Clean Energy Technologies

7. Nuclear

7.1 Lifetime Extension and Generation Optimization

7.2 Next-generation Fission Reactors

7.3 Fusion Power

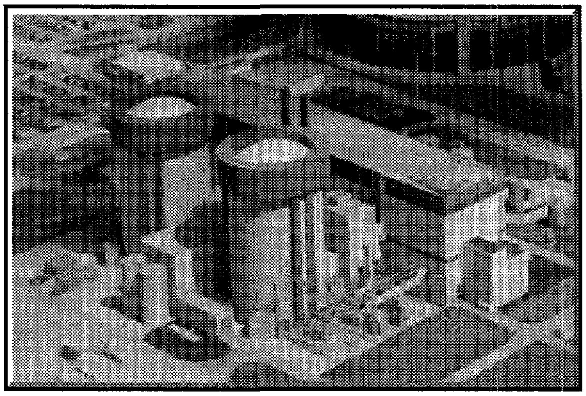
7.1 LIFETIME EXTENSION AND GENERATION OPTIMIZATION

Technology Description

Currently, 107 privately-owned nuclear power plants generate nearly 21% of U.S. electricity (about 100 GWe installed capacity). Nuclear power plants emit negligible GHGs during operation. Technology can be applied to nuclear and nonnuclear equipment in existing plants to enable them to produce more electricity during their operating lifetimes (generation optimization.). The operating lifetimes of existing plants also can be extended safely. Most nuclear power plant licenses will expire between 2005 and 2030. If these plants are shut down and replaced with fossil-based generation, CO_2 emissions will *increase* by >100 million MtC/year by 2030 (at 160 g C/kW- h). Extending the lifetimes and optimizing the generation of these plants for 20 years will avoid 1.4 billion MtC.

System Concepts

- Improve availability and maintainability of nuclear plants.
- Provide technology to predict and measure the extent of materials damage from plant aging and to repair or replace damaged components.
- Operate plants at higher power levels based on more accurate measurement and knowledge of safety margins and reduced consumption of on-site electrical power.
- Develop high-burnup fuel for longer fuel cycles and up to 5% higher energy output.



Representative Technologies

- In situ component and vessel annealing, prediction and monitoring of stress corrosion cracking of reactor internals and steam generators, materials cladding processes
- Advanced technologies for on-line condition monitoring of cables and conventional equipment (pumps, motors, valves, etc.) to minimize production losses from unplanned outages
- Replacing aging, hard-to-maintain safety system electronic components with easy-to-maintain advanced electronics
- Materials measurement and diagnostic technologies to determine the condition and fitness of aged materials
- Cost-effective materials and systems repair technologies
- Advanced core loading strategies; nuclear fuel and cladding research

Technology Status/Applications

- Current technology does not adequately determine residual life; overly conservative margins may result in premature shutdown or refurbishment.
- Replacing major components (e.g., steam generators) may be prohibitively expensive; better techniques are needed.
- Some in-service valve testing technology is in place, but current technology fails to detect a significant number of failures.
- Condition monitoring technology has been developed in DOE/EE Motor Challenge Program and for DOE/DP. Advanced electronics technologies have been developed for high energy physics programs. Development is required for application to nuclear plants.

Current Research, Development, and Demonstration

RD&D Goals

- By 2001, provide technologies that can improve the average capacity factor of nuclear power plants to 86%.
- By 2003, provide technologies to measure, diagnose, and repair effects of aging on plant materials, components, and systems, and develop and demonstrate technologies to reduce the regulatory uncertainties of life extension of plants.

RD&D Challenges

- Successful introduction of technologies that are cost-effective and acceptable to regulators
- Reliable operation of sensors in harsh environments

RD&D Activities

- A previous CRADA between DOE/NE and EPRI started development of advanced electronics to replace Westinghouse safety system components.
- Condition monitoring R&D supported by DOE/NE, DOE/EE, DOE/DP, and NRC is providing a relevant technology base.
- There is no current DOE funding for application of advanced technologies to existing LWRs or for aging research.
- NRC sponsors about $16M of research related to materials aging.

Recent Success

- Initial industry decision to commercialize DOE electronics technology for replacing Westinghouse safety system components.
- Nonintrusive evaluation of PWR accumulator discharge check valves has reduced testing time and improved reliability.
- Demonstration of gas-fired thermal annealing of Marble Hill reactor pressure vessel completed in 1996.
- Use of hydrogen water chemistry in BWRs to control stress corrosion cracking.

