# THE GAS-COOLED FAST REACTOR SYSTEM

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## ABSTRACT

The Gas-Cooled Fast Reactor (GFR) system is one of six Generation IV systems selected for cooperative research and development by the Generation IV International Forum. The GFR features a fast-neutron spectrum and closed fuel cycle for efficient conversion of fertile uranium and management of actinides. A full actinide recycle fuel cycle with on-site fuel cycle facilities is envisioned. The fuel cycle facilities can minimize transportation of nuclear materials and will be based on either advanced aqueous, pyrometallurgical, or other dry processing options. The reference reactor is a 600-MWth/288-MWe, helium-cooled system operating with an outlet temperature of 850°C using a direct Brayton cycle gas turbine for high thermal efficiency. Several fuel forms are being considered for their potential to operate at very high temperatures and to ensure an excellent retention of fission products: composite ceramic fuel, advanced fuel particles, or ceramic clad elements of actinide compounds. Core configurations are being considered based on pin- or plate-based fuel assemblies or prismatic blocks.

The GFR is primarily envisioned for missions in electricity production and actinide management, although it may be able to also support hydrogen production. Given its R&D needs for fuel and recycling technology development, the GFR is estimated to be deployable by 2025.

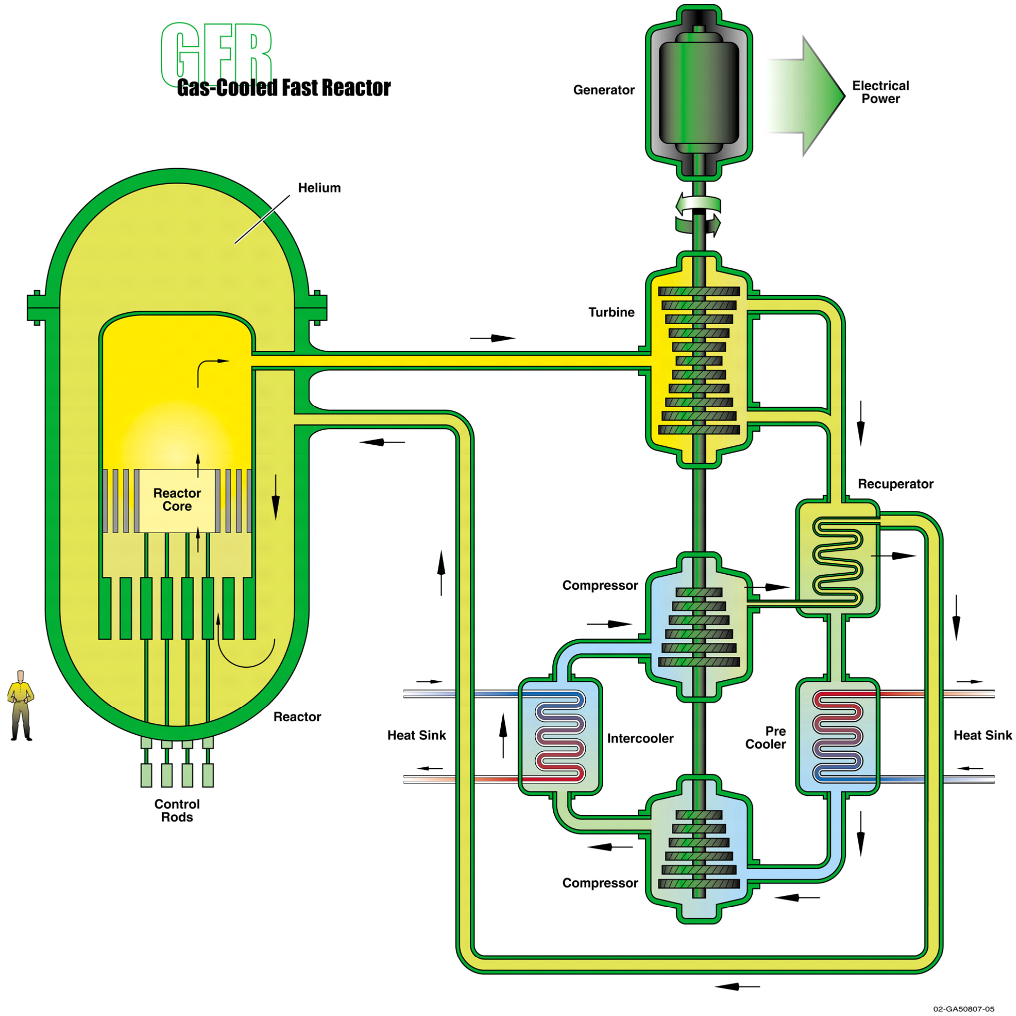
## INTRODUCTION

Generation IV nuclear energy systems target significant advances over current generation and near-term deployment systems in the areas of sustainability, economics, safety and reliability, and proliferation resistance and physical protection. These systems are to be deployable no later than 2030 in both industrialized and developing countries for generation of electricity and other energy products such as hydrogen for use as a transportation fuel and fresh water for world regions facing future shortages. Six Generation IV systems have recently been selected for development by the Generation IV International Forum; they are described in the Generation IV Nuclear Energy Systems Technology Roadmap. Research and development needs for each system are also identified in the Roadmap.

One of the selected Generation IV systems is the gas-cooled fast reactor (GFR) system. The GFR system is top-ranked in sustainability because of its closed fuel cycle and excellent potential for actinide management. It is rated good in safety, economics, and in proliferation resistance and physical protection. This paper describes the GFR, outlines its development status and technology needs, and describes major R&D activities recommended by technical team that developed the generation IV Roadmap.

