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Project Report

Gas Cooled Fast Reactor Research and Development in the European Union

Richard Stainsby,[1] Karen Peers,[1] Colin Mitchell,[1] Christian Poette,[2] Konstantin Mikityuk,[3] and Joe Somers[4]

[1] *AMEC, Booths Park, Chelford Road, Knutsford, Cheshire WA16 8QZ, UK*
[2] *Commissariat à l'Energie Atomique, CEA Cadarache, 13108 Saint Paul Les Durance, France*
[3] *Paul Scherrer Institut, Villigen PSI, Villigen 5232, Switzerland*
[4] *Joint Research Centre, Institute for Transuranic Elements (ITU), P.O. Box 2340, Karlsruhe 76125, Germany*

Correspondence should be addressed to Richard Stainsby, richard.stainsby@amec.com

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Gas-cooled fast reactor (GFR) research is directed towards fulfilling the ambitious goals of Generation IV (Gen IV), that is, to develop a safe, sustainable, reliable, proliferation-resistant and economic nuclear energy system. The research is directed towards developing the GFR as an economic electricity generator, with good safety and sustainability characteristics. Fast reactors maximise the usefulness of uranium resources by breeding plutonium and can contribute to minimising both the quantity and radiotoxicity nuclear waste by actinide transmutation in a closed fuel cycle. Transmutation is particularly effective in the GFR core owing to its inherently hard neutron spectrum. Further, GFR is suitable for hydrogen production and process heat applications through its high core outlet temperature. As such GFR can inherit the non-electricity applications that will be developed for thermal high temperature reactors in a sustainable manner. The Euratom organisation provides a route by which researchers in all European states, and other non-European affiliates, can contribute to the Gen IV GFR system. This paper summarises the achievements of Euratom's research into the GFR system, starting with the 5th Framework programme (FP5) GCFR project in 2000, through FP6 (2005 to 2009) and looking ahead to the proposed activities within the 7th Framework Programme (FP7).

1. Introduction

The European Commission (EC) Gas Cooled Fast Reactor GCFR project was initiated in 2000 under the 5th Framework Programme ([1–3]) and followed in March 2005, by a 4-year project within the 6th Framework Programme [4]. Between the two projects, there was a significant change in emphasis from an evolutionary development, which could be realised on a relatively short timescale, to an ambitious innovative development that could achieve the full potential of the system. This change in emphasis coincided with the Generation IV International Forum (GIF) initiative, which was launched in 2000 and selected GFR as one of the promising systems for development.

The FP6 project recognised that the European experience in gas cooled reactor technology was unparalleled with more than a thousand years of gas thermal reactor operating experience together with the construction of four large sodium-cooled fast reactors and a number of in-depth design studies for gas cooled fast rectors. This experience was dispersed within the member countries and research centres, and the FP6 GCFR STREP was an opportunity to ensure that the value of this experience was realised, further developed, and retained in the next generation of scientists and engineers.

The FP5 GCFR project ([1–3]) was in three parts; the first part reviewed the relevant gas cooled reactor experience to re-establish the extent of the knowledge base and to provide assurance that the lessons had been learnt from previous studies. This formed one of the work packages with two others devoted to safety of gas cooled fast reactors and integration in the nuclear fuel cycle. The FP5 project concluded that the evolutionary concepts were sound and that experience from the thermal reactor operation provided further support for the system and sodium-cooled fast reactor operation provided added confirmation for the fuel, core, and fuel reprocessing. A safety approach was proposed as part of the FP5 project for future GCFRs, which was developed further within FP6, and some critical transients were analysed. The fuel cycle study demonstrated the flexibility of the GFR to adapt to the prevailing needs of the fuel cycle ranging from the traditional breeder role to an incinerator of plutonium and minor actinides.

The renewed interest in GFRs from the 1990s (albeit with a modest level of support) continued the evolutionary development path pursued by the European Gas Breeder Reactor Association and General Atomics during the 1970s. The important change that took place between FP5 and FP6 was the removal of the time constraint that limited the extent of innovation that was possible (see, e.g., [5] for a GFR based on existing technology). Hence the requirement of the 1970s, to be able to introduce a prototype GFR within 2 years, without the intermediate step of an experimental reactor, was transformed to the current situation, where commercial series construction may not be required until the middle of the 21st century. This opens the opportunity to realise the full potential of GFR through innovative design and development.

