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Fast-spectrum Reactors

Chapter 4: Technology Assessments

Background and Current Status

From the initial conception of nuclear energy, it was recognized that full realization of the energy content of uranium would require the development of fast reactors with associated nuclear fuel cycles.[1] Thus, fast reactor technology was a key focus in early nuclear programs in the United States and abroad, with the first usable nuclear electricity generated by a fast reactor—Experimental Breeder Reactor I (EBR-I)—in 1951. Test and/or demonstration reactors were built and operated in the United States, France, Japan, United Kingdom, Russia, India, Germany, and China—totaling about 20 reactors with 400 operating years to date. These previous reactors and current projects are summarized in Table 4.H.1.[2]

Currently operating test reactors include BOR-60 (Russia), Fast Breeder Test Reactor (FBTR) (India), and China Experimental Fast Reactor (CEFR) (China). The Russian BN-600 demonstration reactor has been operating as a power reactor since 1980. The Japanese test reactor (JOYO) and demonstration reactor (Monju) are currently shut down but have been updated for new licensing requirements and are planned for restart. New demonstration reactors have been constructed in Russia (BN-800 with first criticality in June 2014) and India (600 MWe Prototype Fast Breeder Reactor [PFBR]; startup planned in 2015). Other international demonstration projects in the design stage include the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) in 2025 (France), the Prototype Generation-IV Sodium-cooled Fast Reactor (PGSFR) in 2028 (South Korea), and the SVBR-100 in 2017 and BREST-300 in 2020 (Russia). Concurrent with these demonstration reactor projects, all countries with significant nuclear energy commitments have research and development (R&D) efforts directed toward fast reactor technology with associated fuel cycles.

Because the nuclear reactor is the dominant cost of any nuclear fuel cycle, technology innovations to reduce costs are being explored through international R&D efforts (see discussion below). Inherent safety features have been employed and demonstrated in modern fast reactor designs (e.g., passive decay heat removal). In addition, technology for key components and design features is being matured.

The international experience with fast reactors has demonstrated the basic viability of sodium-cooled fast reactor (SFR) technology.[3] However, the SFR technology has not been widely deployed nor commercialized to date.

A variety of fast reactors with different technology (e.g., coolants), unit sizes (100–1500 MWe), and diverse missions (e.g., fuel cycle closure, once-through high "burnup") are being proposed.[4] Fast reactors are envisioned for a wide variety of actinide management strategies, ranging from plutonium recycle (in Russian and French closed cycle) to transuranic recycle (in General Electric Power Reactor Innovative Small Module [PRISM] fuel cycle) to enhanced once-through uranium utilization (in the Traveling Wave Reactor). The fast reactor characteristics also enhance inherent safety behavior and can extend operating cycle length or burnup; such features are particularly important for small reactor applications. With successful technology development, fast reactors are also intended for efficient electricity production (competitive with current reactor technology) and heat production missions (at elevated temperatures, particularly with some coolants), as being pursued in the Generation-IV International Forum collaborations.

Table 4.H.1 International Fast Reactor Experience and Current Projects

Facility	Country	First Critical	Power, MW_t	Primary Coolant
Clementine	USA	1946	5.5 kW	Mercury
EBR-I	USA	1951	1.4	Sodium-Potassium
BR-2	Russia	1956	2	Mercury
BR-5/BR-10	Russia	1958	8	Sodium
DFR	UK	1959	60	Sodium-Potassium
Fermi	USA	1963	200	Sodium
EBR-II	USA	1963	62.5	Sodium
Rapsodie	France	1967	40	Sodium
BOR-60	Russia	1968	55	Sodium
SEFOR	USA	1969	20	Sodium
OK-550/BM-40A	Russia	1969	155 (7 subs)	Lead-Bismuth
KNK-II	Germany	1972	58	Sodium
BN-350	Kazakhstan	1972	750	Sodium
Phenix	France	1973	563	Sodium
PFR	UK	1974	650	Sodium
FFTF	USA	1980	400	Sodium
BN-600	Russia	1980	1470	Sodium
JOYO	Japan	1982	140	Sodium
FBTR	India	1985	40	Sodium
Super-Phenix	France	1985	2990	Sodium
MONJU	Japan	1994/2010	714	Sodium
CEFR	China	2010	65	Sodium
BN-800	Russia	2014	2100	Sodium
PFBR	India	2015*	1250	Sodium
SVBR-100	Russia	2017*	280	Lead-Bismuth
BREST-300	Russia	2020*	700	Lead
ASTRID	France	2025*	1500	Sodium
PGSFR	South Korea	2028*	400	Sodium

