needs of individual countries. However, this is not meant to imply that each of the six concepts should receive equal funding, since the six concepts have been the subject of varying degrees of study in the past, and each is thus at a different state of technological maturity. The Laboratory Directors recommend that the DOE provide an increased level of support sufficient to demonstrate two Generation IV systems (a thermal and a fast spectrum system) in the U.S. by 2020. As soon as is practicable, international cooperation under Generation IV should be expanded to include Russia, which has significant experience with several of the reactor concepts under consideration in Generation IV.

Table. 5.1 The Six Candidate Generation IV Nuclear Energy Systems

Reactor	Coolant	Neutron Spectrum	Electrical Capacity	Fuel Cycle	Non-Electric Applications
Very High Temperature Reactor (VHTR)	Gas (He)	Thermal	600 MWt	Open	Hydrogen
Gas-Cooled Fast Reactor (GFR)	Gas	Fast	288 MWe	Closed	Actinide management, Hydrogen
Super Critical Water Reactor (SCWR)	Water	Thermal or Fast	1700 MWe	Open or Closed	Actinide management (fast option)
Lead-Cooled Fast Reactor (LFR)	Lead Alloy	Fast	50-1200 MWe	Closed	Actinide management, Hydrogen
Sodium-Cooled Fast Reactor (SCFR)	Sodium	Fast	150-1500 MWe	Closed	Actinide management,
Molten Salt Reactor (MSR)	Salt	Epithermal	1000 MWe	Closed	Actinide management

As discussed in Section 3, nuclear energy has the capacity to go beyond electricity markets and provide other energy products. In January 2002, Secretary Abraham announced a new public/private partnership called FreedomCAR [29], and in January 2003, President Bush followed up with a plan to develop and deploy hydrogen as a primary fuel for fuel cell-powered cars and trucks as part of the U.S. effort to reduce dependence on foreign oil. The Laboratory Directors support the Administration's plan to embark on a comprehensive program that includes research on the production, distribution, storage, and use of hydrogen as a transportation fuel. The Laboratory Directors believe that a large-scale, zero-emissions hydrogen production technology is critical to enabling the goal of a truly zero-emissions transportation fuel that also meets our energy security needs.

Nuclear energy represents a unique, high efficiency, zero-emissions capability for manufacturing large quantities of hydrogen from water. At present, it is possible to produce hydrogen by standard electrolysis using nuclear-generated electricity from current reactors, and this process should be explored further. Looking longer term, the DOE should accelerate its research on high-efficiency alternatives including high-temperature steam electrolysis and thermochemical cycles (and some hybrid thermochemical-thermoelectrical cycles) for water splitting. The Laboratory Directors recommend that the DOE substantially increase its investment in research and development to support timely demonstration of:

- hydrogen production technology by 2006, and
- a nuclear high-temperature gas-cooled reactor hydrogen production demonstration by 2010-2012.

***Fig. 5.2 - Goals for Generation IV Nuclear Energy Systems***

***Sustainability–1.*** Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.

***Sustainability–2.*** Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long term stewardship burden in the future, thereby improving protection for the public health and the environment.

***Economics–1.*** Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.

***Economics–2.*** Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.

***Safety and Reliability –1.*** Generation IV nuclear energy systems operations will excel in safety and reliability.

***Safety and Reliability–2.*** Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.

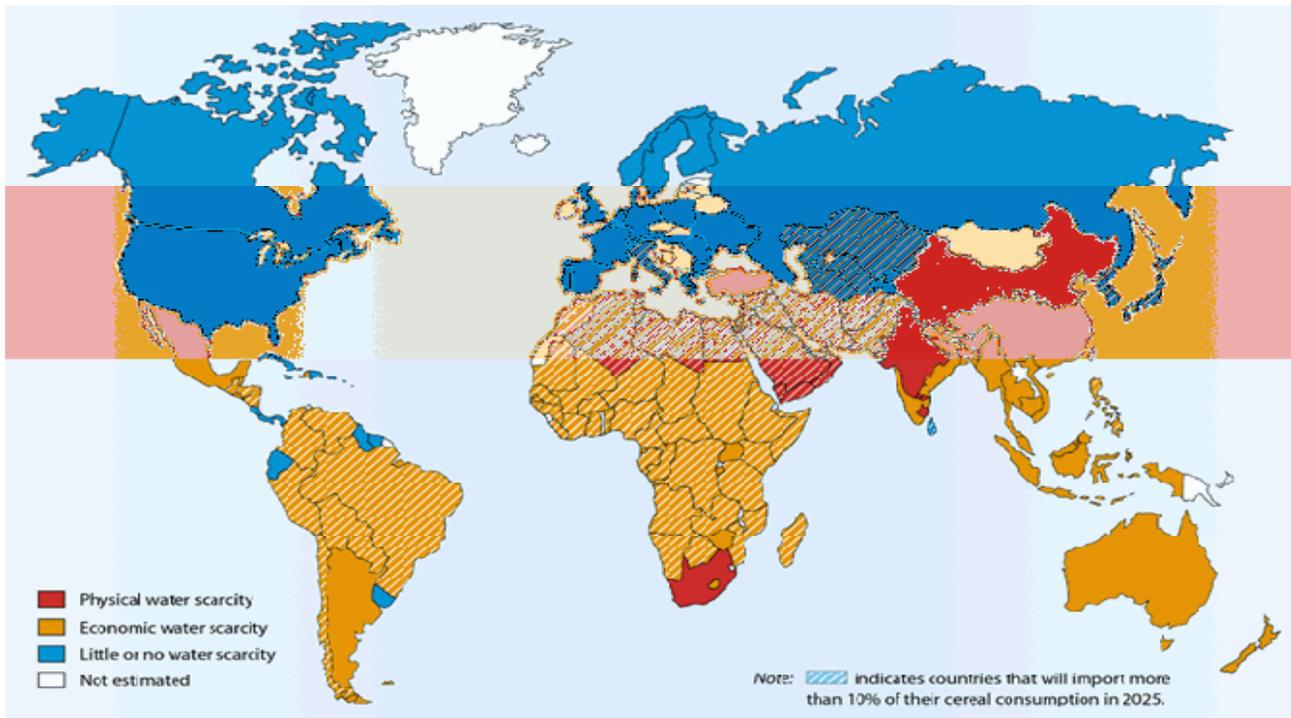
***Safety and Reliability–3.*** Generation IV nuclear energy systems will eliminate the need for offsite emergency response.

