ADVANCED NUCLEAR ENERGY SYSTEM FOR THE TWENTY-FIRST CENTURY

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ABSTRACT

The world needs more energy to improve standards of living and sustain the growing economies. To contribute its share of the future energy demand, an advanced nuclear energy system for the 21st century must effectively manage all of its own waste, be highly proliferation-resistant, provide energy safely, be sustainable, and be economically competitive. One advanced concept that can meet all these requirements simultaneously is a fast reactor system with a closed fuel cycle based on pyroprocessing. Now is a critical time to develop and demonstrate such an advanced nuclear energy system.

1. INTRODUCTION

If the majority of the world's population is to enjoy a comfortable living standard in the 21st century, a substantial energy supply expansion will be required to fuel the necessary economic growth. Currently, some 85% of the world's primary energy comes from carbon-based fuels. Oil, the most versatile fossil fuel, is expected to reach a production peak that cannot be sustained after mid-century. Natural gas supplies are ample for now, but unevenly distributed. Coal is abundant, but may present insurmountable pollution problems. Even in the absence of resource restraints, maintaining fossil's share of world energy production during a century of rapid expansion would be a recipe for long-term environmental damage with significant economic impacts, unless there are breakthroughs in pollution control and carbon sequestration.

It is clear that we must move toward carbon-free sources of energy. Controlled nuclear fusion may be an energy supply for the distant future. Fusion is a fundamental process in the formation of the universe, but trying to harness it for electricity production has been a major scientific challenge for more than 50 years and remains so today. In spite of the distant time horizon, there is a relatively broad level of support for continuation of fusion research and development—in part due to significant technical progress that has been achieved, but mainly due to the enormous potential payoff of an unlimited energy source.

The other choices for expanding non-carbon emitting energy supply are renewables and nuclear. Renewable energy sources—hydroelectric, solar, wind, geothermal, and biomass—must be fully exploited in an expanding global economy, particularly if carbon emissions are to be controlled.

Hydroelectric is the largest contributor of the modern renewables, supplying almost 7% of total energy. However, hydroelectric energy has limited growth potential because of its impacts on land, population, and river ecology. Geothermal energy is restricted in availability because of limited accessibility to geothermal resources. The other options rely on commitment of large land areas and other resources for biomass production, windmills or solar collectors, even to match the output of one base-loaded power plant. Because of these inherent limitations, the renewables other than hydroelectric contribute only about 1% of energy today. Even with aggressive expansion, their contribution could not exceed 15% of the total energy production within 50 years.

The remaining proven carbon emission-free technology capable of large-scale energy production and long-term growth is nuclear energy. Today, nuclear energy contributes almost 20% of the electrical energy around the world. The need to reduce CO_2 emissions means that the fraction of nuclear electricity must grow much larger. The move toward electric cars means a large increase in electricity demand which must be largely supplied by nuclear energy. The conclusion is that it is very likely that we will see a rapid expansion of nuclear power for environmental, economic, and security reasons. Over the past decade, nuclear plants have improved their operational reliability, safety records, and economic competitiveness. However, nuclear energy faces challenges and some crucial questions require answers before a second nuclear era can contribute significantly toward the energy needs of the 21st century.

2. CHALLENGES FOR NUCLEAR ENERGY

There are two issues that must be dealt with promptly: developing a technical solution to the problem of disposition of the nuclear waste that is accumulating at nuclear plants around the world; and improving the international control of materials that could be used in nuclear explosives. In the longer term, expansion of nuclear as a primary energy source is necessary if worldwide economic expansion is to be accommodated, while reducing the emission of carbon compounds that could result in global climate change. Our ability to achieve the longer-term goals depends crucially on near-term activities to begin laying the foundation for the massive infrastructure that will be required for a sustainable large-scale nuclear supply system. Achieving the longer-term goal for nuclear energy will also require successful resolution of three additional issues: maintaining the high level of nuclear power plant safety as more plants are installed, extending uranium resources so that energy potential is not limited by resources availability; and achieving economic competitiveness with other electricity production options. These challenges must be addressed in today's context, as well as that of the near-term and the second half of the century.