* Projected date for first obtain criticality

Description of Technology

Fast reactors utilize materials with high atomic number to avoid the slowing down of fission neutrons (in contrast to water reactors, where the hydrogen moderates neutrons to lower energies). Thus, the energy-producing fission reactions are generated by "fast" neutrons, where the relative probability of neutron capture is significantly reduced, producing excess neutrons that can be utilized to produce new fissile material (via capture in Uranium-238). This favorable neutron balance can be utilized to sustain the fissile material inventory, allowing resource extension. In typical applications, a complementary fuel reprocessing technology is employed to realize this benefit by repeated recycle of the actinide materials (with roughly 10% destruction each pass for conventional fast reactor fuels). This recycle of actinides effectively excludes the long-term heat-producing elements from the fuel cycle waste stream, allowing significant waste management benefits.

A key design issue is the choice of non-moderating coolants. Each coolant has unique properties, operating ranges, and technology development status. In the Generation-IV International Forum, three fast reactor options are being considered—SFR, lead or lead-bismuth cooled fast reactor (LFR), and gas-cooled fast reactor (GFR).[5] The primary advantage of the SFR is technical maturity. Nearly all fast reactor experience (400 operating years, noted earlier) has utilized and refined SFR technology. Thus, basic viability has been demonstrated and the relevant technology challenges are well understood and are being addressed in current international R&D programs (such as the Generation-IV collaboration). The low pressure liquid metal coolant is favorable for natural circulation heat removal, and reactor materials have been successfully demonstrated for the 500°C–550°C temperature range. Key challenges include design and operation of leak-tight steam generators (avoid sodium-water reaction) and equipment inspection in an opaque (liquid sodium) coolant environment.

Some potential advantages of the LFR technology are liquid metal coolant that does not react chemically with water or air, simplifying the heat transport system, and very high coolant boiling point, allowing higher reactor outlet temperature. The major challenge for the LFR is structural material corrosion, with some experience in Russian submarines and promising research for advanced materials and techniques. In addition, significant R&D is required for new fuel forms, coolant handling, and opaque coolant (liquid lead bismuth) inspection techniques.

The primary advantage of the GFR technology is high temperature operations for improved thermal efficiency. The inert, transparent coolant (helium) may have operational benefits, and much of the technology development and challenges (e.g., structural materials) are similar to other high temperature reactor options. A main concern with the GFR technology is safety challenges related to decay heat removal, because it may not be possible to utilize passive techniques at the higher fast reactor power density by using gas coolant. In addition, new fuel development and demonstration are required for the expected radiation damage regime.

A variety of other technology options have been proposed to realize the fuel cycle benefits targeted by fast reactor systems. Fast spectrum breed-and-burn concepts have been proposed to provide extended fuel burnup without recycle. Existing light water reactors (LWRs) could be utilized for initial recycle of recovered plutonium. In general, these limited recycle techniques capture partial benefits for resource extension and waste management compared to a fuel cycle with fast reactors and full recycle. Another approach has been to modify other reactor types for fast spectrum application. Recent studies are considering "high conversion" LWRs, where the water density is severely reduced.[6] Alternately, molten salt reactor (MSR) concepts can be used to control molten fuel and moderator configurations during reactor operations.[4] These alternative reactor options are at a low technical maturity and require significant investment in fuel development, safety analysis, and technology development before they can be truly compared with the other Generation-IV options.

For near-term (within 20 years) deployment of fast reactors, the SFR technology is the only option with sufficient technical maturity.[7] Modern demonstration reactors are being built today, and innovative features for improved economics and safety are being developed. The alternate LFR, GFR, and MSR technologies offer some advantages, particularly for high temperature applications, and may be a future option if current feasibility research on improved materials, fuels, and safety is successful.

Large variations are observed in the estimated cost of commercial fast reactor systems; for current designs, these range from -10% to +40% compared to advanced LWR costs.[8] However, modern large power reactors being developed in national programs (e.g., Japan SFR [JSFR] and BN-1200 in Russia) claim capital costs similar to advanced LWRs. The PRISM design estimated capital costs 20% higher than advanced LWRs,[9] but this estimate included the colocated fuel cycle facilities, and the subsequent SUPERPRISM study with design refinements indicated ~20% more power from a smaller nuclear island.[10] Operating costs similar to conventional LWR reactors are estimated. Near-term demonstration plants can be considered as an indicator of current technology status. It is claimed that the BN-800 plant has a capital cost 20% higher than its Russian LWR counterpart, VVER-1200, with operating costs only 15% higher.[11] These international technology development and demonstration activities are important both to clarify the actual costs and to identify key cost factors for construction and operation of these first-of-a-kind demonstration plants. Conversely, the international research work on key technology innovations (e.g., advanced materials) will facilitate significant cost reductions to current designs, with the goal to make the costs comparable to LWRs.

