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A Technology Roadmap for Generation IV Nuclear Energy Systems Executive Summary

March 2003

Ten Nations Preparing Today for Tomorrow's Energy Needs

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Executive Summary

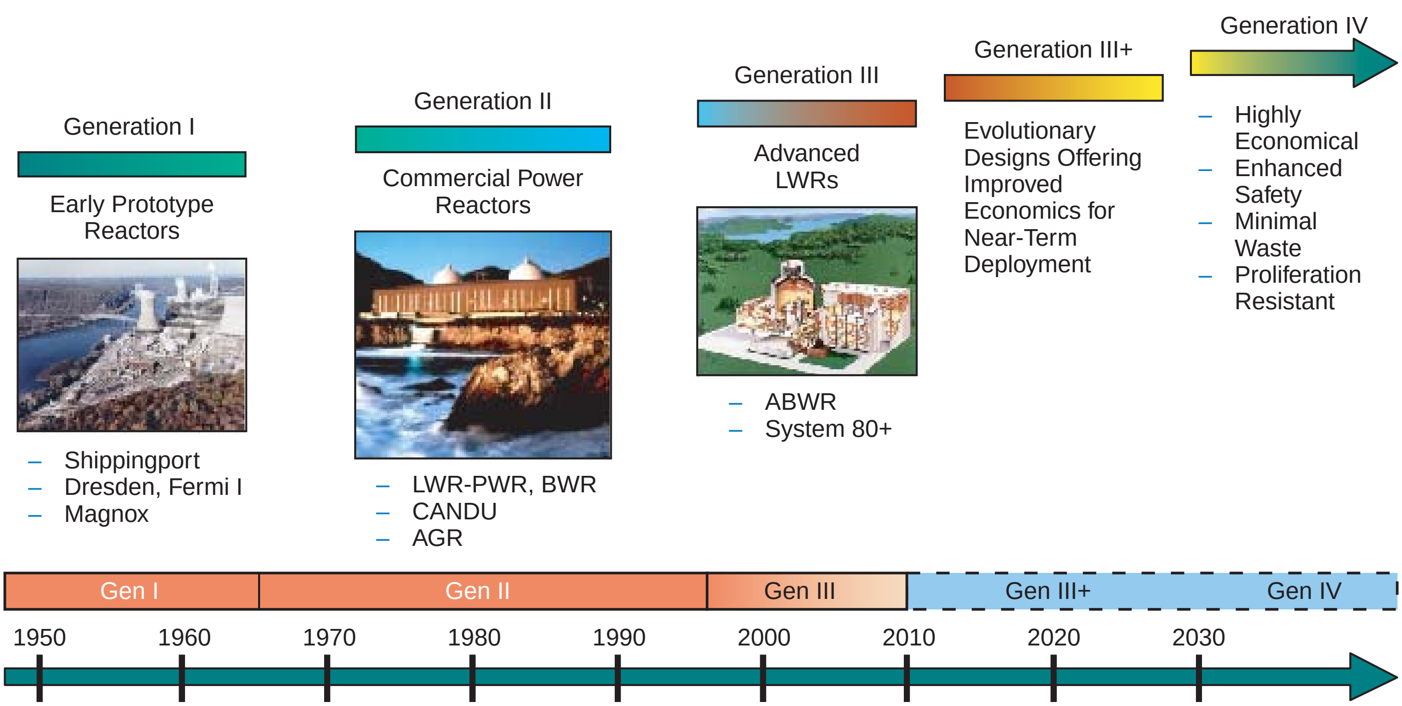
To meet future energy needs, ten countries—Argentina, Brazil, Canada, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States—have agreed on a framework for international cooperation in research for an advanced generation of nuclear energy systems, known as Generation IV. These ten countries have joined together to form the Generation IV International Forum (GIF) to develop future-generation nuclear energy systems that can be licensed, constructed, and operated in a manner that will provide competitively priced and reliable energy products while satisfactorily addressing nuclear safety, waste, proliferation, and public perception concerns. The objective for Generation IV nuclear energy systems is to be available for international deployment before the year 2030, when many of the world's currently operating nuclear power plants will be at or near the end of their operating licenses.

The History of Nuclear Energy Deployment

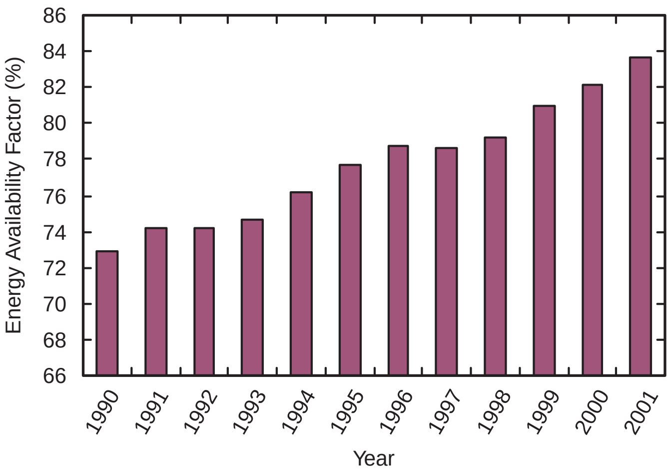
From the early beginnings of nuclear energy in the 1940s to the present, three generations of nuclear energy have been developed: early prototype reactors in the 1950s and 60s, commercial power reactors in the 1970s and 80s, and advanced light water reactors in the 1990s.

The first three generations of nuclear energy have been successful in many ways. For example:

- Nuclear energy supplies a significant share of electricity for today's needs. Nuclear power accounts for 16% of global electricity production. More than 435 reactors around the world provide 356,000 megawatts of electricity in 31 countries.
- Europe obtains 35% of its electricity from nuclear power—more than from any other source—making long-term use of nuclear power an important part of the clean air and climate change strategies in many European countries.
- In the United States, where nuclear energy provides 20% of the electricity, improved efficiency has in the last decade yielded the equivalent of some 20 new



nuclear power plants. In 2001, the average operating cost of the 103 U.S. nuclear power plants was 1.68 cents per kilowatt-hour, second only to hydroelectric power among baseload generation options.



