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DELIVERABLE D4.5

Assessment of timescales and R&D needed to implement the identified solutions

Lead Beneficiary: Jacobs Clean Energy

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EXECUTIVE SUMMARY

The purpose of this report is to evaluate the technology readiness level (TRL) of the Gas-cooled Fast Reactor (GFR) that can help identify future research and development (R&D) requirements. To demonstrate the feasibility of full-scale GFR technology, the 75 MW ALLEGRO demonstrator has been utilised by the SafeG project. ALLEGRO aims to introduce a closed fuel cycle technology that is safe, reliable, efficient, and sustainable, while minimizing high-level nuclear waste production. The report provides an overview of both the GFR and its small-scale prototype, ALLEGRO. Full system details are still uncertain, so critical components are identified, along with known technology barriers. The methodology for assessing TRL is explained, and the TRL assessment matrix covering the nine levels and five streams (system, materials, software, manufacturing and instrumentation) is presented. Based on available information, the TRL assessment is provided for all main components, and R&D needs are identified from available literature. Finally, following five recommendations are made to help progress the development of GFR technology:

System Breakdown Structure (SBS): Develop a detailed SBS for a helium-cooled GFR power plant, highlighting system elements, relationships, and establishing a hierarchy of interactions.

Technology Roadmap: Create an integrated roadmap considering both “pull” and “push” technology strategies. Identify top technical challenges, necessary “pull” technologies, and emerging “push” technologies correlated with existing facilities and research done for VHTRs, HTGRs and SFRs.

Plant Systems Design Approach (PSD): Address cost reduction and safety enhancement in designing next GFR by following the new ASME PSD code, developed by international experts, that integrates hazard analysis, systems engineering, and risk-informed probabilistic design.

Data-Centric Approach: Embrace digital technologies (AI, digital twins) for optimised designs, material assessment, and safety features during design, development and construction.

Digital Knowledge Base: Consolidate research reports from previous projects into a single digital repository for effective Knowledge Management and Knowledge Preservation (KMKP) that can be searched effectively by an AI-powered cognitive search tool. Having a centralised repository will help future endeavours, prevent waste of time/resources on repeating work already done and help inform efficient resource allocation.

CONTENT

1 BACKGROUND

This report is part of Task 4.2 of the "Safety of GFR through innovative materials, technologies and processes" (SafeG) H2020 project and is issued as project deliverable D4.5. The SafeG project is aiming at connecting developers of the ALLEGRO reactor (V4G4) with European and international experts having experience in GFR and HTR research. It is divided into 7 Work Packages. The fourth Work Package (WP4) is Integration of results and standardization. This report comes under Task 4.2 related with assessment of timescales and R&D needed to implement solutions identified in WP1, WP2 and WP3. It will provide basis for continuous national and international research of GFRs, helping to maximise the impact of this project.

2 SCOPE

The main objective is to assess the current TRL of the material, technology and process options selected for GFRs within WP1, WP2 and WP3 to help identify further R&D needed for technology development beyond pre-conceptual phase. This is part of the SafeG deliverable D4.5 "Assessment of timescales and R&D needed to implement the identified solutions (UJV, M44)". It should be noted that smaller scale prototype ALLEGRO is being used to demonstrate the feasibility of full-scale GFR technology.

In this task, the material, technology and process options selected as suitable for GFRs within WP1, WP2 and WP3, are reviewed from the point of view of current TRL and technological aspects, and further R&D needed to push their development beyond pre-conceptual phase are assessed. Finally, high level recommendations are made about future technology development.

3 INTRODUCTION

3.1 GFR

Gas-cooled fast reactor (GFR) is considered as one of the six most promising advanced nuclear reactor technologies. There are many designs of GFRs using air, helium, CO_2 and N_2O_4 as coolants but the SafeG project has considered GFR cooled by helium which is a single phase, chemically inert and transparent coolant. The main advantages of helium-cooled GFR, beside the possibility to close the fuel cycle which is an inherent feature of all fast-spectrum nuclear reactors, are:

- High core outlet temperature leading to high thermal efficiency of the reactor for electricity production, and makes it an ideal source of high-potential heat for hydrogen production and other industrial applications
- Improved core neutronic safety due to low void reactivity feedback coefficient
- Helium is chemically inert and non-corrosive coolant without phase change, reducing risks of accidents caused by coolant chemistry-induced failures
- Helium is transparent, which allows much easier in-service inspections and maintenance compared to liquid metals and salts coolants

Brief history of GFR development is presented by B Hatala [1] that presented ALLEGRO demonstrator as an essential step to establish confidence in the innovative GFR technology. The concept of the ALLEGRO demonstrator was originally developed in the first decade of this century by CEA, featuring a two-loop design, and with thermal power 75 MW. The CEA activities brought the ALLEGRO demonstrator to the Technology Readiness Level (TRL) 2.

According to the GIF Annual report 2023 [2], the signatories of the System Arrangement for collaboration on gas-cooled fast reactor (GFR) research and development (R&D) are the following Generation IV International Forum (GIF) members: Euratom, France and Japan. Two technical projects have been established for GIF collaborations:

• GFR conceptual design and safety, with the Joint Research Centre (JRC) and French Alternative Energies and Atomic Energy Commission (CEA) as members;
• GFR fuel, core materials and fuel cycle, with the JRC, CEA and Kyoto University as members.

Handbook of Generation IV Nuclear Reactors [3] also provides views of international experts on the history of development and research carried out for the Generation IV reactors including the GFR. Views expressed in [1], [2] and [3] have been considered in this review.

3.2 History of ALLEGRO

The R&D collaboration activities pursued in the two GFR technical projects focus on the ALLEGRO gas-cooled fast reactor demonstration concept. The GIF projects have scope for conceptual design, safety analysis, testing of start-up fuel and core materials, and fuel performance modelling.

Four nuclear research institutes and companies in the Visegrad-Four region (ÚJV Řež, a.s., Czech Republic; MTA EK, Hungary; NCBJ, Poland; and 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 GFR concept based on a memorandum of understanding signed in 2010.

The CEA (France), as the promoter of the GFR concept since 2000, supports these joint preparations, bringing its knowledge and experience to building and operating experimental reactors, and in particular fast reactors. Both CEA and the Research Centre Rez (CVR) of Czech Republic are associated members of V4G4. Brief history of ALLEGRO is given by Belovsky [4] and is shown in Fig 1.

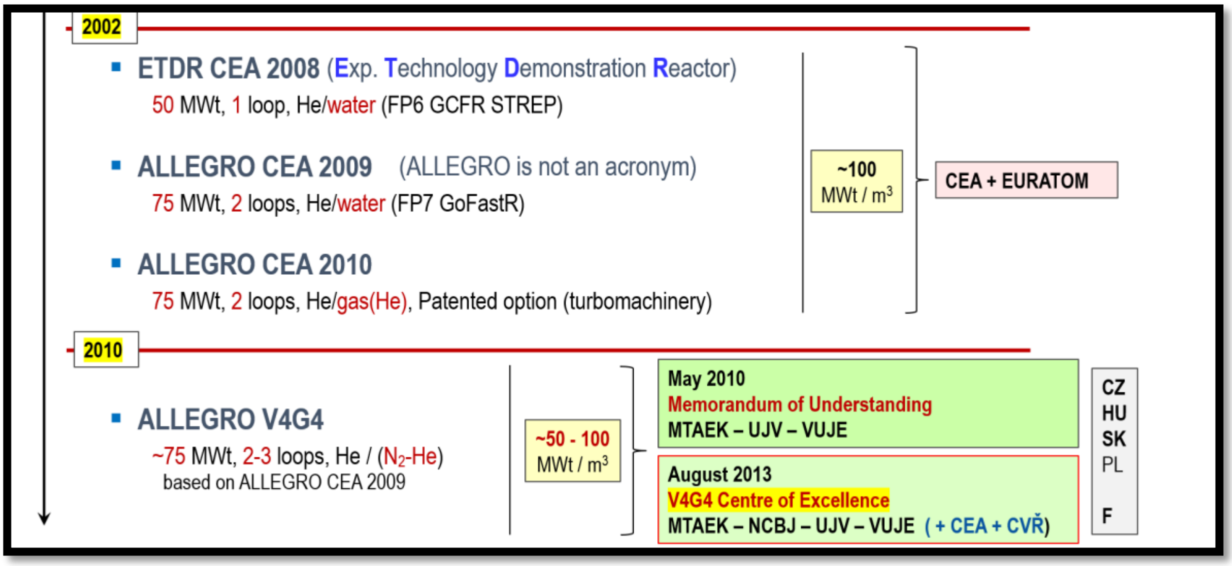

Fig 1. History of Design Concept of ALLEGRO [4]

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 nuclear research institutes and companies 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.

Based on the design specifications and safety requirements, the main components of the Allegro V4G4 system taken from [4] are shown in Fig 2. The TRL of these main components are considered in this report.