***Proliferation Resistance and Physical Protection-1.*** Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

These steps are required to ensure nuclear-derived hydrogen can be available to support the Administration’s goal of having fuel cell vehicles deployed commercially by the middle of the next decade.

Demonstrating the use of existing nuclear power plants to produce hydrogen, coupled with the development of higher efficiency production cycles that capitalize on advanced reactor technology, should enable nuclear-derived hydrogen to meet 25 percent of U.S. transportation fuel demand by 2050. The successful demonstration of Generation IV systems should enable the large-scale deployments that, coupled with the continued use of LWRs, will enable nuclear energy to provide 50 percent of the U.S. electricity supply by 2050. Achieving this objective will reduce U.S. carbon dioxide emissions by an estimated 3 billion metric tons per year, and U.S. oil consumption by an estimated 2 billion barrels per year. Looking worldwide, the use of nuclear energy to produce 10-15 percent of world energy (for electricity, hydrogen production for transportation, and other uses) will reduce world carbon dioxide emissions by up to 6 billion metric tons per year and oil consumption by up to 3 billion barrels per year.

Heat from a nuclear reactor can be used to produce other valuable energy products, including clean water. Much of the world’s population already suffers from a lack of access to clean water, and this problem will only get worse as populations grow and existing sources of clean water are depleted [Fig. 5.3]. Even in the U.S., competition for access to water supplies is leading to regional disputes, especially in the West. Nuclear energy has been or is currently used to desalinate water in many countries, including the U.S., Japan, and Kazakhstan. The Laboratory Directors recommend that the DOE consider increasing its investment in research leading to the deployment of nuclear energy technologies for other process heat applications including the production of clean water to respond to this growing world problem.



**Fig. 5.3 Projected Water Scarcity in 2025 [30]**

***Develop and demonstrate closed fuel cycle technology to produce an economically, socially, and politically sustainable fuel cycle of the future***

The DOE is making notable progress in the development and licensing of a geological repository for directly disposing of untreated spent nuclear fuel at Yucca Mountain, Nevada. As discussed in Section 4, the technical capacity of the planned Yucca Mountain repository is sufficient for currently licensed nuclear plants, but inadequate if new nuclear plants are constructed in the U.S.

There has been a thorough analysis of Yucca Mountain to verify that the public risk associated with operation and eventual closure of the facility is acceptably low. Although there are feasible concepts for substantial reduction of the very long-term risk to future generations, the cost of these concepts simply cannot be justified for managing the waste from current reactors. On the other hand, if national policy calls for an expansion of nuclear power as part of a sustainable energy regime in the U.S., near-term decisions will have to be made for dealing with the far larger quantity of spent nuclear fuel that will be generated. Governmental assurance on the waste issue is needed before private investors will accept the financial risk of ordering new nuclear plants.

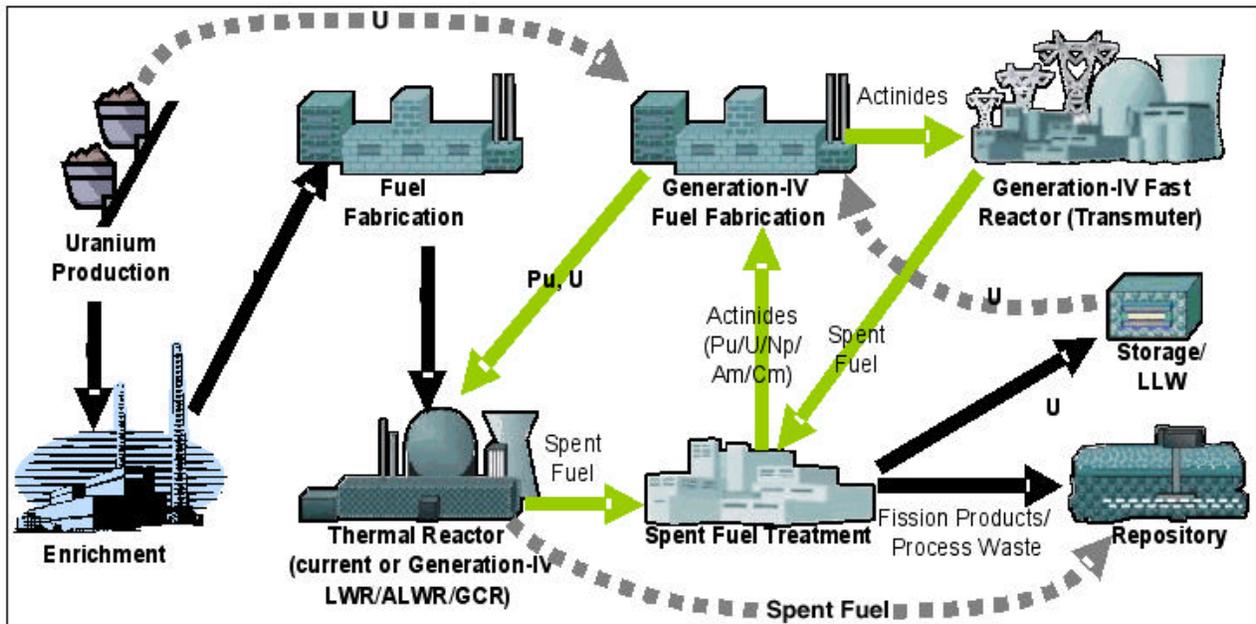
There are two basic choices for dealing with the additional spent fuel: build supplementary geologic repository capacity to store it or recycle it, to make far more efficient use of the space available within a given repository. The latest estimated life-cycle cost of the Yucca Mountain repository is \$58 billion and there are both financial and political incentives for avoiding the need to build more repositories to support an expansion of nuclear power. However, recycling nuclear fuel is expensive in an era of cheap uranium and has been contrary to U.S. national policy for the past 25 years. Because recycling is almost certainly essential for nuclear sustainability, development of a nuclear waste management system based on economic, proliferation-resistant recycle technology is an indispensable governmental action needed if this nation is to include nuclear power as an option for its energy needs.