Getting from the Present to the Future

Fast reactors were initially conceived as a means to “breed” fissile material by producing more new fissile atoms than were destroyed to release energy. In the early days of nuclear development, uranium resources were thought to be scarce, with rapid growth in electricity demand anticipated, driving the desire to extend fuel resources. This concern has not materialized because uranium has proven to be available in sufficient quantities. Thus, the urgency to deploy and commercialize this fuel cycle technology has waned. However, fast reactors also enable approaches that could reduce the waste disposal challenge by productively consuming materials that provide long-term disposal issues. This capability will become more important as nuclear waste management challenges and waste disposal options are clarified to complete the nuclear fuel cycle.

Because financed reactor capital investment is the dominant cost of any nuclear fuel cycle, even small reductions in capital costs or slight improvements in system performance can be important. To this end, a wide variety of innovative features— including compact fuel handling, vented fuel, compact heat exchangers (e.g., printed circuit diffusion bonding and twisted tubes), electromagnetic pumps, alternate heat transport, and containment configurations—have been identified. These features reduce cost by design simplification, system compaction, reduced commodities, and/or improved reactor performance. Some promising technology innovations to significantly reduce the cost of future fast reactors include the following:

- **Advanced materials:** Advanced structural materials could improve reactor costs by enabling compact configurations, higher operating temperatures, higher reliability, and longer lifetimes. Modern materials science techniques are being used to optimize variants of existing alloys for fast reactor application. Studies indicate a 40% reduction in commodities for major reactor components could be realized.
- **Advanced modeling and simulation:** New techniques will exploit modern computational hardware and visualization software. The improved modeling, in tandem with modern validation experiments, will make reactor design tools more predictive, reducing the reliance on calibration and conservative margins. Improved accuracy and better integration of methods will also promote design optimization.
- **Advanced energy conversion systems:** Refined energy production systems, such as a supercritical CO_2 Brayton cycle, offer the promise of improved thermal efficiency. Research needs for advanced heat exchangers (e.g., small tube configurations) and compact components are also being pursued.

In addition to capital cost reduction, future commercialization of fast reactor technology will require low technical risk and high system reliability. Key items that must be addressed for successful application of fast reactor technology include the following:

- **Safety assurance and demonstration:** Inherent safety is a key approach for licensing assurance and cost reduction. Fast reactor resilience to severe accident conditions was demonstrated in the EBR-II inherent safety demonstration tests.[12] A wide variety of design features for prevention and mitigation of severe accidents (e.g., natural circulation decay heat removal) are utilized in modern designs. The benefit and performance of features such as core restraint, seismic isolation, and "core catchers" are being assessed. The performance, reliability, and modeling of such features must be validated.

- **Development of robust recycle fuels:** Fast reactor fuels must cover a wide range of compositions to account for the variability of recycle material feeds and fuel cycle modes. Thus, irradiation testing is needed to assess fuel behavior with inclusion of recycled actinide and/or fission product elements. Furthermore, research is being conducted to reduce fuel cycle costs by extending fuel burnup and improving fabrication techniques.
- **Improved maintenance and inspection techniques:** The development of durable monitoring and repair technology is a key issue for reliable operations. Remote handling and sensor technology is being developed, such as ultrasonic "viewing" techniques for surveillance under opaque liquid metal coolants. Modern sensors are being designed and adapted for in-service inspection and repair applications.

In addition to technology development, institutional challenges for commercial demonstration and deployment of future nuclear technology options (not just fast reactors) include the following:

- The establishment of a licensing framework for advanced reactors
- Sustained R&D infrastructure for training of the next generation of scientists and engineers
- Establishment of mechanisms for financially recognizing the environmental and waste management benefits of nuclear energy options
- Creation of the industrial infrastructure (i.e., supply chain) to produce fast reactors and fuel
- The retention and transfer of essential institutional knowledge and specialized expertise as senior scientists and engineers retire

Endnotes

[1] Because of the need for uranium enrichment and partial fuel burnup in light water reactors, less than 1% of the energy content is converted to useful energy in the current once-through fuel cycle. Conversely, a fast reactor closed fuel cycle can recycle the spent fuel and utilize enrichment tails to achieve resource utilization >90% (depending on losses of actinide materials in the fuel cycle).

