The ALLEGRO Experimental Gas Cooled Fast Reactor Project

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Abstract. ALLEGRO is an experimental fast reactor cooled with Helium being developed by the European V4G4 Consortium “V4G4 Centre of Excellence” of the nuclear research organizations of the Czech Republic, Hungary, Poland and Slovakia associated with CEA, France. Development of ALLEGRO is an important step on the way to the Gas-cooled Fast Reactor, one of the six concepts selected by the Generation IV International Forum and one of the three fast reactors supported by the European Sustainable Nuclear Energy Technology Platform.

The main purpose of the facility is to develop:

- innovative refractory GFR fuels,
- GFR-related components and systems (Helium technologies, fuel handling, …) and
- a safety framework applicable to the specific characteristics of GFRs.

Starting from a reference design studied up to 2009 at CEA, the project is exploring a new target of nominal power (in the range of 30 – 75 MW thermal) and power density (in the range 50 – 100 MW/m^3) compatible with the safety limits and the design requirements. At the same time, the feasibility of a LEU UOX start-up core as alternative to a standard MOX core is being considered. This start-up core, to be used in the first period of the reactor operation, will include experimental positions dedicated to the refractory fuel development.

The paper describes the current status and the perspective steps of the design and safety studies and experimental work to demonstrate the safety & feasibility of ALLEGRO.

Key Words: gas-cooled fast reactor, high temperature, Helium cooling, Generation IV demonstrator

1. Introduction

In order to make nuclear energy production sustainable, the development and deployment of fast reactors is inevitable. Therefore a world-wide cooperation in research and development of fast reactors has been restarted with the participation of the most significant countries applying nuclear energy.

The main advantages of Gas-cooled Fast Reactors (GFRs) beside the closed fuel cycle are:

- High operating temperature, allowing increased thermal efficiency and high temperature heat for industrial applications
- Low value of the void coefficient
- Helium is a chemically inert and a non-corrosive coolant
- Helium is transparent, facilitating in service inspection and repair.

The main drawbacks are related to:

- The need to operate under pressurized conditions
- The low cooling efficiency of Helium, in particular in natural convection.

Central European members of the European Union, the Czech Republic, Hungary and Slovakia 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. Poland, another country of this region, also launched its nuclear power program aiming at 6000 MW_e in total.

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 demonstrator (ALLEGRO) 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 CoE 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.

The paper is devoted to the presentation of the actual situation of the ALLEGRO Project.

2. Goals of the ALLEGRO Project

Fast reactors are very much needed if the worldwide level of the nuclear energy production is intended to be maintained. Three different technologies are considered as most promising (see e.g. SNETP Strategic Research Agenda 2015): Sodium-, Lead-, and Gas-cooled Fast Reactors (SFR, LFR and GFR respectively). None of them, however, is commercially available today in EU. Therefore, all three concepts need to be developed before at least one of them reaches the level of industrial maturity.

The viability of the GFR technology shall be demonstrated by constructing and operating the ALLEGRO reactor. ALLEGRO shall be used not only for technology demonstration but also for the development and qualification of innovative components & systems, first of all the refractory fuel (UPuC pellets in SiC-SiC_f cladding).

3. History in a nutshell

The idea of developing a Helium cooled fast reactor goes back to the 1950 & 1960's. The first realistic concept after year 2000 was elaborated by CEA under support of the EURATOM FP6 GCFR STREP project. The Experimental Technology Demonstration Reactor (ETDR) from 2008 was characterized by 50 MW thermal power, 560 ºC He first core outlet temperature at 7 MPa, one primary loop and water cooling on the secondary side.