2.1 EFFECTIVELY MANAGING NUCLEAR WASTE

When spent fuel is discharged, approximately 95% of the original uranium remains. The other 5% has been transmuted to fission products and elements that are heavier than uranium, commonly called "actinides" in this context. Technically, the most logical approach would be to package only the fission products for permanent disposal in a sturdy waste form designed to minimize release of radioactivity, saving the uranium and actinides for recycle. In particular, recycling of actinides would greatly simplify repository requirements for two principal reasons.

The first reason is that removing actinides from the repository would be a reduction in long-term toxicity due to radioactivity of the waste. The interesting comparison is to the radiotoxicity of natural uranium ore. If all of the heavy elements were removed, the remaining nuclear waste would be less radiotoxic than uranium ore after several hundred years, as illustrated in Figure 1. The spent fuel, including the heavy elements, remains more radiotoxic than uranium ore for some hundred thousand years.

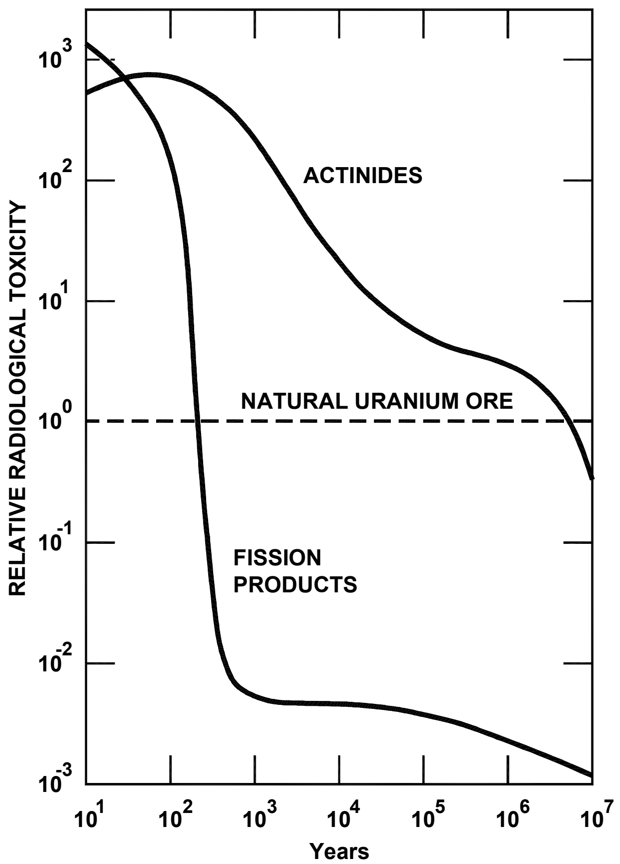

Figure 1. Potential radiological toxicity of spent fuel.

The second reason is that the amount of nuclear waste that can be emplaced into a given repository area depends primarily on its heat generation. Initially, intense heat is produced by radioactive decay of the fission products. But the fission products lose most of their radioactivity relatively quickly, as illustrated in Figure 2. After a few decades, the rate of heat production is controlled by decay of the actinides. Some of these elements remain radioactive for hundreds of thousands of years. Removing the uranium and actinides prior to placing the high-level waste in a repository could greatly simplify the repository thermal design and the capacity can be increased substantially.

