# GAS-COOLED FAST REACTOR (GFR): OVERVIEW AND PERSPECTIVES

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## I. INTRODUCTION

The Gas-cooled Fast Reactor (GFR) system features a high temperature helium cooled fast spectrum reactor. It is associated to a close fuel cycle. The GIF Technology Roadmap [1] identified the GFR as a technology that associates therefore the advantages of fast spectrum systems for long term resources sustainability, in terms of use of uranium and waste minimization (through fuel multiple reprocessing and fission of long-lived actinides) with those of the high temperature (high thermal cycle efficiency and industrial use of the generated heat for hydrogen or industrial process).

The GFR is a fast neutron spectrum system that must be seen as a complement to the SFR deployment, which benefits from a more mature technology, with higher potential performance for a longer term industrial deployment. It uses the same fuel recycling processes. The GFR can also be seen as a sustainable version of thermal spectrum helium-cooled reactors (HTRs), which also benefit from a more mature technology, with fuel recycling and optimal use of mining resources. It uses basically the same technology.

This paper illustrates the technical progress achieved in the countries participating to the GIF effort on the GFR system.

## II. GFR IN GENERATION IV

The GFRs development approach is to rely on technologies already used for the HTRs but with significant advances, in order to reach the objectives stated above. Thus, it calls for specific R&D beyond the foreseen work for thermal HTRs.

The main GFR design specifications as derived from the general objectives of Generation IV systems are:

- Use of gas as a coolant as a means of reaching high temperatures;
- Economic competitiveness by means of simplicity, compactness and efficiency;
- A robust safety demonstration, based on probabilistic safety assessment and defence in depth principles, and including severe accident management.

Additional design specifications of the GFR include:

- Fast neutron spectrum core with a zero (self-breeding) or positive breeding gain, with no or very limited use of fertile blankets in order to:
  - Generate as much fissile material as it consumes, with an optimal use of uranium;

  - Have a fuel cycle fed with only depleted or natural uranium;
  - Achieve homogeneous recycling of all actinides, in order to have no separation of plutonium from other actinides (proliferation resistance).

- Core plutonium inventory not exceeding 10 tons/GWe, in order to have a realistic reactor fleet deployment (in a few decades) and high fuel burn-up.

In the HTR the use of graphite increases the thermal inertia of the core, thereby limiting the maximum temperature during transients. On the other hand, GFR cores have relatively low thermal inertia; design features aimed at overcoming this apparent unfavourable feature include:

- A fuel element based on refractory materials and high thermal conductivity, with the ability to ensure radioactive material confinement up to very high temperatures.
- A primary circuit design based on upward core cooling and a moderate pressure drop for all the primary components and circuit involved in accident scenarios. One essential parameter for safety system performance is gas pressure. The primary helium is pressurized to 7 MPa under nominal conditions. A gas tight envelope enclosing the primary circuit has been added in order to limit the loss of pressure in case of primary loss of coolant. Maintaining high helium density allows the Decay Heat Removal system to rely on moderate pumping power and even on passive natural convection in some situations.

The fuel element is able to withstand high operating temperatures and transients associated with the poor heat capacity of the gas coolant. The main temperature limits are the following:

- An operating temperature, around 1 000°C, that provides a sufficiently ample margin to failure;
- A boundary temperature of 1 600°C below which fission products release is prevented;
- An upper temperature of 2 000°C below which the core geometry can safely be cooled down.

Concerning the objectives of ultimate waste minimization, proliferation resistance and natural resources optimization (zero or positive breeding gain), the major corresponding reactor design options are:

- No fertile blanket and multi-pass recycling of all actinides without separation;
- Loading of 1.1% of Minor Actinides (corresponding to self-recycling);
- A high density fuel with maximisation of actinide content;
- High core power density of about 100 MW/m3;
- A high core power unit of 2 400 MWth (for economic reasons);
- Mean overall core Burn-Up: 5% FIMA.