Global Average Nuclear Energy Availability Factor
Source: IAEA 2002 Nuclear Technology Report

- Several Asian countries have committed to large nuclear energy programs as a way to increase energy security by reducing reliance on foreign sources of energy supply.
- Through the use of nuclear energy, the world avoids the emission of approximately 1800 million tons of carbon dioxide, 15 million tons of sulfur dioxide, and 7 million tons of nitrogen oxide annually.
- In return for access to peaceful nuclear technology, over 180 countries have signed the Non-Proliferation Treaty to help ensure that peaceful nuclear activities will not be diverted to making nuclear weapons.

Challenges to the Expanded Use of Nuclear Energy

Despite nuclear energy's successes, challenges to the long-term expansion of nuclear energy have been encountered that have not been fully resolved:

- Public confidence in the safety of nuclear energy was challenged by the Three Mile Island accident in 1979 and Chernobyl in 1986. The nuclear industry has responded to achieve exceptionally high levels of safety and reliability in the current fleet of more than 435 reactors worldwide. As one indication of this, the percent of time reactors are available to produce electricity has greatly improved over the last decade (see figure). Research and development (R&D) into new nuclear systems should increase public confidence with clear and transparent safety approaches.
- High capital costs have discouraged commercial construction of nuclear plants. For the long term, significant R&D is needed on new systems that will have significantly reduced capital costs and construction times.
- Establishing final repositories for spent nuclear fuel has taken longer than expected. Future long-term expansion of nuclear energy needs to address the optimal use of limited space in geological repositories and achieve the benefits of a closed fuel cycle. This will require significant R&D on fuel cycle technology and new nuclear energy systems that are more sustainable.[1]
- Worldwide deployment of nuclear energy has led to concerns over the vulnerability of nuclear plants to terrorist attack and accumulating plutonium inventories that hold the potential for proliferation of nuclear weapons. R&D into new nuclear systems should provide increased physical protection against acts of terrorism, and increase the assurance that these systems are a very unattractive route for nuclear proliferation.

In spite of these challenges, nuclear energy experienced an economic and regulatory recovery in many parts of the world in the 1990s. For example, nearly all of the 103 commercial light water reactors in the U.S. are expected to file for 20-year license extensions. Thirty-five new reactors are under construction around the world, and several other countries have announced their intent to begin construction of new nuclear power plants. Nonetheless, if nuclear energy is to make a large-scale contribution to meeting future energy needs around the world, new nuclear energy systems need to address issues of safety, economics, waste, and proliferation resistance.

[1] Internationally, and especially in the context of the recent World Summit on Sustainable Development held in Johannesburg in August 2002, sustainable development is usually examined from three points of view: economic, environmental, and social. Generation IV has adopted a narrower definition of sustainability in order to balance the emphasis on the various goal areas. For a more complete discussion of sustainability, see *NEA News*, No. 19.1, available at http://www.nea.fr/html/sd/welcome.html.

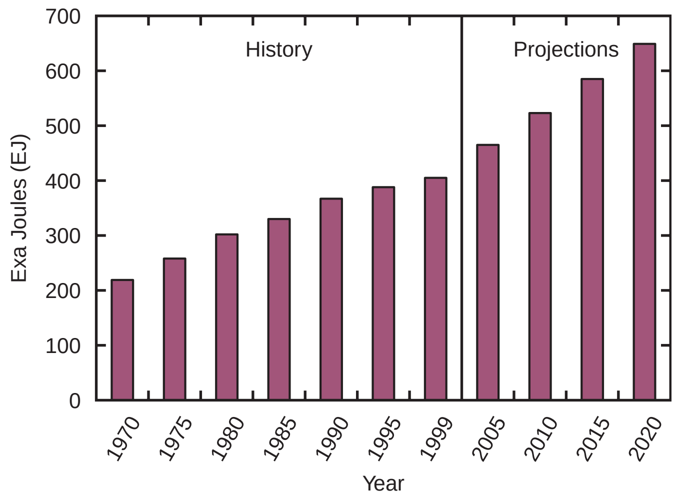
The Need for Generation IV Nuclear Energy Systems

The challenges facing nuclear energy have caused some to conclude that its use should be phased out over the coming decades. The countries of the GIF, and many others around the world, disagree with this conclusion. The world simply has too few energy options available, and we cannot afford to forego any of them, especially one with all of the positive attributes of nuclear energy.

We are moving from a world today of roughly 6 billion people, about half living in poverty, to a world of possibly 10 billion people in the year 2050, all striving for a better quality of life. As the Earth's population grows, so will the demand for energy and all that it brings—greater life expectancy, better health care, improved literacy, and countless other benefits. If the Earth is to support this inevitable growth, we must find ways to produce energy that are cleaner, safer, cost-effective, and that reduce or eliminate the prospect of global warming. Many of the world's nations—both industrialized and developing—believe that nuclear energy will be required to meet these future energy demands without irreparably harming the environment.

The outlook for energy demand underscores the need to increase the share of nuclear energy production. World energy consumption is forecast to rise approximately 60% from 1999 to 2020. Coal and natural gas are projected to provide most of the energy production increase. Thus, the outlook implies an increasing burden from carbon emissions, with the potential for long-term consequences from global climate change. This creates a strong motivation for seeking to increase the share of nuclear-generated electricity above its current 16% level. While current advanced light water reactor systems show promise for stimulating new plant orders, the long-term competitiveness of nuclear energy needs continued development.

The outlook for energy demand within the transportation sector also points to an emerging role for nuclear energy via hydrogen production. Annual growth of 2.5% per year is projected for the transportation sector from 1999–2020. Transportation almost exclusively depends upon petroleum. This dependence has caused fluctuations in fuel prices of 30% and correlates with several 'energy shocks' since the 1970s. This volatility creates a significant need for seeking to diversify with new fuels, such as hydrogen for use in emission-free fuel cells that power electric vehicles. Large-scale production of hydrogen by nuclear energy would be free of carbon emissions. New nuclear energy systems that are specialized for hydrogen production with competitive prices need to be developed to achieve these benefits.



An annual energy demand of 2.5% per year is projected for the transportation sector from 1999 through 2020.

Sources – History: Energy Information Administration (EIA), Office of Energy Markets and End Use, International Statistics Database and *Internation Energy Annual 1999*, DOE/EIA-0219(99) (Washing ton, DO, February 2001). Projections: EIA, World Energy Projection System (2002).