## GFR DESCRIPTION

The GFR system features a fast-spectrum helium-cooled reactor [shown below] and closed fuel cycle. Like thermal-spectrum helium-cooled reactors such as the GT-MHR and the PBMR, the high outlet temperature of the helium coolant makes it possible to deliver electricity, hydrogen, or process heat with high conversion efficiency. The GFR uses a direct-cycle helium turbine for electricity and can use process heat for thermochemical production of hydrogen. Through the combination of a fast-neutron spectrum and full recycle of actinides, GFRs minimize the production of long-lived radioactive waste isotopes. The GFR's fast spectrum also makes it possible to utilize available fissile and fertile materials (including depleted uranium from enrichment plants) two orders of magnitude more efficiently than thermal spectrum gas reactors with once-through fuel cycles. The GFR reference assumes an integrated, on-site spent fuel treatment and refabrication plant.




A summary of design parameters for the GFR system is given in the following table.

| Reactor Parameters | Reference Value |
|---|---|
| Reactor Power | 600 MWth |
| Net plant efficiency (direct cycle helium) | 48% |
| Coolant inlet/outlet temperature and pressure | 490°C/850°C at 90 bar |
| Average power density | 100 MWth/$m^3$ |
| Reference fuel compound | UPuC/SiC (70/30%) with about 20% Pu content |
| Volume fraction, Fuel/Gas/SiC | 50/40/10% |
| Conversion ratio | Self-sufficient |
| Burnup, Damage | 5% FIMA; 60 dpa |

## TECHNOLOGY BASE FOR THE GFR

The technology base for the GFR includes a number of thermal spectrum gas reactor plants, as well as a few fast-spectrum gas-cooled reactor designs. Past pilot and demonstration projects include decommissioned reactors such as the Dragon Project, built and operated in the United Kingdom, the AVR and the THTR, built and operated in Germany, and Peach Bottom and Fort St Vrain, built and operated in the United States. Ongoing demonstrations include the HTTR in Japan, which reached full power (30 MWth) using fuel compacts in 1999, and the HTR-10 in China, which may reach 10 MWth in 2002 using pebble fuel. A 300 MWth pebble bed modular demonstration plant is being designed by PBMR Pty for deployment in South Africa, and a consortium of Russian institutes is designing a 300 MWth GT-MHR in cooperation with General Atomics. The design of the PBMR and GT-MHR reactor systems, fuel, and materials are evolutionary advances of the demonstrated technology, except for the direct Brayton-cycle helium turbine and implementation of modularity in the plant design. The GFR may benefit from development of these technologies, as well as development of innovative fuel and very-high-temperature materials for the VHTR. A phased development path may be drawn from the thermal to the fast-spectrum gas-cooled systems.

