Chapter 4. **System reports**

Gas-cooled Fast Reactor (GFR)

The Gas-cooled Fast Reactor (GFR) system features a high temperature helium-cooled fast spectrum reactor that can be part of a closed fuel cycle. The GFR cooled by helium is proposed as a longer-term alternative to liquid metal-cooled fast reactors. This type of innovative nuclear system has several attractive features: the Helium is a single-phase, chemically inert, and transparent coolant. The high core outlet temperature above 750°C (typically 800-850°C) is an added value of GFR technology.

The reference concept for GFR is a 2 400 MWth plant operating with a core outlet temperature of 850°C enabling an indirect combined gas-steam cycle to be driven via three intermediate heat exchangers. The high core outlet temperature places onerous demands on the capability of the fuel to operate continuously with the high power density necessary for good neutron economy in a fast reactor core. This means the biggest challenge in the development of GFR system. Less significant challenge for GFR is to ensure the decay heat removal in all anticipated operational and fault conditions. Therefore, in the development of commercial GFR it is necessary to establish a type of experimental demonstration reactor for qualification of the refractory fuel elements and for full-scale demonstration of the GFR-specific safety systems. Actually, the ALLEGRO project reactor is to be the proposed demonstration reactor for the reference GIF GFR concept.

The ALLEGRO Gas-cooled Fast Reactor Demonstrator project

The objectives of ALLEGRO project are to demonstrate the viability and to qualify specific GFR technologies such as fuel, the fuel elements, helium-related technologies and specific safety systems (in particular, the decay heat removal function), together with demonstration that these features can be integrated successfully into a representative system. The demonstration of the GFR technology assumes that the basic features of the GFR commercial reactor can be tested in the 75 MWth ALLEGRO project.

The original design of the ALLEGRO consists of two He primary circuits, three decay heat removal (DHR) loops integrated in a pressurized cylindrical guard vessel (see Figure GFR.1). The two secondary gas circuits are connected to gas-air heat exchangers. The ALLEGRO reactor would function not only as a demonstration reactor hosting GFR technological experiments, but also as a test pad for using the high temperature coolant of the reactor in a heat exchanger for generating process heat for industrial applications and a research facility which, thanks to the fast neutron spectrum, makes it attractive for fuel and material development and testing of some special devices or other research works.

The 75 MWth reactor shall be operated with two different cores (see Figure GFR.2). The starting core with UOX or MOX fuel in stainless steel claddings will serve as a driving core for six experimental fuel assemblies containing the advanced carbide (ceramic) fuel. The second core will consist solely of the ceramic fuel and will enable to operate ALLEGRO at its high target temperature.

Central European members of the European Union, the Czech Republic, Hungary and the Slovak Republic are traditionally prominent users of nuclear energy. They intend to use nuclear energy on the long run and besides the lifetime extension of their nuclear units, each country decided to build new units in the coming years. Therefore, four nuclear research institutes and companies of the Visegrad-4 region (ÚJV Řež, a.s. – Czech Republic, MTA EK – Hungary, NCBJ – Poland, VUJE, a.s. – Slovak Republic) decided to start joint preparations aiming at the construction and operation of the ALLEGRO demonstrator of the concept of Generation IV Gas-cooled Fast Reactor (GFR) based on a Memorandum of Understanding signed in 2010. CEA, France, as promoter of the GFR concept since 2000, supports the joint preparations, bringing its knowledge and its experience in building and operating experimental reactors, in particular fast reactors. In order to study safety and design issues and also the medium and long-term governance and financial issues, the four aforementioned organizations created in July 2013 a legal entity, the V4G4 Centre of Excellence, which performed the preparatory works needed to launch the ALLEGRO Project. V4G4 Centre of Excellence is also in charge of the international representation of the project. As a result of the preparatory works it turned out that during the earlier works certain safety and design issues remain unsolved and in several aspects a new ALLEGRO design has to be elaborated. Therefore in 2015, when the ALLEGRO Project was launched, a detailed technical program was established with a new time schedule.

Figure GFR1. The GFR reactor system

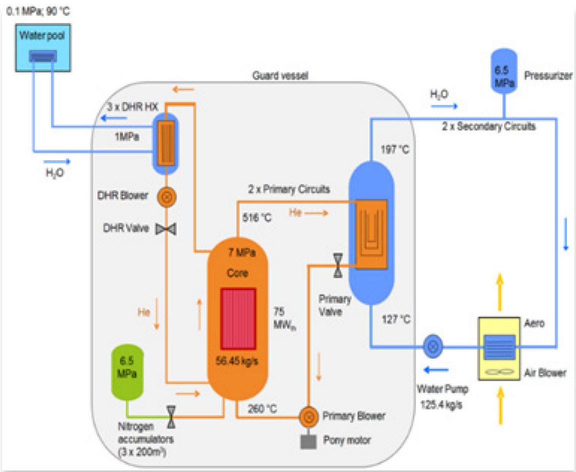
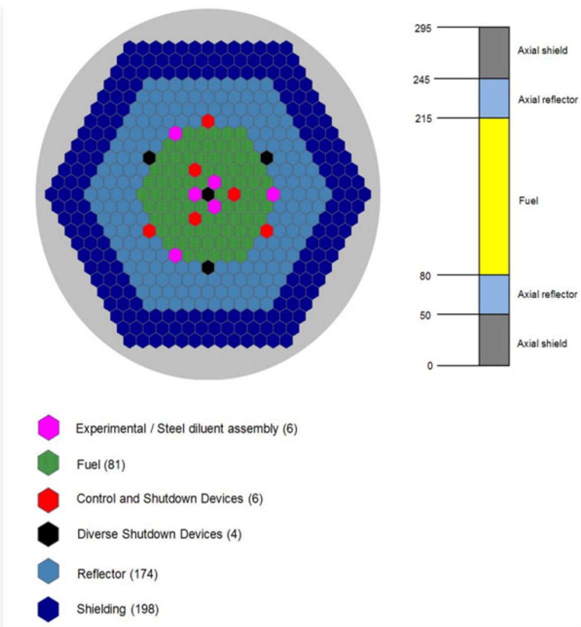