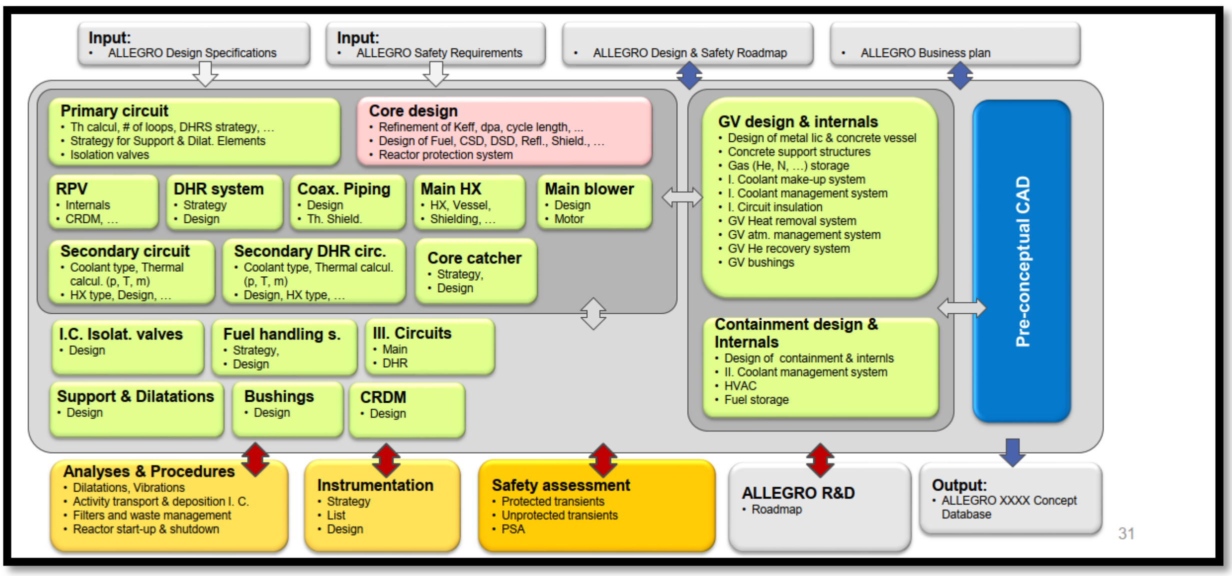

Fig 2. Main components of the Allegro V4G4 system [4]

3.3 ALLEGRO Overview

The objectives of ALLEGRO are to demonstrate the viability and 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 consisted of two helium primary circuits, three decay heat removal (DHR) loops integrated into a pressurized cylindrical guard vessel. The original design is shown in Figure 3 taken from the recent report by C Doderlein [42] presented to GIF in May 2024. In the SafeG project, the design of the Main Heat Exchanger (MHX) was reassessed in D2.4 [22] with two objectives : (i) To allow ALLEGRO to reach high temperatures of its secondary coolant, and, therefore, to allow for successful demonstration of GFR capabilities in cogeneration and hydrogen production. (ii) To get rid of water in the secondary system, which could, in case of an unmitigated leak, compromise the safety of ALLEGRO as it is a fast reactor sensitive to presence of a substantial amount of moderator in the core. There is additional level of complexity in the designing process of the MHX of ALLEGRO, because of the two-step strategy in its operation. First, it has to work with the "driver core" with the core inlet/outlet temperature of 260/530 °C. Then work with the "refractory core" with 400/850 °C, and also lower total mass flow rate. It is not physically possible to fully optimize the main heat exchanger for both the configurations due to the different temperature levels, temperature gradients, and mass flow rates. Replacing the MHX after several years under operation would also present a major task connected with substantial economic and technical challenges. Since the goal of the MHX is to allow showcase of the possibilities of GFR, it was decided that the full optimization will be done for the high-temperature refractory core, and the final design of the MHX will be just checked against the driver core values if it is capable to dissipate enough heat. The final conceptual design of the main heat exchanger is a gas-to-gas helical coil tube-and-shell heat exchanger, with the primary helium gas flowing on the shell side, and a 90 % nitrogen 10 % helium mixture on secondary side flowing inside the tubes. 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 the fast neutron spectrum research facility which is needed for fuel and materials development;
• test some of the special devices or other research work.

TRL of a nuclear reactor depends on the core design. In case of Allegro, two different core designs with different fuel are being considered furthermore all the related sub-systems like the MHX have to be substantiated for both types of cores which complicates the TRL assessment.

The 75 MWth reactor is to 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. This is the end state for GFR to reach TRL 9.

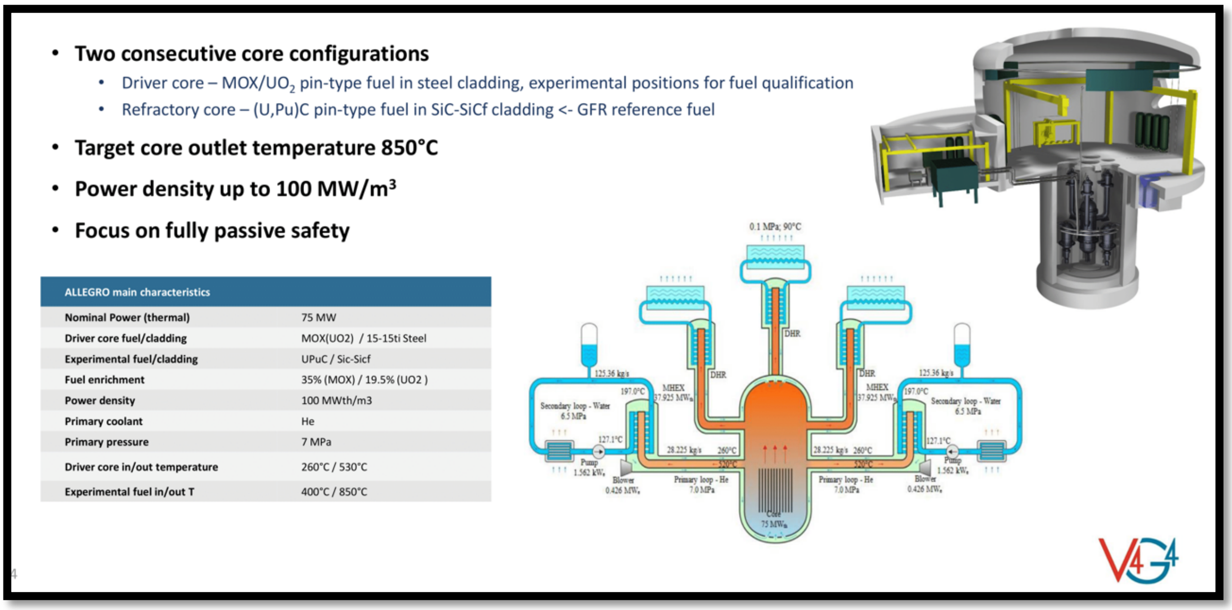

Fig 3. Design overview of ALLEGRO by V4G4 [42]

Review of the SafeG reports indicates that project was aimed to bring the design and safety of this reactor a considerable step further, mainly in the following areas:

• Core safety – significant progress beyond the state of the art of GFR core safety has already been
made (start up core optimization was completed). Further work included optimization of reactivity feedback coefficients and irradiation capabilities of the ALLEGRO core designs.

• Automatic shutdown system – the current design updated, using state-of-the-art knowledge possessed by the consortium members.

• Instrumentation – instrumentation of GFRs identified with detailed analyses and assessment of the possible use of advanced measuring technologies and techniques.

• Decay heat removal system – so far, decay heat removal for GFRs has been solved in a very similar way for all the reference concepts. Within SafeG, effort was put into developing an innovative decay heat removal solution based on cutting edge technology – supercritical CO_2 cycles.

Experiments had to be conducted to test compatibility of materials. These are first-of-a-kind results of structural materials behaviour in He-N2 mixtures at very high temperatures. Application of these results will help applications in GFR and nuclear in general.

Fuel qualification assessment of innovative advanced fuel for GFRs is almost completed. It will provide unique insight into this important issue that can serve as a basis for a general methodology of advanced fuels qualification for advanced nuclear reactors in Europe in the future.

3.4 GFR System

The review has found that the GFR system is still evolving. The full system and the attendant System Breakdown Structure (SBS) have not been finalised. According to the summary published by GIF [5], the GFR system is a high-temperature helium-cooled fast-spectrum reactor with a closed fuel cycle shown in Fig 4. It combines the advantages of fast-spectrum systems for long-term sustainability of uranium resources and waste minimisation (through fuel multiple reprocessing and fission of long-lived actinides), with those of high-temperature systems (high thermal cycle efficiency and industrial use of the generated heat, for hydrogen production for example).

The GFR uses the same fuel recycling processes as the SFR and the same reactor technology as the VHTR. Therefore, its development approach is to rely, in so far as feasible, on technologies developed for the VHTR for structures, materials, components and power conversion system. Nevertheless, it calls for specific R&D beyond the current and foreseen work on the VHTR system, mainly on core design and safety approach.

It should be noted that unlike the VHTRs, GFR does not have graphite. The use of gas coolant without the graphite raises two additional technological challenges. Firstly, without graphite, the core has low thermal inertia that leads to rapid heat-up of the core following loss of forced cooling. Since the power density is high in the GFR, the HTR-type “conduction cool-down” will not work for the removal of the decay heat. So more effective decay heat removal system is needed. Secondly, in the absence of graphite moderator, additional consideration has to be given to the effects of the fast neutron dose on the reactor pressure vessel whereas in HTR the graphite moderator provides protection for HTR systems.

The reference design for GFR is based around a 2400 MWth reactor core contained within a steel pressure vessel. The core consists of an assembly of hexagonal fuel elements, each consisting of ceramic-clad, mixed-carbide-fuelled pins contained within a ceramic hex-tube. The favoured material at the moment for the pin clad and hex-tubes is silicon carbide fibre reinforced silicon carbide. Figure 4 taken from GIF [5] shows the reactor core located within its fabricated steel pressure vessel surrounded by main heat exchangers and decay heat removal loops. The whole of the primary circuit is contained within a secondary pressure boundary, the guard containment.