The U.S. National Energy Policy directs that “in the context of developing advanced nuclear fuel cycles and next generation technologies for nuclear energy, the United States should reexamine its policies to allow for research, development, and deployment of fuel conditioning methods (such as pyroprocessing) that reduce waste streams and enhance proliferation resistance.” Reprocessing or recycle of the residual fuel constituents in spent nuclear fuel has been prohibited by national policy, most recently set forth in 1993 by Presidential Decision Directive-13 (PDD-13). Research on fuel recycle can and is being conducted within the confines of PDD-13, but revision of PDD-13 will be needed to remove the barrier to demonstrations that would precede implementation of an advanced nuclear fuel cycle.

PDD-13 cannot be taken lightly, for it is motivated by a concern about the proliferation of weapons of mass destruction and access to the nuclear material that can be used to make weapons. While the goal of PDD-13 is universally accepted, great differences of opinion exist as to how best to achieve that goal. They range from closing out the nuclear energy option to aggressive expansion and international technological leadership in the field of nuclear energy. As the result of this divergence of views, there is a critical need to establish consistent and coherent risk-informed practices and policies.

Through its Advanced Fuel Cycle Initiative and its Generation IV program, the DOE has begun to sponsor research that could result in an advanced nuclear fuel cycle for the U.S. Six advanced reactor concepts are being considered within an international context, two lines of chemical separations research are being supported, advanced fuels are being designed, and systems studies are being carried out. Once spent fuel is subjected to chemical separation, there are many potential options for managing the constituent parts: transmutation of the actinides in fast-spectrum reactors, recycling plutonium in existing LWRs or advanced thermal reactors, stabilization of fission products in robust waste forms, and transmutation of one or two long-lived fission products.

One concept of an advanced fuel cycle is shown in Fig. 5.4. The left side of the picture shows the open fuel cycle as it stands today in the U.S., without fuel recycle. This portion will remain vitally important in the future, particularly in an international context, so long as uranium prices remain reasonable. The green arrows depict the closed part of the cycle. Recycle through the fast-spectrum reactors plays an essential role



**Figure 5.4 A Closed Fuel Cycle May Enable Reduced Cost and Risk of Geologic Disposal, Improved Proliferation Resistance, and Greatly Extended Nuclear Fuel Supplies**

in eliminating most of the actinides, which is necessary condition for greatly expanding repository capacity. Recycle into existing or advanced thermal reactors can help stabilize the accumulation of civilian plutonium and delay the implementation of fast reactors. Uranium, comprising more than 95 percent of the LWR spent fuel, would be separated and stored as low-level radioactive waste until needed for fuel fabrication some time in the future. Fission products and activated fuel assembly hardware would be destined for the repository, stabilized in engineered waste forms that are much more suitable than spent fuel for enduring geologic time scales. The fuel cycle shown here also allows for the possibility of direct disposal of some spent fuel, such as “deep-burn” fuel, which has been proposed for some gas-cooled reactor concepts.

It is the consensus view of the Laboratory Directors that a closed fuel cycle will be required to facilitate a large-scale, sustainable expansion of nuclear energy. There are many fundamental decisions to be made prior to full implementation of a closed nuclear fuel cycle in the U.S., e.g., selection of proliferation-resistant separations and fuel fabrication technologies, whether or not to use thermal reactors for partial transmutation of plutonium, and the role of government in owning and operating portions of the system. The action required in the near term is to perform the R&D needed to provide the objective basis for making some of these decisions. The goal of this R&D should be to develop integrated technologies capable of providing the following benefits when implemented:

- Eliminating the technical need for a second repository in this century.
- Slowing, reversing, and eventually eliminating the accumulation of plutonium in spent nuclear fuel.
- Enabling an ample fuel supply for centuries.

There is obviously a delicate balance between developing the data necessary to make sound decisions and beginning to implement a system in time to affect the desired outcome, particularly with respect to repository utilization. The Laboratory Directors recommend the goal of demonstrating a closed fuel cycle technology system by 2020. The following actions will be needed in order to achieve this goal:

- Build a pilot facility to demonstrate advanced technology for partitioning waste and recycle by 2010.
- Build a pilot fuel supply and testing facility by 2010.
- As discussed in the previous section, build a fast-spectrum Generation IV nuclear power plant in the U.S. and use it to demonstrate actinide burning in an advanced system by 2020.

### ***Demonstrate technology that will set the world standard for proliferation prevention***

To provide safe, economic al, and secure nuclear energy worldwide requires technologies that could be deployed in any country without posing a proliferation threat. Nations that lack highly developed technology infrastructures need not necessarily be excluded from the benefits of nuclear energy, if technologies and arrangements can be developed that minimize the potential for proliferation of weapons material. This requires the ability to monitor and regulate access to capabilities and materials that could otherwise represent an unacceptable proliferation risk. This ability can be achieved through both new technologies and a strengthened international framework. New technologies include fuels, reactor materials, and integrated systems that enable reduced fuel handling requirements and reduced attractiveness of fuel cycle materials. Additionally, advanced monitoring and control systems are needed that provide high levels of external observability, transparency, plant protection, and information management throughout the fuel cycle. Establishing metrics that clearly define reduced proliferation risk would strengthen the international framework.

A critical first step is to develop and sustain an analytical framework and standards for quantifying the proliferation risk of technologies, systems, and operational arrangements. The appropriate design and development of technologies intended to reduce proliferation risk is dependent on the availability of

appropriate metrics and methods. These methods and metrics must be applicable to individual technologies (e.g., special fuel formulations that are intrinsically unattractive for proliferation), systems (e.g., reactor sites with improved automated monitoring), and operational arrangements (e.g., operations under an enhanced international monitoring regime).

With the establishment of the appropriate (and agreed upon) methods and metrics, specific technologies that enhance proliferation safety should be developed. These technologies should include those that are related to (1) fuels and materials (e.g., advanced fuel formulations that are proliferation-resistant, or materials that can withstand the conditions anticipated with very long lifetime fuels, reducing the need for refueling); (2) integrated reactor systems (e.g., systems such as the sealed core system that can be operated at a host site and removed at end of life without refueling); and (3) advanced information, instrumentation, and control systems (e.g., those that permit simplified operations, enhanced transparency and improved external observability).

In addition, the implications of the introduction of an advanced, closed fuel cycle to the global setting requires careful consideration and the establishment of international controls that go beyond those found in the current international safeguards system. The consideration of options for bilateral and multilateral arrangements that would enable widespread future use of nuclear energy should be the subject of active discussion, analysis and debate. This critical need – the identification of appropriate international frameworks – represents a key interface between technology needs and the realities and complexities of international relations.