These high level objectives imply various additional secondary specifications such as minimization of the reactivity swing per cycle, or minimization of the core pressure drops for example.

## III. GFR DESIGN OPTIONS

Reference option of the GFR is a 1 200 MWe reactor for electricity production.

A significant effort has been carried out since 2001 to propose a first consistent design of the reactor and its fuel. The GFR design is still evolving, however major design directions have been decided on, concerning the fuel, core materials, reactor architecture, and safeguard systems. The current reactor design reaches the initial set of performance:

- Self-generation of Plutonium in the core to ensure Uranium resources saving;

- Uranium fertile blanket free to reduce the proliferation risk;
- A limited mass of plutonium in the core to allow an industrial deployment of the fleet taking into account the initial restricted inventory;
- An ability to transmute long lived nuclear waste resulting from a recycling of the spent fuel, without lowering the other quoted performance;
- A high power conversion ratio (favourable for economics).

In parallel, the safety architecture was thought to cover the potential defects fitted to this system, thanks to the following elements:

- A fuel element that uses refractory materials and withstands very high temperatures;
- A gas voiding reactivity effect in the core naturally not significant;
- A current design allowing the decay heat to be removed in any accidental situations (pressurized or not, even in case of large primary break, including an additional single failure or multiple failures), thanks to different systems of moderate power supply and to a gas tight envelope.
- In addition, natural convection capabilities can be retained in most of the situations (including small primary break), leading to a real advantage in terms of Decay Heat Removal strategy robustness and progressiveness. Thus, these situations can be managed in a passive way, including the total loss of electrical power.

Nevertheless, several technical fields are only partially covered today or they need to be optimized.

***Fuel element:***

At least two fuel concepts have the potential to fulfil the above requirements, that is: a ceramic plate-type fuel element and a ceramic pin-type fuel element. The reference material for the structure is reinforced ceramic, a silicon carbide composite matrix ceramic. The fuel compound is made of pellets of mixed uranium-plutonium-minor actinide carbide. A leak-tight barrier made of a refractory metal or of a Si-based multi layer ceramics is added to prevent fission products diffusion through the clad. GFR fuel development and design studies are presented in J. Somers. [3]

***Core design and performance:***

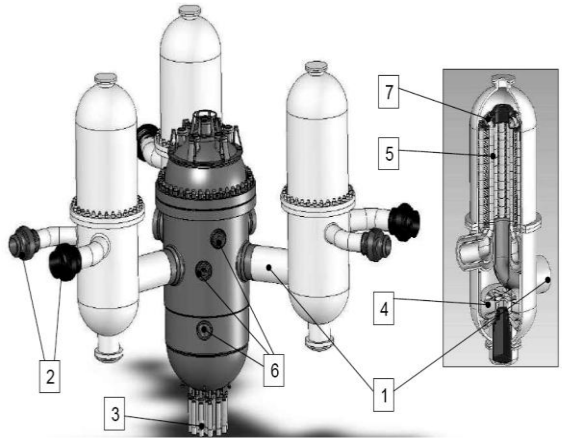
The core layout (246 fissile subassemblies, 24 control rods) has been chosen to be consistent with the maximum power derived from thermo-mechanical and thermal-hydraulic analyses, the requirements of the reactivity control system and the optimized power distribution. The main characteristics of a reference core are summarized in the table below.