The FP6 GCFR STREP was fully integrated into the Generation IV development programme for GFR and shared its ambitious goals. Together with a direct contribution from the European Commission's Joint Research Centre (JRC) towards development of the fuel and core materials, it formed Euratom's contribution to the Generation IV International Forum (GIF). The GCFR STREP was jointly funded by the European Commission and more than 10 participating companies, R&D organizations, and universities, with a total budget of €3.6 M over four years.

During the FP6 project, the European Commission established the "Sustainable Nuclear Energy Technology Platform (SNE-TP)" [6]. This platform sets out a vision for the development of nuclear fission systems within Europe with the aim of increasing sustainability through better use of natural resources, minimisation of waste, and by the replacement of less- (or non-) sustainable technologies. The aims of the SNE-TP are largely aligned with those of Generation IV, but stated from a European perspective. Understandably, fast reactors feature strongly within the strategic research agenda (SRA) [7] of the SNE-TP, as does the development of the nonelectricity applications, such as hydrogen production, using high temperature reactors. The SNE-TP identifies sodium-cooled fast reactors as the best near-term technology that will allow commercial fast reactors to be deployed on the shortest timescale. The alternatives of GFR and the lead-cooled fast reactor (LFR) are considered as being promising candidate technologies for improving the performance of fast reactors in the longer term with the potential of inheriting the non-electricity applications from the high temperature thermal reactors.

The research programme for GFR within the 7th Framework is being drafted at the time of writing this paper. Again, the European project will serve as Euratom's contribution to the GIF, but now this also has to be aligned with vision and the strategic research agenda of the SNE-TP, in which GFR must earn its place as a viable longer term fast reactor technology. Whilst the FP6 project was wide ranging in keeping with spirit of the Gen IV exploratory and preconceptual phases, the FP7 project is more narrowly focused and must demonstrate the viability of GFR for deployment as commercial system.

2. Realising the Full Potential of GFR

The GFR is one of six reactor concepts selected within the GIF [8], three of which are dedicated fast reactors that are attractive because of their potential to meet the Gen IV sustainability goal by both dramatically improving the utilisation of fissile material and by substantially reducing the quantity and radiotoxicity of radioactive waste. Particular merits of GFR are the hard neutron spectrum and the synergy it has with the Very High Temperature Reactor (VHTR), which is also one of the six selected Gen IV concepts. The latter is important for the GFR development strategy, in order to take full advantage of the VHTR development. The two reactor concepts have a common coolant (helium) and both aim for high core outlet temperatures to maximise the thermal efficiency for electricity generation and enhance prospects for hydrogen generation and, as such, share much materials and components technology.

In addition to sustainability, there are important Gen IV goals for Proliferation Resistance, Economics and Safety. The Gen IV goals and their influence on the GFR concept are identified in the GFR System Research Plan [9] and are summarised as follows.

(i) *Sustainability.* This is the key objective for the GFR system. This means full utilisation of uranium resources and calls for the recycling of actinides in a closed cycle. Furthermore, the minimisation of waste and its radiotoxicity requires recycling of both plutonium and the minor actinides together in an integral homogeneous recycling of all actinides present in used fuel. The removal and recycling of certain long-lived fission products (LLFPs) will also be considered.

(ii) *Nonproliferation.* The necessity to avoid, as far as possible, separated materials in the fuel cycle potentially implies minimising the use of fertile blankets. The objective of high burn-up together with actinides recycling results in spent fuel characteristics (isotopic composition) that are unattractive for handling. High burn-ups are the final objective (10–15 at % or more). Minimisation of fuel transport would help proliferation concerns and could be realisable, if very compact facilities can be designed, with onsite fuel treatment.

(iii) *Economics.* A high outlet temperature (850°C or more) is selected for high thermal efficiency, with the use of gas turbine or combined (gas turbine + steam turbine) power conversion cycle and the potential for hydrogen production via the thermo-chemical splitting of water. Gen IV objectives for construction time and costs are also considered.