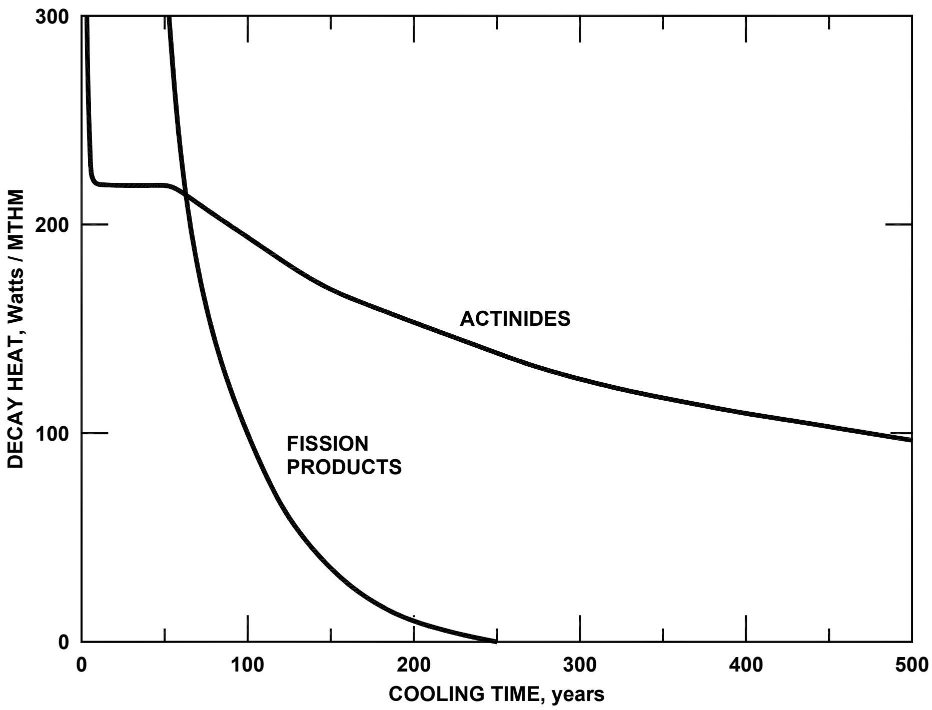

Figure 2. LWR spent fuel decay heat as a function of cooling time.

Even if all actinides were removed from spent fuel, the repository would still be necessary. While the radiotoxicity in nuclear waste could be reduced to less than that of the original uranium ore after a few hundred years, it is still necessary to confine that waste under ground. There are a few long-lived fission products such as ^{129}I, ^{99}Tc, and ^{135}Cs which should be geologically isolated from the biosphere. Further, tiny fractions of the actinides will slip through the recycling process, no matter how efficient it is, requiring long-term geologic isolation.

2.2 CONTROLLING NUCLEAR PROLIFERATION

Since the dawn of the atomic age, governments have wrestled with how to spread the benefits of peaceful nuclear energy while controlling nuclear weapons proliferation. The key to a successful nuclear nonproliferation regime has been and continues to be establishing barriers that prevent access to the materials that can be used in constructing nuclear explosives—highly-enriched uranium and plutonium. Strengthening the international safeguards regime—consisting of international treaties, safeguards systems, independent inspections and monitoring—is the most effective way to deal with national proliferation threats.

The more enduring issue is how to manage the civilian nuclear fuel cycle going forward. Many nonproliferation experts have favored maintaining the once-through fuel cycle for as long as practical, both because of its current economic advantage and because unit accountability of every nuclear fuel assembly provides a reassuring level of international transparency. Given the fact that a closed fuel cycle is essential for the future, then there is a strong incentive to develop proliferation-resistant reprocessing technologies. Such alternative technologies should provide intrinsic barriers, in which the properties of materials, processes and facilities make them proliferation-resistant.

The more important issue in the long term is how to manage the plutonium economy. Plutonium is an integral part of nuclear energy. Fresh commercial reactor fuel contains only uranium, but some 45% of energy is generated by fissioning plutonium that is transmuted from uranium in situ. Each metric ton of commercial spent fuel contains about 10 kg of actinides. Operating reactors around the world discharge more than 70 tons of actinides annually. Ultimately, the best solution for maintaining the inaccessibility of the plutonium is to employ a closed fuel cycle in which actinides are recycled and burned up in the reactor. In a closed fuel cycle, plutonium is contained in safeguarded reactors and fuel cycle facilities; the total amount can be reduced through fission to generate energy. In a once-through cycle, the plutonium is dispersed in many storage locations and the total amounts grow continuously. Furthermore, a total integral system that collocates the reactor plant with its fuel cycle facility is highly desirable in order to eliminate the transportation of spent fuel and freshly fabricated fuel.

2.3 ASSURING CONTINUED NUCLEAR SAFETY

The current generation of nuclear power plants relies on highly engineered, reliable automated safety systems as the ultimate protection against an accident. At least three physical containment barriers are maintained between the radioactive fuel and the environment. In the event of a severe accident, these multiple barriers can be very effective in protecting the public, as the Three Mile Island event proved. But the first line of defense is excellence in reactor operations and technologies that help the highly trained crews maintain the reactor within safe limits. In spite of nuclear energy's current safety status, many people believe that safety improvements will be required if the world's installed capacity is to be increased significantly.