The concept following to ETDR was presented by CEA in 2009 and got name ALLEGRO [1]. It was characterized with 75 MW thermal power, 530/850 ºC first/refractory core He outlet temperature at 7 MPa, two primary loops and water cooling on the secondary side. The primary circuit is enclosed in a guard vessel (close containment), a pressure boundary maintaining sufficient backpressure in the system in case of a LOCA *(see FIG 1.)* This internationally known concept became the Reference design (ALLEGRO CEA 2009) for V4G4 CoE. The EURATOM FP7 GoFastR project (2010-2013) further refined this design. In 2011 CEA patented a GFR system with increased safety in accident conditions based on gas turbo-machinery in secondary circuit that through mechanical coupling with primary blowers ensured decay heat removal during the first more than 12 hours (concept ALLEGRO CEA 2011 [2]).

A new ALLEGRO V4G4 concept (based especially on the ALLEGRO CEA 2009) is under elaboration within V4G4 CoE *(see FIG. 1. and FIG. 2.)* and its main features are discussed in this paper.

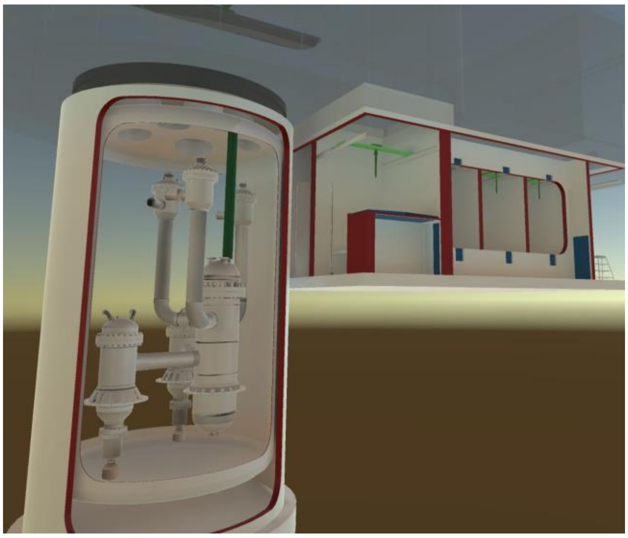

FIG 1.The ALLEGRO reactor in the close containment

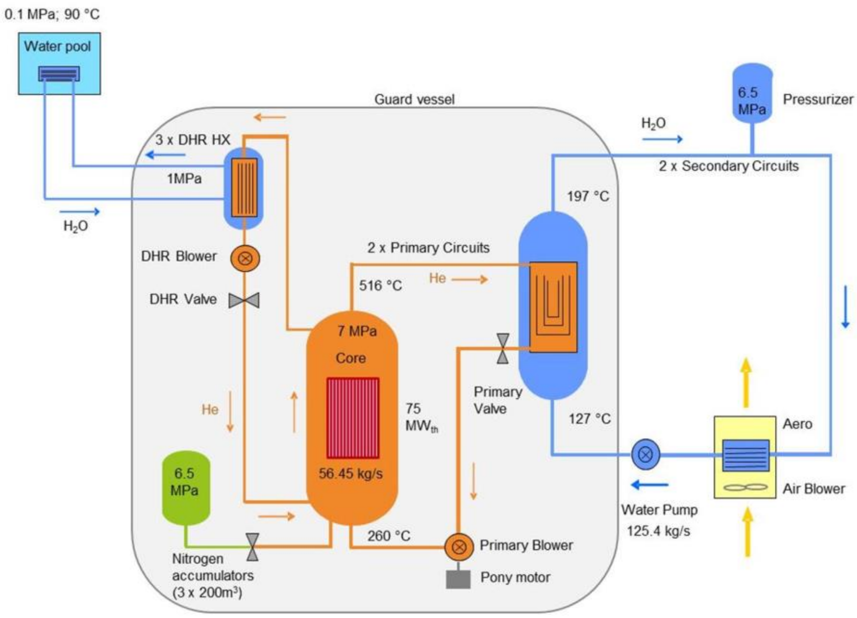

FIG 2. Schematic view of the ALLEGRO reactor

4. Main technical issues leading to a design of ALLEGRO V4G4

4.1. Fuel and core design issues

Gas-cooled Fast Reactors will be fuelled with so called refractory fuel, most probably UPuC carbide pellets in SiC-SiC_f tubes. ALLEGRO cannot use this type of fuel from the very beginning since this fuel is not developed and cannot be qualified without irradiations in GFR conditions and the subsequent PIE. Therefore, according to previous considerations the first cores will be built up from stainless steel cladded fast reactor oxide fuel *(see FIG. 3-6)*. Some core positions will be reserved for the development of the refractory fuels through the irradiation of fragments, rods and sub-assemblies. In these positions (thermally insulated assemblies, shown in pink in *FIG 3.*) an elevated helium outlet temperature (800-850 ºC) is created by reducing the coolant flow rate.