[2] International Atomic Energy Agency. "Status of Fast Reactor Research and Technology Development." IAEA-TECDOC-1691, 2012.

[3] Generation-IV SFR Members. "A Summary of Sodium-Cooled Fast Reactor Development." Progress in Nuclear Energy, 2014.

[4] International Atomic Energy Agency. "Status of Innovative Fast Reactor Designs and Concepts." Supplement to ARIS, October 2013.

[5] Generation-IV International Forum. "Technology Roadmap Update for Generation IV Nuclear Energy Systems." January 2014.

[6] Takeda, R.; Miwa, J.; Maiya, K. "BWRs for Long-Term Energy Supply and for Fissioning Almost All Transuranium." GLOBAL-2007 Conference: Advances in Nuclear Fuel Cycles and Systems, Boise, Idaho, September 2007.

[7] Joint JAEA, CEA, ANL. "Selection of Sodium Coolant for Fast Reactor in the U.S., France, and Japan." Nuclear Engineering and Design, January 2013.

[8] Hoffman, E.; Ganda, F. "The Advanced Fuel Cycle Cost Basis for Reactor Technologies." Transactions of the American Nuclear Society (108:101), June 2013.

[9] General Electric. "A Competitive Integral Fast Reactor with Enhanced Diversion Resistance." Global-99 Conference, 1999.

[10] General Electric. "Economic Assessment of S-PRISM Including Development and Generation Costs." ICONE-9 Conference, 2001.

[11] World Nuclear Association. "Fast Neutron Reactors." October 2014.

[12] Planchon, H.; Sackett, J.; Golden, G.; Sevy, R. "Implications of the EBR-II Inherent Safety Demonstration Tests." Nuclear Engineering Design (101:75), 1987.

Acronyms

ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
CEFR	China Experimental Fast Reactor
DFR	Dounreay Fast Reactor
EBR-I and II	Experimental Breeder Reactor I and II
FBTR	Fast Breeder Test Reactor
FFTF	Fast Flux Test Facility
GFR	Gas fast reactor
JSFR	Japan Atomic Energy Agency Sodium Fast Reactor
KNK	Kompakte Natriumgekühlte Kernreaktoranlage or Compact Sodium Nuclear Reactor Plant
LFR	Lead or lead-bismuth cooled fast reactor
LWR	Light water reactor
MSR	Molten Salt Reactor
PFBR	Prototype Fast Breeder Reactor
PFR	Prototype fast reactor
PGSFR	Prototype Generation-IV Sodium-cooled Fast Reactor
PRISM	Power Reactor Innovative Small Module
R&D	Research and development
SEFOR	Southwest Experimental Fast Oxide Reactor
SFR	Sodium-cooled fast reactor
TRU	Transuranic elements
UNF	Used nuclear fuel

Glossary

Breed and Breeder Reactor	Breeding is the process of producing fissile material, like plutonium-239. It occurs as a result of neutron capture in fertile material, like uranium-238. A breeder reactor is one that produces more fissile material than it consumes.
Burn and Burner Reactor	Burning is the process of fissioning atoms in a reactor. A burner reactor burns or fissions more fissile atoms than it produces. A burner reactor can be used to consume long-lived radioactive materials.
Burnup	Burnup is a measure of thermal energy released by nuclear fuel relative to its mass. It is typically expressed in Megawatt days per metric ton of fuel (MWd/MT).
Fast Neutrons	Fast neutrons are the neutrons released during fission that have high energy levels and are traveling at very high velocity.
Fast Reactor	A fast reactor is a reactor that is designed to have no moderator to slow down or lower the energy of the neutrons released during fission. Therefore, the fissions in the reactor are generated primarily from fast or high energy neutrons. Fast reactors can operate with a number of different coolants including sodium, lead, lead-bismuth, and helium. They can be operated to either breed more fissile material than they consume or to burn more material for waste management benefits.
GFR	The gas fast reactor or GFR is a Generation IV advanced reactor design (https://www.gen-4.org/gif/jcms/c_42148/gas-cooled-fast-reactor-gfr). The proposed reactor design operates at high temperatures and uses helium as a coolant. The reactor uses fast or high-energy neutrons and would likely employ a continuous recycle fuel cycle. Because of the high-temperatures generated, the system is proposed for potential support of a wide range of industrial processes requiring large amounts of heat or steam.
Generation IV International Forum	The Generation IV International Forum (GIF) is an international organization with the specific goal to develop concepts for one or more Generation IV reactor systems that can be licensed, constructed, and operated in a manner that will provide a competitively priced and reliable supply of energy to the country or countries where such systems may be deployed, while satisfactorily addressing nuclear safety, waste, proliferation and public perception concerns. The charter for GIF was signed in 2001. The organization has expanded to include 13 countries that collaborate on the development of Generation IV reactor systems.