The next generation of reactors should incorporate more passive safety features, i.e., design features that protect the plant from damage even in the event of both human effort and failure of one or more of the active safety systems. Passive safety design relies on the laws of nature to ensure the performance of the essential functions of reactor safety: maintaining heat generation and heat removal in proper balance, removal of decay heat and containment of radioactive materials.

The nuclear industry recognizes the importance of passive safety in protecting the investment in the plants. Passive safety features are included in the designs of the current advanced light water reactors, and some of these features have been individually tested in separate experiments. Virtually all new design concepts incorporate some passive safety features, so that regardless of the brand or type of reactor ordered next, passive safety will begin to be introduced into the fleet of nuclear power plants.

2.4 LONG-TERM SUSTAINABILITY

The current generation of nuclear power plants and the new designs that are ready to be commercialized in the next few decades do not have the fuel utilization characteristics to make them sustainable in an expanding energy supply scenario. These reactors can extract less than 1% of the energy in the uranium that is mined for eventual use in their fuel. Although many design improvements have been made in the past 40 years and many more may be possible, this fact of nature cannot be changed.

While sustainability alone is not an urgent driving force for an advanced reactor development program today, sustainability should be one of the primary considerations when choosing between technologies that are capable of doing other jobs. In particular, approximately one-third of the world's energy production is for transportation, currently an exclusive province of fossil fuels. Hydrogen is being proposed as an alternative fuel for transportation and other uses. Since hydrogen produces only water vapor when it burns, there are no serious direct environmental impacts from its use. However, hydrogen is not a primary fuel. It must be manufactured by electrolysis, i.e., using an electric current to decompose water, or by a more efficient, high-temperature thermochemical process. If hydrogen is manufactured by consuming fossil fuels to power thermochemical processing plants, little environmental benefit will be realized. Nuclear-generated electricity or process heat could make a major contribution to hydrogen production.

2.5 OVERCOMING ECONOMIC CHALLENGES

Historically, electric utility companies were expected to carry the substantial debt that went with building capital-intensive base load generating stations that had long operational lifetimes. During construction of the current nuclear power plants, regulatory-mandated changes and other problems stretched the construction time of some U.S. nuclear plants from an expected five years to much longer period so the cost of servicing this debt dramatically increased the total plant cost. Even if the capital cost and the construction schedule are reliably predictable, today's deregulated electricity marketplace places the financial risk of new construction with the utility companies and the time required to construct a new plant is too long to respond to short-term changes in market conditions.

More favorable government policies and regulatory climate are required to entice new plant orders so that the society can benefit from the low generation cost levelized over the plant lifetime. For advanced reactor systems, additional economic benefits can be realized through the avoidance of higher-cost category uranium resources and reduced environmental burdens associated with waste disposal.

3. ADVANCED REACTOR AND FUEL CYCLE CONCEPT FOR THE 21ST CENTURY

There is a growing international consensus that the five requirements discussed above are what the next-generation advanced nuclear system must meet to be broadly acceptable for the 21st century and beyond, namely:

- Reduce the volume and long-term toxicity of nuclear waste.
- Enhance proliferation-resistance of the fuel cycle and keep nuclear materials unsuitable for direct use in weapons.
- Improve safety based on characteristics inherent in the reactor design and materials.

X Provide a long-term energy source not limited by resource constraints so that nuclear can make significant impact on reducing greenhouse gases..
X Be economically competitive with other electricity sources.

The only concept we know of that can meet all five requirements simultaneously is a fast reactor system with a closed fuel cycle based on pyroprocessing. The pyroprocessing developed and demonstrated at Argonne National Laboratory is a key innovation in fuel cycle technology, which promises revolutionary improvements in waste management, nonproliferation characteristics and economics. A simplified pyroprocessing flowsheet is illustrated in Figure 3.