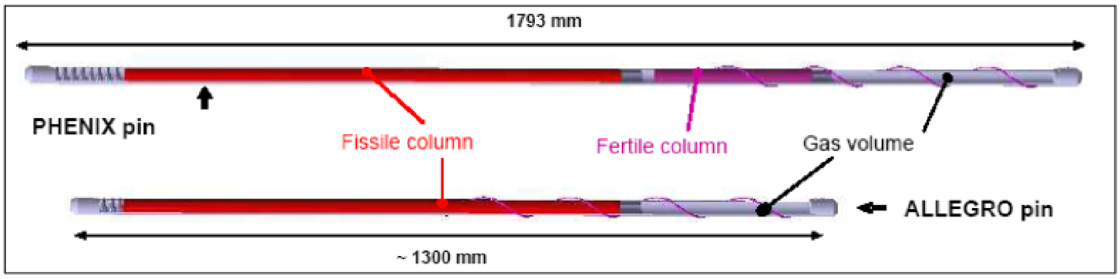

FIG 3. The ALLEGRO fuel pin compared to PHENIX pin [1]

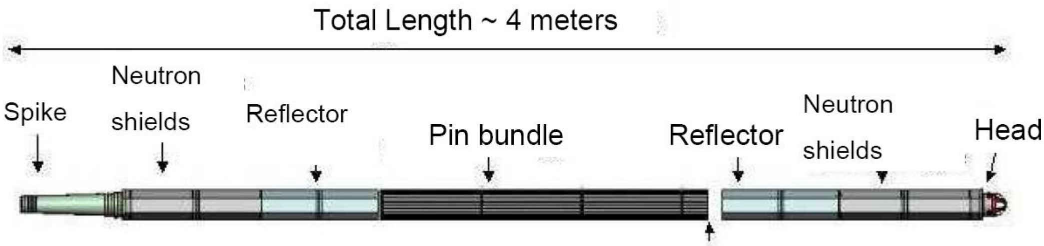

FIG 4. The ALLEGRO fuel pin bundle [1]

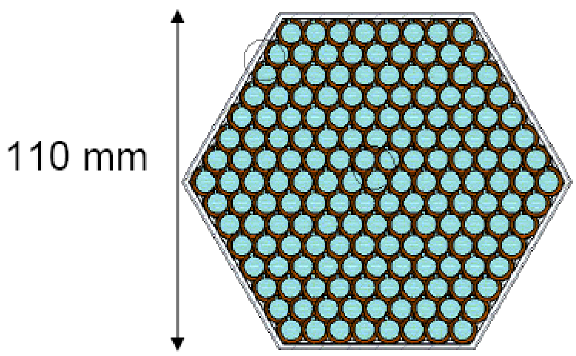

FIG 5. Fuel pin positions within the ALLEGRO fuel pin bundle [1]

