GFR RESEARCH AND DEVELOPMENT PROGRAMME IN V4 COUNTRIES

P. VÁCHA[1], B. KVIZDA[2], Z. HOZER[3], P. DARILEK[2], G. MAYER[3], A. KERESZTURI[3], M. GREN[1], J. KALIVODOVA[4], J. MALESA[5], P. HAJEK[1]

[1] UJV Rez, a. s., Husinec-Rez, Czech Republic
[2] VUJE, a. s., Trnava, Slovakia
[3] Centre for Energy Research (EK), Budapest, Hungary
[4] Centrum Vyzkumu Rez, Husinec-Rez, Czech Republic
[5] Narodowe Centrum Badan Jadrowych, Otwock, Poland

Email contact of corresponding author: petr.vacha@ujv.cz

Abstract

GFR is one of six GENIV reactor technologies selected as most promising by GIF, with a long history of research and development work done in various countries. Modern day GFR research is concentrated mainly in Europe, Japan and USA. European GFR reference concepts are GFR2400, a large-scale commercial reactor, and ALLEGRO, a 75 MWth technology demonstrator. A new project of an advanced modular reactor based on GFR technology called HeFASTo has been developed since 2021 in the Czech Republic. The ALLEGRO development is led by the V4G4 Centre of Excellence consortium associating research organizations, companies and laboratories from Czech Republic (UJV Rez and CVR), France (CEA), Hungary (MTA-EK), Poland (NCBJ), and Slovakia (VUJE). This paper summarizes research projects focused on the development of GFR and ALLEGRO in particular, and describes their position in the broader framework of GFR development program. The key research and development challenges, both common to all GFRs, and specific to the ALLEGRO reactor, are listed in the first part of the paper. These challenges are then divided into areas of scientific interest -fuel, core physics and thermal-mechanics, design of systems and components, materials, safety, thermal-hydraulics, helium-related technologies. All ongoing major research and development projects dedicated to one or more of the identified areas are described with its main planned outputs. The last part of the presented paper is dedicated to description of future plans and identification of areas where further research and development is needed and is not covered by the ongoing projects.

1. INTRODUCTION

Nuclear energy is, to this date, the only large and stabile low-carbon energy source utilized by the humankind. With its growing and widespread recognized importance in the fight against the global climate change [1], the age-old question of available uranium resources once again becomes discussed in relation to the predicted growth in the installed nuclear power capacities for the coming decades [2]. An indivisible part of this issue is the growth in the amount of spent nuclear fuel that is connected to operation of thermal reactors. For this reason, fast reactor technologies with closed fuel cycle seem to be a vital part of the nuclear future.

Three of the most promising fast reactor technologies have been developed as so-called GEN IV reactors within the framework of GEN IV International Forum (GIF). The main goal is to provide inherently safe, environmentally friendly (low CO_2 emissions), proliferation resistant, long lasting, and economically competitive energy source for the 21st century. One of these technologies is the Gas-cooled fast reactor (GFR) [3]. This concept combines the advantages of a fast reactor, with those of the high-temperature gas-cooled reactor technology. It can build on knowledge built by design and operation of both of the mentioned reactor types.

There are several features that makes GFR a promising reactor technology for the future:

- Very high core outlet temperature, that is limited only by resistance of materials used in the primary circuit, resulting in very efficient production of electricity and enabling high-temperature hydrogen production
- Closed fuel cycle enabling multiple reprocessing of the fuel, as well as further utilization of spent nuclear fuel from thermal reactors

— Properties of the coolant - neutronic and optical transparency and no phase changes, enhancing safety of operation and possibilities of in-service inspections

With the indisputably impressive advantages of the GFR come several drawbacks inherent to the technology. First and probably most important is the fact that gas is generally much less effective coolant than water or liquid metals or salts, due to much lower density even at high pressures. This fact has far-reaching consequences in terms of nuclear safety of such an installation. Ensuring continual flow of coolant through the core is vital for core cooling in any kind of transient or accident. The choice of coolant also affects the maximum possible power density of the core, which is, however, still relatively high, reaching up to 100 MW/m^3 [4]. Another set of challenges is connected to fuel handling, due to extremely low density of the coolant at atmospheric pressure (and, therefore, poor heat transfer properties), it is needed to be done at elevated pressure, or using advanced and complex designs of the fuel handling machines.