| **GFR 2400 MWth, Reference core** | |
|---|---|
| CORE – SUB-ASSEMBLY | |
| H/D fissile core | 0.62 |
| Inter-assembly gap (mm) | 3 |
| Fissile height (mm) | 2349 |
| He blade thickness between two plates (mm) | 4.00 |
| FUEL ELEMENT | |
| Plate thickness (mm) | 8.4 |
| Clad thickness (mm) | 0.85 |
| Internal liner (µm) | 40+10 = 50 |
| Pellet diameter (mm) | 11.285 |
| Pellet height (mm) | 6.5 |
| OPERATING CONDITIONS | |
| Core pressure drop (MPa) | 0.14 |
| Tmax fuel (°C) | 1318 |
| Tmax clad (°C) | 920 |
| CERAMIC PLATE CORE – MAIN FEATURES | |
| TRU enrichment (%) | 18.2 |
| Core management (eq. full power days) | 3×600=1800 |
| Average discharge burn up (at% FIMA) | 6.7 |
| Breeding Gain | -0.03 |

***Primary system:***

The reactor pressure vessel is a large metallic structure (inner diameter 7.3 m, overall height 20 m, weight about 1000 tons, and thickness of 20 cm in the belt line region).

The material selected, a martensitic 9Cr1Mo steel (industrial grade T91, containing 9% by mass chromium, and 1% by mass molybdenum) undergoes negligible creep at operating temperature (400°C). The reference material for the internals is either 9Cr1Mo or stainless steel, typically SS316LN. The global primary arrangement is based on three main loops (3 × 800 MWth), each fitted with one IHX–blower unit, enclosed in a single vessel.



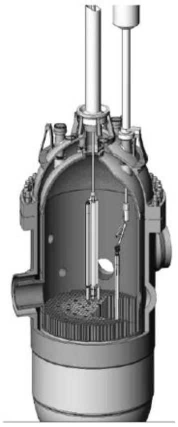
GFR primary system:

1. *Primary cross-duct*
2. *Secondary pipes with isolating valves*
3. *Control Rod Drive Mechanisms*
4. *Primary blower and associated motor*
5. *Compact Heat Exchanger modules*
6. *Pipe connections for Decay Heat Removal systems*
7. *Primary isolation valve*

This component limits the consequence of a concomitant first and second safety barriers rupture (the fuel clad and the primary system).

Specific loops for decay heat removal in case of emergency are directly connected to the primary circuit using a cross duct piping, in extension of the pressure vessel, and are equipped with heat exchangers and forced convection devices.

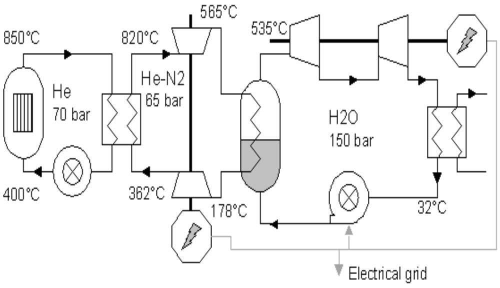
This system arrangement allows the residual power to be extracted in any accidental situations. In addition, thanks to the low pressure drop of the core design, a passive gas natural circulation can be used in most of the situations.

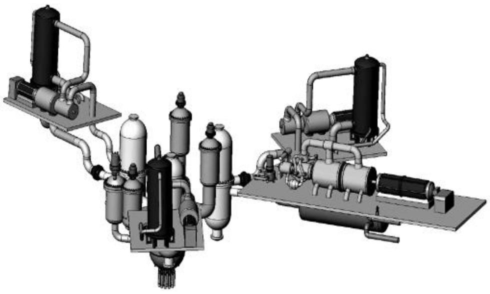


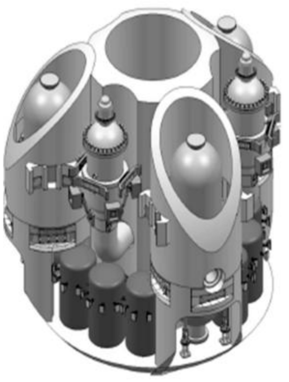
The fuel handling system is based on a jointed arm system, with fuel element loading and unloading using a fuel storage drum *via* lock chambers, the vessel being closed, as shown in the figure on the right. A dedicated forced convection device, located outside the reactor vessel, is designed to cool the spent fuel sub-assembly during its handling.