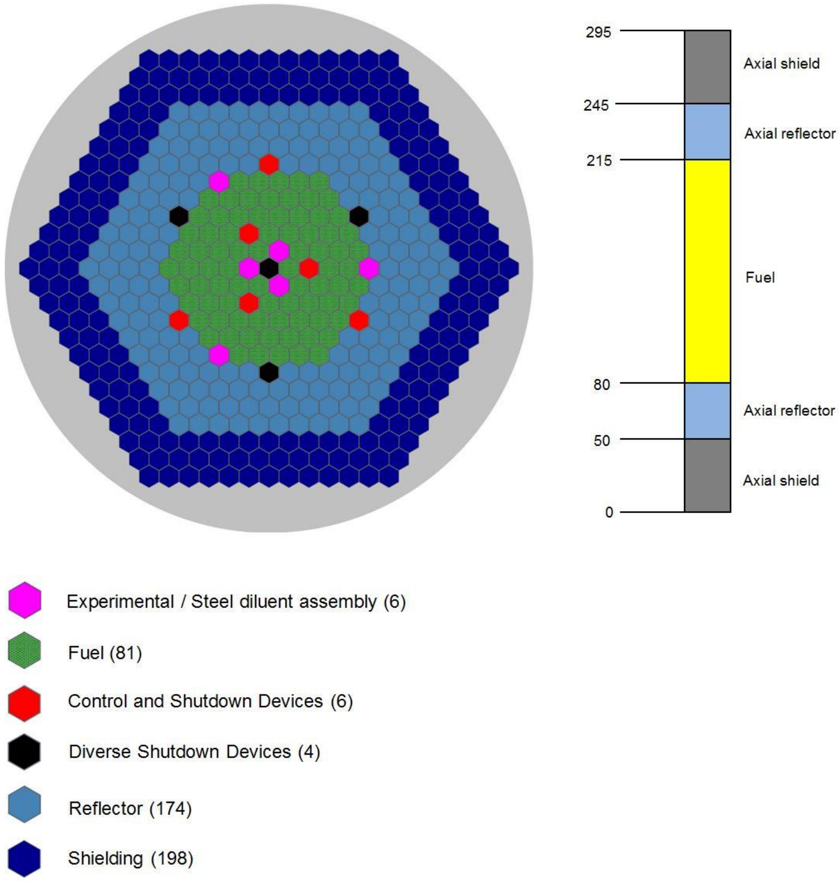

FIG 6. First ALLEGRO reactor cores

A serious problem may emerge if ALLEGRO (or any other Generation IV reactor) is built in V4 countries or in any country not being a nuclear power. This is because qualification and use of MOX fuel involves several legal and proliferation issues. In order to overcome these potential difficulties, now it is investigated whether using <20% enriched UOX pellets a feasible ALLEGRO core can be designed which allows for an acceptably low irradiation time needed for the experimental investigation of refractory fuel. It has to be added that the use of UOX does not solve in itself the future problem of investigating and using refractory Pu-containing fuel. This issue has to be solved by negotiations with the appropriate powers and institutions (EURATOM, IAEA and others).

In the existing design of the ALLEGRO core, safety and control rods of identical type are grouped into two independent groups of absorbers. In order to increase the safety of core design a completely diverse type of absorber has to be developed which would be activated purely by physical principles in a completely passive manner.

4.2. Decay heat removal issues

Decay heat removal in accident conditions is one of the crucial challenges in design of a GFR reactor because of low thermal inertia of the reactor system and relatively high volumetric power density, one order of magnitude higher than in (V)HTRs. The situation in ALLEGRO is further complicated by the wide use of stainless steel in the driver (start-up) core, because e.g. the 15-15Ti (AIM1) stainless steel claddings start to melt already at ~1320 ºC. The acceptance criterion (temperature) for fuel rod failure is even lower.

The original concept of decay heat removal in the 75 MW_t ALLEGRO CEA 2009 (~100 MW_t/m^3 power density) was mainly based on active elements in the decay heat removal (DHR) system, and its malfunction in some cases can easily result in core melting. As the increased use of passive features in safety systems is a pre-requisite of licensing a Generation IV reactor after the Fukushima accident [3], a new concept of combined active-passive DHR system has to be developed. This is why there are several potential elements of the new DHR system under development.