2. GFR REACTOR TECHNOLOGIES

Two concepts of nuclear reactors based on the GFR technology that have been under development in Europe within the V4 (Visegad 4) countries - Czech Republic, Hungary, Poland, Slovakia, are briefly described in the following sections.

2.1. ALLEGRO

ALLEGRO is a concept of a demonstration unit of the GFR technology, with the aim to prove viability, safety, and reliability of the whole concept of a gas-cooled reactor with fast spectrum. It is important to mention here, that, despite the history of GFR development being surprisingly rich with many concepts originating as far to history as the 1960’s [5][[6], no such reactor has ever been built and operated.

It was originally designed by the French Alternative and Atomic Energy Commission (CEA) [7] as the Experimental Technology Demonstration Reactor (ETDR) with thermal power of 50 MWt [8]. The ALLEGRO project, 75 MWt reactor that evolved from the ETDR concept, was led by CEA until 2010. Then, the preparations for know-how transfer from CEA to the Visegrád group (V4) countries, based on Memorandum of Understanding, started.

Main technical features of ALLEGRO are listed in TABLE.1, a cross-section of the facility in FIG. 1.

TABLE 1. MAIN DESIGN PARAMETERS OF ALLEGRO

Parameter	Value	Unit
Nominal power (thermal)	75	MW
Nominal power (electrical)	0	MW
Power density	100	MW/m^3
Fuel	MOX/ SS cladding UPuC/ SiCSifC cladding	
Primary circuit coolant	Helium	
Primary pressure	70	Bar
Core inlet/outlet temperatures	260/516	°C

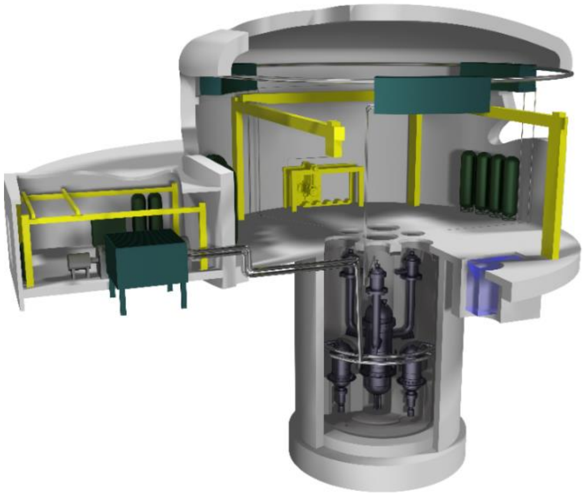

FIG. 1. : *The ALLEGRO Facility*

2.2. HeFASTo

HeFASTo is a new concept of an advanced modular reactor (AMR) based on GFR technology. It has been under development by UJV Rez since 2021 [9]. Its aim is to provide a concept of modern design of GFR, that will be commercially applicable in the fast-changing environment of the energy sector in the 21st century.

Main features of HeFASTo are following:

- Orientation on maximization of economic feasibility by employing maximum possible levels of modularization both in its design and possible applications
- Emphasis was put on the use of exclusively fully passive systems, providing levels of safety unprecedented in a fast reactor
- Maximum utilization of advantages of a fast reactor – very long fuel campaigns with a possibility of utilization of reprocessed nuclear fuel

The design of HeFASTo has several unique features. One of them being the design of the core. It is composed of individual subassemblies containing pin-type fuel elements, however, the whole active core including the control and shutdown elements is held together by a specially designed envelop, that enables manipulation with the active core as if it was a single entity. No manipulation with individual subassemblies is envisaged inside the facility. At the end of cycle, the whole active core is extracted from the reactor pressure vessel, put into a sealed container, and shipped to a reprocessing plant. This procedure significantly lowers the possibilities of proliferation of nuclear material, as well as probability of incidents during fuel handling, compared to manipulation with individual fuel elements. The concept is depicted in FIG.2.