The Laboratory Directors recommend that by 2020, the DOE demonstrate a global nuclear energy technology system consisting of intrinsic and extrinsic safeguards that minimizes proliferation risk. To meet this goal, the following actions are necessary:

- Develop and sustain an analytical framework and standards for quantifying integrated proliferation risk by 2005.
- Accelerated development of affordable technologies and multilateral transparency systems from the cradle to the grave with an integrated demonstration by 2008.
- Recommend an international framework for implementing sustainable global management of nuclear materials and services by 2008.

### ***Effects on the nuclear energy infrastructure***

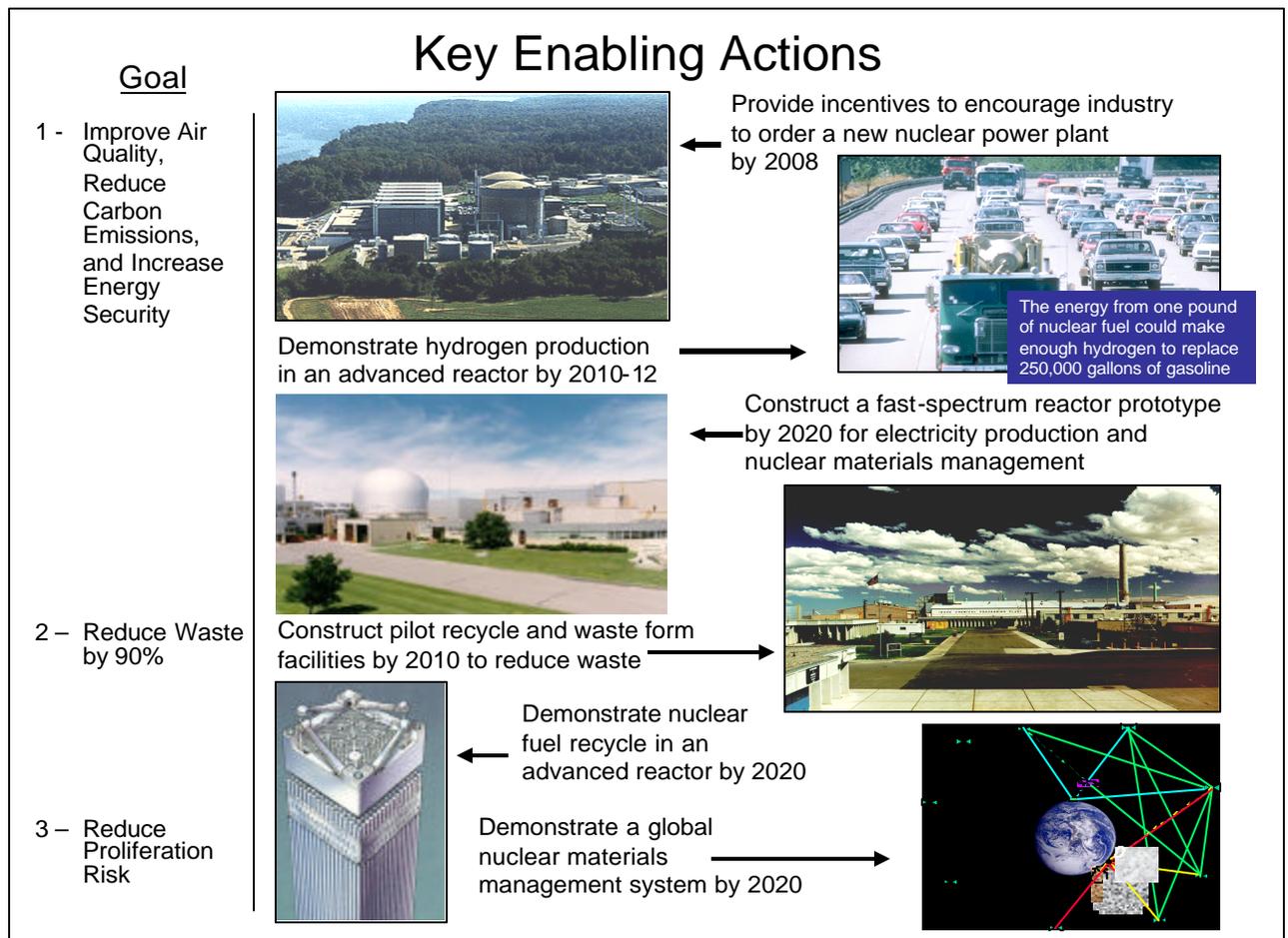
The lengthy hiatus in new nuclear plant orders and the interruptions or termination of many major federal nuclear programs in the 1980s and 1990s have contributed to three negative infrastructure trends:

- *A weakening of the U.S. facility infrastructure for conducting nuclear research and responding to unanticipated problems.* Many facilities within the university and National Laboratory systems have been shut down, and the information infrastructure for sustaining nuclear databases and computational code centers receive inadequate support.
- *The progressive attrition of our national pool of human expertise.* A large fraction of the nation's nuclear experts will retire in the next ten to fifteen years, and current nuclear engineering graduation rates are insufficient to replace them. Additionally, there is a prospect that the nuclear technology leadership in the U.S. will eventually fall to a generation of nuclear engineers who have never designed and built actual nuclear systems.
- *The increasing obsolescence of our base of commercial nuclear energy technology.* U.S. nuclear power plants are largely designed with 1970s-vintage technology. Research and manufacturing organizations in several foreign countries have gained leads on the U.S. in many important advanced technology areas.

The recent resurgence of interest in nuclear energy has slowed these trends somewhat, but much more must be done to support the deployment of new LWRs and the development of Generation IV nuclear power systems as well as to provide the expertise necessary to underpin regulation of nuclear facilities and operations. Enrollment in nuclear engineering programs is still not back at necessary levels, especially at the graduate level. While the current \$152M nuclear energy R&D budget is a major step forward from a few years ago, it is still far too small to perform the R&D necessary to develop Generation IV systems in a timely manner. Restart of shutdown facilities is, in many cases, not feasible; many operating facilities are relatively old, and the cost of needed major new research facilities is measured in hundreds of millions of dollars. Much of the national base of fundamental information on nuclear decay data, cross sections, and dosimetric data and the like has not been updated in years despite the fact that new nuclear systems would require new information.