(iv) *Safety.* The design objective is for no offsite radioactivity release and it requires effectiveness, simplicity, robustness, and reliability of systems and physical barriers. The main development challenges, therefore, are refractory fuels with good fission product retention capability at high temperature (1600°C, or above), the selection of robust structural materials, and the design of effective and highly reliable decay heat removal systems.

With regard to the above goals, two design parameters, temperature and power density, have particular importance. High temperatures are particularly challenging and require innovative fuel and encapsulation concepts. As these are key to the system reaching its full potential, this largely sets the developmental timescale. The power density has a wide-ranging influence, affecting economics (minimisation of fuel inventory, of fuel cycle cost, compactness of the primary vessel), sustainability (reactors with low enough plutonium inventories to allow sufficient flexibility in the fuel cycle for long-term deployment), and safety (in particular decay heat removal in the case of a depressurisation event). Economics and sustainability require higher power densities and safety suggests lower values. The tentative range, approaching 100 MWth/m^3, lies well above gas-cooled thermal reactor values of about 5 MWth/m^3, but still significantly less than sodium-cooled fast reactor power density of about 400 MWth/m^3.

Whilst a phased development path may be drawn from the thermal to the fast-spectrum gas-cooled systems, significant innovation is required to address the technology gaps in order to achieve the ambitious GFR goals. The main technical challenges which are specific to the GFR that must be addressed in demonstrating the viability of the reactor, core and safety systems, and the fuel and fuel cycle processes are:

(i) fuel forms for high temperature operation and tolerance of fault conditions,

(ii) core design, achieving a core that is self-sustaining in fissile material but without the use of heterogeneous fertile “breeder” blankets,

(iii) safety, including decay heat removal systems that address the significantly higher power density (in the range of 100 MWth/m^3) and the reduction of the thermal inertia provided by the moderator in thermal reactor designs, or the liquid metal coolant in other fast reactor systems,

(iv) fuel cycle technology, including simple and compact spent-fuel treatment and refabrication for recycling,

(v) development of core materials with superior resistance to fast-neutron fluence under very-high-temperature conditions with good fission product retention capabilities.

The developmental challenges related to the power conversion system are shared and generally less onerous than those of the VHTR. Alternative conversion cycles are possible and an indirect cycle based on an indirect supercritical CO_2 offers the possibility of a less-challenging moderate-temperature option whilst retaining high thermal efficiency. This option removes the possibility of hydrogen production via thermo-chemical splitting, but still allows its economic production using electrolysis. The latter cycle introduces specific R&D challenges for the power conversion systems that are not shared with the VHTR.

3. Euratom GFR Projects

Two parallel tracks of work have been pursued throughout the FP6 project. These were to develop the concept for a medium-sized to large commercial GFR and to develop the design of a small demonstration plant which has subsequently become known as ALLEGRO. Parallel activities existed in both tracks, concentrating on system design, system safety studies, and methods development. In addition there was a cross-cutting fuels work package aimed at developing fuel concepts for both systems.

3.1. ALLEGRO: A GFR Demonstrator. An experimental reactor is an essential step to establish confidence in the innovative GFR technology. This is in marked contrast to the earlier GCFRs of the 1970s which were based on existing technology to justify the short cut to a prototype/demonstration plant at large size. The proposed experimental reactor, named ALLEGRO, would be the first ever gas cooled fast reactor to be constructed. It will be a small experimental reactor with a power of around 80 MWth. The objectives of ALLEGRO are to demonstrate the viability and to qualify specific GFR technologies such as the fuel, the fuel elements, and specific safety systems, in particular, the decay heat removal function, together with demonstrating that these features can be integrated successfully into a representative system. ALLEGRO will be an essential step in the decisions to be made by 2019 for the launching of a prototype GFR system. As such, it intervenes in the fuel development programme between the small-scale irradiation of materials and fuel samples in material test reactors (MTRs), and available fast reactors, and the full-scale demonstration phase in the prototype GFR.

An important element of the strategy is to take advantage of the synergies with VHTR development. The helium coolant and concepts for energy conversion using a gas turbine are common to both systems, so materials and component research carried out for VHTR are largely relevant to GFR. The implications are that ALLEGRO addresses only the development that is specific to GFR, and having a low power output, it does not require a power conversion system. The main elements of the ALLEGRO system are shown in Figure 1.