**TECHNOLOGY GAPS FOR THE GFR**

Demonstrating the viability of the GFR requires meeting a number of significant technical challenges. Fuel, fuel cycle processes, and safety systems pose the major technology gaps:

- GFR fuel forms for the fast-neutron spectrum
- GFR core design, achieving a fast-neutron spectrum for effective conversion with no fertile blankets
- GFR safety, including decay heat removal systems that address the significantly higher power density (in the range of 100 $MWth/m^3$) and the reduction of the thermal inertia provided by graphite in the modular thermal reactor designs
- GFR fuel cycle technology, including simple and compact spent-fuel treatment and refabrication for recycling.

Performance issues for GFR include:

- Development of materials with superior resistance to fast-neutron fluence under very-high-temperature conditions
- Development of a high-performance helium turbine for efficient generation of electricity
- Development of efficient coupling technologies for process heat applications and the GFR's high temperature nuclear heat.

The GFR has several technology gaps in its primary systems and balance of plant that are in common with the GT-MHR. Also, the development of very-high-temperature materials with superior resistance to fast-neutron fluence and innovative refractory fuel concepts with enhanced fission product retention capability are of generic interest to other types of reactors, including the VHTR and water-cooled reactors.

Target values of some key parameters such as power density and fuel burnup are sufficient for reasonable performance of a first-generation new fuel technology. Because these parameters have a direct impact on technical and economical performance, there is strong incentive for additional performance phase R&D, with the goal of further upgrading the power density to beyond 100 $MWth/m^3$ and the fuel burnup to the range of 15% FIMA.

**GFR R&D SCOPE**

An R&D program is recommended to assess the viability of the GFR and conduct the performance R&D required for successful demonstration of the GFR. This development includes R&D on fuel, fuel cycle processes (treatment and refabrication), reactor systems, balance of plant, and computer codes needed for design studies and safety demonstration. A conceptual design of an entire GFR prototype system can be developed by 2019. The prototype system is envisioned as an international project that could be placed in operation by 2025.

**GFR FUELS AND MATERIALS R&D**

**A. Candidate Fuels**

A composite ceramic-ceramic fuel (cercer) with closely packed, coated (U, Pu)C kernels or fibers is the best option for fuel development. Alternative fuel options for development include fuel particles with large (U, Pu)C kernels and thin coatings, or ceramic-clad, solid-solution metal (cermet) fuels. The need for a high density of heavy nuclei in the fuel leads to actinide-carbides as the reference fuel and actinide-nitrides with 99.9% enriched nitrogen as the backup.

Initially, the research should focus on studying potential candidate fuels and evaluating their technical feasibility based on existing information on the structural integrity and radiation resiliency of the coating system and the chemical compatibility among the different materials for the GFR service conditions (e.g., temperatures up to 1400°C, burnup up to 250 GWD/MTHM, and radiation resiliency up to 100 to 150 dpa). This will lead to the establishment of reference and backup options. These options will undergo a series of irradiation and high-temperature safety tests in concert with fuel modeling activities to establish the performance of the fuel type. Irradiations range from small-scale experiments in existing reactors to large-scale prototype fuel assemblies under representative GFR conditions. The research is expected to take nearly 20 years to complete.

Fuel fabrication techniques must be developed to be compatible with on-site processing for actinide recovery and remote fuel fabrication. Innovative methods such as vapor deposition or impregnation are among the candidate techniques for on-site manufacturing of composite ceramic fuel (cercer, with cermet as backup). For pin-type fuels, ceramic cladding capable of confining fission products will be considered. Samples of irradiated fuels will be used to test current and innovative fuel treatment processes likely to be compatible with remote simple and compact technologies for actinide spent fuel treatment and refabrication before recycling.