The Generation IV Technology Roadmap

In 2001, the GIF agreed to proceed with the development of a technology roadmap for Generation IV nuclear energy systems. The purpose of the roadmap was to identify the most promising nuclear energy systems (consisting of both a reactor and fuel cycle) for meeting the challenges of safety, economics, waste, and proliferation resistance.

As a first step, the GIF agreed on a set of goals for the new systems. The goals have three purposes. First, they serve as the basis for developing criteria to assess and compare the systems in the technology roadmap. Second, they are challenging and stimulate the search for innovative nuclear energy systems—both fuel cycles and reactor technologies. Third, they will serve to motivate

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.*

and guide the R&D on Generation IV systems as collaborative efforts get underway. The GIF defined eight goals in the four broad areas of sustainability, economics, safety and reliability, and proliferation resistance and physical protection (see box).

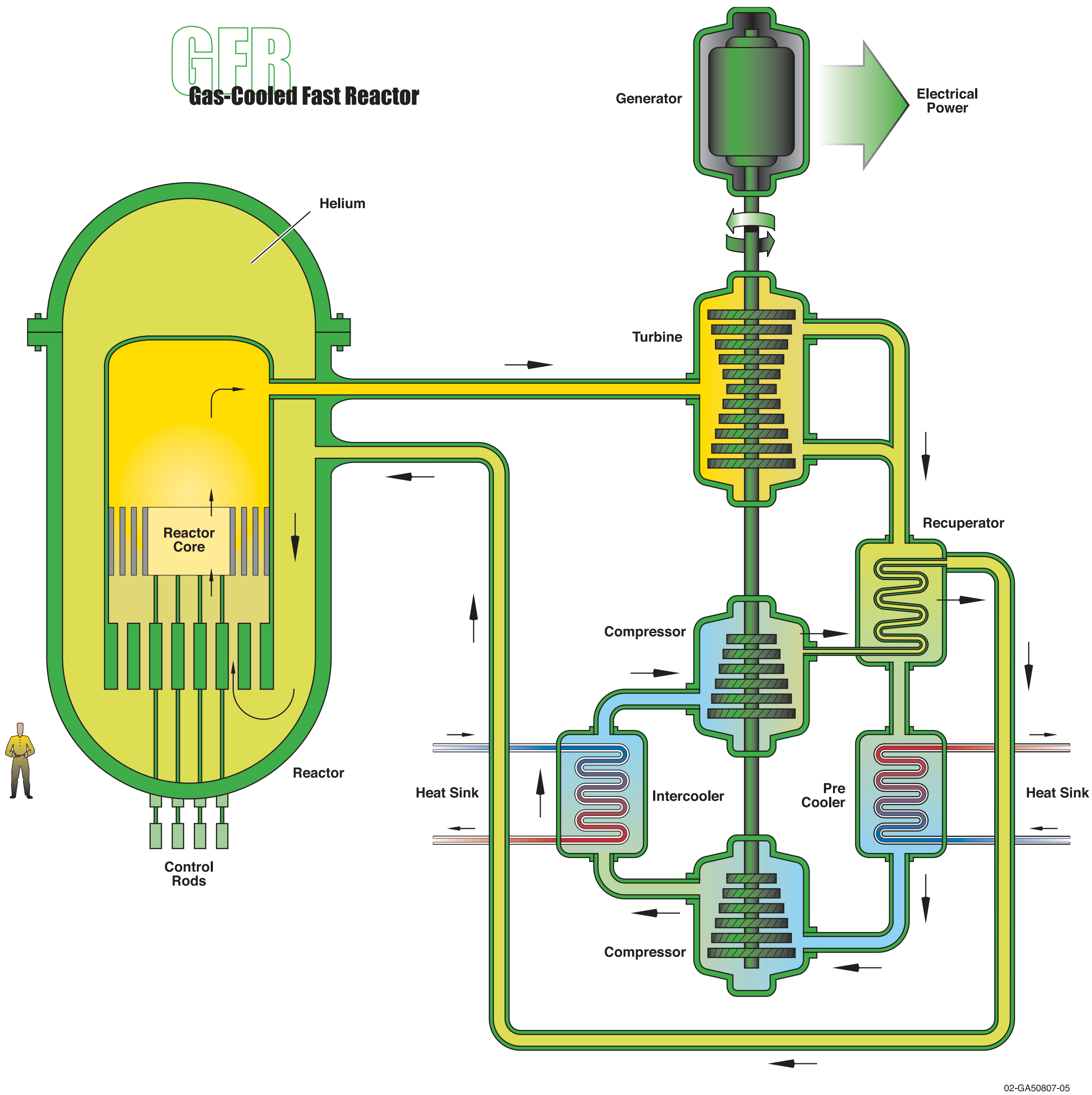
The GIF used more than 100 experts from their countries to evaluate more than 100 concepts proposed by the worldwide R&D community. The Generation IV roadmap process culminated in the selection of six most promising Generation IV systems. The motivation for the selection of six systems is to:

- Identify systems that make significant advances toward the technology goals
- Ensure that the important missions of electricity generation, hydrogen and process heat production, and actinide management may be adequately addressed by Generation IV systems
- Provide some overlapping coverage of capabilities, because not all of the systems may ultimately be viable or attain their performance objectives and attract commercial deployment
- Accommodate the range of national priorities and interests of the GIF countries.