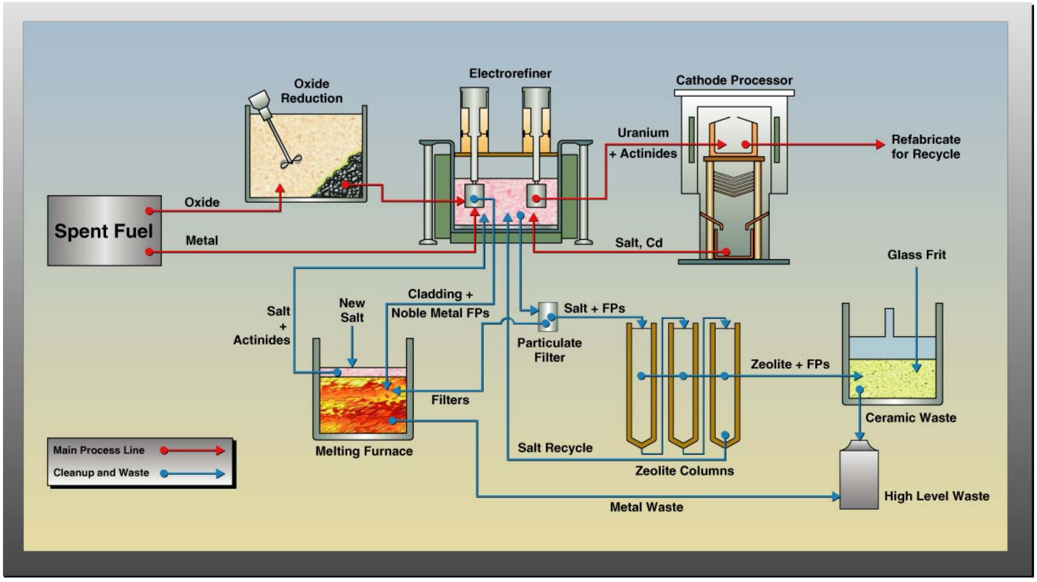

Figure 3. Pyprocessing flowsheet.

The key element of pyroprocessing is electrorefining. Spent fuel rods chopped into small pieces are loaded in the anode basket. Electrotransport takes place in an electrolyte of LiCl-KCl at 500°C. One type of cathode recovers uranium and the second cathode recovers all other actinide elements together: Pu, Np, Am, Cm, and some uranium. The anode basket that contains cladding hulls and noble metal fission products is melted to a metallic high-level waste form. Electrolyte salts that contain most of the fission products are passed through zeolite columns in which fission products are immobilized into the zeolite molecular structure through ion exchange and occlusion. The zeolite powder is then mixed with glass frits and melted at high temperature to form a ceramic waste form, called sodalite.

Pyroprocessing was originally developed for the fast reactor application, but it could treat spent fuel from today's commercial reactors with the addition of a front-end step to convert the oxide to metal. In pyroprocessing, the actinides are easily recovered and recycled back into the reactor for fissioning. Pyroprocessing also eliminates the ability to use the reactor's nuclear materials directly in weapons because it cannot separate pure enough Pu. Instead, it keeps the major nuclear fuels, uranium and Pu, mixed at all times with other actinides and fission products. This mixture is protected against theft or unauthorized diversion because the mixture is extremely radioactive and must be handled remotely with sophisticated and specialized equipment. Pyroprocessing involves compact equipment systems and the fuel cycle facility can easily be collocated with the reactor plant, eliminating the need for nuclear fuel transportation.

The waste reduction and nonproliferation benefits of pyroprocessing were recognized by the National Energy Policy, approved by President Bush in May 2001, which recommended:

> *"in the context of developing advanced nuclear 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. In doing so, the United States will continue to discourage the accumulation of separated plutonium, worldwide."*

> *"The United States should also consider technologies, in collaboration with international partners with highly developed fuel cycles and record of close cooperation, to develop reprocessing and fuel treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation-resistant."*

In order to realize the benefit of actinide removal in waste management, the actinides ultimately have to be recycled as fuel in reactors, where they are beneficially destroyed by fissioning. Fast reactors are ideally suited for burning actinides because actinides can be completely fissioned in a fast spectrum, whereas only limited amounts can be fissioned in a thermal spectrum.

In a thermal spectrum, the higher actinide elements act as poison. Therefore, only about one-third of the original actinides can be fissioned before an inherent reactivity limit is reached. To overcome this inherent reactivity constraint, a heavier loading of actinides can be envisioned. However, this results in a fast spectrum and an unfavorable coolant void reactivity, as illustrated Figure 4. Of course, actinides can be fissioned in a thermal spectrum if the reactivity deficiency is made up by fueling with ^{235}U or Pu. This simply delays the ultimate limit further into the future. In practical terms, Pu or actinide utilization in thermal spectrum reactors can be sustained for decades, but eventually fast spectrum reactors are required for a full utilization of actinides.