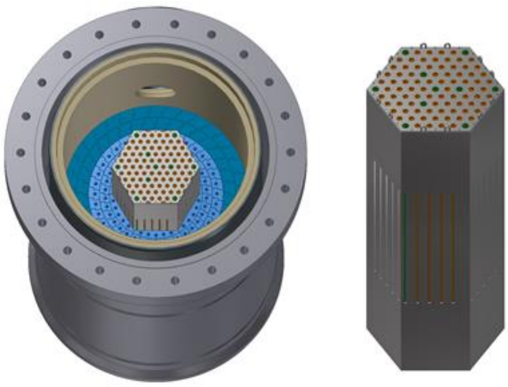

FIG. 2. *Active core of HeFASTo*

On the secondary side of the main heat exchanger, three different modules or their combination can be connected:

— Hydrogen production module utilizing high-temperature electrolysis for very efficient hydrogen production.
— Electricity production module utilizing combined cycle with theoretical efficiency exceeding 44 %.
— Direct high-potential heat distribution for industrial applications, with guaranteed temperature on the side of the customer of 850°C

Main parameters of the HeFASTo reactor are summarized in TABLE 2, an overview of the whole facility is in FIG.3.

TABLE 2: MAIN DESIGN PARAMETERS OF HEFASTO

Parameter	Value	Unit
Nominal power (thermal)	205	MW
Nominal power (electrical)	82	MW
Power density	65	MW/m3
Fuel	UC in SiC-based cladding UPuC in SiC-based cladding	
Primary circuit coolant	Helium	
Primary pressure	75	Bar
Core inlet/outlet temperatures	450/900	°C

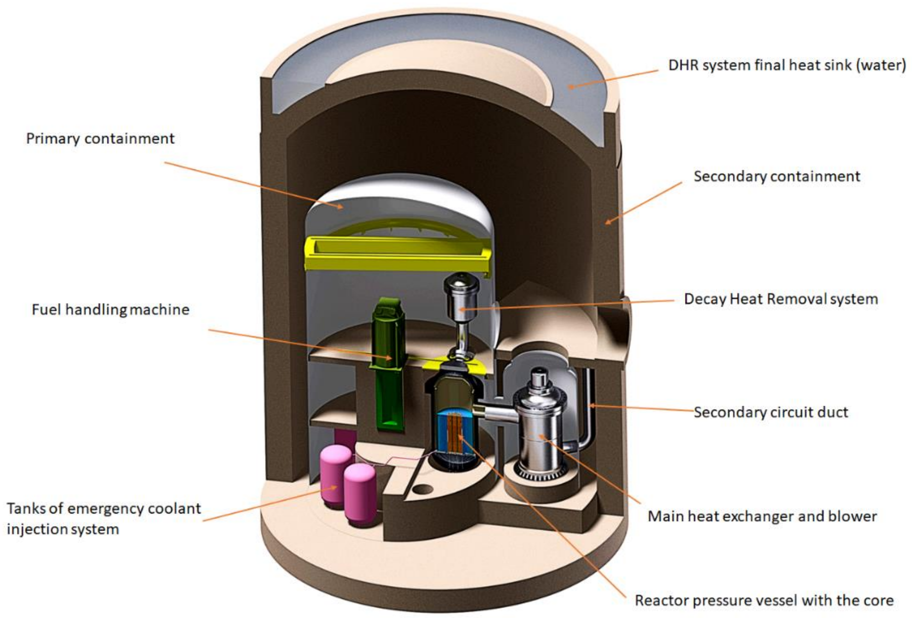

FIG. 3. *The HeFASTo reactor*

3. GFR RESEARCH AND DEVELOPMENT

In 2013, a legal entity "V4G4 Centre of Excellence" (V4G4 CoE) have been established. It connects leading Central European nuclear research organizations and companies from the Czech Republic (UJV Rez), Hungary (EK), Poland (NCBJ), Slovakia (VUJE), and two associated members from France (CEA) and the Czech Republic (CVR). Since 2013, the V4G4 CoE launched preparations to design, build and operate ALLEGRO demonstrator in Central Europe [10].