Each of the six systems selected by the GIF is described here briefly:

Gas-Cooled Fast Reactor System (GFR)

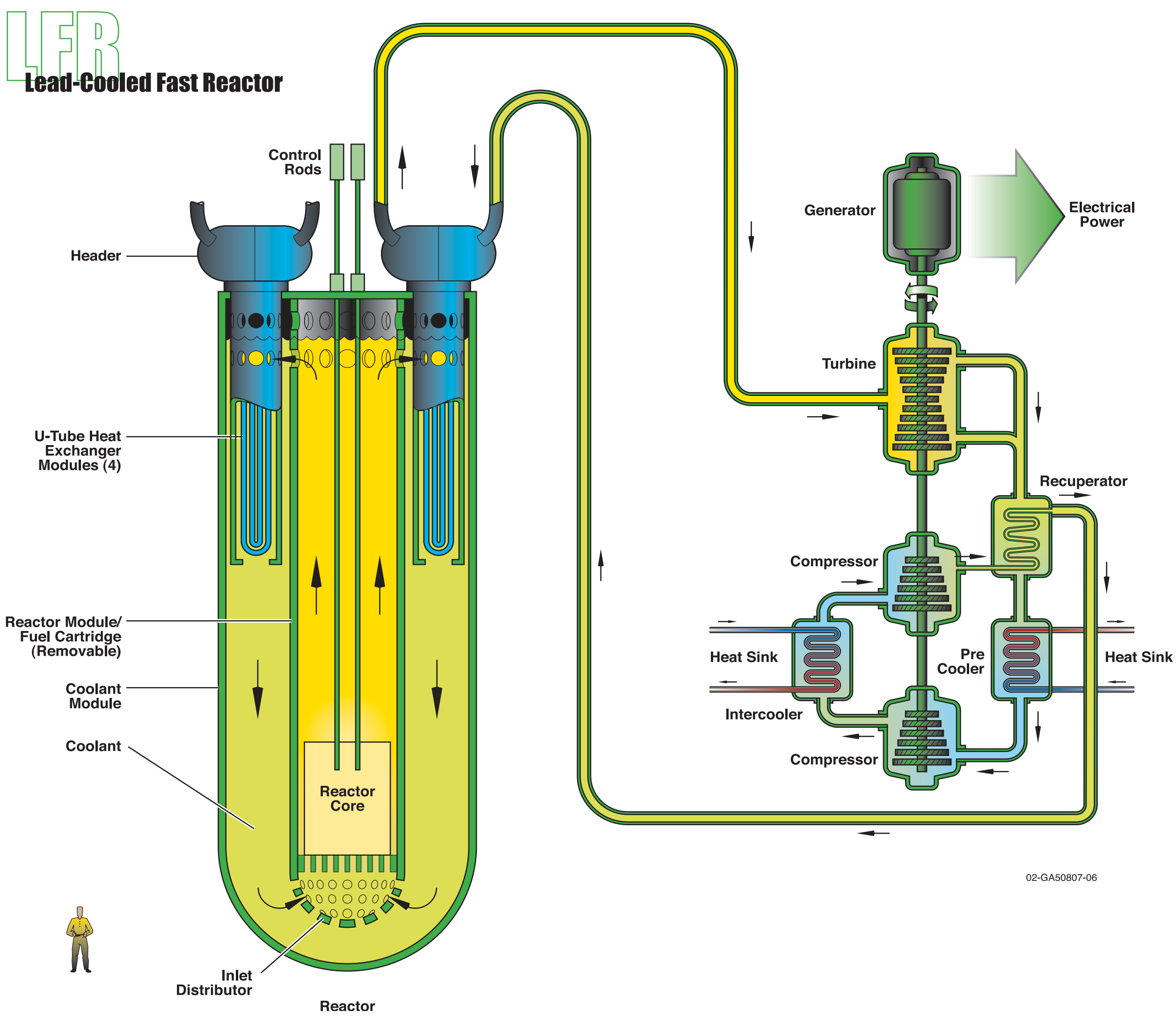
The Gas-Cooled Fast Reactor (GFR) system features a fast neutron spectrum and closed fuel cycle for efficient management of actinides and conversion of fertile uranium.[2] Core configurations are being considered based on pin- or plate-based fuel assemblies or prismatic blocks, with a total core power of 300–600 MWe. The GFR system is strong in sustainability because of its closed fuel cycle and excellent performance in actinide management. It is rated good in safety, economics, and in proliferation resistance and physical protection. It is primarily envisioned for missions in electricity production and actinide management, although it may be able to economically support hydrogen production.



[2] The term *actinides* denotes both major actinides (the uranium and plutonium present in relatively large percentages in spent nuclear fuel) as well as minor actinides (the neptunium, americium, curium, and other heavier elements present in relatively small percentages). A number of the actinides place challenging requirements on the long-term performance of geological repositories. Recycling the actinides into new nuclear fuel for fast-spectrum reactors can be an effective strategy for managing actinides.

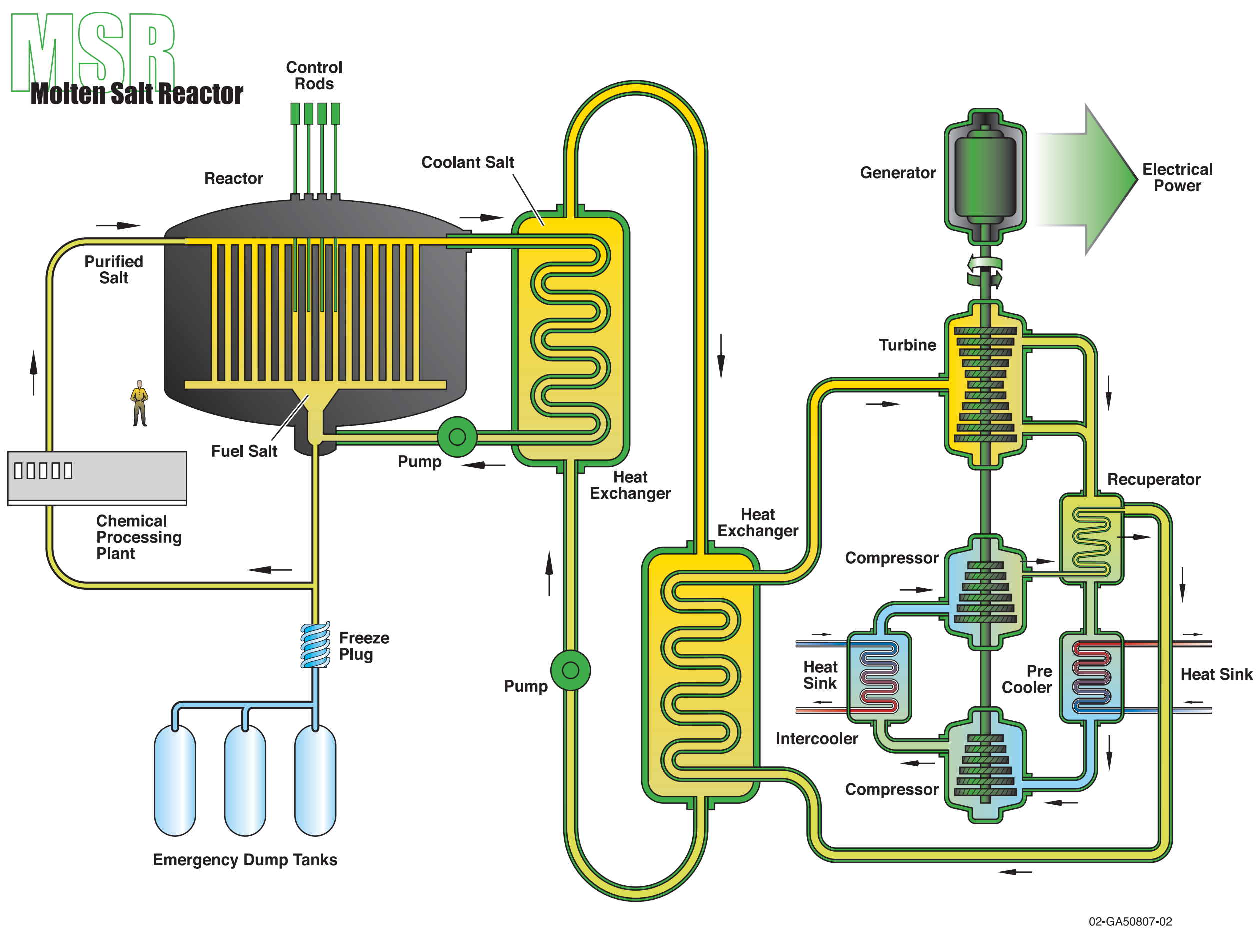
Lead-Cooled Fast Reactor System (LFR)