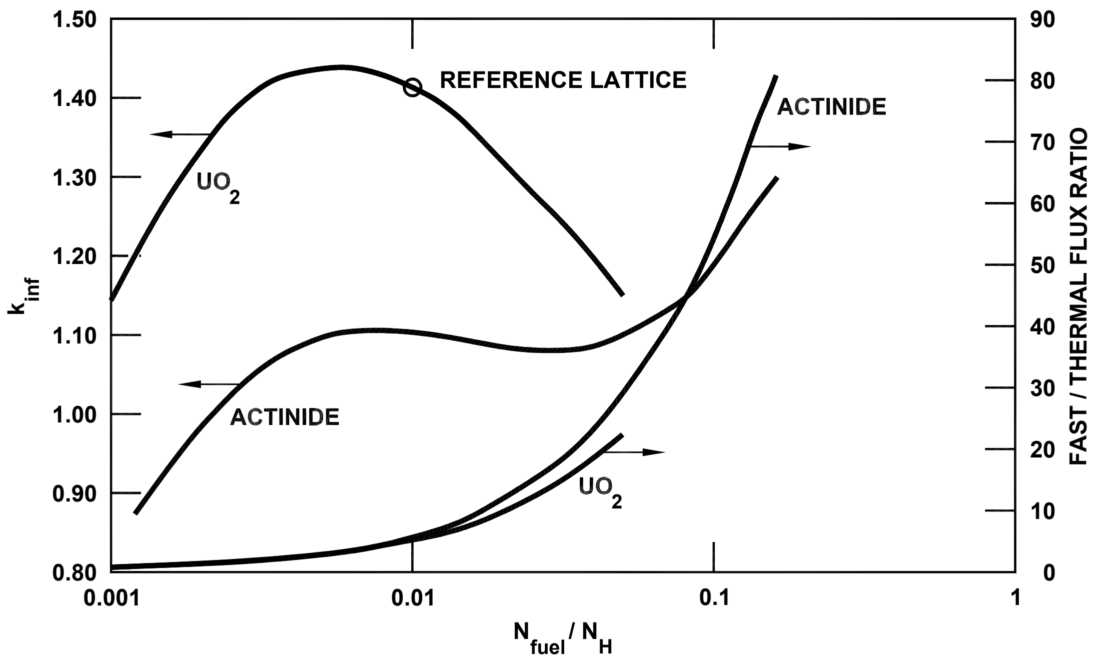

Figure 4. Spectral behavior of UO_2 and actinide fueled LWR lattices.

Today's commercial reactors burn less than 1% of natural uranium, whereas fast reactors can utilize essentially all uranium resources, hence, extending the energy potential by a factor of 100. This enormous increase in the efficiency of resource utilization means that fast reactors combined with advanced fuel cycle are a sustainable long-term energy source to meet the demands of an expanding economy.

Fast reactors can incorporate key design features that lead to an improved level of passive safety, that is, safety would be inherent in its design and materials and not solely dependent on engineered safety systems nor operator actions. A fast reactor, especially fueled with metallic fuel, can be designed for such a passive safety, and this was demonstrated in two landmark tests conducted in EBR-II in 1986.

The tests demonstrated that even most severe accidents would not damage the reactor or release radioactive material. In one test, the power was shut off to the pumps that circulate coolant through the core, and in the other, all heat removal was cut off. In both tests, the reactor safely shut itself down without human or mechanical intervention. The passive safety characteristic is uniquely achieved in the metallic-fueled fast reactor because of a combination of three factors: sodium coolant with a very high boiling temperature, pool design configuration providing thermal inertia, and metal fuel with a small Doppler reactivity effect.

The outstanding record of the EBR-II operation over 30 years demonstrated the advantages of a fast reactor system with sodium cooling. Because the sodium boiling temperature is very high, the cooling system can operate at essentially atmospheric pressure. Sodium is also noncorrosive to structural materials used in the reactor. These unique characteristics of a sodium-cooled system result in superior reliability, operability, maintainability and long lifetime, all of which contribute to low life-cycle costs. For example, the EBR-II steam generators had operated over 30 years without a single tube leak, and after draining of the primary sodium, the original "fit-up" chalk markings were still clearly legible on the reactor vessel wall.