Since 2013, majority of GFR R&D is therefore focused in the V4 countries, under the governance of V4G4 CoE. In the following sections, main areas of scientific interest concerning development of GFR are discussed, and the management structure is described.

3.1. Management of R&D on GFR in V4 countries

The focal point of GFR R&D in the Visegrad countries is the V4G4 Centre of Excellence consortium. It is governed by two bodies – Project Coordination Team (PCT) and Steering Committee (SC). Both these bodies meet at least three times a year. The scope of PCT is technical coordination of R&D work on ALLEGRO project, sharing of information from relevant national research and development projects, and presentation of results achieved in the period since the last PCT meeting. Summary of the PCT meeting is then presented to the members of the Steering Committee, which is the decision-making body of V4G4 CoE. In addition to regular meetings of PCT and SC, ad-hoc expert meetings on particular topics are held whenever there is a need for common agreement on a specific technical issue.

Recently, a need for even more coherent way of management of both the ongoing and the planned R&D on ALLEGRO arose. It was agreed by both PCT and SC that V4G4 should elaborate a complex document containing a summary of the state of the art in ALLEGRO research, ongoing R&D projects, as well as information on priorities, biggest unsolved challenges and needs for further research and development. It was called ALLEGRO R&D Roadmap, and each of the 6 members of V4G4 CoE nominated one representative to the team responsible for its elaboration. The plan is to have a first version available by the end of 2021. Two versions will be prepared, one confidential for the use of V4G4, and one that will be made entirely public.

On the national level, each of the members of V4G4 CoE is responsible for coordination of the activities, both within the national R&D programs and the bilateral or multilateral agreements. General areas of responsibility exist within the consortium; however, it is not strictly applied to each and every submitted proposal of a national project, it is more to be used as a general direction in coordination of national R&D activities on GFRs. Recently, mainly UJV Rez and CVR from the Czech Republic were successful in obtaining financing for GFR research on the national level. However, Slovakia and Hungary both had extensive national-wide research project focused on building competence and development of ALLEGRO. In Poland, a long-term effort has been put into development of the high temperature reactor (HTR) technology, with several major projects supporting the cause. Since there are many cross-cutting issues in designs of GFR and VHTR, development of ALLEGRO benefits from these activities as well.

Common effort of V4G4 and several European and one Japanese partner resulted in a successful elaboration of a common proposal of R&D project to the 2019 Horzion 2020 call of the European Comision (EC). The project was named SafeG, and was ultimately selected for support by EC, starting in October 2020. More information about this project is available in section 5.1.

On the international level, selected experts from the V4G4 member organizations are also representatives of their respective organizations, nations, or Euratom in various projects and bodies under the governance of Generation IV International Forum (GIF), OECD and IAEA. Due to this connecting link, needs in R&D of the GFR technology from the point of view of the V4G4 CoE are vocalized on the international level as well.

3.2. Key R&D challenges in GFR development

The main challenges in development of GFR are connected with three main features of the reactor, connected with the fact that there is no operation experience in the world:

- Very high core outlet temperature leads to extreme demands on properties of the materials used in the primary circuit, especially in the core.
- Gaseous coolant with relatively low total heat capacity (due to low density) is challenging for the design of the safety systems and thermal-hydraulic design of the reactor as a whole.
- Each of the GFR concepts under development would be the “first of a kind” facility with some unique features that were never used so far if it was to be build today. This fact poses a challenge in terms of proving systems and components reliability, as well as their qualification.

Technological challenges can be divided into several topical areas, each connected with one or more high-level challenges described above. They are listed in TABLE 3, alongside with selected key particular issues that need special attention, and possible cross-cutting R&D synergies that might boost the development in the respective area. It can be seen, that for each of the listed key particular issues, there is always at least one other reactor technology that faces the same problem, and, therefore, the potential for cross-cutting R&D between GFR and other reactor technologies is high.

