4

# System reports

## Gas-cooled fast reactor

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 with 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 and typically 800-850°C, is an added value of the GFR technology.

### Design objectives

High-outlet temperature (850°C) for high thermal efficiency and hydrogen production, and a direct cycle for compactness, are key reference objectives. Unit power will be considered in the range of 200 MWe (modularity), up to larger 1 500 MWe. Generation IV (Gen-IV) objectives for construction time and costs are therefore to be considered.

The objective of high fuel burn-up, together with actinide recycling, results in spent-fuel characteristics (isotopic composition) that are unattractive for handling. High burn-up is the final objective.

Consensus has been reached in the project to minimize feedstock usage with a self-sustaining cycle, which requires only depleted or reprocessed uranium feed. This would call for a self-generating core with a breeding gain near zero. So as not to penalize the long-term deployment of GFRs, and based on considerations regarding both the foreseen, available plutonium stockpiles (mainly derived from water reactors' irradiated fuel) and time for GFR fleet development, it is recommended that the initial Pu inventory in the GFR core not be much higher than 15 tonnes per GWe.

### Reference concept

The reference concept for the GFR is a 2 400 MWth plant having a breakeven core, operating with a core outlet temperature of 850°C that would enable 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 economics in a fast reactor core. The core is made up of an assembly of hexagonal fuel elements, each consisting of ceramic-clad, mixed-carbide-fuelled pins contained within a ceramic hextube. The favoured material for the pin clad and hextubes at the moment is silicon carbide fibre reinforced silicon carbide (SiCf/SiC). The entire primary circuit with three loops is contained within a secondary pressure boundary, the guard containment. The produced heat is converted into electricity in the indirect combined cycle, with three gas turbines and one steam turbine. The cycle efficiency is approximately 48%. A heat exchanger transfers the heat from the primary helium coolant to a secondary gas cycle containing a helium-nitrogen mixture, which in turn drives a closed cycle gas turbine. The waste heat from the gas turbine exhaust is used to raise steam in a steam generator, which is then used to drive a steam turbine. Such a combined cycle is common practice in natural gas-fired power plants and so it represents an established technology, with the only difference in the case of the GFR being the use of a closed cycle gas turbine.

### The ALLEGRO gas-cooled fast reactor demonstrator project

The objectives of ALLEGRO are to demonstrate the viability and to qualify specific GFR technologies such as fuel, fuel elements, helium-related technologies and specific safety systems, in particular the decay heat removal function. It will also demonstrate 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 reactor.

The original design of ALLEGRO consists of two helium primary circuits, three decay heat removal (DHR) loops integrated into 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 serve not only as a demonstration reactor, hosting GFR technological experiments, but also as a test pad to:

- use the high-temperature coolant of the reactor in a heat exchanger to generate process heat for industrial applications;
- carry out research in a research facility which – thanks to the fast neutron spectrum – makes it attractive for fuel and materials development;
- test some of the special devices or other research work.

The 75 MWth reactor shall be operated with two different cores: the starting core, with uranium oxide (UOX) or mixed oxide (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, enabling operation of ALLEGRO at the 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 over the long term. In addition to lifetime extensions of their nuclear units, each country has decided to build new units in the future.

Four nuclear research institutes and companies in the Visegrad-Four region (ÚJV Řež, a.s., Czech Republic, MTA EK, Hungary, NCBJ, Poland, VUJE, a.s., Slovak Republic) have decided to start joint preparations aiming at the construction and operation of the ALLEGRO demonstrator for the Gen-IV gas-cooled fast reactor (GFR) concept, based on a memorandum of understanding signed in 2010. The French Alternative Energies and Atomic Energy Commission (CEA), as the promoter of the GFR concept since 2000, supports these joint preparations, bringing its knowledge and its experience to building and operating experimental reactors, and in particular fast reactors.

In order to study safety and design issues, as well as medium- and long-term governance and financial issues, in July 2013 the four aforementioned organizations created a legal entity, the V4G4 Centre of Excellence, which performed the preparatory work needed to launch the ALLEGRO Project. The V4G4 Centre of Excellence is also in charge of international representation for this project. As a result of the preparatory work, it was revealed that during earlier work certain safety and design issues remained unsolved and for several aspects a new ALLEGRO design had to be elaborated. In 2015, therefore, when the ALLEGRO Project was launched, a detailed technical program was established with a new time schedule.