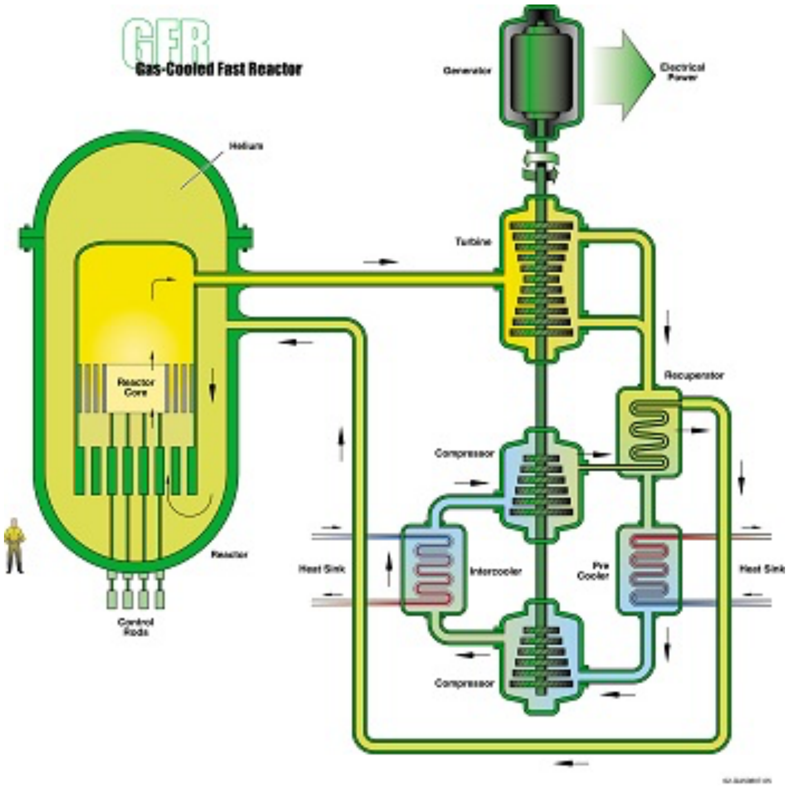

Fig 4. The GFR System [5]

The coolant is helium and the core outlet temperature will be of the order of 850°C. 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 plant so represents an established technology, with the only difference in the GFR case being the use of a closed cycle gas-turbine.

Proliferation resistance of GFR designs have been studied by GIF [6] which found that the GFR's fuel cycle is the same as the one for SFR with aqueous recycling, using depleted U and high Pu content MOX fuel. For physical protection, the present design of GFRs relies on many of the same protective measures used in PWRs (mainly with a reactor containment building) given the fact that inert gas is used as a primary coolant. The report points out that major R&D effort is still needed to further improve provision for core cooling in accident conditions and to practically remove the risk of severe accidents in GFR to comply with the IAEA's DEC requirements.

4 METHODOLOGY FOR TRL ASSESSMENT

Commonly used technique for assessing technology maturity is the TRL system that provides a standard framework for assessing the maturity of a technology. While the TRL system was originally developed to assess the readiness of a single technology, it is not always sufficient for assessing the readiness of complex systems such as the GFRs which involve the integration of several different technologies. In this report, nuclear specific TRLs are considered.

4.1 Background to TRLs

NASA developed TRL's originally in 1974 [7]. The European Commission explored the use of TRL's for nuclear reactor decommissioning (see EU Horizon 2020 [8]) and the UK Nuclear Decommissioning Authority [9] also produced a TRL guide. The main TRLs devised by NASA and also used by ESA for aerospace industry are defined in Table 1.

Table 1. Technology Readiness Levels used by NASA and ESA [7]

Level	Definition
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard functional verification in laboratory environment
TRL 5	Component and/or breadboard (reduced scale) critical function verification in relevant environment
TRL 6	System model (full scale) critical functions demonstration in relevant environment
TRL 7	System model performances demonstration in operational environment
TRL 8	Actual system completed and accepted for operational environment through test and demonstration ("mission qualified")
TRL 9	Actual system "mission proven" through successful mission operations

The EU H2020 [8] TRLs are shown in Table 2 and the three phases of technology development proposed by the NDA(UK) [9] are shown in Table 3. The EU definitions are generic but the NDA(UK) definitions are more nuclear specific. Research, deployment and operations phases have been introduced and the most notable is that inactive commissioning is restricted to TRL 7. A nuclear component/system developed to work with radioactive substances will only reach TRL 8 if active commissioning is carried out.

Table 2. Technology Readiness Levels used by EU H2020 [8]

Technology Readiness Level	Description
TRL 1.	basic principles observed
TRL 2.	technology concept formulated
TRL 3.	experimental proof of concept
TRL 4.	technology validated in lab
TRL 5.	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6.	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7.	system prototype demonstration in operational environment
TRL 8.	system complete and qualified
TRL 9.	actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Table 3. Three phases of nuclear technology development used by NDA(UK) [9]

Phase	TRL	Stage	Description
Operations	TRL9	Operations	The technology is being operationally used in an active facility
Deployment	TRL8	Active Commissioning	The technology is undergoing active commissioning
	TRL7	Inactive Commissioning	The technology is undergoing inactive commissioning. Works testing and factory trials on the final designed equipment using inactive simulants comparable to that expected during operations. Testing at or near full throughput will be expected
	TRL6	Large Scale	Undergoing testing at or near full-scale size. The design will not have been finalised and the equipment will be in the process of modification. It may use a limited range of simulants and not achieve full throughput
	TRL5	Pilot Scale	Undergoing testing at small to medium scale size in order to demonstrate specific aspects of the design
	TRL4	Bench Scale	Starting to be developed in a laboratory or research facility.
Research	TRL3	Proof of Concept	Demonstration in principle that the invention has the potential to work.
	TRL2	Invention and Research	A practical application is invented or the investigation of phenomena, acquisition of new knowledge or correction and integration of previous knowledge.
	TRL1	Basic principles	The basic properties have been established

The GAO of US Govt [10] has taken the nine TRLs and descriptions that NASA, and other organisations had developed and proposed a common description of TRLs shown in Table 4.

Table 4. TRL Definitions proposed by US Govt. Accountability Office [10]

Technology readiness level (TRL)		Description
1	Basic principles observed and reported	Scientific research begins to be translated into applied research and development. Examples include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively low fidelity compared with the eventual system. Examples include integration of ad hoc hardware in the laboratory.
5	Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include high fidelity laboratory integration of components.
6	System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in its relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
7	System prototype demonstration in an operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requirement demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, a vehicle, or space).
8	Actual system completed and qualified through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system proven through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

Source: GAO analysis of agency documents. | GAO-20-48G

It is proposed to take the TRL level description from Tables 3 and 4 and combine it with the methodology proposed by the IAEA [11] that has a simple matrix of five streams of TRLs that are combined to give an overall readiness of a complex system. The five streams are system, materials, software, manufacturing technologies and instrumentation as shown in Table 5.

Such a matrix could be used to combine TRLs for individual technologies and components. The resulting matrix could provide a more holistic view of the readiness of a GFR and help identify areas where further development or testing may be needed. However, it is important to note that any such matrix or framework would need to be tailored to the specific needs and requirements of the GFR being assessed.

Progress along the TRL pathway is characterised by increasing levels of technology development and system integration, as well as increasing fidelity of the simulation or testing environment. The early phases can be performed under laboratory conditions in individual system elements. The intermediate phases increase both the relevance of the environment as well as the level of system integration. The final phase requires actual system demonstration in an operational environment.

4.2 TRL Assessment Matrix

Nine TRLs exist ranging from initial ideas where basic principles are observed and reported to fully robust technologies validated for application in industry. These TRLs give a good idea of maturity and are used by industry and government organisations. The TRL scale is an ordinal scale. The effort or time needed to move from one point to another may not be linear. TRLs are time specific and most importantly context specific. A technology which is mature in one sector may not be mature for GFR application and vice versa. Full 9x5 matrix for TRL is given in Table 5.

Table 5. TRL Assessment Matrix [11]

TRL	System	Materials	Software	Manufacturing	Instrumentation
9	Successful mission operation	Production ready material	Live product with full documentation and track record available	Demonstrated over an extended period	Service proven
8	Test and demonstration	Full operational test	General product ready to be applied in a real application	Significant run lengths	Demonstrated productionised system
7	Prototype demo in an operational environment	Evaluated in development rig tests	Early adopter version qualified for a particular purpose	Economic run lengths on production parts	Successful demonstration in test
6	Prototype demo in a relevant environment	Validated via component and/or sub-element testing.	Product release ready for operational use	Process optimised for capability and rate using production equipment	Applied to realistic location/environment with low level of specialist support.
5	Partial system validation in a relevant environment	Methods for material processing and component manufacture	Beta version with complete software functionalities, documentation, test reports and application examples	Basic capability demonstrated using production equipment	Requiring specialist support
4	Validation in a laboratory environment	Design curves produced.	Alpha version with most functionalities user manual and design file available	Process validated in lab	Lab demonstration of highest risk components
3	Proof of concept	Materials' capability	Prototype architectural design of	Experimental proof of concept completed	Lab test to prove the concept works.

		based on lab scale samples	important functions documented		
2	Technology concept	Agreed property targets, cost & timescales	Algorithm implementation documented	Validity of concept described	Concept designed
1	Basic principles	Evidence from literature	Mathematical formulation	Process concept proposed	Understand the physics

4.3 TRL Framework for GFR

A generic framework presented in Table 5 as a 9x5 matrix that assesses each of the critical technologies has been applied in this TRL assessment. Brief description of the five streams is given in the following sections.

4.3.1 System / Integration RL

In system engineering, a system (or system of interest) is an integrated collection of elements, subsystems, or assemblies designed to achieve a defined objective. These elements encompass various components, such as hardware, software, firmware, processes, people, information, techniques, facilities, services, and other supporting elements. Integration is included in the Systems RL and it is worth noting that integration becomes more significant as higher TRLs are reached. In future, this stream will gain more importance for GFR.

4.3.2 Materials RL

Materials are defined as physical substance used to build the system/subsystem/component in order to fulfil one or more functions; for instance, structural integrity or/and functional purpose such as thermal/electric isolation or anticorrosion. Thus, this includes the structural and the functional materials. For example, the sacrificial material used in the GFR core catcher and the insulation materials in the DHR are considered among the functional materials. Due to high operating temperatures, this stream of development will be challenging. Most probably the materials to be used in GFR have to meet the requirements of the French nuclear code RCC M RX [43]. The code requires study of material's thermal ageing behaviour, creep tests to establish creep fracture stress and creep-strain rule, and fatigue-creep interaction diagrams under envisaged operational conditions (temperature, number of cycles, etc). Experience shows that such material qualification can take decades.