TABLE 3: MAIN CHALLANGES IN GFR R&D

Topical area	Key particular issues	Cross-cutting R&D synergies with
The core	Fuel composition selection Fuel thermal-mechanics behavior Core safety	Other fast reactor technologies (sodium in particular)
Systems and components	Valves Sealing Heat exchangers	VHTRs
	Reactivity control systems	Other fast reactor technologies
Materials	Core materials – cladding, reflector, shielding	Other fast reactor technologies
	Structural materials of primary circuit	VHTRs
	Structural materials for zhe containment	VHTRs
Safety and reliability	Ways of passive safety	GENIII+ reactors
	Severe accident prevention and management	SFR
Thermal-hydraulics	Natural convection	Operating/operated gas-cooled reactors
Helium-related technologies	Coolant purification	(V)HTRs

4. ONGOING NATIONAL PROJECTS ON GFR RESEARCH AND DEVELOPMENT

In this chapter, the ongoing R&D projects in V4 countries and their position in respect to key challenges listen in TABLE 3 are described. One section is dedicated to national projects on GFR in the Czech Republic, that has been very successful recently in securing significant financing for GFR research and development. Ongoing activities in Hungary, Poland and Slovakia are discussed as well. This chapter covers projects co-sponsored by the governments of V4 countries, in-kind contributions of individual members of V4G4 CoE to its projects are not mentioned.

4.3. Ongoing R&D on GFR in the Czech Republic

Main platform for national support of technology research and development in the Czech Republic is Technology Agency of the Czech Republic (TACR). It is an organizational unit of the state that was founded in 2009 by the Act No. 130/2002 Coll. on the support of research, experimental development and innovation. The creation of TA CR is one of the cornerstones of the fundamental reforms in research and development (R&D) in the Czech Republic. The key features of the reform is the redistribution of financial support from the national budget. The Technology Agency of the Czech Republic simplifies the state support of applied research and experimental development which has been fragmented and implemented by many bodies before the reform. [12]. In the past 10 years, UJV Rez and CVR submitted a number of project proposals to various calls of TACR, resulting in more than 10 projects actually supported by the organization, 8 of them being currently ongoing. The ongoing projects are listed in TABLE 4, followed by short description of what areas of interested are covered by the projects.

Another notable achievement is successful full commissioning of an electrical heated 1 MW mock-up of GFR called S-ALLEGRO in 2020. This facility plays a key role in thermal-hydraulics and safety research of GFRs, and will be a vital part of higher-TRL development and testing of systems and components in the near future. The layout and a photo of the facility are depicted in FIG. 4.

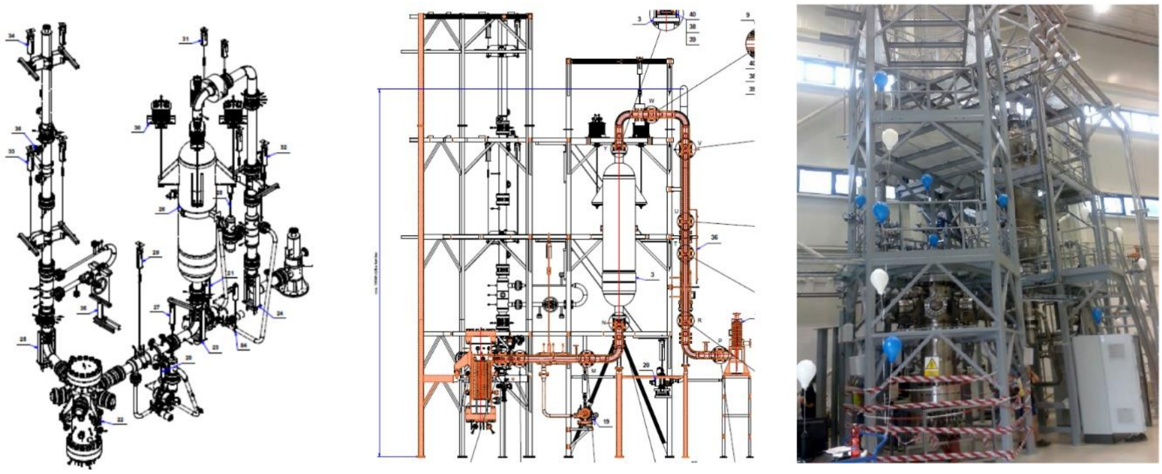

FIG. 4: The S-ALLEGRO facility [11]