**B. Candidate Materials**
The main challenges are in-vessel structural materials, both in-core and out-of-core, that will have to withstand fast-neutron damage and high temperatures, up to 1600°C in accident situations. Ceramic materials are therefore the reference option for in-core materials, and composite cermet structures or inter-metallic compounds will be considered as a backup. For out-of-core structures, metal alloys will be the reference option.

The most promising ceramic materials for core structures are carbides (preferred options are SiC, ZrC, TiC, NbC), nitrides (ZrN, TiN), and oxides (MgO, $Zr(Y)O_2$). Inter-metallic compounds like $Zr_3Si_2$ are promising candidates as fast-neutron reflector materials. Limited work on Zr, V or Cr as the metallic part of the backup cermet option should also be undertaken.

For other internal core structures, mainly the upper and lower structures, shielding, the core barrel and grid plate, the gas duct shell, and the hot gas duct, the candidate materials are coated or uncoated ferritic-martensitic steels (or austenitic as alternative solution), other Fe-Ni-Cr-base alloys (Inco 800), and Ni-base alloys. The main candidate materials for pressure vessels (reactor, energy conversion system) and cross vessel are 21/4 Cr and 9-12 Cr martensitic steels.

The recommended R&D activities include a screening phase with material irradiation and characterization, a selection of a reference set of materials for core structural materials, and then optimization and qualification under irradiation.

The program goal is to select the materials that offer the best compromise regarding:

- Fabricability and welding capability
- Physical, neutronic, thermal, tensile, creep, fatigue, and toughness properties and their degradation under low-to-moderate neutron flux and dose
- Microstructure and phase stability under irradiation
- Irradiation creep, in-pile creep, and swelling properties
- Initial and in-pile compatibility with He (and impurities).

Recommended R&D activities on out-of-core structures consists of screening, manufacturing, and characterizing materials for use in the pressure vessel, primary system, and components (pipes, blowers, valves, heat exchangers).

With respect to materials used for the balance of plant, the development program includes screening, manufacturing, and characterizing heat-resisting alloys or composite materials for the Brayton turbomachinery (turbine disk and fins), as well as for heat exchangers, including the recuperator of the Brayton cycle. Likewise, in the case of nonelectricity energy products, materials development is required for the intermediate heat exchanger that serves to transfer high-temperature heat in the helium coolant to the process heat applications. R&D recommended for these systems is discussed in the Crosscutting Energy Products R&D section.

**GFR REACTOR SYSTEMS R&D**
The innovative GFR design features to be developed must overcome shortcomings of past fast-spectrum gas-cooled designs, which were primarily low thermal inertia and poor heat removal capability at low helium pressure. Various passive approaches will be evaluated for the ultimate removal of decay heat in depressurization events. The conditions to ensure a sufficient back pressure and to enhance the reliability of flow initiation are some of the key issues for natural convection, the efficiency of which will have to be evaluated for different fuel types, power densities, and power conversion unit. Dedicated systems, such as semipassive heavy gas injectors, need to be evaluated and developed. There is also a need to study the creation of conduction paths and various methods to increase fuel thermal inertia and, more generally, core capability to store heat while maintaining fuel temperature at an acceptable level.

**GFR BALANCE-OF-PLANT R&D**
Performance R&D is required for the high-temperature helium systems, specifically:

- Purification, control of inventory, and in-service monitoring of interactions between helium and the materials it contacts
- Heat transfer and flow pattern through the core, the circuits, and the heat exchangers
- Dynamics of the circuits and the structures, acoustics of the cavities.