4.3.3 Software RL

The software TRL stream serves as a valuable tool to assess the maturity of specific software technologies (such as building blocks or tools) within the context of their intended applications. For specific embedded software targeting a specific application and not conceived to be reused in another domain of application (e.g. specific equipment embedded software) the corresponding hardware TRL stream (instrumentation, system) is applicable, the specific software is part of the hardware TRL assessment. However, analytical software used to analyse performance of critical components like core, fuel and DHR may be challenging as verified computational models may not be readily available. The SafeG project seems to have made most progress in the software RL stream.

4.3.4 Manufacturing RL

Manufacturing is the process of converting raw materials, components, or parts into finished goods that meet a customer's expectations or specifications. This stream will pose more challenges at higher TRL when the industrial deployment starts. It is hoped that new Advanced Manufacturing will help.

4.3.5 Instrumentation RL (use of instrument not development of new instrument)

The instrumentation is integration of device(s) into the system that communicates, denotes, detects,
indicates, measures, observes, records, or signals a quantity or phenomenon, or controls or manipulates another device. In GFR applications, instrumentation plays a critical role in diagnostics and control of the reactor as discussed in D3.7. Early review has already indicated that some sensors required for GFR may not be available but future development of smart sensors may help.

No special stream for economics, cost or regulations can be included as regulations sometimes evolve after a technology has been developed and costs are impacted by non-technical issues. In nuclear context, safety remains paramount and is covered by use of appropriate codes and standards.

Overall technology maturity levels improve during a project but there can be various scenarios. TRL assessments done at a specific time can relate to Stage Gate reviews and Design Review (concept/functional/ready for manufacture design). Important point to note is that TRLs are not for a whole plant but are for specific technologies that are needed for a plant.

Technology Readiness Assessment (TRA) for a whole plant can be done by combining the TRLs for all the critical technologies with their respective Integration Readiness Level (IRL). Which is out of scope of this report.

4.4 Benefits and Limitations

TRL assessments can help decide whether a technology is ready for implementation and plan its development. As mentioned earlier, TRLs are for individual technologies not for a system requiring integration of many. There is a need to breakdown a complex system into sufficient number of sub-systems in order to apply TRLs. In absence of a formal System Breakdown Structure (SBS), this review has identified main components/sub-systems later in Section 6.

4.5 Work Plan

The work has been carried out in the following stages as follows:

i. Collect information from WP1, WP2 and WP3.
ii. Review the System Breakdown Structure and identify critical sub-systems/technologies.
iii. Assess TRL focussing only on relevant streams from WP1 (core design for safety and proliferation resistance), WP2 (materials) and WP3 (decay heat removal).
iv. Report "Technology Readiness Level of GFR and R&D Needs" for the project.

Outcome from each of the stages is presented in the following sections.

5 INFORMATION FROM WP1, WP2 AND WP3

The following deliverables from the previous three WPs were identified but only 16 were available for review as the deliverables D1.6[17], D1.7[18], D2.2[20], D2.5[23], D2.6[24], D3.3[27] and D3.8[32] were not issued at the time of the TRL analysis.

5.1 WP1 Deliverables

a) D1.1 [12] Start-up core design optimization (VUJE, M16)
b) D1.2 [13] Refractory core design, preparatory phase (MTA-EK, M24)
c) D1.3 [14] Proliferation resistance assessment (CVR, M24)
d) D1.4 [15] Diversified ways of passive reactor shutdown (VUJE, M24)
e) D1.5 [16] Design of the control and shutdown elements (UJV, M36)
f) D1.6 [17] Refractory core design (MTA-EK, M40) *[Not available at the time of the review]*
g) D1.7 [18] Core reflector and radiation shielding (MTA-EK, M40) *[Not available at the time of the review]*

5.2 WP2 Deliverables

a) D2.1 [19] Innovative cladding materials testing (MTA-EK, M24)
b) D2.2 [20] ALLEGRO Core support plate (UJV, M36) *[Not available at the time of the review]*
c) D2.3 [21] DHR Heat Exchanger (UJV, M36)
d) D2.4 [22] Main Heat Exchanger (CVR, M36)
e) D2.5 [23] Structural materials testing in media (CVR, M45) *[Not available at the time of the review]*
f) D2.6 [24] Advanced manufacturing processes and materials (NCBJ, M45) *[Not available at the time of the review]*

5.3 WP3 Deliverables

a) D3.1 [25] Optimized emergency coolant injection system (VUJE, M20)
b) D3.2 [26] Options for innovative and diversified DHR (UJV, M24)
c) D3.3 [27] Description of the experimental program, interpretation and database of experimental results (CVR, M24) *[Not available at the time of the review]*
d) D3.4 [28] Detailed study of conditions in isolated DHR loop in long-term reactor operation (CTU, M24)
e) D3.5 [29] Options for complete isolation of primary and DHR loops (UJV, M26)
f) D3.6 [30] Options for preconditioning of the DHR loops (VUJE, M30)
g) D3.7 [31] Instrumentation assessment (VUJE, M32)
h) D3.8 [32] Assessment of thermal loads on the core and primary circuit in emergency (UJV, M32) *[Not available at the time of the review]*
i) D3.9 [33] Study of effects of complete isolation of primary and DHR loops on safety (CVR, M36)
j) D3.10 [34] CFD study of core cooling in LOFAs (CTU, M36)

6 SYSTEM BREAK DOWN STRUCTURE AND IDENTIFICATION OF CRITICAL TECHNOLOGIES

Critical technologies are technology elements deemed as critical if they are new or novel, or used in a new or novel way, and are needed for a system to meet its operational performance requirements within defined cost and schedule parameters. These technology elements may be hardware, software, a process, or a combination thereof that are vital to the performance of a larger system or the fulfilment of the key objectives of an acquisition program.

A System Breakdown Structure (SBS) provides a structured view of the system's architecture, highlighting subsystems, components, and their relationships. The reviewer was not able to find any description of the SBS for GFR in any of the deliverables from WP1, WP2 and WP3 listed in Section 5. By systematically breaking down the system, the SBS ensures that all relevant aspects are considered during design. This helps prevent oversights and enhances safety by identifying critical interfaces between subsystems. It also helps to minimise integration challenges and risks.

In absence of an SBS, this review focussed on main components and critical technologies. The main components of the SafeG-GFR include:

Core: The core is where the nuclear fission reactions take place. The nuclear fuel for the SafeG-GFR is not ready. According to the ALLEGRO CEA concept, the reactor will be operated with two consecutive configurations: the driver core (aiming at qualifying the innovative fuel elements) and the refractory core to demonstrate possibility to operate high-temperature GFR. According to [42], the next Horizon Euratom project 'TREASURE' is to propose new methods and means for utilising MOX fuel from LWR for GFR. Its aim will be to reach early basic design stage.

Start-up core design optimization studied in D1.1[12] presents the optimized design of the MOX and UOX fuelled driver core along with their safety features. Safety analyses for both fuel types were performed in two steps – best estimate and conservative calculations - for four enveloping initiating events. The results showed that at the best estimate analyses, maximum cladding temperatures stay below the criteria in many cases. But still, acceptance criteria (mainly Peak Core Temperature) were not fulfilled in many conservative safety analyses.

The Reactor Pressure Vessel (RPV) is a crucial component but there is no SafeG deliverable on RPV. There are no design details available. A review of advanced structural materials for gas-cooled reactors by J. Cizek et al [45] shows that new materials are still being developed. Aim is to have materials with required radiation-induced embrittlement, creep capability and manufacturability. Also, the codes required to qualify advanced structural materials are not ready. Its TRL is low as it cannot be readily built.

Due to the work done in the SafeG project, the Software RL for the core has reached TRL 4 but the Manufacturing and Instrumentation RL remain at TRL 2 for both the driver and the refractory cores.

Fuel: The driver core with MOX/UO2 pin type fuel in steel cladding (core outlet temperature 530 ◦ C) and the refractory core (U,Pu)C in SiC/SiC cladding (a core outlet temperature of 850 ◦C) are being considered which makes the TRL assessment more complicated.

According to the work reported in D1.2 [13], thermal-hydraulics analysis of helium-cooled fast reactors is challenging due to the small number of validated codes. The SafeG activities in WP3 included thermal-hydraulics experiments with the Helium rig (S-ALLEGRO) and benchmarking of TH codes against experimental results. The steady-state conditions were analysed but analysis of transient inputs remains a future task. Therefore, the software is at TRL 4 as all software functionalities are not complete.

Proliferation Resistance and Physical Protection (PRPP) of the GFR Allegro spent fuel reprocessing technology was studied in D1.3 [14]. The report shows that for irradiated MOX fuel, the effect of different burn-up on PRPP is essentially negligible, whereas the use of irradiated UOX fuel would require additional safeguard criteria for application to meet IAEA PRPP requirements for both low and high burn-ups.

D1.5 [16] considered three independent reactivity control methods (CSD, DSD1, and DSD2). It highlighted the need for an extra shielding layer to prevent radiation leakage from the core.
D2.1 [19] mentions that that SiC components will be used in the planned refractory core to be operated at very high temperature. SiC cladding tubes (or more exactly fibre reinforced SiCf/SiC composites) could be produced by different technologies, and D2.1 [19] is not clear which technology will be applicable at industrial scale in the future as published results are restricted. However, testing of SiCf/SiC tube samples is reported to study the effects of ion-irradiation and high temperature environment and mechanical tests conducted to characterize the mechanical load bearing capabilities of the cladding and to test their leak-tightness. D2.1 [19] concludes that SiCf/SiC composite tubes are promising as the primary cladding material for the refractory fuel but fabrication procedure needs further improvement to overcome the observed weaknesses. Therefore, whilst the materials TRL is at 3, the manufacturing TRL is at 2.