Commercialization and Deployment

- Advanced diagnostic techniques are gaining wider acceptance for evaluating the status of safety-related equipment.
- Successful technology may not be sufficient to extend the life of all plants if adverse regulatory or economic factors dominate.
- DOE/EPRI Sustainable Electric Partnership Agreement provides a basis for DOE/industry cooperation and ensures commercial deployment.
- Technology to support plant license renewal needs to be available in the next 5 years to support initial license renewal submittals to NRC.

Potential Benefits and Costs

Carbon Reductions

- 20-year life extension and generation optimization of part or all of existing 100 GWe installed nuclear capacity reduces carbon emissions by

2010	2020	2030
0–15 MtC/year	20–60 MtC/year	60–110 MtC/year

- Carbon emission avoidance from 1996 to 2030 could exceed 1400 MtC

RD&D Expenditures

- Annual federal RD&D budget required for this pathway: to 2010, $30M to $40M/year; beyond 2010, no additional RD&D funds required.

Market

- Indeterminant at this time. Improved operations and life extension could improve the economics of existing nuclear power plants and thus enhance their market acceptance.

Nonenergy Benefits and Costs

- Improves reactor safety because of improved component reliability and better information on component conditions.
- Reduces worker exposures to radiation as a result of shorter maintenance durations.
- Improved U.S. energy security and retention of U.S. nuclear infrastructure, international nuclear influence, and U.S. export potential.

Risk Factors

Technical Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Technologies require engineering development.

Commercial Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

- Technologies must provide cost incentives for industry.
- Regulatory acceptance is issue.

Ecological Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

- Reduced wastes and emissions per unit of nuclear energy generated are expected.

Human Health Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

- Reduced worker exposure to radiation per unit of nuclear energy generated is expected.

Economic Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

- Very high return on investment.

Regulatory Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low — High

- Required NRC approval and lack of demonstration of nuclear plant license renewal.

Key Federal Actions

- Initiate R&D program for research on existing nuclear plant life extension and generation optimization technologies.
- Continue U.S. support for improved nuclear safety in former Soviet countries to reduce the risk of another major nuclear accident.
- Maintain a healthy U.S. nuclear-energy technology and education infrastructure.

7.2 NEXT-GENERATION FISSION REACTORS

Technology Description

A new generation of fission reactors is required to replace or to provide extended capacity for existing LWRs in 2020 and beyond. Evolutionary LWRs of standardized design are available and have received NRC licensing certification. These reactors have been constructed (on schedule) in Japan and South Korea. Advanced LWRs of simplified design and with safety performance based on passive inherent processes are at a late stage of detailed design and NRC review. In the long term, reactors and fuel cycles that are more proliferation-resistant, produce less nuclear waste, and make better use of the energy content in uranium need to be developed.

System Concepts

- Evolutionary and advanced LWR designs: simple, rugged high-design margin, based on proven technologies. Approximately 1300 MWe (evolutionary) and 600 MWe (passively safe), with a design life of 60 years.
- Advanced fission reactors and fuel cycles: concepts that aim to extract the full energy potential of the spent fuel from current generation reactors, while reducing or eliminating potential for proliferation of nuclear materials and technologies and limiting the amount of waste produced.

Representative Technologies

- Advanced PWR reactor system 80+
- Advanced BWR
- Advanced PWR AP600
- Liquid metal reactors
- High-temperature gas-cooled reactors
- Thorium cycle nuclear systems
- Long-life reactors

Technology Status/Applications

- Several evolutionary fission reactors, including the advanced PWR system 80+ and advanced BWRs, have received NRC design certification and are offered for sale. In addition, the advanced LWR AP600 is expected to receive final design approval and design certification soon.
- Advanced reactors and fuel cycles: development is at advanced stage; demonstration is incomplete.
— High-temperature gas-cooled reactor development is focused on high conversion efficiency through direct use of the high-temperature gaseous reactor coolant to power a gas turbine driving a generator (i.e., direct conversion).
— Advanced fuel cycle development has reached pilot demonstration stage in some cases.

Current Research, Development, and Demonstration

RD&D Goals

- Advanced LWRs are available for construction.
- Future federal research should focus on reactors and fuel cycles that are more proliferation-resistant, produce less nuclear waste, and make better use of the energy content in uranium.

RD&D Challenges

- None for advanced LWRs.
- Demonstrate technology for advanced concepts.
— Develop proliferation-resistant fuel cycle concepts.
— Develop safety, waste, and proliferation aspects of advanced fission reactors.

RD&D Activities

- Federally funded development of advanced reactors and fuel cycles has been terminated in the United States.
- Mixed oxide fuel for excess weapons plutonium disposition.
- Treatment of selected spent nuclear fuel for waste disposal.
- There is no federal RD&D budget for reactor development.