ALLEGRO is intended to have three distinct phases of operation based on three different core configurations: a starting core, a starting core in which some of the fuel elements are replaced by modified GFR ceramic fuel

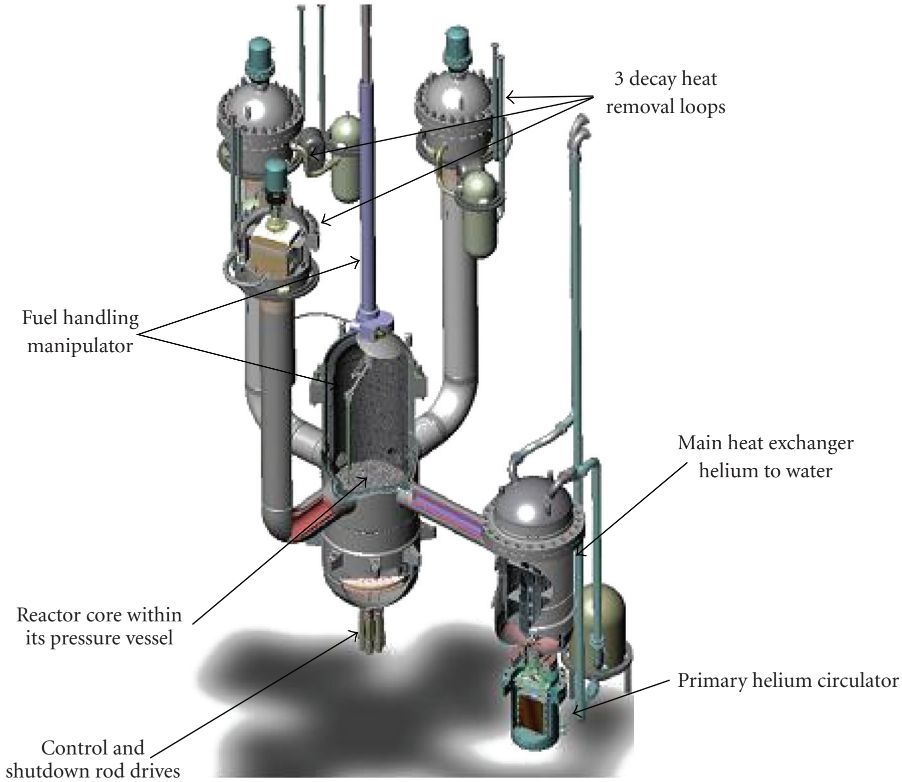

Figure 1: Proposed layout of ALLEGRO, the GFR demonstrator.

elements, and finally a GFR-style all-ceramic demonstration core. The starting core is a fairly conventional fast reactor core based on metallic hexagonal subassemblies containing metal-clad fuel pins which contain mixed-oxide ceramic fuel pellets. Having metal-clad fuel, the outlet temperature of the starting core will be limited to 550°C. The demonstration elements, that will be irradiated within a limited number of positions within the starting core, will contain high-temperature ceramic fuel plates or pins contained within an internally insulated metallic hex-tube, however. The final demonstration elements will be representative of the GFR core and will feature ceramic hex-tubes, such that the core outlet temperature will be increased to 850°C.

The FP6 Euratom contribution to ALLEGRO has been on specific design and safety studies. In-depth studies have been performed in the following areas:

(i) reactor primary system arrangement,

(ii) physics of the starting core,

(iii) fuel subassembly design,

(iv) absorber assembly design,

(v) control and instrumentation,

(vi) reflector and shielding design,

(vii) integration of the design and safety studies,

(viii) risk minimisation measures,

(ix) accident transient analysis.

With regard to the last point, a major programme of benchmarking of transient analysis codes was carried out by cross-comparing the simulations for reference scenarios obtained by different users and different computer codes, ahead of the application of the analysis of real plant transients [10]. This work will be extended in the 7th Framework Programme by comparing the results of these codes against specifically commissioned experimental studies. The current status of the ALLEGRO design can be found in [11].