TABLE 4: ONGOING NATIONAL PROJECTS ON GFR IN THE CZECH REPUBLIC

Project acronym	Main focus	Duration
ALLEGRO	Design and testing of key systems and components for ALLEGRO	2018-2025
MKN	Development of a new class of Zr based alloys and high entropy alloys with optimized properties for Nuclear industry	2018-2024
NOVA	Development of sacrificial materials for core catchers of GFRs	2018-2022
REDEAL	Testing of construction materials in gaseous environments at extreme conditions (high temperature, corrosive environments)	2018-2024
SODOMAHe	Stability and resistance of materials for high-temperature helium-cooled reactors	2019-2025
KOBRA	Development of a passive safety systems for GFRs/VHTRs based on prolongation of primary compressor rundown by utilization of decay heat	2020-2023
MATPRO	Development of "better concrete" based on inorganic polymers for extreme conditions	2020-2024
PMATF	Methods for the characterization, testing, and qualification of irradiated samples of ATF materials	2020-2023

As can be seen from the data listen in TABLE 4, majority of the ongoing projects is focused on material development, since it was identified as the most pressing area. Safety research and development of systems and components closely follow. Relation to key particular issues in GFR R&D, as identified in TABLE 3, is shown in TABLE 5.

TABLE 5: RELATION OF CZECH NATIONAL PROJECTS TO THE MAIN CHALLANGES IN GFR R&D

Key particular issues	Project							
	ALLE GRO	MKN	NOVA	REDEAL	SODO MA	KOBRA	MATP RO	PMATF
Fuel composition selection								
Fuel thermal-mechanics behavior								X
Core safety								
Valves	X							
Sealing								
Heat exchangers	X					X		
Reactivity control systems								
Core materials		X						X
Structural materials of I. circuit				X	X			
Structural materials for containment							X	
Ways of passive safety	X					X		
SA prevention and mitigation	X		X					
Natural convection	X					X		
Coolant purification								

4.4. GFR R&D in Hungary

In Hungary, a major national project on GFR was finished in 2018. With the recent reform of the Hungarian Acamedy of Sciences, and individual entity “Center for Energy research” (EK) was formed, and development of the ALLEGRO reactor is one of its research priorities. Since 2019, EK, alongside with several universities and private companies, are the leading entities in GFR research in Hungary, with focus on reactor physics and nuclear fuel, safety, and thermal-hydraulics. [13] [14].

4.5. GFR R&D in Poland

In Poland, there is currently no ongoing national project focused primarily on the GFR technology. However, Polish HTR program is very broad, with several substantial R&D projects ongoing, and with a plan for a fast deployment of an HTR prototype designed in Poland [15] [16]. Since there is a high number of cross-cutting R&D issues between the HTR and the GFR technologies, experience and results obtained from these projects are valuable contributions for development of ALLEGRO.

4.6. GFR R&D in Slovakia

In Slovakia, a major national project on ALLEGRO development finished in 2015, focused on building of competences and development of the concept. One of the major achievements of the Slovakian GFR program is the successful commissioning and operation of the STU helium loop – an experimental facility aimed at study of natural convection in helium-cooled reactors. First experimental results were already obtained and published [17] [18].

5. ONGOING INTERNATIONAL PROJECTS ON GFR RESEARCH AND DEVELOPMENT

In this chapter, the ongoing R&D projects and their position in respect to key challenges listen in TABLE 3 are described. The following sections are dedicated to international activities, namely the H2020 SafeG project, and international collaboration within GIF and multilateral agreements.

5.1. H2020 SafeG project

Since October 2020, 15 organizations from 7 European countries and Japan have been working together on a 4-years R&D project supported by the European Commission. Detailed description of the project structure, main goals, and roles of individual partners would be enough for a whole dedicated paper, therefore, in this section, only the main areas of R&D are listed, and their connection to key challenges in GFR research and development are discussed.