Transients with depressurized primary circuit (loss-of-coolant accident - LOCA) can be managed in passive mode by using a combination of several design features:

- Gas turbo-machinery is planned in the secondary circuit, aimed at supplying energy for the primary blower in the first hours after initiation of the transient. This solution is based on a CEA patent from 2010 [2], where the primary blower is mechanically connected to the turbo-machinery in the secondary circuit. Both the mechanical inertia and the decay heat dissipation through the main heat exchanger to the secondary circuit should be sufficient to, temporarily, feed the primary blower with enough power to cool the core. As the solution proposed by CEA is very difficult to realize because of technical reasons, a modified solution was elaborated by ÚJV Řež that consists of replacing the mechanical connection between the turbo-machinery and the blower with an electrical connection *(see FIG. 7)*. This electrical connection is independent of the external power supply therefore the loss of external power supply will not endanger the supply of the blower in the first hours after the onset of a transient.
- On the long run the decay heat is to be removed by natural circulation. To increase the intensity of the heat removal nitrogen has to be injected into the primary circuit. In this case, overcooling of the structures in the lower part of the core has to be avoided by design [4].
- The natural circulation itself can be promoted by elevated backpressure in the guard vessel. The circa 0.3 – 0.4 MPa pressure generated by the 7 MPa helium when released from the primary circuit into the 0.1 MPa nitrogen atmosphere of the guard vessel is not sufficient for successful cooling of the core. But backpressure slightly above 1 MPa seems to be sufficient to avoid core melting even without the use of the above mentioned turbo-machinery. Design pressures above 1 MPa will, however, require special design of the guard vessel.

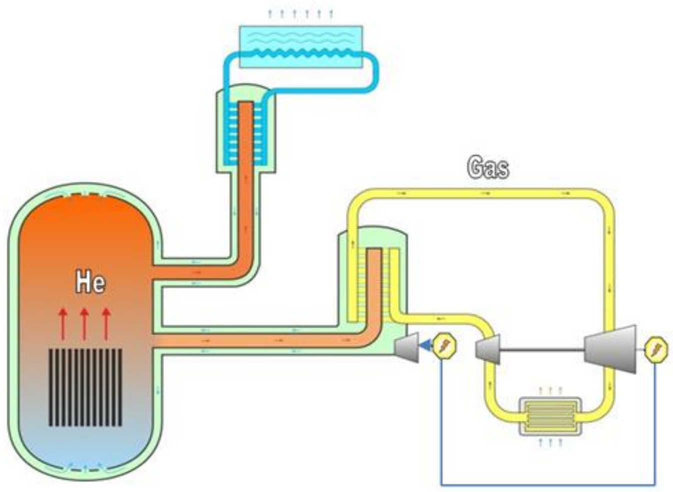

FIG 7. ALLEGRO main circuits and decay heat removal systems

In any case the potential risk of core bypass in a LOCA scenario must be carefully analysed both analytically and experimentally and has to be minimized by design.

Water ingress from a DHR heat exchanger into the primary circuit represents a further challenge. As reaction of stainless steel with steam can result in the loss of coolable core geometry due to degradation of mechanical properties of the stainless steel cladding, there should be a possibility in the design to isolate the affected DHR loop if necessary. The risk of water ingress is the main reason, why now gas is preferred to water in the secondary circuit. For the time being, however, there is no option to replace water in the DHR system.

Generally said, the above mentioned new design features make ALLEGRO a significant step closer to the level of safety required for the Generation IV systems.

4.3. Further technical issues

There are several other important technical issues which have to be solved. Obviously Helium technology is an area where important development is still expected. Certain important aspects were simply not studied earlier in details but their solution is definitely necessary. Some issues of this kind are mentioned below.

The containment system has to be designed from scratch however well-known solutions do exist. Though fuel melt probability should be close to zero, a core catcher system should be built in the containment.

Fuel handling was designed by CEA as far as the removal of spent fuel from the reactor vessel is concerned. Nevertheless the full strategy is still under development as the shielding of irradiated fuel between the reactor vessel and the spent storage facility is not designed. Moreover the existing concept of storing spent fuel is disputable. A temporary wet storage of originally dry fuel elements before storing them in a medium term dry storage facility seems to be an unnecessary inconvenience and presents an extra risk. It has to be studied if instead a temporary dry storage system can be developed. However, cooling and shielding of a dry storage facility may lead to unacceptable consequences both from safety and cost-effectiveness points of view.