**GFR SAFETY R&D**

Because of the high GFR core power density, a safety approach is required that relies on intrinsic core properties supplemented with additional safety devices and systems as needed, but minimizes the need for active systems. After in-depth studies have defined the safety case, safety systems will be demonstrated experimentally. Transient fuel testing, of both the developmental and confirmatory kind, will be conducted. Concurrently, model and code development is required to provide the basis for the final safety case. An integrated safety experiment, simulating the safety case of the GFR, will be prepared. It is expected that the safety experiments will require an integral helium loop on the order of 20 MWth.

**GFR DESIGN AND EVALUATION R&D**

The most important issues regarding economic viability of the GFR are associated with the simplified and integrated fuel cycle, and the modularity of the reactor—this includes volume production, in-factory prefabrication, and sharing of on-site resources.

The GFR design and safety analysis will require development of novel analysis tools capable of modeling the core with its novel fuel and subassembly forms, unusual fuel composition, and novel safety devices. The analysis tools must be validated to demonstrate with sufficient accuracy the safe behavior of the entire system under all operational conditions. This requires new neutronics, thermal-gas dynamics, operation, and safety models, or significant adaptations of existing codes. Validation of the models requires that critical experiments and subassembly mockup testing and possibly other qualification experiments be conducted.

**GFR FUEL CYCLE R&D**

The range of fuel options for the GFR underscores the need for early examination of their impacts on the system, especially its fuel cycle. Existing fuel cycle technologies need to be further developed or adapted to allow for the recycling of actinides while preserving the economic competitiveness of the nuclear option in the medium and long term.

Laboratory-scale processes for treatment of carbide, nitride, or oxide dispersion fuels in ceramic or metal matrices have been evaluated and appear technically feasible. However, extensive experimental work is required in order that the process concepts can be proven feasible for fuel treatment at production scale.

**A. Compatibility of Fuel and Fuel Recycling Technology Options**

The capabilities of both advanced aqueous and pyrochemical processes for recycling the fuel options under consideration will be assessed, while taking into account the facility requirements associated with on-site fuel conditioning and refabrication. R&D on the two options is discussed in the Crosscutting Fuel Cycle R&D section.

The objective for the GFR fuel cycle R&D is to seek solutions for the separation of its unique materials of the matrices and coatings from actinide compounds that (1) develop the capability to treat cercer fuels, as well as coated particle fuel or cermet as a backup, (2) minimize the release of gaseous and liquid effluents to the environment, (3) take into account, starting at the design stage, the management of induced secondary waste from treatment and conditioning, (4) simplify the integration of treatment and fuel manufacturing operations, and (5) allow for integrated in situ treatment.

Both aqueous and pyrochemical processing methods, and combinations of the two processes, will be tested on the inert-matrix fuels. Hybrid processes may prove to be superior in the long run. Candidate processes with reasonable expectations of technical feasibility need to be compared in detail at the conceptual stage. The evaluations will be based on mass-balance flow-sheets and estimates of equipment and facility requirements necessary to meet established criteria for product quality and throughput capacity.

**B. Scale Up and Demonstration**

An important phase of the R&D program will be to demonstrate, at the level of several kilograms of the selected fuel, the treatment and refabrication of irradiated fuel. The objective is to select and demonstrate the scientific viability of a process by the end of 2012. After process screening, mostly with surrogate materials, more in-depth studies of the selected treatment process will be performed in hot laboratories using irradiated fuel samples provided by the irradiation program for fuel development.  The final phase of the development program will consist of demonstrating the technologies associated with the fuel cycle plant of the GFR prototype system.

**SUMMARY**

The GFR offers significant potential to advance generation IV sustainability goals (through its fast spectrum and closed fuel cycle) and economic goals (through its high thermal efficiency, direct cycle energy conversion, capability to produce hydrogen and other energy products, and modular plant arrangement).  Technical challenges to its successful development include the need for new, high-actinide density fuels capable of high temperature operation, high-temperature structural materials that resist fast-neutron irradiation damage, assurance of the targeted level of safety, and achievement of low system cost.  The Roadmap R&D recommendations for the GFR are designed to address these challenges and realize the system's potential to meet the Generation IV goals.

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