Figure GFR 2. The GFR core concept



Fuel cycle and fuel

Fuel development efforts must be conducted in close relation with reactor design efforts so that both the fuel meets core design requirements and that the core operates within fuel limits. Technology breakthroughs are needed to develop innovative fuel forms, which

- preserve the most desirable properties of thermal gas-cooled reactors, particularly to withstand temperatures in accidental situations (for the HTR up to 1 600°C, but to be confirmed by design and safety studies for the GFR);
- resist fast neutron induced damage, to provide excellent confinement of the fission products;
- accommodate an increased heavy metal content.

Alternative geometries of the fuel and innovative claddings should be investigated. The path to the GFR fuel development is intricately bound with ALLEGRO, and an iterative approach will be necessary. ALLEGRO start-up core will consider MOX or UOX fuel pellets deployed in conventional steel cladding tubing, necessitating its own design and licensing programme. An iterative step to a full ceramic demonstration core in ALLEGRO is an essential part of the R&D required for the GFR.

Candidate fuel types already identified are:

- UOX and MOX pellets in 15-15 Ti tubular steel cladding for the ALLEGRO start-up core;
- pin/pellet type fuels characterized with solid solution fuel pellets in a ceramic cladding material, whereby such pins and eventually assemblies would be introduced into the ALLEGRO starting core and eventually as a demonstration.

A significant knowledge is available on MOX fuel but needs to be available to establish the ALLEGRO start-up core.

Data on potential ceramic (particularly SiCf/SiC) and refractory alloys for cladding materials are patchy. These materials need to be adapted in order to cope with the different loads (thermal gradients, interaction fuel-barrier, dynamic loads, etc.), which means that their composition and microstructure need specific dedicated developments.

The main goal of the high temperature experiments is the investigation of the behavior of 15-15 Ti alloy in high temperature helium. Beyond the testing of small tube samples ballooning and burst experiments will be performed at high temperature. Mechanical testing will be carried out to investigate the change of load bearing capability of cladding after high temperature treatments. The cladding microstructure will be examined by SEM and metallography.

The development of qualification procedure for start-up fuel will include the specification of the steps for MOX/UOX fuel with 15-15 Ti cladding including irradiation in reactors with fast spectrum and post-irradiation examination of irradiated fuel samples.

Numerical model development for the start-up core will focus on the extension of the "FUROM" code with fast reactor fuel properties and models in order to simulate fuel behavior for the ALLEGRO start-up core. The validation of the code should be based on sodium-cooled fast reactor fuel past histories.

Testing of SiC claddings in high temperature helium will be carried out to track the potential changes. Mechanical testing and the examination of microstructure with SEM and metallography is planned with the samples after high temperature treatment. In particular, Ion irradiation effect on SiC composites will be investigated in order to evaluate the importance of the significant volume change observed for Hi-Nicalon type-S fiber and C fiber coating. High dose ion irradiation will be carried out with various temperature range including GFR operating temperature for SiC composites. High dose irradiation effect on SiC composites will be examined.

The investigation of high temperature oxidation behavior of SiC composites is important in order to model severe accident studies with air inlet. Various kinds of silicon carbide composites and monolithic SiC ceramics will be oxidized up to 1 500°C. Surface modification of SiC will be carried out based on understanding of oxidation behavior.

The following topics will be analyzed in short term:

Design of the ALLEGRO reactor core:

- UOX core feasibility study using ERANOS, MCNP, SERPENT validated Codes.
- Determination of total reactor power and power density to satisfy both safety limits and irradiation capabilities.
- Formulation of selection criteria to choose an optimal core.

Development of fuel behavior codes for ALLEGRO fuel:

- Collection of material data for fast reactor materials.
- Derivation of reactor physical parameters needed for the FUROM code.
- Implementation of fast reactor material data in the FUROM code.

Tasks related to ALLEGRO fuel qualification and specification:

- ALLEGRO fuel related acceptance criteria.
- Review of fuel candidates for the first core of ALLEGRO.

- Selection of the components of optimal ceramic fuel for ALLEGRO.
- Development of ceramic fuel qualification procedure.

Tasks related to research on fuel materials:

- Review of SiCf/SiC cladding materials.
- Testing UOX/MOX fuel cladding in high temperature He.
- Mechanical testing of UOX/MOX fuel cladding.

Advanced components and materials

Concerning in-core structural materials for the GFR (cladding, reflector, control rod guides, etc.), the main challenge is to develop materials able to withstand fast neutron induced damage together with high temperature ranges. Thus, ceramic materials (monolithic, composite) are the reference option and as a back-up selected composite cermet structures, refractory alloys, and inter-metallic compounds. In addition, the reflector should have specific neutronic properties to reduce neutron leakage efficiently and to protect the surrounding vessels; an inter-metallic compound of Zr and Si is the favored at this stage for this component.

Special issues and technologies

The improvement of decay heat removal capabilities aims at defining and optimizing a simple and robust combination and sequencing of complementary fail-safe solutions during a fast or slow depressurization transient. The main topics to be addressed are:

- Increase core thermal inertia.
- Optimization of key design parameters to enhance natural convection. Determination of required back-up pressure.
- Optimization of DHR Systems:
  - Coupled primary-secondary turbomachines;
  - Injection systems, Heavy gas accumulators.
- Guard vessel and system containment.

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Chair of the GFR SSC and all Contributors