4. THE CURRENT STATUS AND THE FUTURE

Much of the pyroprocessing technology was successfully demonstrated at Argonne-West as part of the three year (between 1997 and 2000) demonstration project treating 100 EBR-II driver fuel assemblies and 18 blanket assemblies. A special committee of the National Academy of Sciences found that this demonstration project met all criteria for success, and the Department of Energy followed with a formal decision to use this technology to treat the remaining 25 metric tons of EBR-II spent fuel. Going beyond EBR-II spent fuel treatment, a full pyroprocessing demonstration could be accomplished using Argonne-West's existing facilities shown in Figure 5. This would include recovery of actinides, qualification of waste forms, and enough production capacity to show that it can work on a commercial scale. It would also demonstrate the conversion of commercial oxide fuels to the metallic form and the ability of compact metal and ceramic forms to safely contain short-lived wastes. A logical next step would be a commercial-scale prototype fuel cycle facility that can process 100 metric tons of LWR spent fuel per year.

There have been over a dozen fast reactors operated around the world. However, we still need a commercial-scale fast reactor demonstration project. It should be established based on the results of an international collaboration. International collaboration will facilitate incorporation of the lessons learned in fast reactor operating experience around the world, and also development of a consensus on the technology of choice. A continued and enhanced international collaboration will be essential to successful demonstration and deployment of the advanced fast reactor system to meet the challenges of the 21st century.

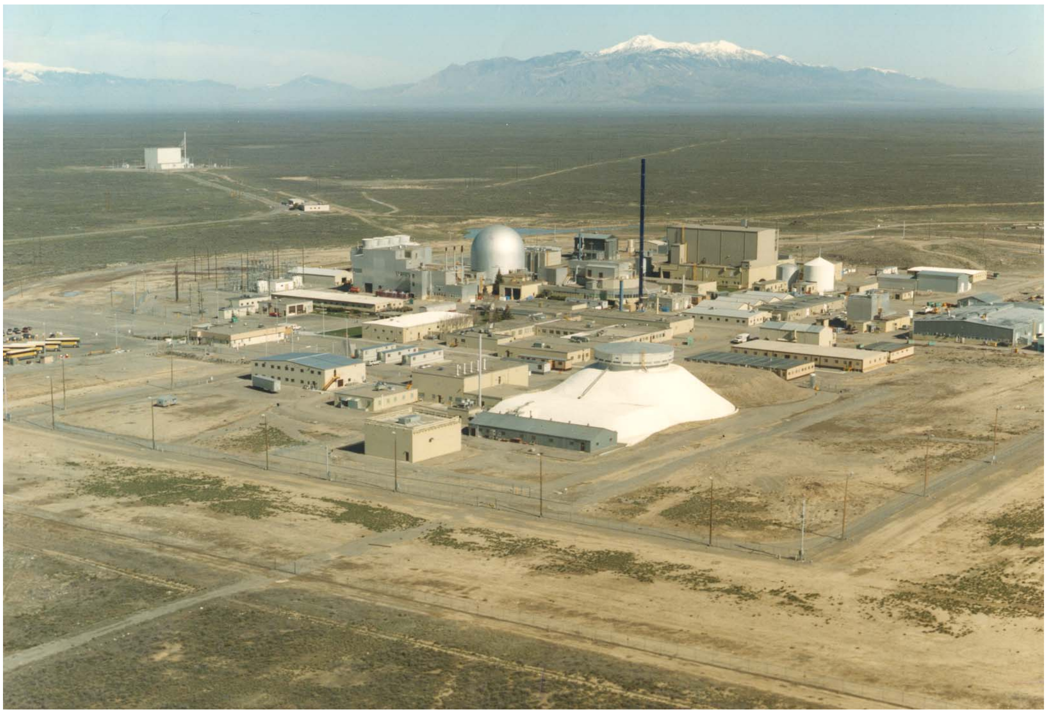

Figure 5. Argonne-West nuclear facilities.