The Lead-Cooled Fast Reactor (LFR) system features a fast neutron spectrum and a closed fuel cycle for efficient management of actinides and conversion of fertile uranium. The system uses a lead or lead/bismuth eutectic liquid-metal-cooled reactor. The reactor is cooled by natural convection and sized between 50–1200 MWe, with a reactor outlet coolant temperature of 550°C, possibly ranging up to 800°C, depending upon the success of the materials R&D. The LFR system is strong in sustainability because a closed fuel cycle is used, and in proliferation resistance and physical protection because it employs a long-life core. It is rated good in safety and economics. The safety is enhanced by the choice of a relatively inert coolant. It is primarily envisioned for missions in electricity and hydrogen production and actinide management with good proliferation resistance.



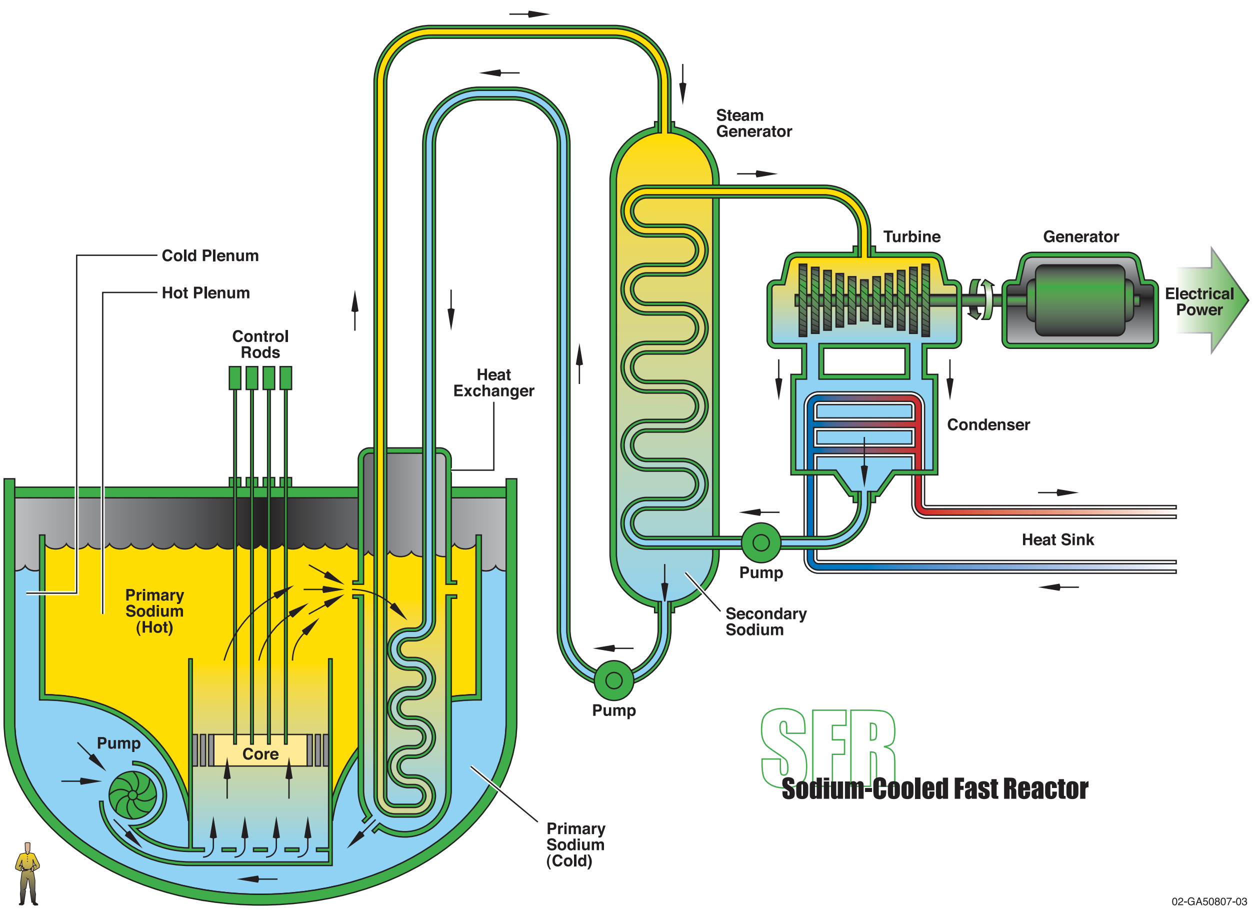
Molten Salt Reactor System (MSR)