Coolant: Helium gas is the selected coolant for the GFR. The coolant circulates through the core, absorbing the heat generated by the fission reactions. It is an excellent choice for high-temperature reactors because it has good heat transfer properties, is chemically inert, and does not become radioactive. According to the reports, research work still needs to be done for helium purification and recovery. Ref [4] mentions development of a demonstration small-scale facility for testing and verification of He recovery from GFR guard vessel atmosphere (N2+He) using a membrane separation. The TRL for coolant can be considered to be between 2 and 3.

Control Rods: Control rods are used to control the reactor's power output by absorbing neutrons and thereby regulating the rate of fission reactions. In some GFR designs, control is achieved by varying the speed of the coolant flow. D1.5 [16] provides a complete pre-conceptual design of the control and shutdown elements of the ALLEGRO reactor. The original design has been updated to increase its reliability and capabilities by adding more diversity. The ALLEGRO concepts uses three independent ways of reactivity control, realized by three diversified and independent sets of control sub-assemblies (named CSD – control and shutdown device, DSD1 – diverse shutdown device 1, and DSD2). Each of the control sub-assembly groups are equipped with the standard electromagnetic latch that disconnects in case of SBO or when the SCRAM signal is received. If this system failed, there is another set of passive means to trigger the reactor shutdown. However, it is all at preconceptual stage, so TRL is 2.

Reflector: The GFR design include a neutron reflector surrounding the core. D1.5 [16] has confirmed that the shielding and reflector blocks remained basically unchanged from previous design and TRL remains at 2.

Heat Exchangers: GFRs use heat exchangers to transfer the thermal energy from the hot helium coolant to a secondary coolant loop, which then drives a turbine to produce electricity.

This is similar to the process in many other types of nuclear reactors. The main heat exchanger makes the
interface between the primary helium circuit and secondary energy conversion circuit with nitrogen and helium mixture. In D2.4 [22], two designs were investigated for the ALLEGRO relevant parameters. Shell & tube and microchannel heat exchangers. The design of the main HX compatible with the ALLEGRO parameters are still at preconceptual design stage where both steady-state and transient simulations have been performed using computer models. The HX is only at technology concept stage and is considered to be at TRL 2.
It is worth noting that lowering the operational parameters to achieve higher TRL is possible. For example, lowering the outlet temperature, switching from carbide to oxide fuel and or switching to helium/steam system could improve TRL quite significantly. The HTR-PM in China [44] has started operation. The hot leg T is around 750C so 100C less than the GFR for Carbide fuel core, and more than the hot leg temperature for oxide fuel core (around 550C). According to the design details reported by WNN [44], the Chinese HTR-PM has graphite moderator which is absent in GFR. As mentioned in the report, absence of graphite poses additional challenges and switch to He/steam has already been discounted by SafeG.

Gas Circulation System: Helium is circulated through the core and heat exchangers by a system of pumps and compressors to maintain proper cooling and heat transfer. The hight temperature operation increases the challenge to ensure leak tightness and qualify materials for high temperature operation. D1.1 [12] mentions that CATHARE software model has been used to represent the dynamic behaviour of a gas system, in particular the behaviour of the turbo-machinery, that has been validated for a wide range of transients, including load following, loss of load and bypass valves transients but no reference has been found on the gas circulation system. However, helium cooled Chinese HTR-PM has been reported to be operating and producing power [44]. The TRL for Gas Circulation System can be high but the operational parameters for GFR are different. Even though the pressure is similar (7MPa) for both reactors, the gas temperature for the Chinese HTR-PM is 750°C and that for the GFR is aimed for 850°C. Important difference is in the circulation path. In case of the HTR-PM, the gas is pumped through pebble-bed core and then flows to steam generator but in case of the GFR, the circulation path is through compact core with high power density and aim is to use it directly in a Brayton cycle gas turbine. Furthermore, based on S-Allegro operational experience the hot duct sealing with no flanges remains problematic.
The overall TRL for Gas Circulation System remains at 2.

Containment Structure: Like all nuclear reactors, GFRs are housed in a containment structure to prevent the release of radioactive materials in case of accidents or malfunctions. The entire primary circuit is contained within a secondary pressure boundary, the guard containment. However, no information on structural design substantiation could be found. The containment design appears to be at conceptual level. Due to lack of information on tests, this main component and relevant technology can be considered to be at TRL 2.

Decay Heat Removal System: Decay heat removal (DHR) system is one of three key safety systems and has been a focus of work package WP3 in the SafeG project. According to D2.3, in the SafeG project, two particular issues have been solved – WP3 considered the overall design of the DHR system focused on maximization of its performance, and the materials issues for the design of the heat exchanger were looked at in WP2. Based on the work done in D2.1 [19], the reference DHR HX design was updated to introduce thermal insulation of the critical parts. D3.2 [26] aimed at bringing a better solution of the decay heat removal, it focussed on system's performance in accident conditions that were analysed by thermal-hydraulics computational codes. Details of a fully functional CFD computational model for simulations of selected states and processes of the DHR loop are presented in D3.4 [28]. In principle, the activities revolved around enhancement of the ALLEGRO reference DHR option.

Two concepts for complete isolation of the main and the DHR loops were studied in D3.5 [29]. One of the discussed solutions is based on experience and design coming from the design of the S-Allegro experimental facility. A coaxial disk valve prototype was developed, manufactured and tested in the S-Allegro facility. The design and function of this component are described in D3.5 [29]. Also, a preconceptual design of a new piston-based coaxial valve was proposed. Both the concepts, should they be used in a real nuclear reactor, will have to be subject to extensive further development and testing.

The performance of legacy DHR design (CEA) and newly proposed DHR design including pre-conditioning device (UJV) was studied in D3.2 [26] and D3.4 [28]. However, the analyses assumed fully isolated DHR loop conditions. The study of DHR loop in normal operation, with operating pre-conditioning device, early after the opening of pre-conditioning device was not fully covered. Therefore, in addition to the TH and CFD analyses from D3.2 [26] and D3.4 [28] the report D3.6 [30] analysed the impact of the pre-heating of the DHR system structures. D3.6 describes the various ideas and proposals of the ALLEGRO DHR pre-conditioning options but these will need instruments for monitoring purposes.

In addition, further development work is needed to study chemical interactions between the insulation materials and the environments. Based on the VHTR studies and other new information, two candidate materials were selected – Duocel SiC-based foam, and a geopolymer doped with MgO. The affordable geopolymer material needs to be further developed with the goal to lower the thermal conductivity. The Duocel foam meets all the performance criteria but its price is very high compared to the geopolymer (up to 100x). There are further manufacturing and material challenges if 3D printing is to be used to produce the components because these materials are less resistant to thermal stress.

In summary, thermal hydraulic analyses done in D3.2 [26], the CFD simulations on conditions in isolated DHR loop in D3.4 [28], the assessment of possibilities for instrumentation and control in D3.7 [31] and operational experience from S-Allegro loop facility, the D3.6 [30] brings the ideas and proposals of the ALLEGRO DHR pre-conditioning options. Based on this the materials TRL for DHR remains at 3.

Core Support and Core Catcher: The core support plate and the core catcher play very important safety related role. According to [4], a project was planned for ALLEGRO-related core catcher research to test UO2/SS corium interaction with innovative sacrificial material. WP2 deliverable D2.2 [20] on core support plate was not available for the review.

Emergency Core Cooling System: The N2 injection system, also known as the Emergency Core Cooling System (ECCS), is one of the critical safety systems in ALLEGRO that fulfils the function of removing heat from the core under postulated plant conditions. This is one of the key challenges in GFR-type reactors to make them inherently and passively safe. The intention is that it must meet all the Design Extension Conditions (DEC) specified by the IAEA. D3.1 focussed on thermal and CFD analyses for core cooling and D3.8 [32] was focused on the ECCS optimization from the RPV structural integrity point of view. There are five design improvement for the ECCS recommended in D3.1 [25] and D3.3 [27] was not available at the time of the review. The materials for the injection nozzles is still to be finalised. Since the design is still being optimised, the ECCS is considered to be at TRL 2.

Instrumentation: D3.7 [31] suggests sensors for transducing physical plant parameters that offer numerous levels of Defence in Depth (DiD). These sensors are used for measurement of temperature, pressure, level measurement, flow, chemical analysis, nucleonic measurements, vibration and displacement, and rotational speed. The recommended sensor list is summarised in D3.7 [31]. However, according to D3.7 [31] suitable sensors fulfilling GFR requirements are not available in the existing manufacturer's product lines and so some development will be required to create suitable options.

Appendix 1 of D3.7 [31] lists additional sensors, such as the Radiation detection & measurement (Matrix Mobile ARIS™), Micro-Epsilon - Displacement Sensor (LVDT), Neutron flux detector (Ultra Electronics), and Neutron flux (Centronic). However, these sensors are not compatible with the ALLEGRO GFR plant due to their mismatch with the core outlet temperature (850^{o}C) and primary circuit pressure (7MPa) requirements. Note that only sensors have been considered and other types of instruments (Human-System Interfaces, software and hardware for analogue/digital control systems) have not been considered. Therefore, the instrumentation TRL is still at 2.

7 TRL ASSESSMENT CRITERIA

According to IAEA [11], The definition of key terms such as “laboratory environment”, “relevant environment”, “operational environment”, “component” and “system” must be defined for this methodology to be applied sensibly. These terms must be articulated in the explanation of TRL’s for each issue. Table 6 presents a summary of associated models, performance requirements and environments for each of the nine TRLs.