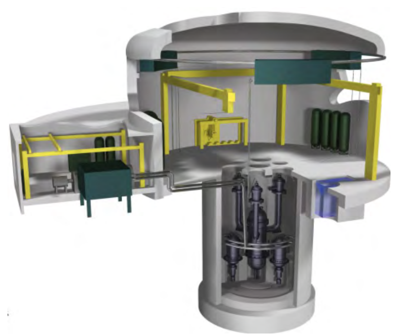
### Fuel cycle and fuel

Fuel development efforts must be conducted in close relation with reactor design efforts so that both the fuel meets core design requirements and 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 high-temperature reactor [HTR] up to 1 600°C, and to be confirmed through design and safety studies for the GFR);
- resist fast neutron-induced damage, to provide excellent confinement of the fission products;
- accommodate increased heavy metal content.

Figure GFR-1. ALLEGRO Systems



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

The candidate fuel types already identified are:

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

A significant amount of knowledge is available on MOX fuel, but more 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 inconsistent. These materials need to be adapted in order to cope with the different loads (e.g. thermal gradients, interaction fuel-barrier, dynamic loads), which means that their composition and microstructure need specific developments. The main goal of high-temperature experiments is to investigate the behavior of 15-15 titanium (15-15Ti) 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 the load-bearing capacity of cladding after high-temperature treatments. The cladding microstructure will be examined by scanning electron microscopy (SEM) and metallography.

The development of a qualification procedure for start-up fuel will include specification of the steps for MOX/UOX fuel with 15-15Ti 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 FUROM code with fast reactor fuel properties and models in order to simulate fuel behavior for the ALLEGRO start-up core. Validation of the code should be based on sodium-cooled fast reactor fuel histories.

Testing of SiC claddings in high-temperature helium will be carried out to track potential changes. Mechanical testing and the examination of the microstructure with SEM and metallography is planned with the samples after high-temperature treatment.

The ion-irradiation effect on SiC composites will be investigated in order to evaluate the importance of the significant volume change observed for hydrogen (Hi)-Nicalon type-S fibre and C fibre coating. High-dose ion irradiation will be carried out with various temperature ranges, including

GFR operating temperatures for SiC composites. The high-dose irradiation effect on SiC composites will be examined.

The investigation of high-temperature oxidation behavior of SiC composites is important for severe accident studies. 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 the understanding of oxidation behavior.

The following topics will be analyzed in the short term:

Design of the ALLEGRO reactor core:

- UOX core feasibility study using ERANOS, MCNP, SERPENT;
- 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 the reactor's 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 the 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.

### The SafeG project

The SafeG project has received funding from the Euratom Horizon 2020 program NFRP-2019-2020-06, under grant agreement no. 945041. The global objective of the SafeG project is to further develop GFR technology and strengthen its safety. The project will support the development of nuclear, low-$CO_2$ electricity and the industrial process heat generation technology through the following main objectives:

- to strengthen the safety of the GFR demonstrator ALLEGRO;
- to review the GFR reference options in materials and technologies;
- to adapt GFR safety to changing needs in electricity production worldwide, with increased and decentralized portions of nuclear electricity, by studying various fuel cycles and their suitability from safety and proliferation resistance points of view;
- to bring in students and young professionals, boosting interest in GFR research;
- to deepen the collaboration with international, non-EU research teams, and relevant European and international bodies.

The main task of the project is to respond to the safety issues of the GFR concept and to introduce the key safety systems of the ALLEGRO reactor. An important part of the design is to acquire new experimental data using recent research from experimental devices and special computational programs to carry out safety analyzes and the study of relevant physical phenomena. The SafeG project takes into account the most urgent questions and open issues concerning the GFR technology and the ALLEGRO demonstrator. To answer these questions, the SafeG project is divided into six technical work packages and one co-ordination work package.

The ambitions of the SafeG project can be divided into four tasks:

1) Completing the ALLEGRO demonstrator safety concept:

- core optimization from the neutronic, thermo-hydraulic and thermo-mechanic points of view;
- design of diversified reactor control and reactor shutdown systems;
- passive decay heat removal strategy completed with the design of fully passive systems for the decay heat removal tested on the experimental helium loop.

2) Upgrading the ALLEGRO demonstrator design and GFR concept through innovative materials and technologies, such as fuel cladding based on SiC composition, and construction materials capable of withstanding the extreme temperatures used for the primary system and safety-related systems.

3) Linking national research activities and creating an integrated platform that aims to share knowledge, and results achieved, as well as to co-ordinate activities, and spread new ideas and findings throughout the scientific society worldwide.

4) Expanding cooperation between Europe and Japan on GFR research through the sharing of knowledge about advanced high-temperature resistant materials for fuel rod claddings and other primary system components.

**Branislav Hatala**
Chair of the GFR SSC, with contributions from GFR members