The Molten Salt Reactor (MSR) system features an epithermal to thermal neutron spectrum and a closed fuel cycle tailored to the efficient utilization of plutonium and minor actinides. In the MSR system, the fuel is a circulating liquid mixture of sodium, zirconium, and uranium fluorides. The reference plant has a power level of 1000 MWe. The system operates at low pressure (about 5 atmospheres) and has a coolant outlet temperature above 700°C, affording improved thermal efficiency. The MSR system is strong in sustainability because of its closed fuel cycle and excellent performance in waste burndown. It is rated good in safety, and in proliferation resistance and physical protection, and it is rated neutral in economics because of its large number of subsystems for maintenance of the fuel and coolant. It is primarily envisioned for missions in electricity production and the final burn of plutonium and minor actinides.Sodium-Cooled Fast Reactor System (SFR)



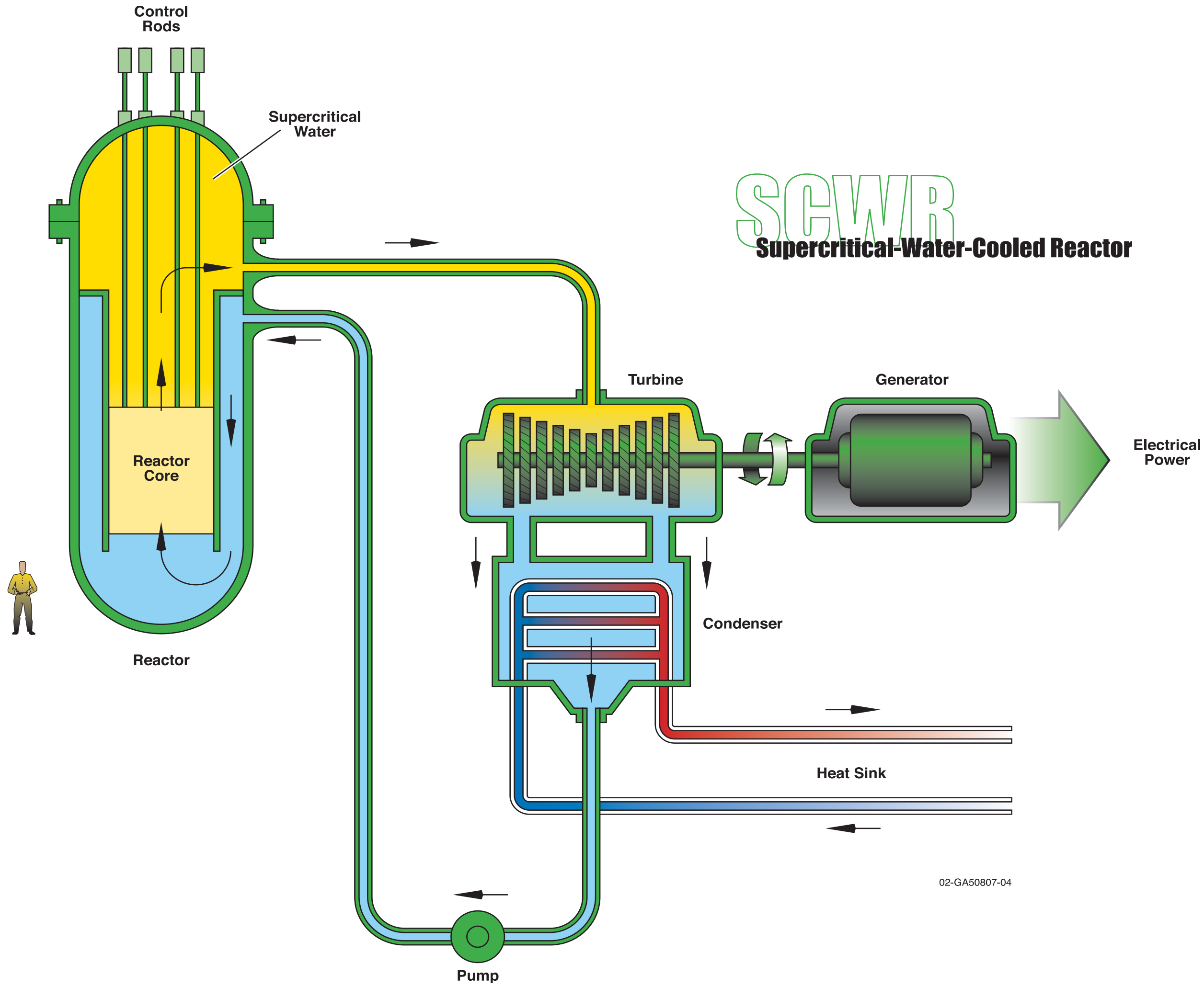
Sodium-Cooled Fast Reactor System (SFR)

The Sodium-Cooled Fast Reactor (SFR) system features a fast neutron spectrum and a closed fuel cycle for efficient management of actinides and conversion of fertile uranium. A full actinide recycle fuel cycle is envisioned with two major options: One is an intermediate size (150 to 500 MWe) sodium-cooled reactor with a uranium-plutonium-minor-actinide-zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in collocated facilities. The second is a medium to large (500 to 1500 MWe) sodium-cooled fast reactor with mixed uranium-plutonium oxide fuel, supported by a fuel cycle based upon advanced aqueous processing at a central location serving a number of reactors. The outlet temperature is approximately 550°C for both. The SFR system is strong in sustainability because of its closed fuel cycle and excellent potential for actinide management. It is rated good in safety, economics, and proliferation resistance and physical protection. It is primarily envisioned for missions in electricity production and actinide management.