Fortunately, if the DOE follows the path forward recommended by the Laboratory Directors, it will of necessity build new research, development, and demonstration facilities and attract new scientists and engineers to the nuclear field [Fig. 5.5]. This will have the natural and desirable effect of restoring the U.S. nuclear infrastructure, which has been weakened by the interruption and termination of most U.S. nuclear energy programs. Specifically, the DOE will find that in achieving the goals, it will make sustained and substantial investments in the nuclear R&D infrastructure on four fronts:

- *University nuclear education*: Increased financial support will be available to directly support students, especially at the graduate level, and faculty in the form of grants, fellowships, and



**Fig. 5-5 Certain Enabling Actions are Critical to the Expanded Use of Nuclear Energy World-Wide**

competitively awarded research funding. This support will both aid the university nuclear infrastructure that remains operational, as well as provide more general support for less specialized infrastructure such as computers. The DOE's Nuclear Energy Research Advisory Committee (NERAC), issued a series of recommendations in 2000 [31] for supporting university nuclear energy research programs and research and training reactors. These recommendations were aimed at strengthening university nuclear engineering programs, university training and research reactors, and university-National Laboratory interactions. The DOE has established many of the program elements called for by NERAC, but still must implement the remaining recommendations and significantly increase support for university programs.

- *National Laboratory resources:* Increased nuclear energy R&D will rebuild expertise within key DOE National Laboratories that have and will continue to constitute the core competence for nuclear technology. DOE facilities have historically conducted large scale, high technical risk research that university and industry-based facilities have been unable to support. In particular, DOE will retain or establish the capability to perform large-scale reactor and fuel cycle prototype testing. The best of the nuclear infrastructure at these laboratories will receive increasing support. As DOE expands its nuclear energy research programs, a long-range plan should be developed for a coordinated shutdown of unused facilities at their end-of-life and start-up of modern replacements. Many of the facilities the DOE will need to construct could serve as international user facilities to support the whole of the nuclear enterprise.
- *Base nuclear technologies:* The DOE will find that as it works to develop new nuclear technologies, it will be advantageous to support a base technology program that includes nuclear data, materials, thermal fluids, codes and models, and other technologies. Support will be increased for national nuclear data and code centers, and a systematic effort will need to be undertaken to assess the state of nuclear data, facilities for measuring such data, and nuclear-related computer codes to identify what information needs to be obtained to enable the next generation of reactors.
- *Information preservation:* As the DOE expands its nuclear energy research programs, it will find it cost-effective to support a concerted effort to ensure that technology developed in the past is preserved and leveraged in ongoing programs.

These steps will provide the technological base and infrastructure that will form the underpinnings necessary for the U.S. to have a future commercial nuclear enterprise. The following section describes the level of investment in programs and infrastructure necessary to carry out these steps and meet the recommended goals.

## 6. Resource Requirements

The July 2002 letter from six DOE National Laboratory Directors to the Secretary of Energy called for an additional \$1 billion above planned nuclear energy R&D and infrastructure investment over the next five years. This recommendation recognized that a successful nuclear energy R&D program will require a large investment in research and infrastructure, but will be well worth the investment. History is an excellent guide in this regard; the total U.S. government investment in nuclear fission research and development over the past 50 years [32] is roughly equal to the yearly revenue of nuclear-generated electricity in the U.S.

The additional funds recommended by the Laboratory Directors would be used to accelerate and enhance the departmental nuclear energy, reactor waste, and nuclear materials management programs. As stated in the Laboratory Directors' July 2002, letter to the Secretary, these steps are necessary:

- *“To assist the deployment by the U.S. industry of multiple new power plants by 2020*
- *To reduce actinide waste and plutonium stockpiles by closing the fuel cycle*
- *To restore the industrial and R&D infrastructures*
- *To provide technologies and strengthen the regime for safeguards integrated within existing and advanced fuel cycles; and*
- *To provide sustainable energy sources that mitigate global climate change and water availability issues.”*

As discussed in Section 5, there are four actions that must be taken in the near term to enable nuclear energy to achieve the goals set forth in this plan. DOE resource requirements associated with each of these four actions are discussed below:

### ***Provide significant incentives for-near-term deployment of new nuclear power plants in the U.S.***

Nuclear Power 2010 has helped renew industry interest in building new nuclear generating facilities. The Laboratory Directors recommend that the DOE continue this program at or above the current level of investment, to demonstrate to industry that the government's support for new nuclear generation is real and will be sustained.

Many of the recommendations for additional industry assistance discussed in Section 5 call for legislative actions that will not necessarily involve increases to the DOE's nuclear energy R&D budget. Therefore, the resources required to implement these additional actions are not included in the overall resource requirements presented below.

The Nuclear Energy Plant Optimization (NEPO) program has succeeded in its goal of helping industry improve the efficiency of current plant operations, and could contribute knowledge and technology that helps improve the economics of new plants. As long as industry remains engaged in the program and the cost-share arrangement, the DOE should continue its current level of investment in the NEPO program.

### ***Develop and demonstrate advanced Generation IV reactor systems that can support a major expansion of nuclear energy – for both electricity production and generation of hydrogen for transportation – in the first half of the 21<sup>st</sup> century***

The DOE's present level of investment in Generation IV is quite simply inadequate for thoroughly investigating even one of the six candidate concepts. The rest of the Generation IV International Forum

could soon begin to question the U.S. commitment to Generation IV if the DOE's contribution does not increase dramatically.

If the U.S. is to have one or more Generation IV concepts ready for commercial deployment by 2020, it must be in a position to complete construction of two Generation IV nuclear energy systems – a thermal- and a fast-spectrum system – in the next decade. The need for two systems is derived from the fact that the Generation IV program addresses two distinct missions; efficient electricity and hydrogen production and actinide management. The Laboratory Directors recommend that the DOE strive to demonstrate advanced nuclear-hydrogen production process technology by 2006, build a thermal-spectrum, gas-cooled reactor to demonstrate efficient electricity and nuclear-hydrogen production by 2010-2012, and build a fast spectrum reactor to demonstrate a closed fuel cycle technology system by 2020. Putting the DOE on a path to meet these dates will require a Generation IV program of about \$45 million in FY 2004, with significant funding growth in the following years.