Table 6. Models, performance requirements and environments for each TRL Level [11]

TRL	Associated models	Performance requirements	Required Tests and Environment representativeness	Comments
1	n/a	In elaboration	No	
2	n/a	In elaboration	No	
3	Mathematical (+experiments)	Partly defined	No	For monitoring progress (technology viability)
4	Mockup (Breadboard/testbed)	Partly defined	Laboratory	For monitoring progress
5	Sub-scale Engineering Model	Fully defined	Relevant	Enables implementation phase (with higher risks)
6	Full scale Engineering Model	Fully defined	Relevant	Enables implementation phase (with lower risks)
7	QM	Fully defined	Operational	Possible use of Engineering Qualification Model or prototype
8	Actual Hardware	Fully defined	Operational	End of development
9	Actual Hardware	Fully defined	Operational	Operationally proven

According to this definition, any technology proven by ALLEGRO will be at TRL 4 and the rest remain below level 4. Summary of the prototypes and tests under prototypical conditions is as follows:

1) S-ALLEGRO is a large-scale facility including an electrically heated mockup of ALLEGRO with 1MW power and prototypical coolant, temperature (up to 850°C) and pressure (up to 7 MPa). It is under operation and several experimental campaigns have already been done. Its main purpose is to test the safety systems and to simulate the operation and transients in a GFR, but, along with it, quite a lot of development had to be done – so far, it shows

excellent leak tightness (helium seals), all the valves work, after some additional testing and upgrading, as they should (preconditioning system, main shutoff valves). The DHR system works even better than in some calculations. In summary, the project team have prototyped and tested at a smaller scale the sealing system, including low-diameter penetrations and bushings (up to 80 mm), the valves in the primary system, and the principle of the DHR system. The blower is of much different type (high-speed compact radial) than normally present in a gas-cooled reactor, so it will not be counted.

2) For the core catcher, the sacrificial material has been prototyped and tested under relevant conditions on a laboratory scale.
3) For the helium makeup systems, several Czech national projects dealt with purification of impure helium at prototypic conditions – only gases.
4) For the guard vessel internals, the material of choice (geopolymer) has been tested for thermal ageing and thermal and radiation stability – with excellent results.

The rest is calculations and lab tests at non-prototypical parameters so far and will be considered to be at TRL 3 or 2. Known technical barriers that remain for the main systems and their main components are given in Table 7.

Table 7. Known technical barriers for main systems

System	component	Known technical barriers		
Core	Refractory Fuel and cladding	Fuel and cladding materials not fully qualified	Extremely limited amount of experimental fast reactors in the world => little to no irradiation of relevant materials at relevant conditions at the moment	Lack of software to analyse transient conditions
	Neutron reflector and shielding	Higher temperatures and doses than in SFRs	extra shielding layer needed on top of the core	
	Reactivity control and shutdown	Completely different CSD design than	PRPP issues with UOX fuel	

		other fast reactor types		
	Core support plate	Material selection - Higher operation temperature of the plate than in other similar reactors	Material selection - Transient operation more similar to PWRs than SFR/LFR (coolant injection)	
Primary circuit	Reactor pressure vessel			
	Core barrel and thermal insulation	Higher temperatures and doses than in HTRs		
	Blowers			
	High-temperature gas/gas heat exchangers			
	Sealing			
	Passive shutoff valves			
	Ducts			
Power conversion system	High temperature material			
Helium storage and makeup system				
Decay Heat Removal System	Material challenges for Decay heat removal heat exchanger			

	Preconditioning system			
	Ducts			
	Secondary circuit and UHS			
Emergency gas injection system	Storage tanks	Injection nozzle materials		
	Rupture discs			
Core catcher	Cooling system	Existing core catcher designs qualified for PWRs or SFRs – entirely different characteristics		
	Sacrificial material			
Primary containment (Guard Vessel)	Structure			
	Supporting structures of the primary circuit	High thermal load to structures close to the primary circuit		
Secondary containment	Structure			
Fuel management	Fresh fuel storage and management			
	Fuel handling system			
	Spent fuel management			

8 TRL ASSESSMENTS

Results of the TRL assessment of each of the main system of Safe-GFR are presented in Table 8. The deliverables D1.6[17], D1.7[18], D2.2[20], D2.5[23], D2.6[24], D3.3[27] and D3.8[32] were not available for review which impacted TRL assessment of the latest designs of the Emergency Gas Injection and Core Catcher as shown in Table 8.

TRL assessment becomes complicated because of choice between different designs is not clear. However, it will only impact TRL of that specific sub-system/stream but the overall TRL remains same. For example, the UC/PuC core will have lower TRL than UOX/MOX core in the materials, software and manufacturing streams but TRL for system stream remains the same. In case of design improvements, where possible, TRL assessment is shown of the original/reference design and the new updated design proposal.

Table 8. TRL assessment of main components of Safe-GFR

System Name	System	Materials	Software	Manufacturing	Instrumentation
Core MOX	4	5	4	5	4
UC	2	3	4	2	2
Primary Circuit	2	3	3	2	2
Power Conversion System(HX) Gas to Water	2	3	2	2	2
Gas to Gas	2	3	4	2	2
He Storage and Makeup	2	3	2	2	2
DHR System-Original	2	2	2	2	2
Updated	2	4	4	3	3
Emergency Gas Ejection-Original	2	3	4	2	2
Updated *	-	-	-	-	-
Core Catcher-Original	2	4	3	2	2
Updated *	-	-	-	-	-
Primary Containment	2	2	3	2	2
Secondary Containment	2	2	3	2	2
Fuel Management (PRPP) - MOX	4	5	4	5	4
UC	2	2	2	2	2

*Not available for review.

The MOX fuel has already been developed and used in the industry, therefore its TRL for SafeG-GFR is much higher for the materials, software and manufacturing streams when compared with the TRL of UC fuel. Similarly, the gas-to-gas heat exchanger has been extensively analysed in the SafeG project where two designs were investigated. So, it scores higher TRL in the software stream.

The SafeG project enhanced the ALLEGRO reference DHR option. Additional thermal insulation of critical parts was introduced and thermal-hydraulics codes used to simulate system performance raising the TRL in the materials, software and manufacturing streams.

The SafeG deliverables reporting the improvements carried out for the emergency gas injection and the core catcher by the SafeG project were not available but it is known from other literature that they have increased in the materials, software and manufacturing streams.

For overall TRL of each component/system the lowest TRL amongst the five streams (system, materials, methods, manufacturing and instrumentation) is selected. Finally, the SafeG project has reported that additional safeguarding issues remain for the UOX fuel.
Most GFR designs were likely to be in the lower to mid-range of the TRL scale, somewhere between TRL 1 (basic principles) to TRL 4 (validation in lab). The specific TRL would depend on factors like the progress in design, testing, and the existence of operational prototypes or pilot plants. This review shows that the SafeG project raised TRL for GFR in a number of areas as shown in Table 8.

TRL for a whole reactor technology is taken as the lowest value of TRL amongst all the critical technologies/components that make the reactor. In case of the SafeG GFR, it can be deduced from Table 8 that the overall TRL is at 2.

8.1 Target TRL

For future technology development programme and any R&D needs, it is important to define the target level to achieve for each of the system, materials, software, manufacturing and instrumentation. When setting the target, the following should be considered:

- Purpose of the project
- Safety classification
- Criticality
- Project stage gate reviews

9 STRATEGY AND DEVELOPMENT PLAN

The TRL assessment has shown that almost all of the critical technologies are below TRL 3. Moving from TRL 3 to higher levels involves several challenges:

9.1 Challenges

Technical Challenges

a) Scaling Up: Ensuring the technology works at a larger scale (e.g., from lab prototype to full system).
b) Integration: Integrating various components seamlessly.
c) Performance and Reliability: Meeting performance requirements consistently whilst improving reliability and robustness.

Operational Challenges:

a) Field Testing: Conducting field tests in real-world conditions.
b) Safety and Security: Addressing safety risks and cybersecurity concerns.
c) Maintenance: Designing for ease of maintenance and repair.

Regulatory and Certification Challenges:

a) Certification: Obtaining necessary certifications (e.g., safety, environmental).
b) Compliance: Meeting regulatory standards.
c) Documentation: Preparing comprehensive documentation.

In addition, there will be the usual project management challenges of ensuring effective collaboration with technology partners, researchers and regulators in addition to meeting the resource constraints, budgets, time scale and skilled workforce.

9.2 ALLEGRO R&D Needs

According to [4] Allegro R&D needs identified before the SafeG project were:

- Short-term priorities driven by the design requirements are:
    - Coolability in protected transients using natural convection
    - Feasibility of Guard vessel for elevated pressure
    - Optimization of DHR system (valves, HX, pressure drop, fully passive option…)
    - Turbomachinery
    - Potentially alternative cladding material for the driver core
    - Optimization of ECCS (material issues not solved)

- Simulation tools need additional validation
    - Neutronic & thermohydraulic codes
    - Fuel performance codes

- Short-term priorities in the development:
    - Achieve reasonable level of safety using passive systems (where possible)
    - Design UOX-based driver core while maintaining required power density and irradiation characteristics

In terms of technology development, Ref [4] had identified the following:

- Safety of oxide cores (MOX or UO2)
    - System thermohydraulics (core coolability), GV (& core catcher) issues
- Helium technology
    - He quality management, recovery, tightness, components (valves, HXx)
    - Subassembly TH, Insulation, fuel handling, instrumentation, …

- Computer codes:
    - Benchmark activities: ERANOS, MCNP, SERPENT, KIKO, HELIOS, SCALE, CATHARE2, RELAP5, MELCOR 2.1

- Materials qualification
    - Composite Matrix Ceramic clad, Metallic clad for oxide core
    - Control rods & elements, S/A structural materials
    - Thermal barriers, Other structures (core catcher, structural materials)

- Fuel qualification
    - Oxide fuel, Carbide fuel

The areas requiring R&D to study and optimize the PRPP characteristics of GFRs identified in [6] are:

- Ensure that a comprehensive evaluation of the PRPP characteristics of the GFR includes the fuel cycle processes that are common to other GEN IV reactor systems.
- Identify the sensitivities of emergency shutdown cooling systems to external hazards.