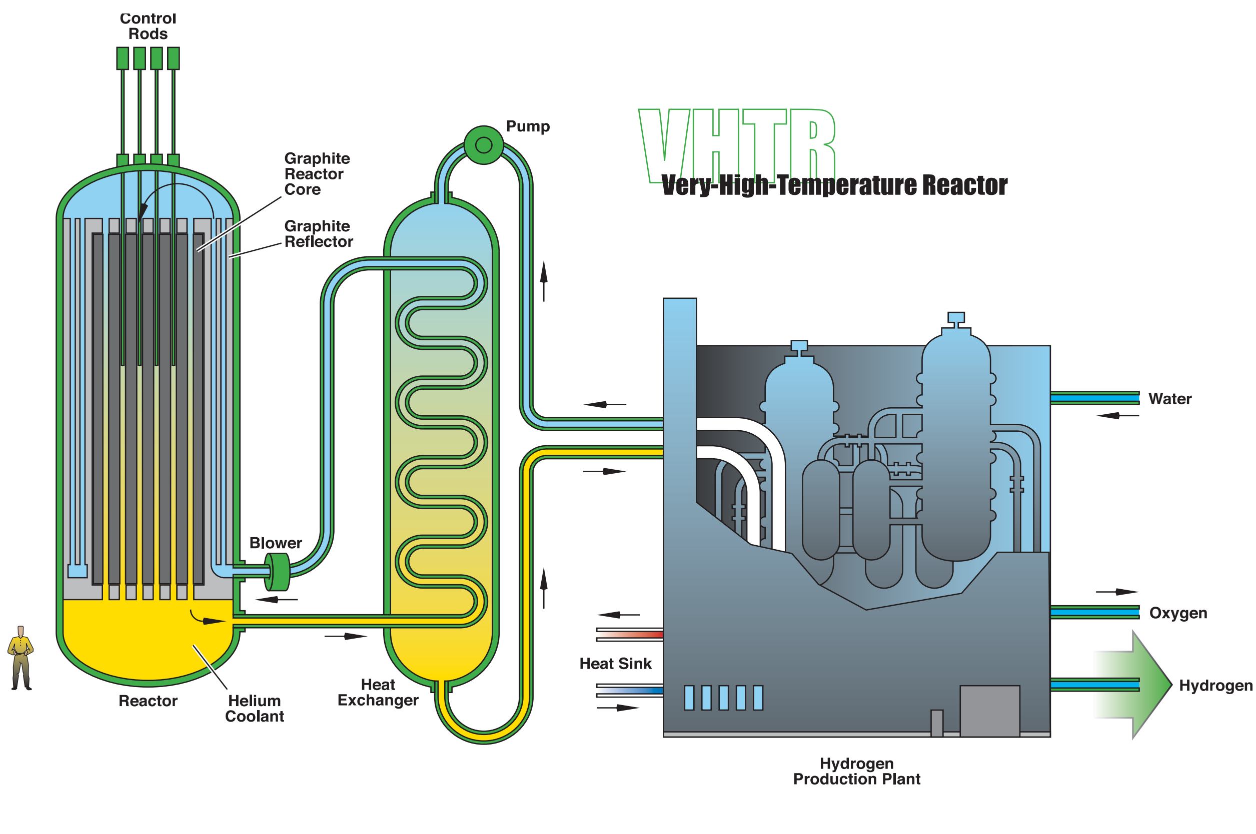
Supercritical-Water-Cooled Reactor System (SCWR)

The Supercritical-Water-Cooled Reactor (SCWR) system features an open cycle with a thermal neutron spectrum reactor as the primary option. The system uses a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water to achieve a thermal efficiency approaching 44%. The reference plant has a 1700-MWe power level and a reactor outlet temperature of 550°C. The SCWR system is highly ranked in economics because of the high thermal efficiency and plant simplification. The SCWR is rated good in safety, and in proliferation resistance and physical protection. The SCWR is primarily aimed at electricity production, where its high thermal efficiency and plant simplification may provide a breakthrough in system economics.



Very-High-Temperature Reactor System (VHTR)

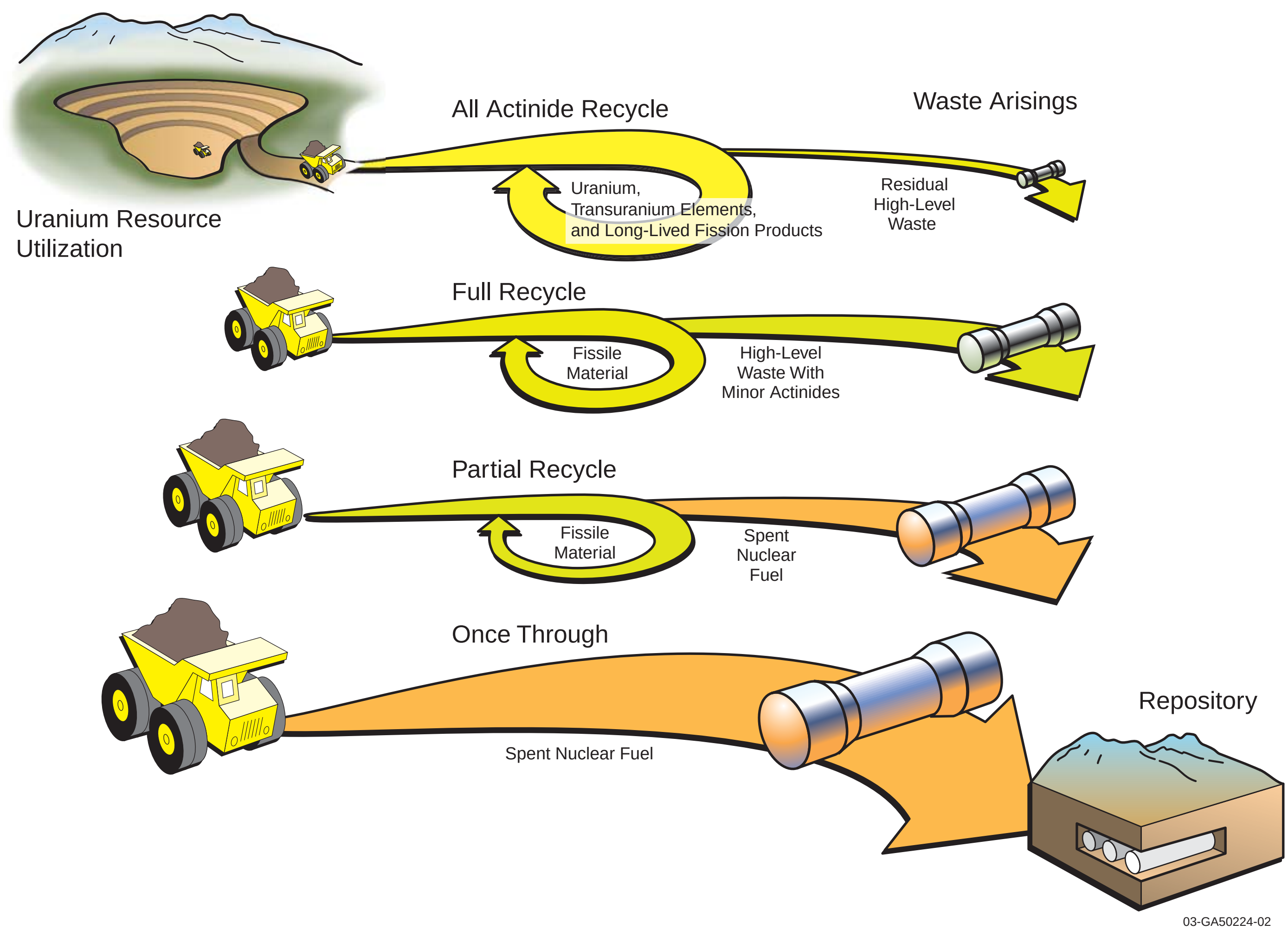
The Very-High-Temperature Reactor (VHTR) system uses a thermal neutron spectrum and a once-through uranium cycle. The VHTR system is primarily aimed at nearer-term deployment of a system for high-temperature process heat applications with a focus on thermochemical hydrogen production at superior efficiency. The VHTR system has coolant outlet temperatures above 1000°C, which enables high efficiency thermochemical water-splitting without carbon emissions. The reference reactor concept has a 600-MWth helium-cooled core based on either the prismatic block fuel of the Gas Turbine–Modular Helium Reactor (GT-MHR) or the pebble fuel of the Pebble Bed Modular Reactor (PBMR). Operating at an efficiency of over 50%, such a plant would produce over 200 metric tonnes of hydrogen per day. This is the equivalent of over 300,000 gallons of gasoline per day.



