Gas-Cooled Fast Reactor

The GFR system features a fast-neutron-spectrum, helium-cooled reactor, and a closed fuel cycle. The high outlet temperature of the helium coolant makes it possible to deliver electricity, hydrogen, or process heat with high efficiency. The reference reactor is a 1200-MWe system with an outlet temperature of 850°C. A direct Brayton cycle gas turbine provides high thermal efficiency.

Several fuel forms hold the potential to operate at very high temperatures and to ensure excellent retention of fission products. These forms include composite ceramic fuel, advanced fuel particles, and ceramic-clad elements of actinide compounds. The GFR reference has an integrated, on-site spent fuel treatment and refabrication plant.

Advantages and challenges: It is anticipated that GFR systems will minimize the production of long-lived radioactive waste and make it possible to utilize fissile and fertile materials (including depleted uranium) a hundred times more efficiently than thermal spectrum systems.

Key challenges: the core design, the helium turbine, and the development of new fuels and materials capable of operating at temperatures of 850°C. The design is intended to overcome the consequences of cooling with a high-pressure gas having poor thermal characteristics.

Very-High-Temperature Reactor

The VHTR is a graphite-moderated, helium-cooled reactor with a thermal neutron spectrum. It is designed to be a high-efficiency system that can supply electricity and process heat to a broad range of high-temperature and energy-intensive processes.

The reference reactor is a 600 MWth core connected to an intermediate heat exchanger to deliver process heat. The reactor core can be a prismatic block core or a pebble-bed core. Fuel particles are coated with successive layers of high-temperature materials, then formed either into graphite-coated pebbles, or compacts embedded in graphite blocks. The reactor supplies heat with core outlet temperatures up to 1000°C, which enables such applications as hydrogen production or process heat for the petrochemical industry.

Hydrogen can be efficiently produced from water by thermochemical reactions such as the iodine-sulfur process, or the bromine-calcium process, by high temperature electrolysis, or with additional natural gas by the steam reformer process.

Thus, the VHTR
offers high-efficiency electricity production and a broad range of process heat applications, while retaining the desirable safety characteristics in normal as well as off-normal events.

The basic technology for the VHTR has been well established in former High Temperature Gas Reactor plants around the world. The technology is being advanced through near- or medium-term projects led by several plant vendors and national laboratories.

**Advantages and challenges:** As the basic technology for VHTR systems has already been established in high temperature gas reactor plants, the design is an evolutionary development. However, the system’s aim of operating above 1000°C presents significant challenges in terms of fuel and materials development, as well as safety under transient conditions.

**Lead-Cooled Fast Reactor**

The LFR features a fast-spectrum lead or lead/bismuth eutectic liquid-metal-cooled reactor and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides. It has excellent materials management capabilities because it operates in the fast-neutron spectrum and uses a closed fuel cycle for efficient conversion. It can also serve as a burner to consume actinides from spent LWR fuel, and as a burner/breeder with thorium matrices.

An important feature of the LFR is the enhanced safety that results from the choice of molten lead as a relatively inert coolant. In terms of sustainability, lead is abundant and hence readily available. More important, fuel sustainability is greatly enhanced by the conversion capabilities of the LFR fuel cycle.

The LFR was primarily envisioned for electricity and hydrogen production, and actinide management. Given its R&D needs in the areas of fuels, materials, and corrosion control, a two step process leading to industrial deployment of the LFR system has been envisioned: by 2025 for reactors operating with relatively low primary coolant temperature and low power density; and by 2035 for more advanced designs.

The **Small Secure Transportable Autonomous Reactor** (SSTAR), developed in the United States, is a small factory-built turnkey LFR plant operating on a closed fuel cycle with very long refueling interval (15 to 20 years or more), and a cassette core or replaceable reactor module. The current reference design for the SSTAR in the United States is a 20 MWe natural circulation reactor concept with a small shippable reactor vessel. Specific features of the lead coolant, the nitride fuel containing transuranic elements, the fast spectrum core, and the small size combine to promote proliferation resistance. SSTAR also enables fissile self-sufficiency, autonomous load following, simplicity of operation, reliability, transportability, and a high degree of passive safety.

A supercritical carbon dioxide Brayton cycle power converter enables conversion of the core thermal power into electricity at a high plant efficiency of 44%.

The main advantages of the LFR system are its expected fuel efficiency, its capabilities in terms of nuclear materials management (thereby mitigating proliferation risks) and the reduced production of high-level radioactive waste and actinides.