From the above mentioned R&D needs, the SafeG project according to [42] has accomplished the following:

- Options for innovative and diversified DHR
- Isolation valves for main circulation loop and for DHR loop
- Structural analysis of Core support plate
- Design changes on spacer ring and Fixation supports
- Gas-Gas Heat exchanger design overview

Notable achievements of the SafeG project are:

- Advanced manufacturing processes and materials e.g. additive fabrication tests on components (HX)

- GFR Needs for Nuclear Standardization and Codes established through a review of available codes and standards applicable to high temperature reactors, with specific focus on Gas-cooled Fast Reactors

- CFD study of core cooling in LOFAs accomplished by analysis of coolant flow between groups of fuel sub-assemblies

- Thermal hydraulic benchmarking of computational thermal-hydraulic tools using the results from the S-ALLEGRO facility

- Update of the ALLEGRO reference design that included core and reflector re-design using genetic algorithm optimization

The SafeG project has mostly focussed on the materials and software streams of TRL with some attention being paid to the manufacturing and instrumentation streams but system integration has not been considered. It is recommended that all five streams should be given equal weightage in future technology development.

In terms of meeting the GFR technology challenges, the SafeG focus has been rightly on the cooling issues related with the DHR and core cooling. Another big challenge of high neutron dose that impacts materials due to lack of core moderator has not been addressed.

10 CONCLUSIONS

Literature search has shown that several gas-cooled fast reactor designs have been proposed and studied by various organisations but the TRL of all have remained conceptual level. The SafeG project has managed to raise the TRL to 4 for some of the selected sub-systems/components by lab testing and by using small scale prototype, ALLEGRO. According to the three phases of nuclear technology development used by NDA(UK) [9], SafeG has lifted the GFR from purely conceptual stage to early deployment stage in some selected areas. However, the overall TRL remains at 2.

The review has shown that there are no significant scientific challenges but there are several engineering and technology development challenges that have to be overcome to raise the TRL. The biggest challenge is in the materials stream, particularly in development and qualification of materials for the reactor vessel, primary system, in-vessel structural components and the DHR system to meet the GFR operating conditions at high temperature. In the manufacturing stream the biggest challenge is the fuel to meet the GFR performance and safety requirement including passive cooling and decay heat removal. Advances in manufacturing technologies and novel materials will hopefully resolve these issues, bringing GFRs closer to becoming a reality.

Further attention needs to be paid to control and instrumentation to ensure reliability and safety in extreme operational conditions of GFRs over projected lifetimes. The software stream has definitely benefitted from the work done under the SafeG project in terms of development and validation of simulation models for thermal, CFD and neutronics analyses. Two streams of TRL assessment matrix that have not received much attention to date are the manufacturing and systems integration. It is understandable as typically, these streams become dominant at higher TRLs. System integration TRL steam should start to get some priority as the GFR TRL are developed further.

No special stream for economics, cost or regulations can be included as regulations sometimes evolve after a technology has been developed and costs are impacted by non-technical issues. Although fully passively safe GFRs are possible at lower power densities, their economic competitiveness remains challenging.

11 RECOMMENDATIONS

Based on this review, following five recommendations are made.

11.1 System Breakdown Structure

The first step is to develop a detailed System Breakdown Structure (SBS) for a GFR power plant. It should highlight the system's elements and their relationships and establish a hierarchy of interactions within the power plant.

11.2 Technology Roadmap

An integrated technology roadmap for GFR needs to be developed that includes both "pull" and "push" technology strategies. It should consider a wide range of pathways to advance the GFR technology. There should be a conscious choice to favour existing technology, or high TRL to avoid R&D pitfalls, reduce uncertainty, reduce time to market and development cost. AI-enhanced Horizon Scanning is recommended to help identify existing technologies. Main technology areas are already known along with the main barriers. Teams of Subject Matter Experts can be requested to:

- Identify the top technical challenges that, if met, would achieve needed performance
- Identify the "pull" technologies needed to support the capabilities
- Identify emerging "push" technologies that could meet the challenges.

The teams can correlate their technology pathways with the existing facilities/capabilities and pull in relevant research done for VHTRs, HTGRs and SFRs to create time-phased plans for technology development. For example, HTGR experience in primary circuit, Helium purification, heat exchanger, containment and SFR fuel and fuel recycling can be considered after taking due account of the absence of core moderation in GFR (the graphite moderator provides protection for HTR systems). In addition, off the shelf components for standardised secondary system can be considered. The roadmap should pay attention to control and instrumentation to ensure reliability and safety in extreme operational conditions of GFRs over projected lifetimes.

11.3 Plant Systems Design Approach

The challenge for designing the next generation of nuclear power plants will be to reduce cost whilst increasing safety and that calls for a different design approach. There are two major challenges. The first is to reduce the cost of building new nuclear power plants. The second challenge is to increase safety. After the Fukushima event, the safety requirements have been toughened by the IAEA's Design Extension Conditions that require plants to withstand multiple hazards and extreme hazards. The nuclear industry is responding to this challenge of reducing cost without compromising safety by taking part in the development of new Plant Systems Design (PSD) code that will change the way design and construction is done. There is an initiative that is being taken by committee of international experts under the aegis of ASME to develop the PSD code. As explained by Hill et al [35], it is a technology neutral standard that provides a framework, including requirements and guidance, for design organisations.

In traditional nuclear industry approach the design process goes through concept, preliminary design, detail design, construction, commissioning and operation. The emphasis is mostly on component design not on system design and the whole design process is sequential. It is like a 'waterfall' approach where components are designed in stages and then hazard assessments are done to prove safety of a system. The PSD standard aims to bring in three main changes: (a) integrate process hazard analysis in the early stages of design; (b) incorporate and integrate existing systems engineering design processes, practices and tools with traditional architect engineering design processes, practices and tools; and (c) to integrate risk informed probabilistic design methodologies with traditional deterministic design. Main feature and advantage of this new PSD code being developed is that it employs systems based approach to integrate design and safety and has been discussed at GIF [36].

11.4 Data Centric Approach to Design and Construction

In the realm of engineering, the approach to designing and constructing new plants is evolving. Traditionally, an experience-based empirical approach was favoured, but now there's a shift toward a more mechanistic methodology. However, with the advent of the Fourth Industrial Revolution (I4.0), digital technologies like artificial intelligence (AI) and digital twins are making waves. These tools leverage historical data to optimize designs, assess new materials, and enhance safety features.

One of the big challenges for GFR is development and qualification of new materials that can costly and take long time. This material test work can be optimised by combining AI with probabilistic methods as shown by A Ye [37]. Moving forward, development projects should embrace AI deployment and adopt a data-centric approach to both design and construction. M Ortiz-de-Zunga [38] has demonstrated how AI has been used to detect flaws in welds more efficiently by using Phased Array Ultrasonic Testing (PAUT). This has the potential to replace more expensive Radiograph based testing. Also, she has shown how success rate of Advanced Manufacturing like the Electron Beam welding can be improved by AI [39].

11.5 Digital Knowledge Base

It is recommended to bring together all the research reports from previous projects into one single digital knowledge base for more effective Knowledge Management and Knowledge Preservation (KMKP) for future development of GFR. This can be achieved by deploying AI-powered cognitive search tools that can extract relevant information from large number of unstructured documents. This can provide right information to the right people at the right time. This technology has been demonstrated in the nuclear industry. Its application has been discussed with nuclear regulators at the Nuclear Supply Chain conference [40] held by OECD/NEA. Prinja [41] has reported three use cases. The first involves a pilot project carried out by Jacobs clean energy to digitise part of their nuclear archived reports. The second relates to creation of a digital knowledge base of Molten Salt Reactor (MSR) research reports for Generation IV International Forum and the third is related with use of AI powered cognitive search tool to demonstrate extraction of relevant code requirements for French nuclear code RCC MRX being done for CEN Workshop 64. A demonstration of AI-powered cognitive search tool using a trial licence of 'Goldfire' software supplied by Acuris is provided in Appendix-1. Having a centralised repository will help future endeavours, prevent waste of time/resources on repeating work already done and help inform efficient resource allocation. Future development of GFR will strongly benefit from a digital knowledge base, AI tool and KMKP. In addition, these technologies can be used to perform explorative and targeted horizon scanning to identify trends, opportunities, risks and threats related with a particular topic.

At this stage one can only make general recommendations because lack of definition of full system, its SBS and Technology Road Map makes it difficult to see the gaps and make any specific recommendation. Five general recommendations have been made to help future development work to increase the GFR TRL. The use of helium in GFRs builds on decades of R&D efforts for HTRs, and future projects should leverage this experience.

12 ABBREVIATIONS

CEA	Atomic Energy Commission
CFD	Computational Fluid Dynamics
DEC	Design Extension Conditions
DHR	Decay Heat Removal
EU	European Union
GBR	Gas Breeder Reactor
GEN IV	Generation Four (nuclear reactors)
GFR	Gas-cooled Fast Reactor
GCFR	Gas-cooled Fast Reactor
GIF	Generation IV International Forum
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
IRL	Integration Readiness Level
JRC	Joint Research Commission
KMKP	Knowledge Management and Knowledge Preservation
LMFBR	Liquid Metal Cooled Fast Breeder Reactor
MOX	Mixed Oxides (fuel type)
NASA	National Aeronautics and Space Agency
NDA	National Decommissioning Agency
PAUT	Phased Array Ultrasonic Testing
PRPP	Proliferation Resistance and Physical Protection
PSD	Plant System Design
PWR	Pressurised Water Reactor
RL	Readiness Level
SBS	System Breakdown Structure
SiCf/SiC	Silicon carbide fiber-reinforced/silicon carbide
SNETP	Sustainable Nuclear Energy Technology Platform
SS	Stainless Steel
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
UOX	Uranium Oxide (fuel type)
UPuC	Uranium Plutonium Carbide
ZrC	Zirconium Carbide

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16) D1.5 Design of the control and shutdown elements (UJV, M36)
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18) D1.7 Core reflector and radiation shielding (MTA-EK, M40)
19) D2.1 Innovative cladding materials testing (MTA-EK, M24)
20) D2.2 ALLEGRO Core support plate (UJV, M36)
21) D2.3 DHR Heat Exchanger (UJV, M36)
22) D2.4 Main Heat Exchanger (CVR, M36)
23) D2.5 Structural materials testing in media (CVR, M45)
24) D2.6 Advanced manufacturing processes and materials (NCBJ, M45)
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14 APPENDIX – 1 : AI-POWERED COGNITIVE SEARCH OF RESEARCH REPORTS

This appendix includes demonstration of AI-powered cognitive search tool using a trial licence of 'Goldfire' (software supplied by Acuris). Goldfire is a semantic search tool that uses Natural Language Processing to read and understand the documents to provide answers to the queries. All the documents stored safely on Jacobs servers are read by the tool and a digital Knowledge Base is created and stored. It is not a Generative AI tool i.e. it only provides the answers that it finds in the documents. Conventional search technology only extract keywords but does not know underlying meanings but cognitive search tool extracts underlying meaning to get back precisely relevant answers. Another advantage is that Goldfire tool comes with a library of over 170 million technical documents (books, journals and articles), codes and standards and patents information.