A system of accident management measures should be developed as these measures are completely missing at present. A special attention should be devoted to radiation protection considerations.

5. The ALLEGRO Project Preparatory Phase

It was agreed that the ALLEGRO Project will consist of two main phases which are further subdivided to phases:

Preparatory phase (2015/2025)

- Definition of the basic safety and performance goals, specifications (2015/2016)
- Pre-conceptual design (2017/2020)
- Conceptual design (2021/2025)

Realization phase (after 2025)

- Basic Design
- Detailed Design
- Siting and Licensing
- Construction

- Operation

In 2015 the Design and Safety Roadmap of the Preparatory Phase was approved. It consists of 47 tasks (most of them divided into sub-tasks). The leading organization and the contributing organizations are given. The objective of the (sub-) tasks is defined. The level to be reached at the various stages of the design is determined and some further information is also provided.

During the Definition of the basic safety and performance goals the Design Requirements and Objectives as well as the Safety Requirements and Objectives were approved. The basic system data were specified.

During the Pre-conceptual design phase the options of the new design will be preliminarily chosen and finally the Introductory Safety Analysis Report will be prepared.

During the Conceptual design phase the main design options will be decided and justified and the Preliminary Safety Analysis Report will be elaborated. The needs for system qualification will be fixed.

During the Preparatory Phase national nuclear R&D projects and EURATOM projects will provide the main source of funding of Design/Safety activities. The positive example is Hungary, where a national nuclear R&D project covers the Hungarian contribution for 2015-2018, and Slovakia, where a national nuclear R&D project covered the first stage of activities. The current EURATOM FP7 ESNII+ and H2020 VINCO projects contribute to the success of the ALLEGRO efforts. In Slovakia and the Czech Republic similar projects are under preparation. The V4G4 members and their collaborators applied for the EURATOM financing of the H2020 ALFA project which could significantly contribute to achieve the goals of the Preparatory Phase. Experimental activities have also started. In the Czech Republic the SUSEN project financed by the EU Structural Funds is already running. In Poland, government recently announced the programme to deploy thermal High Temperature Gas-cooled Reactors (HTGR) to provide industrial heat. This will create additional possibilities for development of nuclear helium cooling systems.

The ALLEGRO Project is controlled by the V4G4 Steering Committee. In order to organize the joint activities a Project Coordination Team is established. It is the forum of harmonising activities of the various national and international projects with the tasks of the Design and Safety Roadmap. In order to prepare solutions for legal issues a Working Group on Governance and Financing was also established.

6. Considerations about the Realization Phase

After the Preparatory Phase will have been completed, the ALLEGRO development has to be based on a completely new framework. A preliminary vision has been elaborated on the Realization Phase of the ALLEGRO Project and this vision has to be refined in the coming years.

According to this vision a new consortium has to be established for the Realization Phase in a form unknown at present for EU. The consortium should include:

- Representatives of the interested European governments (perhaps the V4 research institutes may play this role)
- The Licensee
- An industrial company which will take care on the preparation of the basic and detailed design and the documents needed for licensing and which will be the main contractor during construction.

The financial means shall be at the disposal of the new consortium. Intellectual Property Rights of the design created during the Preparatory Phase will be an important contribution to the capital of the consortium to be created.

The legal aspects of creating such a consortium are still to be elaborated. It seems to be a common issue for any Generation IV reactor developments in Europe therefore a joint effort is envisaged.

7. Closing remarks

Nuclear energy remains one the major components of electricity production in the 21st century. Fast reactors will play a crucial role in developing the sustainable use of nuclear energy. In the last years the GFR development restarted and has been driven by the European Consortium “V4G4 Centre of Excellence” The ALLEGRO reactor can fulfil the role of a European GFR technology demonstrator allowing for fast neutron irradiation of ceramic fuel and other perspective reactor materials.

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