**Molten Salt Reactor**

The MSR system contains an integrated fuel cycle, and produces fission power from a molten salt fuel circulating in a fast or epithermal-spectrum reactor. In the MSR system, the fuel is a circulating liquid of sodium, zirconium, and uranium fluorides. The molten salt fuel flows through graphite core channels, producing an epithermal spectrum. The heat generated in the molten salt is transferred to a secondary coolant system through an intermediate heat exchanger, and then through a tertiary heat exchanger to the power conversion system. The reference plant has a power level of up to 1000 MWe. The system has a coolant outlet temperature of 700°C, possibly ranging up to 800°C, enabling improved thermal efficiency.

The closed fuel cycle can be tailored to the efficient burn-up of plutonium and minor actinides. The MSR’s liquid fuel allows addition of actinides such as plutonium, and avoids the need for fuel fabrication. Actinides and most fission products form fluorinides in the liquid coolant. Molten fluoride salts have excellent heat transfer characteristics and very low vapor pressure, which reduce stresses on the vessel and piping.

The main benefits of the MSR system are that it offers an integrated fuel cycle, embodying a burner/breeder reactor concept while taking advantage of the excellent heat transport properties of molten salt. These properties imply that the thermal power output would be higher, and the building housing a MSR could be smaller than that needed for other reactor concepts.
The main challenge is that molten salt chemistry and handling promote corrosion of reactor components, which requires development of new materials. Another challenge is refinement of the fuel cycle.

**Sodium-Cooled Fast Reactor**

The SFR features a fast-spectrum, sodium-cooled reactor and a closed fuel cycle for efficient management of actinides and conversion of fertile uranium. It is designed for management of high-level wastes and, in particular, management of plutonium and other actinides. Important safety features of the system include a long thermal response time, a large margin to coolant boiling, a primary system that operates near atmospheric pressure, and intermediate sodium system between the radioactive sodium in the primary system and the power conversion system. Water/steam and carbon-dioxide are being considered as the working fluids for the power conversion system to achieve high thermal efficiency, safety, and reliability. With innovations to reduce capital cost, the SFR can serve markets for electricity.

The fuel cycle is based on a full actinide recycle with three major options. The first option is a large size (600 to 1500 MWe) loop-type sodium-cooled reactor with mixed uranium-plutonium oxide fuel, supported by a fuel cycle based on advanced aqueous processing at a central location serving a number of reactors.

The second option is an intermediate size (300 to 600 MWe) pool-type reactor; and the third a small size (50 to 150 MWe) modular-type sodium-cooled reactor with uranium-plutonium-
minor-actinide-zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in facilities integrated with the reactor. The outlet temperature is approximately 550°C for all three concepts.

The SFR system already benefits from considerable technological experience, and also offers the potential to operate with a high conversion fast spectrum core, with the resulting benefit of increasing the utilization of fuel resources. The envisaged SFR capability to efficiently and nearly completely consume trans-uranium as fuel would reduce the actinide loadings in the high-level radioactive waste it produces. Such reductions would bring benefits in the radioactive waste disposal.
requirements associated with the system, and enhance its non-proliferation attributes. Reducing the capital cost and improving passive safety, especially under transient conditions, are the major challenges for the SFR system.

**Supercritical-Water-Cooled Reactor**

The SCWR system is a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water (374°C, 325 MPa). The supercritical water coolant enables a thermal efficiency about one-third higher than current light-water reactors. The balance of plant is considerably simplified because the coolant does not change phase in the reactor, and is directly coupled to the energy conversion equipment. The reference system is 1700 MWe with an operating pressure of 25 MPa, and a reactor outlet temperature of 510°C, possibly ranging up to 550°C. The fuel is uranium oxide. Passive safety features are incorporated, similar to those of simplified boiling water reactors.

The SCWR system is primarily designed for efficient electricity production, with an option for actinide management based on two options in the core design: the SCWR may have a thermal or fast-spectrum reactor; or it may have a closed cycle with a fast-spectrum reactor and full actinide recycle based on advanced aqueous processing at a central location.

The system is based on existing light water reactor technology, providing extensive worldwide experience in construction and operation. Proposed designs are likely to provide high thermal efficiency and a simplified system configuration. A SCWR design could be developed with a fast neutron spectrum. Fast neutrons with higher kinetic energies would enable the system to produce at least as much fissile material as it consumes.

However, this concept’s tendency to have a positive void reactivity coefficient, together with the potential for design basis loss-of-coolant accidents, are likely to make this difficult to develop. The other major challenges for the SCWR are to develop a viable core design, accurately estimate the heat transfer coefficient, and develop materials for the fuel and core structure that will be sufficiently corrosion-resistant to withstand SCWR conditions.

*For more information: George Theus, Metallurgical Engineering Inc., Aurora, IL 60504; 630/723-0068; gjtheus@comcast.net.*