The DOE is supporting several small research efforts to investigate the use of nuclear energy systems for the production of hydrogen, but it does not at present have a stand-alone program in this area. Such a program should be initiated as the DOE has proposed, to ensure that nuclear production of hydrogen is given the high priority that it deserves based on its potential payoff. As various hydrogen production cycles progress through the research and into the development phase, there will come a need for a large-scale non-nuclear facility to test these cycles under near-prototypic conditions. The Laboratory Directors recommend that the DOE act in the near-term to begin planning for such a facility, with the goal of having such a facility available by 2006. In the interim, the DOE will need to support the construction of the bench- and laboratory-scale equipment needed to prepare hydrogen production cycles for large-scale testing. Accelerating the research into nuclear-hydrogen production processes and beginning the design of a non-nuclear test facility will require that the Nuclear Hydrogen Initiative be funded at about \$20 million in FY 2004.

The DOE has lost (or never had) the capability to conduct much of the research that will be required under Generation IV (as well as under AFCI and other programs). Some of this capability can be found in the countries participating in the Generation IV International Forum, but many of the facilities required are outdated or are already oversubscribed. To conduct a thorough evaluation of Generation IV nuclear energy systems and advanced fuel cycles will require the U.S. to restart and/or refurbish old research facilities and invest in new facilities. Part of the needed set of facilities and capabilities are defined in the Generation IV Roadmap. Following the release of the Roadmap, the DOE should prepare a nuclear R&D infrastructure plan to determine specifically what capabilities and facilities are required to enable informed technology decisions to be made to meet the goals and target dates listed in the Laboratory Directors' Action Plan.

In the process of developing Generation IV nuclear energy systems and associated fuel cycles, the DOE will likely need to support a robust base technology program. Such a program will provide research results that could benefit all of the research programs discussed in this plan, and will have the added benefit of encouraging more researchers to enter the nuclear field. The current DOE Nuclear Energy Research Initiative (NERI) program, an investigator-initiated program whose R&D broadly supports many of the initiatives described above, provides a basis for one component of a base technology program.

***Develop and demonstrate closed fuel cycle technology to produce an economically, socially, and politically sustainable fuel cycle of the future***

AFCI, like the Generation IV program, must be accelerated if the U.S. is to be in a position to make informed, timely decisions regarding the future nuclear fuel cycle. It is the consensus view of the Laboratory Directors that a closed fuel cycle will likely be required to facilitate a large-scale, sustainable expansion of nuclear energy. It is also the view of the Laboratory Directors that the U.S. should strive to be in a position

to make informed fuel cycle decisions in about five years. A consensus has yet to be reached regarding exactly when the U.S. could best benefit by moving toward a closed fuel cycle or what technological approach the U.S. should follow; those questions should be addressed through research and systems studies under AFCI.

The recommended research effort should lead to the construction of a pilot facility to demonstrate advanced technology for partitioning waste and recycle by 2010. A pilot fuel supply and testing facility should also be constructed by 2010. Finally, as discussed in the previous section, the DOE should plan to build a fast-spectrum Generation IV nuclear power plant in the U.S. and use it to demonstrate actinide burning in an advanced system by 2020. Putting the U.S. on a path to meet these objectives will require AFCI program funding of about \$95 million in FY 2004.

### ***Demonstrate technology that will set the world standard for proliferation prevention***

New technologies are needed in the areas of the global management of nuclear materials; development of fuels, reactor materials, and integrated systems that enable reduced refueling requirements and reduced attractiveness of fuel cycle materials; advanced monitoring and control systems for improved plant operations; and enhanced safeguards to provide high levels of external observability, plant protection, and information management. As a first step, a program should be instituted to establish metrics for measures to reduce proliferation risk and to develop technical approaches to achieve proliferation risk reduction. \$10 million is included for this purpose in the FY 2004 AFCI program recommendation above.

### ***Effects on the nuclear technology infrastructure***

Reaching the nuclear energy deployment goals set forth in the Action Plan will require the cooperative endeavors of each segment of the nuclear R&D infrastructure and nuclear industry. Industry (reactor vendors, reactor operators and A&E firms), government (the DOE and its National Laboratories), and universities each have important roles to play:

- Industry will have the lead in the Nuclear Power 2010 program and increasingly important roles in Generation IV and AFCI as these programs make the transition from research and development through the demonstration phase to (commercial) deployment.
- The government's role involves undertaking the pre-competitive research and development for Generation IV and AFCI, as well as playing a supporting role in NP 2010, focused upon removing government-created barriers in legislation, assisting in the resolution of generic technical issues, and providing other support consistent with the national interest.
- The university role is that of providing underlying research best suited to their infrastructure and using that research basis to help provide the degreed and graduate professionals to staff industry, government and the National Laboratories. A significant portion of the university programs should be integral to the Generation IV and AFCI.

In this regard, the National Laboratories and universities form part of the underlying infrastructure, which will carry out much of the research and the base technology programs that support technology development. Such an infrastructure would include facilities and capabilities such as irradiation facilities, recycle facilities, fuel fabrication laboratories, flow loops, computation simulation, and other facilities and capabilities.

As part of an effort to implement the recommendations of the Laboratory Directors, it is imperative that the DOE take steps to ensure that the U.S. does not forget what it already knows. Nuclear technology researchers are reaching retirement age at an alarming rate and in many cases are not being replaced. The DOE should support a concerted knowledge preservation effort to ensure that technology developed in the

past is preserved and leveraged in ongoing programs. \$5 million for knowledge preservation and base technology programs is included in the FY 2004 Generation IV program recommendation above.

**Overall Resource Requirements**

To implement the recommendations in the Action Plan, DOE’s investment in nuclear energy R&D and infrastructure should be increased from the present level of about \$152M per year, as follows:

**Table 6.1 – Near-Term Nuclear Energy R&D Funding Recommendations**

	FY 2003 Approp.	FY 2004	FY 2005	FY 2006	FY 2007	FY 2008
DOE Nuclear Energy R&D and Infrastructure Investment	\$152M	\$250M	\$300M	\$350M	\$425M	\$500M

The specific program recommendations for FY 2004 are:

**Table 6.2 – FY 2004 Nuclear Energy R&D Funding Recommendations**

<b>Program</b>	<b>FY 2004 DOE Request</b>	<b>FY 2004 Recommendation</b>
AFCI	\$63M	\$95M
Generation IV	\$10M	\$45M
Nuclear Hydrogen Initiative	\$4M	\$20M
Other NE R&D Programs (including university programs, NERI, Nuclear Power 2010, and other programs)	\$69M	\$90M
<b>TOTAL</b>	<b>\$146M</b>	<b>\$250M</b>

Looking longer term, accomplishing the goals outlined in this Action Plan will require a sustained government commitment totaling less than \$10B. The benefits of this investment to U.S. energy security, environmental quality, and national security are substantial. The opportunity that this activity represents to provide for sustainable world peace, freedom from the threat of global conflicts over energy supplies and the proliferation of nuclear weapons, prosperity for the world’s peoples deriving from abundant and affordable energy supplies, and protection of the global environment with clean, emissions-free nuclear energy, constitutes a legacy of leadership fully befitting the United States of America.