The SafeG project contains four technical work packages (WPs), a work package dedicated to training and education activities, and two work packages for communication and project management. The four R&D work packages are following:

— WP1: Core safety, proliferation resistance
— WP2: Innovative materials and technologies for enhancing safety of GFRs
— WP3: Innovative solutions for decay heat removal
— WP4: Integration of the results, standardization, codes

Total effort to be spent for solving of technical problems within these four WPs is 576 person-months, or 48 person-years, with total budget of 4.5 M€. TABLE 6 summarizes individual tasks of the WPs and their connection with the key challenges in GFR R&D.

TABLE 6: RELATION OF SAFEG WPS TO THE MAIN CHALLANGES IN GFR R&D

Key challenge	WP1	WP2	WP3	WP4
Fuel composition	X	X		
Fuel thermal-mechanics behavior		X		
Core physics	X			
Valves			X	
Sealing				
Heat exchangers		X	X	
Reactivity control systems	X			
Core materials		X		
Structural materials of I. circuit		X		
Structural materials for containment				
Ways of passive safety			X	
SA prevention and mitigation				
Natural convection			X	
Coolant purification				

5.2. International collaboration

In this section, ongoing work that is coordinated in the framework of two international collaboration platforms, is described. One of them is Generation IV International Forum, which includes a dedicated section on GFR development with two ongoing international projects. The other one is a project inside of UJV-CVR-JRC multilateral agreement.

In the framework of GIF, a project dedicated to conceptual design and safety of ALLEGRO has been ongoing, as well as a project on GFR fuel safety. Within the conceptual design and safety project, activities complementing the work done within the Czech national projects, and the SafeG project, have been ongoing, within Euratom and France collaboration. The GFR fuel safety project focuses mainly onto development of SiC-based cladding materials for GFRs. Euratom, France, and Japan have been collaborating on this task.

Under the UJV-CVR-JRC multilateral agreement, one project dedicated to GFR is ongoing, led by UJV Rez. It complements the Czech national project “NOVA”, using the unique equipment and knowhow of JRC Karlsruhe in the field of precise measurements of thermo-physical properties of materials.

6. PLANNED R&D FOR THE NEAR FUTURE NOT COVERED BY ONGOING PROJECTS

As can be seen from the data in TABLE 5 and TABLE 6, which summarize all the ongoing projects in their relation to the key challenges in GFR R&D, most of the key areas are covered by at least one ongoing R&D project. However, there are three exceptions – fuel composition and enrichment, helium sealing, and helium-related technologies. However, the levels of maturity of solutions for GFR in these three fields are very different.

In helium-related technologies, a long-term R&D program consisting of several consecutive national project was finished in 2020 in the Czech Republic, with results in form of prototypes, patents, and certified methodologies, covering the topics of helium purification, and separation of other non-condensable gases from helium.

Concerning helium sealing at high temperatures and pressures, several solutions were investigated, developed, and tested in the framework of the projects mentioned above. Moreover, there are currently two helium facilities under operation by CVR in the Czech Republic (S-ALLEGRO) and STU in Slovakia (STU helium loop). Both these facilities operate at high temperatures and pressures (7MPa and up to 850°C), and, therefore, sealings are tested there in the prototypical conditions. Both facilitates show remarkable level of leak tightness both in the cold and the hot state.

GFR fuel material composition, fabrication, testing etc. remain the only area where new research and development is vital, and there is no project ongoing. The concept of carbide fuel is relatively old, and quite extensive work had been done in the past, however, the experiments were not conducted for GFR prototypical conditions (high-enough temperature, GFR-specific cladding materials etc.). On the other hand, such a project would be very expansive, demanding in terms of equipment such as having a fast-spectrum reactor with a helium loop available for irradiation of samples, and generally very complex and challenging. The goal of GFR developers is to utilize the MBIR reactor for such development, once it will be in operation.

7. CONCLUSIONS

GFR technology research and development in the Visegrád Four (V4) countries has a tradition of more than a decade. Top organizations in nuclear R&D from the Czech Republic, Hungary, Poland and Slovakia formed an organization called V4G4 Centre of Excellence in 2013, that serves for coordination of national and international research and development projects on GFR in Europe. Two European GFR reactors are briefly introduced in the paper – the demonstration unit ALLEGRO, and a concept of advanced modular reactor HeFASTo.