In this trial, a digital Knowledge Base (KB) was created of all the SafeG deliverables and the associated references.

As an example, the following three research queries were made using only the SafeG Knowledge Base:

1. Decay Heat Removal

   DHR has been extensively studied in the SafeG project. Question was asked regarding challenges facing the DHR. Two most relevant documents were identified as D3.9 and D3.5 as shown in Figure A1.

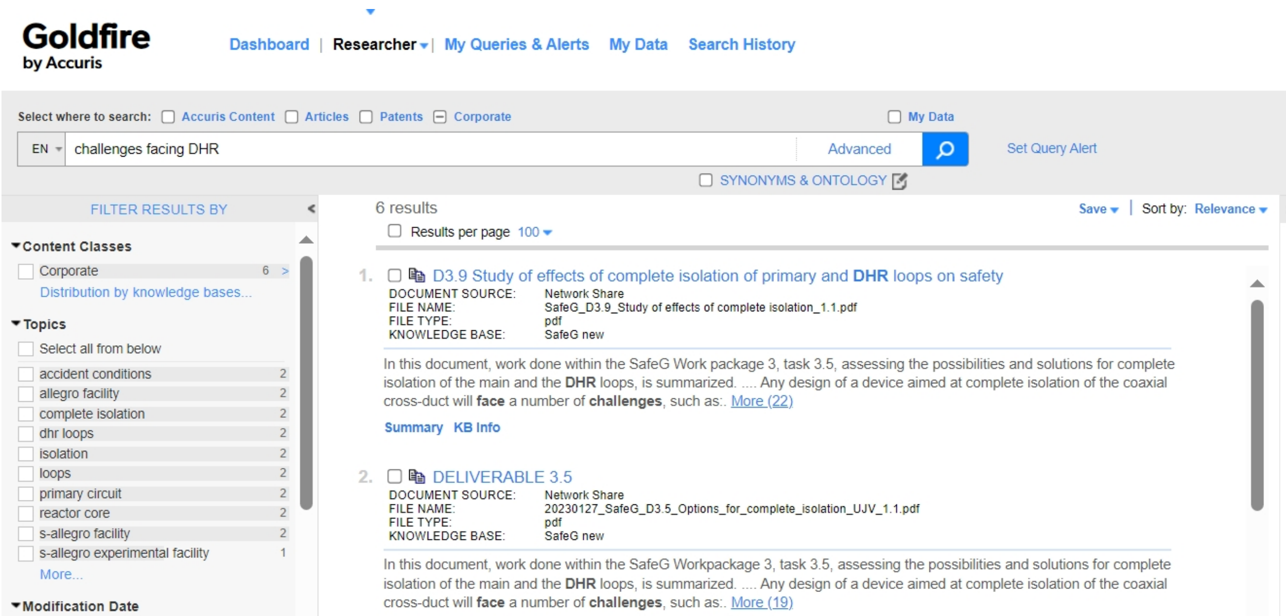

Fig. A1. Search results for challenges facing DHR

The tool can also search for concepts related with the topic. In case of 'DHR' it identified 200 concepts. Clearly the 'DHR loop' and 'DHR system' were the two top concepts discussed in the SafeG KB. The top 20 concepts related with DHR are shown in Fig A2. Along with the concepts, the tool also displays the more specific topics related with the search. 14 specific topics were found for DHR which are shown in Fig A3. By selecting any of the specific topics, the tool will display relevant extracts from the documents for ready reference.

Query	DHR
Lens name	Concepts
Fact	**Frequency**
DHR loop	15
DHR system	13
DHR blower	8
DHR HX	8
DHR valve	6
DHR decay heat removal	5
passive DHR system	4
isolated DHR loop	3
DHR crossduct	3
DHR structure	3
DHR valves open	3
DHR concept	2
DHR system HX	2
DHR loop No.1	2
ALLEGRO DHR System Description	2
DHR isolation valve	2
DHR strategy	2
DHR pressure	2
DHR operation	2
DHR duct	2

Fig. A2. Top 20 concepts related with DHR

Query	DHR
Lens name	More Specific
Fact	**Frequency**
depressurized DHR	1
LOCA + SBO + DHR	1
non-safety-related DHR	1
water-cooled DHR HX	1
independent DHR	1
Diversified DHR	1
preconditioned DHR	1
modified DHR HX	1
horizontal DHR HX	1
passively operated DHR	1
water-filled DHR	1
operational DHR	1
old DHR	1
he/water DHR HX	1

Fig. A3. More specific topics on DHR

2. System Breakdown Structure

Another topic of interest was to see if there was any information on the System Breakdown Structure (SBS). As can be seen from Fig A4, there was no information available on SBS in the entire SafeG KB.

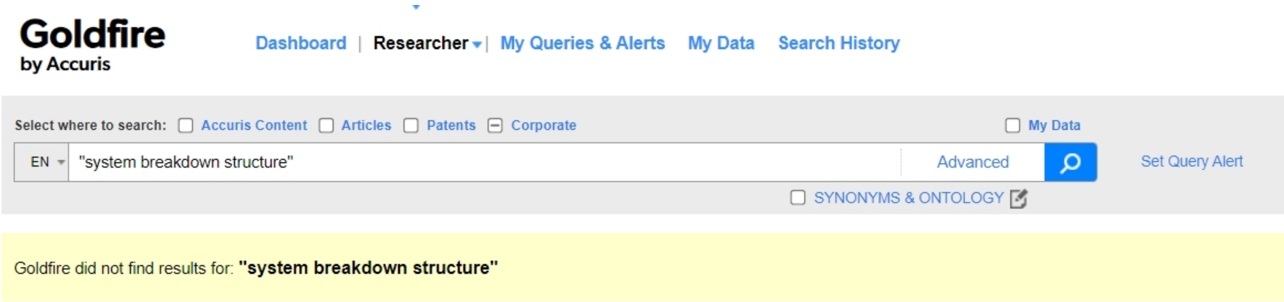

Fig. A4. Search results for System Breakdown Structure

3. Helium Purification

When asked about helium purification, the tool identified two top results from D3.1 and D2.4. As shown in Fig A5, it extracted the information "the ECCS injecting helium to the main system during LOCA can be part of the helium makeup and purification system" from D3.1 and "the required helium atmosphere can be readily adjusted using the available helium purification and dosing system" from D2.4.

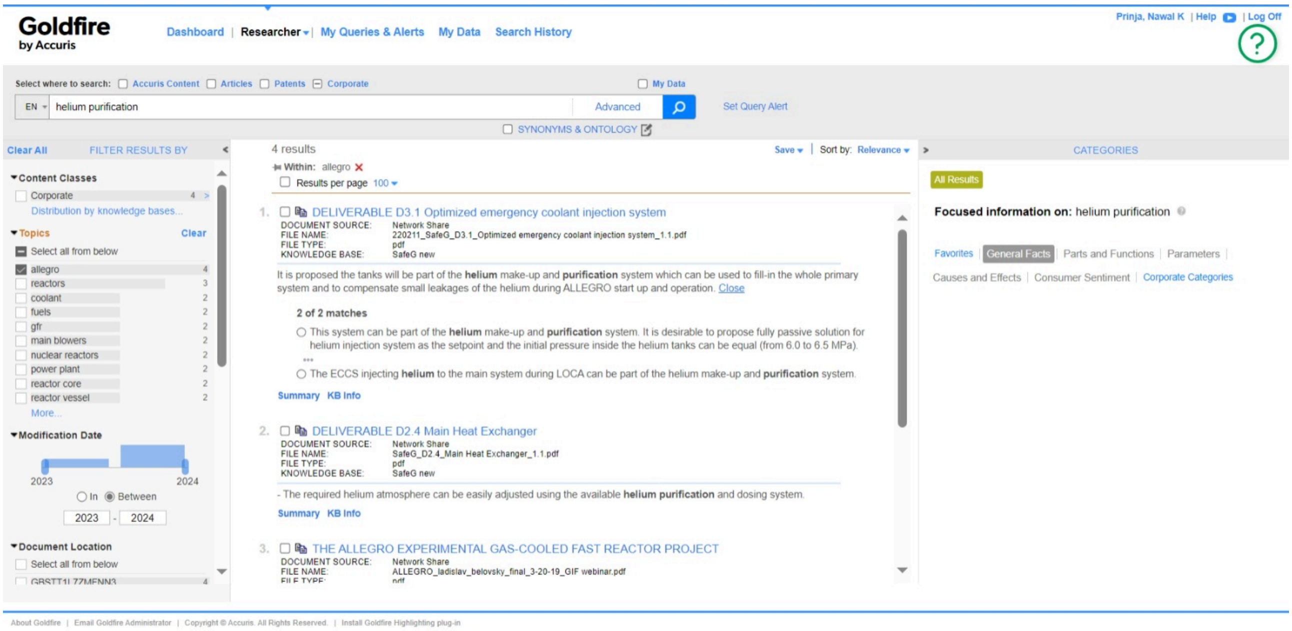

Fig. A5. Search results for helium purification

The time taken to obtain the search results for each of the above three questions was less than 20 seconds.