## 7. Summary

The Laboratory Directors' Action Plan builds on the recommendations of their July 2002 letter by setting three challenging goals and associated objectives and enabling actions. The following summarizes the goals, objectives, and enabling actions, as well as the estimated total cost and potential benefits.

*Goal #1: Reduce air pollution and global climate risk and improve energy security by meeting an increasing fraction of future U.S. and world energy needs through safe and economic nuclear energy solutions*

*Objective:* 50 percent of US electricity and 25 percent of U.S. transportation fuels produced by nuclear energy by 2050

Enabling Actions – to achieve this objective requires that new nuclear plants be built in the U.S. in the near-term, advanced technologies for the nuclear production of hydrogen be developed and demonstrated in a timeframe that supports the Administration's goals for the FreedomCAR program, and improved waste management options be available to manage the spent fuel generated by new nuclear plants. Specific actions needed to meet the objective include:

- As envisioned by the Administration's National Hydrogen Energy Roadmap, undertake R&D to develop a hydrogen fuel system including production, storage, distribution and use
- Commit in 2004 to build a gas-cooled reactor to demonstrate nuclear-hydrogen and electricity production, and complete construction by 2010-2012
- Demonstrate advanced nuclear-hydrogen production process technology (in a non-nuclear facility) by 2006, to support the gas-cooled reactor project
- Enable industry to place an order for at least one new nuclear power plant by 2008
- Build a next-generation, fast-spectrum liquid metal-cooled nuclear power plant in the U.S. by 2020, for the purpose of electricity production and nuclear materials management

Estimated Cost: \$5B

*Objective:* Cooperatively develop internationally deployable systems to enable 10 to 15 percent of world energy to be produced by nuclear means by 2050 (with systems that are proliferation-resistant, economic, safe, sustainable, and physically protected)

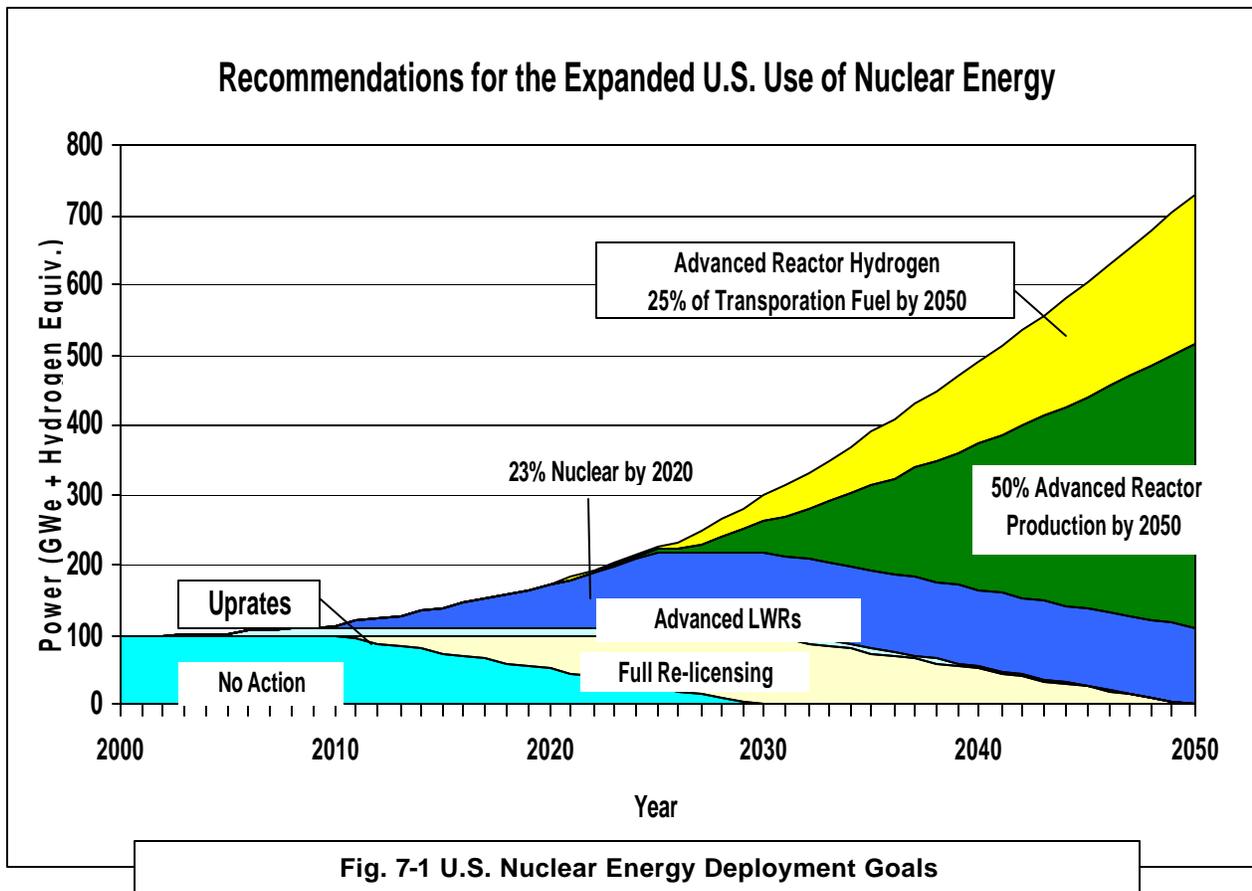
Enabling Actions:

- Develop international cooperative programs by 2005 to allow increased international deployment of nuclear systems
- Strive to implement a U.S.-Russian agreement for cooperative research consistent with the commitment from the Bush-Putin summit.
- Work with international partners to jointly build a next-generation nuclear power plant abroad by 2025

Estimated Cost: \$0.5B for initial technology development support

Achieving this goal will have the benefits of:

- Reducing U.S. carbon dioxide emissions by 3 billion metric tons per year and world carbon emissions by up to 6 billion metric tons per year by 2050,
- Enhancing energy security by replacing oil with nuclear-generated hydrogen for transportation use. This will reduce U.S. oil consumption by 2 billion barrels per year and world consumption by up to 3 billion barrels per year by 2050,
- Rejuvenating the U.S. nuclear infrastructure, and
- Advancing U.S. leadership in nuclear technology and providing significant commercial opportunities for U.S. industry



*Goal #2: Achieve a 90% reduction of reactor waste requiring repository disposal by 2050 by significantly reducing the amount of uranium, plutonium, and minor actinides in disposed waste*

*Objective:* Demonstrate a closed fuel cycle technology system by 2020

Enabling Actions – demonstration of a closed fuel cycle system requires that research conducted under the AFCI program be accelerated, to support construction of key facilities needed to demonstrate closed fuel cycle concepts. Specific actions needed to meet this objective include:

- Build a pilot facility to demonstrate advanced technology for partitioning waste and recycle by 2010
- Build a pilot fuel supply and testing facility by 2010
- Demonstrate actinide burning in an advanced system by 2020

Estimated Cost: \$2B

Achieving this goal will have the benefits of:

- Eliminating the technical need for a second repository in this century,
- Compared with the once-through fuel cycle, achieving a 50 percent reduction of plutonium inventories in U.S. used fuel, and
- Enabling the technology to sustain the nuclear energy fuel supply for centuries

**Goal #3: While expanding the use of nuclear technology world wide, reduce the threat of nuclear weapons proliferation**

**Objective:** By 2020, demonstrate a global nuclear energy technology system consisting of intrinsic and extrinsic safeguards that minimizes proliferation risk

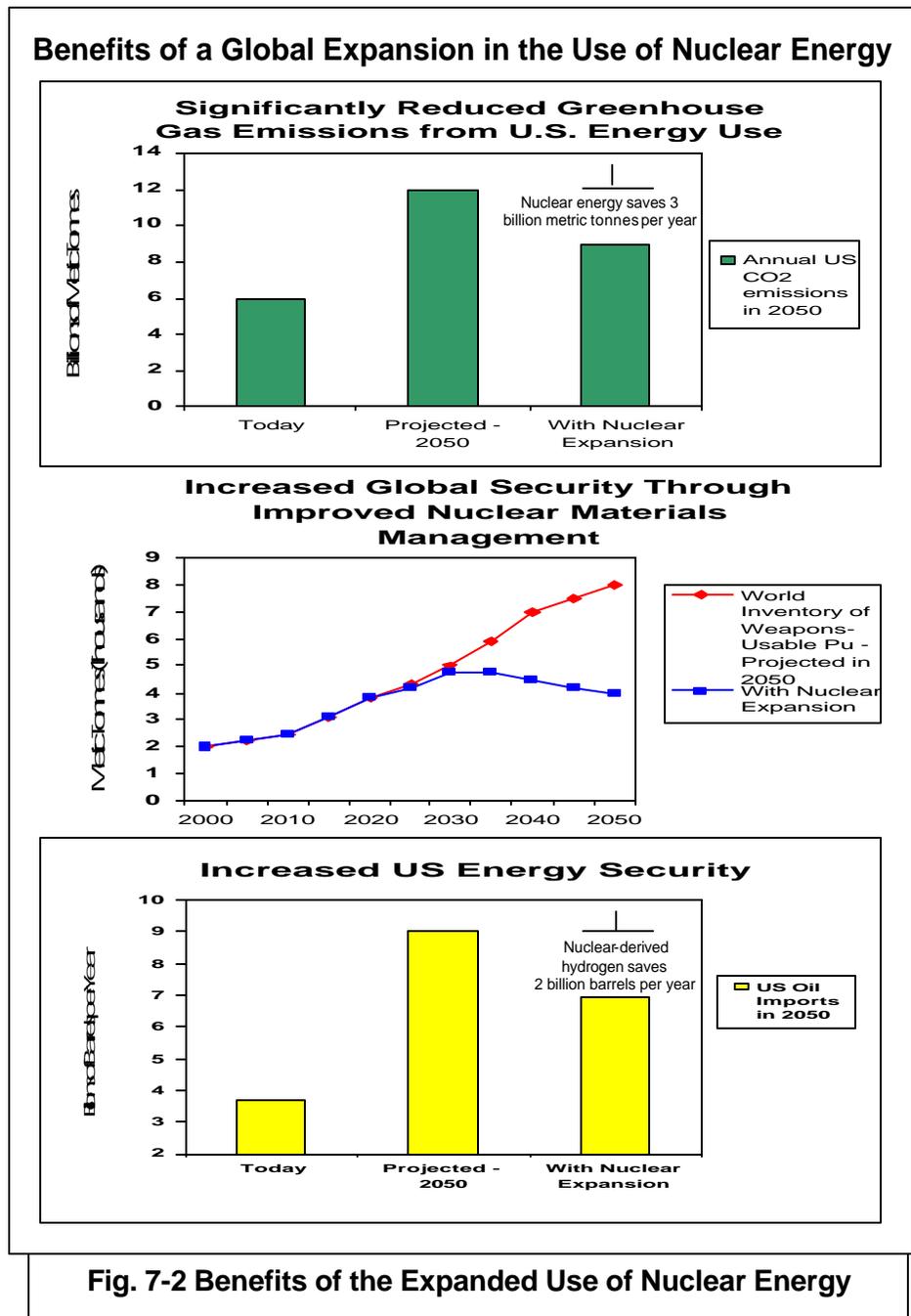
Enabling Actions – meeting this objective requires that the U.S. exert its leadership in the development of new nuclear energy systems, including both reactors and fuel cycles, and that as part of this effort the U.S. lead the way in first quantifying and then addressing the proliferation risk posed by various elements of the nuclear fuel cycle. Specific actions needed for the U.S. to exert this leadership include:

- Develop and sustain an analytical framework and standards for quantifying integrated proliferation risk by 2005
- Accelerated development of affordable technologies and multilateral transparency systems from cradle to grave with an integrated demo by 2008
- Recommend an international framework for implementing sustainable global management of nuclear materials and services by 2008

Estimated Cost: \$1B

Achieving this goal will have the benefits of:

- Establishing U.S. approaches and technology as world standards for proliferation resistance by 2015, and
- Enabling the elimination of 50 percent of the world stock of weapons-capable plutonium by 2035



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