3.2. GFR Development. At the start of the exploratory phase, a matrix was prepared for the Gen IV GFR studies to facilitate sharing the work between the members. This matrix identified seven combinations of design options. These option studies lead to a preselection of a reference concept and alternatives. The GFR options were as follows:

(1) 600 MWth reference case: high volumetric power (∼100MW/m^3), challenging dispersed fuel (high ratio fuel/matrix), and high temperature direct cycle,

(2) 600 MWth step to reference case: high volumetric power (∼100MW/m^3), challenging dispersed fuel (high ratio fuel/matrix), He at lower temperature as primary coolant, and SC CO_2 as secondary coolant,

(3) 2400 MWth dispersed fuel case: high volumetric power (∼100MW/m^3), more accessible cercer fuel (50/50), and high temperature direct cycle,

(4) 2400 MWth pin case: high volumetric power, SiC clad fuel, and high temperature direct cycle,

(5) 2400 MWth, or more, particle fuel case: moderate volumetric power, particle fuel, and high temperature direct cycle,

(6) 2400 MWth, or more, pin case: moderate volumetric power, SiC clad oxide fuel, and high temperature direct cycle,

(7) generic 2400 MWth indirect cycle (He, SC CO_2) case.

Cases 1 to 5 were with dense fuel (carbide or nitride) and actinide compound. The option grid allowed comparison between concepts as follows:

(i) Case 1 ⇔ Case 2: direct versus indirect cycle comparison at 600 MWth,

(ii) Case 1 ⇔ Case 3: 600 MWth versus 2400 MWth comparison,

(iii) Cases 3, 4, 5, and 6: fuel options and design effect,

(iv) Cases 3 and 4 ⇔ Case 7: direct versus indirect cycle comparison at 2400 MWth.

When the seven cases were shared between the international partners, the European Union took responsibility for the comparison between Cases 1 and 2. These had a common core design with 600 MWth unit power, high volumetric power (~100 MW/m^3), and the challenging dispersed fuel (high ratio fuel/matrix). A low-pressure loss core was also a design objective to enhance the prospect of natural circulation under loss of flow conditions and to reduce blower power consumption under depressurisation faults. The Euratom FP6 project was therefore able to compare the impact of the direct /indirect power conversion cycle on a common basis.

The first priority for the project was to establish an overall reference definition for the 600 MWth GFR direct cycle design. The preliminary system layout is shown in Figure 2. This shows the reference arrangement with a vertical power conversion system (on the right in the figure) with control rod drive mechanisms (CRDMs) above the core and upward flow of the coolant, although alternatives, such as CRDMs below the core, were also considered. This reference serves as the basis for the design and safety studies, which will eventually be fed back into the GFR reference design.

Studies of the impact of minor actinides recycling on the self-sustaining core were carried out, both from the point of view of core neutronic design and the impact of including minor actinides on the safety characteristics of the core. A design concept was established based on the 600 MWth reference that was used as the basis for these actinide transmutation safety studies.

The main objective of the work was to compare the performance of the direct and indirect cycle options. The reference design for the direct cycle was based on the assumption that the helium Brayton cycle developed for the GT-MHR high temperature reactor concept [12] was suitable, provided that a reactor outlet temperature of 850°C could be achieved. The arrangement of the reactor and PCS vessels was taken to be the same as for GT-MHR, that is, the “side-by-side” arrangement based on the use of a vertical axis turbomachine, as shown in Figure 2. The indirect cycle was based on a supercritical CO_2 gas turbine cycle which required a lower core outlet temperature of 680°C. To some extent the choice of direct or indirect cycle was superseded by the shift of emphasis, instigated by the GIF, towards the 2400 MWth plant. Using four 600 MWth power conversion units was considered impractical because of the poor economics of scale resulting from a four-fold increase in the number of moving parts. Similarly, extrapolation of helium turbine and magnetic bearing technology up to the 2400 MWth was considered to be too large and to carry too much technological risk. About the same time, in some HTR programmes, combined cycles were indicating much less risk and more favourable economics. In such a cycle, a small helium (or helium-nitrogen) gas turbine makes best use of the high-temperature heat source, whilst the bulk of the power is generated by a large steam turbine that makes use of the waste heat from the gas turbine. This is an established technology in gas-fired plant, and requires a small extrapolation to be matched with a nuclear heat source. The layout of the containment building for the reference concept for a 2400 MWth GFR with an indirect cycle is shown in Figure 3.