Recent Success

- Advanced LWRs have received design certification from NRC.
- An advanced BWR is operating in Japan, having been built in less than 5 years.

Commercialization and Deployment

- Advanced LWRs are being developed overseas. Two advanced BWRs are operating in Japan, a system 80+ is under construction in Korea, and two advanced BWRs have been ordered by Taiwan.
- None are foreseen for the United States in the immediate future under present conditions.
- Carbon taxes or other incentives will make advanced LWRs cost competitive.

Potential Benefits and Costs

Carbon Reductions

- Estimated carbon emissions reductions are as follows:

2010	2020	2030
0	~10 MtC/year	10 to 40 MtC/year

RD&D Expenditures

- Little or no funding needed for current generation advanced LWRs.
- Annual federal RD&D budget required for this pathway: to 2010, $50/M/year; 2010 to 2020, $100M/year; 2020 to 2030, $150M/year.

Market

- Indeterminant at this time. Potentially large international and domestic markets.

Energy Resources

- With full use of the known U.S. uranium resources, nuclear can supply 65,000 quads.

Nonenergy Benefits and Costs

- Energy security; a reduction in dependence on oil.
- Maintenance of U.S. influence in world nuclear arena, facilitating U.S. policy goals.

Risk Factors

Technical Risk

(1) 2 3 4 5 6 (7) 8 9 10

Low — High

- For advanced ALWRs, the risk is small.
- Advanced fission reactors require large-scale technology demonstration before commercialization in 2030 and beyond.

Commercial Risk

1 2 3 4 (5) 6 7 8 9 10

Low — High

- Nuclear power has a mature infrastructure. Lack of purposeful progress toward a waste repository for the spent fuel is an issue. If no plant is ordered, the United States will eventually lose the capability to construct reactors.

Ecological Risk

1 2 3 (4) 5 6 7 8 9 10

Low — High

- Small.

Human Health Risk

1 2 (3) 4 5 6 7 8 9 10

Low — High

- Small.

Economic Risk

1 2 3 4 (5) 6 7 8 (9) 10

Low — High

- Moderate for advanced ALWRs because of the economic effects of deregulation and political opposition.
- High for other reactors.

Regulatory Risk

(1) 2 3 4 (5) 6 7 8 9 10

Low — High

- Low for the advanced ALWRs given NRC design certification.
- Moderate due to required NRC approval and need for demonstration.

Key Federal Actions

- Achieve purposeful progress toward the creation and licensing of a repository for spent nuclear fuel.
- Restart R&D on advanced fission reactor concepts, possibly using international collaboration.

7.3 FUSION POWER

Technology Description

Particle inertia or magnetic fields are used to confine a hot plasma to produce energy from deuterium/tritium fuel. Deuterium is abundantly available from water, and tritium is produced within the fusion plant from abundant lithium. The energy of the fusion reactions is used to generate electricity at central power plants.

System Concepts

- Strong magnetic fields produced by superconducting coils confine plasmas with temperatures of several hundred million degrees Celsius. Some heat from the fusion reactions remains in the fuel to sustain its high temperatures; the rest is carried out by neutrons to be absorbed in a surrounding blanket that serves both as a heat source to produce power and as a medium for producing the tritium.
- Compressed fuel microcapsules ignite and burn, producing repetitive pulses of heat in a reaction chamber. Multiple chambers for each beam can improve efficiency, and flowing liquid metal walls in the chamber can serve as blankets.

Representative Technologies

- Large, high-current density superconducting magnets, ion beams (energies 100–1000 keV), millimeter wave high-power microwaves, high-power radio-frequency sources and launchers, and particle fueling apparatus.
- Heavy and light ion beam accelerators, solid-state and exciter-gas lasers, and target fabrication technologies are required for inertial fusion.
- Structural materials with low activation properties will eventually be required to fulfill the ultimate potential of fusion devices. Tritium generation and heat recovery systems are other common nuclear system technologies required for both.

Technology Status/Applications

- Moderate size fusion experiments in tokamaks, with plasmas at temperatures needed for power plants, have produced more than 10 MW of fusion power.
- A commercial power plant scale tokamak (1500 MW_{th}) is being designed in an international project by the world's major fusion institutions.
- The physics of sub-ignited targets has been developed with glass lasers, and underground test results have resolved feasibility questions of high gain for power plants.
- The target physics of ignition and high gain, using glass lasers, are objectives of the National Ignition Facility (NIF), now under construction.