The extent of the R&D program on GFR in the V4 countries is growing by year, as of 2021, there are 8 ongoing national projects, one ongoing European project, and three ongoing international projects dedicated to development of the technology. The projects cover a vast range of topics of high importance for further development of GFR reactors, with a substantial budget and manpower available.

In the future, the topic of fuel development and qualification will probably be the most crucial in order to bring the GFR technology to the higher technology readiness levels. General boost of interest in the accident tolerant fuel materials and advanced technology fuel materials means that the until-now GFR-specific fuel will be further investigated also outside the GFR development teams, which will result in faster deployment of the technology.

REFERENCES

[1] BRUCKNER, T. et al.: Energy Systems. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014

[2] Uranium 2020: Resources, Production and Demand, Joint Report by the Nuclear Energy Agency and the International Atomic Energy Agency, 2020

[3] Gas-Cooled Fast Reactor (GFR), online, https://www.gen-4.org/gif/jcms/c_9357/gfr, 31.5.2021

[4] POETTE, C., BRUN-MAGAUD, V., MORIN, F., PIGNATEL, J.F., STAINSBY, R., MIKITYUK, K., 2009. ALLEGRO: the European gas fast reactor demonstrator project. In: Proceedings of the 17th International Conference on Nuclear Engineering ICONE17 July 12-16, 2009, Brussels, Belgium.

[5] SIMON, R. H. et al: Gas-cooled fast breeder reactor demonstration plant, Proceedings of the ANS Topical Meeting on Gas-cooled Reactors, Gatlinburg, USA, 1974

[6] CHERMANNE, J. et al.: Past and future programmes of the GBR Association, Proceedings of the IAED Study Group Meeting on Gas-cooled Fast Reactors, IAEA, Minsk, Belarus, 1972

[7] STAINSBY, R. et al.: Gas cooled fast reactor research in Europe, Nuclear Engineering and Design 241, 2011

[8] POETTE, C. et al.: The European Union’s experimental gas-cooled fast reactor project, International conference on the physics of reactors, Interlaken, Switzerland, 2008

[9] ÚJV Rez, a. s.: ÚJV Řežpředstavila HeFASTo — druhý malýreaktor české provenience a první svého druhu v Evropě, press release in Czech language, https://www.ujv.cz/file/edee/2021/05/tz_hefasto_ujv_rez_2_2021_final.pdf , 27.5.2021

[10] “Central Europe’s V4 Nations Establish Generation-IV Centre Of Excellence”, online at https://www.nucnet.org/news/central-europe-s-v4-nations-establish-generation-iv-centre-of-excellence, 31.5.2021

[11] ATEKO, a. s. : S-ALLEGRO Experimental Helium Loop, online at https://www.ateko.cz/media/cache/file/a9/ATEKO_S_ALLEGRO_Experimental_Helium_Loop_2020.pdf 31.5.2021

[12] Technology Agency of the Czech Republic, https://www.tacr.cz/en/technology-agency-of-the-czech-republic/ 31.5.2021

[13] HÓZER, Z. et al: Development of new cladding types for nuclear fuel, IOP Conference Series Materials Science and Engineering 903:012004, August 2020

[14] MAYER, G: Hot duct break transient with two- and three-loop ALLEGRO models, Nuclear Engineering and Design 370, 2020

[15] SOBOLEWSKI, J.: Energy policy of Poland until 2040, 5th Workshop on Attaining Carbon Neutrality, April 14, 2021

[16] SOBOLEWSKI, J: Poland Nuclear Energy Development Plan, 2nd Webinar towards HTR2021, Djakarta, December17th, 2020
[17] URBAN, F., et al. (2017). Research of natural circulation in the experimental helium loop of STU. AIP Conference Proceedings 1889(1):020047, DOI: 10.1063/1.5004381.
[18] KNÍŽAT, B., et al. (2015). CFD Simulation of a Natural Circulation Helium Loop, Scientific Proceedings Faculty of Mechanical Engineering 23(1), DOI: 10.1515/stu-2015-0006