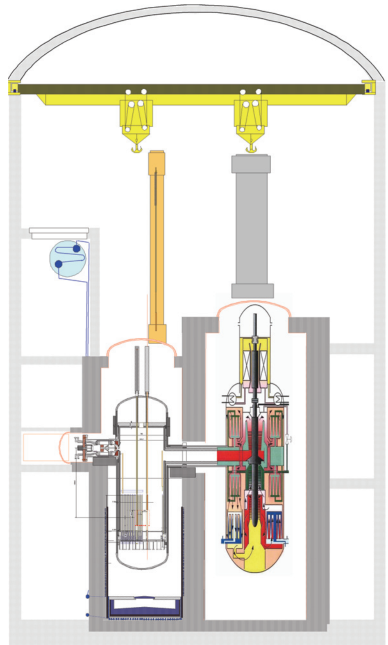

Figure 2: Proposed layout for a 600 MWth GFR with direct cycle.

3.3. Fuel Concepts Development. The greatest challenge facing the GFR is the development of robust high temperature refractory fuels and core structural materials, capable of withstanding the in-core thermal, mechanical, and radiation environment. Safety (and economic) considerations demand a low-core pressure drop, which favours high coolant volume fractions. The zero breeding gain demand restricts the level of plutonium enrichment leading to a demand for high fissile material volume fractions.

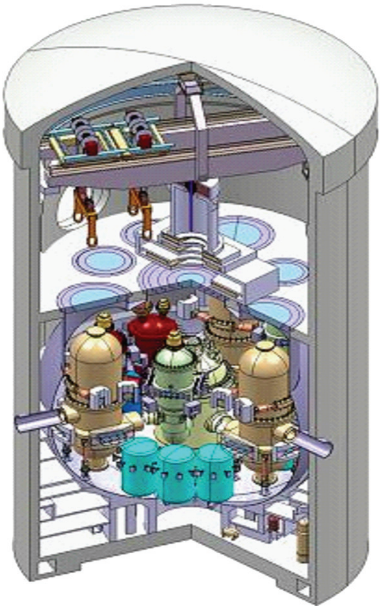

Figure 3: Layout of the 2400 MWth GFR in its containment building.

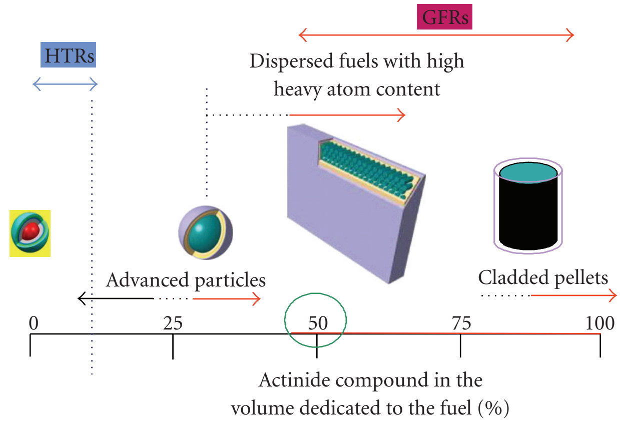

Figure 4: Candidate fuel concepts for GFR.

The concepts now considered are based on incremental innovation of the traditional pellet/pin concept and in the longer term deployment of more radically innovative concepts such as the ceramic coated fuel elements embedded in a ceramic or metallic matrix (CERCER or CERMET); see Figure 4. Candidate compositions for the fissile compound include carbides, nitrides, as well as the oxides. Materials for the encapsulation include ODS steel and SiC for pin formats and ceramic matrices (e.g. SiC, ZrC, TiN) for dispersion fuels in a plate format. Initial selection of the fuel and its cladding will be guided by irradiation tests to be carried out in materials test reactors, such as the High Flux Reactor at Petten, or in available sodium-cooled fast reactors. The final selection and confirmation of the fuel and its encapsulation will require feedback from irradiation in ALLEGRO and because of the high degree of innovation, parallel development paths are required. Whilst there is most experience with oxide fuel, which will be used for the ALLEGRO starting core with conventional stainless steel cladding, the Gen IV goals drive towards the higher density carbide and nitride fuels and high temperature clad. The nitride and carbide are preferred to the oxide as they enable a higher content of actinide per unit volume and permit lower operating temperatures, on account of their superior thermal conductivity.