Generation IV Reactor	Generation IV reactors are the next generation of reactors that are currently being researched for potential deployment in the future. Reactors operating today are primarily Generation II and III designs. New reactors under construction in the United States are considered Generation III+.
High Level Waste	High level waste or HLW is the highly radioactive liquid and solid materials resulting from the reprocessing or recycling of used nuclear fuel. HLW contains the bulk of the fission products from used nuclear fuel and some uranium and transuranic elements. HLW would be disposed in a geological repository.
LFR	Lead or lead-bismuth cooled fast reactor or LFR is a Generation IV advanced reactor design (https://www.gen-4.org/gif/jcms/c_9358/lfr). The proposed reactor design operates with molten lead as a coolant. The reactor uses fast or high-energy neutrons and would likely employ a continuous recycle fuel cycle.
LWR	Light Water Reactors are the standard reactor design deployed today. They use normal water (H_2O) as the coolant and neutron moderator to lower the energy of the neutrons to thermal levels. The fuel is typically uranium dioxide pellets that are placed into cladding of a zirconium alloy. The system can operate with low-enriched uranium. In the United States and a number of other countries, LWRs are operated using a once-through fuel cycle, but some countries also deploy a limited recycle option.
Moderator (neutron)	Material used to lower the energy level of neutrons (from fast to thermal) that are generated from fission. Moderators are materials like natural water, heavy water, or graphite. The energy of the neutron is lowered due to collisions with the moderator atoms.
MSR	Molten Salt Reactor or MSR is a Generation IV advanced reactor design (https://www.gen-4.org/gif/jcms/c_9359/msr). The MSR is distinguished by its core in which the fuel is dissolved in molten fluoride salt. The salt is both the fuel and coolant. The reactor can be designed to operate with either low or high-energy neutrons. The MSR has been proposed for operation as both a once-through fuel cycle and a continuous recycle fuel cycle.
Nuclear Fuel Cycle	Nuclear Fuel Cycle or NFC is the series of industrial processes, which involve the production of electricity from uranium in nuclear power reactors (http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Introduction/Nuclear-Fuel-Cycle-Overview/). The processes can vary depending on reactor type and on the disposition of used nuclear fuel.

Reprocessing or recycling	Reprocessing is the chemical treatment of used nuclear fuel to separate uranium and plutonium and possibly transuranic elements from the fission products. The recovered uranium, plutonium, and transuranic elements can be recycled to a reactor to be burned. The fission products can be converted to high-level waste for disposal. Example technologies include aqueous-based processes like PUREX and dry processes like electrochemical recycling.
SFR	Sodium-cooled Fast Reactor or SFR is a Generation IV advanced reactor design (https://www.gen-4.org/gif/jcms/c_9361/sfr). The proposed reactor design operates with molten sodium as a coolant. The reactor uses fast or high-energy neutrons and would likely employ a continuous recycle fuel cycle.
Thermal Neutron	A neutron whose energy has been reduced by collisions with moderator materials such that the neutron is in thermal equilibrium with the medium in which it is interacting.
Transuranic elements	Transuranic elements or TRU are artificially made, radioactive elements that have an atomic number higher than uranium in the periodic table of elements such as neptunium, plutonium, americium, and others.
Traveling Wave Reactor	The traveling wave reactor is a fast reactor design that has also been termed the breed and burn concept. Most of the fissile material for this reactor design is bred from fertile material like uranium-238. A small amount of enriched fissile material is needed to start the reaction. In theory the zone in the reactor where the bulk of the fission occurs moves over time as material is bred in adjacent regions, hence the traveling wave. A reactor design of this type is currently being developed by TerraPower (http://terrapower.com/).
Used Nuclear Fuel	Used Nuclear Fuel or UNF are fuel assemblies that have been removed from a nuclear reactor after being used to power the reactor. UNF can be either recycled or disposed as a waste.