Current Research, Development, and Demonstration

RD&D Goals

- Optimize the toroidal magnetic option for an attractive fusion power plant; maintain a vigorous search for improved magnetic concepts; and collaborate in an international project to demonstrate sustained fusion power production at the gigawatt (thermal) level in a tokamak.
- Establish the technological basis for an efficient, low-cost ion beam using an induction accelerator, and demonstrate useful gain from compression and burn of NIF targets.
- Qualify low-activation materials that allow fusion plants to achieve their ultimate environmental potential.

RD&D Challenges

- Develop magnetic geometries optimal for heat containment that at the same time (1) minimize technical complexity, (2) maximize fusion power density for good economics, and (3) operate in a continuous mode.
- Understand target requirements for high gain; reduce the development cost of candidate drivers; and develop long-life chambers and low-cost microcapsule targets.
- Develop low-activation materials that also meet structural and compatibility criteria.

RD&D Activities

- Coordinated world-wide magnetic fusion physics efforts center on improved performance. Programs to advance various technologies are proceeding at different paces, with materials and nuclear technologies lagging.
- Inertial fusion efforts are concentrated on igniting fusion targets.
- Modest efforts to develop beam and laser driver technologies have begun in several programs around the world.
- The FY 1997 U.S. budget is $232M.

Recent Success

- More than 10 MW of fusion power was produced in a tokamak for about 1 second, using deuterium-tritium fuel.
- New tokamak modes of operation that could lead to high-performance continuous operation have been discovered.
- Results from underground tests in the United States have resolved fundamental questions of feasibility of high gain for efficient fusion power plants.
- Results from the NOVA laser at Lawrence Livermore National Laboratory have confirmed the validity of computer models used to predict ignition and gain in the NIF.
- Vanadium alloys show promise as a low-activation structural material in magnetic fusion devices, and liquid walls for inertial fusion chambers promise to avoid life-limiting radiation damage.

Commercialization and Deployment

- Large central-station electrical generating plants could be commercialized late in the second quarter of the twenty-first century; the timescale depends on a sustained international effort and success in that R&D.
- Fusion power plants would replace aging and environmentally abusive power generators and fill a potential multi-billion dollar market sector.
- Many technologies developed for fusion are currently used in the commercial sector. Prominent are plasma processing for etching semiconductor chips, hardening of metals, thin-film deposition, and plasma spraying and lighting applications. Other applications arising from this research include medical imaging, heat removal technologies, destruction of toxic waste, X-ray lithography and microscopy, micro-impulse radar, precision laser cutting, large-scale production of precision optics, and high-power microwave and accelerator technologies.

Potential Benefits and Costs

Carbon Reductions
- By late in the next century, fusion power could reduce carbon emissions by 500 MtC/year.

RD&D Expenditures
- FY 1997 federal RD&D expenditures were $232M.
- PCAST has recommended the federal budget increase to $280M/year. This study agrees with that funding estimate. This level would maintain a program focused on three key principles: (1) a strong domestic core program in plasma science and fusion technology; (2) a collaboratively funded international fusion program focused on ignition and moderately sustained burn; and (3) participation in an international program to develop practical low-activation materials for fusion energy systems.
- Present worldwide levels (~$1.5B/year) are required through 2020. When large-scale pilot or demonstration plants are appropriate, additional funding may be needed.

Market
- Undetermined at this time.

Energy
- Could provide unlimited energy if economically viable.

Nonenergy Benefits and Costs
- Energy security, owing to the easy availability of its fuel, would be ensured. Fusion plants present no proliferation issues and are inherently safe against thermal runaway excursions.

Risk Factors

Technical Risk

1 2 3 4 5 6 7 ⑧ 9 10

Low — High

- The scientific risk is moderate. Confidence in producing fusion power will come from the next (international) step in the magnetic fusion program and the NIF research on targets.
- Technology risk is high, given the technical complexity.

Commercial Risk

1 2 3 4 5 6 7 ⑧ 9 10

Low — High

- Marketplace energy cost is 2–3 cents/kWh; power costs are 6–10 cents/kW. The cost of fusion power could improve somewhat; competing systems may become more costly if environmental costs are included.

Ecological Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Operation poses very low ecological risk.
- — If low-activation materials are used, plant decommissioning generates low-level waste of low risk to the environment.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Health risks to the public are low, and worker health and safety should be controlled by procedures.

Economic Risk

1 2 3 4 5 6 7 ⑧ 9 10

Low — High

- Plant capital costs will be high.

Regulatory Risk

1 2 3 4 5 6 7 8 9 10

Low — High

- Not applicable. Fusion should come under regulations different from those for fission.

Key Federal Actions

- Federal R&D funding for fusion is essential and requires a long term commitment.
- — The United States' part in the international effort needs to be strongly coordinated with all other work in fusion.
- Industrial involvement will be essential once feasibility is established.