A review was carried out which covered the irradiation experience in a number of former programmes in which pellet/rod, particle rod, and particle plate geometries were deployed. Fabrication technology to produce new fuel types has been studied and developed. Promising processes have been identified within the review, some of which have been assessed and compared, with further work required in the 7th Framework Programme. A strategy for the development of selected processes will be produced. Finally, the planning and design of irradiation tests of promising fuel and cladding material candidates will be undertaken in the 7th Framework Programme.

3.4. Dissemination of Project Information. The knowledge generated in the Euratom GFR projects contributes to the long-term development programme, which will span a number of Framework Programmes and is planned for successful completion over 3 decades. The access to knowledge generated within the project is made available to all the participants of any given project. It is intended that the knowledge generated contributes to the collaboration on Gen IV GFR and in return the knowledge generated by the Gen IV GFR partners will be available to participants with the Euratom projects.

It is important to raise public awareness and improve the public's perception generally of the nuclear industry. The project maintains a communication action plan to facilitate this. As well as contributing papers to journals and international conferences, Euratom projects provide material and contribute to the initiatives that are taken by the European Commission in the preparation of public information announcements and in engaging wider international involvement of non-European nations.

3.5. Education and Training. The objective of the training activities within Euratom's GFR projects is to contribute, in this particularly innovative field, to the transfer of knowledge from experienced scientists to the young engineers and researchers.

It is essential to have a project with a vision and long-term goal to attract newly qualified scientists and engineers. This is the first requirement, and the gas cooled reactor projects of which the Euratom GFR projects are important contributions, as well as giving access to the larger Gen IV GFR project. It is also important to have a project of sufficient size to be able to deploy a balanced multidisciplinary team combining experienced engineers and scientists together with those who are being trained.

There is a significant knowledge base on gas cooled and fast reactor technologies within Europe, which is essential to pass on to the next generation. An important way to do this effectively is by application to a project with challenging R&D goals that require the knowledge base and can continue to further develop the knowledge. Euratom recognises that much of this experience rests in "old" hands and appreciates the need to promote young engineers and scientists who will progressively assume responsibility so that they have leading roles taking the project into the future framework programmes.

During the course of the 7th Framework Programme, training courses for young scientists and engineers will be organised, related to the GFR activities, some of which will be in conjunction with the sister sodium-cooled fast reactor and high temperature gas reactor projects.

4. Conclusions

Euratom has sponsored research programmes into the development of the gas cooled fast reactor system within the 5th and 6th Framework Programmes and has called for a follow-on project in FP7. The FP6 and FP7 projects provide Euratom's input into the GFR system in the Generation IV International Forum. These projects have been prepared by many European companies, research institutions and are fully integrated in the Gen IV GFR programme which is now dependant upon the task sharing between partners, including the Euratom contribution, to achieve the milestones up to the end of the viability phase in 2012.

In detail, the FP6 project has covered

(i) 600 MWth and 2400 MWth plant options,

(ii) ALLEGRO core and system design,

(iii) GFR and ALLEGRO safety analyses, including the analysis of selected transients,

(iv) qualification and benchmarking of the transient analyses codes through a series of benchmark exercises,

(v) a review of candidate fuels and core materials, including their fabrication and irradiation;

(vi) education and communication to foster understanding of the growing needs for nuclear power in general, and for the technology of the GCFR in particular, are a specific goals of the project.

An important outcome from the exploratory studies is the identification of the R&D needs and the specification of the programme by which they will be achieved, leading to construction of ALLEGRO and its missions in the GFR R&D programme. This programme will form the basis for the on-going Euratom 7th Framework Programme contribution from 2009 onwards.

Acknowledgments

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