Fuel Cycles for Generation IV Nuclear Energy Systems

To better understand the wide range of fuel cycle options and benefits, four general classes of nuclear fuel cycle were evaluated, ranging from a once-through fuel cycle to a fast reactor fuel cycle with full recycle of long-lived actinide elements from the waste stream. Not surprisingly, the once-through cycle is the most uranium resource-intensive and generates the most waste (in the form of used nuclear fuel). However, the amounts of waste produced are still quite small and manageable compared to other energy technologies, and existing uranium resources are sufficient to support a once-through cycle well into this century. The limiting factor facing a large expansion in the use of a once-through cycle, at least in the near-term, appears to be the availability of repository space worldwide. In the longer term, uranium resource availability could also become a limiting factor. Therefore, as reflected in the Generation IV goals, a challenge to long-term, widespread deployment of Generation IV nuclear energy systems is to ensure they operate using fuel cycles that minimize the production of long-lived wastes while conserving uranium resources.

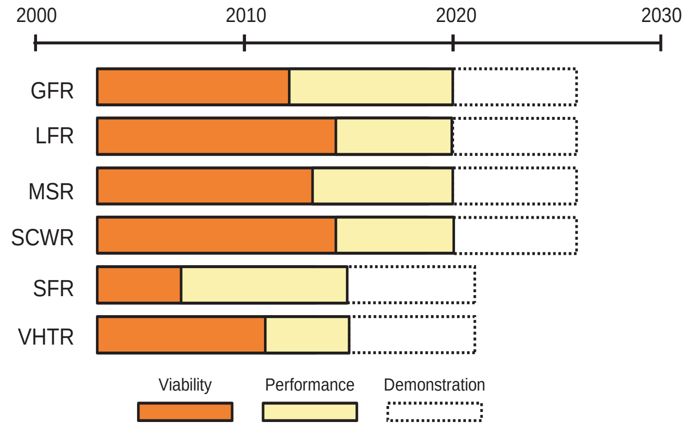
These findings underscore an important point about the future widespread use of nuclear energy—it is unlikely that one particular reactor concept will be the preferred means to meet all of the Generation IV goals. Rather, a combination of reactor types is likely to be employed, forming a nuclear energy system in which each reactor type is used in the role(s) that it fills best.



Generation IV Research and Development

The technology roadmap describes the required system R&D necessary to develop each of the six systems and the approximate time to completion. In addition to concept-specific R&D, the roadmap recognizes that certain R&D tasks may support the advancement of multiple systems. Therefore, crosscutting R&D in the areas of fuel cycle, fuels and materials, energy products, risk and safety, economics, and proliferation resistance and physical protection are also defined in the roadmap.

The progression of R&D activities is in phases. The first is the *viability* phase, where the principal objective is to resolve key feasibility and proof-of-principle issues. Emphasis on the viability of the system is intended to yield answers before undertaking large-scale technology development. The second phase is the *performance* phase, where the key subsystems (such as the reactor, recycling facilities or energy conversion technology) need to be developed and optimized. This phase ends when the system is sufficiently mature and performs well enough to attract industrial interest in large-scale demonstration of the technology. The third phase is the *demonstration* phase, which has a number of options as to the nature of the scope, size, and length of time such a demonstration will have, as well as the nature of the participation of industry, government, and multiple countries in the project. Owing to the new and innovative technology, it is felt that any Generation IV system will need a demonstration phase. With successful demonstration, a system may enter a *commercialization* phase, which is an industry action. [For caption, take off heading (System Development Timelines) and use it for caption, with *development* and *timelines* lower case.]



With six most promising Generation IV systems and ten countries in the GIF, the approach to building integrated programs for any of the systems is an important issue. The GIF countries have expressed a strong interest in collaborative R&D on Generation IV systems. However, each country will participate only in the systems that they choose to advance. The technology roadmap has been structured to allow the independent assembly of collaborative R&D programs. The GIF countries are now taking up the organization of significant collaborations to work toward a successful development of next-generation nuclear energy systems.

For more information on the Generation IV Initiative,
please visit the Generation IV web page at:

http://nuclear.gov

Or contact the Office of Technology and International Cooperation,
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U.S. Department of Energy
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To download electronic versions of the full technology roadmap and its
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http://gif.inel.gov/roadmap/