***Power conversion system:***

The current choice is the indirect combined cycle with He-$N_2$ mixture for the intermediate gas cycle. The cycle efficiency is approximately 45%, based on assumed component efficiencies and pressure drops. A schematic view of this power conversion system is shown below.





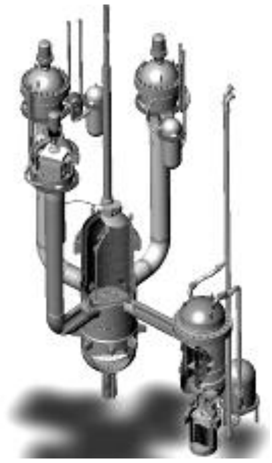


A gas tight envelope, acting as additional guard containment, has been designed to provide and maintain a backup pressure in case of large gas leak from the primary system. It is a metallic structure, initially filled with nitrogen slightly over the atmospheric pressure to reduce air ingress capabilities.

## IV. TOWARDS A DEMONSTRATION REACTOR

Finally, an experimental demonstration and technology reactor, named ALLEGRO, is proposed to be built in the coming decades.

With a thermal power around 80 MWth, it will not produce any electricity. At first, it is foreseen to demonstrate the viability of the GFRs system file, no reactor of this type having been ever built before. ALLEGRO incorporates, at a reduced scale, all the architecture and the main materials and components foreseen for the GFR, not included the power conversion system. Its safety principles are those proposed for the GFRs: core cooling through a gas circulation in all situations, ensuring a minimal pressure level in case of a leak thanks to a specific guard containment surrounding the primary system. It will also mainly contribute to the development and qualification of an innovative refractory fuel element that withstands high temperature levels, which is one of the key points to assess the GFR system.



## V. GFR AS A PLATFORM FOR EDUCATION

A number of PhD and Master Student studies related to detailed analysis of different aspects of GFR transient and steady-state neutronics, thermal-hydraulics and fuel behavior have been performed or underway. Examples of PhD studies are:

- Development and application of an advanced fuel model for the safety analysis of the Generation IV GFR. [9] A new fast-running 2D computer model of the plate-type GFR fuel was developed, benchmarked against 3D finite-element simulation and applied to the safety analysis, providing thus considerable improvement in the fuel temperature predictions in accidental situations.
- Development of the control assembly pattern and dynamic analysis of the Generation IV GFR. [10] The work has contributed to the detailed elaboration of the GFR control assembly system, including neutronics and thermal-physical aspects. The comprehensive 3D analysis of control rod withdrawal accidents has provided better understanding of the dynamic response of the GFR core to asymmetric reactivity perturbations.
- Improvement of the inherent and passive safety characteristics of the GFR. [11] A number of improvements of the GFR DHR capability under accident conditions were analytically studied, including the use of the gas-gas DHR heat exchanger, heavy gas injection in loss-of-coolant accident, use of Brayton cycle for DHR, etc.

## VI. CONCLUSION

The GFR system is a Helium-cooled fast neutron spectrum reactor. It takes advantage of the fast spectrum for long term resources sustainability, in terms of use of uranium and waste minimization, and of the high temperature gas coolant for high thermal cycle efficiency and industrial use of the generated heat.

A coherent development of all the components (fuel element, core, primary system, large components) has been done through the GIF collaboration together with evaluation of safety and performance that bring today a positive image of such a technology.

A development program has been set-up among the countries that contribute to its study that should validate the fuel and technology options by 2020.

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## Nomenclature

| | |
|---|---|
| DHR | Decay Heat Removal |
| EFR | European Fast Reactor |
| FIMA | Fission of Initial Metal Atoms |
| GIF | Generation IV International Forum |
| GFR | Gas-cooled Fast Reactor |
| HTR | High Temperature Reactor |
| RPV | Reactor Pressure Vessel |
| SRP | System Research Plan |
| TRU | Trans-Uranium element |

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